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Soheil Shayegh & Shouro Dasgupta

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Soheil Shayegh [a] and Shouro Dasgupta [a,b,c,d]

[a]RFF-CMCC European Institute on Economics and the Environment (EIEE), Centro Euro-Mediterraneo sui Cambiamenti Climatici, Milan, Italy; [b]Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Milan, Italy; [c]Department of Environmental Sciences, Informatics and Statistics, Università Ca' Foscari Venezia, Venezia, Italy; [d]Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science (LSE), London, UK

ABSTRACT
Women in developing countries are more exposed to the adverse effects of climate change. We develop a structural model to study the long-term impacts of climate and socioeconomic changes on labour supply and the pay gap between male/female and high-skilled/low-skilled labour. We calibrate our model with empirical evidence on the impacts of increasing temperatures on labour availability in two general economic sectors with high and low exposure to rising temperatures. Using five waves of nationally representative micro-survey data in South Africa from 2008 to 2017, we find that while high-skilled labour availability is insensitive to climate change, higher temperatures have a negative impact on working hours of low-skilled labour specially among women in the high-exposure sector. We incorporate these findings in an overlapping generations (OLG) model to show that climate-induced reduction in labour availability increases the relative wages of low-skilled female labour and reduces the wage gap between male and female labour in the high-exposure sector, and between high-skilled and low-skilled female labour, in general. Considering climate change damages both on sectoral productivity and on labour availability, we project that by the end of the century, the output per adult will drop by about 11 percentage points under a severe climate scenario. This calls for more targeted adaptation policies that build on the potential benefits of climate change in reducing gender inequality and empowering women to take up more active roles in designing and implementing such policies at the local level.

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Gender inequality; labour; wage; skill; Africa; South Africa

1. Introduction

Climate change affects natural and human systems at an unprecedented rate (Smith et al. 2015). The socioeconomic impacts of climate change vary across regions and economic sectors depending on their adaptive capacity. While some populations such as those in coastal areas are directly affected by changes in the natural environment (Hinkel et al. 2018), other vulnerable populations might suffer the impacts of climate change indirectly through changes in various aspects of their socioeconomic environments (Burke et al. 2015; Carleton & Hsiang 2016; Dasgupta et al. 2021) such as demographic change (Casey et al. 2019) and migration (Shayegh 2017). In labour markets, increasing temperatures may result in a non-linear reduction in hours worked in industries with high exposure to heat such as agriculture and construction (Antonelli et al. 2020; Bale et al. 2002; Graff Zivin & Neidell 2014). Reduction in labour supply can then impact the overall productivity of these labour-intensive industries (Shayegh et al. 2020; Somanathan et al. 2015). In this paper, we focus on the gender dimension of climate change by investigating its impact on women's labour force availability specially in high-exposure sectors such as agriculture in developing countries.

1.1. Effects of climate change on Women's well-being

Climate change has an asymmetric impact on genders. Women in developing countries, in particular, are more vulnerable to the impacts of climate change (Nagel 2015; Sorensen et al. 2018). Compared to men, women are more physiologically susceptible to high temperatures and less tolerant of heat stress (Desai & Zhang 2021). Exposure to high temperatures also contributes to birth defects and other reproductive complications that directly impact women's health (Van Vuuren et al. 2011). Furthermore, women in developing countries are socioeconomically more vulnerable to the impacts of climate change due to their higher rates of anaemia and malnutrition (Goh 2012), and their lower education and socioeconomic status (Sorensen et al. 2018). For example, household survey data and focus group interviews have highlighted the role of education and accessibility to land and other resources in determining the sensitivity of women farmers to climate change (Pérez et al. 2015). Women are also at higher risk of physical and domestic violence due to rising temperatures (Henke & Hsu 2020). In South Africa in particular, there is a growing concern over climate-driven domestic violence against women as temperatures rise unprecedentedly (Chersich et al. 2019).

CONTACT Soheil Shayegh soheil.shayegh@eiee.org

Growing evidence of climate change's unequal impact on women has led some researchers to suggest that gender disparities in vulnerability to climate change reflect pre-existing gender inequalities and even reinforce them. Using a sample of developing states between 1981 and 2010, it has been shown that climate shocks and disasters have a broadly negative impact on gender equality (Eastin 2018). This is due to a decline in women's economic and social rights as a result of the increase in temperatures, and climate-related disasters. Other studies have investigated a broader range of countries and have found that in all countries, regardless of their development status, a gender gap prevails in both income and assets (Jost et al. 2016). Other studies have framed climate change impacts on poverty (Cannon 2002) and income inequality (Eastin 2018) in a broader context of climate justice (Terry 2009).

Furthermore, it has been shown that women in rural areas of African countries have less access to adaptive measures such as common property resources and financial resources such as cash for purchasing goods or services to shield them against the consequences of climate change (Pérez et al. 2015). To overcome these barriers to adaptation, women empowerment can play a crucial role in improving women's position in decision making in different levels from household to a national parliament. Studies have shown that women in rural areas are more concerned about environmental issues and can play a proactive role in supporting policies regarding environmental restoration (Yadav & Lal 2018).

1.2. Climate change and gender in rural areas of South Africa

Although South African economy and labour market are closer to those of middle-income countries such as Thailand and Brazil and distinct from those of lower-income developing countries such as Pakistan, Haiti and Tanzania (Fields 2011), still when it comes to the women's role in rural communities, many of them are involved in the agricultural sector and their livelihood and those of their families depend on their supply and the farm's productivity, both of which are subject to negative impacts of climate change. Hence, as climate change damages expand from the individual level to South Africa's communities and economic sectors such as farming and agriculture, they exacerbate pressure on women's health and well-being in rural areas and negatively impact their productivity and income (Flatø et al. 2017).

Although the impacts of climate change on women's well-being have been qualitatively examined through several case studies (Louis & Mathew 2020; Vincent et al. 2010), most of these studies fail to devise a mechanism that can explain how environmental factors through changes in labour supply may trigger demand for a different type of labour and therefore, change the wage inequality. Furthermore, empirical findings about the impact of climate change on women's employment in developing countries and specially the pay gap between male and female labour paint a less clear picture. While some studies show a positive relationship between environmental factors such as rainfall shocks and women's income in agricultural sector (Mahajan 2017), other studies have found that rain shocks can reduce women's employment in rural Africa (Bhalotra & Umana-Aponte 2010). Such inconsistencies in empirical studies highlight the need for a case-by-case approach to investigate the linkage between climate stressors (e.g. temperature increase, floods, droughts, etc.) and women's employment in specific regions and countries.

1.3. Our contribution

In this paper, we go beyond establishing a mere statistical relationship between climate stressors (e.g. temperature rise) and working time by developing a theoretical framework capable of explaining the relationship between environmental changes and their long-term impact on labour availability and wage inequality.

First, we use a comprehensive dataset from five waves of a longitudinal national household survey in South Africa between 2008 and 2017 to investigate the relationship between temperature and weekly working hours. We follow the recent literature on the labour impact of climate change (Dasgupta et al. 2021; Shayegh et al. 2020) where temperature increases were shown to have a larger impact on the supply of low-skilled labour than on the supply of high-skilled labour. In this paper, we add to this literature and go one step further to show that within the low-skilled labour population, female labour is more vulnerable to an increase in temperature than male labour which in turn, can improve the gender pay gap within the economic sector with high-exposure to heat which employs mainly low-skilled labour.

Second, we use a conceptual framework and develop an overlapping generations (OLG) model with different types of labour based on their skill and gender, and with damage functions calibrated to the findings from our empirical study. We account for asymmetric impacts of climate change on labour availability (female/male and high-skilled/low-skilled labour) and sectoral productivity (high-exposure/low-exposure sectors). We analyse the prospect of wage inequality among different labour types and gender under moderate demographic projections of the second Shared Socioeconomic Pathway (SSP2) (Lutz 2017) and different temperature trajectories driven from four Representative Concentration Pathways (RCPs) (Moss et al. 2010).

Finally, our findings confirm that climate change decreases the relative availability of female low-skilled labour who are usually employed in sectors with high-exposure to heat. Keeping everything else constant, a reduction in labour availability causes the relative wages of low-skilled female labour to increase which closes the wage gap between male and female low-skilled labour as well as the wage gap between low-skilled and high-skilled female labour. The gender impact of climate change, therefore, can be modelled similar to the impact from other external shocks such as war. In the case of war, however, the decline in the supply of male labour, due to their more direct participation in the war, leads to an increase in female labour participation (Acemoglu et al. 2004).

Our results also show that relative gains from closing the gender pay gap are likely to be compensated by the overall negative impact of climate change on economic output under all projections of climate change[1].

2. Empirical evidence

2.1. Background data

We use econometric evidence from a longitudinal survey data in South Africa to focus on the impact of weekly temperature on the supply of workforce and income in different sectors with an emphasis on differentiated impacts by gender. There is evidence that as maximum temperature increases above 30°C, workers in the U.S. industries with high climate exposure reduce the time allocated to labour (Graff Zivin & Neidell 2014) and the total output reduces subsequently (Antonelli et al. 2020; Somanathan et al. 2015). However, there is a lack of micro-founded evidence on gender-differentiated impact of temperature on individuals' working time and wage.

Our data come from five waves (2008–2017) of the National Income Dynamics Study (NIDS) conducted by the Southern Africa Labor and Development Research Unit (SALDRU) based at the University of Cape Town[2]. This is the first nationally representative panel study of households in South Africa and uses a stratified, two-stage cluster sample design to sample households in the nine provinces of the country. NIDS primarily examines the livelihoods of individuals and households over time and provides information on coping with shocks, poverty and well-being; fertility and mortality; migration; labour market participation and economic activity; human capital, health and education; and vulnerability and social capital. Our labour supply variable is based on the actual number of hours worked in a given week the primary occupation of the respondent while income is defined as total income earned by the respondent from the primary occupation in a given month.

The survey also provides information on the occupational code for each respondent, we re-categorize the 10 occupational codes for the primary occupation into; high-exposure (agricultural, hunting, forestry and fishing; mining and quarrying; and construction), low-exposure (manufacturing and utilities) and services (private household service; NGO, foreign government; wholesale and retail; transport, storage and communication; finance and insurance; and community service). Table 1 shows the wages by gender and exposure-level in South Africa for the five waves with the numbers suggesting a significant difference in wages between males and females in all the three sectors. Sociodemographic information such as age, years of schooling, and marital status are provided during the week of the survey while the health conditions question requests information from the 30-days before the interview.

Climatic data come from the Global Land Data Assimilation System (GLDAS) v2.1. This is a global gridded reanalysis dataset (Rodell et al. 2004) with a spatial resolution of 0.25° × 0.25° and 3-hourly temporal resolution. We aggregate the climatic data to the weekly and cumulative periods. The climatic data are merged with the data from the NIDS survey using the coordinates of the households and date of interviews (Figure 1.)

2.2. Climate change impacts on labour supply

Following Antonelli et al. (2020), Dasgupta et al. (2021), and Shayegh et al. (2020), we use the econometric framework below to investigate the impact of temperature on labour supply in South Africa;

$$d_{it} = f(temp_{dt}) + \delta X_{it} + \phi Z_{hm} + \theta_p + \gamma_t + \epsilon_{it} \tag{1}$$

We utilize a truncated Poisson and the panel nature of the NIDS dataset to investigate the impact of weekly maximum temperature on the number of hours worked in the primary occupation for low-skilled and high-skilled workers[3]. Our dependent variable (d_{it}) is the number of hours worked (labour supply) by an individual worker i in a given week t. $f(temp_{dt})$ represents the non-linear impact of maximum weekly (in the same week as reported working hours) district-level temperature on labour supply, the number of working hours may increase due to temperature increases at relatively cold temperatures, however, beyond a threshold – incremental increases in temperature may have a negative impact (Antonelli et al. 2020; Galloway & Maughan 1997; Graff Zivin & Neidell 2014; Shayegh et al. 2020). This is controlled for by including both the linear and second-degree polynomial terms of maximum weekly temperature. We use weekly maximum temperature instead of weekly mean temperature as Shayegh et al. (2020) show that weekly labour supply in South Africa is more responsive to weekly maximum temperature instead of mean temperature. We also control for precipitation as a robustness test, however, we do not find statistically significant impact of precipitation on labour supply in South Africa. This is in line with Antonelli et al. (2020), who find no impact of weekly precipitation on weekly working hours in Uganda.

