Please find our revised manuscript attached, along with a version with the differences from the Discussion manuscript highlighted.

Some readers might wonder why a long model run is argued to be comparable with the statistics that could be drawn from an ensemble. This correspondence is legitimate under ergodic assumptions in a sufficiently representative long-term experiment allowing the invariants of motion to be thoroughly manifested.

The debate on whether the experimental outcome is sensitive to the initial conditions also merits some clarification to the reader. On one hand, the transient dynamics may naturally be sensitive to the initial conditions, particularly in unstable system configurations where uncertainties propagate rapidly. These do not pose a fundamental problem here since transient dynamics are not the object of the study. On the other hand, for a given set of parameters and fixed model structure, the asymptotic behaviour of a dynamical system will define a statistically invariant outcome, consistent with equilibrium statistical physics (e.g. shaped by attractors in dissipative systems). That is, while the transient dynamics are indeed sensitive to the initial conditions, in dissipative systems the asymptotic behaviour will exhibit similar statistical physics irrespective of the initial conditions - for given model parameters and structure.

We agree that this asymptotic regime is where we conduct the analyses presented. We show the approach to this steady-state behavior in the new Figure 2 and attempt to clarify our intention better in the Methods section.

Further elaboration on the physical context of the problem, the experiments and results would also be highly beneficial to the paper. In this sense, the manuscript would benefit from placing the kinematic lessons into dynamic context, i.e. complementing a motion-descriptive with physical considerations that help the reader better understand the dynamics at play.

On a more specific note (as raised by one of the reviewers), the reported shift in the ITCZ would merit some brief additional comment based on supporting arguments available in the literature.

We added discussion of the ITCZ changes seen and their likely physical-dynamic explanation with references to related work and relevant previous experiments, as well as more details on the experimental set-up.

Overall, there are questions raised by the reviewers that might be wondered by the broader readership. By openly addressing them in the manuscript as done in the peer-review process, the authors will quench potential controversy before it has the chance to ignite.

At this stage, the authors are then encouraged to proceed with their review efforts, paying special attention to the recommendations arising in the peer-review process.

Yes, as detailed in our earlier response, we have made many changes in the paper to address the peer reviewer comments.
Ocean-atmosphere interactions modulate irrigation’s climate impacts

Nir Y Krakauer1, Michael J Puma2,3,4, Benjamin I Cook3, Pierre Gentine5, and Larissa Nazarenko2,3

1Department of Civil Engineering and NOAA-CREST, The City College of New York, New York, NY, 10031, USA
2Center for Climate Systems Research, Columbia University, New York, NY 10025, USA
3NASA Goddard Institute for Space Studies, New York, NY 10025, USA
4Center for Climate and Life, Columbia University, Palisades, NY 10964, USA
5Earth and Environmental Engineering, School of Engineering and Applied Science, Columbia University, New York, New York, USA

Correspondence to: NY Krakauer (nkrakauer@ccny.cuny.edu)

Abstract. Numerous studies have focused on the local and regional climate effects of irrigated agriculture and other land cover and land use change (LCLUC) phenomena, but there are few studies on the role of ocean-atmosphere interaction in modulating irrigation climate impacts. Here, we compare simulations with and without interactive sea surface temperatures of the equilibrium effect on climate with and without interactive sea surface temperatures. We find that ocean-atmosphere interaction does impact the magnitude of global-mean and spatially varying climate impacts, greatly increasing their global reach. Local climate effects in the irrigated regions remain broadly similar, while non-local effects, particularly over the oceans, tend to be larger. The interaction amplifies irrigation-driven standing wave patterns in the tropics and midlatitudes in our simulations, approximately doubling the global mean amplitude of surface temperature changes due to irrigation. The fractions of global area experiencing significant annual-mean surface air temperature and precipitation change also approximately double with ocean-atmosphere interaction. Subject to confirmation with other models, these findings imply that LCLUC is an important contributor to climate change even in remote areas such as the Southern Ocean.

