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Further evidence of impacts of large-scale wind farms on land surface temperature

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ABSTRACT

Large wind farms are power plants that generate clean energy from a renewable source. They are increasingly being installed and operated to replace and complement fossil fuel power plants in an effort to help reduce greenhouse and other pollutant emissions (American Wind Energy Association, 2012 [1]; American Wind Energy Association, 2011 [2]; Global Wind Energy Council, 2011 [3]; US Department of Energy, 2008 [4]; Wiser et al., 2007 [5]). Wind energy can have a positive economic impact and numerous locations on the planet are good candidates for wind energy production. Any direct environmental impact of large-scale wind farms needs to be investigated because it could impact agriculture, economics, health, society, and technology. A recent study showed that surface temperature is observed to increase directly downwind of large wind farms [6]. This research, performed concurrently, shows that similar and complementary results are obtained for a different location, and using remotely sensed temperature data obtained from a different satellite, at higher resolution and for a longer time span. Satellite remote sensing observations from Landsat 5 Thematic Mapper are used to study temperature changes over the San Gorgonio Pass Wind Farm from 1984 to 2011, with a pixel resolution of 120 m. A warming trend is consistently observed downwind of the wind farm.

Contents

1. Introduction

Wind energy is increasingly becoming the predominant renewable energy alternative to fossil fuels and its use in generating electricity is an essential component of efforts to decrease carbon dioxide emissions in an attempt to counter the anthropogenic element of the already apparent effects of our changing climate [1,2,4,5]. According to global installed wind power capacity statistics compiled by the Global Wind Energy Council [3], while the US and China leads the effort in terms of total installed capacity, on a per capita basis, Germany far exceeds either country in wind energy production. With increases in the number and scale of operational wind farms worldwide, it is ever more important to examine the effects on the environment of this renewable energy solution. Several recent studies have begun to use computer modeling techniques to simulate the local hydrometeorological impacts of wind farms. Only one complete meteorological field campaign is known to have been conducted that is actually within an operational wind farm in which an increase in surface temperature was

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observed at night and into the morning hours downwind of the wind farm [7]. Other meteorological data that have been used in various studies related to environmental impacts of wind farms have been acquired from measuring stations near the subject wind farms but not from within the wind farm itself. Current studies in progress are incorporating field campaigns involving the direct collection of measurements in the field involving deployment of ground-based data acquisition systems to continuously gather local meteorological information. Other studies related to environmental impacts of wind farms have centered on one or more avian species [8,9] as well as various aesthetic characteristics of wind farms and their siting [10].

While there are numerous studies that examine a wide range of environmental impacts of wind farms, there are not nearly as many studies regarding local meteorological impacts as well as the use of remote sensing techniques, which is the central focus of this study. With increases in the number and scale of operational wind farms worldwide, it is ever more important to examine the interaction between wind turbines and the environment to empirically quantify effects. As wind moves across the blades of a wind turbine, the kinetic energy of such air in motion is converted into electrical energy. By extracting the momentum of the wind in such a manner the natural exchanges between low altitude atmosphere and surface layers are disturbed hence altering local hydrometeorology and atmospheric dynamics [7,11,12]. Computer modeling and simulations have been the primary means of analysis in terms of assessing atmospheric and meteorological impacts attributed to large wind farms [7,13–18]. Only one complete meteorological field campaign is known to have been conducted that is actually within an operational wind farm in which an increase in surface temperature was observed at night and into the morning hours downwind of the site [6]. Others have focused on the interaction between turbines and the atmosphere used in estimations of both the global and regional atmospheric energy losses due to these interactions [13,14,19,20]. Such findings using a model-based approach concluded that the energy losses due to wind farms are high immediately downwind of wind farms but over large geographical regions the atmospheric effects are quite small [14].

A recently published comprehensive study shows surface temperature increases associated with large wind farms in west-central Texas [6]. In their investigation MODIS data from year 2003–2011 was utilized, with a pixel resolution of 1 km. The study presented here further validates these findings, and extends the analysis to a different geographic region, using different data encompassing a longer time period and further emphasizes that satellite-based remote sensing techniques have significant value in studying the impacts of wind farms on the environment at both local and regional levels.