The term δX_{it} represents individual-level covariates including age (and its second-degree polynomial), educational qualification and health condition. The term ϕZ_{hm} represents the log of monthly household income (and its second-degree polynomial) in month m. Our base specification also includes year-season [4], week and household-level (θ_p) fixed-effects capturing all time-invariant household attributes affecting labour supply. ϵ_{pt} is a random error-term. These fixed-effects allow us to identify the effects of weekly temperature with the plausibly exogenous variation in temperature over time within districts and within seasons, thus, the temperature-related parameters are estimated from weekly variations within a district.

We estimate Equation (1) separately for the labour in low and high-exposure sectors. Our standard-errors are clustered

Table 1. Average wages by gender and sector in South Africa.

Wages (South African rand)	Wave 1	Wave 2	Wave 3	Wave 4	Wave 5	Average
Male (high-exposure)	1896	2629	3334	4252	5783	3579
Female (high-exposure)	1328	1967	2030	2803	3585	2343
Male (low-exposure)	3659	4443	4271	5690	8024	5217
Female (low-exposure)	2335	2284	3210	3791	4723	3269
M/F ratio (high-exposure)	1.43	1.34	1.64	1.52	1.61	1.53
M/F ratio (low-exposure)	1.57	1.95	1.33	1.50	1.70	1.60

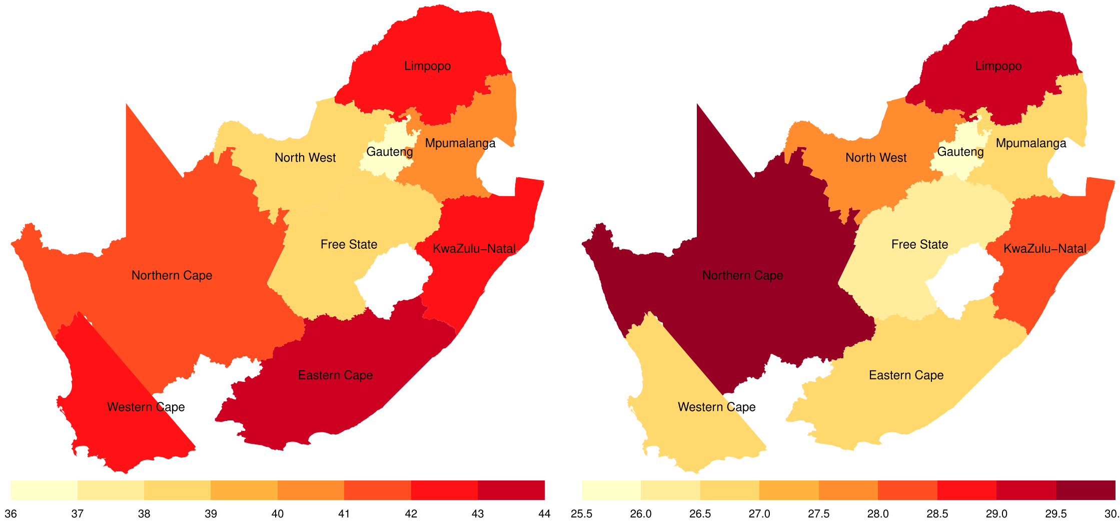

Figure 1. Maximum temperature (left panel) and mean temperature (right panel) by province in South Africa.

at the district-level. Finally, we compute marginal effects of change in temperature as the change in the labour supply of a given respondent that occurs from an increase in temperature of 0.2°C. This is calculated as the first derivative of the number of weekly hours worked with respect to weekly temperature from the regression model specified in Equation (1). The marginal-effects for each type of labour are then used to calibrate our OLG model. One caveat of this econometric specification is the focus on labour supply and not on the equilibrium effects in terms of wage adjustments. Since, we examine climate impacts at the household-level, data availability makes it difficult to incorporate production (e.g. crop yields) effects. However, for the theoretical modelling, we use the global estimates of productivity loss in each sector (Desmet & Rossi-Hansberg 2015) which allows us to account for indirect effect of climate change on labour supply. Another caveat is that we do not consider unemployment as an alternative to decreased working hours in our study. Although the NIDS provides some information about unemployment at the household level, these data cannot be fully utilized in our econometric setup. Therefore, the omission of the unemployment in labour force can potentially limit the implications of the results in terms of wage adjustments.

2.3. Econometric results

The results presented in Table 2 suggest that in the high-exposure sector, the supply of male workers is maximized at a weekly maximum temperature of 27.6°C. However, for female workers, the optimal maximum temperature is significantly lower at 26.7°C. This is particularly concerning because not only women earn much less compared to men (Table 1) but also the temperature threshold beyond which their weekly working hours decline is lower. This lower optimal temperature for female workers suggest that their productivity is peaked earlier compared to male workers and the negative impacts of clime change begin at a lower temperature level (Figure 2), this difference in optimal temperatures can be partially explained by physiological differences between men and women in response to thermoregulation (Andérson et al. 1995; Iyoho et al. 2017).

We do not find differentiated impacts on male and female workers in the low-exposure sector, with optimal conditions for both groups being maximized at 28.6°C (Figure 3). We also control for total weekly precipitation; however, this variable is not statistically significant (columns 5–8 in Table 2) and it does not influence the magnitude or statistical significance of the other variables. The grey shaded area shows the range of projected increases in maximum temperature under RCP2.6 and RCP8.5 scenarios in South Africa. In all the marginal plots above, the projected values are beyond the optimal temperatures (peaks) maximizing labour supply. Given the optimal temperature maximizing female labour supply is lower than the one maximizing male labour supply, future increases in maximum temperature are likely to have a greater adverse impact on female working hours compared to their male counterparts.

2.4. Robustness tests

As a robustness test, we estimate Equation (1) for both genders differentiating by exposure-level of the corresponding sector. The results in Figure 4 suggest that the labour supply in the high-exposure sector is maximized at a maximum weekly temperature of 26.3°C while the optimal temperature in the low-exposure labour force is higher at 28.1°C. The results also show that being female has a negative and statistically significant impact on weekly labour supply in both sectors.

Furthermore, we re-estimate Equation (1) using an OLS specification taking the natural log of the number of hours worked in a given week. We add 1 to all the observations of labour supply before the log transformation to ensure that the zero values are included in the regression. The results from this specification (Figure 5) suggests that the labour supply in the high-exposure sector is maximized at a maximum weekly temperature of 25.3°C while the optimal

Table 2. Main regression results.

	(1) High-exposure male	(2) High-exposure female	(3) Low-exposure male	(4) Low-exposure female	(5) High-exposure male	(6) High-exposure female	(7) Low-exposure male	(8) Low-exposure female
Age	−0.030***	−0.020***	−0.040**	−0.085***	−0.031***	−0.022***	−0.044**	−0.081***
	(0.000)	(0.000)	(0.036)	(0.000)	(0.001)	(0.000)	(0.031)	(0.009)
Age-squared	0.0003***	0.0002**	0.0005***	0.001***	0.0003***	0.0002**	0.0005***	0.001***
	(0.003)	(0.025)	(0.000)	(0.000)	(0.008)	(0.029)	(0.002)	(0.004)
Married	5.214**	−1.877**	6.147**	−1.369**	5.213**	−1.878**	6.158**	−1.375**
	(0.011)	(0.034)	(0.028)	(0.030)	(0.015)	(0.036)	(0.024)	(0.031)
Years of schooling	0.617	0.877	1.259**	1.852**	0.619	0.814	1.241**	1.856**
	(0.216)	(0.335)	(0.048)	(0.027)	(0.210)	(0.214)	(0.044)	(0.022)
Health condition	−1.256***	−2.852***	−1.025***	−2.111***	−1.261***	−2.859***	−1.039***	−2.210***
	(0.000)	(0.000)	(0.004)	(0.000)	(0.000)	(0.005)	(0.005)	(0.006)
Log of income	0.124**	2.185**	2.101**	2.147**	0.128**	2.184**	2.111**	2.544**
	(0.018)	(0.041)	(0.031)	(0.036)	(0.020)	(0.045)	(0.035)	(0.030)
Log of income squared	−0.007***	−0.127**	−0.124**	−0.115**	−0.007***	−0.130**	−0.128**	−0.110**
	(0.000)	(0.020)	(0.034)	(0.029)	(0.004)	(0.021)	(0.044)	(0.020)
Max temperature	0.314**	0.266***	0.305***	0.457***	0.315**	0.267***	0.306***	0.455***
	(0.018)	(0.006)	(0.000)	(0.002)	(0.021)	(0.001)	(0.000)	(0.000)
Max temperature squared	−0.006**	−0.005***	−0.005***	−0.008***	−0.006**	−0.005***	−0.006***	−0.008***
	(0.030)	(0.006)	(0.001)	(0.003)	(0.036)	(0.009)	(0.008)	(0.000)
Total precipitation					−0.522	−0.001	−0.581	−0.047
					(0.550)	(0.211)	(0.633)	(0.300)
Observations	16,132	12,996	15,615	12,458	3,921	1,372	1,372	16,920

Note: *p*-values in parentheses *** p<0.01, ** p<0.05, * p<0.10, $+p < 0.15$

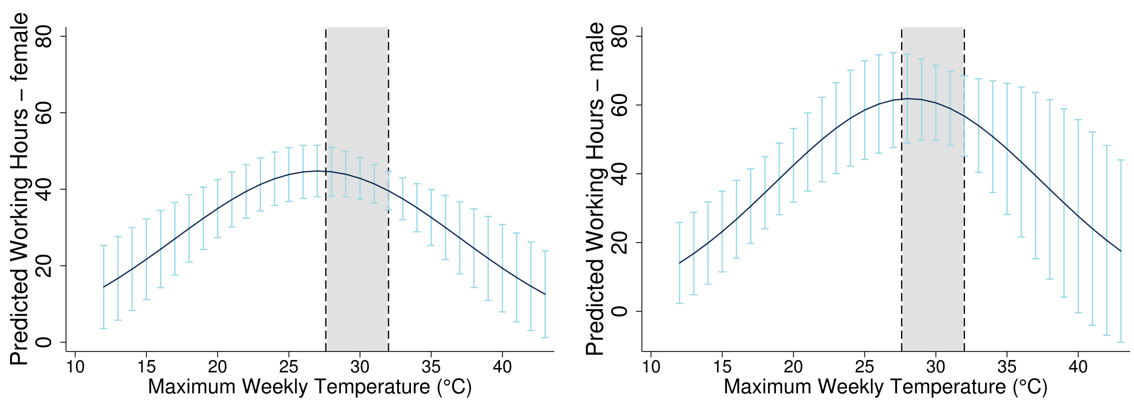

Figure 2. Non-linear relationship (dark navy line) between weekly maximum temperature and labour supply in the high-exposure sector with 95% confidence interval (light blue spikes). Grey shaded area shows a projected increase in maximum temperature under RCP2.6 and RCP8.5. Left panel shows the impact on female workers in the high-exposure sector ($N = 12, 996$) and the right panel shows the impact on male workers in the high-exposure sector ($N = 16, 132$). Specification controls for maximum weekly temperature (and its second-degree polynomial), age (and its second-degree polynomial), marital status, education level, health condition, total household income (and its second-degree polynomial) and household, week and year-season fixed-effects.

