CALIFORNIA AND OREGON HUMIDITY AND COASTAL FOG

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1. INTRODUCTION

One of the most troublesome weather phenomena along the California and Oregon coast is fog. Fog is defined by the National Weather Service (NWS) as "a visible aggregate of minute water particles that restricts visibility." The intensity of fog varies and has been quantified with the following levels: 0 to <1 km visibility equals dense fog, 1 to <5 km visibility equals moderate fog, and 5 to <11 km visibility equals light fog (Leipper, 1994).

The limited visibility associated with fog is responsible for a loss of time and money in all forms of transportation, including commercial shipping, military operations, airplane flights, and car travel. In addition to limiting the range of human sight, fog also limits the performance of infrared and electro-optical sensors. Fog also plays an important role in the radiation balance by absorbing and reradiating outgoing longwave radiation and reflecting or absorbing incoming shortwave radiation. For this reason, creating an accurate global climate model is nearly impossible if fog is not well-understood.

Traditionally fog forecasting has relied on local expertise and experience with trends and signals in local conditions. Because fog development is closely tied to complex local topography, no "universal fog forecasting scheme" has been used. Observational studies are scarce, and few papers on coastal fog exist in the technical literature. Understanding the physical processes that cause fog formation and dissipation is crucial to accurate fog forecasting, and better forecasts will enable more appropriate preparation for and response to this common meteorological event.

In order to better understand fog occurrence along the California and Oregon coast, this study is broken into two parts. To gain a large-scale picture of coastal fog, Part I examines meteorological data from thirteen coastal surface stations, seven radar profiler stations, five cooperative observing stations, 700 hPa synoptic maps, and GOES 9 visible satellite images for the months of June to October 1996. To better understand the physics of fog formation, including precise timing and mechanisms of formation and dissipation, Part II uses a one-dimensional, primitive-equation, second-order turbulence closure model to test fog behavior under various initial conditions and forcings. Preliminary results show that the model is sensitive to initial profiles of temperature and moisture, to subsidence rates, to wind speed, and to entrainment across the inversion. The model's current bulk flux algorithm tends to cut off the surface forcing from

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sensible and latent heat fluxes. By fixing these fluxes, the model more realistically recreates the diurnal cycle of fog formation and dissipation.

2. THEORIES OF FOG FORMATION

Three primary processes influence fog formation: cooling, moistening, and the vertical mixing of air parcels with different temperatures and humidities. The mechanisms work together in many different sequences which can result in fog.

Historically, fog has been classified by the two main processes that result in its formation: radiation and advection. Radiation fog is most commonly found over land on still winter nights. Longwave radiational cooling of the surface lowers the air temperature to the dewpoint, and condensation occurs. Due to the high specific heat of seawater and the high specific humidity of marine air, this effect is not observed over the ocean. Advection fog forms when an air mass moves from one environment to another. When warm, moist air moves over cooler water, such as that formed by upwelling along the California coast, the cool water causes the air to cool and condense, forming fog. Alternatively, fog can form when cool, stable, moist air moves over warmer water. The warmer water generates turbulence, mixing, and a larger latent heat flux. This mixes the moisture up into the marine atmospheric boundary layer (MABL), where the air saturates, condenses, and forms fog.

Of the other processes playing a role in fog formation, the main distinguishing factor between fog and stratus formation is the height of the MABL inversion. A low inversion keeps the saturated layer near the ground or sea surface, forming fog. A higher inversion layer often allows deeper mixing and raises the lifting condensation level, which determines where stratus clouds form. One explanation is that the lifting condensation level rises because deeper mixing incorporates dry air from aloft into the MABL, producing a greater vertical extent over which moisture is distributed. The air cools through adiabatic lifting before it reaches saturation, condenses, and forms droplets. Several studies summarized by Leipper (1994) show that fog occurs when MABL inversion heights are less than 400 m and generally does not occur when the inversion is higher.

