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Paper:

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1 **Abstract**

2

3 The importance of temperature in the determination of the yield of an annual crop (groundnut; *Arachis*
4 *hypogaea* L. in India) was assessed. Simulations from a regional climate model (PRECIS) were used with
5 a crop model (GLAM) to examine crop growth under simulated current (1961-1990) and future (2071-
6 2100) climates. Two processes were examined: the response of crop duration to mean temperature and the
7 response of seed-set to extremes of temperature. The relative importance of, and interaction between,
8 these two processes was examined for a number of genotypic characteristics, which were represented by
9 using different values of crop model parameters derived from experiments.

10

11 The impact of mean and extreme temperatures varied geographically, and depended upon the simulated
12 genotypic properties. High temperature stress was not a major determinant of simulated yields in the
13 current climate, but affected the mean and variability of yield under climate change in two regions which
14 had contrasting statistics of daily maximum temperature. Changes in mean temperature had a similar
15 impact on mean yield to that of high temperature stress in some locations and its effects were more
16 widespread. Where the optimal temperature for development was exceeded, the resulting increase in
17 duration in some simulations fully mitigated the negative impacts of extreme temperatures when sufficient
18 water was available for the extended growing period. For some simulations the reduction in mean yield
19 between the current and future climates was as large as 70%, indicating the importance of genotypic
20 adaptation to changes in both means and extremes of temperature under climate change.

21

22

23 **Keywords:** crop yield, temperature threshold, climate change, climate model, crop model, extremes

1 **1. Introduction**

2 Under climate change, increases in both the mean and extremes of temperature are expected for many
3 parts of the globe (IPCC, 2001a). These changes can impact the growth and development of crops in a
4 number of ways. Temperature is a key determinant of evaporative and transpirative demand, particularly
5 in tropical regions (e.g. Priestley and Taylor, 1972). Sustained temperature increases over the season will
6 change the duration (from sowing to maturity) of the crop (e.g. Roberts and Summerfield, 1987) whilst
7 short episodes of high temperature at critical stages of crop development can impact yield independently
8 of any substantial changes in mean temperature (e.g. Wheeler et al., 2000; McKeown et al., 2005).

9
10 High temperature stress is perhaps the most complex and least accurately quantified of the processes
11 described above. Threshold temperatures for flower production and seed abortion have begun to be
12 identified by field and controlled environment studies for a number of crops, including wheat, rice, maize
13 and groundnut (see e.g. Ferris et al., 1998; Rötter and Van De Geijn, 1999; Ismail and Hall, 1999; Matsui
14 et al., 2001). This has enabled crop simulation models to begin to simulate the impact of heat stress (e.g.
15 Matthews et al., 1995; Challinor et al., 2005c). This means that some crop models can be used to explore
16 the various pathways through which temperature impacts crop yield.

17
18 A full assessment of the impacts of changes in temperature involves an analysis of the socio-economic
19 impacts resulting from the biophysical processes. For this reason, integrated assessments of the impacts of
20 climate change often simulate crop yield, land-use change and world food trade. The treatment of crop
21 growth and development in these assessments tends to be based on empirical methods. For example, Parry
22 et al. (2004) used parameterisations of crop model functions, whilst Fischer et al. (2002) used observed
23 statistical relationships based on those of Doorenbos and Kassam (1979). These methods are pragmatic
24 advances, but they do not account for the possible impacts of high temperature stress. In some cases intra-
25 seasonal variability in weather is accounted for at only the coarsest temporal resolution (i.e. monthly).

26

1 Changes in atmospheric carbon dioxide concentration and in the seasonal cycle may mean that statistical
2 relationships between weather and crop yield developed under the current climate are not valid under
3 climate change (Challinor et al., 2005b). The increasing recognition of the importance of weather
4 extremes, intra-seasonal variability and climate thresholds is reflected in crop modelling studies (e.g.
5 Semenov and Porter, 1995; Easterling et al, 1996; Semenov and Barrow, 1997; Hansen and Jones, 2000;
6 Challinor et al., 2005c; Porter and Semenov, 2005). Used in conjunction with weather inputs, process-
7 based crop models provide a method for the quantification of the impact of the causative pathways
8 between weather and yield, and the interaction between these pathways and plant characteristics (e.g.
9 Sinclair and Muchow, 2001). Weather stations are one possible source of data for crop simulation models
10 (e.g. Sultan et al., 2005). However, if yields are to be simulated over large areas or for future climate
11 scenarios then alternative sources of data are needed. Weather inputs over large areas commonly come
12 from gridded climate model output of the kind used by Challinor et al. (2005a,b).

13
14 This study uses regional climate modelling simulations for the current climate and one future climate
15 scenario, together with a process-based crop model, to quantify the impact of temperature changes on the
16 crop. The impacts are examined using a number of sets of crop parameter values, representing different
17 crop responses to the mean and extremes of temperature. Two key responses in particular are analysed: the
18 impact of mean temperature on duration, and the impact of extremes of temperature at a critical stage of
19 crop development (flowering). The primary objective of the study is to explore the importance of
20 genotypic selection in response to changes in the mean and extremes of temperature. This includes
21 assessment of the relative importance of, and interaction between, these processes for the case of
22 groundnut (*Arachis hypogaea* L.) in India. The secondary objective is to highlight regions within India
23 that are at risk from the changes in temperature statistics that are expected under climate change. Since
24 only one climate change scenario is used no attempt is made to make firm projections regarding crop
25 productivity changes.

1 **2. Materials and methods**

2

3 **2.1 Crop and climate models**

4 Two climate simulations from the joint Indo-UK program (IITM, 2004) on climate change were used in
5 this study. As part of this program the PRECIS regional climate model

6 (<http://www.metoffice.com/research/hadleycentre/models/PRECIS.html>) was used to simulate present-day

7 and future climates. For the present-day (baseline) case the HadAM3 general circulation model (GCM)

8 was run with observed sea surface temperatures in order to produce the boundary conditions for PRECIS.

9 For the future climate simulations a coupled GCM (HadCM3) was used to simulate changes in climate

10 and these changes were added to the baseline values in order to produce the boundary conditions.

11 Availability of the data at the time of the present study limited the scenarios used to a baseline 1961-1990

12 simulation, and a 2071-2100 A2 simulation, both without sulphur. The A2 scenario is one of the most

13 extreme scenarios, with emissions rising monotonically from present-day values (<10 Gt of carbon) to

14 over 25 Gt of carbon in 2100 (IPCC, 2001b).

15

16 The crop model used in this study is the General Large-Area Model for annual crops (GLAM; Challinor *et*

17 *al.*, 2004,2005c). This was designed in order to capitalise on the predictability that is suggested by large-

18 area relationships between weather and climate (Challinor *et al.*, 2003). The model is sufficiently complex

19 as to allow mechanistic simulation of crop-climate processes, and sufficiently simple for use over large

20 areas, without the need to parameterise sub-regional variability. GLAM has been used to simulate

21 groundnut pod yields with observed gridded data (Challinor *et al.*, 2004), reanalysis data (Challinor *et al.*,

22 2005a,b) and probabilistic seasonal forecast data (Challinor *et al.*, 2005b). In this way, understanding of

23 processes (such as the role of intra-seasonal variability) and confidence in simulation results for climate

24 change has been developed using simulation in the current climate (see e.g. Stooksbury and Michaels,

25 1994). On the whole these studies show that mean yields are simulated well by the model, with the

26 standard deviation being too small over most of India and too large in parts of the southern Indian

27 peninsula. The pattern of inter-annual variability in these studies (as measured by the correlation

1 coefficient between observed and simulated yields) is simulated well in the northwest of India, and with
2 variable accuracy in other regions.

