A Climatology of Solar Radiation Attenuation During Fog Episodes in the Central Valley of California

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Introduction
During the winter season, portions of the Central Valley in California experience as many as twenty-five days with widespread radiation fog (Holets and Swanson 1981). The development of radiation fog in this large valley system is reported routinely from October through April, with the months of December and January recording the most occurrences. During the winter season, the synoptic-scale circulation brings an alternating pattern of cyclonic weather systems followed by large anticyclones. The winter season storms often produce persistent rainfall across the Central Valley, which adds to soil moisture and raises the level of boundary layer moisture. The anticyclones that follow these storms bring clear skies, calm surface winds, and surface-based temperature inversions, which encourage radiation fog formation.

The development of valley-wide radiation fog was the focus of a study by Underwood et al. (2004). In that study, the Geostationary Operational Environmental Satellite (GOES) Nighttime Fog Product (NFP) was used to detect variability in fog development parameters during nighttime hours across the Central Valley. Fog depth and areal extent were found to vary substantially from south (near Bakersfield) to north (near Chico). Other radiation fog studies conducted in the Central Valley over the past twenty years include Suckling and Mitchell (1988), who investigated urban radiation fog at four locations near Sacramento, and Lee (1987), who briefly described visible satellite images showing preferential dissipation of radiation fog over urban locations in the Central Valley. Herckes et al. (2002), Collett et al. (1999a), Collett et al. (1999b), Hoag et al. (1999), and Lillis et al. (1999) conducted radiation fog studies in the San Joaquin Valley as part of the 1995 Integrated Monitoring Study.
These studies focused on various aspects of radiation fog chemistry in the San Joaquin Valley.

Researchers have assessed the synoptic and local-scale meteorological conditions that are required precursors for radiation fog development in other parts of the world, including the Hudson River Valley in New York, (Meyer et al. 1986; Fitzjarrald and Lala 1989; Meyer and Lala 1990), the Netherlands (Duynkerke 1991), the Nord-Pas de Calais region of northern France (Guedalia and Bergot 1994), and Northern India (Pasricha et al. 2003).

**Background**

One aspect of dense fog that is apparent to even the casual observer is the reduction in sunlight that reaches the surface during such an event. Solar radiation is essential for numerous ecological processes, including evapotranspiration (ETo) and photosynthesis. A simulation experiment found that frequent fog occurrences in the Atlantic maritime provinces of Canada reduced ETo losses by one to six percent (Yin and Arp 1994), and in the absence of adequate solar radiation, decreased water loss (via transpiration) can lead to increased seasonal carbon fixation in forest species (Burgess and Dawson 2004). Additionally, Herzog et al. (1998) found that ETo losses from forest canopies are most significant where the canopy is least coupled with the atmosphere, causing internal competition for water resources within individual trees.

This study will develop a climatology of shortwave radiation (SWR) attenuation attributable to prolonged fog episodes in the Central Valley, and describe the impact of SWR attenuation on ETo and surface temperature in the region.

Upon entering the earth’s atmosphere, SWR, measured in Wm$^{-2}$, may be considered a conserved quantity. SWR, however, may be transmitted, reflected, and absorbed as it encounters atmospheric gases, liquid or frozen water, suspended particulates, and other constituents of the atmosphere. This relationship can be described in terms of a single wavelength ($\lambda$) as:

$$\psi + \alpha + \xi = 1 \quad (1)$$

where $\lambda$ represents a particular wavelength, $\psi$ represents the amount of SWR at wavelength $\lambda$ that is transmitted by constituents in the atmosphere, $\alpha$ represents the amount reflected, and $\xi$ represents the amount absorbed. This relationship is fundamental in understanding the interaction of solar radiation with the atmosphere and its impact on climate and ecological processes.
earth’s atmosphere, $\alpha$ the amount of SWR at wavelength that is reflected by constituents in the earth’s atmosphere, and $\xi$ the amount of SWR at wavelength that is absorbed by constituents in the earth’s atmosphere (Oke 1993). The amount of SWR partitioned to each of the three variables is a function of the wavelength and the size of the atmospheric constituent or the material composition and color of a surface.

