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## LETTER

## Crop failure rates in a geoengineered climate: impact of climate change and marine cloud brightening

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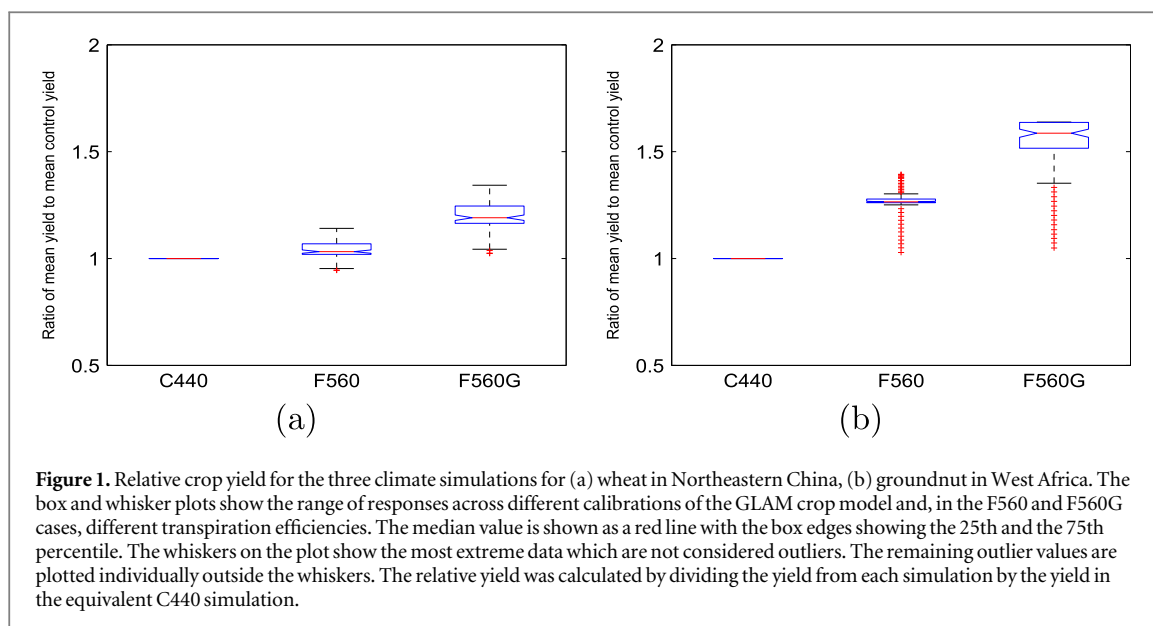
The impact of geoengineering on crops has to date been studied by examining mean yields. We present the first work focusing on the rate of crop failures under a geoengineered climate. We investigate the impact of a future climate and a potential geoengineering scheme on the number of crop failures in two regions, Northeastern China and West Africa. Climate change associated with a doubling of atmospheric carbon dioxide increases the number of crop failures in Northeastern China while reducing the number of crop failures in West Africa. In both regions marine cloud brightening is likely to reduce the number crop failures, although it is more effective at reducing mild crop failure than severe crop failure. We find that water stress, rather than heat stress, is the main cause of crop failure in current, future and geoengineered climates. This demonstrates the importance of irrigation and breeding for tolerance to water stress as adaptation methods in all futures. Analysis of global rainfall under marine cloud brightening has the potential to significantly reduce the impact of climate change on global wheat and groundnut production.

