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An experimental study of summertime coastal fog and its inland penetration in Northern California

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INTRODUCTION

The occurrence and continental inundation of marine stratocumulus and fog along the California Coast during summer has been linked to many environmental concerns including redwood ecosystem vitality, air traffic control, power grid load balancing, and radiative climate forcing. Furthermore, some recent studies have indicated that the fog frequency may be declining under the influence of the current climate warming trend [Johnstone & Dawson, 2010]. An exploratory study was conducted this past summer (July 13 – Sept 13, 2012) at the Bodega Marine Laboratory and Pepperwood Preserve, a large nature reserve located 40 km inland in Sonoma County (Fig. 1, below), in order to investigate fog formation, persistence, and penetration through the orographic gap east of Bodega Bay in the Pacific coastal mountain range. Analysis of the synoptic patterns and in-situ meteorological observations, including visibility and boundary layer depth, are presented with the aim of improving fog forecasts and elucidating the principal physical parameters that control summertime fog formation and dissipation along the Northern California Coast. A better understanding of its synoptic variability may lead to improved understanding of the processes that control this important component of the Earth System on climatic time scales.

Experimental Setting

The mean synoptic situation during the experiment is shown with reanalysis data below. While the surface pressure field is dominated by the Pacific H situated some 1800 km offshore, the 700 hPa geopotential heights indicate persistent troughing a few hundred km upwind of the coast. This synoptic pattern is similar to other high fog frequency years (e.g. 1951).

Figure 1. Map of the region: (A) the Pepperwood Preserve (375 m elevation) inland North of Santa Rosa, and (B) the UC Davis Bodega Marine Lab on the Bodega headlands, at a 40 km distance. A Vaisala FD12P visibility sensor was deployed at each site. The break in the coastal mountains east of Bodega Bay is known as the Petaluma gap, where ancillary flow to that entering the Golden Gate is fed into California's interior Central Valley.

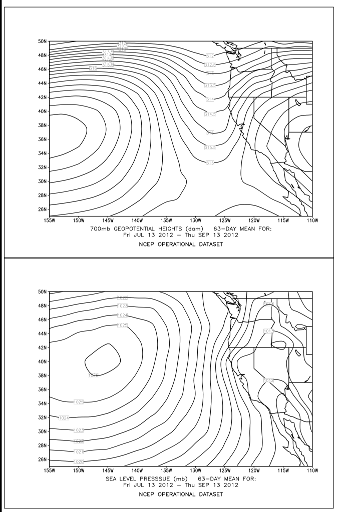


Figure 2. 700 hPa geopotential height and sea level pressure fields for the two month experiment. The strong surface anticyclone and meridionally aligned trough axis are features common to foggy years.

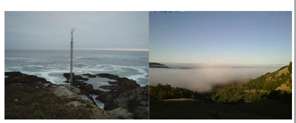


Figure 3. Pictures of typical summertime stratocumulus at Bodega Bay (left), and the early morning recession of the stratus's inland extent at Pepperwood (right).

Diurnal Patterns of Summertime Coastal Fog at Bodega Bay

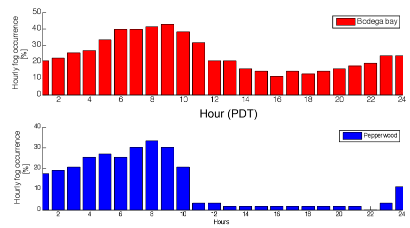
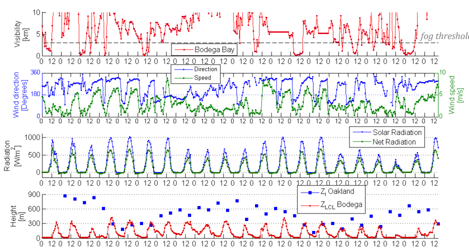


Figure 4. The fog at the coastal site exhibited a diurnal cycle very similar to that of typical marine stratocumulus. The inland fog evinced a similar pattern with a ~10% lower peak and an a.m. burn off that was usually complete by 11:00 PDT. Although less fog on the ground was observed inland, there were cases with fog at Pepperwood but not at Bodega Bay. These cases were found to always be a lifted Sc deck along the coast with an inland branch in contact with the surface of the elevated terrain. The visibility threshold for fog at Bodega Bay was determined to be 3 km, while at Pepperwood it was 10 km.