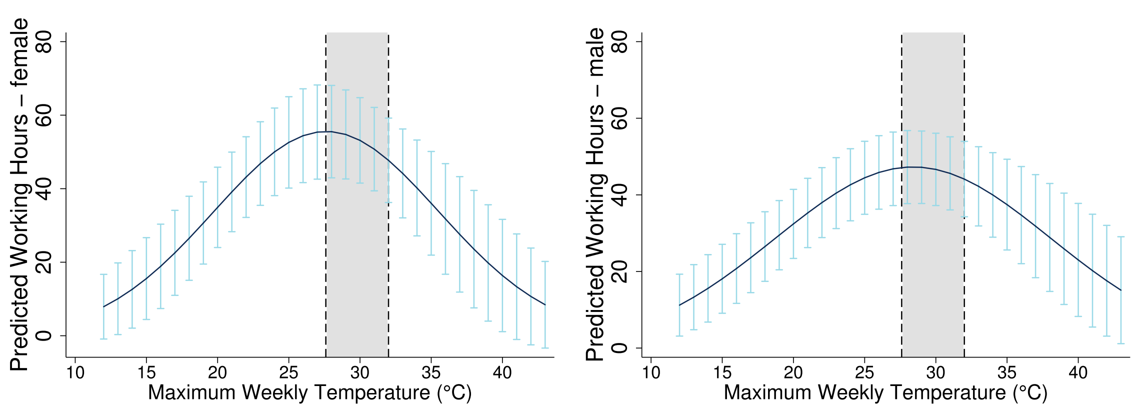

Figure 3. Non-linear relationship (dark navy line) between weekly maximum temperature and labour supply in the low-exposure sector with 95% confidence interval (light blue spikes). Grey shaded area shows projected increase in maximum temperature under RCP2.6 and RCP8.5. Left panel shows the impact on female workers in the low-exposure sector and the right panel shows the impact on male workers in the low-exposure sector. Specification controls for mean monthly temperature (and its second-degree polynomial), age (and its second-degree polynomial), education level, health condition, total household income (and its second-degree polynomial), and household, week, and year-season fixed-effects.

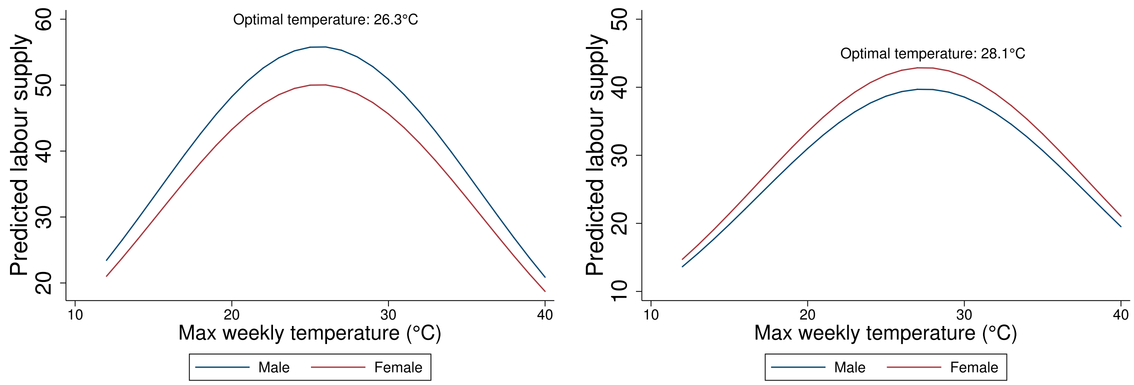

Figure 4. Non-linear relationship between weekly maximum temperature and gender differentiated (male: navy line; female: red line) labour supply. Left panel shows the impact on the high-exposure sector ($N = 16, 246$) and the right panel shows the impact on the low-exposure sector ($N = 15, 969$). Specification controls for maximum weekly temperature (and its second-degree polynomial), age (and its second-degree polynomial), gender, education level, health condition, total household income (and its second-degree polynomial) and household, week and year-season fixed-effects.

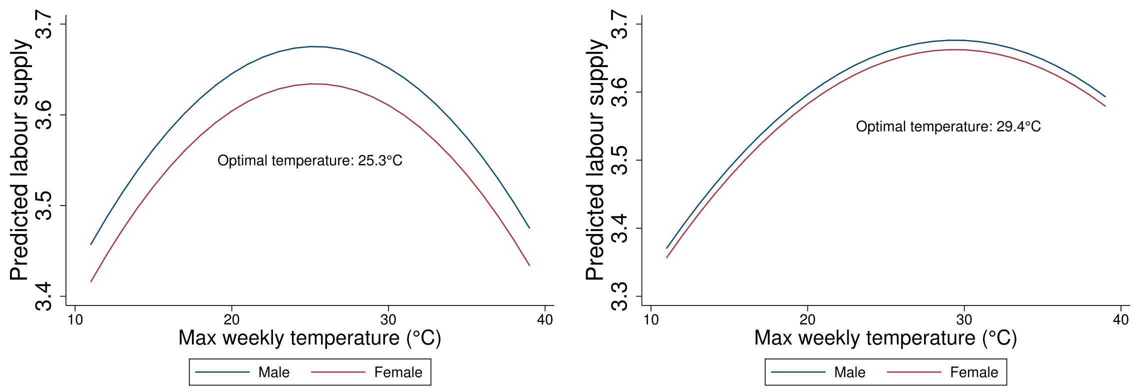

Figure 5. Non-linear relationship between weekly maximum temperature and gender differentiated (male: navy line; female: red line) labour supply using an OLS specification. Left panel shows the impact on the high-exposure sector ($N = 16, 246$) and the right panel shows the impact on the low-exposure sector ($N = 15, 969$). Specification controls for maximum weekly temperature (and its second-degree polynomial), age (and its second-degree polynomial), gender, education level, health condition, total household income (and its second-degree polynomial) and household, week and year-season fixed-effects.

temperature in the low-exposure sector is higher at 29.4°C. Both of these additional regressions support our findings in the main specification (Figure 4).

We run a number of additional robustness tests focusing on different fixed-effects. When week fixed-effects are replaced by month fixed-effects, male labour supply in the high-exposure sector is maximized at a weekly maximum temperature of 27.3°C (difference of −0.3°C from the main specification) while the optimal temperature for female labour supply in this sector is 26.5°C (difference of −0.2°C from the main specification). We also run an additional specification with province fixed-effects instead of district fixed-effects. In this case, the optimal weekly temperature maximizing labour supply for male workers in the high-exposure sector is 27.7°C (difference of +0.1°C from the main specification) while female labour supply in this sector is maximized at 26.6°C (difference of −0.1°C from the main specification). Overall, the results of these tests indicate that our main specification in Table 2 is robust and can be used for calibration of the OLG model.

To explore the impact of cumulative warming over a year on male and female labour supply, we replace the weekly maximum temperature specification with a binned daily maximum temperature specification (Table A1 in the Appendix). Daily maximum temperature is grouped into 5°C with two additional ones; below 10°C and above 40°C. The results from these regressions are in line with the main specification, showing that additional days of maximum temperature in the bins below the reference bin increases labour supply in South Africa for both men and women. However, additional days in the bins in the higher temperature level bins result in a decrease in labour supply. Furthermore, these negative impacts on labour supply are higher on female labour supply in both the low and high-skilled sectors.

2.5. Impact of temperature on labour through income

We also look at the impact of temperature on labour supply through using a two-stage least squares (2SLS). In the first-stage, we derive a relationship between cumulative precipitation in the 12 months before the interview and total income (I_{it}) for each individual worker i at time t. Since I_{it} is endogenous, cumulative precipitation in the previous 12 months is used as an exogenous instrument. This specification is important as there might be reverse causality between income and labour supply. As for the validity of the instrument, cumulative precipitation is likely to effect total income but should not affect weekly labour supply.

$$Z_{it} = \{P_{it}\} \tag{2}$$

However, contemporaneous weekly in the week of the survey was conducted is likely to have a direct impact on labour supply. To estimate this effect, total income, which is endogenously determined, is instrumented. All additional control variables in the second-stage are included in the first-stage regression, including household and time fixed-effects.

Our findings show that cumulative precipitation has a positive impact on total income in South Africa. Importantly, we reject the under-identification test (Kleibergen-Paap rk LM statistic) but cannot reject the Hansen test based on the *J*-statistic (over-identification test of all instruments). Both these results indicate that the instrument used is valid. While Jayachandran (2006) finds that *rain shock* (based on the distribution of annual rainfall) affects labour supply in the agricultural sector, we use cumulative precipitation in the previous 12 months before the interview as an instrument. Further, Jayachandran (2006) examines the impact at the sub-national level in India while we focus on the individual and household-level responses, as such the impact of cumulative is less likely to affect labour supply.

The results from the 2SLS regression (Table 3) show that the optimal weekly temperatures maximizing labour supply are lower than those estimated from the OLS regression in Section 2.3. In the low-skilled sector, male labour supply is maximized at 25.3°C while female labour supply is maximized at a lower temperature level of 24.3°C compared to 27.6°C and 26.7°C, respectively, estimated from the OLS regression. Unlike the OLS specification, the 2SLS specification shows differentiated optimal temperature levels between male and female workers in the high-skilled sector.

3. Theoretical model

We consider a simple model of labour market dynamics based on an overlapping generation (OLG) framework (Casey et al. 2019; Diamond 1965; Galor 2011) with two genders, two skill levels of labour, and two economic sectors. We keep the structure of the model simple in order to capture most of the transformation characteristics of economy and labour.[5] Our model differs substantially from the earlier attempts (Casey et al. 2019; Shayegh et al. 2020) to model labour dynamics in the OLG framework in three distinct aspects:

- *Gender-specific labour force*: we explicitly account for the population of male and female participants in the labour force.
- *Gender-specific climate impact*: we further assign different supply factors to each group of labour depending on their skill level and gender.
- *Gender-specific outcomes*: finally and based on these modifications, we are able to modify the model and report the outcomes such as wages based on gender specifications of the labour force.

We assume that the economic sectors are either high-exposure (e.g. agriculture) with only low-skilled labour (Caselli & Coleman 2001; Gollin et al. 2014) or low-exposure (e.g. manufacturing) with only high-skilled labour. We assume climate change impacts both the availability of labour depending on gender and skill level and also the productivity of production in each sector which induces additional damages to the final output. We present the results of the main setup with both damages here. The results of the model with damages on labour availability only, and with damages on economic productivity only, are provided in the appendix.

In our model, individuals live for two periods and are assigned a gender (male or female) and a skill level (high-skilled or low-skilled). At the beginning of each period, parents decide about the number of children and the level of education they will provide to them which determines what skill level these children will possess in the next period. The model can be solved to yield the optimal education and fertility decision

Table 3. 2SLS regression: impact of temperature on labour supply through income.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Low-skilled male		Low-skilled female		High-skilled male		High-skilled female	
	First stage	Second stage	First stage	Second stage	First stage	Second stage	First stage	Second stage
Log of income		0.111**		0.094**		0.136**		0.109**
		(0.041)		(0.030)		(0.027)		(0.044)
Age	−0.028***	−0.028	−0.026***	−0.024***	−0.039***	−0.079***	−0.021***	−0.026***
	(0.002)	(0.466)	(0.000)	(0.006)	(0.000)	(0.002)	(0.000)	(0.006)
Age-squared	0.0003	0.0003***	0.0003***	0.0004***	0.0004***	0.001***	0.0003	0.0004**
	(0.241)	(0.003)	(0.009)	(0.005)	(0.005)	(0.000)	(0.222)	(0.017)
Married	2.665***	5.021***	−2.741***	−4.228***	3.044***	6.227***	−2.004***	−4.51**
	(0.000)	(0.002)	(0.000)	(0.004)	(0.009)	(0.006)	(0.002)	(0.027)
Years of schooling	0.886**	0.910**	0.774**	0.709**	1.24***	1.333***	0.809**	0.747**
	(0.033)	(0.026)	(0.015)	(0.033)	(0.008)	(0.004)	(0.019)	(0.039)
Health condition	−0.635***	−1.899***	−0.859***	−2.599***	−0.552***	−1.274***	−107***	−2.072***
	(0.003)	(0.001)	(0.006)	(0.001)	(0.000)	(0.000)	(0.002)	(0.000)
Max temperature	0.442***	0.304***	0.433***	0.292***	0.460***	0.318***	0.388***	0.311***
	(0.009)	(0.004)	(0.002)	(0.000)	(0.000)	(0.008)	(0.006)	(0.000)
Max temperature squared	−0.008***	−0.006***	−0.008***	−0.006***	−0.008***	−0.006***	−0.008***	−0.006***
	(0.003)	(0.009)	(0.007)	(0.005)	(0.008)	(0.000)	(0.000)	(0.007)
Cumulative 12-month precipitation	0.108**		0.117***		0.711*		0.136*	
	(0.021)		(0.000)		(0.113)		(0.108)	
Observations	16,132	16,132	12,996	12,996	15,615	15,615	12,458	12,458
Optimal temperature (°C)		25.3		24.3		26.5		25.9

Note: Robust *p*-values in parentheses *** p<0.01, ** p<0.05, * p<0.10, $+p < 0.15$.

in each period. The emphasis of the model is on the education level of children and how parents make such decision by maximizing their utility function. Detailed description of this OLG model is presented in the appendix. The model is solved for each generation to calculate the number of high-skilled and low-skilled children of each gender for the next generation given the future climate change projections and the predicted wage differences in the labour market.