3
4 The parameter values used in this study were those for groundnut developed by Challinor et al. (2004),
5 since this has been tested extensively (Challinor et al., 2004, 2005a,b,c). The one exception to this is that
6 since net radiation input data is used the surface albedo in the crop model is set to zero. The
7 parameterisation of high temperature stress, which was not included in Challinor et al. (2004), follows
8 Challinor et al. (2005c; hereafter GLAM-HTS - high temperature stress). The parameterisation of water
9 stress near anthesis follows Challinor et al. (2006). One further modification to the GLAM-HTS
10 parameterisation was made: a minimum value of 40°C (suggested by the data of Vara Prasad, 1999 and
11 Kakani, 2001) for one of the critical temperatures (T_{lim}) was introduced, since the standard
12 parameterisation produced some unrealistically low values when used with the climate data in this study.

14 **2.2 Calibration methods**

15 GLAM is calibrated by varying the yield gap parameter (YGP) and choosing the value that minimises the
16 difference between observed and simulated yields. YGP simply multiplies the potential maximum rate of
17 change of leaf area index in order to give a value that is limited by non-climatic factors such as pests,
18 diseases and nutrients. In practice YGP can also act to correct bias in the input weather data (Challinor et
19 al., 2005b). The yield data for calibration are from the district-level database of agricultural returns
20 compiled by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru,
21 India. The time series of pod yield (1966-1989) for each individual district was linearly detrended to 1966
22 levels in order to remove the influence of improved varieties and management methods. Each grid cell
23 was assigned uniquely to a district (one-to-many mapping) according to the location of its centre. The
24 yield data include both the monsoon (rainfed) season and winter (irrigated) season. Figure 1 presents the
25 mean and standard deviation of the yield data. Challinor et al. (2003, 2004) have more discussion on these
26 data.

1 In developing calibration methods for the present study, two separate methods were developed. Appendix
2 1 describes these methods and the resulting choice of calibration method for the remainder of the study.
3 The use of YGP values calibrated using the baseline climate in projections of future climates raises an
4 important issue: will changes in YGP between the two time periods be greater than the climate-induced
5 changes in yield? Challinor et al. (2005b) showed that providing the technology trend has been removed,
6 fluctuations in the calibrated value of YGP on decadal timescales are small, at least between the 1960's
7 and the 1990's.

8

9 *2.3 Crop simulation experiments*

10

11 Six crop simulation experiments, with varying crop parameter values, were carried out. Parameters were
12 varied in order to simulate different genotypic responses to two key processes: (i) the impact of high
13 temperatures near flowering, and (ii) the impact of mean temperature on crop duration. The crop model is
14 formulated such that the choice of parameter values for each of these processes does not affect the
15 response of the crop to the other process. All simulations used the same sowing window (Reddy, 1988);
16 the crop is sown on the first day in which the soil moisture exceeds a specified threshold (see Challinor et
17 al., 2004).

18

19 Following GLAM-HTS, the parameters used to determine the critical temperatures (step (i) above) and/or
20 the response of harvest index to P_{tot} were changed in order to simulate a sensitive (SEN), moderately
21 sensitive (MOD) and tolerant (TOL) crop genotype. The simulations of GLAM-HTS showed that the
22 impact of high temperatures near anthesis (flowering) in GLAM can be heavily dependent on the temporal
23 pattern of flowering (i.e. the fraction of total flowers associated with yield that form each day). This
24 temporal pattern is determined by the choice of flowering distribution, F. For the present study, the choice
25 of tolerant (TOL) or sensitive (SEN) crop parameter values was found to provide greater variability in
26 yield than the choice of F within crop genotype. Hence a single flowering distribution (F3 from GLAM-
27 HTS) was used for all the simulations reported.

1
2 Simulations for the baseline climate were carried out using the MOD parameter set; there is little
3 difference between this simulation and a simulation using either TOL or SEN. The results presented for
4 the future climate scenario are for the TOL and SEN cases. The response of crop development rate to
5 mean temperature was varied using the optimal temperature (T_{opt}): one set of simulations used $T_{opt}=28^{\circ}\text{C}$,
6 which is at the lower end of the observed range, and is the calibrated value used in previous GLAM-
7 groundnut studies over India. A second set of simulations used $T_{opt}=36^{\circ}\text{C}$; this is at the high end of the
8 observed range for groundnut (Ong, 1986). Hence the six simulations carried out consist of three for each
9 value of T_{opt} : a baseline (current climate) simulation, and two 2071-2100 simulations (TOL, SEN). The
10 baseline $T_{opt}=36^{\circ}\text{C}$ simulation was only used to assess percentage changes from the 2071-2100 projection;
11 the $T_{opt}=28^{\circ}\text{C}$ baseline run was used for assessing the skill of the simulations. Simulations for 2071-2100
12 are referred to using the high temperature stress parameter set, followed by the value of the optimal
13 temperature for development (e.g. SEN-28).

14
15 The six simulations were repeated with the high temperature stress parameterisation switched off.
16 Together with an analysis of the impact of high temperatures on the rate of change of harvest index, this
17 allowed quantification of the sensitivity of yield changes (between the baseline period and the projection)
18 to processes associated with mean and extreme temperatures. The results of this analysis are presented in
19 section 4. The simulations are listed, together with the figures in which they are presented, in table 1.

20
21 Since the uncertainty associated with the CO_2 fertilisation effect, both simulated and actual, is substantial
22 (Kimball et al., 2002; Challinor et al., 2005d; Ainsworth and Long, 2005) this process is not examined in
23 this study; the transpiration efficiency and water-use characteristics of the crop are held constant between
24 the two time periods studied. This means that whilst one contribution to the uncertainty in yield simulation
25 is avoided, caution is needed in any direct interpretation of yield projections. Note, however, that despite
26 accounting for the beneficial effects of carbon dioxide, Mall et al. (2004) projected decreases in soybean
27 yields across India under doubled CO_2 . Whilst this projected decrease is not necessarily a consensus

1 result, there is some evidence that projected increases in crop yield under elevated CO₂ may, due to high
2 temperature stress, result in no increase in yield (Vara Prasad et al., 2002; Sivakumar et al., 2005). There
3 is also some evidence that the beneficial impacts of CO₂ may not be as large as previously thought (Long
4 et al., 2005). These observations are merely suggestive, however; there may be an interaction between
5 high CO₂ and high temperature stress that, if parameterised, would produce different results. This is
6 clearly an area for future work.

7

8 **2.4 Analysis methods**

9 In order to examine the changes in climate between the two time slices, differences in the mean and
10 standard deviation of climate variables were calculated. In addition, the number of days in July (when the
11 crop usually flowers) with temperatures exceeding a given threshold was computed by analysing daily
12 maximum temperature (T_{max}). Differences in this statistic between the two time slices indicate regions
13 where the risk of high temperature stress increases. This statistic can also be adjusted in order to determine
14 the extent to which changes in exceedance rates in a grid cell are due to changes in the mean of T_{max} , both
15 the mean and the variance, or the shape of the probability distribution function (Ferro et al., 2005;
16 Appendix 2). This analysis can begin to distinguish the impacts of different types of change in the PDF of
17 temperature: changes in the mean affect crop duration (see e.g. GLAM-HTS) and changes in variance can
18 have a greater impact on extreme temperatures (e.g. Katz and Brown 1992). The contribution of changes
19 in the mean, variance and shape of the temperature distributions to changes in temperature threshold
20 exceedance is assessed using this method in section 3.2.