Figure 5. The time series of hourly data at Bodega Bay from Jul 17–Aug 9. Note how the visibility is low during both onshore & offshore flow (independent of the intermittent land breeze.) The LCL is calculated from the hourly dew point depression. Assuming overcast conditions based on the shape of the solar radiation trace, it is clear that the skies remain Sc covered on days when the regional boundary layer height (from Oakland sounding) remains higher than the LCL.



General Characteristics of Inland Fog at Pepperwood

The occurrence of fog at Pepperwood was generally easier to forecast and behaved according to a few basic governing principles: When the air temperature dropped below the offshore SST and the regional boundary layer was between approximately 400 – 900 m.

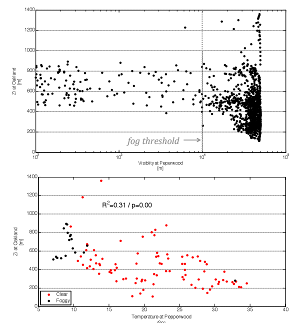
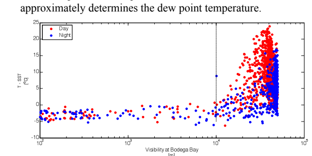


Figure 6. (top) Fog at Pepperwood seems to only form when the regional boundary layer inversion base is above 400 m (altitude of the site is 375 m amsl), but below ~900 m. (bottom) Shallower boundary layers tend to be warmer inland, possibly due to greater daytime heat flux divergence and subsidence warming.

Figure 7. The difference of air temperature at Pepperwood and the sea surface temperature at the NOAA buoy offshore indicates that overnight fog develops at Pepperwood when the land temperature drops below the offshore SST, which approximately determines the dew point temperature.



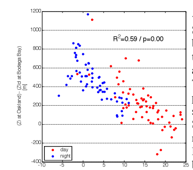


Figure 8. A measure of Sc thickness was estimated by the difference between the Oakland inversion base and the LCL at Bodega Bay. This correlates well with the proximity of the inland surface temperature to the SST offshore. A similar relationship is found for the Bodega Bay surface temp but with reduced r² (=0.21).

Forecast Difficulties along the Coast

The occurrence of fog at Bodega Bay was more challenging to forecast. Most (~80%) of the missed forecasts involved unforeseen clearings. Although there appear to be mild correlations to expected parameters such as upwelling index, subsidence, and warm air advection none explain very much of the coastal fog synoptic variability.

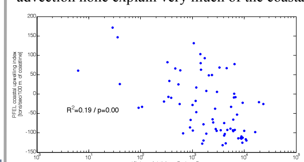


Figure 9. The best synoptic correlate found was the PFEL upwelling index 12-24 hr in advance of the visibility along the coast. The correlation coefficient for this upwelling index and near shore SST is not that much larger (r²=0.25).

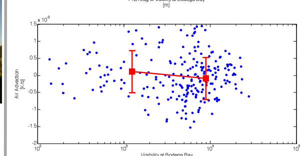
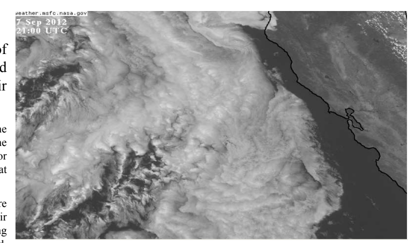


Figure 10. Fog at Bodega Bay is somewhat more prevalent under conditions of past (1d lag) warm air advection [Kim & Yum, 2012], as calculated using reanalysis winds & SST out to about 1,000 km upwind. However, it is by no means a failsafe predictor.



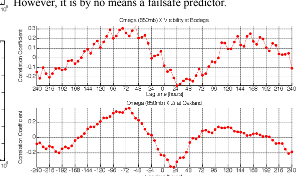


Figure 11. Anther parameter that crudely tracks visibility at Bodega Bay is the NCEP reanalysis vertical velocity (ω), with increased fogginess 24 hr after a shoaling of the Oakland boundary layer, 6 hr before. This condition was called out by Lewis et al. [2003] and others, but is not the entire picture. Excessive low level subsidence will suppress the inversion below the LCL eliminating the formation of fog

Figure 12. GOES visible image of stratocumulus deck retreated from the coast south of Cape Mendocino. This was within a period of poor (5-day) forecast skill for the coastal fog.

Concluding Hypothesis: While large-scale subsidence is a concomitant of coastal fog (greater upwelling, lower near shore SSTs, warmer aid advection) there is an optimum interval because excessive subsidence will eliminate the MBL, and shortwave troughing offshore may be the key modulating factor.

Acknowledgements

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