

We would like to thank all of the reviewers for the thorough and insightful suggestions and comments. We made substantial changes to the manuscript, replaced one figure, and completed an additional model simulation in response to the feedback we received. We feel that the manuscript has improved significantly as a result of these thoughtful reviews. Please find our detailed responses to the reviewer's comments below.

Please note that the **reviewer comments are shown in black** and **our author responses are in blue**. Where changes have been made in the manuscript, the page and line number(s) are given. In some cases, to highlight changes to passages in the manuscript, these sections are copied and pasted from the manuscript.

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### **Reviewer #1: Oliver Lopez**

#### **Summary:**

The manuscript presents a study of the impacts that a sprinkler irrigation scheme in a land surface model have on the latent and sensible heat fluxes, and more substantially in the soil moisture state on a small, high resolution domain containing center-pivot sprinkler irrigation systems. The study explores the sensitivity of the results to two parameters: the irrigation intensity as prescribed by an input data set (GRIPC), and the greenness vegetation factor (GVF) used to scale the irrigation amount depending on the growth stage of the crops. The soil moisture state is compared to fixed soil moisture probes and a gridded soil moisture product, both using Cosmic Ray Neutron Probes. Including irrigation in land surface models is becoming more important to properly characterize the state and fluxes in agricultural regions, and thus efforts to evaluate the impact that either the choice of irrigation scheme or their input datasets have on the model results is certainly relevant to HESS. The study introduced modifications to the irrigation scheme such as using a real-time greenness vegetation factor data (as opposed to a climatological one) and also introduced a modification in the method to develop a soil moisture gridded product.

Overall, the manuscript is well written and the conclusions reached are sufficiently supported by the results. However, there are some few comments that I think would improve the readability of the manuscript, particularly with the description of some of the input datasets (GRIPC and in situ irrigation) as well as part of the methodology. Therefore, my recommendation is acceptance with minor revision.

#### **General comments**

1. The title refers to "*non-traditional*" and "*human-practice*" datasets. However, it is not clear what the authors mean by these two concepts. It might be the case that "*non-traditional*" is referring to the use of Cosmic Ray Neutron probes, but this is not obvious. In contrast, "*human-practice*" data is defined in Page 6, line 13 to be the irrigation amount. However, it is not clear if this term is referring to the GRIPC dataset used throughout the study (which is

based not only on human data, but also on remote sensing data), or to the amount of irrigation applied at two sites, as mentioned in Page 6, line 10.

We consider the 'human-practice' dataset to be the information on irrigation amounts and timing and the 'non-traditional' dataset to be the Cosmic Ray Neutron Probe datasets, both stationary and gridded. To clarify this, as well as to provide more details about the evaluation data in response to General Comment 3 below and several of Reviewer 4's comments, a new section has been added to the Methods called 3.2 Evaluation Data.

This new section begins (Page 8, Lines 24-25):

"The non-traditional, CRNP soil moisture data products and human-practice data gathered in Franz et al., (2015) are used to evaluate the sprinkler irrigation algorithm in LIS."

In this new section, with respect to the human-practice data and irrigation amount description (comment 3 below), the manuscript now reads (Page 8, Line 25-27):

"Human-practice data in the form of the irrigation amount and dates of irrigation application at one irrigated soybean and one irrigated maize site were reported via personal communication to Franz et al., (2015)."

Also with respect to the non-traditional dataset clarification, this section now reads (Page 9, Line 8):

"Additional non-traditional data from Franz et al., (2015) include a soil moisture product that uses the spatiotemporal statistics of the observed soil moisture fields..."

2. Related to the previous comment: although a reference is given for the GRIPC dataset, a brief description of this dataset would benefit the manuscript. An estimate of the uncertainties related to this dataset would also be helpful.

The following sentences describing the GRIPC have been added to Page 8 Lines 1-8:

"The GRIPC dataset integrates remote sensing, gridded climate datasets, and responses from national and sub-national surveys to estimate global irrigated area. The dataset closely agrees (96% at 500 m) with the USGS M1rAD-US2007 dataset (Pervez and Brown, 2010) and assessment of GRIPC against field level inventory data showed an 84% agreement in Nebraska (Salmon et al. 2015). This dataset represents a significant improvement in defining irrigated areas as compared to previous configurations of this model and scheme (Lawston et al. 2015) in which irrigated areas were defined using the 24-category USGS landcover classification, based on data from the 1990's. However, the GRIPC dataset overestimates irrigation intensity in the study area,..."

3. Also related to the first comment: a description of the irrigation data from the study in Franz et al. (2015) is also worth including. This is especially important in Figure 7, where irrigation at the maize site is shown, as well as in the text (Page 12, lines 14-16).

A description of the irrigation data has been included in the new 'Evaluation Data' section (3.2). Please see comment #1.

4. The methodology for defining the growing season was not included in the Methods section. It is however mentioned later in the Discussion section on Page 15, lines 13-14 *"The method for determining the start and end of the growing season, based on the 40% annual range in climatological GVF, proved to be reliable for this study area and climate"*.

The details of the determination of the irrigation season have been added to the Methods section when first introduced. Page 10, Line 7-8 now reads:

*"The growing season, addressed in question three, is a function of the gridcell GVF (i.e., 40% annual range in climatological GVF; Ozdogan et al. 2010)..."*

### Minor comments

1. Page 2, line 9: (referring to observational data) *"are generally not obtainable at the scale of LSMs"* and Page 5, lines 19-21: *"available at the same spatial scale as LSMs"*

What do the authors mean by scale of LSMs? land surface models can be run at a great range of scales. Perhaps the authors are talking specifically about high-resolution LSMs such as in this study? If so, please specify this.

Yes, we mean high-resolution but also are referring to the fact that observation data are often not available in spatially continuous/gridded fashion. This has been clarified:

Page 2, Line 9-10: *"...are generally not obtainable in a spatially continuous format at the scale of high-resolution LSMs..."*

Page 5, Line 23: *"...area average soil water content...available at the same spatial scale as high-resolution LSMs"*

2. Page 4, line 1: *"For example, a flood irrigation parameterization. . ."*

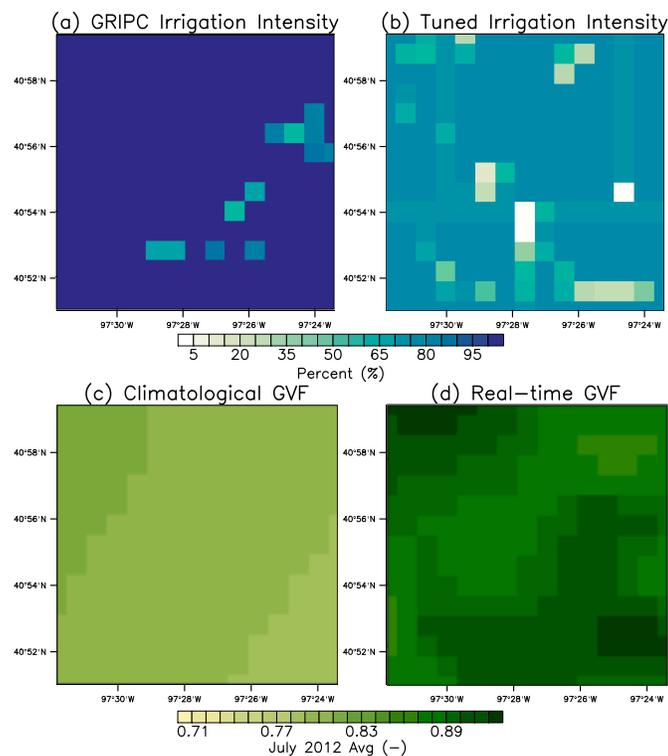
It is not clear if this is referring to scheme number 1 or 2 defined above in Page 3, lines 19-22. The text would benefit if this term ("flood irrigation parameterization") would be included in Page 3, lines 19-22 where applicable.

A sentence has been added to clarify here. The sentence at Page 3 Line 20 now reads:

“This need has been addressed via irrigation parameterizations in LSMs that largely fall into three types of schemes: 1) defined increases to soil moisture in one or more soil layers (Kueppers and Snyder, 2011; de Vrese et al. 2016), **sometimes referred to as flood (Evans and Zaitchik 2008),...**”

- Figure 1: The titles in each sub-figure are confusing. Perhaps the titles could read (top left, top right, bottom left, bottom right): “GRIPC irrigation intensity”, “Tuned irrigation intensity”, “Climatological GVF”, and “Real-time GVF” to better identify what is being shown. Furthermore, the figure would improve by the inclusion of labels “a”, “b”, “c” and “d”. Finally, the colorbar for the top figures (which is the same for both) could be shown in the center as it was done for the bottom figures.

All of the suggested changes have been made to Figure 1:



- Page 11, line 2: “*the SPoRT GVF is greater than climatology in June*”  
Please clarify: do the authors mean “greater than climatological GVF”?

Yes, this has been changed in the manuscript to ‘greater than climatological GVF.’ (Page 12, L7)

- Page 11, lines 3-4. “*However, in September, the SPoRT GVF detects the (negative) vegetation response to the July drought and irrigation amount and flux impacts are reduced*”.

What do you mean by “the sport GVF detects the negative vegetation response to the July drought?” is it because it is a real-time product as opposed to the climatological product and the fact that 2012 was particularly dry?

Yes, exactly. This has been rephrased to clarify:

“...the SPoRT GVF detects vegetation stress caused by a July flash drought, resulting in reduced GVF, irrigation amounts, and flux changes.” (Page 12 L8-9)

6. Page 11, lines 4-7. *“These seasonal scale impacts illustrate that the NLDAS-2 forcing (e.g. precipitation) data, via changes to soil moisture, drives the irrigation timing during the growing season and that the behavior of the irrigation scheme is consistent with expectations of human triggering of irrigation during dry and wet periods”.*

I am not sure I follow completely what is meant here. Is this saying that we expect irrigation triggering when there is no (or small amounts of) precipitation and no triggering when there is? If so, then this is already phrased better in the next lines (page 11, lines 9-10): *“At the interannual and seasonal scale, irrigation amounts and impacts are driven primarily by background rainfall regime, given by the forcing precipitation, with only small changes evident between the methods”.*

Yes, the first sentence is meant to convey that irrigation is being triggered when there is little precipitation, as we would expect farmers to do. The second sentence is meant to re-iterate the triggering but also to point out that all three irrigation simulations had very similar results at the interannual and seasonal scales. This is set up as a contrast to the forthcoming daily scale results that show much larger differences in fluxes between irrigation experiments.

The first sentence has been re-worded to clarify:

*“These seasonal scale impacts illustrate that the NLDAS-2 forcing (i.e., precipitation) data, via changes to soil moisture, constrains the irrigation timing during the growing season, and that the soil moisture threshold is sufficient in triggering irrigation during rain-free periods”*

7. In Figure 7, why not include the soil moisture from the CRNP gridded soil moisture product as well for comparison with the fixed probes?

We compared the CRNP gridded soil moisture time series to the CRNP stationary probes at the three sites and noticed that the gridded product had a small dry bias. This is confirmed by the Franz et al. (2015) paper that also notes a small dry bias in the gridded product that is likely a result of the rover driving on and sensing drier, gravel roads. This is in contrast to the CRNP stationary probes that are “painstakingly calibrated.” Since the goal of this figure was to illustrate the impact of irrigation on the soil moisture time series and how well those changes are reproduced by the model, we show only the best available observations at these two sites, which are the CRNP stationary probes. The utility of the gridded product lies in the

areas where we don't have the probe data and as such, we use it to get a better understanding of how the model performs over the larger area (rather than at the individual sites).

8. Page 13, lines 11-12 *"In this study, we modify the spatial regression technique to treat irrigated and non-irrigated areas differently by using the CRNP (irrigated) rainfed data in the regression for (irrigated) non-irrigated gridcells"*.  
I am not sure I follow the last part with the parentheses "by using the CRNP (irrigated) rainfed data in the regression for (irrigated) non-irrigated gridcells". Could you please clarify this?

Please see comment #9

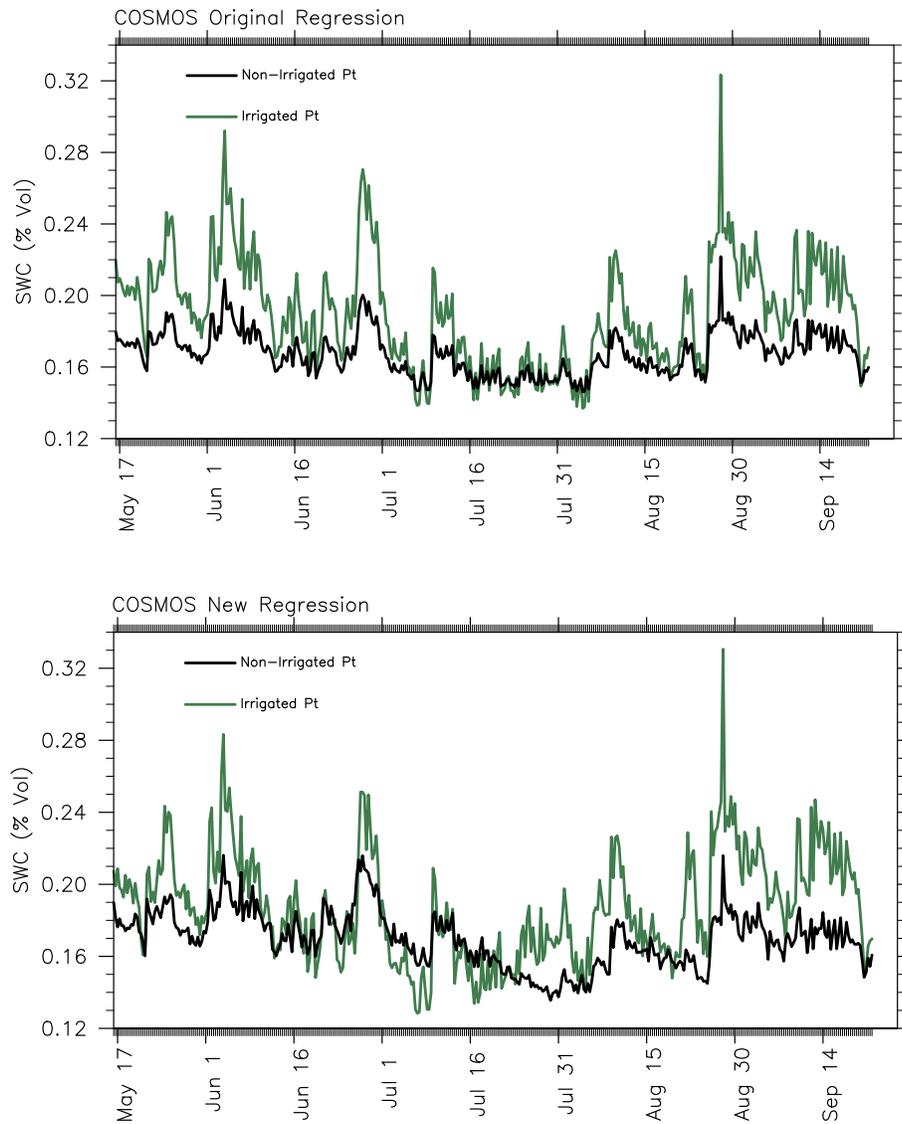
9. Referring to the same text in the last comment, in my opinion, since this is also a novel contribution (the modification of the spatial regression technique for the gridded product), a comparison between the previous and the new product could be included as supplementary material.

In response to both comments 8 and 9, this section has been rephrased, expanded upon, and relocated to Page 9 Line 8-17 in the new Section 3.2 (Evaluation Data). It now reads as follows:

"Additional data from Franz et al., (2015) include a gridded soil moisture product that uses the spatiotemporal statistics of the observed soil moisture fields, as obtained via the CRNP rover surveys, and a spatial regression technique to create a 1-km, 8-hour gridded soil moisture product for the growing season (May – Sept, 388 values). Franz et al., (2015) used the average of the three stationary CRNP probes as the regression coefficient, which can smear the spatial differences between irrigated and rainfed areas. In this study, we modified the spatial regression technique to treat irrigated and non-irrigated areas differently by using the CRNP rainfed probe in the regression for non-irrigated gridcells and the average of the two irrigated CRNP probes for the irrigated gridcells. This results in a gridded soil moisture product that retains the spatiotemporal differences of the rainfed and irrigated areas. Irrigated and non-irrigated gridcells are defined by an estimated irrigation mask created using the landcover map of Franz et al. 2015 from ground observations. A comparison of the original and new regression products at an irrigation and non-irrigated point is given in the Supplement.

As the text states, the following figures have been added to the supplement to show the difference between the new and original regression products. With the original regression technique (a) few differences are seen between the irrigated and rainfed points, especially during the dry-down period in late July to early August. The averaging of the probes results in a levelling off of soil moisture during this time. (b) The new regression technique results in the non-irrigated point showing decreasing SWC during the dry down period, as at the CRNP

rained probe, while the irrigated point shows increasing SWC due to irrigation during the dry down. This explanation has been added to the supplement figure caption (below).



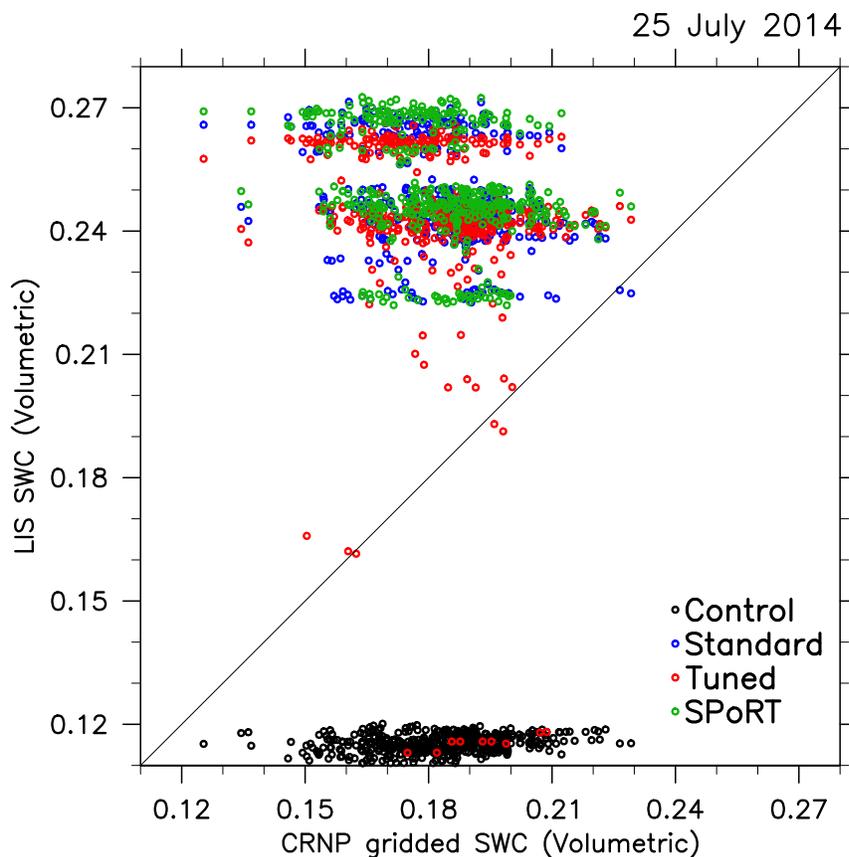
**Supplement 1.** Time series of soil water content at an irrigated and non-irrigated point given by the gridded CRNP product using (a) the original regression from Franz et al., 2015 (b) the new regression used in this study that treats irrigated and non-irrigated areas differently. With the original regression technique (a) few differences are seen between the irrigated and rainfed points, especially during the dry-down period in late July to early August. The averaging of the probes results in a levelling off of soil moisture during this time. (b) The new regression technique results in the non-irrigated point showing decreasing SWC during the dry down period, as at the CRNP rainfed probe, while the irrigated point shows increasing SWC due to irrigation during the dry down.

10. Page 13, lines 17: “during which irrigation was applied at the irrigated maize site”

Only at the maize site? or the whole domain shown in Figure 1? The caption reads “when irrigation was applied at the irrigated maize and soybean sites”. To my understanding, the maize site and soybean sites are only parts of the whole domain, and this figure (Figure 8) is showing a spatial comparison of the whole domain.

Yes, the reviewer is correct. The figure showed the whole domain, which includes the irrigated sites, but is not exclusively the irrigated sites. The intention for that statement was to emphasize that the CRNP gridded observations are at least partially impacted by the irrigation that we know is occurring in at least some areas on that day. This figure has been changed from a CDF to a scatterplot as per Reviewer 3’s comments and the caption has been reworded to that below with the reviewer’s comments in mind:

“Figure 8. Scatterplot of the gridcell soil moisture content (volumetric) given by the irrigation simulations as compared to the CRNP gridded soil moisture product.”



11. Figure 8: In the legend, consider changing “CoSMOS” to “CNRP” to be consistent with the rest of the paper.

The legend has been updated in the new Figure 8. Please see previous comment (#10).

12. Page 14, lines 9-10 *“Furthermore, when irrigated and non-irrigated areas are averaged separately, the irrigated (Control) simulations match the distribution of irrigated (non-irrigated) areas well”*.

Again, I do not understand the use of the parenthesis here “irrigated (non-irrigated)”.

This sentence has been rephrased:

*“Furthermore, when irrigated and non-irrigated areas are averaged separately, the irrigated and control simulations match well the distribution of irrigated and non-irrigated areas, respectively (Fig. 9b)”*

#### **4 Technical corrections**

All of the following technical corrections have been made.

1. Page 7, line 19 *“as evidenced by only 5% of the gridcells having intensity less than 100% (Fig 1)”*

I think this should be “Fig 1a” instead of “Fig 1”.

2. Page 7, line 22 *“(i.e. observationally tuned: Fig 1)”*

I think this should be “Fig 1b” instead of “Fig 1”.

3. Page 7, lines 19 and 22 and Page 8, line 4.

Check consistent use of either “(Fig X)” or “(Figure X)”.

4. Figure 6: Label in Y-axis “Change in Domain Avg Qle” instead of “Doman”

5. There is a dot missing in Page 13, line 24 before “The model distributions do not match the CRNP CDF, which instead shows. . .”

