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Irrigation enhances precipitation at the mountains downwind

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Abstract

Atmospheric circulation models predict an irrigation-rainfall feedback. However, actual field evidences are very weak. We present strong field evidence about an increase in rainfall at the mountains located downwind of irrigated zones. We chose two regions, located in semiarid southern Spain, where irrigation started at a well defined date, and we analyzed rainfall statistics before and after the beginning of irrigation. Analyzed statistics include the variation of (1) mean rainfall ΔP, (2) ratio of monthly precipitation to annual precipitation Δr, and (3) number of months with minimum rainfall episodes ΔP_{min} after a transition period from unirrigated to irrigated conditions. All of them show statistically significant increases. ΔP and Δr show larger and more statistically significant variations in June and July. Their variation is proportional to the mean annual water volume applied in the neighboring upwind irrigation lands. Variations in ΔP_{min} are statistically significant in the whole summer. That is, the number of months with some rain displays a relevant increase after irrigation. However, increase in rainfall while statistically significant is distributed over a broad region, so that it is of little relevance from a water resources perspective. The joint increment in ΔP and ΔP_{min} after the irrigation transition period denotes a net increase in the number of months having a minimum cumulated precipitation in summer.

1 Introduction

Irrigation-precipitation feedback may play an important role in modulating changes in the hydrologic cycle at different scales. Irrigation represents arguably the most dramatic land-use change from the perspective of rainfall (Pielke et al., 2007). The net addition of water moisture to the air in the boundary layer due to evaporation triggers convection, and should be reflected in a net increase of rainfall, during the irrigation season.

Theoretical and modelling studies indeed predict that irrigation causes an increase in rainfall due to the soil moisture-atmosphere interaction (Eltahir, 1998; Zheng and

Eltahir, 1998; Boucher et al., 2004; Guo et al., 2006). Furthermore, Atmospheric General Circulation Models (AGCMs) have predicted the existence of regional “hot spot” feedback zones, regions that concentrate moisture feedback. This is manifested in precipitation during the boreal summer (June through August) in the Great Plains of North America, the Sahel, equatorial Africa and India (Koster et al., 2004). All AGCMs predict variations in rainfall as a net result of the irrigation-precipitation feedback. However, they show a great deal of variation, both in terms of patterns and the overall strength of feedback. That is, model simulation outputs are highly uncertain. The uncertainty might be reduced if the feedback was properly characterized by field measurements (Koster et al., 2006).

Despite of the above results, actual field evidences supporting irrigation-rainfall feedback are surprisingly weak. Earliest studies were performed at the Columbia River basin. Stidd (1975) found an increase in rainfall not only downwind but also upwind of irrigation fields, while Fowler and Helvey (1974) found no evidence of feedback. The traditional reference for feedback is the work of Barnston and Schickedanz (1984) who found an increase in precipitation associated to nearby irrigated lands in the Texas Panhandle region of the Great Plains over the time period of 1931–1970. The result was obtained by a principal component analysis of warm-season precipitation and irrigation data. Nevertheless, Moore and Rojstaczer (2001) performed the same principal component analysis for the same region over a different time period (1948–1997) and found no statistically significant evidence for a consistent irrigation effect in the monthly precipitation data. Moore and Rojstaczer (2002) revisited the Texas Panhandle region, analysing precipitation patterns in the summer months of 1996 and 1997. In their study no distinct spatial trends in precipitation intensity were observed either. Nevertheless, they observed that storms show larger coherence and size within an “anomaly area” about 90 km downwind of the irrigation area, indicating elongated storms, greater storm duration, or both. Unfortunately, the duration of the observation interval is too short and the impact too far away to draw a strong conclusion.

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Our conjecture is that the feedback should concentrate in the mountains downwind the irrigation fields because the adiabatic cooling of moist air caused by upwards flow should promote condensation and rainfall (Smith, 1979; Smith et al., 1997; Lin et al., 2001). The objective of this paper is to test the above conjecture at two areas, where rainfall records are available both before and after the beginning of irrigation.

To test this conjecture, we sought irrigation areas meeting the following requirements:

(a) Located in semiarid watersheds.

(b) Undergo a well defined change from unirrigated to heavily irrigated conditions.

(c) Availability of weather stations with long rainfall records located at the downwind (mean summer wind direction) adjacent mountains (see Fig. 1).

(d) Display a homogeneous irrigated land scheme with a high irrigation water demand in summer.

2 Methods

We selected two irrigation areas (Fig. 1):

2.1 Study zones

The main premise of the study is that irrigation in the plains causes an increase in summer precipitation at the adjacent downwind mountains: (1) Upper and Lower Vegas (ULV), and (2) Lower Guadalquivir (LG). These zones are separated by the Sierra Morena range, which stretches for 400 km East-West across southern Spain, forming the border of the central plateau (Meseta Central) of Iberia, and acting as a divide between the valleys of the Guadiana River to the north and the Guadalquivir River to the south.