**1. Introduction**

Climate change as a result of anthropogenic influences, such as burning fossil fuels and altering land use, is having an impact across the world (Stocker *et al* 2013). There have been several methods suggested to ameliorate some of the effects of climate change, via either mitigation or explicit geoengineered modifications. One such geoengineering method is marine cloud brightening, which was originally suggested nearly 25 years ago (Latham 1990). Marine cloud brightening, which is a solar radiation management (SRM) method of geoengineering, has the aim of preventing adverse temperature changes (Shepherd 2009, Jones *et al* 2009, 2011, Latham *et al* 2012a) and has been suggested as a method of restoring polar sea ice coverage (Latham *et al* 2012a, Parkes *et al* 2012) and reducing coral bleaching (Latham *et al* 2013). It involves seeding unpolluted marine stratocumulus clouds in an effort to increase the cloud droplet number and thus reflectivity (Twomey 1977). Marine cloud brightening alters the water cycle of the planet

and therefore modifies the global precipitation distribution (Jones *et al* 2009, 2011, Latham *et al* 2012a).

The impact of geoengineering schemes such as marine cloud brightening on vegetation and crops has not received much attention. Changes in primary productivity have been investigated in Jones *et al* (2009, 2011), where it was found that the combination of climate change and marine cloud brightening lead to a reduction in primary productivity in the Amazon and a smaller increase in primary productivity in Africa. An investigation into bio-geoengineering, where crops were simulated with an increased albedo showed a positive feedback loop where cooling reduced evaporation and therefore increased primary productivity (Singarayer *et al* 2009). Changes in primary productivity were investigated in Kravitz *et al* (2013) where a top of atmosphere radiation balance was used to calibrate a solar radiation reduction geoengineering scheme, the increased carbon dioxide fraction lead to an increase in primary productivity across much of the tropics. The impacts of both climate change and geoengineering on food production



so far have been investigated in Pongratz *et al* (2012), Xia *et al* (2014). In Pongratz *et al* (2012) a climate change scenario increases global wheat and rice yield but decreases maize yield. With the deployment of stratospheric sulphate aerosol, another proposed SRM scheme, global yields of maize, rice and wheat increase. In Xia *et al* (2014) an ensemble of climate models were used to simulate maize and rice yields in DSSAT and found that geoengineering via SRM in an atmosphere with increasing carbon dioxide concentrations leads to an increase in maize yield but a decrease in rice yield. However, neither Pongratz *et al* (2012) nor Xia *et al* (2014) assessed changes in the variability of crop yields or the frequency of crop failure.

## 2. Method

### 2.1. Climate model simulations

The HadGEM1 climate model (Martin *et al* 2006) was used to perform a control, a climate change, and a marine cloud brightening simulation (Latham *et al* 2012a), which are referred to hereafter as C440, F560 and F560G respectively, these simulations have been known as control (Con), changed (Car), and brightening (MCB) in previous publications (Latham *et al* 2012a, 2012b, Parkes *et al* 2012, Latham *et al* 2013, 2014). The climate model was run in a N96L38 configuration, with a horizontal resolution of  $1.875^\circ \times 1.25^\circ$  and 38 vertical levels extending up to 39 km. The C440 simulation has a projected 2020 level of carbon dioxide, which was defined as 440 ppm. The F560 and F560G runs have carbon dioxide levels which increase by 1%/year until reaching double preindustrial levels at 560 ppm. The carbon dioxide levels are then held static at the double preindustrial levels. Within the model F560G is simulated by setting the cloud droplet number concentration to  $375 \text{ cm}^{-3}$

within the three regions shown in figure 1(a) of Latham *et al* (2012b). The total area of the three regions is 3.3% of the world surface, this is made up of the North Pacific region 0.7%, South Pacific 1.5% and South Atlantic 1.1%. Each simulation is run for 70 years to allow the model to reach equilibrium with the final 20 years used for input into the crop model. Within the climate model the only greenhouse gas modified to simulate the future climate was carbon dioxide, therefore the impacts of other gases are not assessed. This may result in less significant climate change than found in a RCP4.5 simulation which includes methane, CFCs, HCFCs and oxides of nitrogen Meinshausen *et al* (2011).