1 Introduction

Anthropogenic land cover and land use change (LCLUC) affects climate by modifying water, sensible heat, and radiation fluxes at the land surface (Chase et al. 2000; Gordon et al. 2005; Brovkin et al. 2006; Fundell et al. 2007; Krakauer et al. 2010; Mahmood et al. 2014). One important mode of LCLUC has been the dramatic expansion in irrigated agriculture over the past century. Resultant local climate changes, notably growing-season daytime cooling resulting primarily from increased evapotranspiration, have been diagnosed from observations (Bonfils and Lobell 2007; Lobell and Bonfils 2008). Remote (non-local) impacts of irrigation are less well constrained. Global climate models (GCMs) can be run with and without an irrigation scheme to assess local climate effects as well as remote impacts (such as downwind enhancement of precipitation), which would be difficult to deduce with confidence from observations alone (Lo et al. 2013; Alter et al. 2015). Because the propagation mechanisms may not be easily observable and because trends in observations are often dominated by the effects of other climate forcings (Lo et al. 2013; Alter et al. 2015; de Vrese et al. 2016).

Many GCM studies of irrigation’s climate impacts have been conducted with prescribed sea surface temperatures...
(SSTs) (Boucher et al., 2004; Puma and Cook [2010]; Lo and Famiglietti, 2013; de Vrese et al., 2016), while several did include ocean-atmosphere interaction (Lobell et al., 2006; Cook et al., 2011, 2015). Various studies have highlighted the importance of interactive atmosphere-ocean coupling for accurately reproducing various phenomena in GCMs. These include Indian monsoon rainfall (Kumar et al., 2005; Wu and Kirtman, 2004; Shukla et al., 2014) and the relationship between sea level pressure and SST trends (Copey et al., 2006; Meng et al., 2012). Further, the oceans may be important for amplifying modulating responses from LCLUC forcings, providing an additional source of memory that can allow anomalies to persist and carry over between seasons. For example, studies of afforestation and deforestation at high Northern latitudes (Bonan et al., 1992; Swann et al., 2006; Meng et al., 2012). Further, the oceans may be important for amplifying modulating responses from LCLUC forcings, providing an additional source of memory that can allow anomalies to persist and carry over between seasons. For example, studies of afforestation and deforestation at high Northern latitudes (Bonan et al., 1992; Swann et al., 2006; Meng et al., 2012). Further, the oceans may be important for amplifying modulating responses from LCLUC forcings, providing an additional source of memory that can allow anomalies to persist and carry over between seasons. For example, studies of afforestation and deforestation at high Northern latitudes (Bonan et al., 1992; Swann et al., 2006; Meng et al., 2012).

In this study, therefore, we investigate the possible role of atmosphere-ocean interaction in modulating the irrigation climate forcing impact of irrigation on climate. We conduct GCM simulations of steady-state climate with and without present-day irrigation extents and with either prescribed SSTs or a thermodynamic slab ocean model.

2 Methods

2.1 Model runs

We analyze several different model experiments to investigate irrigation forcing of climate, all using the GCM ModelE2 (2° latitude × 2.5° longitude resolution), the latest version of the GISS atmosphere general circulation model, with 40 vertical layers in the atmosphere and updated physics (Schmidt et al., 2014; Miller et al., 2014). Irrigation water is added to the vegetated fraction of the grid cell at the top of the soil column, beneath the vegetation canopy. Irrigation rates are nominally for the year 2000, taken from a global gridded reconstruction (Wisser et al., 2010) (Figure 1). This reconstruction estimates irrigation demand based on combining maps of irrigated areas and crop types with crop-specific evapotranspiration scale factors, with a special allowance for maintaining a constant flood depth in paddy rice areas (Wisser et al., 2010). Water for irrigation is initially withdrawn from rivers and lakes in the same grid cell. If irrigation demand is not satisfied by these surface sources, water is added under the assumption that it is taken from groundwater sources that are not represented in the model (i.e., ‘fossil’ groundwater). The irrigation rate is kept constant over the course of the day and applied for every sub-daily time step. Irrigation water will either infiltrate the soil column or runoff run off to the streams in the grid cell. The total amount of irrigation water summed to averaged 0.019 mm per day (6.8 mm per year) globally (3500 km² per year total), with a mean of 0.46 mm per day (168 mm per year) over irrigated land grid cells (defined as those for which the average irrigation amount was at least 0.1 mm per day). Additional details and discussion of the irrigation scheme are in Puma and Cook (2010) and Cook et al. (2011). As opposed to ‘Irrigation’ (irrig) runs, in ‘Control’ (ctrl) runs no irrigation water was applied.