The ULV irrigated land is located in the province of Badajoz, along the main course of the Guadiana River (Fig. 1). Irrigation started in 1963, as part of the "Badajoz" regional development plan. Several reservoirs were built in the Guadiana River and its main tributaries. Additionally, a dense irrigation network was set up. Access to large volumes of water became easy, and traditional agriculture changed to intensive farming in the region. Some 121.000 ha are irrigated nowadays with an endowment of 8500 m^3/ha/yr, giving a mean annual irrigation volume of 1028 hm^3. The predominant wind direction during the summer is from northwest (Font and I. N. M., 1983), as the Atlantic air flows towards the north side of Sierra Morena and its minor ranges that run transversely from NW to SE (i.e. mountain ranges of Monsalud, Rinconada or Tudia to name a few). We have selected 11 meteorological stations (all that have long rainfall records) located in these minor mountains ranges (dark red rhombus). Additionally, two meteorological stations located in the plains surrounding the irrigation land will be used as reference stations (light blue rhombus).

The LG irrigated land belongs to the lower part of the Guadalquivir River Basin. It is located in the left side of the river, close to the city of Seville (Fig. 1). Irrigated agriculture had been traditionally practised for hundred of years in this zone. A surface of some 60 000 ha, with a mean endowment of 9300 m^3/ha/yr, yielding a mean annual irrigation volume of 558 hm^3. The latter represents half of the irrigation water volume applied in the ULV irrigated land. Wind blows predominantly from the southwest during the summer (Font and I. N. M., 1983), partly because of the geography and proximity of the Guadalquivir River (Robinson, 1984). This wind direction carries irrigation moisture towards the minor ranges that run the south face of Sierra Morena from NW to SE transversely (i.e. mountain ranges of Castillo, Cabras, and Alcudia among others). Long rainfall records are available at 7 meteorological located in these mountains downwind of the irrigation lands (dark red circles in Fig. 1). Three reference stations (light blue circles) have been selected in the valley for comparison.

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Both areas can be considered semiarid with annual rainfall hardly reaching 550 mm and potential evaporation close to 1000 mm. Irrigation demand in both areas concentrates during the summer, which is very dry (Fig. 2).

2.2 Statistical analysis

Preliminary inspection of the observed meteorological data provides some evidences that summer rainfall has changed after irrigation in terms of both occurrence (Fig. 3) and volume (Fig. 4).

Temporal evolution of the summer months (June, July and August) precipitation displays a clear difference between a reference meteorological station (Badajoz), and Barcarrota, which is located in the mountains downwind the ULV irrigation land (Fig. 3). The frequency of dry months looks unaffected by the beginning of irrigation. However, a clear decrease in the frequency of dry months can be observed at Barcarrota.

Figure 4 displays the mean monthly precipitation for June, July and August, before and after the Irrigation Transition Period, at both reference and mountains downwind stations. Reference stations show a slight decrease, whereas rainfall volume tends to increase at meteorological stations located in the mountains downwind of the irrigation lands.

In view of these observations, three different statistics will be analyzed:

1. Variation of mean rainfall ΔP.

2. Ratio of monthly precipitation to annual precipitation Δr.

3. Number of minimum rainfall episodes ΔP_{min}, i.e. days with total rainfall below 2 mm.

A test of significance is performed for these three statistics to determine whether the irrigation has a statistically significant effect on the response variable (i.e. ΔP, Δr or

ΔP_{min}) or not. The null and alternative hypotheses are:

- H_0:μ_B=μ_A the mean value of the response variable before (μ_B) and after (μ_A) the irrigation transition period does not change.
- H_1:H_0 is false.

The test of significance is a well known technique (O'Mahony, 1986; Moore, 1995; Spiegel and Stephens, 1999; to name a few). Therefore, only a brief summary is outlined below.