### 2.2. Crop model simulations

The three climate model simulations were used to drive a crop model in order to simulate yields of spring wheat in Northeastern China and groundnut in West Africa. The crop model used was the General Large Area Model (GLAM) for annual crops, which is a process-based model specifically designed for regional scale modelling (Challinor *et al* 2004). The coupling of the models is one directional with GLAM using the output from the climate model but not feeding any data back. Full details of the crop model simulations are given in the supplementary information and are summarized here.

GLAM is driven using daily weather data, specifically minimum and maximum temperature, precipitation and downwelling shortwave radiation. It was run on the climate model grid, using the daily weather data produced by the climate model. GLAM also requires soil data, a planting window, and a set of parameter values suitable for the crop and location in question. These input data and parameter sets follow Challinor *et al* (2010) for the simulation of spring wheat in Northeastern China and Vermeulen *et al* (2013) for

the simulation of groundnut in West Africa. These regions were selected as GLAM has been used to simulate crops in these regions before and gives us confidence in the results. However, two changes were made for this study. Firstly, the albedo of the land surface was changed to 0.15 for both locations in order to be consistent with the vegetation field in the climate model. Secondly, the normalized transpiration efficiency (Pa) and the maximum transpiration efficiency ( $\text{kg ha}^{-1}$ ) were increased when simulating yields in the F560 and F560G climates to account for the carbon dioxide fertilization effect. In order to account for uncertainty in the magnitude of this effect, three different pairs of values (low, moderate, high) were used, see SI table 2 and SI table 3.

For each of the three climates, the impact of water stress and of high temperatures during flowering was assessed by performing a sensitivity experiment simulating crops adapted to each of these stresses in turn. Adaptation to water stress was simulated by removing any water limitation on leaf growth or biomass accumulation. This represents a plant that can continue growing during periods of drought or a fully irrigated crop. Adaptation to high temperatures during flowering was simulated by turning off the high temperature stress during flowering routine (described in Challinor *et al* (2005)).

GLAM simulates the response of crops to weather and uses a single calibration parameter, the 'yield gap parameter' (YGP), to account for reductions in yield due to non-climatic factors (Challinor *et al* 2004), these factors include pests, diseases and nutrient deficiency. The YGP reduces yields by reducing the crop's leaf area index. Crop yields were simulated using the full range of values for the YGP (0.01 to 1 in steps of 0.01). The impact of a F560 or F560G climate on crop yields was analysed for each YGP separately. Therefore, a consistent response across YGPs indicates that the results of the study are independent of the crop model calibration procedure.

The impact of a F560 climate and a F560G climate on crop yields was assessed by examining both changes in mean yields and changes in the crop failure rate. Two levels of crop failure were considered: mild and severe. The thresholds for crop failure were calculated using the C440 simulation and were defined as 1 and 1.5 standard deviations below the mean for mild and severe crop failure respectively. The thresholds were calculated for each grid cell and for each value of YGP separately.

### 3. Results

#### 3.1. Climate model results

The changes in seasonal meteorology, which is defined as the meteorology incident on the crop, from the C440 simulation to the F560 and F560G simulations are summarized in table 1 (see SI figure 1 and SI figure 2 for

**Table 1.** Change in total precipitation (cm/season) and mean seasonal temperature (K) from the C440 simulation for wheat in Northeastern China and groundnut in West Africa. The total precipitation and mean temperature are calculated from planting to harvest for each grid cell and these values are then averaged across all grid cells in the region.

	F560	F560G
Northeastern China		
Precipitation (cm/season)	-2.4	-0.45
Temperature (K)	+1.1	+0.21
West Africa		
Precipitation (cm/season)	+3.8	+28.8
Temperature (K)	+0.93	-0.95

more detail). In China, both F560 and F560G are warmer and receive less precipitation than C440. However, the changes in temperature and rainfall are smaller in F560G than in F560. In West Africa, F560 is warmer than C440 and F560G is cooler than C440, both by approximately 1 K. F560 is wetter than C440 and F560G is much wetter than both. Marine cloud brightening has a direct impact on solar radiation over the sea and in the immediate vicinity to the seeding, however the changes in solar radiation in regions distant from the seeding is much smaller.

