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Response to Referee # 1

In italics the original comments; in normal font our responses.

The manuscript presents a new model analysis of the combined effect of water and heat stress. The results are based on the parametrization of wheat during anthesis. The manuscript is well written and structured. The new model formulation and results are relevant to a broad audience. The supplementary describes the model formulation and assumptions in great detail with appropriate references.

We thank the Referee for their supportive comments.
As detailed below, should we be offered the possibility to revise our manuscript, the main changes we propose are:

i) to better justify the approach to the modelling of the soil water balance, and the parameterization of irrigation;
ii) to report information on the system's water fluxes, under the different precipitation and irrigation scenarios;
iii) to clarify in which sense the results presented in the manuscript can quantify the role of irrigation in reducing the risk of heat damage.

The major points to reconsider are the hydrology of the model and the irrigation. The results suggest that the temperature difference (Tc-Ta) is sensitive to the soil moisture value. The main nonlinearity seems to be at around 0.33 (Fig. S2). The drainage and runoff are handled by removing instantly all water above the s1 value. Is this a good assumption during all the different precipitation scenarios and irrigation? It may be that discarding instantly runoff and drainage and not including any ponding may not be realistic in the high precipitation case (P=1100 mm) for 30 cm rootzone depth. What was the ratio of drainage and runoff to precipitation in the different simulations? Have the authors considered modeling the drainage using for example hourly time step when soil moisture exceeds the field capacity? Or some other more explicit approach that might increase the time soil stays wet? Could a more explicit approach to drainage, runoff and ponding result in a larger difference in the results between the soil textures? Allowing drainage and runoff to operate for a longer time may be important when analyzing the 21 day period.

Stimulated by the Referee's comment, we have investigated in depth the implications of the simplifying assumptions related to the soil water balance. Specifically, we compared two approaches for the modelling of the losses via surface runoff and deep percolation.
The simplest approach is the one we had employed in the original submission, assuming an instantaneous loss of water whenever inputs would bring soil moisture above the threshold s_1. The advantage of this approach is that it can be run at the daily time scale, i.e., at the same scale at which the leaf temperature model is currently run, without incurring in numerical issues stemming from the nonlinear dependence of soil water losses at high soil water contents.
The second approach considers runoff from saturation excess (but not from infiltration excess), and the nonlinearity of soil hydraulic conductivity and hence percolation below the rooting zone. In this case, the losses via deep percolation are assumed to change with soil moisture as (Clapp and Hornberger, 1978)

$$LQ = K_{sat} s^{2b+3},$$

where K_{sat} is the soil hydraulic conductivity at soil saturation and b is an empirical exponent (the same used to link soil moisture and soil water potential; Eq S24 in the original submission). For sandy loam, K_{sat}=0.8 m d^{-1} and b=4.90. This approach is more mechanistic than the one based on the threshold s_1, since it explicitly considers the soil hydraulic conductivity and its dependence on soil texture and moisture content. The disadvantage is that, due to the high nonlinearity of the hydraulic conductivity, it requires being solved at a subdaily time scale to avoid large numerical errors (in the analyses below, the integration step was set to 15 min; shorter steps do not alter our conclusions).

To focus on the effects of the soil water balance model and avoid any potential confounding effect (e.g., due to differences in plant water uptake due to different soil moisture levels), we performed this model comparison assuming a fixed dependence of soil water uptake on soil moisture, of the form

$$ET = \begin{cases} ET_{max} & s \geq s^* \\ ET_{max}\dfrac{s}{s^*} & s < s^*, \end{cases}$$

where ET_{max} is the transpiration rate under well-watered conditions and s^* is the soil moisture level corresponding to incipient stomatal closure. This dependence is in line with that emerging from the full model (Fig. S2d in the submitted manuscript). In the analyses below, these values were estimated based on the full model output. Specifically, we set ET_{max}= 4 mm d^{-1}, which corresponds to a surface conductance G_s of 0.39 mol m^{-2} s^{-1}, in line with the model results at intermediate air temperature (see Fig S6c in the submitted manuscript). And we set $s^* = 0.32$, based on the soil moisture level that marks a substantial reduction in the total leaf-level conductance in water vapor (Fig S2d in the submitted manuscript). These values are also well aligned with literature values (e.g., Laio et al., 2001).

We run the two models in parallel, forced by the same realization of the precipitation input. We determined the cumulated inputs via irrigation; and losses via evapotranspiration, runoff and deep percolation, over periods of 21 days (i.e., the assumed length of anthesis); and the ratios between these quantities and the cumulated precipitation. We tested all the precipitation scenarios included in the original manuscript.