Let consider two random samples of sizes N_1 and N_2 that are drawn from two normal populations $N(\mu_1,\sigma_1)$ and $N(\mu_2,\sigma_2)$. Let consider further that these two samples have means given by m_1 and m_2 and standard deviations given by s_1 and s_2, respectively. To test the hypothesis H_0 that both samples come from the same population $N(\mu,\sigma)$ (i.e. $\mu_1 = \mu_2 = \mu$ as well as $\sigma_1 = \sigma_2 = \sigma$) is used the t-score given by

$$t = \frac{m_1 - m_2}{\sigma\sqrt{\left(\frac{1}{N_1} + \frac{1}{N_2}\right)}} \tag{1}$$

where

$$\sigma = \frac{N_1 s_1^2 + N_2 s_2^2}{N_1 + N_2 - 2} \tag{2}$$

The t-score follows is a Student's t distribution with ν=N1+N2-2 degrees of freedom. This distribution is given by

$$Y_\nu(t) = \frac{\Gamma\left(\frac{\nu+1}{2}\right)}{\sqrt{\nu\pi}\,\Gamma\left(\frac{\nu}{2}\right)}\left(1 + \frac{t^2}{\nu}\right)^{-\frac{\nu+1}{2}} \tag{3}$$

It is possible to test the null hypothesis H_0 respect to any critical limit P_c and its corresponding critical level t_c (see Eq. 4) for a given $Y_\nu(t)$. H_0 is accepted if t-score lies inside the interval $-t_\mathrm{c}$ to $-t_\mathrm{c}$ and is rejected otherwise.

$$P_\mathrm{c} = \int_{-t_\mathrm{c}}^{t_\mathrm{c}} Y_\nu(t)dt \tag{4}$$

3 Results

Tables 1 and 2 summarise results for ULV and LG irrigation lands, respectively. These tables provide the mean values of the three statistics for every meteorological station, lighting when the increments are statistically significant. Additionally, monthly mean values of the statistics are provided by grouping reference stations (RSs), and stations located in the mountains downwind of irrigation land (MSs).

Simple inspection of these tables reveals a different behaviour of MSs and RSs. Mean values tend to increase at the former, but decrease at the latter. This result suggests that irrigation affects the way it rains in the neighbouring downwind mountains, probably modifying the synoptic climate structure and trend at the local scale.

The variation of mean rainfall at MSs in ULV shows a common positive variation in June and July. In August, the general trend in ΔP is ambiguous, even showing statistical significant decreases in the meteorological stations of Barcarrota, Freguenal de la Sierra and Santos de Maimona. Analogously, the variation at MSs in LG also implies rainfall increases during June and July, and an unclear trend in August. Nevertheless, variations at LG do not have the same statistical significance than in the case of ULV. The difference might be explained by the smaller irrigation surface, and applied irrigation volume in the lower Guadalquivir irrigation land. After the irrigation transition period, ΔP shows an almost general positive variation in the meteorological stations located in the mountains downwind of both irrigation lands (80% and 76% cases in ULV and LG, respectively). The mean summertime ΔP in ULV is 5 mm, and 2.7 mm in LG. The ratio between ΔP in ULV and LG is 1.85. This value is very close to the ratio between the mean annual irrigation volumes in ULV and LG, which equals 1.84. In the reference stations, ΔP behaves clearly different, showing mean decreases of 2.2 mm in both study zones.

The ratio of monthly precipitation to annual precipitation at MSs in ULV and LG increases in 87% and 81% of cases, respectively. Increments are larger in June and July than in August. The mean summertime Δr is 1.10% in ULV and 0.67% in LG. The ratio between Δr in ULV and LG is 1.64, being also close to the ratio between the mean annual irrigation volumes in ULV and LG. This result indicates that rainfall in summer is increasing respect to the mean annual precipitation. As a result, summer has become wetter at MSs after the irrigation transition period. Mean summertime Δr decreases 0.1% at the reference stations in both study zones.

The statistic ΔP_{min} investigates whether the irrigation increases frequency of minimum rainfall episodes (e.g. event precipitation larger than 2 mm). Tables 2 and 3 show positive ΔP_{min} at MSs in 85% of cases at both ULV and LG. The mean summertime ΔP_{min} is 11.5% in ULV and 10.9% in LG. As can be shown, there are a number of positive increments with statistically significance after the irrigation transition period, that are observed in June and July, but also in August. This result indicates that the positive variation in ΔP during the summer results from a net increase in ΔP_{min} rather than sporadic large rainfall episodes. The latter would give an increase in ΔP but not in ΔP_{min}. Therefore, the joint increment in ΔP and ΔP_{min} after the irrigation transition period denotes an increase in the number of minimum rainfall months. The variation in ΔP_{min} at the reference stations is analogous to the variation obtained for the other two statistics. Mean summertime ΔP_{min} decreases 1.17% and 5.13% at the reference stations in ULV and LG, respectively.

It is unclear whether the decrease in rainfall at RSs is mechanistically linked to the increase at MSs. On one hand, the vertical fluxes associated to evaporation might cause a reduction in rainfall at the valleys. On the other, significant decreases in rainfall during the second half of the XXth century have been reported (Ayala-Carcedo, 1996; Esteban-Parra et al., 1998) and linked to global climate change.