Irrigation and Control simulations were carried out with two different ocean configurations. The simplest involves forcing the atmosphere model with prescribed, annually repeating monthly sea surface temperatures (SSTs) and sea ice. Average The SSTs and sea ice values are computed based on-are based on average 1996 to 2004 data using from the Hadley Center analysis (Rayner et al., 2003). We refer to this as the atmosphere-only, fixed-SST, or A configuration. In the second configuration (referred to as ‘q-flux’ mode, interactive-SST, interactive-(surface)-ocean, or O configuration), the ocean is represented as a 65-m deep mixed layer, with a prescribed internal heat source to represent the effects of horizontal and vertical ocean mixing and advection. Forcings such as greenhouse gas concentrations were also held constant across years, and based on values from around the year 2000 (Cook et al., 2011).

The four simulations – irrig-A, ctrl-A, irrig-O, ctrl-O – were run 60 years each. The q-flux mode takes approximately 10 years to reach equilibrium under constant forcings, so we analyzed only the last 50 years of each simulation—which represent approximately steady-state conditions that show internal system variability under the different model configurations (i.e., with fixed SST or q-flux ocean, and with or without irrigation). Figure 2 illustrates the approach to equilibrium of the simulations. The A runs stayed at the essentially the same temperature (up to internal year-to-year variability) from the first year, but had 0.4 W m⁻² more radiation entering Earth than leaving. This was because the observation-based fixed SST was cooler than needed for radiative equilibrium with the imposed greenhouse gas concentration (Hansen et al., 2005), although surface temperature and other climate variables did remain at steady state within the fixed-SST model configuration. In the O runs, the radiative imbalance largely resolved itself within a few years by SSTs and surface air temperatures warming around 0.3 K, and a difference of 0.1 K between the irrig and ctrl runs in the equilibrium mean temperature was also evident (Figure 2).

2.2 Analysis of differences between runs

For climate variables of interest, we considered irrig-ctrl differences in the monthly fields for both the A and O configurations. The irrig-ctrl difference field for the A set of experiments is referred to as ∆A, and the irrig-ctrl difference field for the O set of experiments is referred to as ∆O. The

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The significance of $\Delta A$, $\Delta O$, $\Delta \Delta$, either at individual grid points or spatially averaged, was estimated using a Student’s t-test on their time series over the 50-year analysis period, with the degrees of freedom adjusted based on the lag-1 autocorrelation of the time series. This adjustment is based on the notion of effective sample size in time series analysis, taking as the null hypothesis that the difference time series is red noise with zero mean (Jones [1975], Bretherton et al., [1999]).

As metrics of overall irrigation and ocean configuration impacts, we looked at the mean and the root mean square (rms) of $\Delta A$, $\Delta O$, $\Delta \Delta$ aggregated globally over irrigated areas (which we defined as grid cells and months where the applied irrigation was over 0.1 mm day$^{-1}$); non-irrigated land areas; and ocean areas. We considered annual means of these quantities as well as seasonal means. For seasonal means, aggregation was performed only over the zone of the Northern Hemisphere where the vast majority of the irrigation takes place ($8^\circ$-$46^\circ$N, 92% of global irrigation), to preserve consistent seasonality.

We focus on climate variables that quantify directly conditions and moisture status at the Earth’s surface (surface air temperature, SST [only over ocean], precipitation, soil moisture [only over land], cloud fraction); terms in the surface energy balance that are affected by irrigation (latent and sensible heat fluxes); and circulation-related quantities (sea-level pressure and geopotential height, geopotential height, and meridional jet stream velocity fields) that can provide insight into how irrigation effects on surface energy and water balance could propagate to impact climate in distant regions.