21

22 The choice of threshold temperature for the analysis described above was 34°C. A sensitive groundnut
23 variety would show some impacts of high temperature stress for mean 8am-2pm temperatures above this
24 value during flowering. Hence this choice corresponds to the onset of heat sensitivity in a groundnut crop
25 (Vara Prasad et al., 2001) More importantly, it is a temperature above which other crops are likely to be
26 affected by heat stress: threshold temperatures for wheat, rice and maize are estimated to be in the region
27 30-36°C, and durations of the order of hours can be enough to impact the crop (Rötter and van de Geijn,

1 1999). Note that threshold temperatures for temperate crops may be lower than those of tropical crops
2 (Wheeler et al., 1996; Matthews and Wassmann, 2003); McKeown et al. (2005) used a threshold of 30°C
3 to explain the impacts of high temperatures on annual horticultural crops.

4
5 A number of yield-related quantities were analysed: final pod yields and the percentage of pods setting are
6 direct model output. Percentage changes in yield between current and projected climates always use
7 simulations with the same value of T_{opt} (28 or 36 °C). The fraction of pods setting due to temperature stress
8 only was calculated by discounting the impact of water stress on pod-set in the model. In some years in
9 some regions the seasonal cycle of temperature is such that the thermal time requirement of the crop is not
10 met. These crop seasons are not included in the analysis.

11 12 **3. Results**

13 14 **3.1 Baseline climate**

15 The accuracy of GLAM in simulating the mean and standard deviation of yield is shown in figure 2. Over
16 most of India, mean yields are simulated well and the standard deviation (σ_s) is underestimated. The main
17 exception to this is the central and eastern parts of the southern peninsula, where simulated mean yields
18 are too low and σ_s is too high. This is also the region where simulated rainfall is too low (see IITM, 2004)
19 with mean values being between 100 and 400mm over most of this region. These low values are likely to
20 contribute to the poor simulation of yields in this region. Another contributing factor may be the lack of
21 simulation of the irrigated crop; when averaged over the 1966-89 period, the area under irrigation
22 accounts for up to 25% of total growing area over this region. Simulation of yields in this part of India has
23 been improved by bias correction of seasonal total rainfall towards observations, and by use of a later
24 planting window, in at least one study (Challinor et al., 2005a). The results for the simulation of yields in
25 the baseline climate are broadly similar to those of previous studies (see section 2.1).

1 *3.2 Climate change scenario*

2

3 The climate projection for 2071-2100 shows various changes in climate that are relevant to crop growth
4 and development. The mean of cumulative precipitation during the simulated growing season increases
5 over most of India (by up to 60%) and the standard deviation also increases in most regions (by up to
6 20%). Mean growing-season temperature increases everywhere from its baseline values (mostly 24-28
7 °C), most markedly in the north-west (increases of up to 5 °C). The variability of mean temperature
8 increases over most of India (by up to 0.5 °C).

9

10 The response of the crop to changes in precipitation and temperature is that, over most of India, the mean
11 and variability of yield fall between the two simulation periods (figure 3). Since precipitation over most of
12 India increases between the two periods, this is not the cause of the yield decreases. Rather, it is changes
13 in crop duration across India, and incidence of high temperature stress in parts of the north and south, that
14 cause the changes in yield. These causes are examined in more detail below.

15

16 *High temperature stress*

17 An indication of likely crop responses to high temperatures comes from examining the increase, between
18 the two time slices, in the mean number of July days with $T_{max} > 34^{\circ}\text{C}$. The analysis is based on daily
19 maximum temperatures with the annual cycle and inter-annual trend removed (see Appendix 2). Increases
20 of over ten days are simulated in the north and southeast, resulting in an expansion of the areas
21 experiencing long-term temperature stress (see below). When the increase in temperature exceedance is
22 adjusted for changes in the mean and variance, a difference between the high temperatures in the north
23 and the south emerges: the increase in exceedance in the south is due primarily to a change in the mean,
24 whereas an additional change in variance contributes significantly to the increase in the north. The former
25 behaviour is typical of the response of sea-surface temperatures (e.g. Ferro et al. 2005) with which land
26 temperatures in the southeast are associated. These features are exemplified in figure 4 by the frequency
27 distributions of temperatures from two grid points representative of the northern and southeastern regions.

1 Variances in the northern region increase more than two-fold (not shown explicitly), amplifying the
2 frequencies of high temperatures.

3
4 The duration of high-temperature events (number of consecutive days with temperature exceeding 34°C)
5 also has an impact on crop yield (GLAM-HTS). The simulated change in the mean duration of these
6 events between the baseline and scenario run shows increases of up to ten days in the north and increases
7 of more than fifteen days in the southeast. Analysis of lagged temperatures using autocorrelations, and of
8 lagged temperature extremes using scatter plots (not shown), reveal that there is little change between the
9 baseline and projected climates in the serial dependence of temperature. Hence the increases in the
10 duration of high temperature events can be explained by the changes in temperature means and, for the
11 north, variances mentioned previously.

12
13 It is not possible to examine impacts on yield using analysis of weather fields alone, since the precise
14 timing of weather events relative to the development of the crop is a key determinant of yield (Wheeler et
15 al., 2000). Hence we now move on to look at output from the crop model. Temperature stress near
16 anthesis is significant in the climate projection, but not in the baseline simulation (figure 5). The
17 differences between the SEN-28 and TOL-28 varieties are also significant. In particular, in the north SEN-
18 28 produces a decrease in mean yields, whilst TOL-28 results in an increase in mean yields. Yield
19 increases in the TOL-28 case are mediated via a change in duration (see below).

20
21 Regions where the variability of yield increases between the two time slices (figure 3) tend to have
22 unrealistically low values of standard deviation in the baseline simulation (figure 2). Hence another
23 method for examining the interannual variability is needed; an indication of the extent of risk of crop
24 failure induced by temperature stress is given by the number of years when the total number of pods
25 setting is below a threshold value. For parts of India, failure events, defined using a pod-set threshold of
26 60%, occurs less than once in thirty years in the baseline simulation, and become a one in 21 (TOL-28) or
27 one in 10 (SEN-28) year event in the 2071-2100 projection (figure 5).

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Correlations between yield and the fraction of pods setting (figure 6) show the regions where high temperature stress and/or water stress is a significant determinant of yield. There is a marked difference between SEN-28 and TOL-28, most of which is due to temperature, as opposed to water, stress. The baseline and SEN-28 simulations are also markedly different. The TOL-28 simulations, however, look more like the baseline simulation.

Duration

Increases in mean daily temperature can either decrease or increase the duration of the crop, depending on whether the temperature exceeds that which is optimal for the rate of crop development, T_{opt} . The contrast in behaviour between the two chosen values of T_{opt} is illustrated in figure 7, which shows the statistics of the changes in duration between the two time slices. Simulations with $T_{opt}=36^{\circ}\text{C}$ show decreases in mean duration, across all of India, of between 10 and 35 days. Simulations with $T_{opt}=28^{\circ}\text{C}$ show similar decreases in some regions, but show lengthening duration of up to 20 days in some regions.