4 Conclusions

Irrigation impacts rainfall at the basin scale, causing an increase in precipitation at the adjacent mountains located downwind of the Upper and Lower Vegas and Lower Guadalquivir irrigation lands. In the case of ULV the mean variations in ΔP are 8.5 mm, 5.4 mm and 1.1 mm for June, July and August, respectively. In the case of LG the same monthly mean ΔP variations are 3.2 mm, 3.9 mm and 0.9 mm. Increments in precipitation have greater statistical significance in June and July than in August. This corroborates the controversial findings of Barnston and Schickedanz (1984) in the Texas Panhandle region of the Great Plains.

The increase in rainfall is distributed over a broad region. Therefore, it is not sufficient to generate runoff and increase available water resources. However, it is sufficient to increase the specific weight of summer precipitation respect to the other seasons. The obtained mean monthly Δr variations at MSs in ULV are 2.6%, 0.5% and 0.2% for June, July and August, respectively. In the case of LG the same monthly mean Δr variations are 1.2%, 0.7% and 0.1%. Mean variations in Δr display also greater statistical significance in June and July than in August.

Modelling studies indeed predict that irrigation causes an increase in rainfall due to the soil moisture-atmosphere interaction. In this regard we have obtained ΔP and Δr mean variations in MSs that are proportional to the mean annual water volume applied in the neighbouring upwind located irrigation lands. This result might help to reduce the modelling uncertainty in the simulated strength of the irrigation-rainfall feedback (Guo et al., 2006), and lends support to climate models, whose credibility is a controversial issue in itself (Koutsoyiannis et al., 2009).

After the irrigation transition period, summers at MSs in the mountains downwind the irrigation lands have become wetter. Irrigation has increased the number of summer months with a cumulated precipitation larger than 2 mm. The obtained mean monthly ΔP_{min} variations at MSs in ULV are 8.3%, 13.4% and 12.7% for June, July and August, respectively. In the case of LG the same monthly mean ΔP_{min} variations are 6.0%, 16.1% and 10.7%. Variations are statistically significant in the three months. The joint positive variation in ΔP and ΔP_{min} after the irrigation transition period denotes an increase in the net number of minimum rainfall months.

The different trend observed in MSs and RSs for the three selected statistics, reveals that irrigation-precipitation feedback may locally induce rainfall in-homogeneities inside a given synoptic rainfall/climate trend. It should be noted that the values of the statistics from the reference weather stations decreased. Such behavior, throughout southern Spain, has been regarded by Ayala-Carcedo (1996) and Esteban-Parra et al. (1998) as an early warning of the predicted climate change.

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References

Ayala-Carcedo, F. J.: Reducción de los recursos hídricos en España por el posible cambio climático, Tecno ambiente, 64, 43–48, ISSN 1133-4665, 1996 (in Spanish).

Barnston, A. G. and Schickedanz, P. T.: The effect of irrigation on warm season precipitation in the southern Great Plains, J. Clim. Appl. Meteorol., 23, 865–888, 1984.

Boucher, O., Myhre, G., and Myhre, A.: Direct human influence of irrigation on atmospheric water vapour and climate, Clim. Dynam., 22, 597–603, doi:10.1007/s00382-004-0402-4, 2004.

Eltahir, E. A. B.: A soil moisture-rainfall feedback mechanism. 1. Theory and observations, Water Resour. Res., 34(4), 765–776, 1998.

Esteban-Parra, M. J., Rodrigo, F. S., and Castro-Diez, Y.; Spatial and temporal patterns of precipitation in Spain for the period 1880–1992, Int. J. Climatol., 18, 1557–1574, 1998.

Fowler, W. B. and Helvey, J. D.: Irrigation increases rainfall? (response), Science, 188, 281 pp., 1975.

Guo, Z., Dirmeyer, P. A., Koster, R. D., Bonan, G., Chan, E., Cox, P., Gordon, C. T., Kanae, S., Kowalczyk, E., Lawrence, D., Liu, P., Lu, C. H., Malyshev, S., Mcavaney, B., Mcgregor, J. L., Mitchell, K., Mocko, D., Oki, T., Oleson, K. W., Pitman, A., Sud, Y. C., Taylor, C. M., Verseghy, D., Vasic, R., Xue, Y., and Yamada, T.: GLACE: The Global Land–Atmosphere Coupling Experiment. Part II: Analysis, J. Hydrometeorol., 7, 611–625, 2006.

Font, I. and I. N. M. (Instituto Nacional de Meteorología): Atlas climático de España, edited by: Ministerio de Transportes-Turismo y Comunicaciones and I. N. M., Madrid, 43 pp., 1983.