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**Reviewer #2:****Summary:**

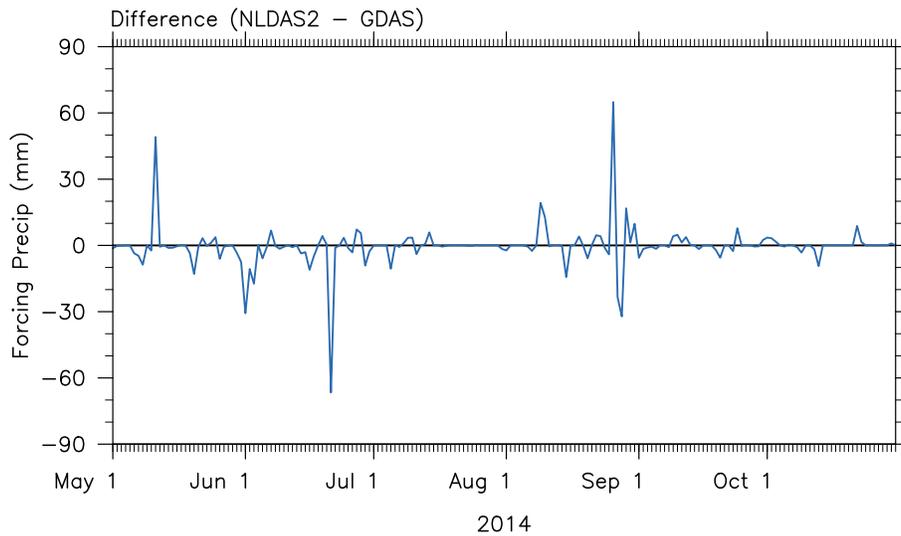
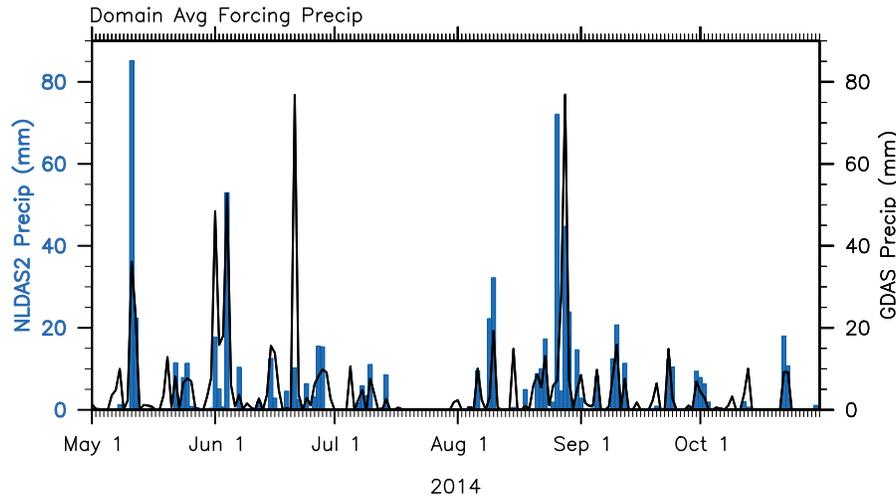
The authors provide a useful and clearly-written evaluation of irrigation simulated by an advanced Land Surface Model. These types of evaluation are in short supply, and the use of CRNP in model evaluation is, to my knowledge, novel and potentially quite useful. I believe that the Discussion Paper is of sufficient interest and quality for publication in HESS. That said, the numerical experiments presented in the study are rather limited. Sensitivity to GVF dataset and irrigation intensity factor are evaluated, but none of the many other factors that the authors list are explored. This may lead to the wrong impression that the tested factors are the most important when simulating irrigation, when I see no evidence presented by the authors that this is in fact the case. Ideally, the authors should present a more inclusive set of sensitivity tests to inform future modeling studies about the relative importance of different factors. If this is not possible, or if the authors view it as unnecessary, then a more convincing justification for the choice of experiments is required.

**General Comments:**

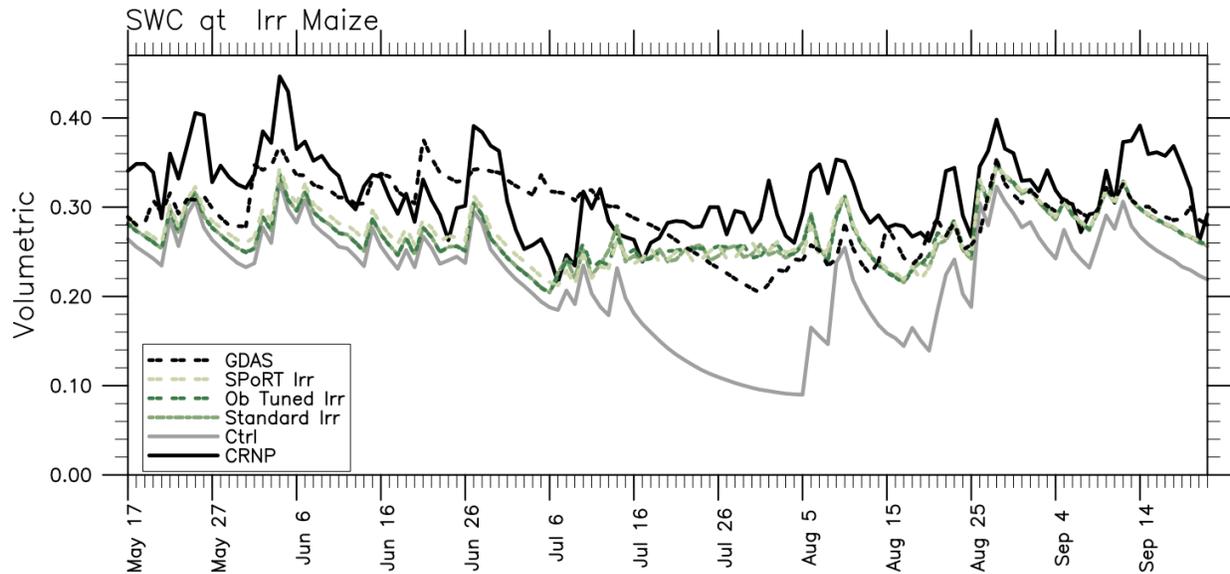
1. Meteorological Forcing: In the abstract and at several other passages in the text the authors emphasize the importance of high quality meteorological forcing data for accurate simulation of irrigation. Their results suggest that NLDAS is high quality, as shown most convincingly by the temporal match of simulated irrigation to spikes in observed soil moisture. I believe that NLDAS is high quality and that these results show impressive performance at local scale. But I'm not sure that the authors can actually make any conclusions about the importance of forcing data to irrigation simulations, given that they do not compare NLDAS simulations to simulations with any lower quality forcing dataset. Yes, it is intuitive that simulations with NLDAS will be better, but the numerical experiments don't demonstrate this, and they don't show us *how* important it is. This is particularly the case when one considers spatial or temporal scale. The authors nicely demonstrate that simulations are more realistic at larger and longer scales than they are at local and shorter scales. How important is meteorological forcing if we are concerned with large and long time scales? Additional simulations with an alternative, poorer quality meteorological forcing dataset would be the obvious way to test this, but the authors might find other ways to make the point.

The foundational study for this work, Ozdogan et al., (2010), evaluated this scheme at larger (continental U.S.) and longer (yearly) time scales with annual water withdrawals and county level data. For this study, the primary interest is in evaluating the scheme performance at smaller and shorter timescales, so a robust evaluation of the meteorological forcing at large and long timescales is beyond the scope of this work. With respect to the support for the NLDAS2 conclusions, however, the reviewer raises some good and justified questions.

In response, we have completed an additional run equivalent to the Standard irrigation run in all aspects (e.g., GRIPC irrigation intensity, climatological GVF) except that we used GDAS meteorological forcing instead of NLDAS2. GDAS is coarser resolution (1/4 degree) and does not include rain-gauge corrections. GDAS supplies a greater total amount of precipitation in the May through July time period. See figures:



The greater total amount of precipitation from GDAS results in a wetter soil column leading up to and throughout the mid-to-late July rain-free period, delaying the onset of irrigation triggering by the scheme. As a result, the soil moisture starts out wetter in mid-July than the other irrigation simulations (forced with NLDAS2) and even the CRNP, then dries out to a level below that of the other schemes (as a result of moisture being sustained in the root zone and prohibiting irrigation). The irrigation is finally triggered at the beginning of August, a few days prior to the return of precipitation to the area. See figure below (top layer soil moisture):



This simulation adds support to the conclusion that accurate precipitation data is essential to constrain the irrigation triggering. A brief description of this additional run has been added to the discussion section.

The newly added part of the Discussion (Page 16, Line 1-11) reads:

“For this small domain, the NLDAS2 precipitation proved to be sufficiently accurate, matching well that given by the nearby York, Nebraska AWDN. However, for other regions, reliable meteorological forcing may not be available. To further explore the impact of the forcing precipitation on the irrigation triggering, an additional simulation was completed that is equivalent to the Standard irrigation run in all aspects (e.g., GRIPC irrigation intensity, climatological GVF) except that the Global Data Assimilation System (GDAS) meteorological forcing is used rather than NLDAS2. In contrast to NLDAS2, GDAS is coarser resolution (1/4 degree) and does not include rain-gauge corrections. Results show that GDAS supplied a greater amount of total of precipitation in May through July 2014, creating a wetter soil column and prohibiting irrigation triggering in mid-to-late July, in contrast to observations and the other irrigation simulations. As a result, the soil moisture dynamics of the GDAS simulation at the maize site differ substantially from the CRNP observations and the NLDAS2-forced simulations. These results underscore the need for highest quality datasets available for the area of interest, which for this region and time frame was NLDAS2.”

2. Thresholds: The authors appropriately emphasize the importance of selecting proper thresholds for soil moisture and GVF at several points in the text. But the manuscript does not offer any evaluation of either. In both cases a single threshold is applied and attributed to previous studies. It would be quite interesting to know how the impact of using different GVF datasets compares to differences caused by small changes in GVF threshold. And how does a

modest change in threshold impact total water use, as compared to the tested sensitivity to prescribed irrigation intensity?

The sensitivity of the irrigation scheme to the soil moisture and GVF thresholds has already been examined in the Ozdogan et al., (2010) for a larger area that includes our study region. The 50% of field capacity soil moisture triggering threshold was selected by their study as being most appropriate based on discussions with local experts, including some in Nebraska, as well as through trial and error (Ozdogan et al., 2010). As this is the same scheme used here, we didn't consider it necessary to re-test the SM threshold and instead accepted it as being the best for this region based on current literature. The accurate timing of irrigation triggering shown in the results supports that this threshold was reasonable.

Although the gridcell GVF *value* is used to calculate the crop root zone and to scale the amount of water applied, the GVF *threshold* is only used to determine the start and end of the irrigation season. As a result, a small change in the GVF *threshold* would only increase or decrease slightly the length of the irrigation season. The GVF threshold for our region gives an appropriate irrigation season of June – September, so we didn't consider it necessary to change this threshold at all.

I understand that no study can be comprehensive on all parameters, but I don't fully understand why the authors chose to look only at GVF dataset in GRIPC irrigation intensity when other subjective modeling decisions might have as large or larger impacts on the simulations. If possible I would encourage the authors to expand their sensitivity test in order to justify the selection of these two factors as the focus of study.

The main objectives of this study were not necessarily to turn every knob, but instead to take the best available collection of default datasets we have (e.g., those that someone new to model would probably choose) and to see how well it performs (i.e., the Standard run). Then secondarily, to determine if it is possible to improve upon that standard model performance by either 1) incorporating additional information to tailor the datasets to our study area (Tuned irrigation intensity), or 2) by using a new and improved GVF dataset (SPoRT) that detects vegetation response to soil stress. Rather than a blanket sensitivity study, these were targeted in areas where we knew we could improve the model/datasets based on solid information.

The focus on irrigation intensity and GVF datasets for potential improvement to model performance is two-fold:

- 1) Irrigation intensity and GVF are critical to **both** the *triggering* of irrigation and the calculation of the *amount* of irrigation water applied. As a result, flaws in the scheme could be made more apparent by switching out these datasets. Additionally, these two datasets (SPoRT GVF and GRIPC irrigation intensity) are brand new and have not been used with an irrigation scheme until now.

- 2) The other datasets that play a role in irrigation triggering, (i.e., landcover, soil texture, soil type, crop type) were by default homogeneous across the study area and were appropriate for the area based on the ground truth we had. For example, the landcover for every grid cell in the domain was 'croplands'. At 1 km resolution, there is not a better classification of these gridcells than cropland (e.g., even the gridcells that contain small buildings or roads still occupy < 50%; croplands is dominant land use). Similarly, we didn't have additional information to be able to improve upon the default soil type or texture. With regards to crop type, the data from Franz et al., (2015) showed 81% maize and 19% soybean, in contrast to 100% maize in the default crop type map. As a result, we did an additional run with tuned crop type and altered max root depth. The results of this run are presented as a note in the Discussion (Page 16, Lines 12-21) rather than featured prominently. This was done with the intention of simplicity (i.e., to minimize confusion that could be caused by introducing another iteration) because this run was not significantly different than the other irrigation runs.

### **Minor Comments:**

Page 3, line 20: This list of options misses flood irrigation simulation (unless it's supposed to be covered by #1). Several studies have employed flood irrigation, including Yilmaz et al. (2014), Leng, and Evans & Zaitchik (2008).

The intent was for flood to be covered by #1. The sentence has been edited to clarify:

Page 3, Line 20: "1) defined increases to soil moisture in one or more soil layers (Kueppers and Snyder, 2011; de Vrese et al. 2016)., sometimes referred to as flood (Evans and Zaitchik, 2008),"

Section 2.3: It would be useful to include a sentence or two on why CRNP measurements are sensitive to soil moisture. Many readers (myself included) are not deeply familiar with this technique.

An additional sentence has been added to section 2.3 (Page 5 Lines 18-20) addressing this point (bolded):

**"The theoretical basis for the CRNP method follows that fast neutrons injected into the soil by the CRNP will be slowed more effectively by collisions with hydrogen atoms present in soil water than by collisions with any other element (Visvalingam and Tandy, 1972). Thus, the neutron density measured by the probe is inversely correlated with soil moisture..."**

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## Reviewer #3:

### I. Summary

This manuscript examines the issue of developing and validating realistic irrigation schemes for use in land surface models (LSMs). In this study, the authors utilize observation-based datasets of irrigation intensity and green vegetation fraction (GVF) to tune the LSM irrigation amounts, which are validated against data obtained from Cosmic Ray Neutron Probes (CRNP). The main conclusion of the authors is that the timing, amount, and spatial spread of irrigation are more sensitive to the choice of irrigation scheme at smaller spatiotemporal scales than at larger, more typical scales for regional climate models. Given the balance of evidence presented and the use of a novel dataset (CRNP) for addressing this issue, it seems that the authors have arrived at robust and meaningful conclusions that would be worthwhile additions to HESS and to the field of hydrology, in general. While I have no major qualms with the content or substance of the manuscript, I do present below some more minor comments for improving the robustness and presentation of the results.

### II. General comments

A. NLDAS-2 – The authors mention several times throughout the manuscript the need for “high-quality” meteorological forcing and point out repeatedly the accuracy of the precipitation data from NLDAS-2 for their domain. While it certainly seems that NLDAS- 2 provides accurate forcing over this domain (and is a high-quality dataset, in general), I echo Reviewer 2 in cautioning against drawing far-reaching conclusions about NLDAS- 2 from this limited study. The entire study domain is 15 x 15 km, very small even for typical regional climate model simulations; the entire domain would fit in 4 grid cells of NLDAS-2 (1/8 degree horizontal resolution). Is there evidence that NLDAS-2 would provide equally accurate data for a different domain within the same region, or in a different region or year? If so, then I would provide a sentence or two explaining the skill of NLDAS-2 over the general region (e.g., Great Plains/Midwest) during the growing season (perhaps from the Xia study). If not, then please temper the language emphasizing the high quality of NLDAS-2 with the understanding that the spatial domain of this study is extremely limited and that NLDAS-2 may not be as accurate in other agricultural regions in North America.

As per reviewer 2’s suggestion, an additional run with GDAS forcing was completed and a brief description of the results is now included in the Discussion section (Page 16, Lines 1-11). In this newly added paragraph, we’ve taken care to add qualifiers to the NLDAS2 statements. The section now reads as follows, with bolded words to emphasize the tempered language about NLDAS2:

**“For this small domain**, the NLDAS2 precipitation proved to be sufficiently accurate, matching well that given by the nearby York, Nebraska AWDN. **However, for other**

**regions reliable meteorological forcing may not be available.** To further explore the impact of the forcing precipitation on the irrigation triggering, an additional simulation was completed that is equivalent to the Standard irrigation run in all aspects (e.g., GRIPC irrigation intensity, climatological GVF) except that the Global Data Assimilation System (GDAS) meteorological forcing is used rather than NLDAS2. In contrast to NLDAS2, GDAS is coarser resolution (1/4 degree) and does not include rain-gauge corrections. Results show that GDAS supplied a greater amount of total of precipitation in May through July 2014, creating a wetter soil column and prohibiting irrigation triggering in mid-to-late July, in contrast to observations and the other irrigation simulations. As a result, the soil moisture dynamics of the GDAS simulation at the maize site differ substantially from the CRNP observations and the NLDAS2-forced simulations. **These results underscore the need for highest quality datasets available for the area of interest, which for this region and time frame was NLDAS2.”**

### III. Specific comments

A. Page 14, line 10 – “These results suggest that if this domain were one gridcell in a larger, coarser resolution domain (e.g. 15 km spatial resolution), the variation in the gridcell soil moisture (given here by the domain average) over the growing season would be representative of observations.”

It would be interesting to see a supplemental model analysis with coarser-resolution grid cells (either in this paper or a future one) that validates this hypothesis. For example, what is the spatial threshold at which large-scale forcings begin to dominate the changes in the soil moisture signal?

We agree that this is an interesting question and appreciate the suggestion! This will certainly be an area of future study using the flexibility of the LIS system (resolution, forcing, and inputs).

B. Page 15, line 9 – “. . .indicating that the model is quite insensitive to the maximum root depth change. . .”

Some common irrigated crops, such as alfalfa, have max root depths of 2+ meters. Though irrigated alfalfa is much less common in Nebraska when compared to corn and soybeans, it would be instructive to not make the above claim about the insensitivity of the model to max root depths unless other crops with much larger or smaller max root depths have been tested.

This sentence has been rephrased to emphasize that the root depth sensitivity tested was only for a small change to a specific crop (Page 16 L19-22):

“The results of this analysis showed little difference between this simulation and the others, indicating that the model is insensitive to small changes (up to 20%) in the maximum root depth. However, land surface models that have a more complex treatment of crops, study areas with greater heterogeneity of crop types, or

experiments that replace a particular crop with one that has a vastly deeper root system, are examples beyond the scope of this study that could potentially result in a greater sensitivity of the model results to crop root depth.”

C. Page 15, line 22 – “. . . a growing number of options for irrigation intensity datasets in the coming years”.

A new global irrigation dataset (the Historical Irrigation Dataset) was published through HESS rather recently (S. Siebert, M. Kummu, M. Porkka, P. Döll, N. Ramankutty, and B. R. Scanlon (2015), "A global dataset of the extent of irrigated land from 1900 to 2005," Hydrology and Earth System Sciences. DOI: 10.5194/hess-19-1521-2015). It may deserve a citation here because of its recent development and global coverage.

It is certainly appropriate and has been added.

D. Figure 1 – Are the spotty areas of low irrigation intensity in the Tuned plot over urban areas? A brief explanation of this in the text may be warranted.

The spotty areas indicate the irrigation intensity has been reduced due to the presence of roads, wetlands, rainfed fields, and/or buildings. Of the three gridcells with 0% irrigation intensity, two contained mixed-use land, small buildings, and roads (though, not built up enough to really be considered ‘urban’). The remaining 0% irrigation intensity gridcell contains the rainfed site given in the CRNP observations.

The figure caption has been updated as follows:

**“Figure 1.** (a) GRIPC irrigation intensity (percent) given by Salmon et al. (2015) used in the Standard and SPoRT simulations and (b) the observationally tuned irrigation intensity used in the Tuned simulation. **The spotty nature of Tuned indicates irrigation intensity has been reduced due to the presence of roads, wetlands, rainfed fields, and/or buildings.** Also shown is the average greenness vegetation fraction (unitless) in July 2012 given by (c) NCEP climatology used in the Standard and Tuned simulations and (d) SPoRT real-time dataset used in the SPoRT run.”

E. Figure 2 – It would be helpful to mention in the figure caption that SPoRT uses the climatological GVF in years 2009 and 2010 (as is already mentioned in the text) to avoid confusion.

The caption has been updated to include this information (bolded) and now reads:

**Figure 2.** Domain and monthly averaged GVF from the NCEP climatological GVF dataset, used in the Standard run, the SPoRT GVF dataset used in the SPoRT run, and the difference between the two (SPoRT – Climatology). **As the SPoRT dataset is not available prior to 2010, the long-term SPoRT simulation uses climatological GVF for 2009-2010,**

**and the SPoRT GVF dataset is incorporated in December 2010 and used throughout the rest of the simulation.”**

F. Figure 4 – I don’t believe that IRR was ever defined (in either the main text or the figure caption).

For all captions, “IRR - Ctrl” has been replaced with (i.e., each irrigation run minus Controll). The legend have been updated in Figures 7 and 9 so that they don’t include IRR and are consistent with the other legend labels.