Correlations between simulated duration and yield (figure 8, left panels) show where duration is a significant determinant of yield. These correlations change sign between the two simulation periods. Positive correlations are easily understood: the longer the duration of the crop, the greater the accumulated biomass. Negative correlations are less trivially explained. Correlations are negative mostly in regions where duration and vapour pressure deficit (VPD) are positively correlated (figure 8, right panels); the increase in the number of these positive correlations between the two simulation periods is associated with co-located increases in negative correlations between yield and duration. The relationship between these two correlations is explained as follows: increases in crop duration are associated with temperature increases. Increases tend to be greater in maximum daily temperature than in minimum daily temperature (not shown), and this leads to an increase in the amplitude of the diurnal cycle. This in turn results in an increase in the estimated daily mean values of VPD (calculated using the parameterisation of Tanner and

1 Sinclair, 1983). In GLAM, as in observations (e.g. Zwart and Bastiaanssen, 2004), higher VPD is
2 associated with lower yields because it reduces transpiration efficiency.

3

4 **4. Sensitivity analysis**

5

6 The results presented above show that the impact of changes in the mean and extremes of temperature
7 varies geographically. The contrasting yields obtained when different responses to changes in the mean
8 and extremes of temperature are prescribed (figure 3) show that both reproductive and developmental
9 processes are important in determining the nature of this response. The following analysis focuses on the
10 relative importance of, and interaction between, these two processes. The analysis centres on the 153 grid
11 cells north of 25 °N.

12

13 Three sets of simulation data, each one quantifying the impact on yield of a different set of processes, are
14 examined. Firstly, the impact of high temperature stress alone was estimated by taking the impact of
15 temperature on the fraction of pods setting (see section 2.4) and using the GLAM-HTS equations to
16 calculate the impact on the rate of change of harvest index, and hence yield (see Challinor et al., 2005c).
17 Secondly, yields from the simulations with the high temperature stress parameterisation turned off (see
18 section 2.3) were examined. Finally, the impact on yield of all simulated crop processes was examined by
19 using the simulations presented in section 3. Each of these three sets of simulation data consists of four
20 genotypic parameters sets, SEN-28, TOL-28, SEN-36 and TOL-36, as used in section 3.

21

22 The impact of the projected climate on yield for each of the twelve simulations is presented in figure 9.
23 From left to right, the first four boxes show the results when high temperature stress is not considered.
24 Here the impact of seasonal mean temperature can be seen. Where T_{opt} is exceeded less often or not at all
25 (as in the 36 °C case) mean yields fall significantly due to a shortening of crop duration. The same process
26 is evident in the simulations with all parameterisations switched on (the last four boxes in figure 9); here,
27 the impact of seasonal mean temperature on yield is greater than that of tolerance to high temperatures.

1 The last four boxes also show the result seen in figure 3: for $T_{opt}=28^{\circ}\text{C}$, the degree of tolerance to high
2 temperatures can affect the sign of the change in yield.

3
4 The middle four boxes of figure 9 show the impact of high temperature stress only. These can be used to
5 assess the relative importance of the timing of flowering (which is different for different values of T_{opt})
6 and the degree of tolerance to high temperature stress. The greatest similarity in impact is across T_{opt} rather
7 than across tolerance, showing that for this particular case, the degree of tolerance is a greater determinant
8 of yield than the timing of flowering. Note, however, that we have only sampled two possible flowering
9 periods, which is far from comprehensive. The degree of tolerance affects not only mean yield, but also
10 yield variability: the SEN parameter set has a greater range of values than TOL. Hence the degree of
11 tolerance influences the response of the crop to interannual variability in temperature extremes during
12 flowering.

13
14 Comparing the three different SEN-28 simulations shows that the simulation of high temperature stress
15 only produces results that are closer to the all-processes simulation than the simulation without high
16 temperature stress; hence this genotypic parameter set is dominated by high temperature stress. In
17 contrast, TOL-28 is dominated by the impact of changes in seasonal mean temperatures (i.e. the second
18 and tenth bars are similar). For $T_{opt}=36^{\circ}\text{C}$, seasonal mean temperature dominates in both the SEN and
19 TOL case.

20

21 **5. Discussion**

22

23 This study set out to examine the importance of the mean and extremes of temperature in the
24 determination of the yield of an annual crop in India. Mean temperature affects duration, which is an
25 important determinant of yield in the current climate simulations, and less important in the climate
26 projection (figure 8). However, this result depends on the choice of optimal temperature for crop
27 development, which is not well constrained. Challinor et al. (2005d) found that uncertainty in the value of

1 the optimum temperature for development is an important component of the total (climate plus crop)
2 uncertainty in a climate change projection.
3
4 High temperature stress is not a major determinant of yield in the current climate simulations, but becomes
5 important in parts of the north and south under climate change with the parameter sets used in this study
6 (figures 4 and 5). Increases in the magnitude and duration of high temperature events in northern and
7 south-eastern growing regions are due to increases in the means and, for the north, variances of
8 temperature frequency distributions (figure 4). Whilst groundnut is not a major crop in northern regions
9 (see e.g. Challinor et al., 2003), this result is a first indicator of the risk to other short-duration annual
10 crops, many of which have a similar response to mean and extreme temperatures (section 2.4). The
11 regions in the north of India which show increased risk to crop production coincide with the regions of
12 continued and/or increased climate sensitivity under doubled CO₂ calculated by O'Brien et al. (2004).
13 Work on the quantification of the impacts of high temperature stress on crop yield based on future climate
14 projections is at an early stage. Whilst there are few published studies in this area, there is some
15 qualitative evidence of increased risk to crop production, similar to that seen in the current study, in parts
16 of Africa (Huntingford et al., 2005).
17
18 Genotypic differences in tolerance to high temperature stress have been documented in many annual crops
19 (Wheeler *et al.*, 2000). In groundnut, Craufurd *et al.* (2003) screened 22 genotypes using controlled
20 environments in order to identify genotypes that were tolerant or sensitive to high temperature stress at
21 flowering or at microsporogenesis (3 days before flowering). They listed 6 groundnut genotypes, of
22 diverse origin, that were heat tolerant at these stages. The modelling approach demonstrated in the current
23 study can be used with the detailed information from such genotype screens in order to properly
24 investigate the extent of genotypic adaptation to high temperature stress associated with climate change
25 within current crop germplasm. Equally, the potential for crop adaptation to climate change through
26 breeding for improved tolerance to high temperatures can be explored in a robust manner within this
27 modelling framework.

1

2 The relative importance of mean and extremes of temperature varies geographically, and depends upon the
3 genotypic parameters (section 4). The impact on yield of changes in duration resulting from seasonal
4 mean temperature changes can have a greater magnitude than that of high temperature stress (figure 9) and
5 its effects can be more widespread (figure 3). Where the optimal temperature for development is exceeded
6 the resulting increase in duration can mitigate and even counteract the negative impacts of reproductive
7 temperature threshold exceedance on yield, provided that there is sufficient water for the crop to benefit
8 from the extended duration. The magnitude and sign of this effect depends on the degree of tolerance of
9 the crop to temperature extremes; hence yields are particularly threatened when water availability and/or
10 mean temperature shorten the duration of a crop which experiences and is sensitive to high temperatures
11 during flowering. The degree of sensitivity determines the response of not only mean yields, but also the
12 magnitude of interannual variability (figure 9).

13

14 Increases in maximum temperature between the two time periods studied are associated with increases in
15 the diurnal temperature range and hence in VPD (section 3.2). Due to the high temperatures involved, the
16 regions where this occurs will tend to be co-located with regions where reproductive temperature
17 thresholds are being exceeded. Hence, as well as the impact of mean temperatures on the rate of
18 development, which are linear for $T < T_{opt}$, there is a non-linear response to diurnal temperature amplitude,
19 of the kind described by Porter and Semenov (2005).