Koster, R. D., Dirmeyer, P. A., Guo, Z., Bonan, G., Chan, E., Cox, P., Gordon, C. T., Kanae, S., Kowalczyk, E., Lawrence, D., Liu, P., Lu, C. H., Malyshev, S., McAvaney, B., Mitchell, K., Mocko, D., Oki, T., Oleson, K., Pitman, A., Sud, Y. C., Taylor, C. M., Verseghy, D., Vasic, R., Xue, Y., and Yamada, T.: Regions of strong coupling between soil moisture and precipitation, Science, 305, 1138–1140, doi:10.1126/science.1100217, 2004.

Koster, R. D., Guo, Z.-C., Dirmeyer, P. A., Bonan, G., Chan, E., Cox, P., Gordon, C. T., Kanae, S., Kowalczyk, E., Lawrence, D., Liu, P., Lu, C.-H., Malyshev, S., McAvaney, B., Mitchell, K., Mocko, D., Oki, T., Oleson, K., Pitman, A., Sud, Y. C., Taylor, C. M., Verseghy, D., Vasic, R., Xue, Y., and Yamada, T.: GLACE: The Global Land-Atmosphere Coupling Experiment: Part 1: Overview, J. Hydrometeorol., 7, 590–610, doi:10.1175/JHM510.1, 2006

Koutsoyiannis, D., Makropoulos, C., Langousis, A., Baki, S., Efstratiadis, A., Christofides, A., Karavokiros, G. and Mamassis, N.: *HESS Opinions*: "Climate, hydrology, energy, water: recognizing uncertainty and seeking sustainability", Hydrol. Earth Syst. Sci., 13, 247–257, doi:10.5194/hess-13-247-2009, 2009.

Lin, Y. L., Chiao, S., Wang, T. A., Kaplan, M. L., and Weglarz, R. P.: Some common ingredients of heavy orographic rainfall, Weather Forecast., 16, 633–660, 2001.

Moore, D. S.: The Basic Practice of Statistics, edited by: Freeman, W. H. and Co., New York, 1995.

Moore, N. and Rojstaczer, S.: Irrigation-induced rainfall and the Great Plains, J. Appl. Meteorol., 40, 1297–1309, 2001.

Moore, N. and Rojstaczer, S.: Irrigation's Influence on Precipitation: Texas High Plains, U.S.A., Geophys. Res. Lett., 29(16), 1755, doi:10.1029/2002GL014940, 2002.

O'Mahony, M.: Sensory Evaluation of Food: Statistical Methods and Procedures, CRC Press, New York, 492 pp., 1986.

Pielke Sr., R. A., Adegoke, J., Beltran-Przekurat, A., Hiemstra, C. A., Lin, J., Nair, U. S., Niyogi, D., and Nobis, T. E.: An overview of regional land-use and land-cover impacts on rainfall, Tellus B, 59, 587–601, 2007.

Robinson, E.: Dispersion and fade of atmospheric pollutants, in: Air Pollution and Plant Life, edited by: Treshow, M., Wiley, New York, 15–37, 1884.

Smith, R. B.: The influence of mountains on the atmosphere, Academic Press, Adv. Geophys., 21, 87–230, 1979.

Smith, R. B., Paegle, J., Clark, T., Cotton, W., Forbes, G., McGinley, J., Pan, H. L., and Ralph, M.: Local and remote effects of mountains on weather: Research needs and opportunities, B. Am. Meteorol. Soc., 78, 877–892, 1997.

Spiegel, M. and Stephens, L.: Schaum's outlines of Statistics, 3rd edn., McGraw-Hill, New York, 538 pp., 1999.

Stidd, C. K., Fowler, W. B., and Helvey, J. D.: Irrigation increases rainfall?, Science, 188(4185), 279–280, 1975.

Zheng, X. and Eltahir, E. A. B.: A soil moisture-rainfall feedback mechanism. 2. Numerical experiments, Water Resour. Res., 34(4), 777–785, 1998.

Table 1. Variation of monthly precipitation (ΔP), ratio of monthly to annual precipitation (Δr), and minimum rainfall (ΔP_{min}) after the Irrigation for Upper-Lower Vegas. NB and NA stand for the number of meteorological stations with available data used in the analysis before and after the Irrigation Transition Period, respectively. Grey shaded cell mean that the variation is statistically significant.