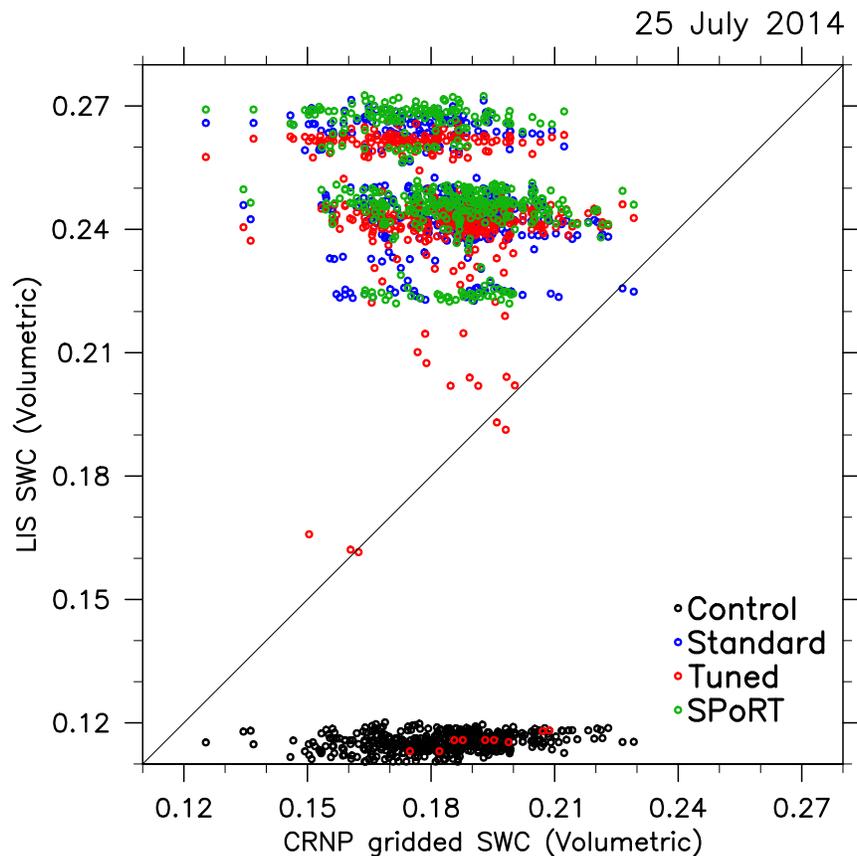
G. Figure 4 – The boundaries of Layer 4’s soil depths are only mentioned here, not in the main text. Since crop roots barely extend into this layer (max root depths of 1 or 1.2 m), perhaps this further explains why there seems to be much more variability in soil moisture between irrigation simulations in Layer 3 than in Layer 4.

Yes, the reviewer is correct. To call attention this fact, Page 11, Lines 15-16 have been updated to read:

“Increases in the third soil layer, **which includes the root zone**, are quite consistent annually with a near doubling of the soil moisture when irrigation is turned on.”

H. Figure 8 – I think that the presentation of “spatial” CDFs in this figure is rather non- intuitive. To me, it would be much more intuitive to see the differences in the spatial distributions of soil moisture within the domain using a histogram, especially since each CDF is plotted for only a single time step and thus there is no “accumulation” of data over time. In this figure, since data is accumulated spatially (in two dimensions) rather than temporally (in one dimension), the shape of the CDF would be rather arbitrary and would partly depend on the order in which you spatially sample the grid cells.

Thanks much for this suggestion. This figure has been changed to a scatterplot of the gridded observations versus the LIS simulations:



The text has been updated accordingly and all mentions of ‘temporal CDF’ have been changed to ‘CDF’ (Page 14 L11-23):

“The LIS-simulated soil moisture variability in time and space is evaluated against the CRNP gridded soil moisture product, described in Sect. 3.2. The spatial variability is assessed first with a scatterplot generated using all gridcell soil moisture values from the LIS simulations and the modified CRNP product aggregated at 4, 12, and 20 UTC on 25 July 2014 (Fig. 8). Next, the temporal variability is assessed using a CDF of the domain-averaged soil moisture values from May 5 to Sept 22 at 8-hour intervals (Fig. 9).

Figure 8 shows that the Control simulation does not match the observations in magnitude or variability, instead showing uniformly dry soil across the domain (e.g., range of 0.01 versus more than 0.1 in observations). The spatial variability is increased in the irrigated simulations, but these runs exhibit jumps between clusters of values as a result of irrigation triggering and dry down across the domain. The different levels of clustering shown by the irrigated simulations are a result of the input parameter datasets, as triggering and timing are dependent on these datasets. Although the Control

simulation is too dry, the irrigation overcompensates and increases the soil moisture to levels beyond that shown in the gridded observations. These results suggest that the model, even with the irrigation algorithm turned on, is not able to accurately simulate the small-scale (i.e., field scale) heterogeneity in soil moisture that is present in the CRNP data...”

I. Figure 8 – Neither the figure nor the figure caption explain what is being plotted in the figure. Units would also be appreciated (even if unitless).

Please see notes above notes about the updated Figure 8.

#### **IV. Technical corrections**

**All of the following technical corrections have been made as suggested. We thank the reviewer for his/her attention to detail.**

**With respect to comment “S” below, the text has been changed to (Page 9 L12-14):**

“In this study, we modified the spatial regression technique to treat irrigated and non-irrigated areas differently by using the CRNP rainfed values in the regression for non-irrigated gridcells and the average of the irrigated CRNP probes for the irrigated gridcells.

- A. Page 1, line 17 – “at the interannual scale, but become. . .” – Remove the comma.
- B. Page 2, line 23 – “previous evaluation efforts, and introduces...” – Remove the comma.
- C. Page 3, line 14 – e.g., “de Vrese et al. 2016” – Please be consistent with placing commas after “et al.” in internal citations.
- D. Page 4, line 1 – “with a two different. . .” – Remove “a”.
- E. Page 4, line 2 – “in the U.S. Central Great Plains. . .” – “Central” should be lowercase.
- F. Page 4, line 5 – “Tuinenburg et al., 2014), or in. . .” – Remove the comma after “2014)”
- G. Page 4, line 15 – No need for commas surrounding “such as these”.
- H. Page 4, line 23 – “. . .to reproduce county and water resource region irrigation water usage. . .” – Change to “. . .to reproduce irrigation water usage within counties and water resource regions. . .”.
- I. Page 5, line 17 – Change “c.f.” to “cf.”.
- J. Page 5, line 19 – “reliable, area-average soil water content” – Throughout the manuscript, please change to “area-averaged” or “domain-averaged” (as in the above example) when being used as an adjective and “area average” and “domain average” when being used as a noun.
- K. Page 6, line 9 – Change to “Sect. 3”.
- L. Page 7, line 22 – “i.e. observationally tuned” – Change all instances of “i.e.” and “e.g.” to “i.e.,” and “e.g.,”.
- M. Page 8, line 8 – “more sophisticated, but computationally expensive. . .” – Remove the comma.
- N. Page 8, line 8 – “such a dynamic. . .” – Change to “such as”.
- O. Page 8, line 14 – Change to “bias-corrected”.

- P. Page 11, line 14 – “the SPoRT run increases latent heat flux by more than  $100 \text{ W m}^{-2}$  more than Standard” – Change to “latent heat flux in the SPoRT run is more than  $100 \text{ W m}^{-2}$  greater than Standard”.
- Q. Page 12, line 15 – Add a space between “ $\text{mm day}^{-1}$ ” and “(not shown)”.
- R. Page 12, line 25 – Add a comma after “(e.g., satellite)”.
- S. Page 13, line 11 – “CRNP (irrigated) rainfed data. . .” – I would discourage this par- enthetical style (it already seems to have confused other reviewers). If you must use it, I would recommend putting the parenthetical expression second, e.g., “CRNP irrigated (rainfed) data”. However, I would instead prefer this and related sentences to be written as: “by using the CRNP irrigated and rainfed data in the regression for irrigated and non-irrigated gridcells, respectively”.
- T. Page 13, line 23 – Add a period after “dependent on these datasets”.
- U. Page 13, line 25 – Change “exhibit” to “exhibits”.
- V. Page 14, line 5 – Hyphenate “deficit based”.
- W. Page 14, line 11 – Hyphenate “coarser-resolution”.
- X. Page 16, line 3 – Remove the comma after “LSM framework”.
- Y. Page 16, line 4 - Remove the comma after “latent heat flux”.
- Z. Page 16, line 21 – Remove the comma after “soil moisture”.
- AA. Page 16, line 23 – Change to “USDA Census of Agriculture”.
- BB. Page 17, line 1 – Hyphenate “satellite based”.
- CC. Page 17, line 2 – Add period after “(Kumar et al., 2015)”.
- DD. Page 17, line 4 – Change “premiere” to “premier”.
- EE. Page 17, line 23 – Capitalize “a” after Myhre, and ditto for all other instances of mixed case for author names in the reference list.
- FF. Page 18, line 8 – Be consistent with italicizations: Either italicize all journal names or keep them all as plain text.
- GG. Page 18, line 8 – Change “hess” to “HESS”.
- HH. Page 18, line 28 – What does “Received” mean?
- II. Page 19, line 3 – Be consistent with capitalization of the article titles: Either capitalize only the first word and proper nouns (standard practice) in every title or capitalize all words in every title.
- JJ. Page 20, lines 5-9 – I think that these lines are in a slightly different font than the other references.
- KK. Page 21, lines 2-3 – See above comment.
- LL. Page 21, line 23 – What is “Artn”? Article number?
- MM. Fig. 1 caption – Please define the units of irrigation intensity (even if unitless).
- NN. Fig. 4 caption – Add a colon after “LSM default layers”.
- OO. Fig. 4 caption – Be consistent with parenthetical notes: Delta Z is included for the middle layers but not for the top or bottom layers.

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**Reviewer #4:**

**General comments:**

This is an interesting paper on the evaluation of an irrigation scheme within a land surface modeling framework. This is an area that needs research and I see this a potentially valuable contribution on the matter.

While generally well written, the structure and organization of the Background (particularly Section 2.3) and the Methods sections needs to be improved to ensure a better flow and enhanced readability. The study region, models, input datasets and evaluations should be described in a more logical and orderly manner with less intermixing. These issues are described in more detail in the specific comments below. The discussion section is very short and would benefit from more elaboration and high quality insights on the limitations and challenges as well as opportunities for irrigation modeling.

[A new section has been added to the methods and more information has been added to the Discussion. Please see specific comments below.](#)

Some of the used input datasets need more justification. GVF is an important dataset for the irrigation modeling but is reported at coarse resolution (3 and 16 km) inconsistent with the resolution of the LSM (1 km). Not clear to me why a 1 km based version isn't used here. The MODIS phenology product (produced at 500 m resolution) would probably be more useful in this context for establishing the start and duration of the growing season.

[Please see specific comments 10 and 12 for detailed responses.](#)

I'm also a bit concerned that 1 km isn't the most appropriate scale to do irrigation modeling and accuracy assessments as you will inevitable run into mixing of rainfed and irrigated fields given the characteristic size of the fields. LSM runs at 500 m resolution would probably have been more appropriate, also considering the scale of the CRNP validation dataset, and feasible using widely available surface inputs generated at consistent resolutions.

[Mixing of rainfed and irrigated fields is certainly an issue that arises in irrigation modeling, even at 1 km, which is considered high resolution for land-atmosphere interactions and regional weather modeling studies. However, 1 km is the highest resolution we can run, while still being appropriate and relevant to our broader goals.](#)

[The spatial resolution of 1 km is the most appropriate scale for this study for two main reasons:](#)

- 1) The highest resolution input datasets we have are 1 km, so running at 500 m would not improve our results in this study; it would simply give the same information broken up into more gridcells.
- 2) The broader context goal of evaluating this irrigation scheme is for its later use in land-atmosphere interaction studies (Page 2, paragraph 1; Section 2.1). It is difficult and typically not advisable to run a coupled atmospheric model at 500 m, especially for land-atmosphere interaction studies. The behavior of the planetary boundary layer (PBL) in atmosphere/mesoscale models, such as WRF, is determined by the PBL parameterization. These parameterizations are not recommended for use at 500 m as some of their assumptions break down at such fine scales.

**Specific comments:**

- 1) Page 1 L14: Please define the scale associated with “high resolution”

High resolution is 1 km in this case.

- 2) Page 1 L19: What precisely does the “human practice data” consist of?

Human practice data is the irrigation timing and amount. This has been clarified in the newly added section 3.2 – Evaluation Data.

- 3) Page 1 L21: “two irrigated fields” – what irrigated fields are you referring to here (soybean and maize)?

Yes, this is clarified in the newly added section on Evaluation Data (3.2).

- 4) Page 2 L21 and L25: Please define what you mean by coarse and high resolution here.

- 5) Page 6 L1-7: This paragraph reads a bit confusing with mentioning of all the different temporal and spatial resolutions. A bit unclear what product version is used for the evaluation. Does the 12x12 km survey area correspond to the 15x15 km domain of this study? Why the domain difference?

All of the evaluation data is explicitly defined in the newly added Evaluation Data section (3.2). The 12x12 km survey area is contained entirely within the 15 x 15 km domain area of the study. The grid projection (UTM) used in the Franz et al. (2015) study is not directly compatible with the grid definitions in LIS. Therefore, since we couldn't recreate the exact grid, we made a slightly larger domain to ensure that the entirety of the Franz domain was contained within the LIS simulation domain.

- 6) Page 6 L8-16: This Section adds to the confusion by repeating some of the statements above and also adding additional evaluation datasets (human practice data etc.) not related to the CRNP (although that is the title of the Section). Differences between the CRNP and COSMOS

datasets should be clarified, if any. The finishing paragraph relates the overall objectives and novelty of the work, which don't belong here. This Section requires some revision – the evaluation components might be more appropriately positioned in the method section. You may need a completely separate section for describing the additional datasets mentioned here.

COSMOS is the observing network of stations and rovers, while CRNP refers to the observing instrument. The first sentence of Section 2.3 makes the distinction:

“A potential solution to fill the gap between point and remote sensing observations of soil moisture is the Cosmic-Ray Neutron Probe (CRNP) **method**, organized through the Cosmic Ray Soil Moisture Observing **System** (COSMOS), which **has ~200 probes operating globally since 2011.**”

The source of the human-practice data is Franz et al. 2015, which is described in this section, and thus why the human-practice data is mentioned here.

We have shortened this paragraph by removing details of the evaluation data and have instead incorporated these details into a new section 3.2, called Evaluation Data, as suggested by the reviewer. The novelty statement has been moved to the last paragraph of the introduction.

7) Section 2.3: The CRNP data description is currently part of the introduction/background part of the manuscript. While it makes sense to mention and introduce the data as a useful validation source in this context, I feel that the detailed description of the actual dataset used here for evaluation purposes should be moved to a separate section in the Methods section (or Methods and data section). Here you could appropriately describe all the datasets used in the study.

Details about the CRNP data from the Franz et al. study used for evaluation in our study have been moved to a new sub-section of the Methods, called Evaluation Data (3.2), as per the reviewer's suggestion.

8) Section 3: I would start this with a description of the study area and domain to set the stage.

9) Section 3.1: I find this section quite confusing to read as it includes both modeling and evaluation details and references to elements described in Section 3.2. I think you need to rethink the organization of the Method section adopting a more logical organization for improved flow and readability. Personally, I would prefer to have all model descriptions first before the description of experiments and evaluations to be performed.

This section does not include any evaluation details. It describes the land surface model and modeling framework (paragraph 1), the time period for the simulations (paragraph 2), introduces the four simulation experiments (paragraph 3), and then details the important distinctions between the four simulation experiments (remaining paragraphs).

10) Page 8 L1-5: So why isn't the GVF datasets provided at 1 km to be consistent with the LSM resolution?

The resolution of the NCEP climatological GVF used in this study is 1 km. The statement about the 16 km GVF dataset was included as part of the summary of results from Case et al., (2014); their study used 16 km climatological GVF. Admittedly, it did read like the climatological GVF used in this study is also 16 km. We removed these extra details from the Case et al., 2014 study description as they are unnecessary and added confusion. We also added the resolutions of the GVF datasets when introducing them. Page 7 Lines 17-29 now read (bold is newly added):

“The SPoRT run makes use of the GRIPC irrigation intensity dataset, like the Standard run, but uses a real-time GVF product at **3 km spatial resolution** from NASA-MSFC’s Short Term Prediction, Research, and Transition Center (SPoRT; Case et al., 2014). This is in contrast to the other runs that use climatological GVF at **1 km** from the National Centers for Environmental Prediction (NCEP).”

With respect to the resolution of input datasets more generally, we always use the best available, most appropriate input datasets for our application. Although we like to use high-resolution whenever possible, the highest resolution is not always the best available. This is the situation with our SPoRT dataset. Although the SPoRT GVF dataset is produced at 0.01 degree (~ 1 km), there was a change in the Continental US grid in Feb 2012 that impacted the 1 km dataset. We used the 3 km dataset instead of 1 km to avoid potential inconsistencies resulting from the grid change in 2012 (in the middle of our long-term spinup).

You also need to specify precisely what the GVF product is used for, when first introduced. From what I can read later in the manuscript it is predominantly used to determine the start and end of the growing season; couldn’t you use the MODIS phenology product (see comment 12) more appropriately for this purpose? In addition, this product is available for the full duration of the study.

The GVF dataset is used in irrigation scheme in two main ways:

- 1) It is involved in the determination of the irrigation season, as the reviewer notes. This is a central feature of the Ozdogan et al. (2010) irrigation algorithm. While it is certainly possible to use a different method, such as the MODIS phenology for determining the irrigation season, this would be a considerable deviation from the irrigation scheme and therefore would be counter to the goals of the study, which are to evaluate this particular scheme.
- 2) GVF is used to define the crop root zone, which impacts the amount of water applied by the irrigation scheme. The maximum root zone for each crop type is defined by a lookup table; the GVF is multiplied by the maximum root zone to determine the crop root zone. In this way, the scheme mimics the season cycle of crop root growth. More water is applied for greater crop root depth. Therefore, GVF is important for defining the irrigation season, triggering irrigation, and for determining the amount of irrigation water applied by the irrigation scheme.

The land surface model does not explicitly use a phenology dataset, such as MODIS EVI or NDVI, but rather uses proxies of Greenness Vegetation Fraction (GVF) and Leaf Area Index. The SPORT GVF dataset is based on NDVI, and therefore in essence translates the MODIS NDVI information into a form that the model can use (GVF).

11) Page 8 L12-15: You need to mention the resolution of these in- put datasets.

The resolution of each dataset has been added to this paragraph. It now reads as follows, with the additions shown in bold italics:

“Additional datasets common to all simulations include MODIS – International Geosphere Biosphere Program (MODIS-IGBP) land cover **at 1 km**, State Soil Geographic (STATSGO?) soil texture **at 1 km**, University of Maryland crop type **at 1 km**, and National Land Data Assimilation System – Phase 2 (NLDAS2, Xia et al., 2012) meteorological forcing at **1/8<sup>th</sup> degree (approximately 12 km)** that includes bias corrected radiation and gauge-based precipitation.”

Is the UMD crop type product static or is a separate classification provided for each year? The annual Cropland Data Layer ([https://www.nass.usda.gov/Research\\_and\\_Science/Cropland/SARS1a.php](https://www.nass.usda.gov/Research_and_Science/Cropland/SARS1a.php)) product (provided at 30 m) is updated for each year to account for crop rotations and changing crop type patterns and might be a more correct source to use for something like this.

The UMD crop type product is static. We agree that the Cropland Data Layer is a great improvement on static crop maps and we have discussed integrating the CDL into LIS. However, for this study, because of the small domain and the detailed ground observations we have, the CDL would not have added value beyond the ground truth provided by the Franz group. We completed the default crop type run and an additional crop type run with an observationally tuned map (detailed in the Discussion section) and found no significant differences. As a result, we believe a run with the CDL would not have differed significantly from either of these two runs.

12) Page 9 L4-5: The GVF product is used for establishing the length and timing of the growing season. A more appropriate source for this would be the MODIS global vegetation phenology product (MCD12Q2) currently produced at 500 m resolution that is also more consistent with the LSM resolution and the CRNP validation dataset (and the scale of irrigation effects). Reasons for not using something like this should be addressed.

As discussed above, a main feature of the Ozdogan et al. (2010) irrigation scheme is the determination of the irrigation season based on a threshold of the GVF. While it is certainly possible to use a different method, such as the MODIS phenology for determining the irrigation season, this would be a considerable deviation from the scheme and therefore would be counter to the goals of the study in evaluating this particular scheme.

The land surface model does not explicitly use a phenology dataset, such as MODIS EVI or NDVI, but rather uses proxies of Greenness Vegetation Fraction (GVF) and Leaf Area Index. The SPORT GVF dataset is based on NDVI, and therefore essentially translates the MODIS NDVI information into a form that the LSM can use (GVF).

13) Page 9 Section 4: A brief intro statement would be useful here.

We don't believe an intro statement is necessary here as the previous paragraph sets up the organization of this section.

14) Page 10 L7: The relationship used to compute the root zone length from GVF should be provided in the methodology.

The root zone length calculation, as it applies to the irrigation scheme, is described on Page 10, Lines 11-12.

“...,while the root zone is the product of the maximum root depth (as defined by crop type) scaled by the GVF to mimic a seasonal cycle of root growth.”

15) Page 12 L6: This is the first mentioning of a rainfed validation site within the study domain. Details like this should be provided in the method section (preferably in a dedicated study region section).

The rainfed site was mentioned in Section 2.3 but has been moved to the new Evaluation Data section (3.2).

16) Page 13 L8-13: This should be moved to the methodology section. A shorter summary of the CRNP would suffice here.

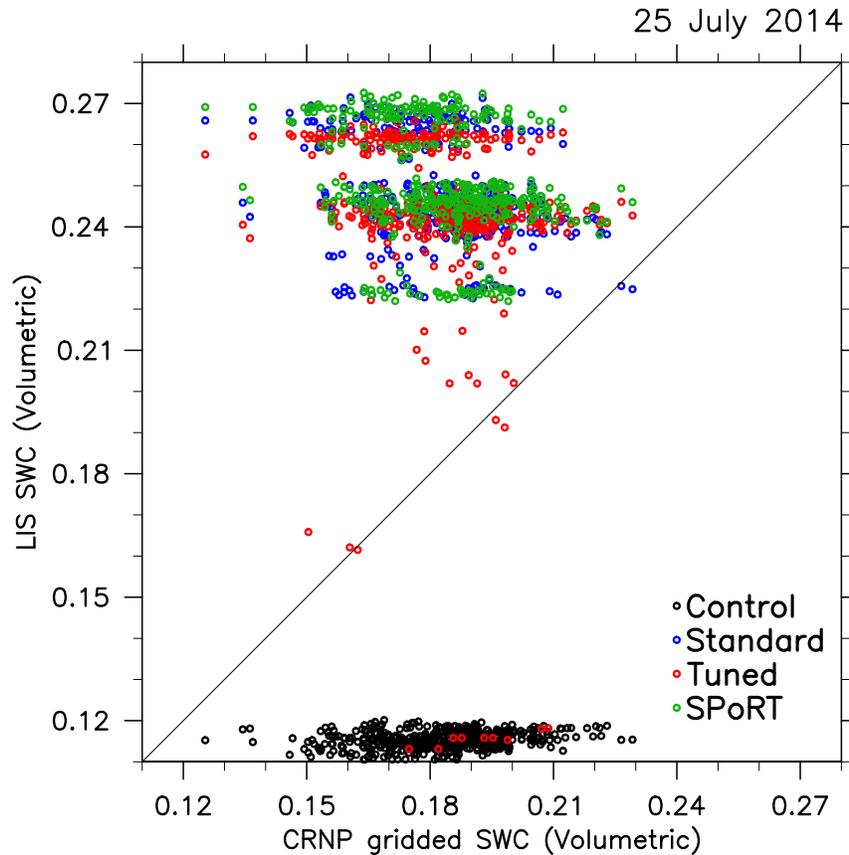
The description of the CRNP gridded soil moisture product and the alterations made to the regression for this study have been moved to the new Evaluation Data section (3.2)

17) Page 13 L15: Not clear what modifications were made to the COSMOS product; provide a section reference or more details here. Also a bit confused about the references to both CRNP and COSMOS as they are presumably the same thing?

