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The influence of large dams on surrounding climate and precipitation patterns

Ahmed Mohamed Degu,[1] Faisal Hossain,[1] Dev Niyogi,[2] Roger Pielke Sr.,[3] J. Marshall Shepherd,[4] Nathalie Voisin,[5] and Themis Chronis[6]

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[1] Understanding the forcings exerted by large dams on local climate is key to establishing if artificial reservoirs inadvertently modify precipitation patterns in impounded river basins. Using a 30 year record of reanalysis data, the spatial gradients of atmospheric variables related to precipitation formation are identified around the reservoir shoreline for 92 large dams of North America. Our study reports that large dams influence local climate most in Mediterranean, and semi-arid climates, while for humid climates the influence is least apparent. Clear spatial gradients of convective available potential energy, specific humidity and surface evaporation are also observed around the fringes between the reservoir shoreline and farther from these dams. Because of the increasing correlation observed between CAPE and extreme precipitation percentiles, our findings point to the possibility of storm intensification in impounded basins of the Mediterranean and arid climates of the United States.

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1. Introduction

[2] Large dams (according to the International Commission on Large Dams (ICOLD), a large dam is defined as one with an embankment height of more than 15 meters or a storage volume exceeding 3 million m^3) and their impounded reservoirs are types of infrastructures that trigger most often a large-scale change in land use and land cover (LULC) due to the multiple purposes they serve. With the construction of a dam, more arable land may be irrigated with impounded surface water and the downstream regions may become more urbanized due to a reduced risk of flooding and the increased availability of products and electricity. Such systematic changes to land cover can lead to increased availability of local moisture and significantly impact mesoscale circulation [*Niyogi et al.*, 2010; *Takata and Yasunari*, 2009]. Herein, we refer to mesoscale as essentially 'local' and between the ranges of 10–100 km. One such local effects of LULC change can be a modification of rainfall [*Avissar and Liu*, 1996; *Cotton and Pielke*, 2007; *Pielke et al.*, 2009]. Thus, if dams are regarded as a catalyst for systematic change in LULC, then it is physically plausible to expect a gradual change in the local climate and rainfall patterns in the impounded river basin attributed directly to the multiple land use development that reservoirs produce.

[3] While the impact of climate variability and change on artificial reservoirs has been studied at local/regional scales for some time [see, e.g., *Hamlet and Lettenmaier*, 1999; *Christensen et al.*, 2004], the converse (impact of reservoirs on local/regional climate) has not been explored as much. It has been recently argued that very little is known on how artificial reservoirs (hereafter interchanged with 'dam') modify storms under certain atmospheric conditions and the consequential implication on hydrology and dam safety [*Hossain et al.*, 2010; *Hossain*, 2010]. Dam design in engineering assumes as "stationary" the design parameters of extreme rainfall during its service span, a practice that is now being increasingly questioned and researched for better methods [*Milly et al.*, 2008; *Villarini et al.*, 2009]. Understanding the influence exerted by large dams on the surrounding (local) climate is therefore key to establishing if artificial reservoirs inadvertently modify precipitation patterns in impounded river basins. In this study we therefore seek an answer to the open question – *What is the influence of large dams on local climate and the probable effect on precipitation patterns?*

2. Study Region, Data and Methods

[4] Using a database of dams from the Global Water Systems Project Digital Water Atlas [*GWSP Digital Water Atlas*, 2008], we studied ninety-two (92) large dams located in various Koppen-Geiger climate zones of the United States (Figure 1) [*Peel et al.*, 2007]. To understand the potential land cover changes near the dams, we also identified the main purpose of each dam as belonging to one of three broad categories (irrigation, hydropower and 'other'). Here, 'other' includes applications such as flood control, domestic water supply and recreation. Our premise is that the existence of a dam is a necessary (if not sufficient) indicator of land cover change near reservoirs and can therefore help explain features of our observational findings. For example, irrigation-based dams result in intensified agriculture near reservoirs, whereas hydropower dams most likely contribute to only sporadic land cover change through urbanization.