			ΔP (mm/month)			Δr (%)			ΔP_{min} (%)		
	Code	(NB/NA)	Jun	Jul	Aug	Jun	Jul	Aug	Jun	Jul	Aug
Downwind stations											
Barcarrota	A	(24/37)	10.3	2.0	–4.1	2.5	0.4	–1.0	31.8	23.1	18.0
Cabeza del Buey	B	(25/35)	6.5	4.6	–0.2	1.9	0.6	0.1	–17.7	1.1	0.0
Fregenal de la Sierra	C	(17/38)	4.3	3.5	–7.0	1.2	0.5	–0.9	14.3	9.8	10.2
Helechal	D	(14/34)	12.8	1.9	4.5	2.8	0.3	1.0	4.3	33.7	27.8
Los Santos de Maimona	E	(19/34)	7.1	2.9	–2.7	2.7	0.4	–0.2	18.2	14.7	2.6
Malpartida de la Serena	F	(14/38)	3.9	7.7	0.7	2.5	1.2	0.2	10.1	22.6	25.9
Monterrubio de la Serena	G	(14/39)	12.2	5.7	2.3	3.2	0.9	0.4	15.0	8.7	19.1
Puerto Hurraco	H	(20/38)	10.0	3.9	7.6	3.9	0.2	0.8	15.8	–5.3	10.5
Valle Serena	I	(14/39)	2.8	4.6	1.5	1.7	0.9	0.3	–11.0	21.5	14.0
Valverde de Llerena	J	(18/37)	13.5	–1.9	–0.3	3.1	–0.3	0.1	7.8	6.2	2.6
Mean increment			8.5	5.4	1.1	2.6	0.5	0.2	8.3	13.4	12.7
Reference stations											
Badajoz	K	(73/39)	–3.2	–1.0	–0.1	–0.1	–0.2	0.1	–6.5	–1.8	2.0
Usagre	L	(23/39)	–0.4	–1.4	–7.3	1.1	–0.1	–1.0	4.7	–1.9	–3.5
Mean increment			–1.8	–1.2	–3.7	0.5	–0.2	–0.5	–0.9	–1.9	–0.7

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Table 2. Variation of monthly precipitation (ΔP), ratio of monthly to annual precipitation (Δr), and minimum rainfall (ΔP_{min}) after the Irrigation for Lower Guadalquivir. NB and NA stand for the number of meteorological stations with available data used in the analysis before and after the Irrigation Transition Period, respectively. Grey shaded cell mean that the variation is statistically significant.

			ΔP (mm/month)			Δr (%)			ΔP_{min} (%)		
	Code	(NB/NA)	Jun	Jul	Aug	Jun	Jul	Aug	Jun	Jul	Aug
Downwind stations											
Bélmez	a	(26/28)	3.7	1.8	–2.1	**1.4**	**0.4**	–0.2	3.1	**9.8**	**19.2**
Espiel	b	(24/29)	1.5	**5.4**	–0.8	0.7	**0.9**	0.1	–4.1	**32.1**	5.1
Fuenteobejuna	c	(26/31)	4.0	**8.0**	4.3	1.5	**1.5**	**0.6**	–3.3	**27.1**	**13.6**
Hinojosa del Duque	d	(28/28)	4.1	**6.0**	–1.9	0.8	**1.1**	–0.3	10.7	**11.0**	**7.2**
Pantano Guadalmellato	e	(56/23)	1.9	**2.2**	0.2	1.0	**0.1**	0.1	3.0	**17.9**	**10.8**
Peñarroya	f	(53/9)	6.3	–1.8	7.8	2.8	–0.2	**0.7**	27.3	–6.1	**8.6**
Pozoblanco	g	(48/29)	0.9	**5.6**	–1.3	0.1	**1.1**	–0.1	5.6	**21.1**	**10.1**
Mean increment			3.2	3.9	0.9	1.2	0.7	0.1	6.0	16.1	10.7
Reference stations											
Córdoba	h	(15/23)	–5.8	–1.4	0.1	–0.1	–0.2	0.1	**–10.0**	**–8.4**	**10.0**
San Fernando	i	(108/23)	–3.6	–1.0	**–1.1**	–0.1	**–0.2**	–0.1	**–10.7**	**–10.1**	–1.1
Sevilla	j	(23/27)	–8.7	**2.2**	**–1.4**	–0.6	0.2	0.3	**–23.4**	7.1	0.5
Mean increment			–6.0	–0.1	–0.8	–0.3	–0.1	0.1	–14.7	–3.8	3.1