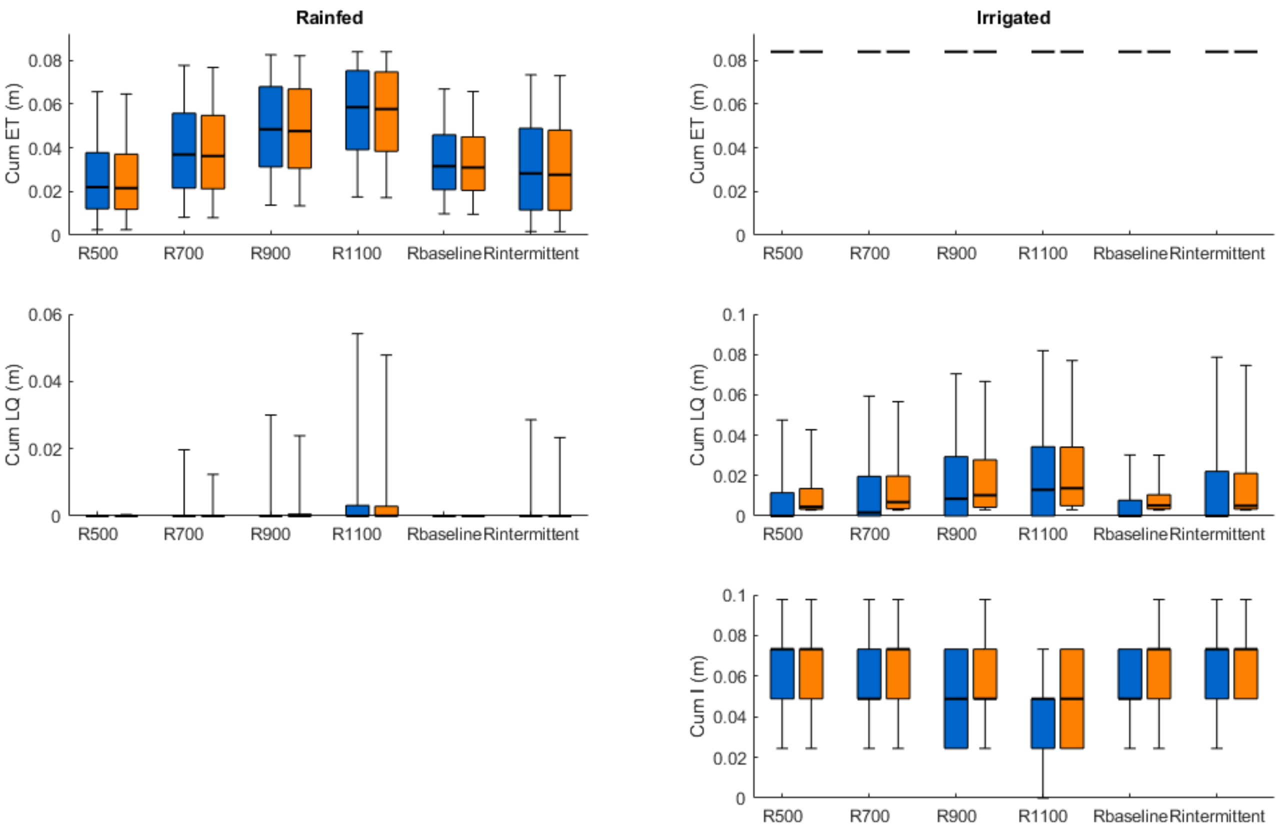

Figure 1.1: Distribution of 1000 21-day cumulated evapotranspiration (top row), runoff and deep percolation (middle row) and irrigation (bottom row), for rainfed (left) and irrigated cropping (right), for the two soil water balance models: in blue, the outputs of the model used in the original submission, whereby soil water contents above the threshold s_1 are lost instantaneously (at the daily time scale); in orange, the outputs of the model assuming a power-law dependence of deep percolation on soil moisture and runoff via saturation excess. Each pair of boxes refers to a different rainfall scenario: from left to right, average total annual precipitation of 500, 700, 900 and 1100 mm, with average event depth of 15 mm (R500, R700, R900 and R1100 respectively); and the two scenarios with a total average annual precipitation of 600 mm, but differing in average precipitation frequency λ_p and event depth α_p (Rbaseline, α_p=8.2 mm; λ_p=0.2 d^{-1}; Rintermittent, α_p=23.5 mm; λ_p=0.07 d^{-1}). The thick horizontal line denotes the median value, the box extends from the first to the third quartile, and the whiskers from the 5^{th} to the 95^{th} percentile. All the other parameters are reported in Table S2 of the original submission. Because a stress avoidance irrigation is implemented, the cumulated evapotranspiration for irrigated cropping (top right) equals the maximum possible evapotranspiration, i.e., $21ET_{max}$, with no variability induced by the stochasticity of precipitation occurrence.