### 3 Results

#### 3.1 Impact of interactive SST on spatial-mean irrigation responses

Irrigation-induced surface air cooling, though still concentrated over the irrigated land areas, spread over ocean areas in the interactive-SST simulation. Global-mean above-ocean surface air temperatures decreased 0.08 K and sea surface temperatures decreased 0.07 K (Table 1). In the fixed-SST irrigation simulation, precipitation slightly decreased over the irrigated areas and increased elsewhere. Compared to the fixed-SST irrigation simulation, the cooling over the oceans slightly reduced evaporation and precipitation in the interactive-SST simulation. Interactive SST did not significantly modify the global mean enhancements in soil moisture and cloudiness due to irrigation (Table 1). Irrigation-induced evaporative and sensible surface heating fluxes were both slightly diminished in the interactive-SST simulation, consistent with the cooler surface temperatures and reduced precipitation (Table 1). As expected, the mean atmospheric pressure responded inversely to the temperature change, with higher pressure in the irrigated areas (consis-
tent with the reduced precipitation there). The mean 300-mb height decreased significantly more in the interactive-SST simulation even in the irrigated areas, showing that, compared to fixed SST, interactive SST spreads the cooling due to irrigation throughout the atmospheric column (Table 1). The meridional jet stream velocity was slightly higher in the runs with irrigation, although the effect of interactive SST ($\Delta\Delta$) was only significant over irrigated areas (Table 1).

Table 2 shows changes by season (averaged over $8^\circ-46^\circ$N) for surface air temperature. Over land, the cooling is greatest in the summer and fall, when the largest amount of irrigation water is applied, and the mean amount is not significantly affected by whether SST is interactive. Over the ocean, cooling is more uniform across seasons, and is much greater in the interactive SST simulation (Table 2).

### 3.2 Impact of interactive SST on spatial variability of irrigation responses

The global or zonal Northern Hemisphere mean impacts just shown conceal much spatial variability in the response to irrigation, which is best depicted in maps. The rms of the spatial field of irrigation response for the same climate variables shows that interactive SST tends to increase this spatial variability over the ocean and non-irrigated land, even for variables such as over-ocean cloud cover and jet stream velocity for which the mean response is not significantly affected, implying that interactive SST on the whole enhances non-local irrigation impacts on climate. One exception is that interactive SST decreases the spatial variability in latent and sensible heat irrigation responses over the ocean, presumably because in those simulations SST can adjust the interactive SST adjusts to changes in air temperature in a way that reduces the equilibrium change in surface fluxes (Table 3).

We show illustrative maps of the seasonal-mean irrigation response with and without interactive SST ($\Delta A, \Delta O$). Under fixed SST, irrigation-induced changes in surface air temperature (Figure 3) are primarily local to major irrigation regions such as India, China, and the USA, and effects in the ocean tend to be small, except in the North Pacific. Under interactive SST, irrigation-induced regional changes tend to have larger amplitude ($\sim0.8$ compared to $\sim0.4$ K; Table 3) and are also found in the tropical and southern oceans. Under fixed SST in boreal boreal winter, the middle and high northern latitudes show a stationary wave pattern of alternating warm and cool anomalies due to irrigation (which during that sea-
### Table 1. Mean impact of irrigation on climate quantities with and without interactive sea surface temperatures.