[1]Department of Civil and Environmental Engineering, Tennessee Technological University, Cookeville, Tennessee, USA.
[2]Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, Indiana, USA.
[3]CIRES, University of Colorado at Boulder, Boulder, Colorado, USA.
[4]Department of Geography, University of Georgia, Athens, Georgia, USA.
[5]Pacific Northwest National Laboratory, Richland, Washington, USA.
[6]Hellenic Center for Marine Research, Anavyssos, Greece.

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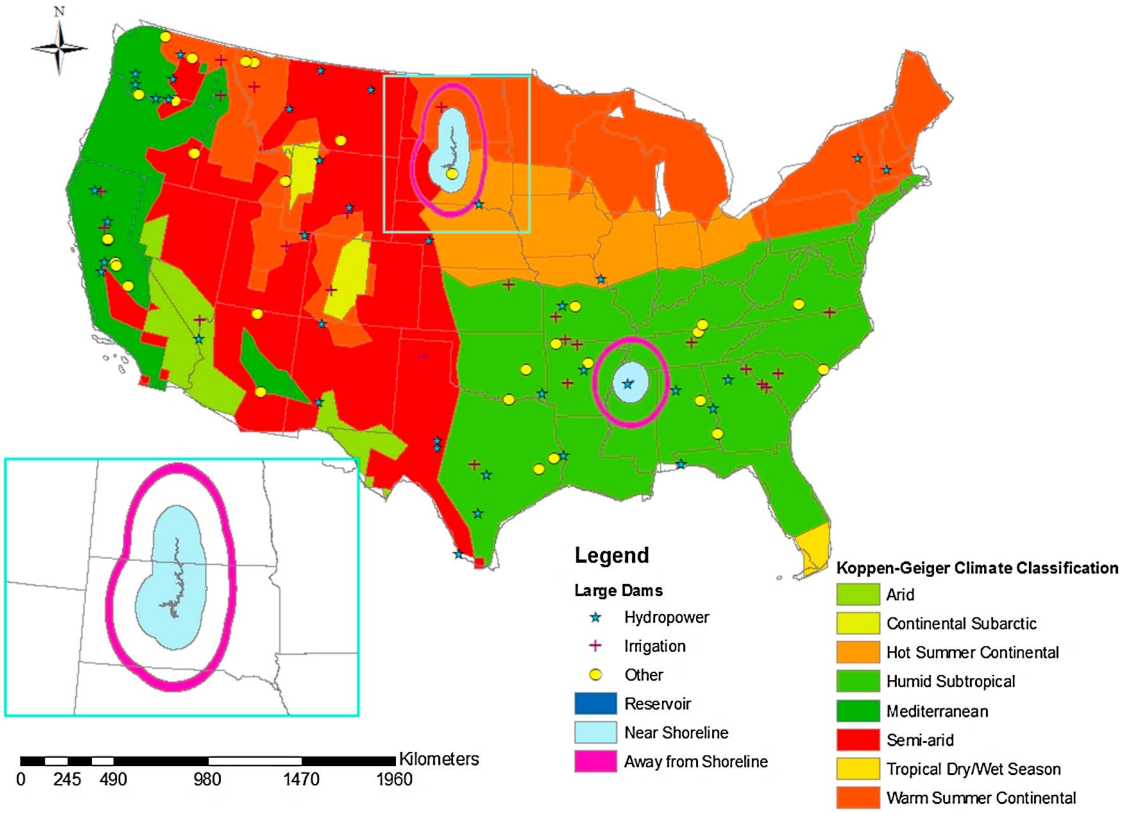

Figure 1. Location of the ninety-two large dams used in the study. Each colored region represents a climate zone according to the Koppen-Geiger classification. Symbols indicate the main purpose of the dam. The three spatial bands for elucidating the influence of large dams on local climate are also shown.