COSMOS is the observing network, CRNP is the instrument. COSMOS was a typo here and has been corrected to 'CRNP'. More description has been added about the changes to the spatial regression and they've been moved to the new Evaluation Data section (3.2).

18) Page 13 L14-15: I wonder if a non-cumulative PDF wouldn't be better in this context?

This comment echoes that of reviewer 3 in that this information could be presented in a more effective manner. This figure has been changed to a scatterplot:



19) Page 14 L6: I believe that the GVF is provided at 3 km (and 16 km) rather than 1 km resolution, correct?

The SPoRT GVF is provided at 3 km, but the climatological GVF is provided at 1 km. Please see comment #10.

20) Section 5: The discussion is very brief and lacks more substantial and high quality discussion elements on limitations, challenges and opportunities.

A paragraph has been added to the Discussion that addresses the concerns of reviewers 2 and 3 related to the choice of meteorological forcing dataset (Page 16, Line 1-11):

“For this small domain, the NLDAS2 precipitation proved to be sufficiently accurate, matching well that given by the nearby York, Nebraska AWDN. However, for other regions, reliable meteorological forcing may not be available. To further explore the impact of the forcing precipitation on the irrigation triggering, an additional simulation was completed that is equivalent to the Standard irrigation run in all aspects (e.g., GRIPC irrigation intensity, climatological GVF) except that the Global Data Assimilation System (GDAS) meteorological forcing is used rather than NLDAS2. In contrast to NLDAS2, GDAS is coarser resolution (1/4 degree) and does not include rain-gauge corrections. Results show that GDAS supplied a greater amount of total of precipitation in May through July

2014, creating a wetter soil column and prohibiting irrigation triggering in mid-to-late July, in contrast to observations and the other irrigation simulations. As a result, the soil moisture dynamics of the GDAS simulation at the maize site differ substantially from the CRNP observations and the NLDAS2-forced simulations. These results underscore the need for highest quality datasets available for the area of interest, which for this region and time frame was NLDAS2.”

An additional paragraph has been added discussing the potential limitations of the uncoupled configuration used in this study (Page 17 Lines 3-9):

“Recent work by Decker et al., (2017) shows that atmospheric feedbacks can reduce the irrigation demand simulated by a land surface model. That is, a coupled model configuration allows the atmosphere to respond to the irrigation application, moistening the near surface, and reducing the need for additional irrigation as compared to the same model run uncoupled. A limitation of the work presented here is therefore the lack of the atmospheric feedback in the uncoupled configuration. However, the Decker et al., (2017) results indicate that a coupled configuration would likely reduce irrigation amounts simulated by the model. As the irrigation demand was greater in the model than in the human-practice observations, the coupled atmosphere has the potential to reduce irrigation amounts to be more in line with those observed.”

Other limitations of the study are presented in paragraphs 1 and 3 of the discussion. Challenges are discussed extensively in the Background section. The future of irrigation intensity datasets is detailed in Page 17 Lines 10-17.

21) Page 15 L3-8: These are useful details that should have been provided in the methodology or result sections

A description of the triggering datasets and exactly how they impact triggering is included in the methodology section (Sect. 3.3). The relative importance of the triggering datasets is included here, not in the methodology, because this is a main finding of the study.

22) Page 15 L9-12: Not sure I understand this correctly, particularly the part about the scaling by GVF being more important than changes in rooting depth.

The logic here is as follows. First, the maximum crop root zone is multiplied by the GVF (non-dimensional number 0-1) to mimic a seasonal cycle of root growth. The amount of water added by the irrigation scheme is then dependent on the depth of the crop root zone (more water applied for crops that have deeper roots). To determine the potential impact of crop rooting depth specification, we completed an additional run where we used an observationally tuned crop map and changed the maximum root depth of maize and soybeans. It was concluded that the impacts of the crop root depth on irrigation amounts and fluxes were insignificant compared to the influence of the scaling of the crop root zone.

23) Page 15 L13: The method for determining the start and end of the growing season hasn't been described anywhere, but it must be. Justifications for adopting that methodology (rather than relying on existing phenology products for instance) should also be provided.

The details of the irrigation season have been added to the method section when first introduced. Page 10, Lines 6-7 now reads:

“The growing season, addressed in question three, is a function of the gridcell GVF (i.e., 40% annual range in climatological GVF; Ozdogan et al. 2010)...”

This method is used as it is a main feature of the Sprinkler irrigation algorithm. Please see comment 12.

### **Technical corrections:**

1) Page 4 L1: “with a two different..” - should be “with two different..”

This has been changed.

2) Page 4 L23: “..water resources region. . .”?

This has been reworded to:

“reproduce irrigation water usage within counties and water resource regions, respectively”

3) Page 5 L14: use “high resolution” rather than “high-resolution”

4) Figure 5: I would also show the irrigation amounts here as done in Figure 7. Why is the impact of irrigation high when no irrigation is applied (e.g., during rain events)?

The observed irrigation amounts are not shown because this figure is used to analyze only model results/datasets, not observations. It would be possible to show simulated irrigation amounts for all irrigation runs, but that would make the figure much more confusing/busy without contributing additional information. We feel that the combination of forcing precipitation and flux changes due to irrigation already make it readily apparent when irrigation is being triggered.

As compared to the rain-free periods, the impact of irrigation is dramatically reduced during rain events. There is still some impact to fluxes during rain events in the summer because the soil column in the irrigated simulation is generally wetter than control due to the memory of previous irrigation, even if irrigation does not occur on that day.

5) Figure 5: Issue with the legends – they are not consistent with what is shown; currently I can only distinguish two different line styles.

This figure shows changes from control in each model configuration for latent and sensible heat fluxes. Latent heat flux changes are shown in blue and sensible heat flux changes are shown in red. The line style corresponds to the model configuration. Therefore, the change from Control in latent heat flux when using irrigation and the SPoRT GVF dataset is shown in the blue dotted

line. Only two lines are distinguishable because the Tuned and Standard configurations do not differ enough from each other at this scale to be distinguishable. This is a main conclusion shown in the figure.

6) Figure 5: a and b rather than top and bottom should be used for more precise figure referencing in the manuscript. This also applies to the other figures.

All figures have been updated to use the (a),(b), etc.

# Assessment of Irrigation Physics in a Land Surface Modeling Framework using Non-Traditional and Human-Practice Datasets

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**Abstract.** Irrigation increases soil moisture, which in turn controls water and energy fluxes from the land surface to the planetary boundary layer and determines plant stress and productivity. Therefore, developing a realistic representation of irrigation is critical to understanding land-atmosphere interactions in agricultural areas. Irrigation parameterizations are becoming more common in land surface models and are growing in sophistication, but there is difficulty in assessing the realism of these schemes, due to limited observations (e.g., soil moisture, evapotranspiration) and scant reporting of irrigation timing and quantity. This study uses the Noah land surface model run at high resolution within NASA's Land Information System to assess the physics of a sprinkler irrigation simulation scheme and model sensitivity to choice of irrigation intensity and greenness fraction datasets over a small, high resolution domain in Nebraska. Differences between experiments are small at the interannual scale, but become more apparent at seasonal and daily time scales. In addition, this study uses point and gridded soil moisture observations from fixed and roving Cosmic Ray Neutron Probes and co-located human practice data to evaluate the realism of irrigation amounts and soil moisture impacts simulated by the model. Results show that field-scale heterogeneity resulting from the individual actions of farmers is not captured by the model and the amount of irrigation applied by the model exceeds that applied at the two irrigated fields. However, the seasonal timing of irrigation and soil moisture contrasts between irrigated and non-irrigated areas are simulated well by the model. Overall, the results underscore the necessity of both high-quality meteorological forcing data and proper representation of irrigation for accurate simulation of water and energy states and fluxes over cropland.

## 1 Introduction

Irrigation is vital to feeding the world's population, accounting for ~40% of global food production and 20% of arable land (Molden, 2007; Schultz et al., 2005). Approximately 70% of global freshwater withdrawals (FAO, 2010) are used to meet the demand for irrigation, thereby altering the hydrologic cycle and raising questions about water resources sustainability. As a result, irrigation modeling studies have sought to understand the impacts of irrigation on ambient weather (Sorooshian et al., 2011, 2012), precipitation and streamflow (Harding and Snyder 2012a,b; Kustu et al., 2011), and regional to global climate (Lo and Famiglietti, 2013; Puma and Cook, 2010). Although the atmospheric response is often sensitive to the details of the irrigation scheme used in modeling studies, the observational data needed to fully vet an irrigation scheme (e.g., irrigation timing, practices, and co-located soil moisture) are generally not obtainable in a spatially continuous format at the scale of high-resolution LSMs, making robust evaluation difficult and casting doubt on conclusions about downstream impacts on regional weather, precipitation, and long term climate.

The impact of water resources management practices such as irrigation on the water cycle is significant enough that the World Climate Research Program (WCRP) has identified anthropogenic changes to the continental water cycle as a Grand Science Challenge to be addressed over the next 5 to 10 years (Trenberth and Asrar, 2014). In response, the Global Energy and Water Cycle Exchanges project's (GEWEX) Hydroclimatology Panel (GHP) and Global Land/Atmosphere System Study (GLASS) have begun a joint effort to advance the representation of human water resources management in land surface and coupled models (van Oevelen, 2016). To effectively meet these challenges, new, non-traditional datasets are needed to evaluate and improve representation of irrigation in models and to assess the processes by which simulated irrigation impacts the water cycle.

The work presented here touches on each of these issues by comprehensively assessing a sprinkler irrigation algorithm in a land surface model (LSM) and evaluating the results with both conventional and non-traditional datasets. The integration of human practice data (i.e., irrigation amount and timing), physical observations (e.g., soil moisture point and spatial observations), and model simulations to evaluate the sprinkler algorithm and its impacts on soil moisture is a key and novel feature of this study. The paper is organized in the following way: Sect. 2 provides relevant background on recent irrigation modeling efforts with an emphasis on differences in irrigation schemes and previous evaluation efforts, and introduces

gridded soil moisture from the Cosmic-Ray Neutron Probe method (CRNP) as a potential tool for evaluation of land surface model irrigation. A description of the experimental design, including the land surface modeling framework and the irrigation algorithm, are presented in Sect. 3. Sect. 4 describes the results, first in the context of model sensitivity and secondly through an evaluation of the model simulations with observations. A discussion of the results and the applicability of this study to future irrigation modeling efforts are discussed in Sect. 5, and conclusions are stated in Sect. 6.

## 2 Background

### 2.1 Irrigation physics

Irrigation increases soil moisture and therefore has the potential to influence local and regional clouds, precipitation, and ambient weather via land-planetary boundary layer (PBL) coupling processes (Santanello et al., 2011). By increasing latent and decreasing sensible heat fluxes, near surface temperature is reduced within irrigated areas (Bonfils and Lobell, 2007; Kanamaru and Kanamitsu, 2008). The irrigation-modified land energy balance alters the proportion of heat and moisture contributed to the PBL, thereby influencing PBL growth and entrainment (Kueppers and Snyder, 2011; Lawston et al., 2015). As a result, the PBL over irrigated areas is often shallower and moister, potentially resulting in alterations to convective cloud development (Adegoke et al., 2007; Qian et al., 2013). Irrigation applied over large areas not only affects local ambient weather, but models indicate that it can also modify precipitation patterns in areas remote from the source (de Vrese et al., 2016), which can further alter streamflow (Kustu et al., 2011). Extensive irrigation projects, such as the Gezira Scheme in East Africa, have been shown to influence regional weather by changing circulation and precipitation patterns (Alter et al., 2015).

These significant potential impacts of irrigation on temperature, clouds, precipitation, and related fluxes necessitate an appropriate representation of irrigation in coupled land-atmosphere models. This need has been addressed via irrigation parameterizations in LSMs that largely fall into three types of schemes: 1) defined increases to soil moisture in one or more soil layers (Kueppers and Snyder, 2011; de Vrese et al., 2016), sometimes referred to as flood (Evans and Zaitchik, 2008), 2) the addition of water as pseudo-precipitation to mimic sprinkler systems (Ozdogan et al., 2010; Yilmaz et al., 2014), and 3) modifications to vapor fluxes as a proxy for increased evapotranspiration resulting from highly efficient (e.g., drip) irrigation (Douglas et al., 2006; Evans and Zaitchik, 2008). These schemes are generally dependent on parameter input datasets and

user defined thresholds, affording a degree of customization, but also introducing uncertainty and potential error. Model sensitivity to the selection of datasets and thresholds is not trivial, as differences can alter the magnitude of irrigation-induced changes to the water and energy budgets. For example, a flood irrigation parameterization with ~~a~~ two different triggering thresholds resulted in up to  $80 \text{ W m}^{-2}$  difference in average seasonal latent heat flux increase in the U.S. ~~c~~ Central Great Plains (Lawston et al., 2015). In another case, Vahmani and Hogue (2014) tested several irrigation demand factors and irrigation timing in their urban irrigation module, finding fluxes, runoff, and irrigation water are sensitive to both inputs. Additionally, the same parameterization used in a different model (Kueppers et al., 2008; Tuinenburg et al., 2014); or in the same model but at a different resolution (Sorooshian et al., 2011) has also produced different coupled atmospheric impacts.

## 2.2 Evaluation of irrigation in LSMs

10 The sensitivity of atmospheric predictions to the details of the irrigation scheme makes it imperative to systematically evaluate irrigation parameterization, datasets, and thresholds in a controlled modeling study to determine the levels of uncertainty in the perturbation and subsequent results. However, datasets required for evaluation, such as irrigation amount, irrigation timing, and co-located continuous soil moisture observations, are not widely available, making it difficult to evaluate irrigation schemes (Kueppers et al., 2007). Modeling studies that have included some assessment of the irrigation  
15 scheme have used comparisons to annual water withdrawals for irrigation (Lobell et al., 2009; Pokhrel et al., 2012), outdoor water use (Vahmani and Hogue, 2014), recommended amounts of irrigation (Sorooshian et al., 2011, 2012), or irrigation water usage reported by the U.S. Geological Survey (Ozdogan et al., 2010). Bulk estimates; such as these; are often not used for robust evaluation, but rather indicate that the simulated results are reasonable.

In some cases, additional analysis of the observations has been successful in converting estimates to quantities usable for  
20 comparison. For example, Pei et al. (2016) used a potential evapotranspiration ratio to estimate June, July, and August irrigation usage from USGS yearly county-level estimates in order to validate irrigation amounts in the WRF-Noah Mosaic coupled model. The study found good agreement between the amounts simulated and that of the modified observations at 30 km horizontal resolution. In other cases, county and coarser resolution irrigation estimates have been used to constrain the irrigation algorithm output. Leng et al. (2013, 2014) calibrated the irrigation scheme in the Community Land Model (CLM)  
25 to reproduce irrigation water usage within counties and water resource region~~county and water resources region irrigation~~

~~water usage~~, respectively. Taken together, these studies exhibit recent progress made in irrigation modeling evaluation at regional to continental scales, but the datasets employed are insufficient for evaluation at high resolution and shorter (e.g., season to sub-monthly) time-scales.

As soil moisture is the primary control over fluxes and vegetation health, an evaluation of soil moisture sensitivity to irrigation is equally as important as realistic irrigation estimates. Such evaluation is challenging as it demands soil moisture observations that are temporally and spatially continuous and at high enough resolution to resolve an irrigation signal. Satellite remote sensing has obvious potential to reach these goals, but retrievals of soil moisture are generally too coarse (i.e., ~25-40 km spatial resolution) and exhibit limited skill, at best, in detecting an irrigation signal (Kumar et al., 2015). At the other spatial extreme, point observations of soil moisture values are not representative of the larger area average (Entin et al., 2000). The aggregation of these observations into homogeneous, quality controlled datasets, such as the North American Soil Moisture Database (NASMD, Quiring et al., 2016) and the International Soil Moisture Network (ISMN, [www.ipf.tuwien.ac.at/insitu](http://www.ipf.tuwien.ac.at/insitu)), are promising for LSM evaluation more broadly, but in-situ measurements in irrigated fields, needed for irrigation scheme evaluation, are still sparse.

### 2.3 Cosmic-ray neutron probe (CRNP)

A potential solution to fill the gap between point and remote sensing observations of soil moisture is the Cosmic-Ray Neutron Probe (CRNP) method, organized through the Cosmic Ray Soil Moisture Observing System (COSMOS, Zreda et al., 2012), which has ~200 probes operating globally since 2011. CRNP is a new and novel way to obtain high-resolution, semi-continuous soil moisture observations, and as a result, has the potential to advance LSM and irrigation parameterization development. The CRNP is placed above the ground and measures neutrons produced by cosmic rays in the air and soil over a diameter of 300+/- 150 m, depending on atmospheric pressure and humidity (c.f. Desilets and Zreda, 2013 and Kohli et al., 2015). The theoretical basis for the CRNP method follows that fast neutrons injected into the soil by the CRNP will be slowed more effectively by collisions with hydrogen atoms (present in soil water) than any other element (Visvalingam and Tandy, 1972). Thus, the neutron density measured by the probe is inversely correlated with soil moisture and can be calibrated using local soil samples to an error of less than 0.03 m<sup>3</sup> m<sup>-3</sup> (Franz et al., 2012). The result is reliable, area-

average soil water content integrated to a depth of ~20-40 cm, depending on water content, bulk density, and lattice water, available at the same spatial scale as high-resolution LSMs (Franz et al., 2012) .

The characteristics of the CRNP, including the non-contact, passive data collection, make the CRNP portable and able to collect data while in motion. Desilets et al. (2010) first used a roving CRNP in Hawaii to obtain transects of soil moisture at highway speeds. More recently, Chrisman and Zreda (2013) and Dong et al. (2014) used the roving CRNP at the mesoscale in Arizona and Oklahoma. Franz et al., (2015) mounted a large CRNP instrument to the bed of a pickup truck and completed roving surveys during the growing season of 2014 in a 12 x 12 km area of eastern Nebraska. The instrument collected ~300 neutron counts every minute and was driven at a maximum speed of 50 km per hour, allowing for high resolution maps to be generated via geostatistical interpolation techniques. The spatial locations of each neutron measurement are given by the midpoint of successive rover locations and together are spatially interpolated via kriging to 250 m resolution. The surveys were completed every 3-4 days from May to September. In addition, 3 fixed probes were located inside the domain continuously recording soil moisture. Franz et al. (2015) used the fixed and roving data with a simple merging technique to produce 8-hour soil moisture products at 1, 3, and 12 km resolutions.

The work presented here uses ~~the these~~ data and products gathered and generated in Franz et al. (2015) for the evaluation of a sprinkler irrigation algorithm in a LSM environment, described in Sect. 3. ~~Specifically, the data are available for the 2014 growing season and include: timing and amount of irrigation water applied at two sites (one maize, one soybean), soil water content from a stationary COSMOS probe at these two irrigated sites, plus a rainfed site of mixed soybean and maize, and lastly, high resolution gridded soil moisture at 3-4 day temporal resolution during the growing season (May to Sept) from the CRNP rover. The integration of human practice data (irrigation amount), physical observations (soil moisture point and spatial observations), and model simulations to evaluate the sprinkler algorithm and its impacts on soil moisture is a key and novel feature of this study.~~ The main goals of this work are first to assess the physics of the simulated sprinkler irrigation, and secondly to evaluate the realism of the irrigation amounts and impacts to soil moisture.

### 3. Methods

#### 3.1 Models and experimental design

NASA's Land Information System (LIS; Kumar et al., 2006) is used in this study to assess the performance of the Sprinkler irrigation scheme. LIS is a land surface modeling and data assimilation system that allows users to choose from a suite of land surface models which can then be run offline while constrained and forced by best available surface and satellite observations. LIS can be fully coupled to the Weather Research and Forecasting model (WRF, Skamarock et al., 2005) in the NASA Unified WRF (NU-WRF, Peters-Lidard et al., 2015) framework. This configuration, LIS-WRF, has been used at the regional scale to assess the downstream impacts of irrigation on the PBL, but the performance of the irrigation scheme was not assessed (Lawston et al. 2015).

In this study, the Noah land surface model (Chen et al., 2007) version 3.3, was run offline within the LIS framework at 1 km spatial resolution over a 15 x 15 km area in eastern Nebraska, near the town of Waco. The size and location of the domain were designed to encompass the study area of Franz et al. (2015) to make use of the CRNP rover data, human practice information, and point and spatial observations produced by their work, as discussed in Sect. 2.

The LIS simulations were run for 6 years (1 Jan 2009 to 31 Dec 2014) yielding daily output. The long-term simulation output was used to initialize restart-simulations for the growing seasons of 2012 and 2014 to produce hourly output for more detailed investigation during these periods, and the 3-5 year spinup periods, respectively, were shown to be sufficient for this region (Lawston et al., 2015). The analysis focuses on these two years (i.e., 2012 and 2014) to evaluate the irrigation algorithm during contrasting antecedent soil moisture conditions (e.g., relatively dry and wet, respectively), and to assess the performance of the scheme using the CRNP observations available in 2014.