3.1. Wage dynamics

One of the key underlying mechanisms of the mode is that the wage ratios among high-skilled and low-skilled labour and among male and female labour are controlled by the child-rearing cost ratios that depend on each child's gender and their assigned level of education. The wage ratios are also controlled by the ratio of damages to the availability of the labour of each gender and skill level (see Equations (A4) to (A7) in the appendix). As a result, the negative impacts of climate change on the availability of a certain group of labour (e.g. low-skilled female labour) will create a demand for this type of labour that can be foreseen by parents and will result in a long-term adjustment in the labour market and consequently in the wage ratios. However, the negative impact of climate change on a sector's productivity (e.g. high-exposure sector's productivity) will result in a production loss which increases the price and subsequently, the wages of labour in that sector. This will create an incentive for a labour reallocation into this sector. For example, the more negative impact of climate change on the high-exposure agricultural sector, increase the wages of low-skilled labour employed in this sector and therefore, reduces the return on to acquiring skills, incentivizing parents to spend less resources on their children's education and instead, to have more children with lower education (i.e. the quantity–quality trade-off). As supply increases, wages fall and the long-term wage ratio remains unchanged. Therefore, climate change damages to labour supply and demand (through sectoral damages) have very different implications for wage inequality and gender pay gap: long-term wage inequality is only driven by the damages to labour availability, while short-term wage shocks can be attributed to both damages to labour availability and sectoral productivity. As the focus of this paper is on the long-term impact of climate change on gender pay gap, the results presented in the next section are mainly driven by the sensitivity of labour availability to temperature rise.

The indirect effects (i.e. general equilibrium effects) of climate change on labour market are captured by the utility optimization conditions at the household level. Any change in the demand for a specific type of labour in one sector has an impact on the reallocation of the labour market and the demand for labour in the other sector. In particular, in the case with constant labour availability (i.e. constant supply factors), the wage ratios (Equations (A4) to (A7) in the Appendix) are proportional to the ratio of child-rearing costs which are assumed fixed. Therefore, once climate change impact on labour productivity in one sector is realized, the labour redistribution will guarantee that the wages (and labour demand) in the other sector are also adjusted so that the wage ratios stay constant at the equilibrium in long-term. This fact is shown in the 'climate demand model' in Figure A4 in the Appendix where we have considered climate change impacts on labour productivity only and not on labour availability.

4. Projections of climate change effects on labour availability and gender inequality

Starting from year 2000 and moving forward with 20-year time steps, at every point in time, we can combine the key equations which describe the wage ratios of male to female labour and high-skilled to low-skilled labour (i.e. Equations (A20), (A21), (A24) (or (A25)), and (A29) in the appendix) to obtain the optimal allocation of children of each gender and skill level for the next period. The results are presented under four RCP scenarios. Panel (a) in Figure 6 demonstrates the climate characteristics of the four RCPs. Under RCP2.6 scenario, the average weekly maximum temperature in South Africa increases from 27.8°C in year 2000 to 28.7°C in year 2100 while under RCP8.5 it increases by more than 4°C by the end of this century (panel (a) in Figure 6).

Panel (b) in Figure 6 on the other hand, is the skill ratio projection of SSP2 which is used to calibrate the exogenous growth rate of technological change in our model. The skill ratio in South Africa is projected to grow substantially from about 1.5 in year 2000 to 64.5 by the end of the century.

In order to analyse and compare the impacts of climate change on different levels and components of a socioeconomic

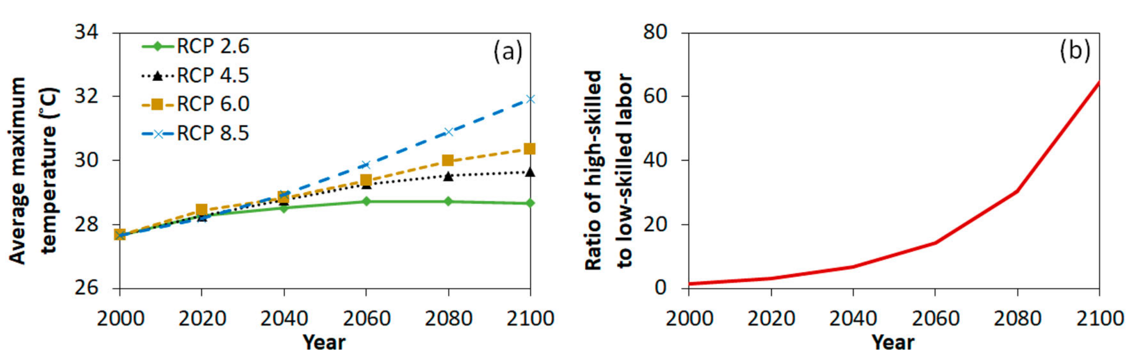

Figure 6. The climate and socioeconomic projections for South Africa under SSP2 and four RCP scenarios. (a) Average annual maximum temperature projections. (b) Ratio of high-skilled to low-skilled adult population projection under SSP2 from the Wittgenstein Centre projections (Lutz et al. 2014).

system, we develop two cases. The first case (Reference) assumes that climate conditions remain unchanged throughout the century. This case provides a baseline for comparing different impacts of climate change. In the second case, we investigate climate change damages to labour supply by considering four different RCP scenarios. Figure 7 examines the effect of different climate pathways on labour supply and wage differences in each case. As discussed earlier in the empirical results section and shown in panel (a) in Figure 7, the high-skilled *supply factor* for both genders is insensitive to the change in temperature while the relative low-skilled *supply factor* for male labour is increasing compared to female labour as shown in panel (b). This indicates the vulnerability of low-skilled female labour working in the high-exposure sector as demonstrated by our empirical analysis in Section 2.

The broader impact of change in relative labour supply on wage ratios and especially on gender pay gap is studied in subsequent panels in Figure 7. Under the Reference case, the ratio of male to female *supply factor* is fixed and therefore, the wage ratio of high-skilled to low-skilled labour remains constant over time as a result of Equations (A4) and (A5) in the appendix. In contrast, under all RCP scenarios, the wage gap between high-skilled and low-skilled labour decreases for both genders but such decline is more noticeable among female labours (e.g.

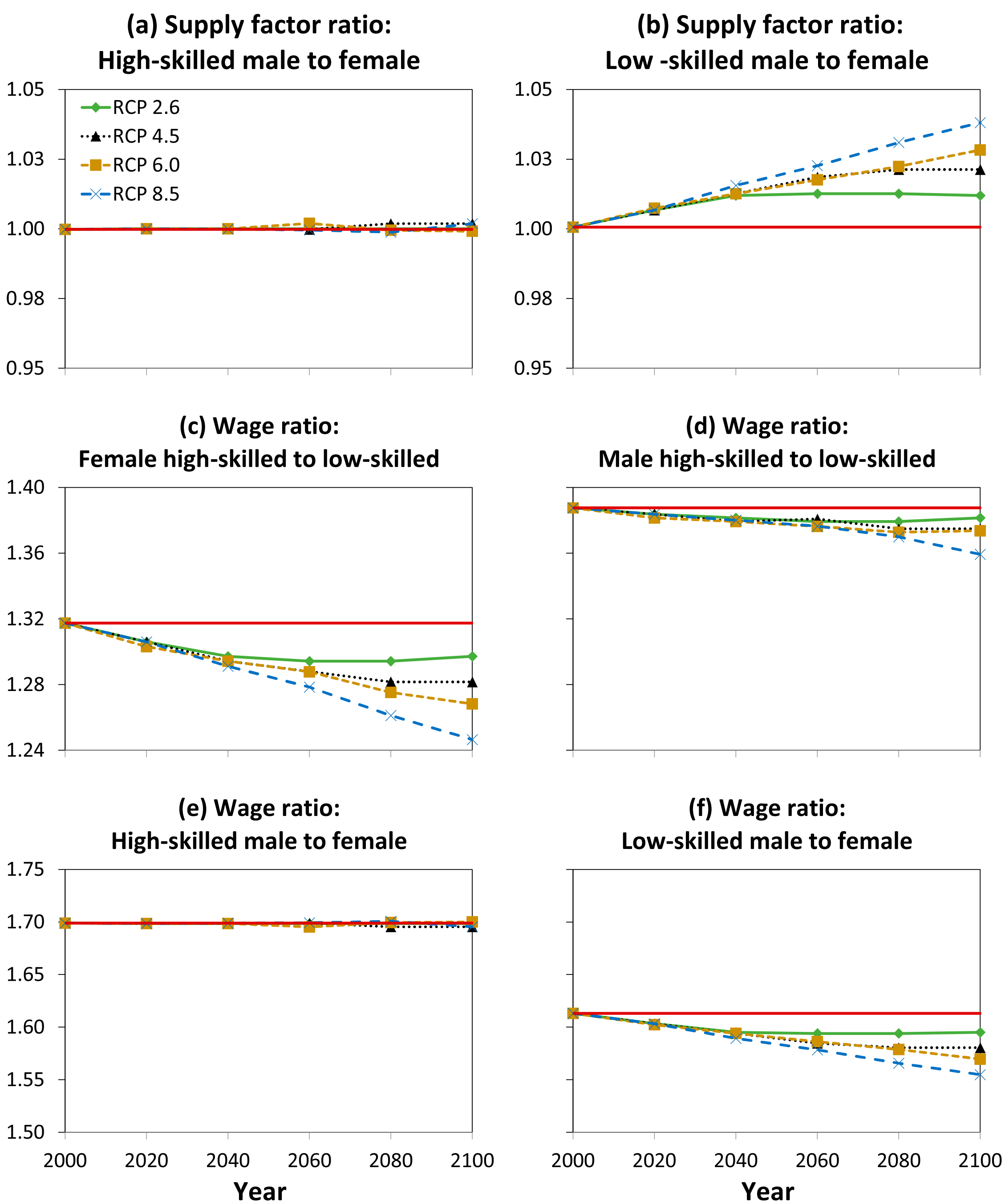

Figure 7. Projections of climate change impacts on gender pay gap in South Africa under four RCP scenarios: (a) ratio of supply factor for high-skilled male to female, (b) ratio of supply factor for low-skilled male to female, (c) wage ratio of male high-skilled to low-skilled labour, (d) wage ratio of female high-skilled to low-skilled labour, (e) wage ratio of high-skilled male to female labour and (f) wage ratio of low-skilled male to female labour.

the wage ratio of high-skilled to low-skilled female labour reduces by about 5% from 1.32 in 2000 to 1.24 in 2100 under RCP8.5 scenario as shown in panel (c) while it reduces by just 2% from 1.39 in 2000 to 1.36 in 2100 for male labour as shown in panel (d)).

The impact of climate change on gender pay gap (i.e. the wage gap between male and female labour) is shown in panels (e) and (f) for high-skilled and low-skilled labour, respectively. As high-skilled labour supply is insensitive to climate change, the wage gap in the low-exposure sector remains unchanged across all RCP scenarios. However, as the *supply factor* ratio of low-skilled male to female labour increases due to climate change (panel (b)), the relative wages of low-skilled female labour increases (see Equation (A5) in the appendix).