[5] For the atmospheric observational record, variables considered relevant to mesoscale precipitation patterns were obtained from the National Center for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR) data base [*Mesinger et al.*, 2006]. These variables were: 1) Convective Available Potential Energy (CAPE; in Joules/kg); 2) specific humidity (kg/kg); and 3) surface evaporation (kg/m^2). Being a reanalysis product, NARR provides a quality-controlled, finer-resolution atmospheric dataset over North America which can be used to develop an improved understanding of the influence of large dams on surrounding climate patterns as diagnosed by CAPE, specific humidity, and surface evaporation. We applied the NARR dataset at daily steps spanning a period from 1979 to 2009 (30 years). The data was available at the 32 km spatial grid intervals.

[6] We studied the climatology of the selected NARR variables for three spatial bands (Figure 1): 1) over the reservoir; 2) near the shoreline (a band between shoreline and 100 km away from the shoreline); and 3) away from the shoreline (a band starting at 100 km from the shoreline and extending beyond with approximately the same area as (2)). Each of the 92 large dams (Figure 1) was manually digitized around the shoreline to derive the bands in raster format for mapping to the corresponding NARR data. The first 100 km band (near shoreline) is considered as the region of climate change attributable mostly to the reservoir impact on mesoscale circulations (Figure 1).

[7] We focused on the 30 year daily average of the selected NARR variables. As a purely observational study, the objective was to identify detectable changes in the long-term magnitude of these variables and thereby elucidate the spatial gradients as one moved away from the reservoir. We also studied the climatology as a function of growing season (April–Oct) and non-growing season (Nov–March) because the impact of irrigation as a major forcing on local climate would likely be pronounced during the growing season.

3. Results and Discussion

[8] Figures 2a and 2b show the 30 year average spatial gradient (i.e., relative variation from one band to another) for the three selected atmospheric variables. This climatologic average is shown for the whole season and for a cross section of the large dams located in most climate zones of the US. It is evident that the large dams in Mediterranean climates exert the strongest influence (in terms of relative change in the surrounding area of the reservoir) on climate closer to the reservoir shoreline (compare band III with II or I with II in Figure 2a). Large dams in the humid subtropical climates of the Southeast seem to have a negligible influence on the local climate. Another aspect that emerges from Figure 2a is that all three variables appear clear first-order indicators of local climate change for large dams in Mediterranean climates, while the influence of dams on surface evaporation and specific humidity is relatively less detectable for other climates.