To capitalize on the controlled nature of the study area and the irrigation scheme's dependence on green vegetation fraction (GVF) and irrigation intensity, discussed in detail in section 3.3.2, four types of simulations were completed and will hereafter be referred to as the 1) Control, 2) Standard, 3) Tuned, and 4) SPoRT simulations. The Control run is the only simulation that has the irrigation scheme turned off. The Standard simulation differs from Control only in that the sprinkler irrigation scheme is turned on and the Global Rainfed, Irrigated, and Paddy Croplands (GRIPC; Salmon et al., 2015) dataset is used to prescribe irrigation intensity at 1km resolution needed for the sprinkler algorithm. The Tuned simulation uses an

edited irrigation intensity map, described in more detail below, rather than GRIPC. The SPoRT run makes use of the GRIPC irrigation intensity dataset, like the Standard run, but uses a real-time GVF product at 3 km spatial resolution from NASA-Marshall's Short Term Prediction, Research, and Transition Center (SPoRT; Case et al., 2014). This is in contrast to the other runs that use climatological GVF at 1 km from the National Centers for Environmental Prediction (NCEP). Additional datasets common to all simulations include MODIS – International Geosphere Biosphere Program (MODIS-IGBP) land cover at 1 km, State Soil Geographic (STATSGO) soil texture at 1 km, University of Maryland (UMD) crop type at 1 km, and National Land Data Assimilation System – Phase 2 (NLDAS2; Xia et al., 2012) meteorological forcing at 1/8<sup>th</sup> degree (~12 km) that includes bias-corrected radiation and gauge-based precipitation.

The GRIPC irrigation intensity dataset, used in the Standard and SPoRT simulations, integrates remote sensing, gridded climate datasets, and responses from national and sub-national surveys to estimate global irrigated area. The dataset closely agrees (96% at 500 m) with the USGS M<sub>Ir</sub>AD-US2007 irrigation dataset (Pervez and Brown, 2010) and an assessment of the GRIPC dataset against field level inventory data showed an 84% agreement in Nebraska (Salmon et al., 2015). This dataset represents a significant improvement in defining irrigated areas as compared to previous configurations of this model and scheme (Lawston et al. 2015) in which irrigated areas were defined using the 24-category USGS landcover classification, based on data from the 1990's. However, the GRIPC dataset overestimates irrigation intensity in the study area. The GRIPC dataset irrigation intensity is unrealistically high in the study area, as evidenced by only 5% of the gridcells having intensity less than 100% (Fig. 1a). To correct for this overestimation, the Tuned simulation uses an irrigation intensity map created by reducing the GRIPC irrigation intensity according to a land use map generated from ground truth observations (Franz et al., 2015), thereby more accurately reflecting irrigation patterns in the study area (i.e., observationally tuned; Fig. 1b). ~~The SPoRT run makes use of the GRIPC irrigation intensity dataset, like the Standard run, but uses a real-time GVF product from NASA Marshall's Short Term Prediction, Research, and Transition Center (SPoRT; Case et al., 2014). This is in contrast to the other runs that use climatological GVF from the National Centers for Environmental Prediction (NCEP).~~

The SPoRT GVF, used only in the SPoRT simulation, is created using normalized difference vegetation index (NDVI) from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra and Aqua satellites and as such reflects the vegetation response to temperature and precipitation. In this way, the SPoRT GVF dataset captures interannual variability in vegetation that is missed by climatological GVF (Figure 2). Additionally, SPoRT GVF ~~has higher spatial resolution (i.e., 3 km vs. 16 km for climatology) and~~ has been shown to improve the simulated evolution of precipitation in a severe weather event as compared to GVF from climatology when using LIS coupled to a numerical weather prediction model (Case et al., 2014). The use of the SPoRT GVF dataset can be viewed as a middle-of-the-road approach between a simple representation of vegetation (e.g., climatology) and more sophisticated, ~~but~~ computationally-expensive methods, such as dynamic vegetation or crop growth models (e.g., Harding et al., 2015; Lu et al., 2015). As the SPoRT dataset is not available prior to 2010, the long-term SPoRT simulation uses climatological GVF for 2009-2010, and the SPoRT GVF dataset is incorporated in December 2010 and used throughout the rest of the simulation.

~~Additional datasets common to all simulations include MODIS—International Geosphere-Biosphere Program (MODIS-IGBP) land cover, State Soil Geographic (STATS-GO) soil texture, University of Maryland (UMD) crop type, and National Land Data Assimilation System—Phase 2 (NLDAS2; Xia et al., 2012) meteorological forcing that includes bias corrected radiation and gauge-based precipitation.~~

### **3.2 Evaluation Data**

The non-traditional, CRNP soil moisture data products and human-practice data gathered in Franz et al., (2015) are used to evaluate the sprinkler irrigation algorithm in LIS. Human-practice data in the form of the irrigation amount and dates of irrigation application at one irrigated soybean and one irrigated maize site were reported via personal communication to Franz et al., (2015). These two irrigated sites are also equipped with stationary CRNP probes that continuously monitored soil moisture throughout the growing season of 2014. A third CRNP stationary probe is located in a rainfed field of mixed soybean and maize. Collectively, these data will be used to evaluate the impact of irrigation on soil moisture dynamics and the ability of the model to reproduce these impacts at the irrigated sites. In addition, precipitation data from the nearby York, Nebraska Automated Weather Data Network (AWDN), operated by the High Plains Regional Climate Center (HPCC, <http://www.hprcc.unl.edu/index.php>) are used to understand the background regime leading to the irrigation timing.

Additional non-traditional data from Franz et al., (2015) include a soil moisture product that uses the spatiotemporal statistics of the observed soil moisture fields, as obtained via the CRNP rover surveys, and a spatial regression technique to create a 1-km, 8-hour gridded soil moisture product for the growing season (May – Sept, 388 values). Franz et al., (2015) used the average of the three stationary CRNP probes as the regression coefficient, which can smear the spatial differences between irrigated and rainfed areas. In this study, we modified the spatial regression technique to treat irrigated and non-irrigated areas differently by using the CRNP rainfed probe in the regression for non-irrigated gridcells and the average of the two irrigated CRNP probes for the irrigated gridcells. This results in a gridded soil moisture product that retains the spatiotemporal differences of the rainfed and irrigated areas. Irrigated and non-irrigated gridcells are defined by an estimated irrigation mask created using the landcover map of Franz et al. 2015 from ground observations. A comparison of the original and new regression products at an irrigation and non-irrigated point is given in the Supplement.

### **3.32 Irrigation scheme**

The preferred method of irrigation in Nebraska is the center pivot sprinkler system (NASS, 2014), and as such, we evaluate the sprinkler irrigation algorithm in LIS. The sprinkler scheme is described in Ozdogan et al. (2010) and was preliminarily tested and compared against two other irrigation schemes (drip and flood) available in LIS in Lawston et al. (2015). Sprinkler applies irrigation as precipitation when the root zone moisture availability falls below a user-defined threshold. In this study, we use a threshold of 50% of the field capacity, after Ozdogan et al. (2010).

In an effort to reproduce appropriate timing and placement of irrigation, a series of model checkpoints must be passed to allow for irrigation triggering. These checkpoints essentially boil down to four main questions:

- 1) Is the land cover irrigable?
- 2) Is there at least some irrigated land?
- 3) Is it the growing season?
- 4) Is the soil in the root zone dry enough to require irrigation?

The first two questions invoke direct tests against the static datasets (land cover and irrigation intensity, respectively), while the remaining two questions require additional calculations involving one or more time-varying datasets. The growing season, addressed in question three, is a function of the gridcell GVF (i.e., > 40% annual range in climatological GVF;

[Ozdogan et al., 2010](#) as described in ~~Ozdogan et al. (2010)~~ and results in a season that spans roughly June through September in the study area. The last question, the determination of irrigation requirement, is dependent on two main features – the soil moisture and the definition of the root zone. Soil moisture is influenced by the meteorological forcing (e.g., how much rain falls and where) and soil texture (e.g., how long the moisture sticks around), while the root zone is the product of the maximum root depth (as defined by crop type) scaled by the GVF to mimic a seasonal cycle of root growth. Taken together, this means that the irrigation scheme is primarily controlled by six datasets: landcover, irrigation intensity, soil texture, crop type, meteorological forcing, and GVF.

For this limited study area, the land cover, crop type, and soil texture are homogenous throughout the domain as given by the input datasets (croplands, maize, and silt loam, respectively), meaning any heterogeneity in irrigation amounts and impacts can be attributed to only the meteorological forcing, GVF, and irrigation intensity. As the meteorological forcing is the same for all simulations, the experimental design leverages the unique characteristics of the controlled domain to assess the sensitivity of the irrigation algorithm specifically to changes in irrigation intensity and GVF; two important and common datasets in irrigation modeling. The irrigation algorithm is assessed first in the context of its physical response to forcing at the interannual, seasonal, and daily scales, and secondly, the results are evaluated against available observations in the growing season of 2014 (i.e., model performance).

## 4. Results

### 4.1 Model sensitivity at the interannual scale

Figure 3 shows the domain and monthly averaged irrigation amount applied for each of the three irrigation runs over the full six-year period. Interannual variability in the background precipitation (i.e., summer drought or pluvial periods) is reflected in the irrigation requirement, with dry seasons, such as 2012, exhibiting large irrigation demand, while wet seasons like 2011 and 2014 result in markedly less water applied. The average irrigation amount varies little between the experiments at this scale, around  $1 \text{ mm day}^{-1}$ , but a few features of the dataset differences are apparent. The irrigation algorithm scales the amount of water applied by multiplying with the irrigation fraction value. The GRIPC irrigation dataset has greater irrigation intensity values everywhere in the domain, and as a result, the Standard run always applies more water than Tuned. The

SPoRT run is less consistent in relation to the other methods; at times applying more water than both methods (e.g., July 2012), at others applying less (e.g., Sep 2012). This behavior is determined by the relative magnitude of the SPoRT GVF as compared to climatological GVF (Figure 2), as the GVF scales the root zone such that more water is applied by the irrigation scheme to more mature crops.

5 Figure 4 shows the percent change from control in soil moisture for each of the irrigation runs and each model soil layer. Irrigation increases soil moisture in all soil layers and all simulations. Increases in the third soil layer, which includes the root zone, are quite consistent annually with a near doubling of the soil moisture when irrigation is turned on. The top and second layer fluctuations resemble the irrigation amount time series, indicating that the top two layers are more sensitive to the amount of irrigation water applied. These layers respond more quickly to irrigation, while percolation, and therefore  
10 time, is needed to impact the deeper soil layers. Differences between the irrigation runs are virtually undetectable in the top and second layers, but the cumulative impact of the differences in irrigation amounts and timing are reflected in differences in the third soil layer. The third and fourth layers are deeper and thicker (0.6 m and 1.0 m thickness, respectively) and as such are able to hold more water than the top and second layers (0.1 and 0.3 m thickness).

#### 4.2 Model sensitivity at the seasonal scale

15 Figure 5 shows the average daily change from control in latent ( $Q_l$ ) and sensible ( $Q_h$ ) heat fluxes (left axis) as well as the daily precipitation amount from the NLDAS-2 meteorological forcing data (right axis) for May-October 2012 and 2014. Limited rainfall throughout the 2012 season resulted in the triggering of irrigation frequently throughout the growing season, including a stretch through July and August where irrigation was triggered somewhere in the domain every day (not shown). The 2014 growing season featured much more frequent precipitation, limiting consistent irrigation to late July and early  
20 August. The flux impacts follow the timing of irrigation triggering, steadily growing throughout the summer in 2012, up to  $200 \text{ W m}^{-2}$ , and emerging during dry down periods in 2014. Sharp decreases in flux impacts in the time series are the result of individual precipitation events, as the soil is not dry enough to trigger irrigation during and immediately following heavy rainfall events. In 2012, the SPoRT GVF is greater than ~~climatology~~ climatological GVF in June, resulting in more water applied and greater flux impacts in SPoRT than Tuned or Standard early in the season. However, in September, the SPoRT  
25 GVF detects the vegetation stress caused by a July flash drought, resulting in reduced GVF, irrigation amounts, and flux

~~impacts the (negative) vegetation response to the July drought and irrigation amount and flux impacts are reduced.~~ These seasonal scale impacts illustrate that the NLDAS-2 forcing (i.e., precipitation) data, via changes to soil moisture, ~~drives~~ constrains the irrigation timing during the growing season, and that the soil moisture threshold is sufficient in triggering irrigation during rain-free periods. ~~and that the behavior of the irrigation scheme is consistent with expectations of human triggering of irrigation during dry and wet periods.~~

#### 4.3 Model sensitivity at the diurnal scale

At the interannual and seasonal scale, irrigation amounts and impacts are driven primarily by background rainfall regime, given by the forcing precipitation, with only small changes evident between the methods. At the diurnal scale, however, the choice of greenness and irrigation intensity datasets becomes more influential to irrigation impacts. Figure 6 shows the change from control in domain average latent heat flux for each of the irrigation runs for three diurnal cycles in July 2012 and the differences from control in latent heat flux at noon, spatially. All irrigation runs result in large increases to the latent heat flux, but while Tuned and Standard are relatively close in magnitude, latent heat flux in the SPoRT run is more than 100 the SPoRT run increases latent heat flux by more than 100 W m<sup>-2</sup> more than Standard greater than Standard during peak heating. Spatially, the SPoRT simulation has a larger change from control everywhere in the domain as compared to Standard and Tuned, which exhibit similar magnitude of differences and spatial heterogeneity. The impacts on surface fluxes indicate that the choice of dataset, especially GVF, will likely impact coupled simulations, such as those with LIS-WRF.

In summary, the landcover, GVF, soil texture, meteorological forcing, irrigation fraction, and crop type all influence irrigation amounts in ways that are physically consistent with expectations for crop water use. For example, it is expected that the irrigation requirement is greatest for densely irrigated areas of mature crops with dry soil; the model reproduces this scenario by applying the greatest amount of water to gridcells that have high GVF (i.e., more mature crops and deeper roots), low soil moisture (from lack of precipitation), and high irrigation intensity.

## 4.4 Model performance

### 4.4.1 Evaluation of irrigation amounts and CRNP soil moisture evaluation

The simulation of irrigation amounts and timing as well as impacts on soil moisture are evaluated for the growing season of 2014 using field observations near Waco, Nebraska, as described in Sect. 3.2. Figure 7 shows daily irrigation and rainfall amounts (right axis), as well as the volumetric soil water content (left axis) from the in-situ CRNP (solid black line) and all model simulations (green lines) at the rainfed and irrigated maize sites. The [York AWDN](#) precipitation data confirm that 2014 was a relatively wet growing season, as was originally noted in the examination of Fig. 5b. The soil at the rainfed site gradually dries out between July 15 and August 5, the only consistent rain-free period of the summer (Fig. 7a). The dry down timing is simulated well in the Control and Tuned simulations, as irrigation is not included in Control and is prohibited at the rainfed site in Tuned, as defined by the edited irrigation intensity map (i.e., 0% for this gridcell). In contrast, the Standard and SPoRT simulations consider the rainfed gridcell to be 100% irrigated, as given by the GRIPC dataset, and as a result, both runs incorrectly trigger irrigation at this site, increasing SM during the dry down period.

At the irrigated maize site, irrigation is applied during the rain-free period in mid- July and early August and during a second, shorter stint late in August (red bars, Fig. 7b). The model simulations generally overestimate the amount of irrigation water at the irrigated site, applying an average of 8-15 mm day<sup>-1</sup> (not shown), while the observations show that the irrigated field generally received 5 mm day<sup>-1</sup>. In contrast to the rainfed site, the CRNP observations show SM increases or remains steady in mid-July through early August due to irrigation by the farmer at the maize site.

The triggering of irrigation during the dry down period is simulated well by the model as evidenced by the soil moisture differences between the Control and irrigated runs at the irrigated maize site (i.e., dry down versus steady SM levels, respectively). The SM given by the irrigated simulations matches the CRNP observations more closely than Control during the dry down period. This indicates that the combination of NLDAS-2 forcing and the triggering thresholds are sufficient to activate irrigation during rain-free periods, even in a wet year. Each irrigated LIS simulation applies enough irrigation water to maintain the SM levels, with small but inconsequential variations in the day to day to variability.

The soil water content observations are consistently greater than that of the model at both the rainfed and irrigated sites. However, it is common for soil moisture probes, other observations (e.g., satellite), and land surface models to exhibit

different soil moisture climatologies that are largely a function of different representative depths of the soil (e.g., in model vs. CRNP). The spikes in soil moisture shown in the probe observations are represented well by the model, once again indicating the accuracy of the NLDAS-2 meteorological forcing data, even at this local scale. Overall, these results show that the irrigation scheme simulates well the irrigated versus rainfed soil moisture differences when the irrigation location is specified properly by the irrigation intensity dataset (in this case, the Tuned simulation).

#### 4.4.2 Evaluation with CRNP gridded product

In order to assess whether soil moisture heterogeneity due to irrigation across the domain is captured accurately, simulations are evaluated against the CRNP gridded soil moisture product. The gridded product from Franz et al. (2015) uses the spatiotemporal statistics of the observed soil moisture fields, as obtained via the CRNP rover, and a spatial regression technique to create a 1 km, 8 hour gridded soil moisture product for the growing season (May—Sept, 388 values). In this study, we modify the spatial regression technique to treat irrigated and non-irrigated areas differently by using the CRNP (irrigated) rainfed data in the regression for (irrigated) non-irrigated gridecells. This results in a gridded soil moisture product that retains the spatiotemporal differences of the rainfed and irrigated areas.

The LIS-simulated soil moisture variability in time and space is evaluated ~~in time and space~~ against the CRNP gridded soil moisture product, described in Sect. 3.2. The spatial variability is assessed first with a histogram ~~using a comparison of the cumulative distribution functions (CDFs) generated~~ generated from using all gridcell soil moisture values from the LIS simulations and the modified COSMOS-CRNP product aggregated at 4, 12, and 20 UTC on 25 July 2014 (Fig. 8). ~~shown in Figures 8-9.~~ Analyzed first is the CDF of all soil moisture values in the domain for two separate days, July 25 and July 30, during which irrigation was applied at the irrigated maize site (Fig. 8). As this CDF provides information about the variability of soil moisture spatially in the study area at one particular time, it is hereafter referred to as a ‘spatial CDF’ (Fig. 8). ~~Next, the temporal variability is assessed using a CDF~~ Also examined is a CDF of the domain-averaged soil moisture values from May 5 to Sept 22 at 8-hour intervals ~~intervals (the same as the COSMOS product; 388 values Fig. 9).~~ hereafter referred to as the ‘temporal CDF’ (Fig. 9).

Figure 8 shows that the Control simulation does not match the observations in magnitude or variability, instead showing uniformly dry soil across the domain (e.g., range of 0.01 versus more than 0.1 observations). The spatial variability is

increased in the irrigated simulations, but these runs exhibit jumps between clusters of values as a result of irrigation triggering and dry down across the domain. The different levels of clustering shown by the irrigated simulations are a result of the input parameter datasets, as triggering and timing are dependent on these datasets. Although the Control simulation is too dry, the irrigation overcompensates and increases the soil moisture to levels beyond that shown in the gridded observations. These results suggest The spatial CDFs (Figs 8a-b) show uniformly dry soil in the control simulation while the irrigated runs exhibit a step-like behavior as a result of irrigation triggering and dry down timing across the domain. The different levels of steps within the irrigated simulations are a result of the input parameter datasets, as triggering and timing are dependent on these datasets. The model distributions do not match the CRNP CDF, which instead shows a majority of soil moisture values that are wetter than the control simulation but drier than the irrigated simulations and exhibit a smoother distribution. These CDFs suggest that the model, even with the irrigation algorithm turned on, is not able to accurately simulate the small-scale (i.e., field scale) heterogeneity in soil moisture that is present in the CRNP data. The heterogeneity at this time and space scale results from the fact that center pivot irrigation systems typically take about three days to complete one rotation, so that the most recently treated slice of the field is always wetter than the rest. Further, individual decisions made by farmers on and immediately preceding this date (USDA-NASS, 2014) are not captured by the strict soil moisture deficit-based rules imposed by the irrigation algorithm, nor by the uniform land cover and soil texture, soil type, and slowly varying GVF datasets at 1km resolution.

In contrast, the bulk temporal variability in soil moisture in both irrigated and non-irrigated areas during the growing season is simulated well by the model (Fig. 9). The temporal-CDF shows that the model matches the CRNP distribution more closely when the irrigation algorithm is turned on (Fig. 9a). Furthermore, when irrigated and non-irrigated areas are averaged separately, the irrigated and Control (Control) simulations match well the distribution of irrigated and non-irrigated (non-irrigated) areas, respectively well (Fig. 9b). These results suggest that if this domain were one gridcell in a larger, coarser-resolution domain (e.g., 15 km spatial resolution), the variation in the gridcell soil moisture (given here by the domain average) over the growing season would be representative of observations. That is, the heterogeneity and smaller scale processes resolved in the high-resolution domain, though unable to reproduce specific field-scale behavior, appropriately scale up to coarser resolution. At coarser time and space resolutions, the decisions made by individual farmers become less

important, in favor of the larger scale features (e.g., timing of precipitation during the growing season), that influence and drive the collective behavior of human practices in this region.

## 5. Discussion

Although the responses of the modeled states and fluxes to simulated irrigation will vary depending on the LSM and irrigation scheme used, the results of this study are broadly relevant to irrigation modeling development as a whole. In particular, this study demonstrates the importance of supplying a land surface model with high-quality input datasets. Of primary importance are the datasets that control irrigation triggering (e.g., landcover, meteorological forcing, irrigated area), as the details of irrigation application are relevant only after irrigation is triggered at the proper locations and at the correct times during the season. Once reasonable timing and placement have been established, the datasets that regulate the amount of water applied (e.g., irrigation intensity, root depth, GVF) become important. These datasets may require a certain degree of customization, depending on the available information about irrigation practices, water district regulations, and land use in the study area, to ensure an appropriate amount of water is applied.

For this small domain, the NLDAS2 precipitation proved to be sufficiently accurate, matching well that given by the nearby York, Nebraska AWDN. However, for other regions, reliable meteorological forcing may not be available. To further explore the impact of the forcing precipitation on the irrigation triggering, an additional simulation was completed that is equivalent to the Standard irrigation run in all aspects (e.g., GRIPC irrigation intensity, climatological GVF) except that the Global Data Assimilation System (GDAS) meteorological forcing is used rather than NLDAS2. In contrast to NLDAS2, GDAS is coarser resolution (1/4 degree) and does not include rain-gauge corrections. Results show that GDAS supplied a greater amount of total of precipitation in May through July 2014, creating a wetter soil column and prohibiting irrigation triggering in mid-to-late July, in contrast to observations and the other irrigation simulations. As a result, the soil moisture dynamics of the GDAS simulation at the maize site differ substantially from the CRNP observations and the NLDAS2-forced simulations. These results underscore the need for highest quality datasets available for the area of interest, which for this region and time frame was NLDAS2.