<table>
<thead>
<tr>
<th></th>
<th>Irrigated land</th>
<th>Non-irrigated land</th>
<th>Ocean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Δ(A)</td>
<td>Δ(O)</td>
</tr>
<tr>
<td>Surface air temperature (°C)</td>
<td>18.764</td>
<td>-0.665***</td>
<td>-0.697***</td>
</tr>
<tr>
<td>Sea surface temperature (°C)</td>
<td>21.676</td>
<td>0</td>
<td>-0.0674</td>
</tr>
<tr>
<td>Precipitation (mm d(^{-1}))</td>
<td>3.085</td>
<td>-0.032</td>
<td>-0.082***</td>
</tr>
<tr>
<td>Soil moisture (mm)</td>
<td>462.7</td>
<td>60.5***</td>
<td>56.6***</td>
</tr>
<tr>
<td>Cloud cover (%)</td>
<td>50.27</td>
<td>1.28***</td>
<td>0.96***</td>
</tr>
<tr>
<td>Latent heat (W m(^{-2}))</td>
<td>55.56</td>
<td>9.08***</td>
<td>8.38***</td>
</tr>
<tr>
<td>Sensible heat (W m(^{-2}))</td>
<td>-47.99</td>
<td>6.03***</td>
<td>5.49***</td>
</tr>
<tr>
<td>Sea-level pressure (mb)</td>
<td>1010.36</td>
<td>0.47***</td>
<td>0.39***</td>
</tr>
<tr>
<td>300-mb height (m)</td>
<td>9459.55</td>
<td>-1.99***</td>
<td>-4.58***</td>
</tr>
<tr>
<td>Meridional jet (m s(^{-1}))</td>
<td>20.36</td>
<td>+0.29***</td>
<td>+0.49***</td>
</tr>
</tbody>
</table>

Means are for the ctrl-A (no irrigation, fixed SST) simulation. Significance level (two-tailed) of differences due to interactive sea surface temperatures: not significant (\(p > 0.05\)), \(0.05 < p < 0.01\), \(p < 0.01\), \(p < 0.001\).

### Table 2. Mean impact of irrigation on seasonal surface air temperature (°C, averaged over 8°-46°N) with and without interactive sea surface temperatures.

<table>
<thead>
<tr>
<th></th>
<th>Irrigated land</th>
<th>Non-irrigated land</th>
<th>Ocean</th>
<th>Mean</th>
<th>Δ(A)</th>
<th>Δ(O)</th>
<th>Δ(A)</th>
<th>Δ(O)</th>
<th>Δ(A)</th>
<th>Δ(O)</th>
<th>Δ(A)</th>
<th>Δ(O)</th>
<th>Δ(A)</th>
<th>Δ(O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter (DJF)</td>
<td>10.407</td>
<td>-0.660-0.607***</td>
<td>-0.633***</td>
<td>-0.026</td>
<td>10.302</td>
<td>-0.036</td>
<td>-0.130</td>
<td>-0.094</td>
<td>19.282</td>
<td>0.000</td>
<td>-0.188***</td>
<td>0.188***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spring (MMA)</td>
<td>19.414</td>
<td>-0.622***</td>
<td>-0.663***</td>
<td>-0.041</td>
<td>18.530</td>
<td>-0.118*</td>
<td>-0.165***</td>
<td>-0.047</td>
<td>20.522</td>
<td>-0.021***</td>
<td>-0.170***</td>
<td>0.149***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer (JJA)</td>
<td>26.242</td>
<td>-0.674***</td>
<td>-0.726***</td>
<td>-0.052</td>
<td>26.333</td>
<td>-0.329***</td>
<td>-0.396***</td>
<td>-0.066</td>
<td>24.342</td>
<td>-0.030***</td>
<td>-0.178***</td>
<td>0.147***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fall (SON)</td>
<td>19.474</td>
<td>-0.885***</td>
<td>-0.891***</td>
<td>-0.006</td>
<td>19.580</td>
<td>-0.225***</td>
<td>-0.307***</td>
<td>-0.082</td>
<td>23.487</td>
<td>-0.020***</td>
<td>-0.163***</td>
<td>0.143***</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Means are for the ctrl-A (no irrigation, fixed SST) simulation. Significance level (two-tailed) of differences due to interactive sea surface temperatures: not significant (\(p > 0.05\)), \(0.05 < p < 0.01\), \(p < 0.01\), \(p < 0.001\).

### Table 3. Root mean square impact of irrigation on time-mean climate quantities with and without interactive sea surface temperatures.