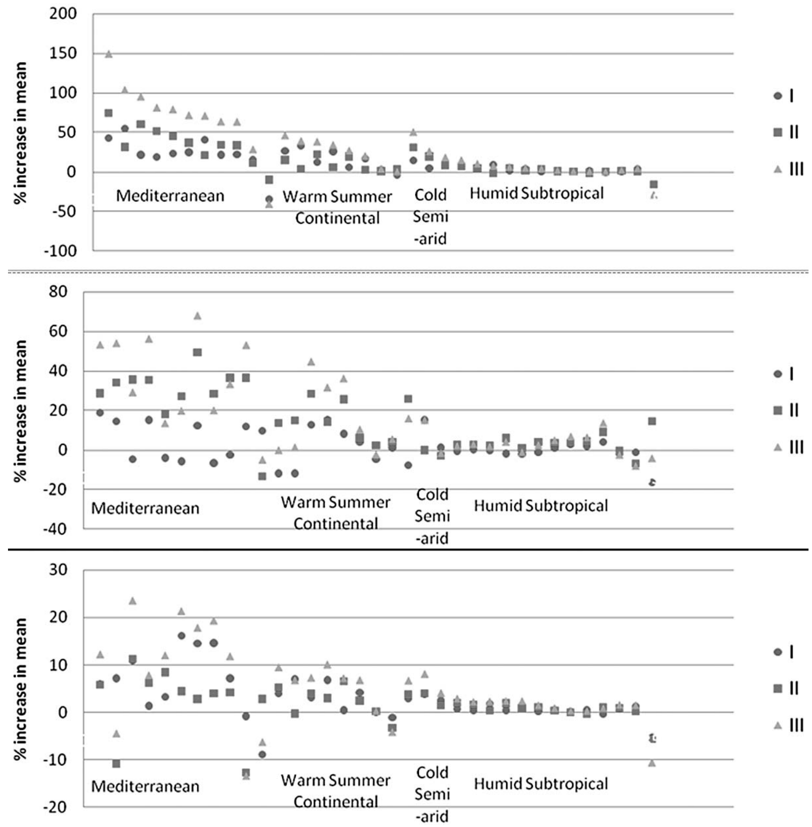

Figure 2a. Spatial gradients exerted by dams for the whole season (% increase of the 30 year climatologic mean from one spatial band to another). Each dam is represented on the x-axis for a specific scenario. The last three data points from right represent selected dams in hot summer continental and continental subarctic climate zones. (top) CAPE, (middle) surface evaporation, and (bottom) specific humidity. Scenario I − % *increase* = $\frac{\text{(Reservoir Band} - \text{Near Shoreline Band)}}{\text{Near Shoreline Band}} \times 100$. Scenario II − % *increase* = $\frac{\text{(Near Shoreline Band} - \text{Away from Shoreline Band)}}{\text{Away from Shoreline Band}} \times 100$. Scenario III − % *increase* = $\frac{\text{(Reservoir Band} - \text{Away from Shoreline Band)}}{\text{Away from Shoreline Band}} \times 100$.

[9] One way to interpret the findings more physically is to consider the sensible and latent heat fluxes for open water bodies and vegetated surfaces. Humid regions are forested and exhibit comparable moisture fluxes due to transpiration as from evaporation from open water bodies. Thus the clearing of a forest to create an artificial lake is unlikely to create a distinctly different local climate even with irrigation as seen at several irrigation dam locations in South Carolina, Georgia, Tennessee and Arkansas (Figure 1). For semi-arid and Mediterranean regions, the open water body of a reservoir, however, adds sufficiently more moisture than the sparsely vegetated surroundings, resulting in clear spatial gradients of water vapor flux for most dams in this type of climate.

[10] Being an observational study, a more mechanistic analysis is beyond the scope of this study without an atmospheric modeling approach. Interested readers may however refer to *Pielke* [2001] where a comprehensive mechanistic explanation is provided on the influence of spatial distribution of land use (such as irrigation) on CAPE, temperature and humidity. For a more large-scale and basin-wide mechanistic explanation of the water cycle components beyond the mesoscale, readers are also referred to the recent dam effect studies on the Aral sea [*Shibuo et al.*, 2007] and Indian Mahanadi river basin [*Asokan et al.*, 2010].

[11] To better visualize this spatial variation for the three contrasting climates, Figure 3 shows the time series of the 30-year climatology of CAPE for the three spatial scenarios for an example of dams located in Mediterranean, semi-arid and humid climates. The growing season clearly accentuates the difference in CAPE between the band nearest to the shoreline and that farther away from the shoreline for the Mediterranean climate. Figure 2b, on the spatial gradients for the growing season for dams in Mediterranean climates, demonstrate this point more universally. It also indicates (as does Figure 2a, band III) that the largest change in CAPE, surface evaporation and specific humidity exists between the fringes of the reservoir shoreline with region farther from the shoreline.

[12] As a follow-up to the above study on the influence of dams on local climate, we explored the corresponding influence on precipitation patterns using daily rainfall data from the Global Historical Climate Network (GHCN). The GHCN data is an archive for daily weather data from the global climate observing system (GCOS) Surface Network of the National Climatic Data Center (NCDC). This dataset is useful for analyzing activities related to the frequency and