Although the wage inequality between high-skilled and low-skilled female labour and between low-skilled male and female labour decreases as a result of the decline in supply of low-skilled women and the subsequent increase in their wages, the overall impact of climate change on the economic output remains negative. Figure 8 shows the impact of climate change on output per adult under four RCP scenarios compared to the Reference case in panel (a). In the Reference case, the output per adult increases from its initial value of 10,000 to about 60,000 (constant 2010 USD). However, when the labour supply is affected by climate change, the welfare falls further and by about 11% under severe climate change projections of RCP8.5 (panel (b) in Figure 8).

5. Conclusion

External shocks (e.g. war or natural disasters) to the labour market with differential impacts on the supply of male and female labour, may alter the wage gap between male and female labour (Acemoglu et al. 2004). In this paper, we examine the crucial linkage between the impact of climatic stressors on female labour in South Africa. We study historical evidence from a nationally representative longitudinal survey with a wide range of information on household characteristics and labour information to gain an empirical insight into the impact of rising temperatures on supply of female labour in the high-exposure sector compared to their male counterparts. We find that an increase in temperatures initially mobilizes labour in the high-exposure sector and increases the working time up to certain threshold, after which the supply of labour declines at a faster rate for women compared to men. Our empirical results are robust based on a number of different specifications including binned and 2SLS regressions. We use the empirical evidence to calibrate an OLG model to study the future impact of climate and socioeconomic changes on gender pay gap.

In our OLG model, we assume a clear labour division: the high-exposure sector (e.g. agriculture) only employs low-skilled labour and the low-exposure sector (e.g. manufacturing) only employs high-skilled labour. In reality, the labour market is more complex and the labour division among sectors is less clear. However, this simplification allows us to highlight some of the mechanisms through which climate change can alter labour market and impact gender pay gap. We find that the consideration of different climate change damages can have very different outcomes for skill ratio and wage gap among high-skilled and low-skilled labour, and among low-skilled male and female labour.

Climate change reduces the relative availability of low-skilled labour in high-exposure sectors. This translates into a spike in prices and will cause a long-term increase in relative wages of this group of labour as parents are able to experience and internalize these impacts in their child-rearing decision process. In this case, the reduction in relative supply of low-skilled labour (specially among the female labour) will create more demand for this type of labour[6]. In other words, climate change damages to labour availability increase the relative wages of low-skilled labour (specially low-skilled female labour) and close the wage gap between male and female labour in the high-exposure sector. Climate change damages to sectoral productivity on the other hand, create a price shock which increases the demand for a certain type of labour through a short-term impact on relative wages. The wage ratios in the long-term, however, will remain unchanged as labour markets clear and wages are adjusted.

Although the gender pay gap may reduce as a result of climate change impacts on[7] labour supply, the overall impact of climate change on the economy remains negative considering the damages to labour availability and sectoral productivity. Our findings suggest that the total economic output per adult could shrink by up to 11% depending on the future RCP scenario.[8]

It is worth mentioning that in our study,[9] we have not taken into account the potential impacts of future gender pay equalizing policies and as such our results should be treated with

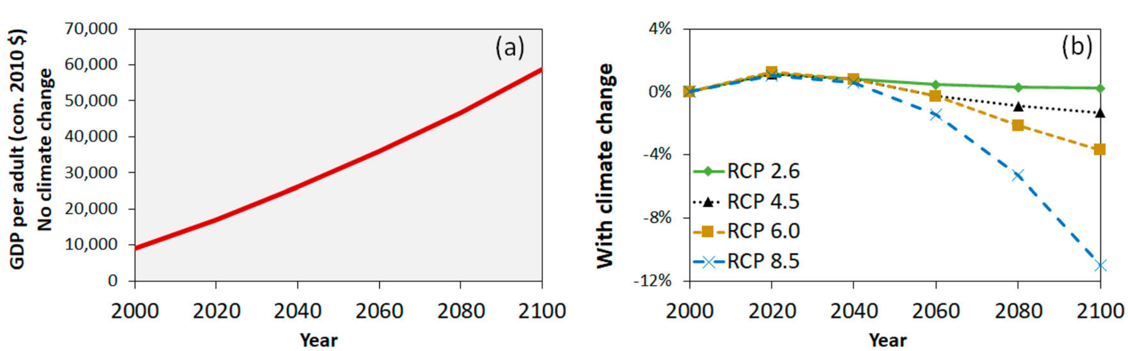

Figure 8. Impact of climate change on the welfare in South Africa under SSP2 and four RCP scenarios: (a) output per adult in the baseline case without climate change, (b) relative change in output per adult considering climate-induced damages.

slight caution. Similarly, we have not considered the issue of child labour in developing countries like South Africa and how it would change our findings. The full analysis of gender role in climate change adaptation and impacts requires a broad investigation of not only economic drivers of demand and supply in labour market but also socioeconomic factors that have historically contributed to inequality between male and female in our societies. This is in particular important when we consider the central role that women can play in implementing successful adaptation strategies. Our results highlight the importance of targeted adaptation policies that can build on the positive impacts of climate change in reducing gender pay gap in rural communities by enabling and empowering women to use this opportunity for investing in their education, and independent smallholder farming practices.

Notes

1. It is important to note that in this paper, we only consider the impacts of rising temperatures and we do not take into account other climatic stressors such as changes in precipitation patterns, droughts, floods, etc. as their impacts on working hours have been shown insignificant in Section 2.
2. http://www.nids.uct.ac.za/
3. Given the lack of evidence on the impact of ambient temperature on the service sector, we do estimate an exposure-response function for this sector
4. In South Africa, seasons are classified as follows; Autumn: March–May, Winter: June–August, Spring: September–November, and Summer: December–February.
5. We do not include the service sector here as there is no conclusive evidence of climate change impacts on this sector.
6. Please note that we have used a CES production function to account for the positive elasticity of substitution between male and female labour.
7. In other words, the supply factor $d^{k,l}$ is the normalized form of variable d_{it} from Equation (1) in Section 2.2.
8. For the rest of the equations, the time subscripts have been suppressed for convenience.
9. Other studies at the global level support such assumptions. For example, a study by Easterling et al. (1997) shows that over the past 100 years, the global maximum temperature has risen by about 0.88°C while the mean temperature has gone up by only 0.5°C.

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Notes on contributors

Soheil Shayegh is a Researcher at RFF-CMCC European Institute on Economics and the Environment (EIEE) in Milan, Italy. He is a former Marie Skłodowska-Curie fellow, and a former postdoctoral research scientist at Carnegie Institution for Science at Stanford University. He got his PhD in Industrial Engineering from Georgia Institute of Technology in Atlanta. His PhD thesis was on stochastic modeling for integrated assessment models of climate change and economy where he focused on developing new tools and approximation algorithms for optimal greenhouse gas emission mitigation policies. Soheil's research has been focused on a broad domain of climate change impacts on human systems and can help policy makers at regional, national, and international levels understand the ongoing threats and prepare for actions that can provide reliable solutions in dealing with these challenges.

Shouro Dasgupta is a Researcher at Fondazione CMCC a Visiting Fellow at the Grantham Research Institute, LSE, and a Lecturer at Università Ca' Foscari Venezia. His main research interests include studying the impacts of climate change on labour, food security, health, and inequality. Shouro's research contributes to advancing knowledge on socioeconomic impacts of climate change, identifying hotspots and vulnerable populations, and supporting the design of tailored policies to mitigate and adapt to these impacts. Shouro teaches courses on Statistics, Economics, and Econometrics at both undergraduate and graduate levels.

ORCID

Soheil Shayegh http://orcid.org/0000-0002-8960-8244
Shouro Dasgupta http://orcid.org/0000-0003-4080-8066

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Appendices

Appendix 1. Cumulative impact of warming

Table A1. Non-linear relationship between temperature and labor supply using bins of daily maximum temperature.

	(1)	(2)	(3)	(4)
	Low-skilled male	Low-skilled female	High-skilled male	High-skilled female
Age	−0.034***	−0.025***	−0.044**	−0.091***
	(0.001)	(0.001)	(0.018)	(0.004)
Age-squared	0.0003***	0.0002**	0.0005***	0.001***
	(0.009)	(0.033)	(0.003)	(0.003)
Married	5.554**	−2.211**	6.022**	−1.425***
	(0.019)	(0.002)	(0.011)	(0.003)
Years of schooling	0.522	0.804	1.633**	1.877**
	(0.274)	(0.204)	(0.021)	(0.020)
Health condition	−1.539***	−2.955***	−1. 001***	−2.142***
	(0.001)	(0.001)	(0.000)	(0.005)
Log of income	0.133***	2.004**	2.155**	2.151**
	(0.010)	(0.030)	(0.021)	(0.030)
Log of income squared	−0.007***	−0.130**	−0.127**	−0.119**
	(0.007)	(0.028)	(0.019)	(0.021)
$< 10°C$	0.167**	0.152**	0.114	0.095
	(0.027)	(0.041)	(0.169)	(0.225)
10°C – 15°C	0.189**	0.177***	0.123**	0.100**
	(0.032)	(0.001)	(0.036)	(0.014)
15°C – 20°C	0.210**	0.185**	0.147*	0.122**
	(0.044)	(0.025)	(0.059)	(0.029)
20°C – 25°C	0.233***	0.204**	0.166**	0.144*
	(0.007)	(0.048)	(0.017)	(0.052)
25°C – 30°C				
30°C – 35°C	−0.244**	−0.269***	−0.155**	−0.171**
	(0.021)	(0.002)	(0.022)	(0.020)
35°C – 40°C	−0.315***	−0.389***	−0.159*	−0.196**
	(0.000)	(0.000)	(0.055)	(0.011)
> 40°C	−0.362**	−0.441***	−0.177*	−0.219**
	(0.019)	(0.005)	(0.059)	(0.026)
Observations	16,132	12,996	15,615	12,458

Note: Grey boxes indicate reference. *p*-values in parentheses *** p<0.01, ** p<0.05, * p<0.10, $+p < 0.15$

Appendix 2. Details of the theoretical model

We assume that the high-exposure economic sector (e.g. agriculture) is denoted by a and uses only low-skilled labor (Caselli & Coleman 2001; Gollin et al. 2014). The low-exposure sector (e.g. manufacturing) is denoted by b and uses only high-skilled labor. Individuals are further distinguished by their gender (denoted by m for male and f for female). With low substitutability between the two types of goods, labor supply is allowed to shift towards more damaged sector where the demand is higher.

A.1. Utility maximization

The objective of each individual is to maximize lifetime utility of consumption and their children's future well-being by making decisions about their own consumption and the education level of their children. The utility function of each adult has two components: immediate consumption and future children's wages based on their gender and skill level. This captures the altruistic attitude of parents:

$$v(c_t, n_t^{s,m}, n_t^{s,f}, n_t^{u,m}, n_t^{u,f}) = (1-\gamma_t)\ln(c_t) + \gamma_t\left[\ln\left(\sum_{k=s,u}\sum_{l=m,f} n_t^{k,l} d_{t+1}^{k,l} w_{t+1}^{k,l}\right)\right], \quad (A1)$$

where $n_t^{k,l}$ is the number of children of gender l with skill level k, c_t is the consumption of a bundle of goods from both sectors, and $w_{t+1}^{k,l}$ is the future wages of children of gender l with skill level k and $d_{t+1}^{k,l}$ is the future *supply factor* taking into account the projected climate change impacts. This factor ranges from zero to hundred percent and reflects the change in labor supply due to climate change. We use the empirical results of individual survey data to estimate the loss in labor supply due to increase in mean temperature.[7] When temperature is at its optimal point, the loss in labor supply is zero (i.e. $d_{t+1}^{k,l} = 1$) and the labor force will be fully accounted for in the production function. However, any deviation from the optimal temperature will result in $d_{t+1}^{k,l} < 1$ and therefore only a fraction of labor will contribute to economic production. Variable γ_t is the total parenting time as a fraction of each individual's time.