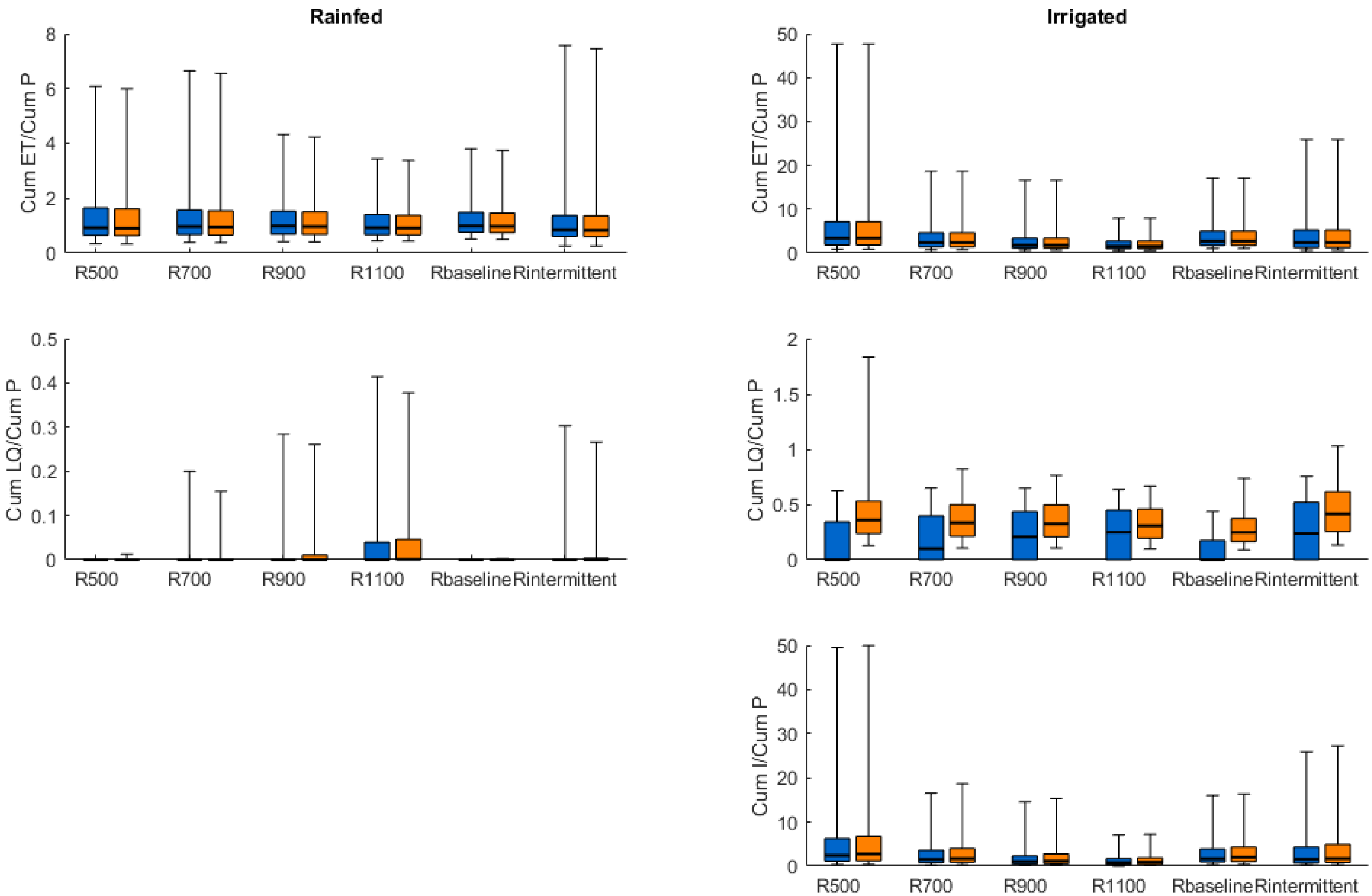

Figure 1.2: Distribution of the ratios of 21-day cumulated evapotranspiration (top row), runoff and deep percolation (middle row) and irrigation (bottom row) to cumulated precipitation, for rainfed (left) and irrigated cropping (right). All the colors and symbols are as in Figure 1.1. The number of ratios is below 1000 when no precipitation was recorded over the 21-day period. The ratio of cumulated evapotranspiration over cumulated precipitation can exceed 1 also in rainfed cropping, because a net reduction in soil water storage can occur over some 21-day periods.