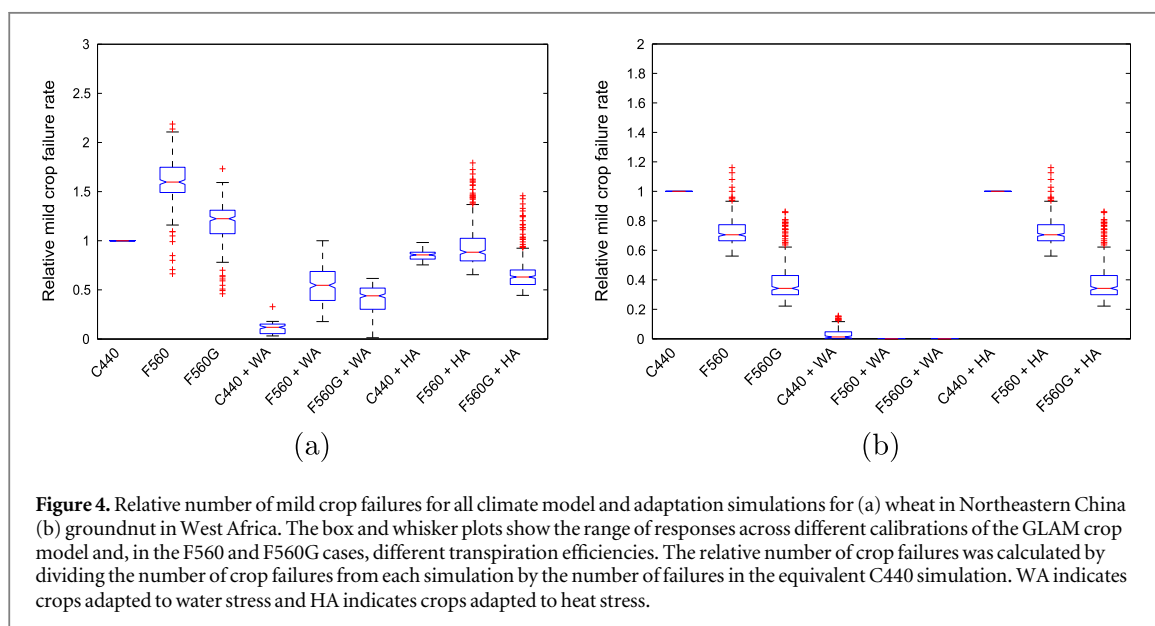
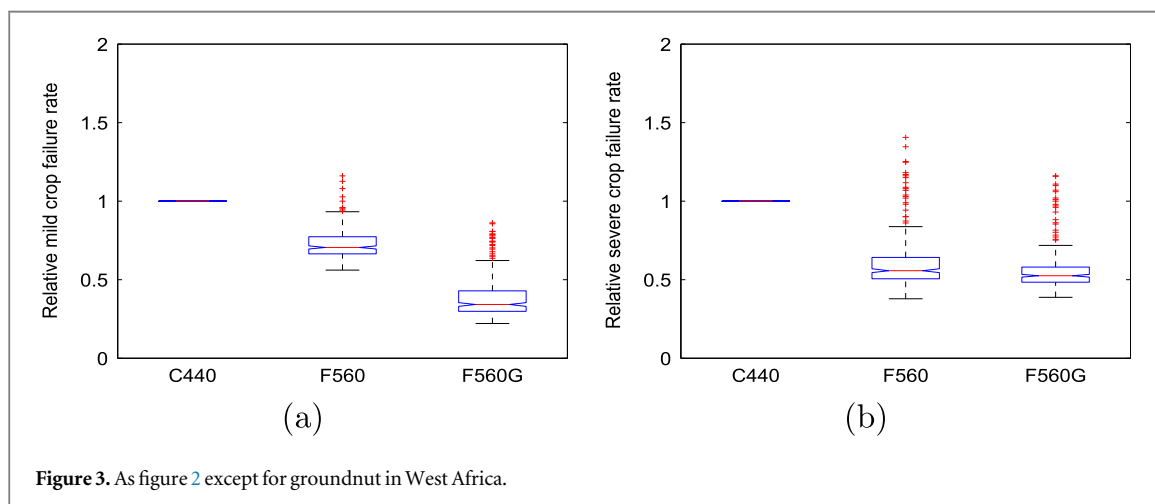