The root systems of crops generally mirror the vegetative state above ground (i.e., GVF), and as such, the model represents root growth by scaling the maximum root depth by the GVF (Ozdogan et al., 2010) and applying a proportional amount of irrigation water. Although the crop type is uniform maize for the limited domain, as given by the UMD crop dataset, Franz et al. (2015) shows a mix of maize and soybeans in the study area. An additional run was completed in which a tuned crop type map was supplied to the model to distinguish between maize and soybean gridcells based on the land use map of Franz et al. (2015) and the maximum root depth was altered to be 1.2 m for maize and 1 meters for soybean. The results of this analysis showed ~~very little differences~~ between this simulation and the others, indicating that the model is ~~quite~~ insensitive to ~~small changes (up to 20%) in the maximum root depth change and that the scaling by GVF tends to be more important than small changes (up to 20% in this case) in maximum root depth.~~ However, land surface models that ~~have contain~~ a more complex treatment of crops, study areas with greater heterogeneity of crop types, or experiments that replace a particular crop with one that has a vastly deeper root system, are examples beyond the scope of this study that could potentially ~~may have result in~~ a greater ~~dependency sensitivity of the model results to~~ crop root depth.

The method for determining the start and end of the growing season, based on the 40% annual range in climatological GVF, proved to be reliable for this study area and climate. However, in arid or semi-arid regions, the 40% threshold applied to a small annual range in GVF can result in a year round irrigation season that may not be representative of regional irrigation practices. Thus, where the annual range in GVF is small (e.g., southern California), more tailoring may be needed to ensure that irrigation occurs only during the local irrigation season.

Recent work by Decker et al., (2017) shows that atmospheric feedbacks can reduce the irrigation demand simulated by a land surface model. That is, a coupled model configuration allows the atmosphere to respond to the irrigation application, moistening the near surface, and reducing the need for additional irrigation as compared to the same model run uncoupled. A limitation of the work presented here is therefore the lack of the atmospheric feedback in the uncoupled configuration. However, the Decker et al., (2017) results indicate that a coupled configuration would likely reduce irrigation amounts simulated by the model. As the irrigation demand was greater in the model than in the human-practice observations, the coupled atmosphere has the potential to reduce irrigation amounts to be more in line with those observed.

This study shows model sensitivity to the irrigation intensity dataset, in terms of where and how much irrigation water is applied. Historically, the Global Map of Irrigated Areas (GMIA; Döll and Siebert, 1999) has been the most widely used irrigation dataset in irrigation modeling studies (Bonfils and Lobell, 2007; Boucher et al., 2004; Guimberteau et al., 2012; among many others) as it was the first reliable global irrigation map, making use of cartographic and FAO statistics.

5 However, progress in satellite remote sensing and ease of access to required datasets will likely result in a growing number of options for irrigation intensity datasets in the coming years (e.g., Siebert et al., 2015).- As such, the results of this study, detailing the potential effects of choice of irrigation intensity dataset on irrigation amounts will likely become more relevant with the expansion in choices of irrigation-related datasets.

## 6. Conclusions

10 This study provided an assessment of the sprinkler irrigation physics and model sensitivity to irrigation intensity and GVF datasets in a LSM framework, and evaluated the results with novel point and gridded soil moisture observations. As expected, model results show that irrigation increases soil moisture and latent heat flux, and decreases sensible heat flux. Differences between experiments with different GVF and irrigation intensity parameters are small at large and interannual scales, but become more substantial at small and subseasonal scales. The irrigation scheme uses GVF as a proxy for plant maturity and scales the amount of water applied accordingly to represent differences in irrigation scheduling based on growth stage. This behavior and the impacts of irrigation on soil moisture and fluxes are physically consistent with expectations of irrigation effects on the land surface.

The evaluation with CRNP observations revealed both limitations and strengths of the irrigation algorithm. Field-scale heterogeneity resulting from the slow rotation rates of center pivot irrigation systems and the individual actions of farmers are not captured by the model. Also, the amount of irrigation applied by the model exceeds that applied at the two irrigated fields. However, the timing of irrigation during the growing season (i.e., late July to early August), which coincided with a stretch of limited rainfall, is simulated well by the scheme. Additionally, the fine scale processes resolved in the small domain appropriately scale up in time and space, indicating the scheme could be used reliably at coarser resolution (e.g., 15 km) in this region. The model skill is due in large part to the accuracy of NLDAS-2 meteorological forcing, land cover, and

irrigation intensity datasets, which are all critical to reproducing the seasonal timing and location of irrigation triggering. Overall, these results underscore the importance of supplying a LSM with high-quality input datasets.

This study has also shown that CRNP distributed soil moisture data can be valuable in LSM and irrigation parameterization evaluation. The CRNP observations provide information about the impact of irrigation on the spatial and temporal variability

5 of soil moisture, and could possibly be used to help identify where and when irrigation occurs. Irrigation timing information is particularly valuable at the scales of this study and larger, where accurate reporting data are not always available. The USDA [C](#)ensus of [A](#)griculture contains some of the most detailed information on the state of agriculture in the U.S., including estimates of irrigated acreage, irrigation method, and crop cultivated. However, the census occurs only once every five years and lacks irrigation timing information. CRNP soil moisture could potentially be used to fill those data gaps. It is

10 logical that satellite-based soil moisture and evapotranspiration would also help in that respect, although a recent study cast doubt on the utility of the former (Kumar et al., 2015).

The flexibility of the LIS framework, and in particular the ability for the user to choose the irrigation scheme, parameters, and model of choice, makes LIS a premiere framework for irrigation studies. However, the general conclusions of this study, as they pertain to irrigation scheme impacts and sensitivity to dataset changes, are applicable to irrigation modeling more

15 broadly. The continued evaluation and improvement of irrigation parameterizations, as discussed here, is an important step towards better understanding human influences on the water cycle and the impacts of such activities in a changing climate.

## 7. Data Availability

Fixed and mobile cosmic-ray neutron probe data is available in Franz et al. (2015) or by request from Trenton Franz.

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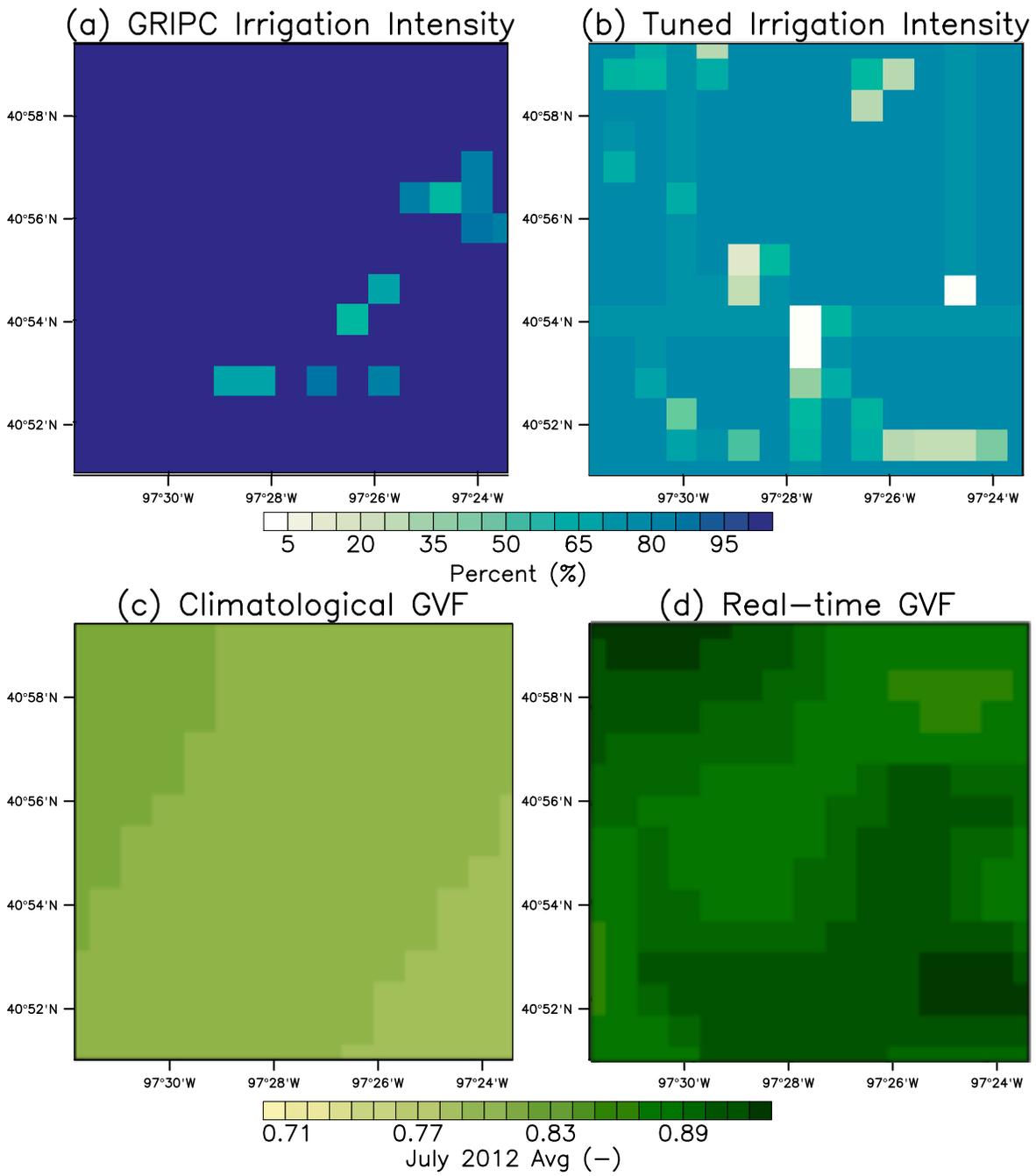
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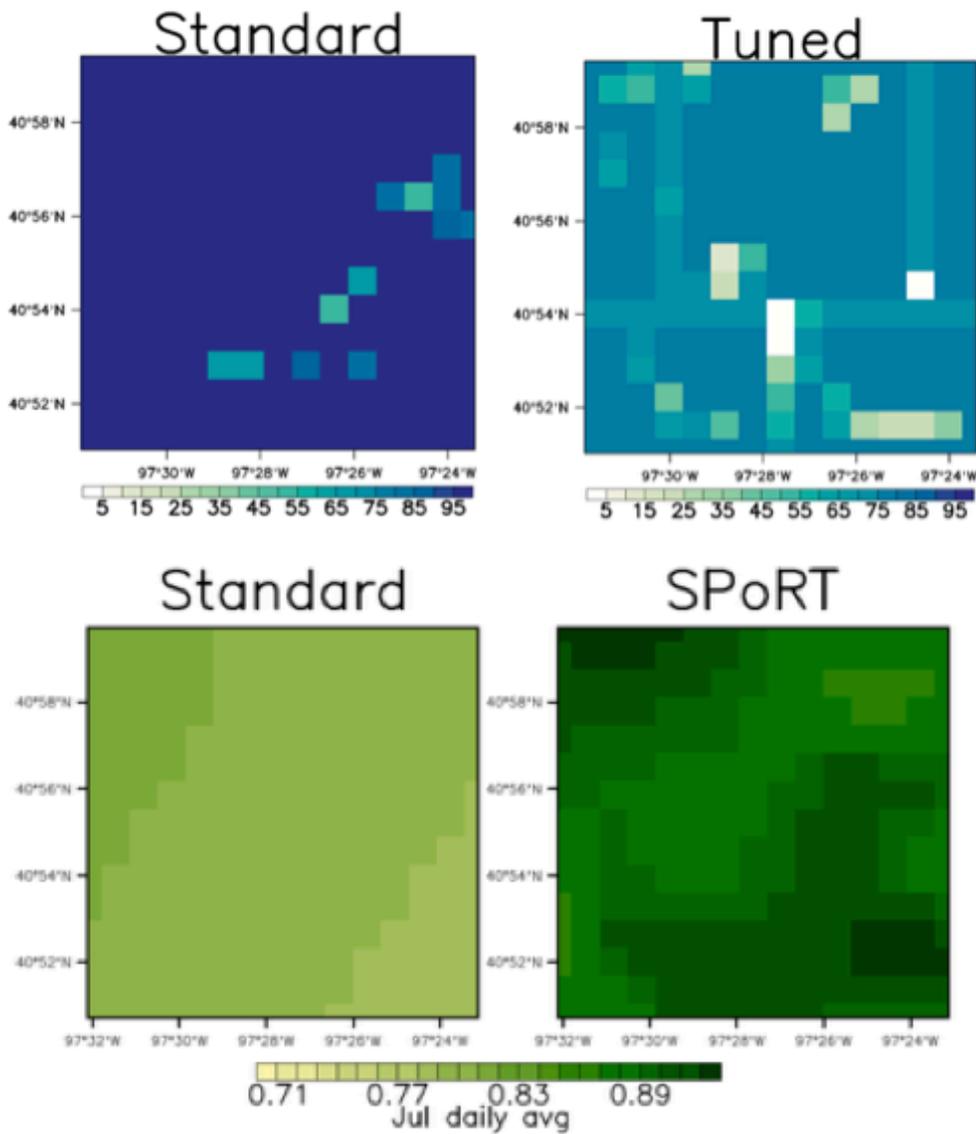


Figure 1: (a) GRIPC irrigation intensity (percent) given by Salmon et al. (2015) used in the Standard and SPoRT simulations and (b) the observationally tuned irrigation intensity used in the Tuned simulation. The spotty nature of Tuned indicates where irrigation intensity has been reduce due to the presence of roads, wetlands, rainfed fields, and/or buildings. Also shown is the average greenness vegetation fraction (unitless) in July 2012 given by (c) NCEP climatology used in the Standard and Tuned simulations and (d) SPoRT real-time dataset used in the SPoRT run. Comparison of the GRIPC irrigation intensity given by Salmon et al. (2015, top left) used in the Standard and SPoRT simulations and the observationally tuned irrigation intensity (top right) used in the Tuned simulation. Average July 2012 greenness vegetation fraction given by NCEP climatology (bottom left) used in the Standard and Tuned simulations and SPoRT real-time dataset used in the SPoRT run (bottom right).

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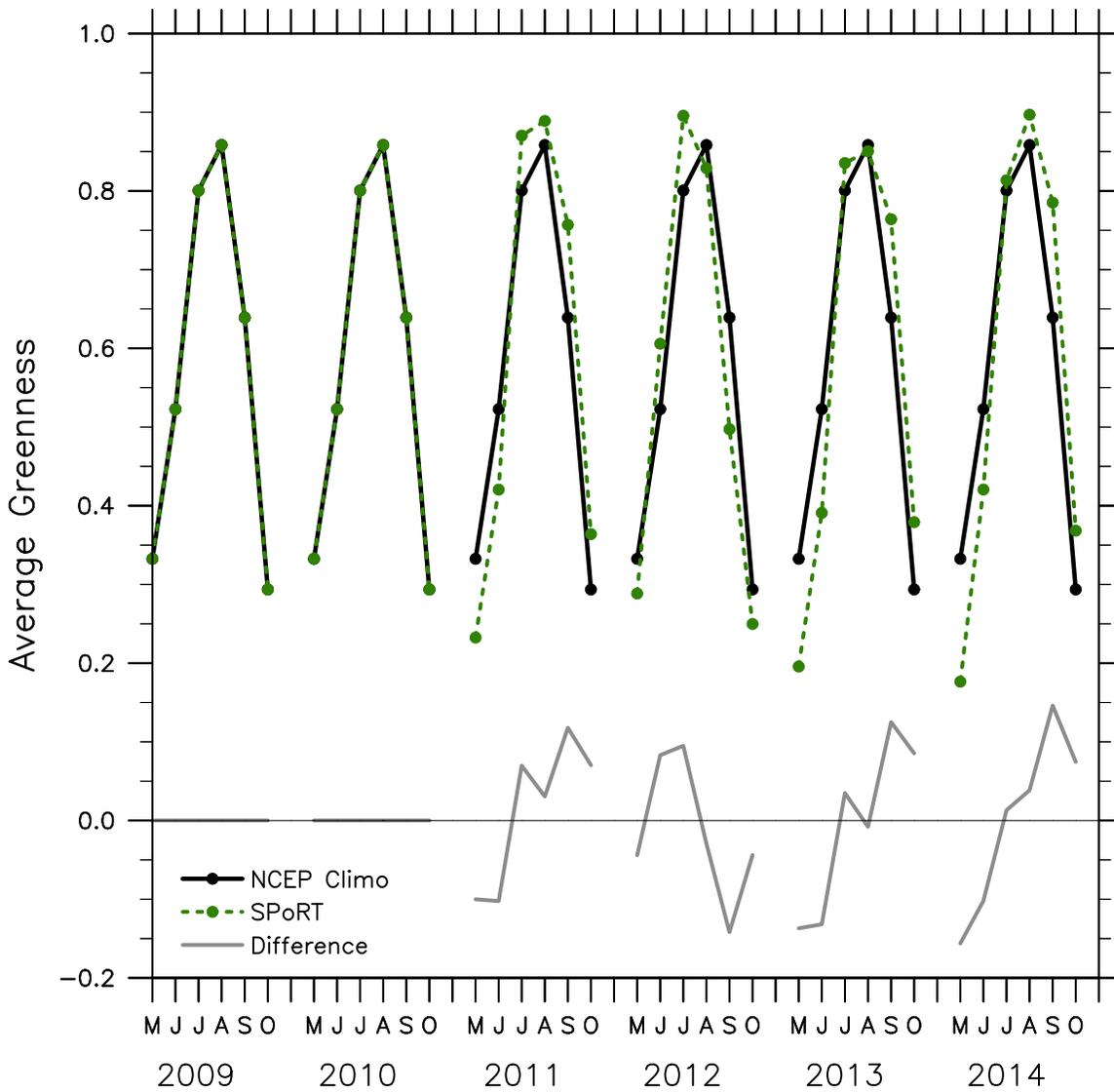


Figure 2. Domain and monthly averaged GVF from the NCEP climatological GVF dataset, used in the Standard run, the SPoRT GVF dataset used in the SPoRT run, and the difference between the two (SPoRT – Climatology). As the SPoRT dataset is not available prior to 2010, the long-term SPoRT simulation uses climatological GVF for 2009-2010, and the SPoRT GVF dataset is incorporated in December 2010 and used throughout the rest of the simulation.

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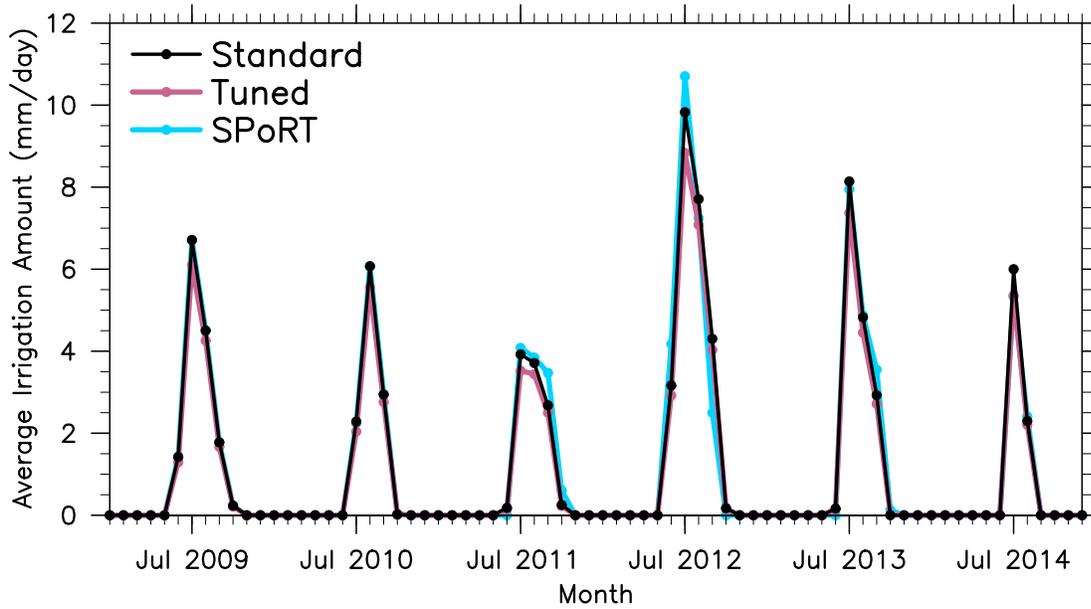


Figure 3. Domain and monthly averaged irrigation amount for each irrigation simulation.