20

21 **6. Conclusions**

22

23 Methods like those employed here can be used to quantify the impact of high temperature threshold
24 exceedance on crops. The results from this study suggest that temperature extremes could be an important
25 determinant of the yield of annual crops, specifically in parts of northern and southern India. Changes in
26 mean temperature, through their impact on development rates, may have a more widespread impact on
27 yield. The magnitude of that impact could be greater than that of heat stress in this climate scenario; this

1 depends upon the cardinal temperatures and thermal time requirements of the varieties grown. The
2 magnitude of the impacts is large – yield reductions of up to 70% – and this illustrates the importance of
3 genotypic adaptation to changes in the mean and extremes of temperature. Repeating this kind of study
4 with crop models designed for use at the field scale, which tend to parameterise more processes than
5 GLAM, would provide a useful perspective on the current study.

6
7 Once this work has been extended to other crops and other climate and emissions scenarios, a more
8 consolidated picture will emerge. Genotypic adaptation to changes in both the mean and extremes of
9 temperature will be important, as is evident from the large differences in the results between the different
10 crop parameter sets used in this study. Changes in thermal time requirement and tolerance to heat stress
11 are two key adaptive methods. Other adaptive methods may include a change in planting date, crop type or
12 management practices (particularly irrigation). When quantifying the benefits of these methods it is
13 important to consider adaptive capacity (see O’Brien et al., 2004 for appropriate methods). This study has
14 focussed more on processes than on the provision of yield estimates. In beginning to quantify the risk of
15 future climates to cropping systems, it is clear that an associated quantification of uncertainty is important
16 (e.g. Challinor et al., 2005d). In particular, since the timing of heat stress is critical, there is considerable
17 uncertainty associated with it. The model used in this study, and those used in most other studies, simulate
18 the impact of heat stress deterministically. A probabilistic approach, which takes into account uncertainty
19 in the timing of heat stress events relative to anthesis, may provide more realistic estimates of the impacts
20 of extreme temperatures.

21

22 **Acknowledgements**

23 The authors are grateful to Rupa Kumar Kolli, and others at the Indian Institute of Tropical Meteorology,
24 for making available the regional climate simulations used in this study. The DEFRA-funded Indo-UK
25 project made these simulations possible.

1 **Appendix 1: Crop model calibration**

2 The calibration procedure varied YGP in steps of 0.05 between 0.05 and 1. Studies of crop yield under the
3 current climate using GLAM have used cross-validation to obtain two values of YGP for each location.
4 Since in the present study the focus is on simulation of the impacts of changes in climate, the full yield
5 time series was used to find a single value of YGP for each location.

6
7 Two methods of minimising the difference between observed and simulated yields were tested. The first
8 method minimises the difference between time-mean observed and simulated yields (and ignores inter-
9 annual variability). The second method uses both the mean and the standard deviation of yield over time.
10 The basis for this method is a decomposition of mean square error in yield (MSE) into systematic bias (in
11 the mean), bias in the standard deviation (σ) and a remaining term that depends upon correlation
12 coefficient (see e.g. Taylor, 2001):

13

$$14 \quad MSE = (\bar{o} - \bar{s})^2 + (\sigma_o - \sigma_s)^2 + 2\sigma_o\sigma_s(1-r) \quad (1)$$

15

16 where o are observed yields, s are simulated yields, bars indicate time-averages and r (which cannot be
17 calculated) is the correlation coefficient between o and s . By setting $r=1$ in the above equation, a value of
18 RMSE of a perfectly correlated time series can be calculated. This value of RMSE is used to determine
19 YGP. The following analysis shows that whilst the assumption of perfect correlation can seriously
20 underestimate RMSE, it is unlikely to seriously bias the resulting values of YGP.

21

22 Calibration of the Yield Gap Parameter on climate data corrects for some of the bias in the climate data,
23 and on the whole GLAM simulates mean yields well (Challinor et al., 2005a,b). Hence this analysis
24 ignores mean bias and focuses on the relationship between σ and r . For a given value of r there is a value
25 of σ_s that minimises RMSE. Call this value σ_{sm} . Only for $r=1$ will $\sigma_{sm}=\sigma_o$. Hence by including σ_o in the
26 calibration, and nudging the model towards correct simulation of standard deviation, RMSE will be

1 increased. If this increase in RMSE is within tolerable limits, then the assumption of perfect correlation is
2 acceptable.

3
4 A polar coordinate plot of correlation coefficient and standard deviation (Taylor, 2001) and the law of
5 cosines, or, less trivially, manipulation of equation 2, can be used to find the ratio of the RMSE associated
6 with σ_{sm} , and the RMSE associated with $\sigma_s=\sigma_o$. The relationship between this ratio (A) and r is as follows:

7
8
$$r = \frac{90 - \cos^{-1}(2A^2 - 1)}{90} \quad (2)$$

9
10 If we are willing to accept that correct simulation of the standard deviation of yield results in a RMSE
11 which would be improved upon by 10% by reducing σ_s , then we set $A=0.9$, and find that $r=0.43$; only
12 below this value is $A<0.9$. For $A=0.71$, $r=0$. Hence the perfect correlation method has the potential
13 advantage of reducing errors in the standard deviation without increasing significantly the RMSE.
14 Whether or not this potential is realised depends upon the simulation results.

15
16 Tests were carried out using both calibration methods in order to decide upon one method for the
17 remainder of the study. For the baseline simulations, the perfect correlation method lowers the maximum
18 error in standard deviation by up to 15% without significantly altering the error in the mean. Hence this
19 method was adopted.

20

21 **Appendix 2: Adjusted temperatures**

22 The mean-adjusted baseline temperatures are $T_{\max} - \bar{T}_{\max} + \bar{T}'_{\max}$, where bars indicated time-averages,
23 primes indicate the future climate scenario, and no superscript indicates the baseline simulation. Thus, if
24 the difference between the current and future climate distributions is only a shift in mean
25 from \bar{T}_{\max} to \bar{T}'_{\max} , then the distributions of the mean-adjusted temperatures and T'_{\max} will be identical.

26 Furthermore, the differences between any properties of these two distributions, such as the frequency with

1 which a high temperature threshold is exceeded, will be zero. The equivalent mean-and-variance-adjusted
2 temperatures are $(T_{\max} - \bar{T}_{\max}) * s' / s + \bar{T}'_{\max}$, where s and s' are the standard deviations in T_{\max} and T'_{\max} .
3
4 Due to the transient nature of the climate forcing (section 2.1), the two adjusted temperatures described
5 above, if based on raw values of T_{\max} , will not be computed from a stationary climate. Seasonal and
6 interannual variability means that temperature values are not taken from a single statistical distribution.
7 This may lead to errors in the attribution of the role of changes in the mean, variance, and the shape of the
8 probability density function (PDF). For example, the sample variance will over-estimate the variability of
9 the temperatures around the trend or cycle. For this reason, the annual cycles and the inter-annual trends
10 were removed from the temperatures prior to the analysis: if $T(i,j)$ is the temperature on the j th day of the
11 i th July at a single grid point in either the baseline or scenario run then the adjusted temperatures $T(i,j) -$
12 $T(i,o) + T(1,o) - T(o,j) + T(o,1)$, where 'o' denotes averaging over an index, are representative of the
13 climate at that location on the first day of the first year of the run.