The dominant soil water balance loss is via evapotranspiration, with deep percolation and runoff playing a secondary role under all precipitation scenarios, and in particular in rainfed agriculture (Figure 1.1). The two soil water balance models lead to similar, albeit not exactly equal, cumulated deep percolation and runoff and its ratio to precipitation (Figure 1.2). An even better match could have been achieved by setting a precipitation-specific threshold s_1 such as to limit the already small discrepancies – something we did not attempt in the above analyses; rather we kept the same threshold as in the original submission. The variability across the 21-day periods and precipitation regimes is larger than that stemming from soil water balance model. Because the quantitative importance of deep percolation and runoff is small, the two water balance models yield very similar cumulated evapotranspiration and irrigation, and their ratios to cumulated precipitation (Figure 1.2). The substantial independence of the cumulative ET of model choice is of particular relevance for the results in the manuscript, since evapotranspiration and leaf temperatures are related, all the other conditions being the same.

Other more complex descriptions of the soil water balance, e.g., explicitly considering runoff by infiltration excess and ponding (e.g., Rigby and Porporato, 2006; Manfreda et al., 2010) might indeed lead to wetter soil, by further reducing the amount of water lost to surface runoff. Nevertheless, based on the quantitative analyses above, we expect the resulting difference in soil moisture, and hence on canopy temperature, to be rather small. Further, a slight underestimation of soil water content would lead to conservative estimates of canopy temperature and the risk of canopy temperature exceeding the threshold for potential damage. An even more realistic description of the soil water balance would require abandoning the concept of the bucket model, for a layered soil water balance. Yet, we believe such a detailed description of the soil component would not match the relative simplicity of the description of the soil-plant-atmosphere continuum currently implemented.

In conclusion, these further analyses and considerations support a simplified approach to the modelling of the soil water balance. We would thus prefer not to alter the current soil water balance description, thus maintaining the consistency of temporal scales across the different submodels. In the revisions, we will however further justify our choice, by briefly discussing the results of the above comparison in Section S5.1 Modeling assumptions and their implications. Moreover, as suggested by the Referee, we will add quantitative information on the ratios of cumulated inputs and losses to cumulated precipitation, by means of a figure along the lines of Figure 1.2, but considering only the model used in the manuscript, to be placed in a new section at the beginning of S3 Additional results, devoted to the water fluxes.

Conversely, we believe there is no need to prolong the time of operation of the hydrological processes. Both in the original manuscript and the figures above, we run the model for a series of concatenated 21-day periods, where the conditions at the end of one period are used at the beginning of the subsequent one. In such a way, the conditions at the beginning of each period are fully stochastic, and reflect a long period of operation of all the hydrological processes. In the revised manuscript, we will further emphasise this point in Section S1.5 Numerical simulations.

The irrigation is triggered whenever soil water potential reached the intervention point which is just above the water stress point of wheat. It would be nice to know what was the resulting average irrigation frequency with this strategy? Is this frequency similar to the typical wheat irrigation frequency? Was the target soil water potential for irrigation optimized to result in typical wheat irrigation frequency? Report also the amount of irrigation and its ratio to precipitation in the result section.

The target soil moisture was not optimized to result in typical wheat irrigation frequencies, but rather set considering an intervention point corresponding to the soil water potential of incipient water stress for wheat; and a specific irrigation technology. The latter at least dictates the amount of water provided by each irrigation application, with more sophisticated approaches able to provide also extremely small water depths, and cheaper, more commonly employed technologies delivering larger water depths at each application (see, e.g., Vico and Porporato, 2011 and references therein). More in general, the resulting irrigation frequency stems from the combination of intervention point, target level, and all aspects of the water balance, from the precipitation amount and timing to plant water uptake. It is thus difficult to choose parameters to match specific irrigation frequencies, as this would require also altering the intervention point and target level depending on precipitation input. Further, in practical application, the irrigation frequency can also be affected by other aspects, for example access to water according to a specific calendar.

We have however determined the irrigation frequency under the current model parameterization; their distributions under the different precipitation scenarios are summarized in Figure 1.3. There is a minimum period between two subsequent irrigation applications (corresponding to the time necessary for the soil moisture to decline from the target level to the intervention point in the absence of precipitation), and hence a maximum frequency of irrigation. Furthermore, because the temporal resolution of the model is the day, the minimum difference in irrigation frequency is $1/21=0.0476\ d^{-1}$. As a result, over a period as short as 21 days, the dependence of irrigation frequency on the precipitation regime is small, although the wettest scenarios have lower median irrigation application frequencies.