<table>
<thead>
<tr>
<th></th>
<th>Irrigated land</th>
<th>Non-irrigated land</th>
<th>Ocean</th>
<th>Mean</th>
<th>Δ(A)</th>
<th>Δ(O)</th>
<th>Δ(A)</th>
<th>Δ(O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface air temperature (°C)</td>
<td>1.289</td>
<td>1.267</td>
<td>-0.989</td>
<td>1.047</td>
<td>*</td>
<td>0.374</td>
<td>0.769</td>
<td>***</td>
</tr>
<tr>
<td>Sea surface temperature (°C)</td>
<td>0</td>
<td>0.549</td>
<td>***</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precipitation (mm d(^{-1}))</td>
<td>0.985</td>
<td>0.977</td>
<td>-0.547</td>
<td>0.590</td>
<td>**</td>
<td>0.847</td>
<td>0.916</td>
<td>***</td>
</tr>
<tr>
<td>Soil moisture (mm)</td>
<td>120.6</td>
<td>119.0</td>
<td>-52.9</td>
<td>59.0</td>
<td>***</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cloud cover (%)</td>
<td>4.64</td>
<td>4.72</td>
<td>-0.041</td>
<td>4.10</td>
<td>-</td>
<td>3.07</td>
<td>3.46</td>
<td>***</td>
</tr>
<tr>
<td>Latent heat (W m(^{-2}))</td>
<td>17.31</td>
<td>17.01</td>
<td>*</td>
<td>5.90</td>
<td>6.19</td>
<td>*</td>
<td>7.96</td>
<td>7.55</td>
</tr>
<tr>
<td>Sensible heat (W m(^{-2}))</td>
<td>12.14</td>
<td>11.94</td>
<td>*</td>
<td>6.22</td>
<td>6.58</td>
<td>*</td>
<td>3.55</td>
<td>3.40</td>
</tr>
<tr>
<td>Sea-level pressure (mb)</td>
<td>1.01</td>
<td>0.97</td>
<td>-1.66</td>
<td>1.47</td>
<td>-</td>
<td>1.45</td>
<td>1.40</td>
<td>-</td>
</tr>
<tr>
<td>300-mb height (m)</td>
<td>17.31</td>
<td>17.68</td>
<td>-25.72</td>
<td>24.93</td>
<td>-</td>
<td>22.27</td>
<td>23.84</td>
<td>*</td>
</tr>
<tr>
<td>Meridional jet (m s(^{-1}))</td>
<td>2.24</td>
<td>2.31</td>
<td>-2.14</td>
<td>2.21</td>
<td>-</td>
<td>2.28</td>
<td>2.57</td>
<td>***</td>
</tr>
</tbody>
</table>

Significance level (two-tailed) of differences due to interactive sea surface temperature: not significant (\(p > 0.05\)), \(0.05 < p < 0.01\), \(p < 0.01\), **\(p < 0.001\).
son is concentrated in the Indian subcontinent). Under interactive SST, these boreal winter anomalies shift locations somewhat (for example, the cooling centered in the eastern USA under fixed SST is attenuated) and persist to a greater extent during the other seasons, and analogous wave patterns are also seen in the Southern Ocean and Antarctica are considerably stronger than under fixed SST. Under interactive SST, surface air temperature anomalies outside irrigated areas tend to be closely associated with SST anomalies of the same sign (Figure 4), which provide a mechanism for the surface air temperature anomalies to persist across seasons.

Under fixed SST, a reduction in 300-mb height (Figure 5) corresponding to cooling of the atmospheric column: Figure 5 is seen primarily around irrigation regions in the northern midlatitudes, while under interactive SST the reduction in the northern midlatitudes is more zonally uniform, and there is also a stronger stationary wave pattern in the Southern Hemisphere roughly corresponding to locations of surface air temperature changes there. Over the oceans, irradiation-induced SST changes in the interactive-SST simulations are similar to surface air temperature changes (with some larger changes in the Arctic and Antarctic margins due to shifts in sea ice distribution—Figure 4), supporting the role of air-sea interaction interactions in driving the divergence in surface air temperature and geopotential height. Irrigation responses between the fixed-SST and interactive-SST simulations. Particularly in boreal winter, the same stationary wave pattern seen for temperature is found in the upper atmosphere, with shifted phase under interactive SST compared to fixed SST phases shifted between the interactive and fixed SST simulations (Figure 5). The meridional jet stream velocity (ujet) changes correspondingly consistent with geostrophic adjustment of the atmospheric circulation: ujet tended to increase on the north side, and decrease on the south side, of areas where 300-mb geopotential height rose, and vice versa where geopotential height dropped (Figure 6).