Rogers and Koracin (1992) state that the important processes affecting the maintenance or dissipation of a fog/cloud layer include longwave radiation, shortwave radiation, cloud-top entrainment instability (CTEI), horizontal variability of surface fluxes, subsidence, wind shear, gravity waves, and precipitation. Longwave radiational cooling from the top of the fog layer promotes turbulent mixing and general cooling throughout the MABL. Sufficiently large radiational cooling at the cloud

top could lower the base of a stratus cloud to the surface, forming fog. However, this cooling can be offset by heating due to entrainment, subsidence, and a positive surface heat flux. Additionally, if incoming shortwave radiation heats the top of the fog/cloud layer more than outgoing longwave radiation cools it, the top of the fog/cloud layer may become warmer than the bottom, thereby forming an inversion layer within the fog/cloud. In this case, a temperature discontinuity occurs within the fog/cloud layer, effectively decoupling the top of the layer from the ocean surface. This limits the vertical transport of moisture and could contribute to the dissipation of a cloud by reducing the moisture input from the sea surface. It could also act to enhance the moisture concentrated near the surface, possibly enhancing fog formation in the lowest levels of the MABL. Other factors that could contribute to the decoupling of the fog/cloud layer are an increase in the entrainment of warmer, drier air from aloft; a decrease in the surface buoyancy flux; and/or an increase in droplet evaporation in the lower layers (Nicholls, 1984).

After examining the connection between fog events and large-scale atmospheric circulation, Filonczuk et al (1995) concluded that fog occurrence is not dominated by local processes. Positive 700 hPa height anomalies correspond with subsiding air and a high occurrence of fog in all regions of the state. Negative 700 hPa height anomalies and a deeper boundary layer correspond with a low occurrence of fog. Examining surface temperature anomalies across the U.S. during times of peak fog events in San Francisco revealed higher than normal temperatures over the Rocky Mountain states and lower than average temperatures over the eastern states. This is consistent with a ridge over the West and a trough over the Southeast. Filonczuk et al (1995) also asserted that when the Pacific High moves inland, there is a greater probability of fog.

3. RESULTS

3.1 Part I: Synoptic Trends

For the months of June through October, 1996, thirteen surface automated meteorological stations, funded by the Office of Naval Research, recorded wind speed and direction, air temperature, pressure, and relative humidity every hour. Because no visibility data is available for these stations, it is assumed that fog is present when the relative humidity reaches 100%. For the same time period, radar profilers measured wind speed, direction, and virtual temperature versus altitude. These instruments are active, low-power, pulsed radars operating at 915 MHz, which calculate the wind speed and direction using Doppler shifted return pulses. In order to verify the validity of the high relative humidity measurements with reports of reduced visibility, human observations of the daily occurrence of weather were obtained from the daily surface data archived at the National Climatic Data Center (NCDC). The locations of all of these stations are illustrated in Figure 1.

Based on the data obtained during the summer of
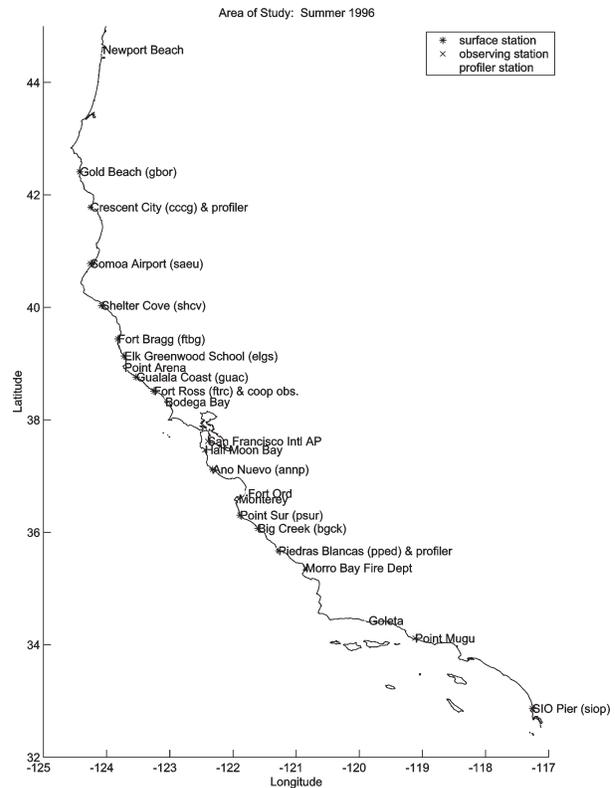
Figure 1. Map of the study area for the summer of 1996, showing meteorological stations, radar profilers, and cooperative observing stations.