Parents have preferences over their own consumption and the expected lifetime earnings of their children depending on what gender and skill level the children have. We normalize the price index of the consumption composite to one. Thus, the budget constraint corresponding to Equation (A1) for every adult is given by:

$$c_t = \left(1 - \sum_{k=s,u}\sum_{l=m,f} \tau^{k,l} n_t^{k,l}\right) w_t. \quad (A2)$$

where $\tau^{k,l}$ is the fraction of time that a parent spent on raising a child of gender l with skill level k. We assume that the child-rearing costs are different for children of different genders and different skill level (i.e. $\tau^{s,f} > \tau^{u,f}$ and $\tau^{s,m} = \tau^{u,m}$). Therefore, the ratio of child raring cost for each gender is different (i.e. $\tau^{r,m} = \frac{\tau^{s,m}}{\tau^{u,m}}$ and $\tau^{r,f} = \frac{\tau^{s,f}}{\tau^{u,f}}$). The maximization of Equation (A1) subject to Equation (A2) yields:

$$\begin{gathered} c_t = (1-\gamma_t) w_t \\ \sum_{l=m,f}\sum_{k=s,u} \tau^{k,l} n_t^{k,l} = \gamma_t. \end{gathered} \quad (A3)$$

Equation (A3) encapsulates the quantity–quality trade-off. Because the total number of children at each time step is given by the SSP2 projections, individuals decide on how to allocate children to different skill levels solving their utility maximization problem.

For individuals to have both types of children, it must be the case that:

$$\tau^{r,m} = \frac{\tau^{s,m}}{\tau^{u,m}} = \frac{d^{s,m}_{t+1}}{d^{u,m}_{t+1}}\frac{w^{s,m}_{t+1}}{w^{u,m}_{t+1}} = d^{r,m}_{t+1}\, w^{r,m}_{t+1} \tag{A4}$$

$$\tau^{r,f} = \frac{\tau^{s,f}}{\tau^{u,f}} = \frac{d^{s,f}_{t+1}}{d^{u,f}_{t+1}}\frac{w^{s,f}_{t+1}}{w^{u,f}_{t+1}} = d^{r,f}_{t+1}\, w^{r,f}_{t+1} \tag{A5}$$

$$\tau^{u,r} = \frac{\tau^{u,m}}{\tau^{u,f}} = \frac{d^{u,m}_{t+1}}{d^{u,f}_{t+1}}\frac{w^{u,m}_{t+1}}{w^{u,f}_{t+1}} = d^{u,r}_{t+1}\, w^{u,r}_{t+1} \tag{A6}$$

$$\tau^{s,r} = \frac{\tau^{s,m}}{\tau^{s,f}} = \frac{d^{s,m}_{t+1}}{d^{s,f}_{t+1}}\frac{w^{s,m}_{t+1}}{w^{s,f}_{t+1}} = d^{s,r}_{t+1}\, w^{s,r}_{t+1} \tag{A7}$$

These equations show that the ratio of wages of children is proportional to the ratio of child rearing.

A.2. Consumption

The level of utility for the labor of skill level k is a constant elasticity of substitution (CES) function given by[8]:

$$c^k = \{\theta(c^k_a)^{\frac{\epsilon-1}{\epsilon}} + (1-\theta)(c^k_b)^{\frac{\epsilon-1}{\epsilon}}\}^{\frac{\epsilon}{\epsilon-1}}, \tag{A8}$$

where ε is the elasticity of substitution, c_a is consumption of goods from the high-exposure sector, c_b is consumption of the goods from the low-exposure sector, and θ is the share of goods from the high-exposure sector.

The consumer optimization problem conditioned on the budget constraint can be formulated using the Lagrangian multiplier λ:

$$Max\left\{c^{k,l} - \lambda\big(p_a c^{k,l}_a + p_b c^{k,l}_b - (1-\gamma)w^{k,l}\big)\right\}, \tag{A9}$$

where p^b and p^a are the prices of goods in the low-exposure and high-exposure sectors, respectively. The solution to this optimization problem provides a relationship between these prices:

$$p_r = \frac{p_b}{p_a} = \left(\frac{1-\theta}{\theta}\right)\left(\frac{c^{k,l}_b}{c^{k,l}_a}\right)^{\frac{-1}{\epsilon}}, \tag{A10}$$

A.3. Production

We adopt a linear production function that captures the fact that production in the high-exposure sector is relatively less skill-intensive (Caselli & Coleman 2001; Gollin et al. 2014). We assume a constant elasticity of substitution (CES) production function with male and female labor in each sector:

$$Y_a = A_a\, D_a\left[\zeta_a(d^{u,m}_{t+1}\,\hat{L}^{u,m}_{t+1})^{\frac{\eta-1}{\eta}} + (1-\zeta_a)(d^{u,f}_{t+1}\,\hat{L}^{u,f}_{t+1})^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}}, \tag{A11}$$

$$Y_b = A_b\, D_b\left[\zeta_b(d^{s,m}_{t+1}\,\hat{L}^{s,m}_{t+1})^{\frac{\eta-1}{\eta}} + (1-\zeta_b)(d^{s,f}_{t+1}\,\hat{L}^{s,f}_{t+1})^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}} \tag{A12}$$

where Y_a and Y_b are outputs in the high-exposure and low-exposure sectors, respectively. $\hat{L}^{k,l}$ is the gross number of labor of gender l with skill level k before accounting for the impacts of climate change on labor supply. Parameters ζ_a and ζ_b are the shares of male labor in the high-exposure and low-exposure sectors, respectively. The elasticity of substitution between male and female labor is indicated by η which is assumed to be equal to 2.9 in both sectors (Acemoglu et al. 2004; Doepke 2005). Variables A_a and A_b are total factor productivity (i.e. technological change) in high-exposure and low-exposure sectors, respectively. Climate change impacts to productivity are captured by productivity factors D_a and D_b which are functions of mean temperature as explained in Subsection A.4.

Technological change evolves exogenously according to:

$$A_{\varkappa,t} = (1+g_\varkappa)A_{\varkappa,t-1}, \quad \varkappa = a, b. \tag{A13}$$

The gross number of labor of gender l with skill level k will be:

$$\hat{L}^{k,l}_{t+1} = N_t\, n^{k,l}_t, \tag{A14}$$

where N_t is adult population at time t. The net number of labor of gender l with skill level k will be calculated by taking into account the impacts of climate change on labor supply:

$$L^{k,l}_{t+1} = d^{k,l}_{t+1}\,\hat{L}^{k,l}_{t+1} \tag{A15}$$

Wages can be calculated by taking the derivative of Equations (A11) and (A12):

$$w^{u,m} = \zeta_a\, p_a\, A_a\, D_a\, d^{u,m}\,(L^{u,m})^{\frac{-1}{\eta}}\left[\zeta_a(L^{u,m})^{\frac{\eta-1}{\eta}} + (1-\zeta_a)(L^{u,f})^{\frac{\eta-1}{\eta}}\right]^{\frac{1}{\eta-1}} \tag{A16}$$

$$w^{u,f} = (1-\zeta_a)p_a A_a D_a d^{u,f}(L^{u,f})^{\frac{-1}{\eta}}\left[\zeta_a(L^{u,m})^{\frac{\eta-1}{\eta}} + (1-\zeta_a)(L^{u,f})^{\frac{\eta-1}{\eta}}\right]^{\frac{1}{\eta-1}} \tag{A17}$$

$$w^{s,m} = \zeta_b p_b A_b D_b d^{s,m}(L^{s,m})^{\frac{-1}{\eta}}\left[\zeta_b(L^{s,m})^{\frac{\eta-1}{\eta}} + (1-\zeta_b)(L^{s,f})^{\frac{\eta-1}{\eta}}\right]^{\frac{1}{\eta-1}} \tag{A18}$$

$$w^{s,f} = (1-\zeta_b)p_b A_b D_b d^{s,f}(L^{s,f})^{\frac{-1}{\eta}}\left[\zeta_b(L^{s,m})^{\frac{\eta-1}{\eta}} + (1-\zeta_b)(L^{s,f})^{\frac{\eta-1}{\eta}}\right]^{\frac{1}{\eta-1}} \tag{A19}$$

This will immediately give us

$$w^{u,r} = \frac{w^{u,m}}{w^{u,f}} = \left(\frac{\zeta_a}{1-\zeta_a}\right)\left(\frac{d^{u,m}}{d^{u,f}}\right)\left(\frac{L^{u,f}}{L^{u,m}}\right)^{\frac{1}{\eta}} \tag{A20}$$

$$w^{s,r} = \frac{w^{s,m}}{w^{s,f}} = \left(\frac{\zeta_b}{1-\zeta_b}\right)\left(\frac{d^{s,m}}{d^{s,f}}\right)\left(\frac{L^{s,f}}{L^{s,m}}\right)^{\frac{1}{\eta}} \tag{A21}$$

That is, the wage ratio of male to female labor in each sector is proportional to their supply ratio. Given the historical gender wage inequality and labor allocation in South Africa, we can calculate the parameters ζ_a and ζ_b using these two equations. Our calculations based on the wage and skill ratios in year 2000 indicate that ζ_a=0.61 and ζ_b=0.63. The male to female ratio of low-skilled and high-skilled labor can be determined from combining these two equations with Equations (A6) and (A7)

$$L^{u,r} = \frac{L^{u,m}}{L^{u,f}} = \left(\frac{\zeta_a}{1-\zeta_a}\right)^{\eta}\left(\frac{d^{u,m}}{d^{u,f}}\right)^{2\eta}(\tau^{u,r})^{-\eta} \tag{A22}$$

$$L^{s,r} = \frac{L^{s,m}}{L^{s,f}} = \left(\frac{\zeta_b}{1-\zeta_b}\right)^{\eta}\left(\frac{d^{s,m}}{d^{s,f}}\right)^{2\eta}(\tau^{s,r})^{-\eta} \tag{A23}$$

Furthermore, dividing Equation (A18) by Equation (A16) and Equation (A19) by Equation (A17), we get

$$\frac{w^{s,m}}{w^{u,m}} = \left(\frac{\zeta_b}{\zeta_a}\right)p_r A_r D_r d^{r,m}(L^{r,m})^{\frac{-1}{\eta}} M^{\frac{1}{\eta-1}} \tag{A24}$$

$$\frac{w^{s,f}}{w^{u,f}} = \left(\frac{1-\zeta_b}{1-\zeta_a}\right)p_r A_r D_r d^{r,f}(L^{r,f})^{\frac{-1}{\eta}} M^{\frac{1}{\eta-1}} \tag{A25}$$

$$M = \frac{\zeta_b(L^{s,m})^{\frac{\eta-1}{\eta}} + (1-\zeta_b)(L^{s,f})^{\frac{\eta-1}{\eta}}}{\zeta_a(L^{u,m})^{\frac{\eta-1}{\eta}} + (1-\zeta_a)(L^{u,f})^{\frac{\eta-1}{\eta}}} \tag{A26}$$

where $p_r = \frac{p_b}{p_a}$, $A_r = \frac{A_b}{A_a}$, $D_r = \frac{D_b}{D_a}$, and $L^{r,l} = \frac{L^{s,l}}{L^{u,l}}$ for the labor of gender l.