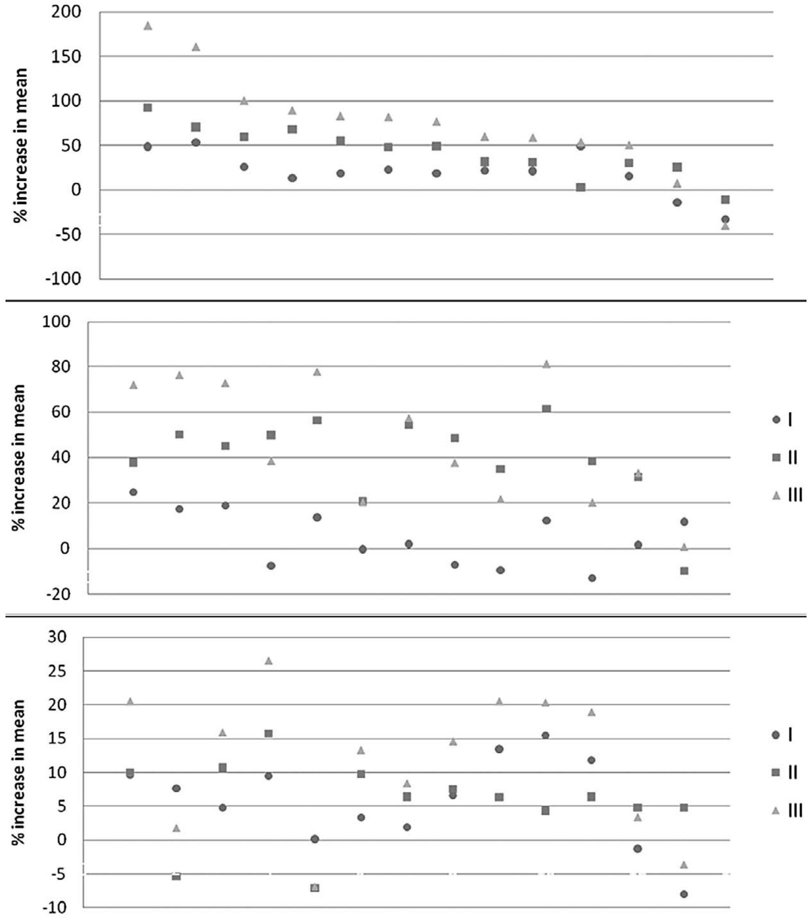

Figure 2b. Same as Figure 2a but for Mediterranean climate and the growing season.

magnitude of averages and extremes as it contains observations at more than 40,000 stations around the world. After an initial quality assessment, we identified a set of precipitation stations from the GHCN dataset that had more than 60 years of fairly continuous data for the US (see Table 1). Using a 30 year moving window, the 50th, 90th, 95th and 99th percentiles (P50, P90, P95 and P99, respectively) were calculated for each year up to the most current year of observation. From the time series of the percentiles, the stations closest to the dams that registered a systematic change (increase/decrease) were shortlisted (Table 1). This list is likely to include stations that have undergone a historical increase due to long-term changes in large scale weather patterns as has been demonstrated by *Cuo et al.* [2009]. However, the separation of such stations is beyond the scope of this study and may somewhat skew the results discussed hereafter.

[13] Figure 4 shows an example of two such shortlisted time series of percentile for GHCN station located closest to a dam. When assessing the systematic increase in the extreme percentiles (P90 and higher) with the dam construction year and the aforementioned NARR data analysis, it appears quite plausible that the systematic land use and land cover change triggered by the dam may have played a role in the modification of rainfall patterns. It is important to note that dams may not only initiate a systematic change in precipitation trends, but they may also accelerate an ongoing trend originating in the pre-dam era by providing additional moisture from changes in weather patterns. To make a preliminary generalization, Table 2 shows the overall correlation of the 30 year climatological value of CAPE (for band II – near the reservoir shoreline) with the average value of rainfall percentile for the shortlisted GHCN stations of Table 1 (3rd column from left). The increasing correlation with higher percentiles, that is also found to be statistically significant ($p < 0.05$) using the t-test, indicates that CAPE can be a reasonable first-cut proxy to attribute the changes in precipitation trends observed in the vicinity of a reservoir.