1996 study, fog exhibits a strong diurnal cycle at all stations, with maximum occurrence in the early morning, and minimum occurrence in the afternoon. When fog is present, surface temperatures and wind speeds are lower, MABL inversion strength is greater, inversion base heights are lower, and inversion top temperatures are higher. At the northernmost stations, the surface wind direction shifts from northerly to southerly during fog events. At approximately 3000 m height, the winds are primarily southerly during fog events and northerly during clear time periods. This corresponds well with 700 hPa synoptic maps, which show a clear correlation of a weak high over California during fog events and a trough passing over the state during clearing, such that fog is about 30% less likely to occur when a trough is in the vicinity. These relationships are demonstrated using summer-long averages and case studies, which are reproduced in Lundquist (1999).

3.2 Part II: Modeling Study

The model used is based on the Mellor-Yamada type, first developed by Mellor (1973) and Mellor and Yamada (1974) as part of a hierarchy of models with various levels of turbulence closure. The model used here was adapted by Koracin and Rogers (1990), who simplified the three-

dimensional model developed by Yamada (1978) to one dimension. Time dependent, advection, and diffusion terms are neglected in the second moment equations (Mellor and Yamada, 1974), classifying this as a level "2.5" model of intermediate complexity. The evolution of q_l (liquid water potential temperature), q_t (total water mixing ratio), wind components, and turbulent kinetic energy (TKE) is modeled explicitly, while the variances and covariances of these variables are parameterized using mixing length theory. Since Koracin and Rogers (1990) found that a simple empirical formulation of the length scale works as well as a prognostic formulation, the master mixing length is defined using a diagnostic equation following Blackadar (1962). The model uses a Gaussian cloud model (GCM) developed by Sommeria and Deardorff (1977), a radiation scheme developed by Fu (1991), and an implicit numerical scheme implemented by Kent (1999).

The model is initialized using data from a four-day sequence of fog observed at the SIO buoys on 14 July to 18 July 1998, which exhibits characteristics near the synoptic means discussed in Part I. Background temperature, humidity, and wind profiles are taken from the San Diego Air Quality Control Board radar profiler at Pt. Loma and the San Diego rawinsonde at the Miramar Naval Air Station. Two specific background profiles are tested. The first is a saturated profile from 12 Z on 16 July 1998, which initialized the model with fog. The second is an unsaturated profile with a very sharp inversion from 0 Z on 14 July 1998.

The model does not tend to form fog over time. If the model is initialized with fog, the fog either remains or burns off. The unsaturated profile was altered to include moister, cooler air and various inversion heights and strengths. However, in all cases where the model is initialized without fog, it does not form. Using the unmodified code, the model tends toward a state of equilibrium, with the latent, sensible, and buoyancy fluxes all tending to zero. This is particularly noticeable as the humidity rises. Although the buoy observations report that the latent heat flux is about 30 W/m^2 in 100% saturated conditions, the model's surface flux subroutine is unable to recreate this situation.

Using the saturated profile to initialize the model with fog, a realistic diurnal profile only results if the fluxes are prevented from tending to zero over time. This problem is avoided by fixing the input to the bulk formula subroutine. By fixing the input surface air temperature at 16.5°C, the input surface air moisture at 13.05 g/kg, and the input sea surface moisture at 14.5 g/kg, the sensible heat flux remains between 13 and 15 W/m^2 and latent heat flux remains between 17 and 19 W/m^2. The fixed fluxes, combined with a subsidence rate of -0.0012 m/s, allows fog to burn off during the day (lifting to stratus) and reform in the evening, corresponding with the diurnal cycle observed at the buoys. The first day the fog barely lifts off the surface. During the second night, the marine boundary layer lifts from 200 m to 300 m, and the second day, the fog lifts to form stratus with a base at 200 m. The stratus layer lowers to the surface the following night, due to longwave cooling and lifts for a shorter duration, forming stratus with a base at 150 m the next day. Experimenting with different subsidence rates shows that allowing the boundary layer to grow enhances diurnal fog dissipation and reformation, whereas preventing growth (through greater subsidence) causes the fog to persist without change.