Precipitation impacts (Figure 7) are strongest over the tropics and subtropics and appear to reflect, for example, a northward shift due to irrigation in the intertropical convergence zone (ITCZ) in and south of India in boreal winter and a southward shift in boreal summer. Boreal summer with the zonal-mean effect under interactive SST being to decrease tropical precipitation north of the Equator and increase it south of the Equator. The summer monsoon precipitation over India is reduced under both fixed and interactive SST, but with interactive SST impacts of irrigation on summer precipitation appear to also be more widespread across southeast Asia (Figure 7). Latent heat impacts (Figure 8) reflect both increased evapotranspiration where there is irrigation and the impacts of nonlocal changes in temperature and precipitation, e.g. less evaporation over western Australia in Austral summer associated with reduced precipitation there due to irrigation under interactive SSTS.

The role of interactive SST in non-local climate forcing can be seen, for example, for precipitation in eastern Africa: de Vrese et al. (2016) performed a modeling study using different atmosphere and land surface models than we utilized, and found that one numerical summary of all modeled climate changes in precipitation due to irrigation with fixed SST are statistically significant, and precipitation over the same regions and season, as the precipitation enhancement moves further south and east. Moreover, this area fraction increases substantially with interactive SST at a precipitation increase for the southern Horn of Africa remains during boreal summer and is enhanced during boreal winter. Thus, ocean-atmosphere interactions may importantly affect the magnitude and location of non-local irrigation impacts on climate, such as those potentially implicated in precipitation trends in eastern Africa for most of the variables discussed here, for example more than doubling (21% to 46%) for surface air temperature and almost doubling (15% to 27%) for precipitation.

4 Discussion

The current work suggests that an interactive-SST (q-flux) model configuration, compared to one with fixed SSTs, results in similar mean local climate effects in the irrigated regions, but generally larger non-local effects, particularly over the oceans. In response to the application of realistic present-day irrigation amounts, the q-flux configuration generates stationary wave patterns across a range of latitudes in climate variables such as surface air temperature, SST, and geopotential height. These wave patterns have fairly large amplitudes (e.g. up to ~1 K in SST, similar to the magnitude of anthropogenic warming impacts warming from anthropogenic greenhouse gas emissions over the past century). The stationary waves generated are qualitatively similar to those previously studied as occurring in response to zonal asymmetries ( Held et al. 2002, Shaman and Tziperman 2005). A recent atmosphere-only GCM study (Koster et al. 2014) identified phase locking and amplification of a planetary wave as a potential mechanism for nonlocal climate impacts of soil moisture changes (such as those imposed by irrigation) in boreal spring and summer, but
Figure 3. Difference in surface air temperature (K) by season due to irrigation with fixed SST ($\Delta_A$) and with interactive SST ($\Delta_O$). Differences not significant at the 0.05 level are hatched gray.

While comparison with such past studies suggests that the occurrence of stationary waves amplified by air-sea interaction in response to irrigation is likely robust, their location and magnitude may be sensitive to, for example, aspects of our atmosphere model parametrization, background climate and ocean fluxes, and details of how the irrigation is applied. Systematic multi-model intercomparisons of responses to irrigation and other LCLUC forcings could aid in under-
The impacts of air-sea interaction on irrigation effects on tropical and monsoon precipitation are qualitatively consistent with previous climate model simulations showing the influence of land surface forcing on tropical circulation. Thus, including vegetation on the land surface strengthened ITCZ, monsoon, and Hadley cell dynamics, as well as intensifying the global water cycle, compared to a desert planet (Fraedrich et al. [1999]). Further, in a previous version of the GISS GCM, implementing an improved representation of vegetation stomatal conductance and photosynthesis dependence on atmospheric humidity and CO₂ concentration decreased biases in precipitation over the oceanic ITCZs and tropical South America (Friend and Kiang [2005]). More specifically, afforestation in the northern midlatitudes shifts the ITCZ northward (Swann et al. [2012]), while deforestation in northern middle and high latitudes shifts the ITCZ south (Chao et al. [2014]). This non-local climate impact of land cover implies that expanded forest cover in Eurasia could explain the wetter conditions in northern Africa inferred for the mid-Holocene (Swann et al. [2014]). In our experiments, irrigation under interactive SST results in tropical precipitation decreasing in the Northern Hemisphere and increasing in the Southern Hemisphere (Figure 4: precip). Since with irrigation (like boreal deforestation in Chao et al. [2008]) exerting its main cooling effect on the Northern Hemisphere and thus increasing northward heat transport and shifting the Northern Hemisphere Hadley cell southward. As Swann et al. (2012) note, “Interaction between sea surface temperatures and the atmosphere is necessary for allowing shifts in large-scale circulation and precipitation.”