4. Conclusion

[14] *Are the spatial climatologic patterns around artificial reservoir significantly different than around those without dams but near natural river-wetland systems?* To answer this question, we performed a random sampling test for the case of Mediterranean and semi-arid climates. One hundred NARR pixels were sampled randomly. These samples were then divided into two categories: 1) those closest to a dam (within a 100 km radius) called 'dam pixels' and 2) those away from a dam (beyond 100 km) called 'no-dam pixels'. For the no-dam pixels, we further identified those that had more than 50% coverage by natural rivers and forested/non-forested wetlands system according the USGS Anderson

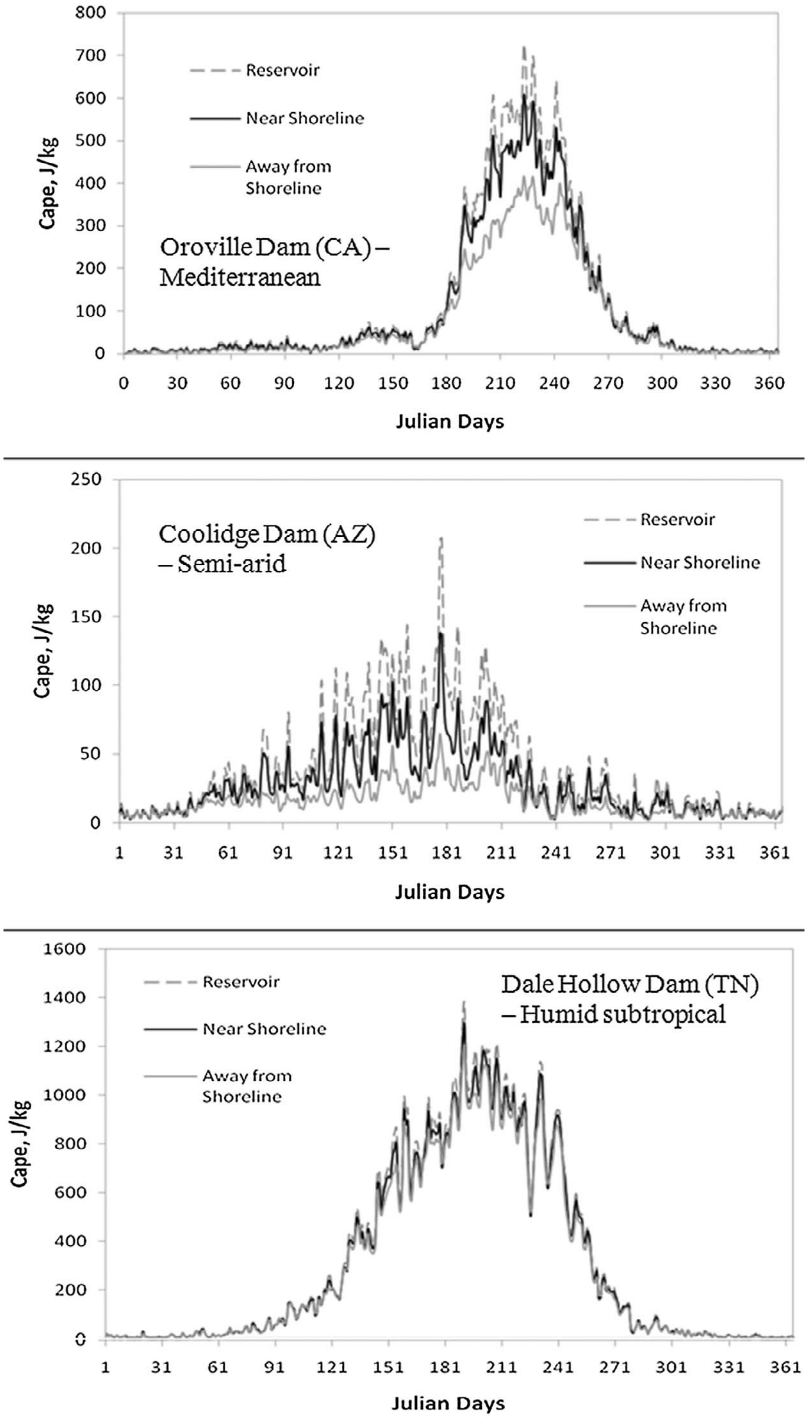

Figure 3. Spatial variation of CAPE around the reservoir shoreline for three dams located in contrasting climates.