The male and female ratio of high-skilled to low-skilled labor can be determined from combining these two equations with Equations (A4) and (A5)

$$L^{r,m} = \frac{L^{s,m}}{L^{u,m}} = \left(\frac{\zeta_b}{\zeta_a}\right)^{\eta} p_r^{\eta}\, A_r^{\eta}\, D_r^{\eta}\,(d^{r,m})^{2\eta}\, M^{\frac{\eta}{\eta-1}}\,(\tau^{r,m})^{-\eta} \tag{A27}$$

$$L^{r,f} = \frac{L^{s,f}}{L^{u,f}} = \left(\frac{1-\zeta_b}{1-\zeta_a}\right)^{\eta} p_r^{\eta}\, A_r^{\eta}\, D_r^{\eta}\,(d^{r,f})^{2\eta}\, M^{\frac{\eta}{\eta-1}}\,(\tau^{r,f})^{-\eta} \tag{A28}$$

Since the total consumption and production in each sector are equal, we can expand Equation (A10) to have:

$$p_r = \left(\frac{1-\theta}{\theta}\right)\left(\frac{Y_b}{Y_a}\right)^{\frac{-1}{\epsilon}} = \left(\frac{1-\theta}{\theta}\right)(A_r\ D_r)^{\frac{-1}{\epsilon}}\ M^{\frac{-\eta}{\epsilon(\eta-1)}} \tag{A29}$$

The consumption of a good from sector $\varkappa$ by adults of each gender and each skill level is calculated by the following equations:

$$c_{\varkappa}^{u,m} = \frac{w^{u,r}}{\Omega} Y_{\varkappa}, \quad c_{\varkappa}^{u,f} = \frac{1}{\Omega} Y_{\varkappa}, \quad c_{\varkappa}^{s,m} = \frac{\tau^{r,f}\ d^{r,f}\ w^{s,r}}{\Omega} Y_{\varkappa}, \quad c_{\varkappa}^{s,f} = \frac{\tau^{r,f}\ d^{r,f}}{\Omega} Y_{\varkappa} \tag{A30}$$

where

$$\Omega = \hat{L}^{u,f} + \tau^{r,f}\ d^{r,f}\ \hat{L}^{s,f} + w^{u,r}\ \hat{L}^{u,m} + \tau^{r,f}\ d^{r,f}\ w^{s,r} \hat{L}^{s,m} \tag{A31}$$

A.4. Climate change impacts

Climate change impacts both the supply of and the demand for labor in both sectors. However, such impacts are channelled through variations in different climate indicators. In the case of labor supply impact, as we showed in our empirical study, maximum temperatures are the significant factors. On the other hand, change in average temperature has been identified as a better proxy for calculating the damages on the labor demand.

A.4.1. Labor supply impacts

The supply of labor of gender l and skill level k is also affected by temperature. The *supply factor* indicated by $d_{t+1}^{k,l}$ in the model is calibrated to reflect the reported change in working hours of labor of different type and gender in the individual surveys as shown in Equation (1). To analyse the effect of future carbon concentrations on the wage dynamics of the model, we consider the concentration projections from four RCP scenarios and their subsequent average annual temperature in South Africa.

However, as mentioned in the empirical section, the damages to labor availability are related to the maximum temperature instead of mean temperature. In order to obtain the future maximum temperature forecasts, we observe a linear relationship between historical values of mean and maximum temperatures[9] for all regions of South Africa from 2000 to 2014 as depicted in panel (a) in Figure A1. We will use the coefficients of this linear relationship to obtain the future maximum temperatures based on the RCP projections of mean temperature.

A.4.2. Sectoral productivity impacts

climate change not only impacts the supply of labor by affecting its availability but also changes the demand side of the labor market by damaging the productivity of each sector. Therefore, we introduce an additional measure to account for the sectoral productivity impact of temperature rise. The productivity factor $D_{\varkappa,t}(T_{mean})$ captures the percentage of productivity after damages related to changes in mean temperature (T_{mean}) (Desmet & Rossi-Hansberg 2015):

$$D_{\varkappa,t}(T_{mean}) = \delta_0 + \delta_1 T_{mean} + \delta_2 T_{mean}^2 \quad \text{for } \varkappa = a, b \tag{A32}$$

The coefficients δ_0, δ_1 and δ_2 describe the quadratic relationship between sectoral damages and mean temperature. We use the values of these parameters provided in a global study which shows that the productivity factor reaches its peak at 21.1°C (high-exposure sector) and 17.4°C (low-exposure sector) with a maximum productivity loss of 90% as shown in panel (b) in Figure A1.

A.5. Model calibration

In order to calibrate the model, we use the initial wages from Table 1 ($w_0^{l,k}$) and available temperature data in year 2000 to obtain the wage ratios and the *supply factor* values ($d_0^{l,k}$) at the first period of the model. We combine this information with data on adult population breakdown for year 2000 ($n_0^{l,k}$) to calculate the child- raring costs from Equations (A4)–(A6):

$$\begin{aligned}
\tau^{u,f} &= \gamma\left(\frac{w_0^{s,f}\ d_0^{s,f}}{w_0^{u,f}\ d_0^{u,f}}\ n_0^{s,f} + \frac{w_0^{s,m}\ d_0^{s,m}}{w_0^{u,f}\ d_0^{u,f}}\ n_0^{s,m} + \frac{w_0^{u,m}\ d_0^{u,m}}{w_0^{u,f}\ d_0^{u,f}}\ n_0^{u,m} + n_0^{u,f}\right)^{-1} \\
\tau^{u,m} &= \frac{w_0^{u,m}\ d_0^{u,m}}{w_0^{u,f}\ d_0^{u,f}}\ \tau^{u,f} \\
\tau^{s,m} &= \frac{w_0^{s,m}\ d_0^{s,m}}{w_0^{u,m}\ d_0^{u,m}}\ \tau^{u,m} \\
\tau^{u,m} &= \frac{w_0^{s,f}\ d_0^{s,f}}{w_0^{u,f}\ d_0^{u,f}}\ \tau^{u,f}
\end{aligned} \tag{A33}$$

We use these values to calculate the share of male labor in each sector from Equations (A20) and (A21):

$$\begin{aligned}
\zeta_a &= \left[1 + \left(\frac{\tau^{u,f}}{\tau^{u,m}}\right)\left(\frac{d^{u,m}}{d^{u,f}}\right)^2 \left(\frac{n_0^{u,m}\ d^{u,m}}{n_0^{u,f}\ d^{u,f}}\right)^{\frac{1}{\eta}}\right]^{-1} \\
\zeta_b &= \left[1 + \left(\frac{\tau^{s,f}}{\tau^{s,m}}\right)\left(\frac{d^{s,m}}{d^{s,f}}\right)^2 \left(\frac{n_0^{s,m}\ d^{s,m}}{n_0^{s,f}\ d^{s,f}}\right)^{\frac{1}{\eta}}\right]^{-1}
\end{aligned} \tag{A34}$$

Given the initial climate conditions in year 2000, the productivity factors $D_{a,2000}$ and $D_{a,2000}$. and their relative ratio $D_{r,2000}$ can be calculated. The ratio of technological change in low-exposure to high-exposure sector can be found by combining Equations (A25) and (A29):

$$A_{r,2000} = \left(\frac{1-\theta}{\theta}\right)^{\frac{\epsilon}{1-\epsilon}} \left(\frac{1-\zeta_b}{1-\zeta_a}\right)^{\frac{\epsilon}{1-\epsilon}} (d^{r,f})^{\frac{-2\epsilon}{1-\epsilon}} (\tau^{r,f})^{\frac{-\epsilon}{1-\epsilon}} \left(\frac{n_0^{s,f}\ d^{s,f}}{n_0^{u,f}\ d^{u,f}}\right)^{\frac{-\epsilon}{\eta(1-\epsilon)}} M_0^{\frac{\epsilon-\eta}{(1-\epsilon)(\eta-1)}} D_{r,2000}^{-1}$$

and

$$M_0 = \frac{\zeta_b(n_0^{s,m}\ d_0^{s,m})^{\frac{\eta-1}{\eta}} + (1-\zeta_b)(n_0^{s,f}\ d_0^{s,f})^{\frac{\eta-1}{\eta}}}{\zeta_a(n_0^{u,m}\ d_0^{u,m})^{\frac{\eta-1}{\eta}} + (1-\zeta_a)(n_0^{u,f}\ d_0^{u,f})^{\frac{\eta-1}{\eta}}}$$

Next, we use the SSP2 projection of skill ratio (i.e. the ratio of high-skilled to low-skilled labor) for the last period in year 2100 (see panel (b) in Figure 6). We use this value in combination with Equations (A20) and (A21) and Equation (A3) to estimate $L_{2100}^{k,l}$, the projected number of labor of gender l with skill level k in the last period. We then calculate the technological ratio for the last period ($A_{r,2100}$). The comparison of the technological ratios at the beginning ($A_{r,2000}$) and at the end ($A_{r,2100}$) will provide us with the growth rate of technology in high-exposure sector g_a in Equation (A13). Other parameter values are taken from previous studies. The full list of parameters and their values are provided in Table A2.

A.6. Model solution

At every time period, the temperature is given from RCP projections and the damages to labor supply (i.e. supply factor), and sectoral productivity (e.g. productivity factor) are calculated. Given the fact that the growth of technological change and the child-rearing costs are exogenous, the number of children of each gender and each skill level can be determined by solving this set of equations simultaneously:

(1) from Equation (A3):

$$\tau^{u,m}\ n^{u,m} + \tau^{u,f}\ n^{u,f} + \tau^{s,m}\ n^{s,m} + \tau^{s,f}\ n^{s,f} = \gamma \tag{A35}$$

(2) from Equation (A22):

$$\frac{n^{u,m}}{n^{u,f}} = \left(\frac{\zeta_a}{1-\zeta_a}\right)^{\eta} \left(\frac{d^{u,m}}{d^{u,f}}\right)^{2\eta-1} (\tau^{u,r})^{-\eta} \tag{A36}$$

Table A2. The parameter set used in the OLG model setup.

Parameter	Description	Value
η	Elasticity of substitution between male and female labor	2.900
ζ_a	Share of male labor in the high-exposure sector	**0.610**
ζ_b	Share of male labor in the low-exposure sector	**0.630**
ε	Elasticity of substitution between goods	0.500
θ	Consumption share of goods from the high-exposure sector	0.275
$\tau^{u,m}$	Child raring cost for low-skilled male children	**0.234**
$\tau^{u,m}$	Child raring cost for high-skilled male children	**0.324**
$\tau^{u,m}$	Child raring cost for low-skilled female children	**0.145**
$\tau^{u,m}$	Child raring cost for high-skilled female children	**0.191**
γ	Total parenting time	0.400
g_b	Annual growth rate of technology in the low-exposure sector	0.010
g_a	Annual growth rate of technology in the high-exposure sector	**0.089**

The bold values are calculated from the calibration of the model to historical data.

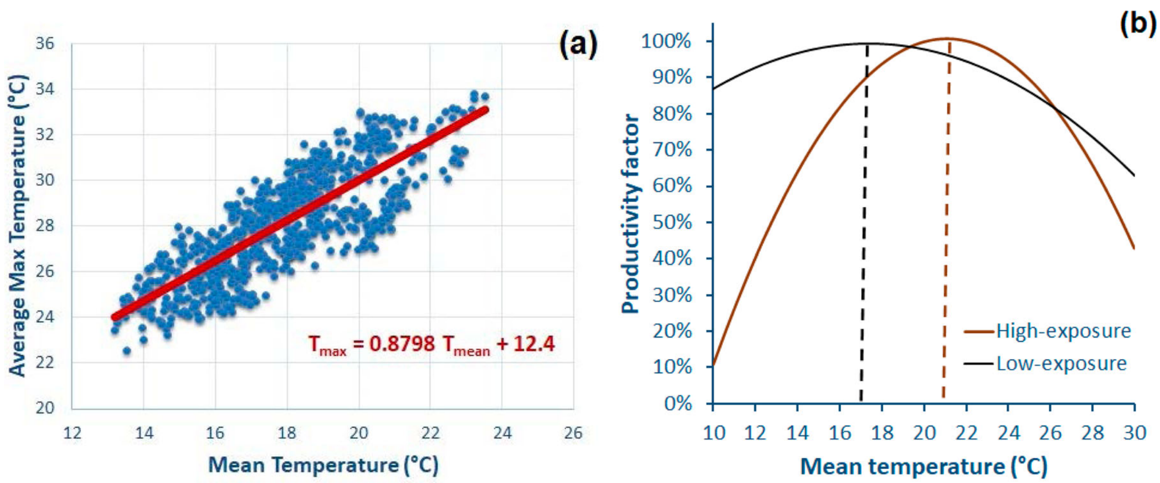

Figure A1. Climate change indicators and impacts (a) historical relationship between mean temperature and maximum temperature in all regions in South Africa for years from 2000 to 2014 with each blue dot representing a regional observation of the mean and the maximum temperatures, and (b) productivity factor for high-exposure and low-exposure sectors as functions of mean temperature based on Desmet and Rossi-Hansberg (2015).