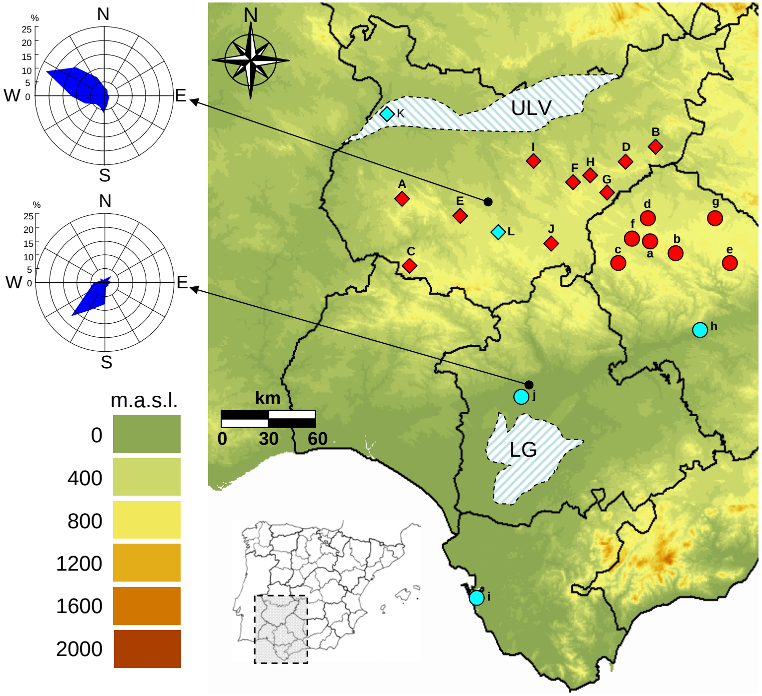

Fig. 1. Map of the study areas showing the location of the Upper and Lower Vegas (ULV), and Lower Guadalquivir (LG) irrigation lands (IL) and their corresponding summer wind rose. Diamond and circle symbols mean ULV and LG meteorological stations, respectively. Red symbols stand for meteorological stations located in mountains downwind the IL. Light blue symbols correspond to meteorological stations located in the plains. The alphabetical codes used to identify the meteorological stations are provided in Tables 1 and 2.

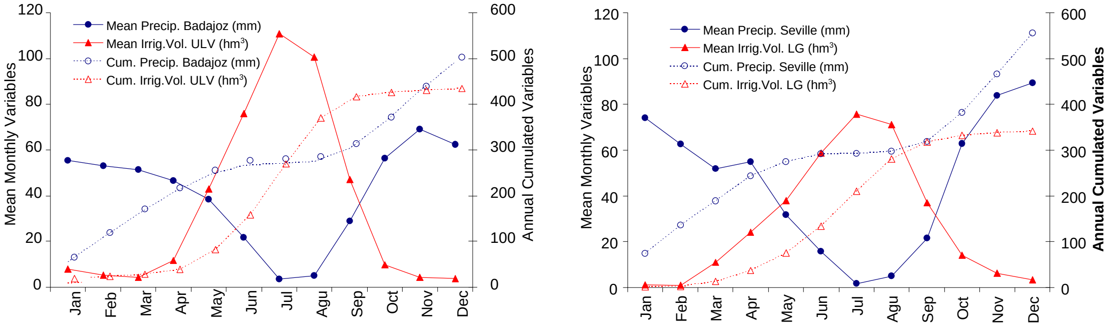

Fig. 2. Monthly distribution of precipitation and applied Irrigation Volumes in the Upper and lower Vegas (left) and the Lower Guadalquivir irrigation land (right). Solid symbols refer to the variables and empty symbols to their corresponding cumulated value. The averaging period for precipitation goes from 1890 to 2001 in the ULV, and from 1951 to 2001 in the LG. The averaging period for irrigation volume goes from 1963 to 2001 in the ULV, and from 1971 to 2001 in the LG.

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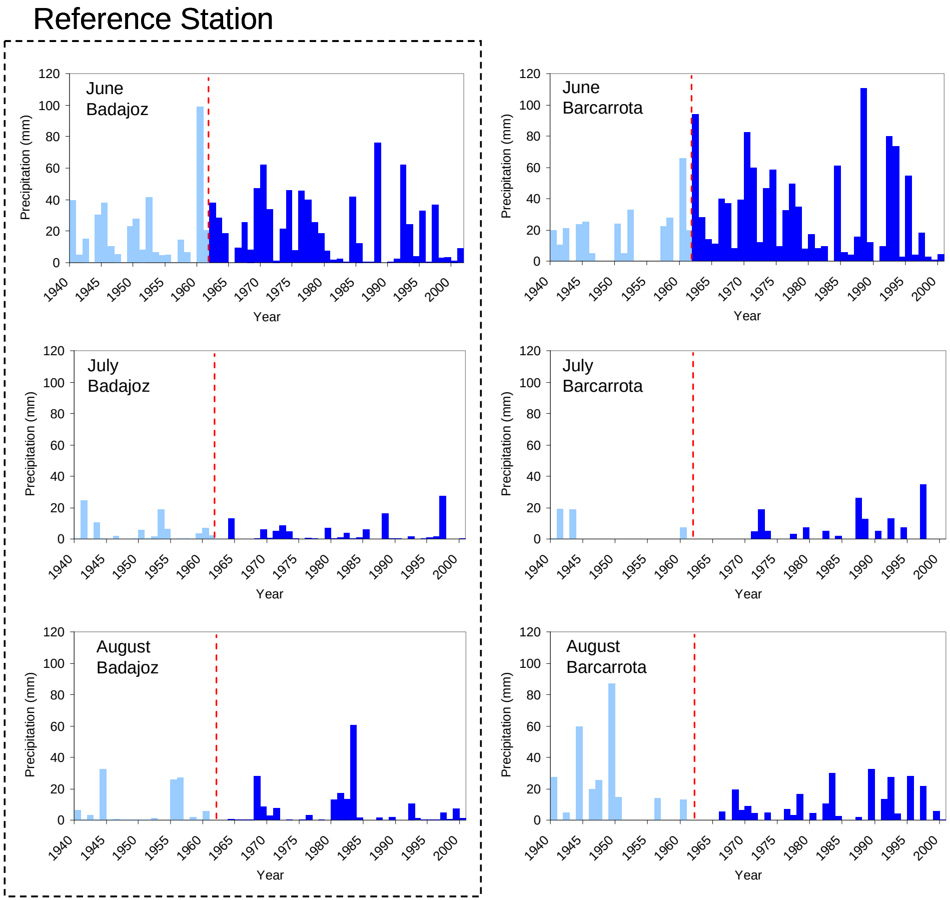