Satellite based remote sensing techniques involving data acquisition and analyses as well as post-acquisition modeling have been employed extensively in locating ideal places for the installation of operational wind farms [21,22]. Relatively simple and straightforward extensions of these same modalities have significant and easily accessible potential value in studying the impacts of wind farms on the environment. The demonstration of the efficiency and easily reproducible nature of such approaches becomes particularly important in examining large-scale wind farms where acquisition of significant meteorological data with ground based sensors would be prohibitive from both a practical and cost perspective. To expand upon this, there is a recognized need to further consider and empirically support the predictions of the existing computer based models which identify specific environmental effects and this paper will aim to also shed light on how this can be accomplished with the application of remote sensing methods and employing readily available data and off the shelf software. As wind power predominantly becomes the renewable energy source choice, it is increasingly important to determine and understand the environmental impacts such installations and operations will have. With any new technology, it is essential to identify the costs and benefits and be sure these costs and benefits are assessed properly to ensure wind power is the right and truly most sustainable and alternative energy source. Many approaches can be taken to effectively accomplish such evaluation. Satellites and other remote sensing techniques including those that are ground-based play an essential role in this assessment process.

The fifth in a series of Landsat satellites, Landsat 5, equipped with the Thematic Mapper (TM) is notably quite good for a variety of environmental studies as it provides seven bands, six in the visible and near infrared (30 m spatial resolution) and one in the thermal infrared (120 m spatial resolution) [23]. Using the thermal band data for land surface temperature (LST) analysis provides a higher resolution than the 1 km MODIS eight-day LST [24] data previously used [6]. Additionally, Landsat 5 has provided data on large scales since 1984 therefore data over a relatively long time period can be examined and encompasses an extensive data set. Other important orbital parameters of Landsat 5 include a 16-day ground coverage cycle and sun-synchronous orbit. All data used in the analysis described in this paper was obtained from the USGS Global Visualization Viewer (GloVis), specifically from the Landsat Archive collection, Landsat 4–5 TM, resolution 240 m. There are multiple methods of obtaining LST from band six [25–28] and for purposes of

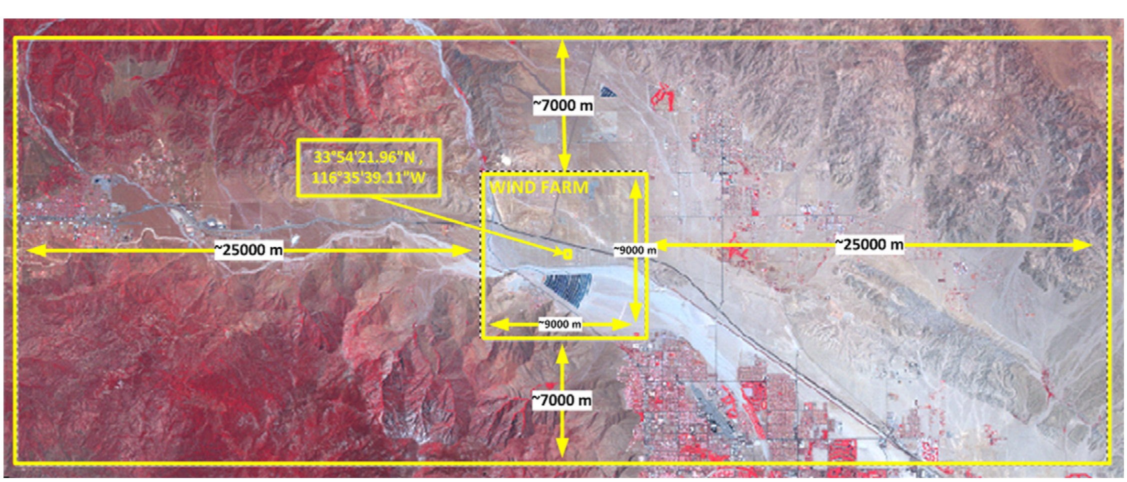

Fig. 1. False color composite image of San Gorgonio Pass wind farm and surrounding area of interest for analysis.

this study and due to site selection, a fairly simple and accepted numerical approximation of LST can be employed using the digital number and converting spectral radiance to degrees Celsius [28].