Low stratus clouds and fog have the propensity to transmit, absorb, and reflect SWR reaching the cloud top. The magnitude of absorption and reflection is dependent on the solar zenith angle, droplet size distribution within the cloud, water content of the cloud, cloud height, and vertical extent or depth of the cloud. Fog depth during widespread winter season episodes in the Central Valley routinely exceeds 300m (Underwood et al. 2004).

**Study Area**
The study area (the Central Valley of California) is presented in Figure 1. Much of the Central Valley lies below 300m in elevation with mountain ranges to the east (Sierra Nevada Range) and west (Coastal Range). The valley is prone to cold air drainage and strong boundary layer temperature inversions during the winter months. The topography and the inversion climatology are two elements that make this region prone to frequent and extensive radiation fog episodes.

**Data**
Data for December and January over the period 1996–2005 were used for this analysis. These two months represent the core of the radiation fog season in the Central Valley. Hourly weather observations were retrieved from the archived data sets for four National Weather Service (NWS) first-order stations (NCDC 2006). A fog-hour was identified by an hourly weather report of “FG” (fog) in the weather log at each station. Six continuous hours of fog were required for the fog episode to be included in the study. Additionally, at least three of the hourly observations must have been reported after sunrise and prior to sunset (approximately 0800–1600PST). These criteria ensure that the fog episodes identified were indeed prolonged and therefore more likely to develop vertically and attenuate SWR.
Solar radiation data, ET0 data, and surface temperature data were obtained from the California Irrigation Management and Information System (CIMIS) (CIMIS 2006). This data set was then paired with weather observations from four NWS first-order weather stations to perform the solar radiation analysis. NWS and CIMIS stations were paired based on proximity between the stations. The station pairs follow:
1) NWS-Oroville (39°29’N, 121°37’W, 57.9m)  
   CIMIS-Durham (39°36’N, 121°49’W, 39.6m)  
2) NWS-Sacramento (38°42’N, 121°35’W, 7.0m)  
   CIMIS-Dixon (38°24’N, 121°47’W, 11.3m)  
3) NWS-Fresno (36°47’N, 119°43’W, 101.5m)  
   CIMIS-Fresno State (36°48’N, 119°43’W, 103.6m)  
4) NWS-Bakersfield (35°26’N, 119°03’W, 149.0m)  
   CIMIS-Arvin-Edison (35°12’N, 118°46’W, 152.4m)

Hourly estimates of Horizontal Solar Irradiance (HIS) were obtained from the University of Oregon’s Solar Radiation Monitoring Laboratory (SRML). This information was accessed via the SRML Web site and matched to the latitude and longitude coordinates of the CIMIS stations listed above. The HIS at each site was calculated in units of Wm⁻²h⁻¹ (SRML 2006).

**Methods**

To estimate hourly SWR attenuation during fog episodes in the Central Valley, an analysis was performed comparing SWR receipt during foggy conditions to SWR receipt during clear-sky conditions. Estimating SWR receipt at the surface for clear-sky conditions required a modeling approach. Many solar-radiation codes and models are available for estimating SWR; however, most of these codes and models require extensive initialization data, which was not available to this study. A linear modeling approach using HIS as the independent variable was chosen for its regional applicability and ease of calculation. The modeling was carried out using the general linear modeling module from the software package Statistica (Statsoft, Tulsa, Oklahoma). The assumptions of normality, linearity, and homoscedasticity were checked for individual variables in the regression equation. The regression variate was checked for the above assumptions as well as for the additional assumption of independence. Normal probability plots (of individual variables and residuals) were employed to check for normality. Scatterplots were constructed to check for linearity between hourly HIS (independent variable) and SWR (dependent variable). Scatterplots of the independent variable and residuals were utilized to check for homoscedasticity. Residual analyses were employed to examine for linearity, homoscedasticity, and independence of the regression variate.