Table 1. Number of GHCN stations in Arid, Continental Subarctic, Hot Summer Continental and Mediterranean Climates that were Analyzed for Detecting Change in Precipitation Percentiles

Climate	Total Number of Stations Analyzed	Number of Stations Showing Increase	Average Distance of Stations in Previous Column From the Nearest Dam (km)
Arid	142	17	183
Continental Subarctic	82	6	131
Hot Summer Continental	1071	54	265
Mediterranean	1009	75	115

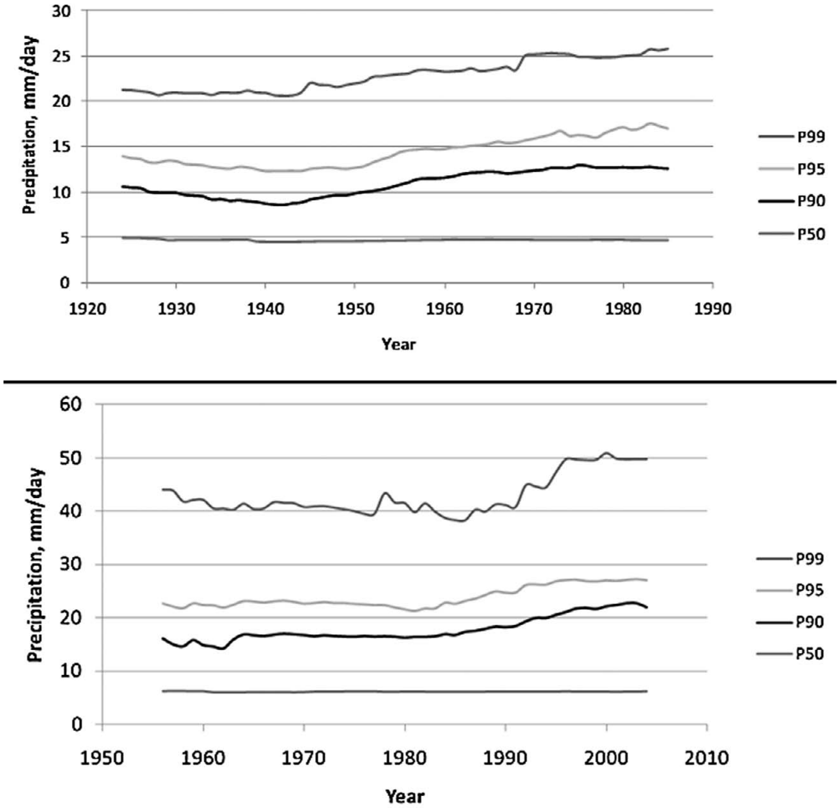

Figure 4. Time series of thirty-year average percentile value for P50, P90, P95 and P99 for GHCN station closest to a dam. (top) GHCN station USC00056513 located 72 kms from Blue Mesa Dam, CO in a continental subarctic climate (construction year 1965). (bottom) GHCN station USC00021514 located 106 kms from Coolidge Dam, AZ in a cold semi-arid climate (construction year 1929).

classification system [*Anderson et al.*, 1976]. This land classification system provides land cover data at a considerably smaller resolution (~30 m) than NARR. Hence, we identified only those no-dam NARR pixels with statistically significant distribution (>50% coverage) of natural rivers and wetlands. Figure 5 shows the CAPE values for these three categories of randomly selected pixels. It is seen that CAPE is found to be enhanced for the 'dam' region and is considerably higher than those with a significant distribution of natural rivers and wetlands. This lends credence to our observational finding that the influence of dams is detectable from the natural (pre-development) scenario for arid and Mediterranean climates.