Our q-flux simulations gave an equilibrium impact of the irrigation forcing on climate. Simulated changes with interactive SST are more plausible, in principle, more physically consistent than those simulated under fixed SST in that energy is being conserved (within, through the constraints of the q-flux surface ocean framework) can also introduce biases. However, in reality, ocean circulation and mixing delay equilibrium with forcings such as irrigation. Since irrigation has only been practiced globally at its current magnitude for the past few decades, it is expected that transient changes in SST due to irrigation for the current climate system would be smaller than the equilibrium changes simulated here, though nonlinear effects on ocean circulation. On the other hand, allowing changes in ocean currents and heat transport could possibly also enhance climate impacts compared to our q-flux configuration (which had effectively constant ocean heat transport). Water diversion for irrigation impacts riverine freshwater fluxes and sea level (Chao et al., 2008; Wisser et al., 2010), which may in turn affect climate in ways not represented in our runs. Preliminary results suggest that the interaction of irrigation and climate can be further explored to better understand the impacts of land use changes on regional and global climate.
inary comparison of SSTs in irrigation and no-irrigation runs of GISS ModelE2 with time-varying forcings and a three-dimensional dynamic ocean model (Cook et al., 2015) suggests that around the year 2000, the amplitude of non-local SST changes due to irrigation might have been $\sim$0.1-0.2 K, instead of the $\sim$0.5-1 K seen here with a q-flux model run to equilibrium. These differences between transient and equilibrium responses to LCLUC in the coupled atmosphere-ocean system should be explored in more detail. In fact, future changes in irrigation are highly uncertain (Wada et al., 2013; Elliott et al., 2014), particularly given the depletion of groundwater sources of irrigation water in many major agricultural areas (Gleeson et al., 2012; Krakauer et al., 2013; Leng et al., 2014). Despite these limitations, our work illustrates the extensive non-local changes in patterns of SST and other climate variables seen in our simulations suggest that studies of irrigation climate impacts that use either global models with fixed SST configurations.
or regional models with fixed boundary conditions [Im et al., 2014; Alter et al., 2015] may miss some of the impact of irrigation on non-local climate.

5 Conclusions

We compared simulations of the equilibrium effect of contemporary irrigation extent on climate with and without interactive sea surface temperatures to show that air-sea interaction does impact the magnitude of global-mean and spatially-varying climate impacts and greatly increase their global reach. In these simulations, air-sea interaction amplified irrigation-driven standing wave patterns in the tropics and midlatitudes, approximately doubling the global mean amplitude of surface air temperature changes due to irrigation. Subject to confirmation with other models and consideration of irrigation’s time evolution, these findings imply that LCLUC may be an important contributor to climate change.
even in remote areas such as the Southern Ocean, and that attribution studies need to consider LCLUC such as irrigation as truly global forcings that affect climate and the water cycle in ocean as well as land areas.

**Code and data availability**

The GISS GCM source code can be accessed from [http://www.giss.nasa.gov/tools/modelE/](http://www.giss.nasa.gov/tools/modelE/) for free download and use. Documentation of model configurations and further references are also available there.

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Figure 8. Same as Figure 3, but for surface latent heat flux differences (W m$^{-2}$).

References

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