2. Materials and methods

2.1. Region of interest

The region of interest (Fig. 1) that was used in this study was the San Gorgonio Pass Wind Farm and surrounding area. As evident in its name, this installation is located within the San Gorgonio Pass of Southern California. The San Gorgonio Pass is defined as the area between the San Bernardino Mountains to the north and the San Jacinto Mountains to the south. The regional climate is classified as arid low latitude desert (hot), or BWh, based on the Köppen climate classification [29]. As of January 2008 the wind farm consists of 3218 turbines [30], which produce 615 MW [31] and is the third largest wind farm in California [30]. The approximate center of the wind farm in terms of geographic coordinates is: 33°54′21.96″N, 116°35′39.11″W (33.9061°N 116.594197°W). As determined through the use of Google Earth's measuring tool, the wind farm covers a roughly square area of approximately of 9 km × 9 km. In previous studies, it has been stated that environmental effects, more specifically hydrometeorological effects as a result of wind farm operation, have been detected 18–23 km downwind of the wind farm [15] hence the area of interest for analysis purposes was defined as approximately 25 km outside of the wind farm outer boundary in both east and west directions. The north and south boundaries are delineated as near to 7 km above and below the wind farm outer boundary. The rectangular analysis region boundaries were approximated using measurement tools in ERDAS IMAGINE with the center of the analysis area being the center of the wind farm. The ~59 km × ~23 km (33.802–34.006°N, 116.277–116.918°W) analysis area encompasses a significant area both upwind and downwind of the wind farm, which is deemed necessary for subsequent analysis.

2.2. Data description

All data was obtained from the USGS Global Visualization Viewer (GloVis), specifically from the Landsat Archive collection, Landsat 4–5 Thematic Mapper (TM), resolution 240 m. Landsat 4 and 5 have a 16-day repeat cycle and each maintains a sun-synchronous orbit. The scenes containing the region of interest have a scene center scan time that have a standard deviation of about ±15 min as the orbital node time for Landsat 5 is 9:45 AM ±15 min at the equator. The TM has a seven band system as follows: 1, visible blue; 2, visible green; 3, visible red; 4, near infrared; 5, mid-infrared; 6, thermal infrared (120 m spatial resolution); 7, mid-infrared (bands 1–5 and 7 have 30 m spatial resolution). This Landsat 5 TM data is being used as it presumptively has more than adequate resolution for the analysis contained herein. An additional practical consideration is that the data is readily available for download and use. The San Gorgonio Wind Farm is in the lower left portion of the identified Landsat scene centered on latitude and longitude coordinates in decimal degrees of 34.6–116.8; the estimated central coordinate of the wind farm has been previously stated in the above section. At the time of this investigation and submission, Landsat 4–5 TM scenes are available for download between November 11, 1982 and November 9, 2011; some are available for instant, free of cost download and use, while others must be ordered so they can be processed (1–3 days for processing) and then are available to be downloaded. The earliest date that data is available for this area is November 11, 1982, as Landsat 4 was launched on July 16th, 1982. However, between March 1983 and March 1984 there are