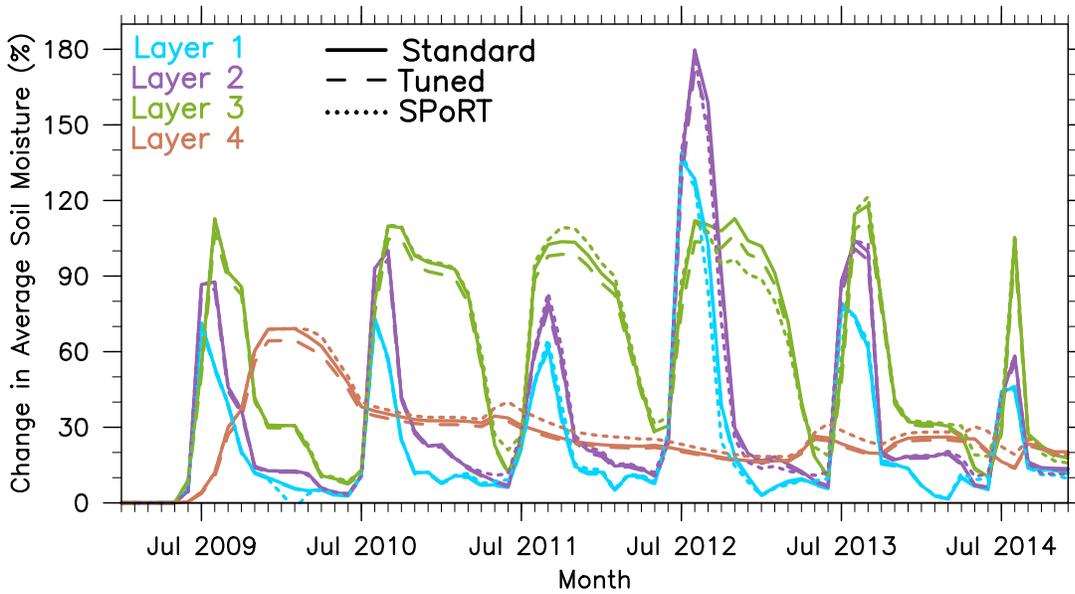
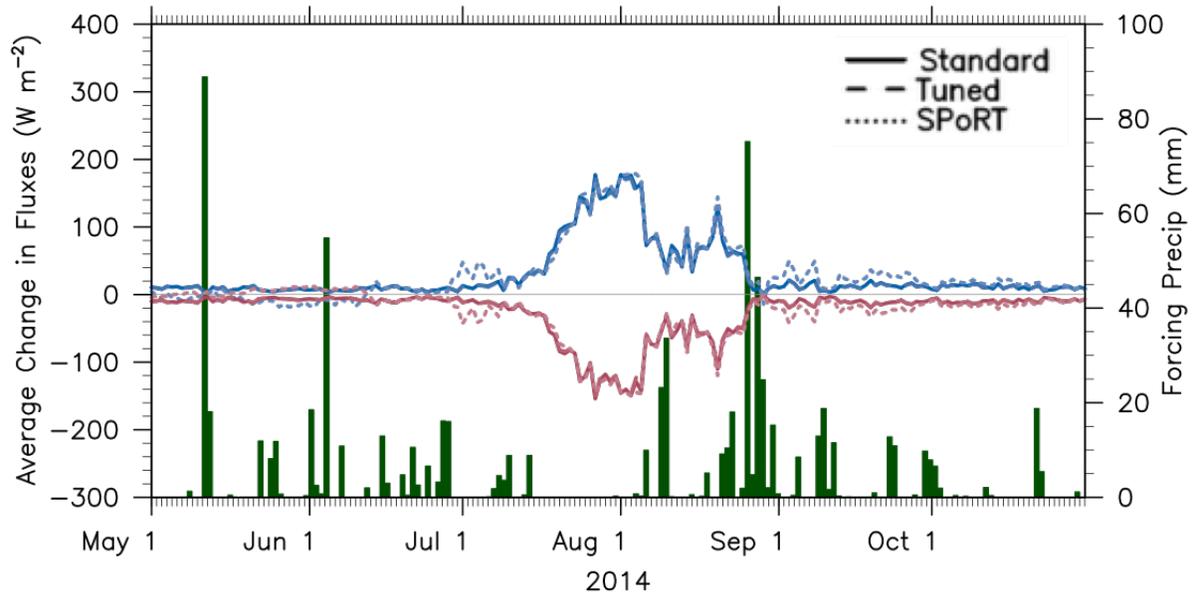
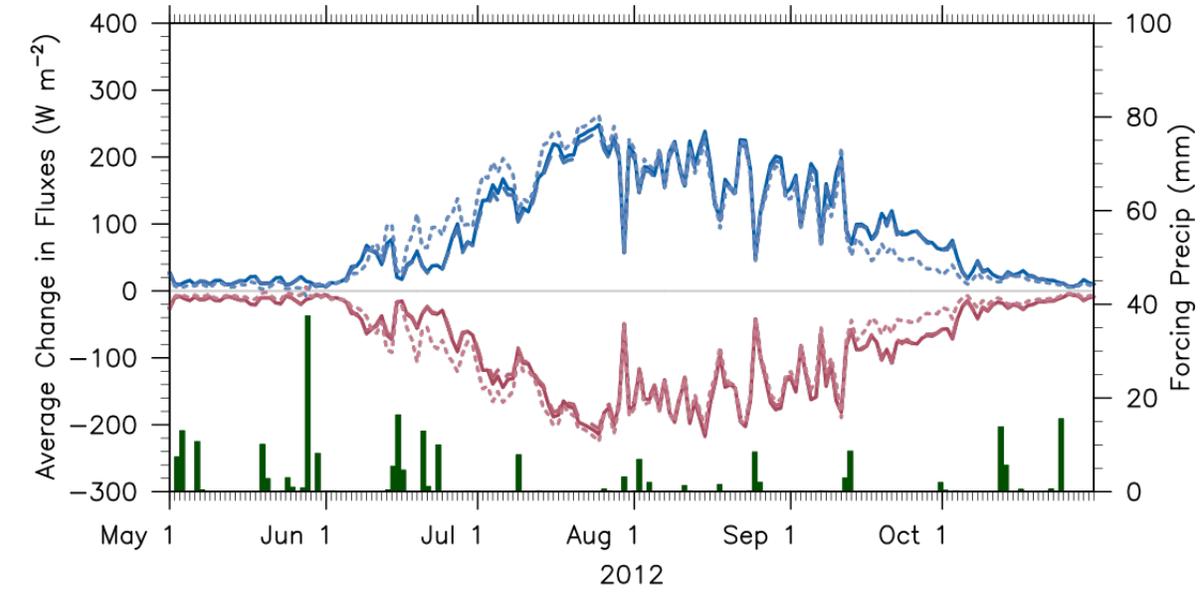
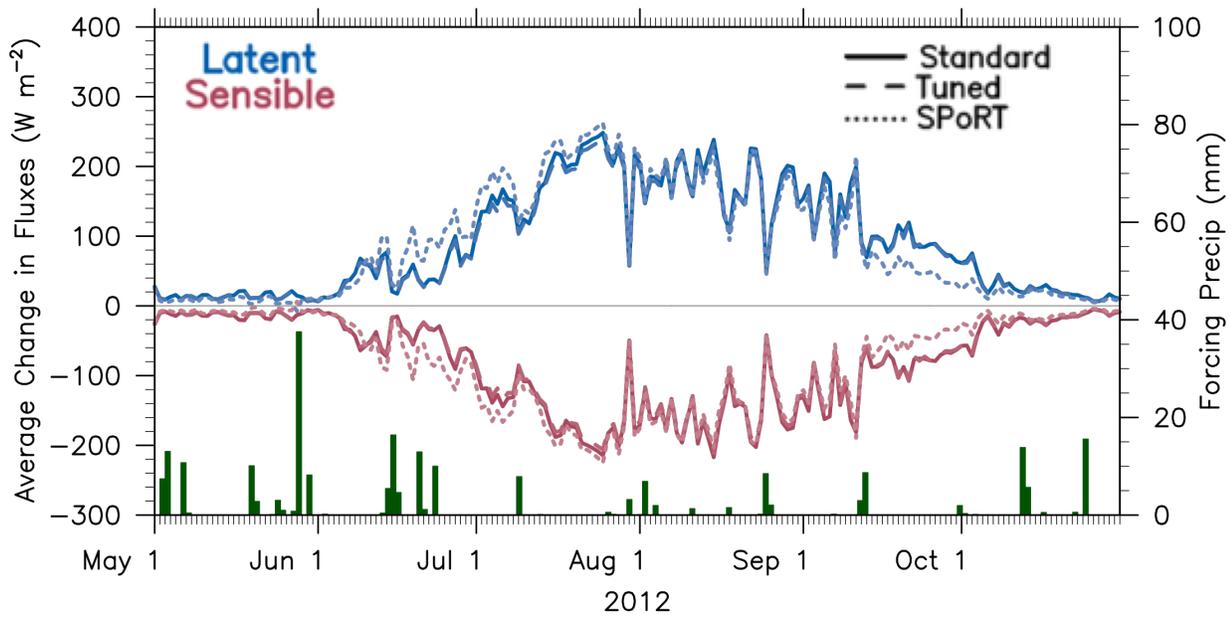


Figure 4. Change from control (IRR - CTRL) in soil moisture for each experiment (line style) and each layer (line color). Layer designations are the Noah LSM default layers: Layer 1 (top layer) is 0 to 10 cm depth ( $\Delta Z = 10$  cm), layer 2 is 10 to 40 cm ( $\Delta Z = 30$  cm), layer 3 is 40 cm to 1 m ( $\Delta Z = 60$  cm) and layer 4 is 1 m to 2 m ( $\Delta Z = 100$  cm).

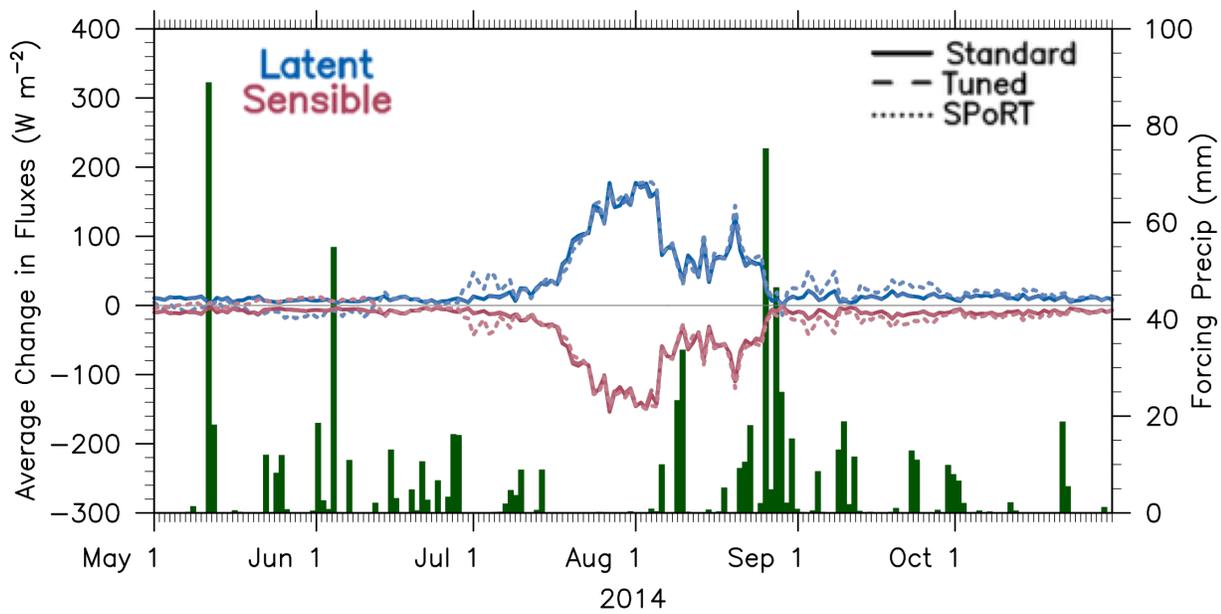
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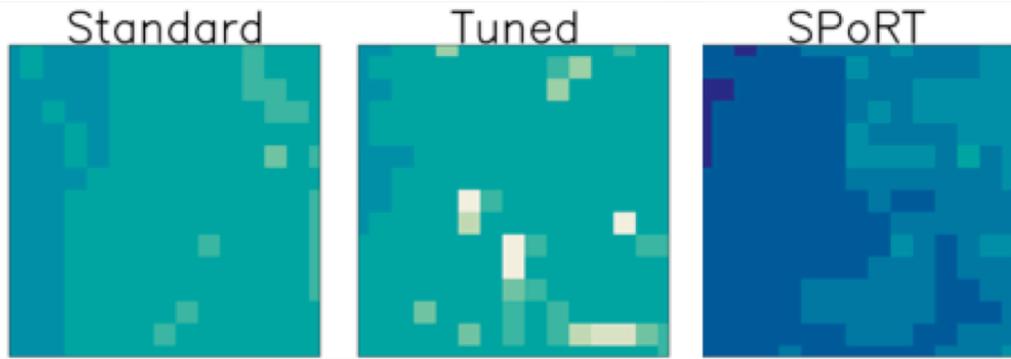
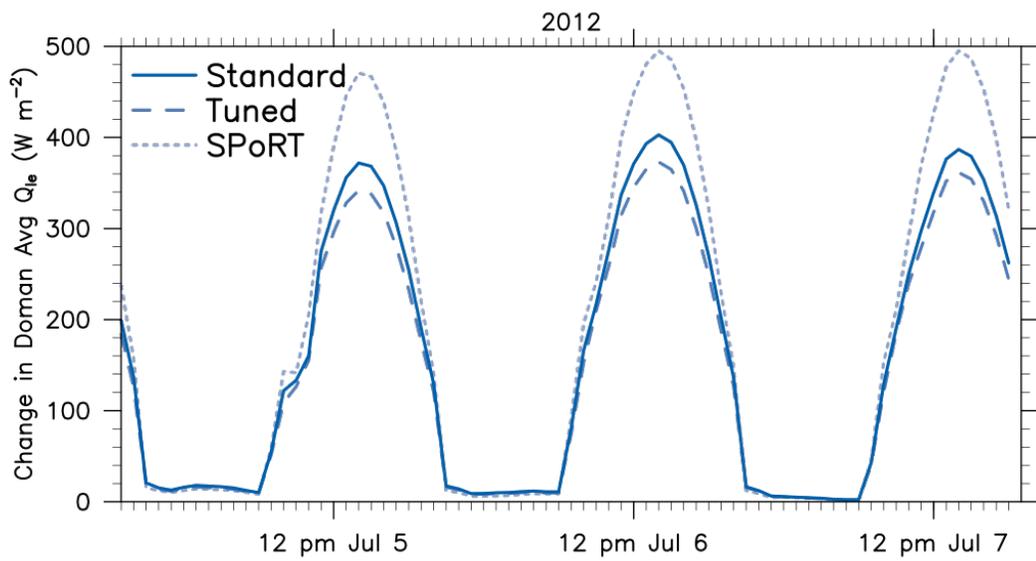
(a)



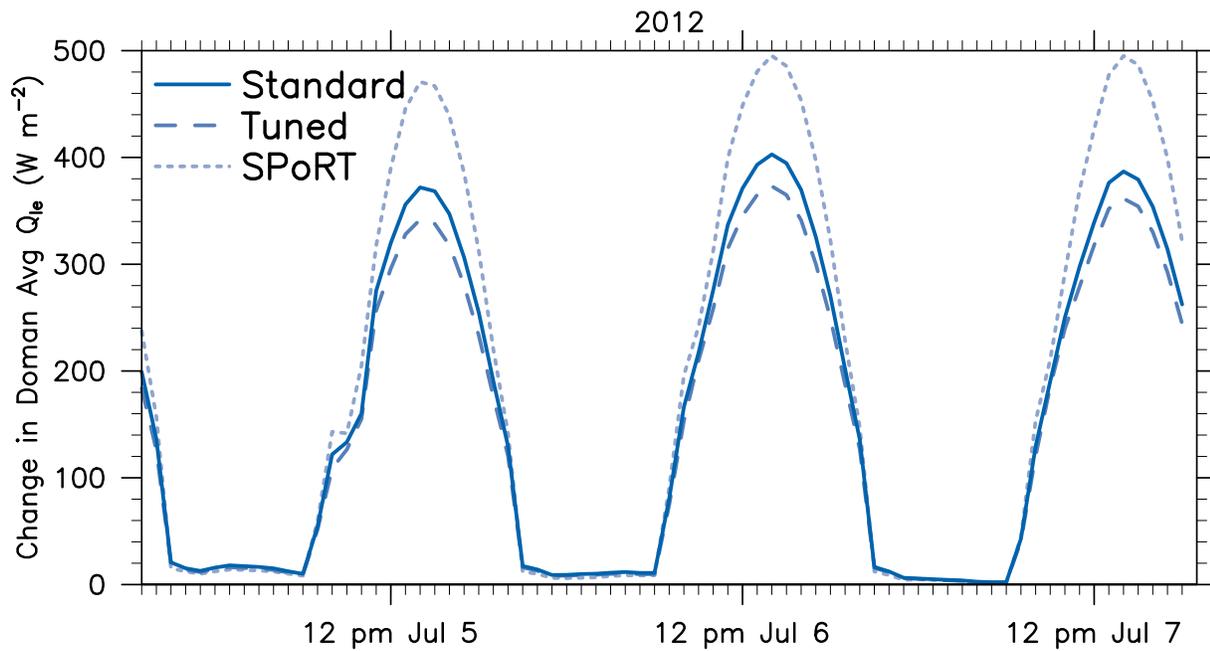
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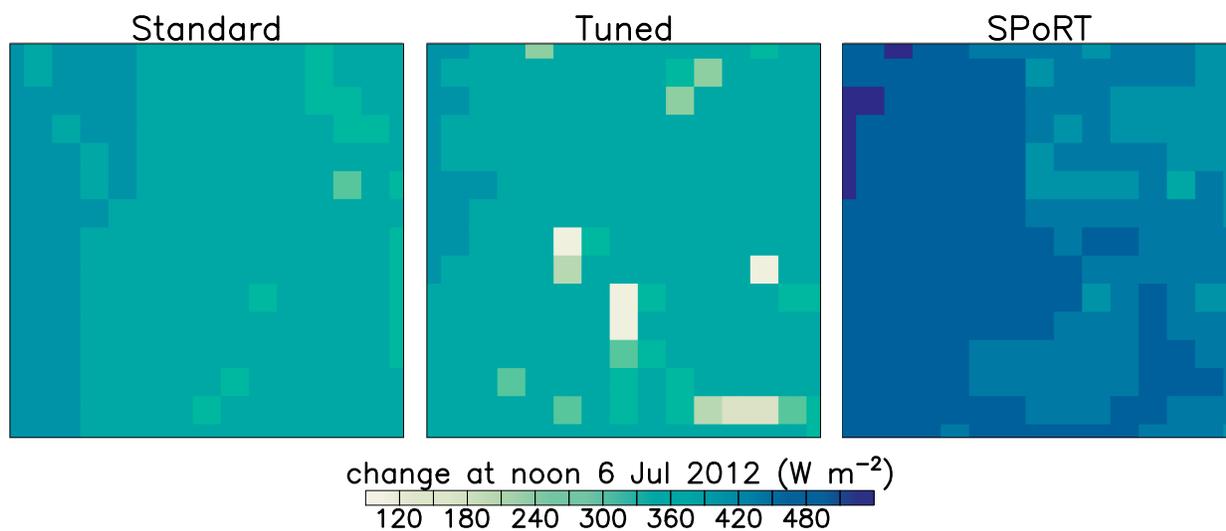
5 **Figure 5. May to September domain average daily change (i.e., irrigation runs - Control) in latent (blue) and sensible (red) heat fluxes (left axis) for (a) 2012 and (b) 2014. Also shown is the domain average daily precipitation from the NLDAS2 forcing data (right axis). May to September 2012 (top) and 2014 (bottom) domain average daily change from control (IRR-CTRL) in latent (blue) and sensible (red) heat fluxes for each irrigation simulation (left axis) and domain average daily accumulated precipitation from the NLDAS2 forcing data (right axis).**



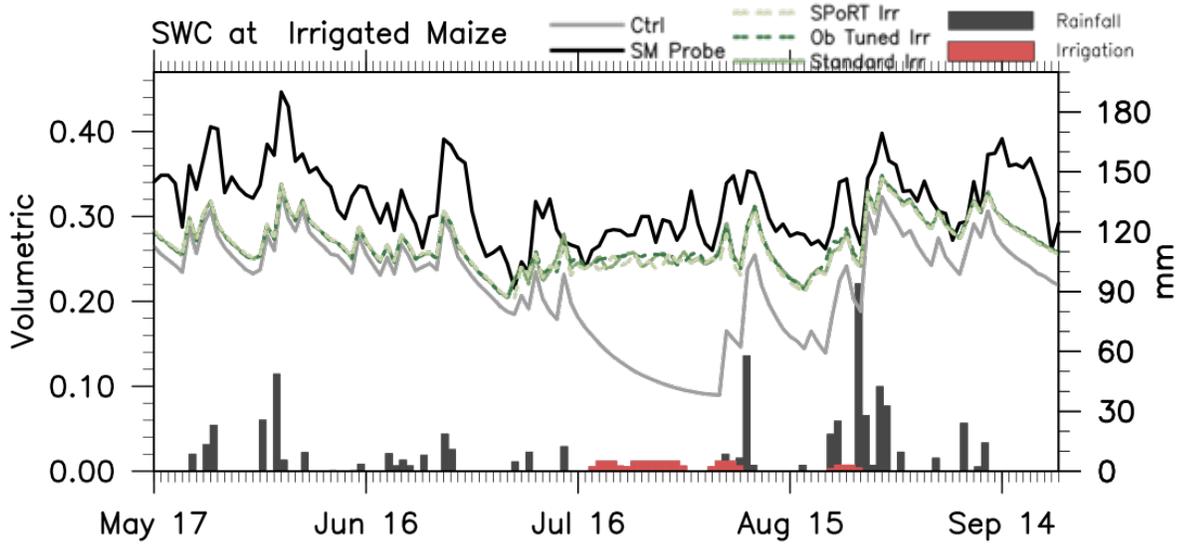
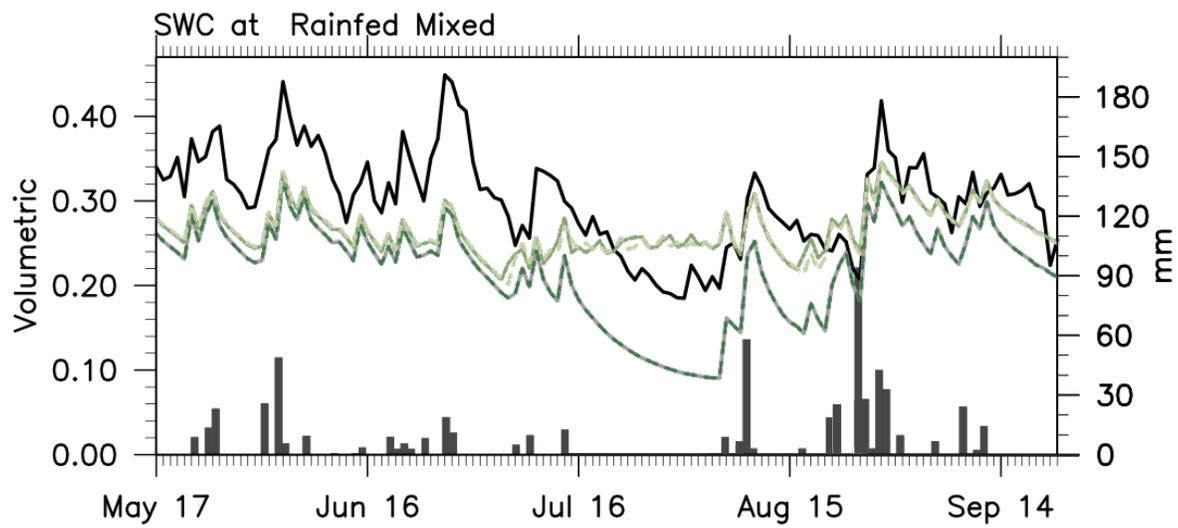
(a)



(b)



