CORRESPONDENCE

Comments on "Regional Impacts of Irrigation in Mexico and the Southwestern United States on Hydrometeorological Fields in the North American Monsoon Region"

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ABSTRACT

For their investigation of the impact of irrigated agriculture on hydrometeorological fields in the North American monsoon (NAM) region, Mahalov et al. used the Weather Research and Forecasting (WRF) Model to simulate weather over the NAM region in the summer periods of 2000 and 2012, with and without irrigation applied to the regional croplands. Unfortunately, while the authors found that irrigated agriculture may indeed influence summer precipitation, the magnitude, location, and seasonality of their irrigation inputs were substantially inaccurate because of 1) the assumption that pixels classified as "irrigated cropland" are irrigated during the summer and 2) an outdated land cover map that misrepresents known agricultural districts. The combined effects of these errors are 1) an overestimation of irrigated croplands by a factor of 3–10 along the coast of the Gulf of California and by a factor of 1.5 near the Colorado River delta and 2) a large underestimation of irrigation by a factor of 7–10 in Chihuahua, particularly in 2012. Given the sensitivity of the WRF simulations conducted by Mahalov et al. to the presence of irrigated agriculture, it is expected that the identified errors would significantly impact surface moisture and energy fluxes, resulting in noticeably different effects on precipitation. The authors suggest that the analysis of irrigation effects on precipitation using coupled land–atmospheric modeling systems requires careful specification of the spatiotemporal distribution of irrigated croplands.

The article by Mahalov et al. (2016, hereafter M16) concerning the impact of irrigated agriculture on hydrometeorological fields in the North American monsoon (NAM) region is both interesting and timely, in light of studies suggesting similar impacts in other monsoon systems (e.g., Douglas et al. 2006; Saeed et al. 2009; Im et al. 2014; Im and Eltahir 2014) and indications of substantial precipitation recycling in the NAM region (e.g., Dominguez et al. 2008, 2016). For their study, M16 used the Weather Research and Forecasting (WRF) Model (Skamarock et al. 2005) to simulate weather over the NAM region in the summer periods of 2000 and 2012, with and without irrigation applied to the regional croplands. In such a study, an accurate depiction of the spatial distribution and seasonality of irrigated agriculture is paramount. Unfortunately, while the authors found that irrigated agriculture may indeed influence summer precipitation, the magnitude, location, and seasonality of their irrigation inputs were inaccurate, calling their findings into question. We deem this important since the sensitivity of the NAM climate system to land cover change has not been established. These inaccuracies have two main causes: 1) the assumption that pixels classified as "irrigated cropland" are irrigated during the summer and 2) an outdated land cover map that misrepresents agricultural districts.

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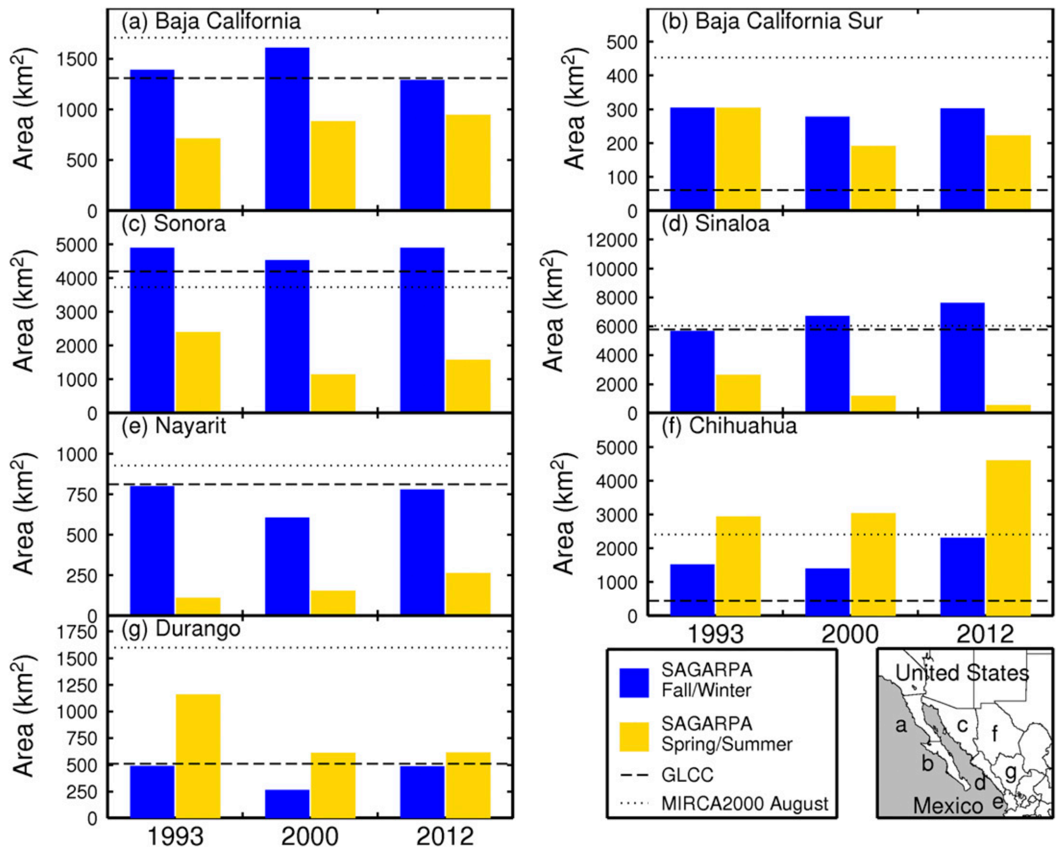