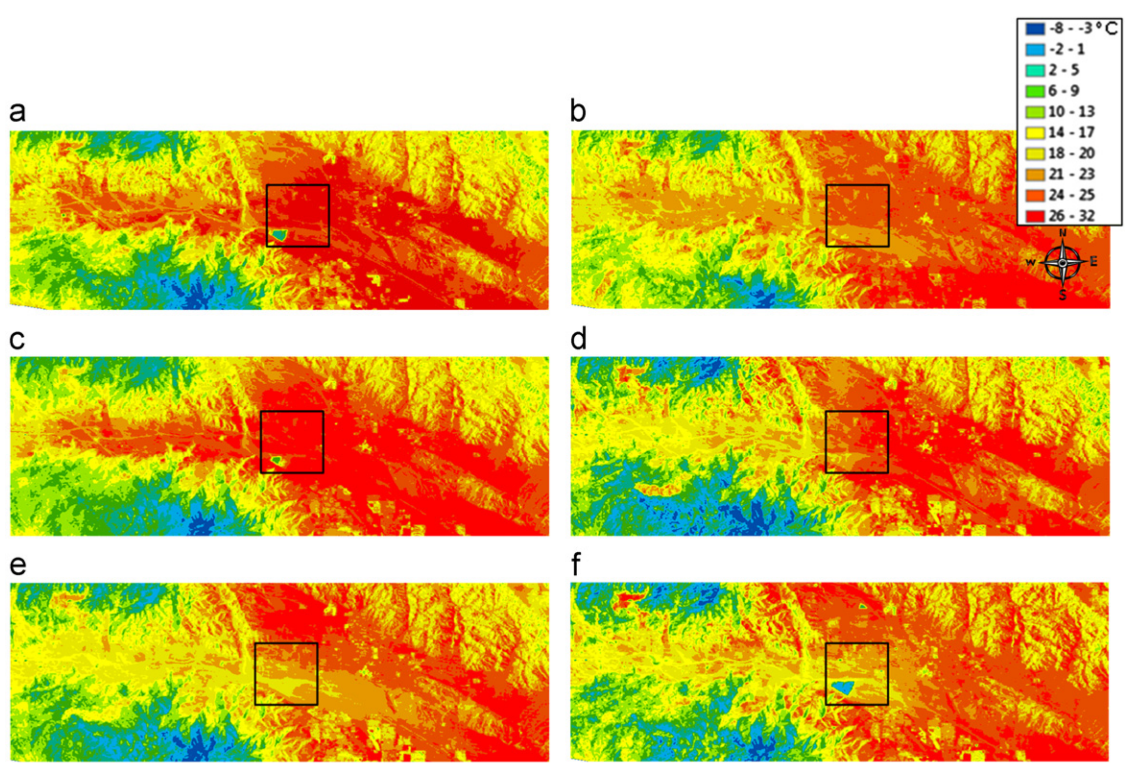

Fig. 2. Subset sample of temperature variation for the area of interest which are representative of the majority of the summer month images showing the same/similar trend. In each image, the black box indicates the approximate area of the San Gorgonio Wind Farm and are from the following dates with wind direction and angle as follows: (a) June 26, 1985, SSE 160°; (b) May 26, 1991, NW 320°; (c) June 22, 1995, WNW 300°; (d) June 19, 2000, NW 320°; (e) June 28, 2003, NW 320°; (f) June 18, 2011, NW 340°. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of the article.)

no scenes available. It appears that this region was either not scanned during this time period by Landsat 4 and therefore the data is missing or the images from that time period have not been made available by USGS. Landsat 5 was launched on March 1, 1984 so this is a clear indication that the data after this date is from Landsat 5. The data collected for this study was derived from scenes containing this area during summer (June ± 2) and winter (December ± 2) months.

2.3. Analysis

Each composite image was created using the data management tools composite image creator in ArcGIS. This process was necessary because the ERDAS model, which was subsequently used to convert the digital number (DN) to a temperature value (°C), required a composite Landsat TM image that contained seven bands with the sixth band being the thermal band. The output files from the model were viewed in ArcGIS to visually assess the temperature variation and assign specific temperature ranges within the image specific colors. This was followed up using statistical and graphical components of Excel and R for the quantitative analysis.