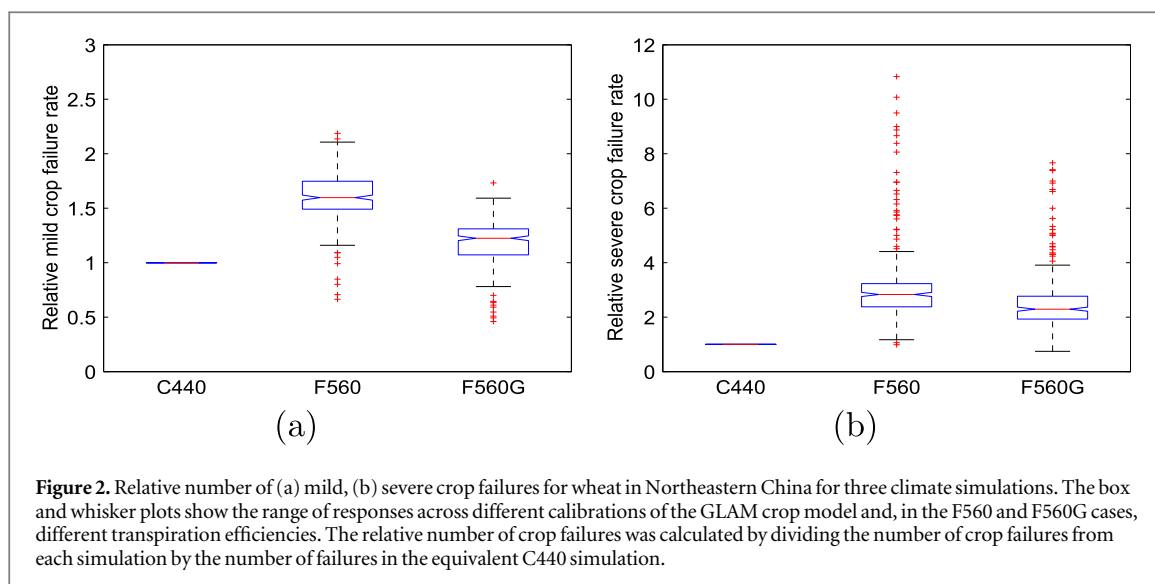
#### 3.2. Crop model results