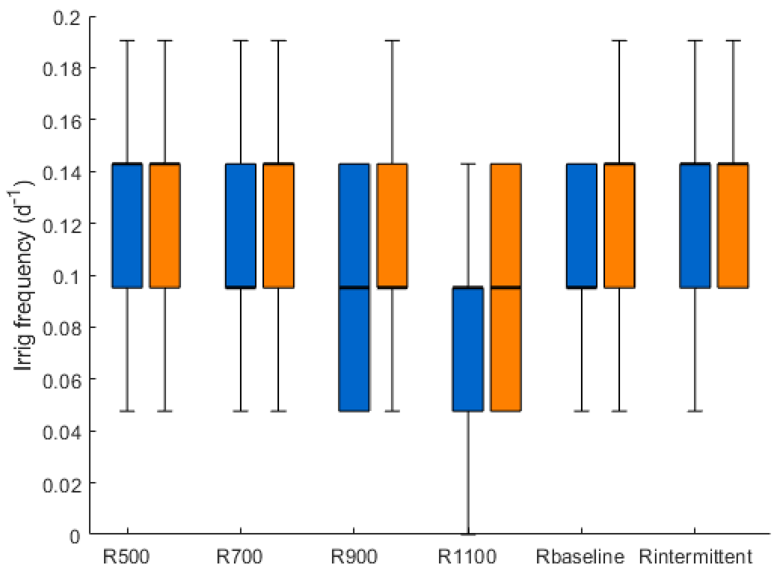

Figure 1.3: Distribution of the average irrigation frequencies during 1000 21-day periods. All colors and symbols are as in Figure 1.1.

Given the number of aspects influencing the irrigation frequency, and to focus on the effects of the statistics of the climatic forcing on canopy temperature, we plan to maintain the choice of the irrigation parameters independent of a specific location. But, motivated by the Referee's questions, in the revised manuscript, we will 1) clarify the rationale behind the choice of the intervention point for irrigation, linking that to the irrigation technology, in Section 2.2 and S1.3.1; 2) state the average irrigation frequency, under the different precipitation scenarios, in the SI (in the new section at the beginning of S3 Additional results, devoted to the water fluxes). We will also try to place the resulting irrigation frequency in a broader context, with reference to common practice, although, as discussed above, many aspects affect the actual irrigation frequency.

Specific comments:
L45: "are directly affected high air temperature"

Thanks for pointing out this typo. The verb will be changed to plural.

L98: Should you rephrase this question? The results and discussion seem to only report that irrigation cannot completely remove the heat stress but there seems to be no quantification of this effect?

While we put more emphasis on the inability of irrigation to completely remove the heat stress, Table 1 offers a quantitative measure of the effects of irrigation, by presenting the reduction in the mean fraction of days during anthesis with canopy temperature exceeding the threshold for potential damage from rainfed to irrigated cropping. Nevertheless, the Referee's comment suggests that this aspect is currently not emerging as clearly as it should. In the revised manuscript, we will thus keep the question as is in the introduction, but better clarify the quantification of the role of irrigation, explicitly explaining the meaning of the percentages reported in the Table in the result section; and referring to the third question in the discussion (first paragraph of Section 4.3 Irrigation reduces but does not cancel the risk of heat stress).

L127: In what sense superficial? Perhaps, surface runoff?

'Surface' runoff is the correct term. L127 will be modified accordingly.

L166: What is the basis of the precipitation parameters? Is intermittent case based on some estimate for some region?

The precipitation parameters were chosen to cover a wide range of regimes, and hence locations, but without reference to a specific region. We selected the different precipitation timings (and hence event depths) for the same precipitation total in a similar way, and considering that for many regions climate change scenarios predicts a decrease in frequency but an increase in intensity of precipitation, and that such a change could be potentially more damaging to crops than the opposite one.
This approach of selecting precipitation parameters has the advantage of allowing the exploration of a wide range of conditions. Linking the analyses to a specific location (and choosing the corresponding changes in rainfall regime based on climate change scenarios) would also limit the breath of air temperatures that can be explored. We would thus prefer to maintain the climatic parameter choice independent from specific locations. Yet, we will clarify this aspect in the revised manuscript, specifically in Section 2.2 Case study.

L298: Reference missing.

A reference to Table 1 should have appeared here.

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