3. Results and discussion

LST of the region of interest was analyzed for both summer and winter scenes of the data set where wind direction was taken into consideration. Visual inspection of the images where the pixels had been converted to temperature in degrees Celsius allowed for a distinct temperature variation and trend to be observed for all images. The legend includes 10 natural breaks, or subsections, of the temperature range encompassing the entire image that were calculated and determined. As clearly shown in the legend, the more blue an area is, the cooler the temperatures and conversely the more red an area is, the warmer the temperatures. The wind direction for the dates the scenes were acquired by the satellite was recorded and the overall prevailing wind direction was NNW based on records collected at a nearby weather station. The overwhelming majority of the summer month images (Fig. 2), as well as the winter month images, depict the same characteristics where the downwind region, south and east of the wind farm, temperatures typically are warmer than those west of the wind farm.

For the first qualitative time series analysis, the pixel values that were visually observed in the qualitative analysis were

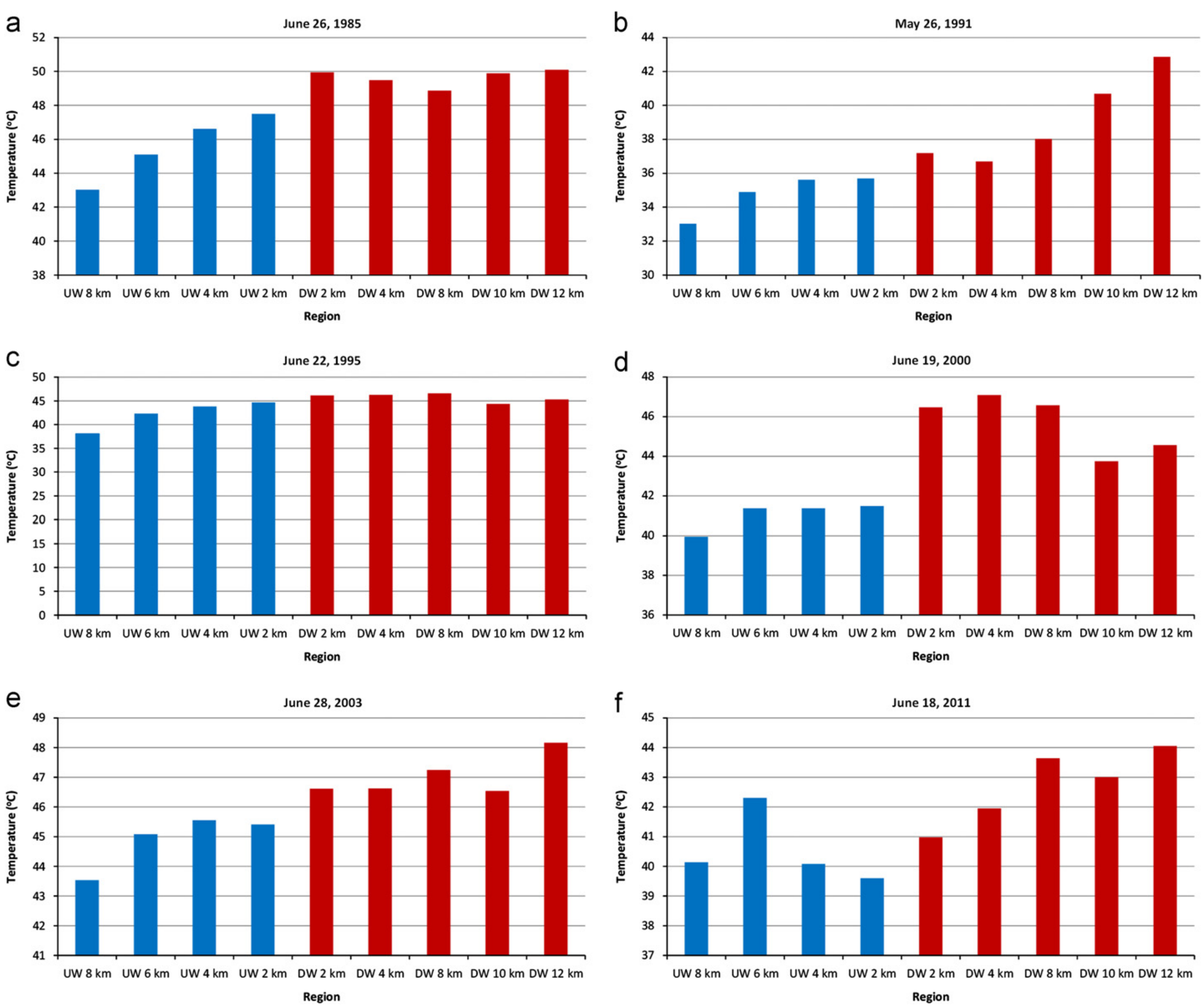

Fig. 3. Comparison of summer LST from upwind and downwind from wind farm as a function of distance. The graphs here correspond with the images in Fig. 2(a)–(f). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

matched with their specific coordinate in a table and transformed into a matrix with the wind farm center and boundaries subsequently defined in the matrix itself. The averages at specific distances away from the center of the wind farm both up and downwind were calculated and graphically displayed as bar charts. Here the visual selection of both up and down wind regions avoided variables, which would affect the analysis, such as elevation and urban areas near the wind farm site. The averaged areas were 2 km × 2 km areas through 10 km downwind and 8 km upwind of the wind farm and were completed for both the summer and winter data sets. While it varied how much warmer the downwind regions were, between four and eight degrees, downwind regions through 12 km upwind are shown to be consistently warmer than the observed upwind region through 8 km downwind for the summer months (Fig. 3). An identical quantitative assessment was completed for winter months and for both summer and winter months, the results were found to be consistent with the results obtained from the qualitative with a warming downwind of the wind farm being observed.