The model designed in this study allowed for estimation of SWR receipt at the surface for any hour as if skies were “clear,” present...
weather was “none,” and surface visibility was “10 miles.” Model input consisted of a dependent variable (SWR) and a single independent variable (HSI); SWR data were obtained from the CIMIS network for each clear-day identified during the POR. The criteria for selecting a clear-day for inclusion in the modeling application included an NWS hourly weather report of “CLR” in the “sky condition” column of the daily summary (which means that 0/8 of the sky is covered with cloud), a blank present weather report (no significant weather reported), and surface visibility listed as ten miles (unlimited visibility). An independent model estimate was calculated for December and January for each of the four analysis sites (a total of eight model equations). For the site at Fresno, an insufficient number of clear days were identified. To remedy this situation, surface data from the first-order station at Visalia was used in place of Fresno to identify a sufficiently large population of clear days. The spatial proximity (approximately 50km) of the two stations provides confidence that the data from Visalia is representative of conditions in the Fresno area.

For the comparative analysis, it is assumed that the hourly SWR receipt at the surface during clear-sky conditions takes the form of:

\[ \text{SWR}_{\text{clr}} = \text{HSI} - (\alpha_c + \xi_c) \]  

where HSI is horizontal solar irradiance, \( \alpha_c \) represents clear-sky reflection, and \( \xi_c \) represents clear-sky absorption.

The amount of SWR reaching the surface hourly during a radiation fog episode (\( \text{SWR}_{\text{fog}} \)) is assumed to be:

\[ \text{SWR}_{\text{fog}} = \text{HSI} - (\alpha_{c+f} + \xi_{c+f}) \]  

where \( \alpha_{c+f} \) and \( \xi_{c+f} \) represent clear-sky plus fog cloud reflection and clear-sky plus fog cloud absorption respectively.

To determine the hourly amount of SWR attenuated by radiation fog, the parameter \( \text{SWR}_{\text{diff}} \) is estimated:

\[ \text{SWR}_{\text{diff}} = \text{SWR}_{\text{clr}} - \text{SWR}_{\text{fog}} \]  

\( \text{SWR}_{\text{diff}} \) is the amount of SWR in units of \( \text{Wm}^{-2}\text{h}^{-1} \), attenuated during a fog episode.
Results
The selection criteria set out above identified a population of ninety-eight fog episodes at the four sites over the POR 1996–2005. The linear modeling application then estimated incoming SWR for each of these days as if the skies were clear. The model’s equations for each month at each location are shown in Table 1.

Comparing the modeled clear-sky conditions to the observed SWR receipt at the four sites in the Central Valley reveals that there is variability in the amount of SWR attenuation from one site to another in the valley. Additionally, the mean hourly percent of SWR attenuation varies both between stations and between hours at a single station. Figure 2 illustrates the mean hourly attenuation of SWR at each of the four stations for the months of December and January. The full extent of the stacked bars represents the hourly amount of SWR expected at the surface during clear-sky conditions. The lightly shaded bars depicted in the figure represent the average values for SWR receipt at the surface (in units of Wm⁻²) during fog episodes. The dark-hatched portion of each bar in the figures indicates the amount of SWR attenuated during a fog episode at a particular hour.

The climographs in Figure 1 suggest that the northern portion of the valley represented by Oroville experiences greater than ninety percent attenuation of SWR in the early morning hours and sees greater attenuation of mid-day SWR in January compared to December. The Sacramento analysis reveals that radiation fog episodes last

Table 1. Least-square Regression Equations Derived for Calculation of SWR (W m⁻²) Based on HSI (W m⁻²) for Clear Days