The differences in projected mean yield are shown in figure 1. For both wheat in China (figure 1(a)) and groundnut in West Africa (figure 1(b)) yields are expected to increase in a F560 climate and increase further in a F560G climate.

The number of crop failures for each of the three climate model simulations relative to the C440 is shown for wheat in China in figure 2. The results for mild crop failure are shown in figure 2(a) and those for severe crop failure are shown in figure 2(b). F560 increases the number of mild and severe crop failures. F560G reduces the number of crop failures relative to F560 but does not return the crop failure rate to the level of the C440 simulation. The average severe crop failure rate under F560G is still three times higher than in the C440 simulation.

The results for groundnut in West Africa (figures 3(a) and (b)) show that F560 reduces the number of crop failures. F560G further reduces the number of mild crop failures but results in a similar number of severe crop failures as F560. This behaviour, where F560G is more effective at reducing mild crop failure than severe crop failure, can also be seen in the results for wheat in China.

Crops adapted to water stress (WA) and crops adapted to heat stress (HA) were simulated to assess the impact of each stress on mean yields and on the crop failure rate. For wheat in China, both water and heat stress limit mean yields and cause crop failure,



with water stress having the biggest impact (e.g. figure 4(a), see SI figure 3(a) and SI figure 4 for full results). Therefore, in China, F560G reduces the

number of crop failures relative to F560 because of the lower temperatures and increased rainfall. For groundnut in West Africa, water stress is the dominant

limitation on mean yields and cause of crop failure, with heat stress having no effect (e.g. figure 4(b), see SI figure 3(b) and SI figure 5 for full results). Here, F560G reduces the number of crop failures because of the increased rainfall. In both cases the increase in rainfall in F560G is complimented by a decrease in incident solar radiation which inhibits evaporation and further increases available water.

#### 4. Discussion

We find that in this case climate change will increase mean yields for both wheat in Northeastern China and groundnut in West Africa. This projected increase in yields is in part due to the carbon dioxide fertilization effect, and for West Africa is also due to increased seasonal rainfall. The climate change projected by the input simulations is however moderate, and has a lower impact than RCP4.5. The increase in mean yields is accompanied by a decrease in the crop failure rate in West Africa. However, climate change is predicted to increase the crop failure rate in China, which is consistent with previous studies (Challinor *et al* 2010). If climate change is more severe than in the input simulations then it is possible that the crop failures will increase in both regions.

The increase in yield variability is likely to be problematic for both subsistence farmers and for consumers, who will see larger fluctuations in prices (Gilbert and Morgan 2010). In particular, studies commonly use variability in yield as a metric for uncertainty, rather than using it to assess changes in the stability of production. We recommend that all crop impact studies assess and report changes in yield variability in addition to mean yield, see also Challinor *et al* (2014). The changes in crop failure rate were a result of the increasing temperatures and the increasing variability in temperatures which leads to seasons with significantly higher or lower yields.

While the simulations conducted here were for two regions only, some indicative conclusions can be made for other regions by referring to the precipitation changed in the global MCB simulations used to drive the crop model. The top five wheat producing countries are China, India, USA, Russia and France, these five nations make up approximately half of global production (FAOSTAT 2014). All of these experience an increase in precipitation under MCB Latham *et al* (2012a). This suggests that MCB has the potential to significantly reduce the impact of climate change on global wheat production. The top five groundnut producing nations are China, India, USA, Nigeria and Sudan (former borders) (FAOSTAT 2014), which account for over 70% of global production. China, India and the USA have been discussed above and Nigeria is part of this study, the precipitation in Sudan is also expected to increase under MCB (Latham *et al* 2012a).

This work has been performed using a single climate model and a single crop model. The uncertainty in the response of climate to increased carbon dioxide levels, particularly in the response of precipitation, has been highlighted in several studies including the IPCC Fifth Assessment Report (see figure 12.10 of Collins *et al* 2013). The mean results from the CMIP5 inter-comparison project show similar results to the F560 scenario with increases in temperature in both. Precipitation changes are similar in West Africa, while in China an increase in rainfall is found, in contrast to the simulation used here (see box TS.6, figure 1 Stocker *et al* 2013). Differences in the climatic response will impact the projections of crop yield, as will the use of different crop models. These results contrast with several studies which have reported reductions in mean crop yield in West Africa with climate change, in Challinor *et al* (2007), Lobell *et al* (2008). This is likely a result of the increase in precipitation in our input simulations compared with a decrease in precipitation in these other studies. The next step would be to use an ensemble of both climate models and crop models, such as combining the GeoMIP and AgMIP projects, this has been started in the work by Xia *et al* (2014).

#### 5. Conclusion

In both China and West Africa, marine cloud brightening is expected to increase yields and reduce the crop failure rate compared to a climate change scenario. Marine cloud brightening may therefore be beneficial for food production in these two regions, furthermore increases in precipitation over the growing areas for these crops indicate that marine cloud brightening may improve wheat and groundnut yields globally. Further work is required to investigate the impact on other crops and in different regions.

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