FIG. 1. Comparison of seasonal irrigated areas from government records (SAGARPA 2016), areas of irrigated cropland pixels from the GLCC classification (Loveland et al. 2000), and seasonal irrigated areas from MIRCA2000 (Portmann et al. 2010) for seven states in Mexico (locations shown in the inset map) for years 1993, 2000, and 2012. Areas of irrigated perennial crops are included in both seasons in SAGARPA bars.

The largest source of error in the study is the mischaracterization of the seasonal cycle of agricultural irrigation. M16 computed the irrigated area fraction of each grid cell by summing the areas of 1-km pixels classified as irrigated cropland in the Global Land Cover Characterization (GLCC; Loveland et al. 2000) land cover classification product. Because the GLCC product does not have information about the time of year during which irrigation was applied to those pixels, the irrigated cropland class more correctly should be interpreted to represent fields equipped for irrigation, of which only a subset might be irrigated at any given time. However, the irrigation scheme used by M16 applied irrigation to all of these fractional areas over the entire simulation period based on soil moisture criteria and without a prescribed cropping schedule. Therefore, this approach implicitly assumed that all areas equipped for irrigation were irrigated during the summer monsoon.

Nevertheless, as shown by government records (SAGARPA 2016) in Fig. 1, fall/winter is the primary cropping and irrigating season, rather than spring/summer, in all of the agricultural districts adjacent to the Gulf of California (Baja California, Baja California Sur, Sonora, Sinaloa, Nayarit). This has been the case dating back to the early 1990s, owing to the prioritization of winter wheat production (exacerbated by whitefly infestations in summer soy crops and cropping schedules of other crops that are incompatible with winter wheat), a fact that is well supported in the literature (e.g., Meisner et al. 1992; Naylor et al. 2001; Morales and Anderson 2001; Lobell et al. 2003; Lobell and Asner 2004; Schoups et al. 2006). Over the states along the Gulf of California, the GLCC irrigated areas in each state corresponded more closely to the winter irrigated areas than the summer areas, which were substantially smaller. In the coastal irrigation districts of Sonora, Sinaloa, and Nayarit, summer irrigated areas were 27%–37%, 9%–20%, and 19%–32%, respectively, of the areas given by GLCC in the years simulated by M16 (Table 1). Biases were smaller in the Mexicali Valley of Baja California, where summer irrigated areas were 67%–72% of the GLCC areas. Although summer irrigated areas in Baja California Sur were larger than the GLCC

TABLE 1. Comparison of spring/summer (plus perennial) irrigated areas from government records (SAGARPA 2016) and areas of irrigated cropland pixels from the GLCC classification (Loveland et al. 2000) for seven states in Mexico for years 1993, 2000, and 2012.

State	GLCC irrigated area (km^2)	SAGARPA spring/summer irrigated area (km^2)			Ratio (SAGARPA/GLCC)		
		1993	2000	2012	1993	2000	2012
Baja California	1311.50	717.38	881.93	947.10	0.55	0.67	0.72
Baja California Sur	61.29	305.38	192.27	221.74	4.98	3.14	3.62
Sonora	4204.24	2393.18	1146.63	1573.41	0.57	0.27	0.37
Sinaloa	5772.07	2644.58	1175.63	515.45	0.46	0.20	0.09
Nayarit	811.27	111.53	156.41	262.82	0.14	0.19	0.32
Chihuahua	437.78	2943.51	3041.94	4608.99	6.72	6.95	10.53
Durango	511.85	1162.31	610.37	614.47	2.27	1.19	1.20

areas, they comprised only a small fraction of the total irrigated extent. Thus, M16 overestimated the areal extent of irrigated crops during the summer monsoon by a factor of 3–10 along the mainland coast of the Gulf of California and by a factor of 1.5 near the Colorado River delta (Baja California).