It is realized that there are some limitations to this study and attempts were made to minimize the effects of such limitations. One limitation in particular placed restraints on the experiments that could be conducted as there was no data prior to installation and operation of the wind farm simply due to the timing of the launch of Landsat 5 and the installation and operation of the wind farm occurred around the same time and because of this, a before and after analysis could not be completed. Despite this, the nearly 29-year data set collected was quite extensive. An additional limitation to the collection of data was the amount of cloud cover within the scenes containing the ROI that was used for the analysis. If a scene has greater than 20% cloud cover, the next available image ±2 months of June or December that had less than 20% cloud cover was chosen. This was done as cloud cover would significantly impact the analysis that was completed. There were also some issues with missing data, but again if this occurred for the month of June or December, the next available image no more than 2 months prior or after was chosen.

4. Conclusions

With the increase in both the number and scale of wind farms, it is essential that we continue to build on our understanding of both the costs and benefits of wind energy at many levels, especially concerning environmental impacts of such installations and this paper defines and utilizes a set of cost effective techniques which contributes to this effort. This paper extends the use of satellite based remote sensing in conjunction with accepted methodologies to provide clearer and more comprehensive insight into the effects of large scale wind farms on land surface temperature. Perhaps most importantly, this effort suggests a readily approachable path forward for expanding such analytical assessment on a larger scale.

One of the most significant aspects of this study was that it demonstrates further that remote sensing imagery can be effectively used in conjunction with easy to use, off the shelf software to analyze and explore the impacts of a large-scale wind farm on the local environment, more specifically in terms of LST. Freely available Landsat 5 TM scenes were selected and processed using an accepted model based approach for determining LST values in the vicinity surrounding and within a large-scale wind farm. With the region of interest defined, the area was analyzed in multiple ways to identify and characterize an observable warming trend downwind of the wind farm as modeled in previous studies and empirically determined in a recent paper [6]. The experimental analysis herein correlated well with similar warming trends that was observed in computer models, a short meteorological campaign [7,13,14] and a similar studying using MODIS data [6].

This study along with other current research regarding local environmental effects helps to provide a more realistic and precise estimate of the impacts large-scale wind farms have on the local environment. The experiments conducted have addressed the effects on temperature at a local level using remote sensing data. This research has been done in a successful effort to better understand and acknowledge what impact current wind energy technology has on the environment as well as to support and encourage the improvement of wind energy technologies to be more sustainable and to better improve the environment in which we live.

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