<table>
<thead>
<tr>
<th>Location</th>
<th>Regression equation</th>
<th>$r^2$</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oroville—December</td>
<td>$y = -22.946 + 0.697x$</td>
<td>0.841</td>
<td>0.000</td>
</tr>
<tr>
<td>Oroville—January</td>
<td>$y = -66.617 + 0.778x$</td>
<td>0.886</td>
<td>0.000</td>
</tr>
<tr>
<td>Sacramento—December</td>
<td>$y = -54.997 + 0.761x$</td>
<td>0.858</td>
<td>0.000</td>
</tr>
<tr>
<td>Sacramento—January</td>
<td>$y = -62.943 + 0.808x$</td>
<td>0.893</td>
<td>0.000</td>
</tr>
<tr>
<td>Fresno—December</td>
<td>$y = -1.821 + 0.515x$</td>
<td>0.657</td>
<td>0.000</td>
</tr>
<tr>
<td>Fresno—January</td>
<td>$y = -1.183 + 0.562x$</td>
<td>0.761</td>
<td>0.000</td>
</tr>
<tr>
<td>Bakersfield—December</td>
<td>$y = -9.632 + 0.599x$</td>
<td>0.819</td>
<td>0.000</td>
</tr>
<tr>
<td>Bakersfield—January</td>
<td>$y = -123.548 + 0.842x$</td>
<td>0.786</td>
<td>0.000</td>
</tr>
</tbody>
</table>

*aAll $r^2$ and p values are significant at the 0.05 level.*

Figure 2a. Hourly climographs of SWR attenuation at sites in the Central Valley. The analysis for December is on the left and January on the right. The x-axis marks daylight hours (0800–1600PST). The y-axis is a measure of SWR in units of Wm⁻². The dark-hatched portions of each bar represent the estimates of SWR attenuation for each hour.
Figure 2b. Hourly climographs of SWR attenuation at sites in the Central Valley. The analysis for December is on the left and January on the right. The x-axis marks daylight hours (0800–1600 PST). The y-axis is a measure of SWR in units of Wm². The dark-hatched portions of each bar represent the estimates of SWR attenuation for each hour.
into the early afternoon in both December and January and that more attenuation (as a percentage of hourly totals) occurs during December fog episodes as compared to January episodes. Fresno seems to experience a uniform hourly attenuation pattern during December fog episodes, with peak SWR receipt during fog episodes peaking at noon. There is, however, more than fifty percent attenuation during each hour that fog is present. In the southern portion of the Central Valley, represented by Bakersfield, fog attenuates more than seventy percent of incoming SWR for all hours 0800–1300PST during January episodes. Underwood et al. (2004) found that radiation fog develops earlier in the diurnal cycle in the southern portion of the valley and that this early development allows fog clouds in the southern valley to grow vertically and reach greater thickness.

Since frequently occurring fog has marked impacts on the ecology of regions prone to such episodes, this section concludes with an assessment of the impact of SWR attenuation on two primary ecological drivers—air temperature and ETo. The mean values of temperature and ETo were calculated for a sample of clear hours and a sample of fog hours from the population of episodes. The sample analysis revealed that temperature was reduced during fog episodes by as little as three percent and as much as thirty-nine percent, with a mean of twenty percent at the study sites. Mean hourly ETo was reduced during fog episodes by sixty-nine percent at Bakersfield, eighty-two percent at Sacramento, eighty-five percent at Oroville, and ninety percent at Fresno.

**Conclusions**

To the residents of the Central Valley, winter-season radiation fogs are seen as an annoyance that on occasion pose a highway hazard or delay air traffic. However, these fog episodes have a tremendous impact on the SWR, ETo, and temperature climatology of the Valley. Through this simple comparative analysis, the Central Valley is shown to experience substantial attenuation of SWR along a north-south transect of the study area. The attenuation of SWR varies from hour to hour at each station (with highest attenuation percentages at earlier hours), and there is significant variability in the percentage of SWR attenuated between December and January at each station. The analysis also suggests that when fog episodes extend into the afternoon hours, the SWR attenuation percentage is still extremely high (greater than fifty percent during each after-
noon hour except 1300 and 1400PST at Sacramento in January). It is during the afternoon hours that the greatest gross attenuation occurs, resulting in the greatest depression of air temperature and the greatest retardation of ETo rates.

The substantial reduction in SWR, air temperature, and ETo across the Central Valley during radiation fog episodes suggests that changes in the long-term fog climatology may have broader implications for the winter season ecology of Central Valley. The long-term fog climatology of this large valley system is, in turn, impacted by in-valley surface fluxes and circulation patterns as well as synoptic scale circulations external to the valley. The interaction, feedback, and long-term variability of these elements is the focus of ongoing research by the authors.

References