In addition, M16 substantially underestimated irrigated areas in the interior state of Chihuahua (Table 1), for which Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación (SAGARPA) records indicated that summer irrigated areas were 7 times the size given by the GLCC in 1993 and 2000, but grew to over 10 times the size of GLCC areas by the second simulation year (2012). The presence of areally extensive irrigated agriculture in Chihuahua, and its expansion in the mid-2000s, is documented well in the literature (Rosson et al. 2003; Varela Diaz et al. 2008; Douglas 2009; Pool et al. 2014; Mumme 2016). Two factors may have contributed to the substantial underestimation of irrigation in Chihuahua: the acquisition dates of the GLCC's source imagery and classification errors. Because the GLCC was derived from the Advanced Very High Resolution Radiometer (AVHRR) imagery, acquired circa 1992–93, it represents land use and land cover from 7 or 8 years prior to 2000 and nearly 20 years prior to the second simulation year of 2012. Therefore, even if it had captured well the irrigated extent in Chihuahua at the time of acquisition, it still would have underestimated the irrigated extent in 2012 by about 35%. In addition, while this land cover map was state of the art at the time of its publication, it contained several limitations (Loveland et al. 1999; Friedl et al. 2002) that more recent map products (e.g., Friedl et al. 2010) have improved upon. These limitations include 1) that the source data were limited to the AVHRR-based normalized difference vegetation index (NDVI), rather than a larger array of spectral characteristics used in subsequent products; 2) that the spatial resolution was relatively coarse (1 km); and 3) that an unsupervised classification scheme was implemented. Consequently, the largest classification uncertainty in the GLCC was the confusion between agricultural and nonagricultural pixels, particularly where patches of agricultural land were small or where the seasonal cycle of greenness of agriculture was difficult to distinguish from that of the surrounding natural landscape (Loveland et al. 1999). This situation describes well the croplands in the interior mountainous areas of the NAM region such as the state of Chihuahua.

An accurate representation of the land fraction under irrigation is crucial since the primary mechanisms that M16 observed influencing downwind precipitation—irrigation-induced changes in convective available potential energy (CAPE), convective inhibition (CIN), atmospheric precipitable water, and circulation patterns—are dependent on the areal extent of irrigation. In irrigated grid cells, when root-zone soil moisture fell below a critical threshold (bracketed by 30% and 90% soil moisture content), M16 applied irrigation uniformly across the cell's irrigated fraction until the soil moisture reached the assigned soil field capacity. This additional soil moisture prompted increases in both the transpiration from crops and the evaporation from the soil. In such an irrigation scheme, the magnitude of additional ET is therefore proportional to the fraction of the grid cell area over which irrigation is applied. This additional irrigation impacts latent and sensible heat fluxes to the atmosphere, the vertical gradients of temperature and humidity, and ultimately CAPE, CIN, and precipitable water (Wallace and Hobbs 2006). As a result, we would expect that the factor of 1.5–10 overestimation of the fractional areal extent of irrigation in M16 would result in a substantial overestimation of the impact of agricultural irrigation surrounding the Gulf of California on downwind precipitation. Similarly, the underestimation of irrigation in Chihuahua could have led to other changes elsewhere.

More recent datasets may offer limited improvements over the GLCC product, but these too have disadvantages. For instance, the Monthly Irrigated and Rainfed Crop Areas (MIRCA2000) dataset (Portmann et al. 2010) has some advantages over the GLCC product, in that it provides a seasonal cycle of irrigated areas, at 5-arc-min spatial resolution, for a period of time (1998–2002) nearer to the years simulated by M16. Rather than relying on remote sensing classification to identify irrigated croplands, MIRCA2000 was derived from government records of harvested areas of irrigated and rainfed crops (FAO 2004), cropping calendars for 26 major crop categories, and a global map of cropland areas (Ramankutty et al. 2008). For comparison with GLCC, we have plotted the August irrigated areas given by the global MIRCA2000 dataset (Portmann et al. 2010) in Fig. 1. In the study region, MIRCA2000 August irrigated areas agreed better with SAGARPA records in Chihuahua than GLCC areas did. However, in the states adjacent to the Gulf of California (e.g., Sonora, Sinaloa), MIRCA2000 had biases similar to those of GLCC. These discrepancies might be due to MIRCA2000's use of national total irrigated areas and cropping calendars, rather than source data of finer granularity directly from SAGARPA. Thus, while MIRCA2000 represents an improvement in Chihuahua, it still does not provide accurate estimates of summer irrigated areas around the Gulf of California.

A potential way around these discrepancies is to bias correct map products to match government records. As a first step in this direction, the GLCC product could be rescaled by the ratios listed in Table 1 for states surrounding the Gulf of California to depict the approximate distribution of irrigated areas in the years of study. A more comprehensive solution that would work better for Chihuahua (which is severely underrepresented in GLCC and for which rescaling would be unrealistic) would be to rescale the MIRCA2000 product in each state and month to match the SAGARPA areas. The difference in resolution between MIRCA2000 and the WRF grid would need to be addressed via resampling.

A second approach could be to compare M16's evapotranspiration (ET) fields to other ET datasets, for example, the MODIS-based MOD16 product of Mu et al. (2011). Bohn and Vivoni (2016) found that, while the MOD16 product is not without errors, it does exhibit cropland ET with approximately the correct seasonality in both Chihuahua and the districts along the Gulf of California. Not only would a comparison with MOD16 be a useful evaluation of the realism of WRF-simulated ET, but a simulation in which WRF ET is adjusted to match that of MOD16 could be an alternative means of approximating the correct seasonality and extent of agricultural irrigation in the region.

Given the limitations identified with the work of M16, it is likely that the effects of irrigated agriculture on altering precipitation patterns during the North American monsoon have not been resolved appropriately. We look forward to future studies that use more accurate representations of the land surface to yield realistic estimates of the downwind impacts of Mexican irrigation on precipitation during the monsoon system.

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