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2

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Period	Parameter set	Figures
1961-1990	MOD-28	1, 5, 6, 7, 8
1961-1990	MOD-36	6, 8
2071-2100	SEN-28	2, 3, 5, 6, 8
2071-2100	SEN-36	6, 8
2071-2100	TOL-28	2, 3, 5, 6, 7, 8
2071-2100	TOL-36	2, 6, 8

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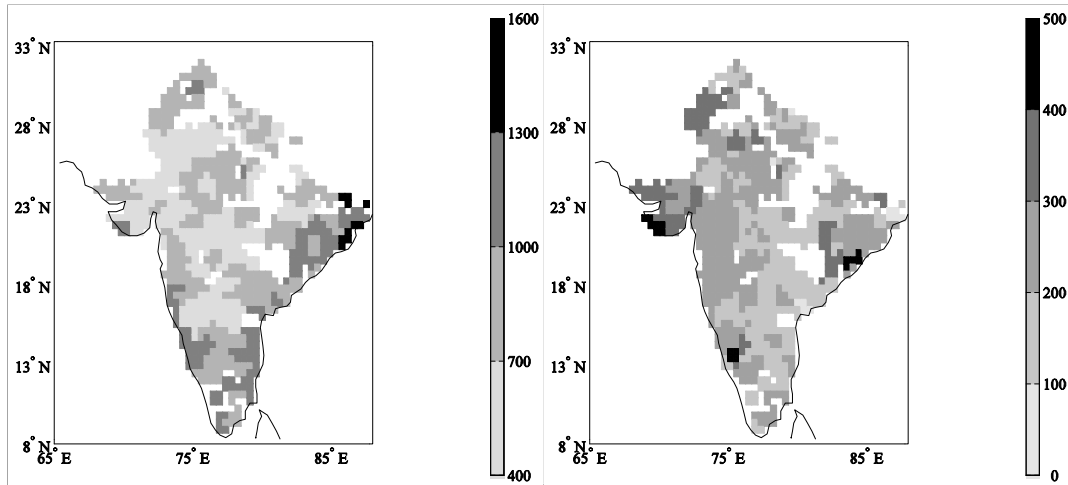
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Table 1. List of simulations carried out and figures where corresponding results appear. Numbers in italics refer to figures with percentage changes across both time series.

1 **Figures**

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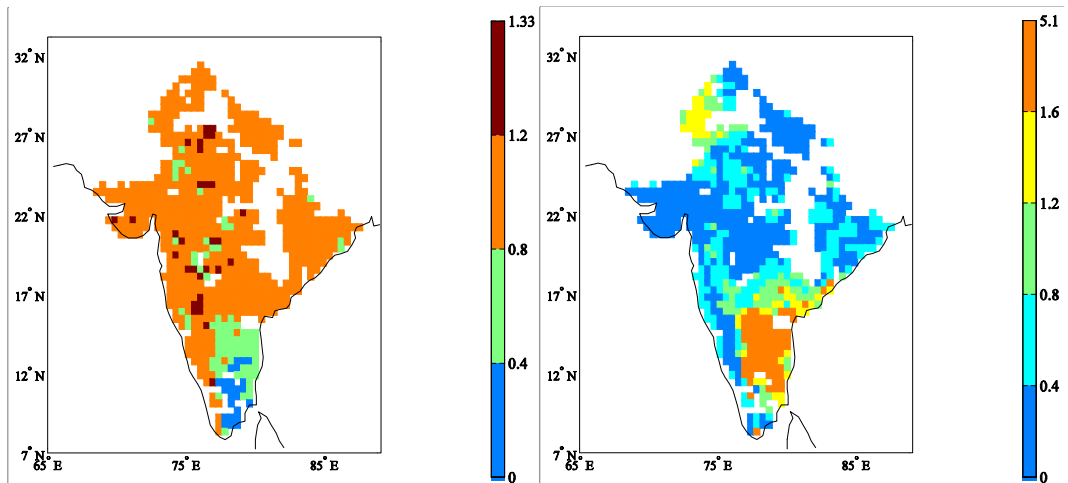
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Figure 1. Mean (left panel) and standard deviation of observed yields, in kg/ha, over the time period 1966-1989. Data have been linearly detrended to 1966 levels, and are presented on the grid used for modelling.



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Figure 2. Ratio of simulated to observed mean (left panel) and standard deviation (right panel) of yield for the baseline simulation with $T_{opt}=28^{\circ}\text{C}$. Only grid cells with at least five years of completed simulations are shown.

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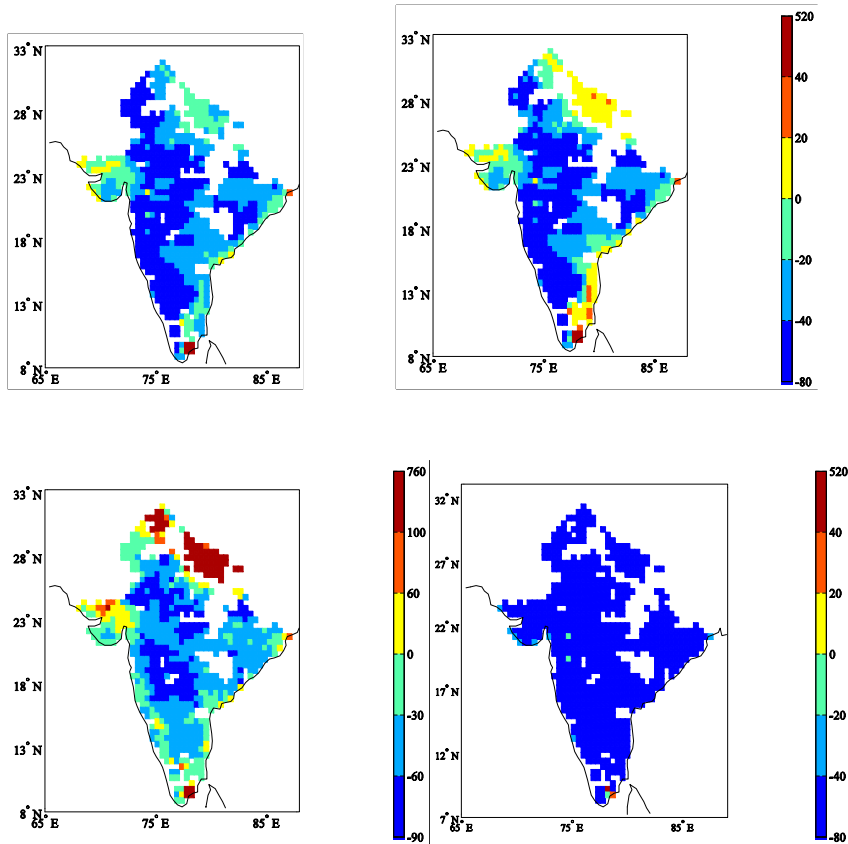
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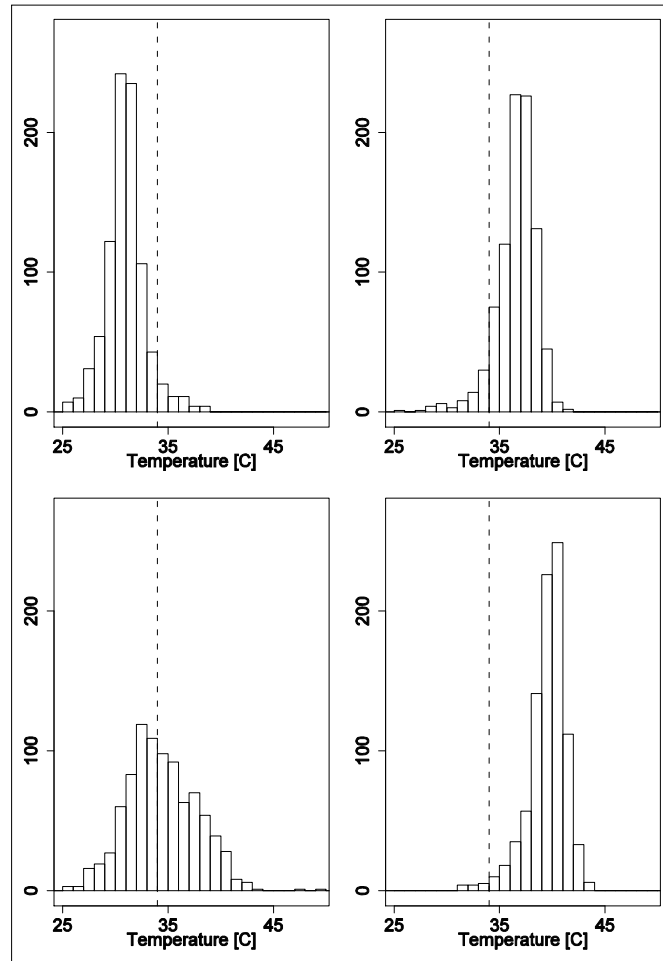