5 **Figure 6. (a) Domain average difference (i.e., each irrigation run minus Control) in latent heat flux for three diurnal cycles in July 2012 (b). Difference in latent heat flux at noon on July 6, 2012. Domain average change in latent heat flux for three diurnal cycles in July 2012 (top). Change in latent heat flux (IRR-CTRL) at noon on July 6, 2012 for each irrigation simulation (bottom).**



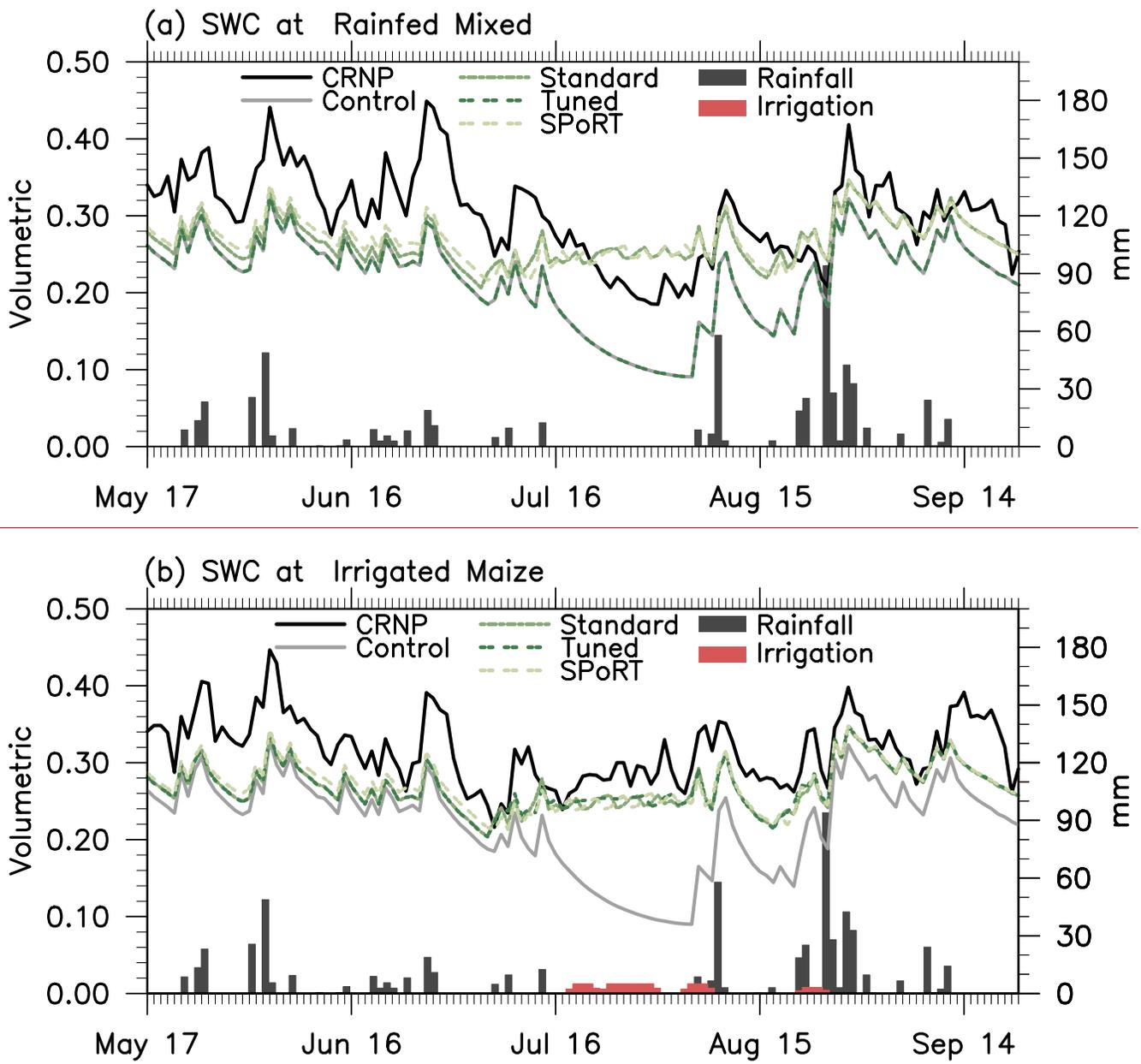
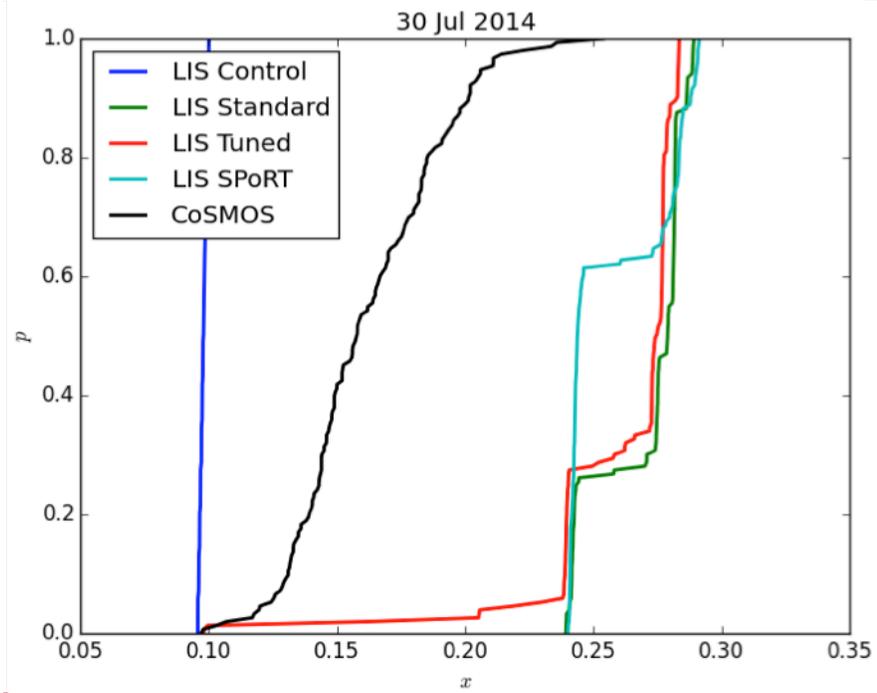
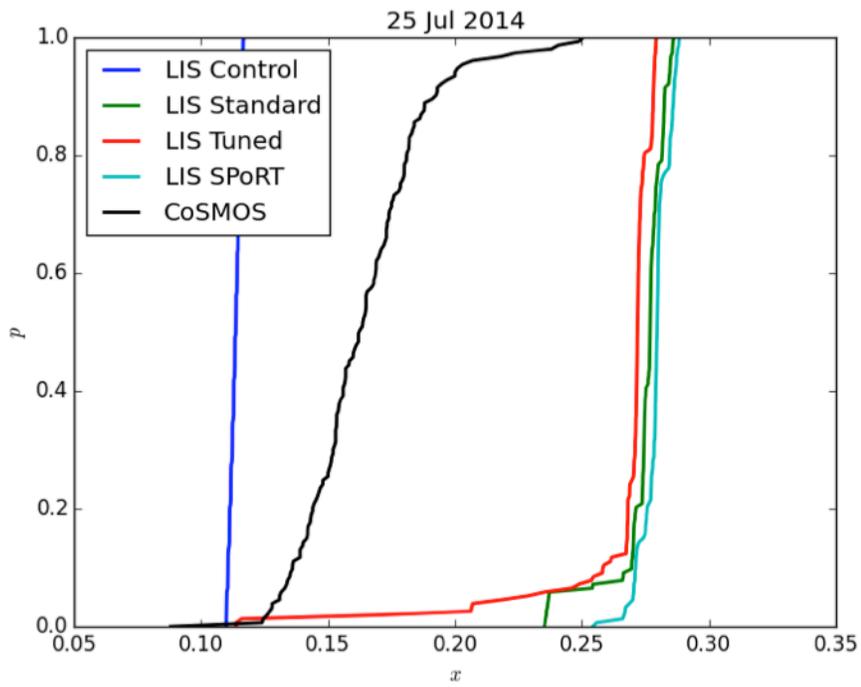


Figure 7. Volumetric soil water content (left axis) at the rainfed (a) and irrigated maize (b) sites. The black solid line shows observations from the CRNP probe, the gray and green lines show the LIS Control and irrigation simulations, respectively. Dark gray bars show accumulated daily precipitation from the Automated Daily Weather Network in York, Nebraska and pink bars show the accumulated irrigation amount at the irrigated maize and soybean sites (right axis). Volumetric soil water content at the rainfed (top) and irrigated maize (bottom) sites (left axis). The black solid line shows observations from the CRNP probe, the gray and green lines show the LIS control and irrigation simulations, respectively. Dark gray bars show accumulated daily precipitation from the Automated Daily Weather Network in York, Nebraska and pink bars show the accumulated irrigation amount at the irrigated maize and soybean sites (right axis).



25 July 2014

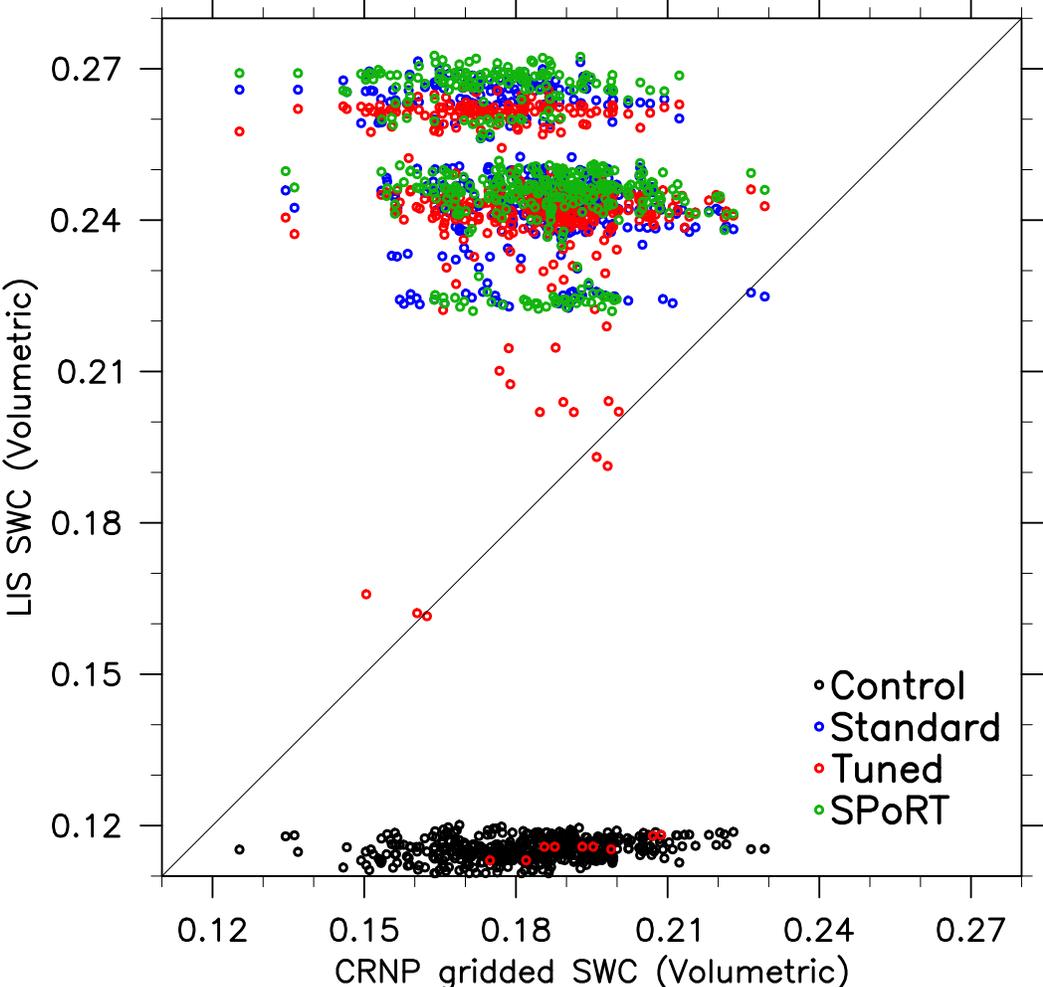
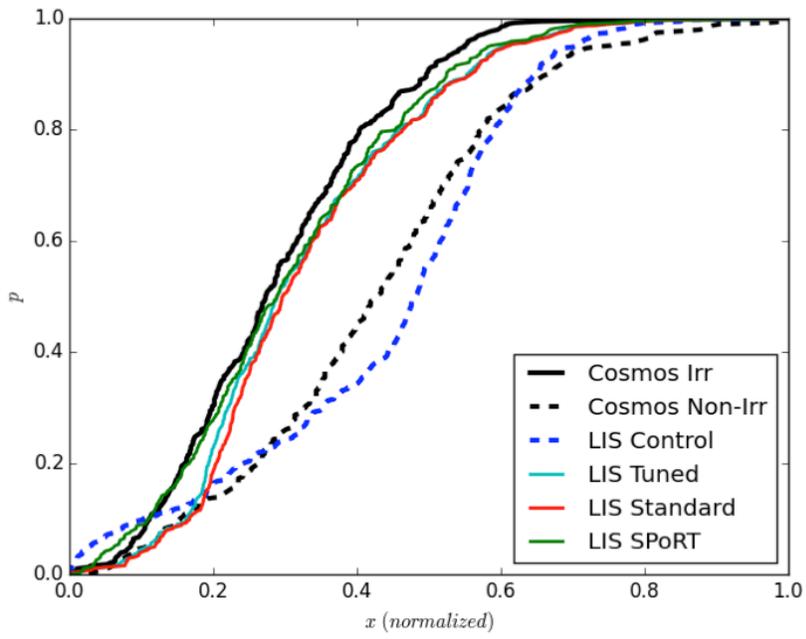
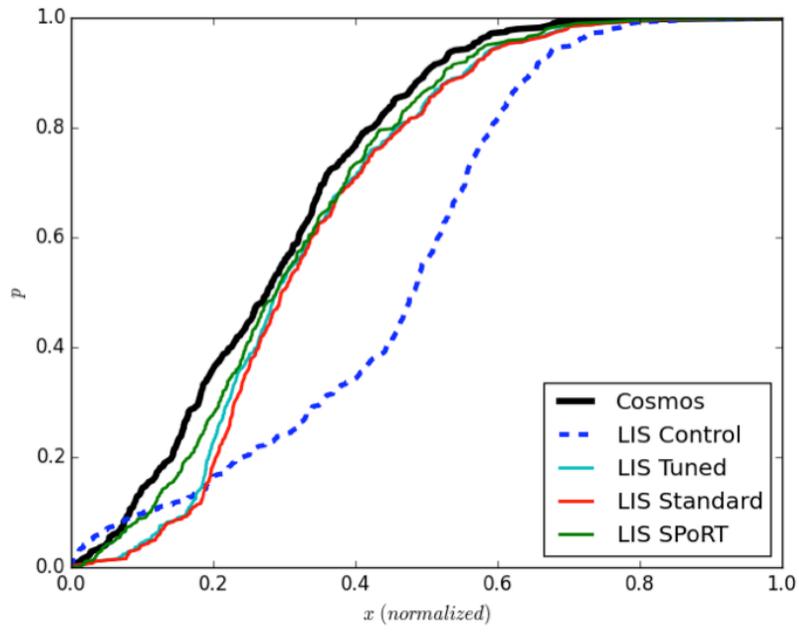


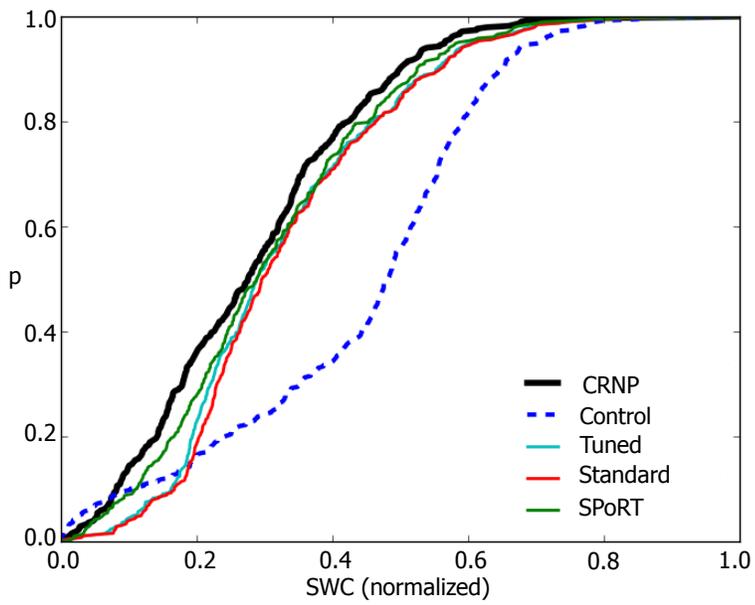
Figure 8. Scatterplot of the gridcell soil water content given by the CRNP gridded soil moisture product as compared to the LIS simulations. Spatial CDF for 25 July 2014 and 30 Jul 2014, two dates when irrigation was applied at the irrigated maize and soybean sites in practice and in the model simulations.

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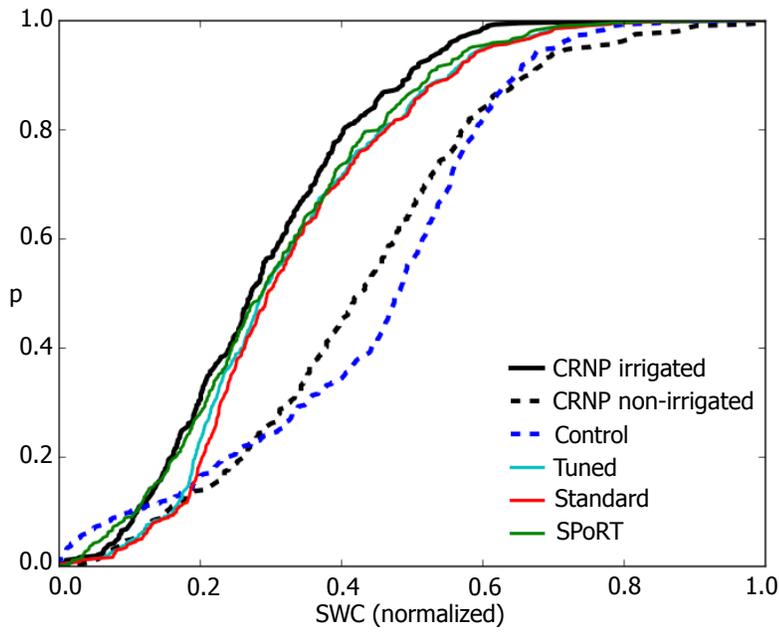
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(a)



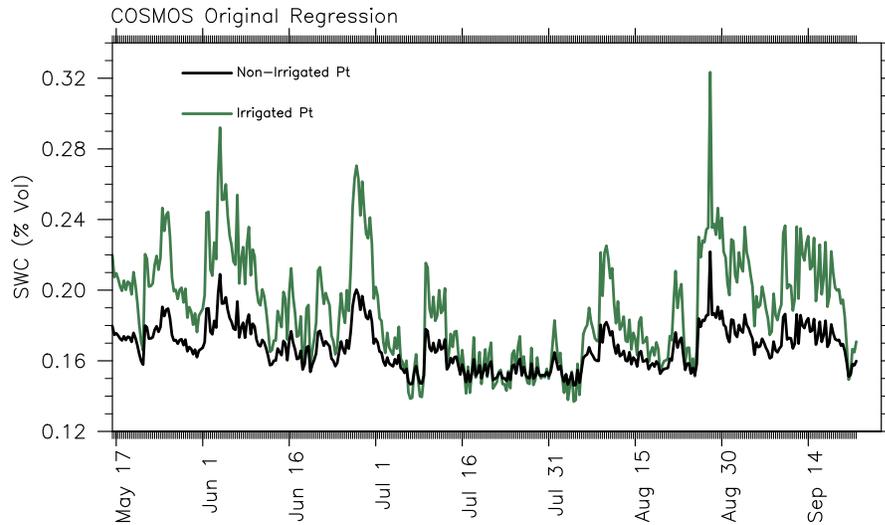
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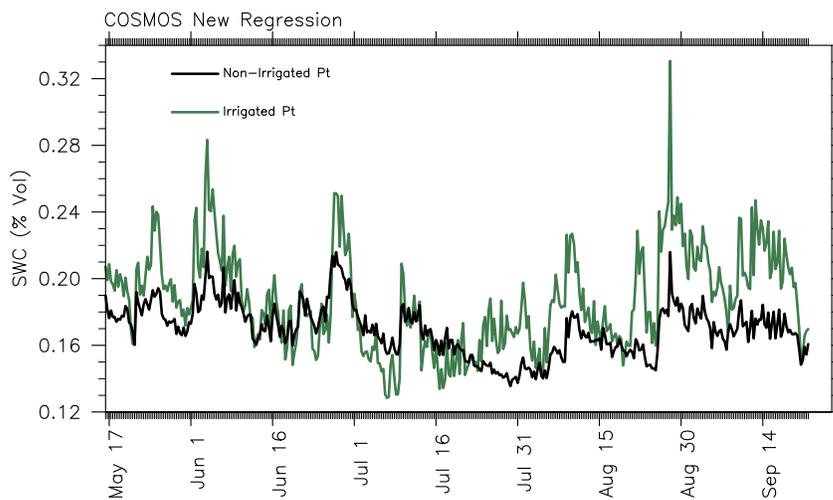
5 **Figure 9. Temporal-CDF of normalized (a) domain averaged and (b) irrigated/non-irrigated spatial average SWC values from May 5 to Sept 16 from the COSMOS observational product (black) and the model simulations (colors).**

**Supplement:**

**(a)**



**(b)**



5 **Supplement 1. Time series of soil water content at an irrigated and non-irrigated point given by the gridded CRNP product using (a) the original regression from Franz et al., 2015 (b) the new regression used in this study that treats irrigated and non-irrigated areas differently. With the original regression technique (a) few differences are seen between the irrigated and rainfed points, especially during the dry-down period in late July to early August. The averaging of the probes results in a levelling off of soil moisture during this time. (b) The new regression technique results in the non-irrigated point showing decreasing SWC during the dry down period, as at the CRNP rainfed probe, while the irrigated point shows increasing SWC due to irrigation during the dry**

10 **down.**

CDF of normalized domain averaged (top) and irrigated/non-irrigated spatial average (bottom) SWC values from May 5 to Sept 16 from the COSMOS observational product (black) and the model simulations (colors).