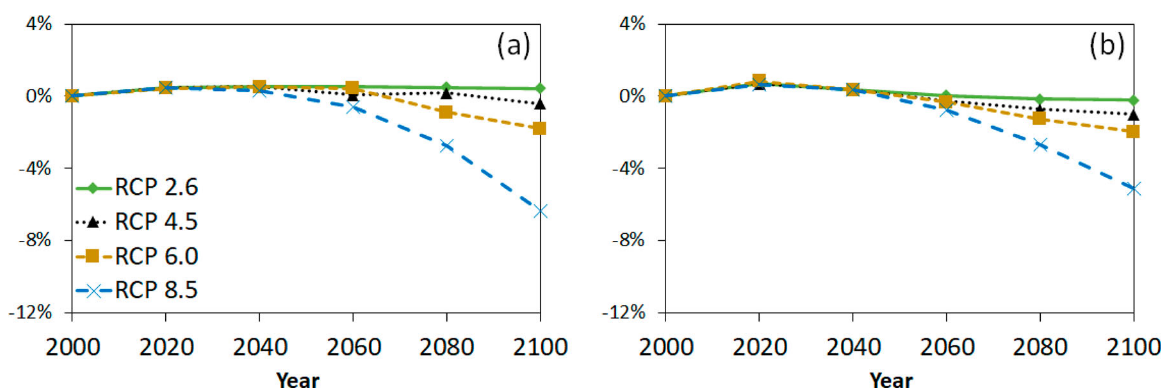

Figure A2. Relative change in output per adult compared to the Reference case without climate change (a) *climate supply model*, (b) *climate demand model*.

(3) from Equation (A23):

$$\frac{n^{s,m}}{n^{s,f}} = \left(\frac{\zeta_b}{1-\zeta_b}\right)^{\eta} \left(\frac{d^{s,m}}{d^{s,f}}\right)^{2\eta-1} (\tau^{s,r})^{-\eta} \tag{A37}$$

(4) from combining Equations (A27) and (A29):

$$\frac{n^{s,m}}{n^{u,m}} = \left(\frac{\zeta_b}{\zeta_a}\right)^{\eta} \left(\frac{1-\theta}{\theta}\right)^{\eta} (A_r\ D_r)^{\eta-\frac{\eta}{\epsilon}} (d^{r,m})^{2\eta-1}\ M^{\frac{(\epsilon-\eta)\eta}{\epsilon(\eta-1)}} (\tau^{r,m})^{-\eta} \tag{A38}$$

The solution to this system of equations provides the optimal decision about the fertility and education level provided to every child in each generation which determines the composition of the labor force in the next generation.

Appendix 3. Alternative setup

Although in the main model, we have considered the climate impacts on both the demand and supply sides of the labor market, the main results are driven by the change in labor supply through the supply factor. We

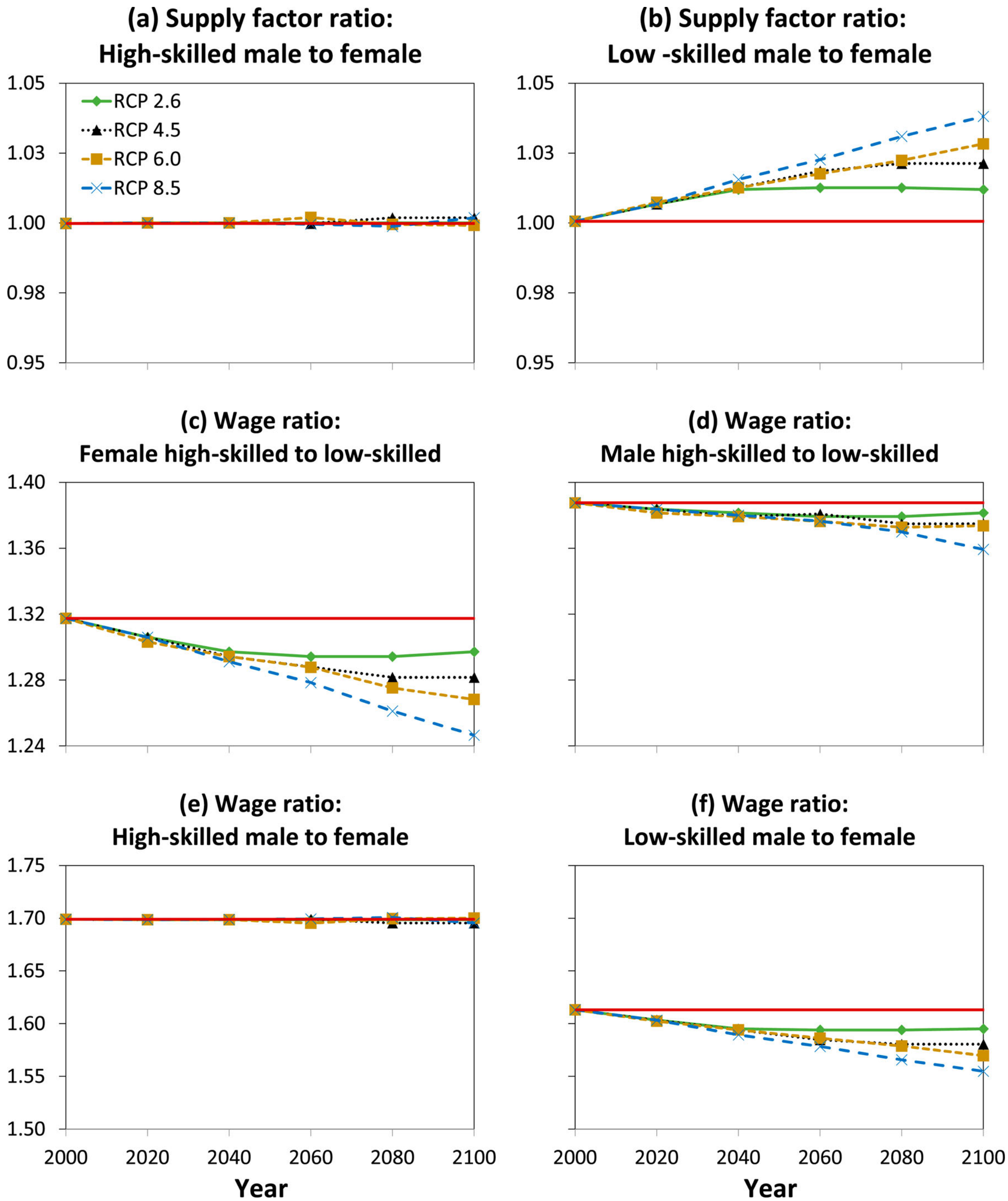

Figure A3. Projections of climate change impacts on gender pay gap in the *climate supply model* under four RCP scenarios: (a) ratio of supply factor for high-skilled male to female, (b) ratio of supply factor for low-skilled male to female, (c) wage ratio of male high-skilled to low-skilled labor, (d) wage ratio of female high-skilled to low-skilled labor, (e) wage ratio of high-skilled male to female labor and (f) wage ratio of low-skilled male to female labor.

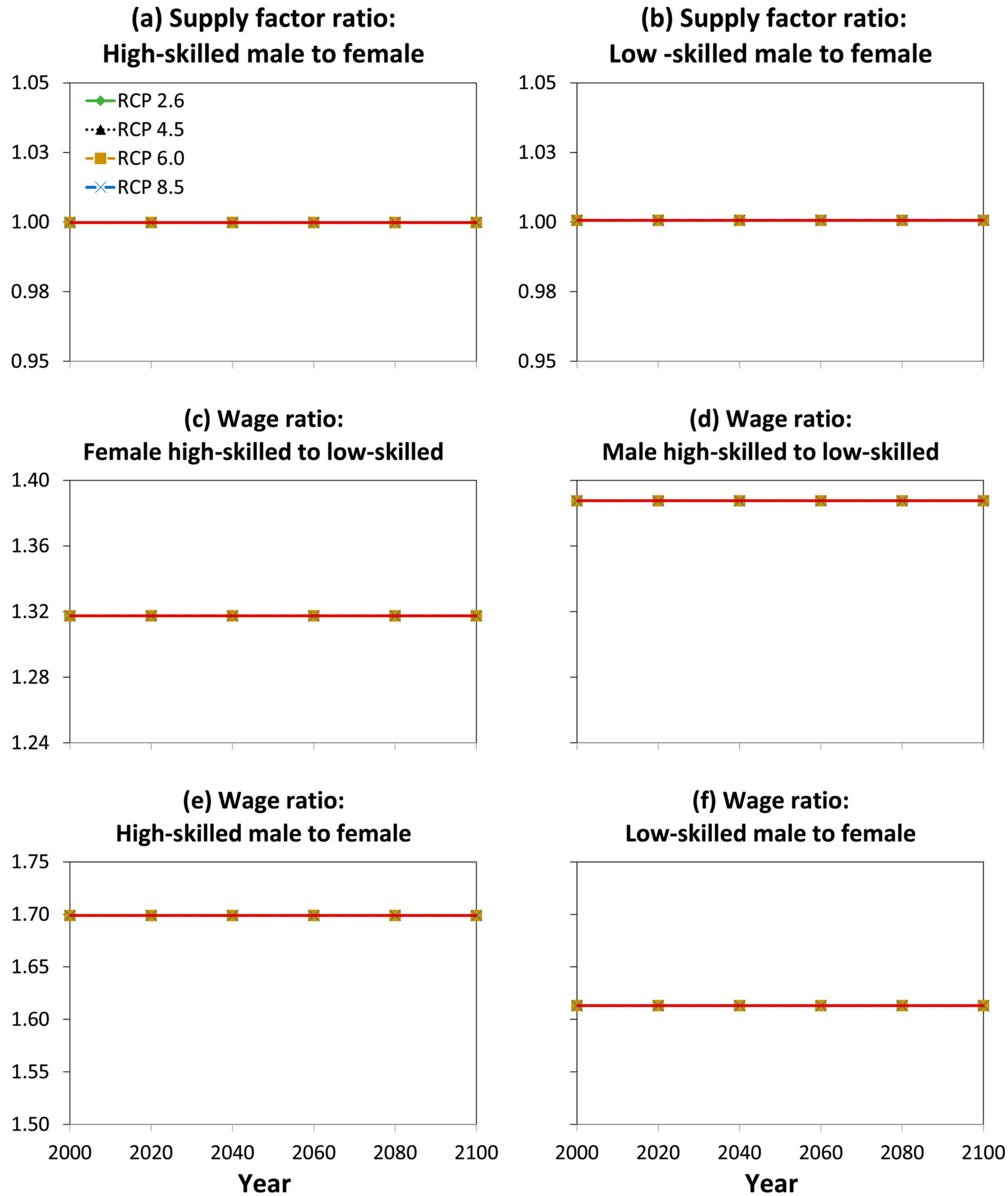

Figure A4. Projections of climate change impacts on gender pay gap in the *climate demand model* under four RCP scenarios: (a) ratio of supply factor for high-skilled male to female, (b) ratio of supply factor for low-skilled male to female, (c) wage ratio of male high-skilled to low-skilled labor, (d) wage ratio of female high-skilled to low-skilled labor, (e) wage ratio of high-skilled male to female labor and (f) wage ratio of low-skilled male to female labor.

demonstrate this by constructing two alternative models. In the first model, we only consider impacts on the supply side (*climate supply model*), and in the second model, we only consider impacts on the demand side (*climate demand model*). Figures A3 and A4 show the main results of these two models, respectively. It is important to note that in our model, the wage ratio (Equations (A4) to (A7)) is only a function of fixed child-rearing costs and supply factors, its value does not depend on the change in productivity factor. Therefore, in the *climate demand model*, the wage ratios remain constant over time and across different RCP scenarios. However, in the *climate supply model*, the wage ratios vary as the supply factor is being affected non-uniformly by climate change.

Although the wage ratios are unchanged in the *climate demand model*, the overall damages to the output per capital is comparable with those in the *climate supply model* as shown in Figure A2.