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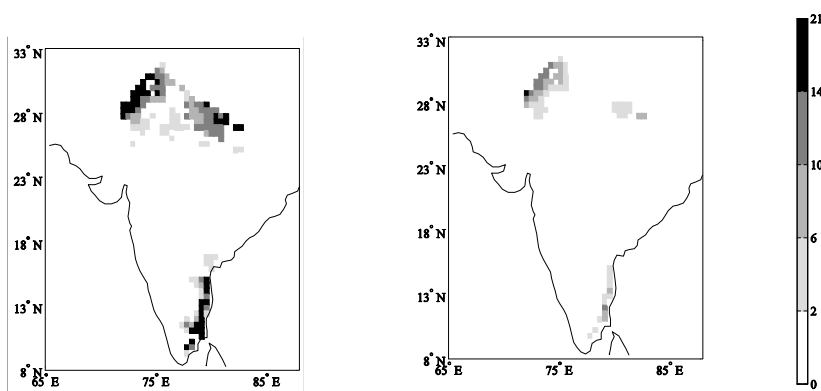
Figure 3. Percentage change in the mean yield for 2071-2100 simulations relative to the respective baseline simulation: SEN-28 (top left panel), TOL-28 (top right) and TOL-36 (bottom right). The corresponding plot of SEN-36 (not shown) is very similar to TOL-36. The percentage change in the standard deviation of TOL-28 is also shown (bottom left).

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Figure 4. Frequency distributions of daily maximum temperatures for two grid cells, one in the north (left) and one in the southeast (right) for the baseline (top) and scenario (bottom). The dashed lines indicate the 34°C threshold. Both grid cells are at 78.90 °E and their latitudes are 27.61 and 10.80 °E.

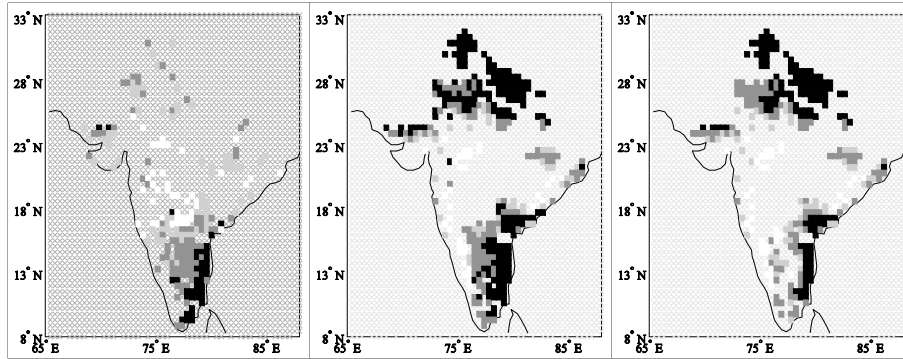


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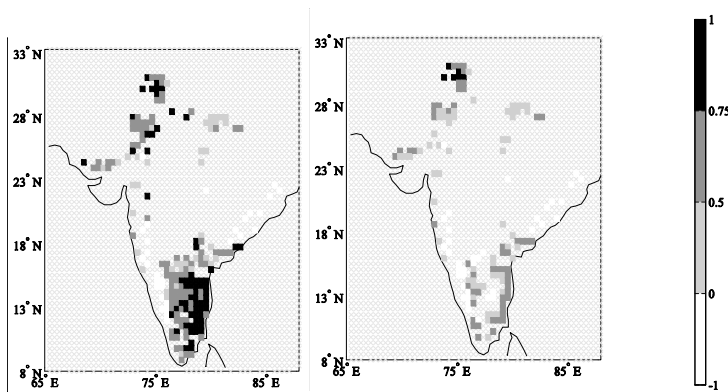
Figure 5. Number of years (from the sample 2071-2100) when the total number of pods setting is below 60% for SEN-28 (left) and TOL-28 (right). This percentage corresponds to the value below which harvest index begins to be reduced in the TOL-28 parameter set. The corresponding plot for the current climate has only two non-zero grid cells (in the north) of value 2.

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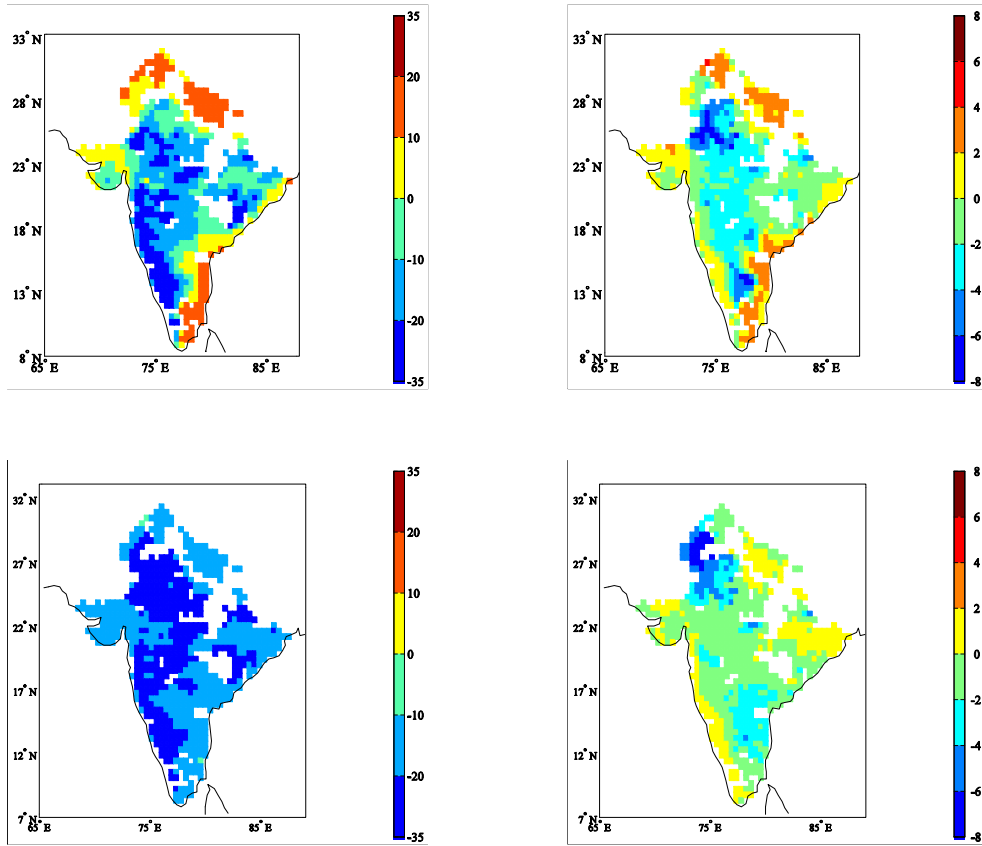
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Figure 6. Correlations between simulated percentage pods and simulated yield for: (i) the baseline simulation (i.e. 1961-1990 MOD-28; top left) and (ii) the 2071-2100 simulations: SEN-28 (top middle) and TOL-28 (bottom left). The temperature-only impact is also shown for the future climate period for SEN-28 (top right) and TOL-28 (bottom right). Only correlations that are statistically significant at the 95% ($r = 0.37$ in this case) level are shown.