[15] Today, there are more than 70,000 dams in the US capable of storing a volume of water almost equaling one year's mean runoff [*Graf*, 1999]. Around the world, the World Commission on Dams (WCD) reports widespread impoundment with about half the world's rivers having a dam along their reach [*World Commission on Dams*, 2000].

Table 2. Correlation Between the Average Rainfall Percentile Value and Climatological CAPE Value for Band II (Near Shoreline) for Shortlisted GHCN Stations of Table 1[a]

	Whole Season		Growing Season	
Percentiles	Correlation	p-Value	Correlation	p-Value
P50	0.52	9.33E-04	0.50	2.01E-03
P90	0.50	1.51E-03	0.48	3.04E-03
P95	0.51	1.07E-03	0.48	3.07E-03
P99	0.68	3.29E-06	0.65	2.12E-05

[a]Statistical significance test is according to the t-test and significant at 95% confidence level.

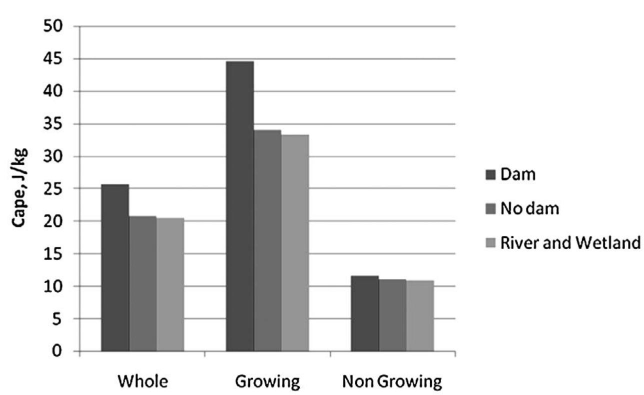

Figure 5. Average (30 year) CAPE value for randomly sampled NARR pixels in Mediterranean and semi-arid climates for three scenarios: 1) near dam within 100 km, 2) no dam within 100 km and 3) near river and wetlands. Scenario 3 represents NARR no dam pixels having more than 50% coverage of rivers and forested/non-forested wetlands. The growing and non-growing seasons refer to the period of April–Oct and Nov–March, respectively.

As we currently try to elucidate the physical role of dams on the inadvertent modification of the local climate and precipitation patterns, an important follow-up study is that of irrigation patterns in the impounded river basins [*Boucher et al.*, 2004; *Lobell et al.*, 2009]. Given that land cover is a first order forcing on local climate change [*Pielke et al.*, 2009], the historical chronology of irrigation patterns and other land cover types around multi-purpose reservoirs needs to be investigated with an atmospheric model to understand how heavy storms are physically modified (become more/less frequent or altered in average intensity). Our conclusion is that such a study will encourage dam building and operating agencies to embrace a more climate-centric mindset for water resources management where dams are regarded as an integral part of the forcings that modify local climate and water cycle variability.

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T. Chronis, Hellenic Center for Marine Research, PO Box 712, GR-19013 Anavyssos, Greece.

A. M. Degu and F. Hossain, Department of Civil and Environmental Engineering, Tennessee Technological University, 1020 Stadium Dr., Cookeville, TN 38505-0001, USA. (fhossain@tntech.edu)

D. Niyogi, Department of Earth and Atmospheric Sciences, Purdue University, Lilly Hall of Sciences, West Lafayette, IN 47907-2054, USA.

R. Pielke Sr., CIRES, University of Colorado at Boulder, Boulder, CO 80309-0216, USA.

J. M. Shepherd, Department of Geography, University of Georgia, Athens, GA 30602, USA.

N. Voisin, Pacific Northwest National Laboratory, PO Box 999, Richland, WA 99352, USA.