Fig. 3. Temporal evolution of the cumulated precipitation for the months of June, July and August, measured in both, the reference meteorological station of Badajoz (left), and the meteorological station of Barcarrota (right), which is located in the adjacent mountains downwind ULV. The dashed red line indicates the beginning of the Irrigation Transition Period.

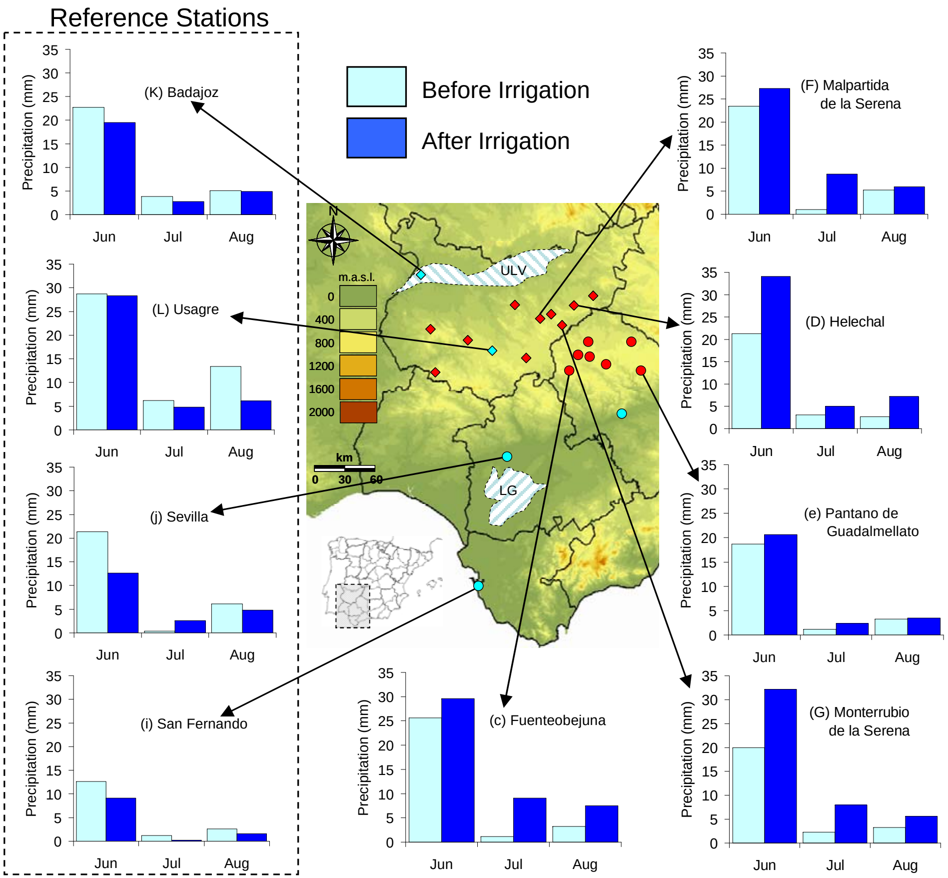

Fig. 4. Mean summer (June, July and August) precipitation before (light blue) and after (dark blue) the Irrigation Transition Period for some reference stations (left side inside the dashed box) and other measuring points located in the mountains downwind of the ULV and LG irrigation areas.

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