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8 **Figure 7.** Change in the mean (left) and standard deviation (right) of crop duration (in days) for
9 simulations with $T_{opt}=28^{\circ}\text{C}$ (left) and $T_{opt}=36^{\circ}\text{C}$ (right), relative to the respective baseline simulation. Note
10 that crop duration is unaffected by the choice of SEN/TOL parameter values.
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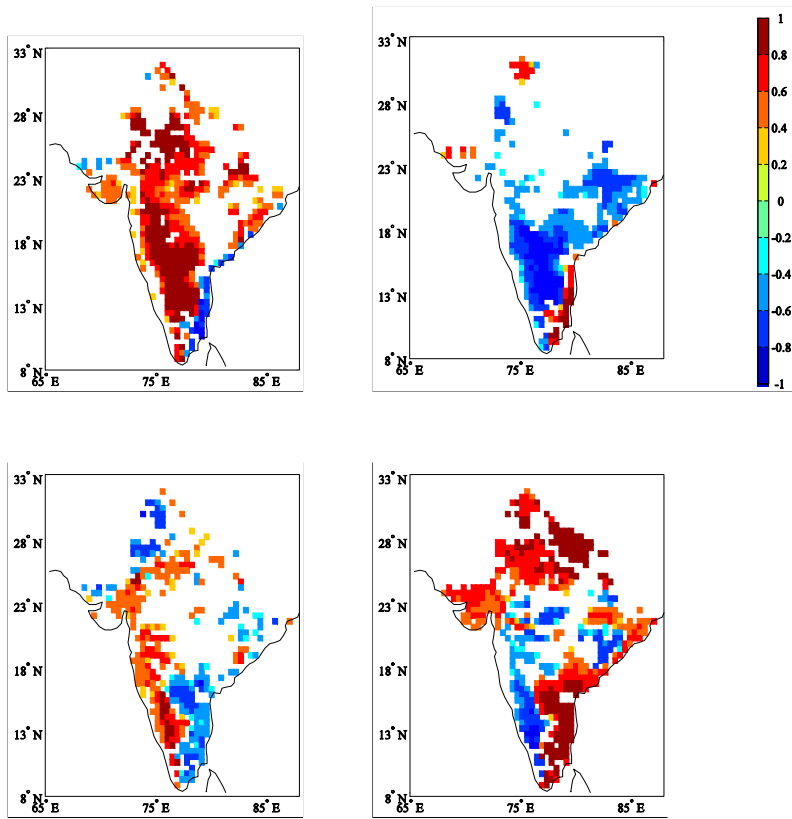
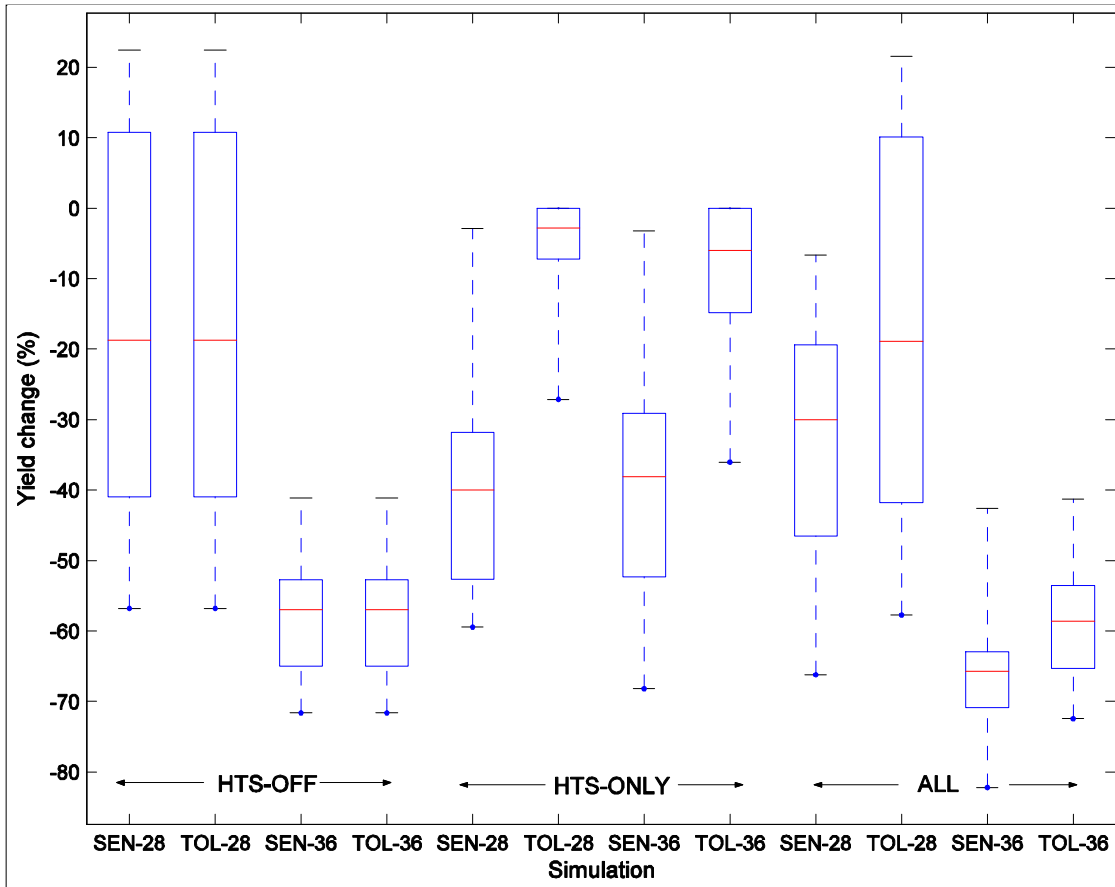


Figure 8. Correlations between simulated duration and: (i) simulated yield (left panels), (ii) VPD (right panels). Upper panels: baseline simulation. Lower panels: TOL-28 future climate simulation. Only correlations that are statistically significant at the 95% ($r = 0.37$ in this case) level are shown.

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Figure 9. Boxplots (the box shows the upper and lower quartiles, the line within shows the median and the whiskers show the full extent of the data) of the percentage change in yield, between the baseline and projection climates, for the 153 grid cells north of 25°N in which groundnut is grown. Twelve simulations are shown, consisting of four genotypic parameter sets and three processes: ‘HTS-OFF’ denotes simulations with the high temperature stress parameterisation turned off; ‘HTS-ONLY’ denotes the calculation of the impact of high temperature stress only; ‘ALL’ denotes the simulation of all the processes that are parameterised in GLAM