Fog in the model dissipates in three ways. First, fog is very sensitive to the subsidence rate. If the rate of subsidence is too high, for example w=-0.004 m/s, the inversion and the fog lower to the surface rapidly. If the rate of subsidence is intermediate, w=-0.002 m/s, the inversion layer stays constant, and the fog may dissipate for other reasons. At a lower subsidence rate, w=-0.001 m/s, the boundary layer and fog may actually grow. The second major cause of fog dissipation is the entrainment of drier and warmer air from aloft. While uniform subsidence lowers the inversion height but leaves the original boundary layer structure intact, entrainment leaves the inversion height alone but acts to bring warm dry air into the boundary layer. Because the model is unstable at low wind speeds, due mainly to the bulk formula's iteration scheme being unable to calculate fluxes in that regime, most model runs were implemented with wind speeds twice as high as those observed at the buoys during fog. These high wind speeds result in high turbulent kinetic energy, which acts to dry and warm the boundary layer in spite of the input of moisture from below. The third method for fog breakup is solar heating. This appears first as heating and drying in the center of the fog layer, which then results in the fog lifting off the surface to form stratus and eventually disappear.

4. DISCUSSION AND CONCLUSION

The processes of fog formation and dissipation are controlled by a complex combination of meteorological processes operating on many different scales. No single process dominates.

On a daily scale, the amount of solar radiation heating the air and the earth's surface is of critical importance. The lower temperatures observed when fog is present, the lower percentage of fog hours at stations with higher average temperatures, and the times of maximum and minimum fog occurrence that correspond to the times of maximum and minimum solar radiation, all support this. The importance of solar heating is also demonstrated by the correlation between cloud cover on satellite images and high relative humidity (i.e. fog) at the surface stations. The cloud cover blocks solar radiation, resulting in lower surface temperatures and more fog. The diurnal cycle observed at the buoys and illustrated in the model runs with fixed fluxes also demonstrate the importance of solar radiation.

For forecasting the likelihood of fog on a state-wide basis, 700 hPa synoptic maps provide the most useful tool. Overall, time periods with a 700 hPa high over California have a 30% greater chance of fog than time periods with a 700 hPa trough in the vicinity. This agrees with the results by Filonczuk et al (1995) that positive 700 hPa height anomalies correspond with a high

occurrence of fog and negative 700 hPa height anomalies correspond with a low occurrence of fog. The physical explanation for this difference is still not well understood. One hypothesis suggests that the subsidence associated with higher pressure results in lower and stronger inversions, which hold marine moisture near the surface, raising humidity levels and favoring fog. Model runs with fixed fluxes and various subsidence rates show that while unrealistically high subsidence rates drop the inversion to the surface and eliminate fog, lower rates promote boundary layer growth and more fog dissipation during the day. With the fluxes fixed and the subsidence rate set at w=-0.002 m/s, the fog did not lift to form stratus during the day, matching conditions reported all along the state during high pressure regimes. A second hypothesis is that the different flow patterns for the two synoptic cases bring in air from regions with contrasting properties. This is supported by the change in 3,000 m wind directions and the higher inversion top temperature reported at all stations during fog events. Perhaps warmer, moister air from the south is brought in during 700 hPa highs while colder, drier air from the north arrives with the 700 hPa trough. The model studies show that fog formation and dissipation depend critically on the background profiles of temperature and moisture both above and below the inversion, so air parcel origin could greatly influence fog behavior. An investigation using back-trajectories for representative air parcels during each of the two cases is suggested.

The one-dimensional model may eventually be useful as a forecast tool to predict the local timing of fog formation and dissipation. However, for accurate forecasts, the background conditions, including profiles of moisture and temperature, and sea surface temperature, must be known precisely. Also, work needs to be done on improving the model's bulk algorithm for calculating sensible and latent heat fluxes to make them more accurate in low wind, high humidity conditions. The mixing parameters also need to be rescaled to better represent entrainment across the inversion. In the meantime, forecasters should rely on synoptic trends, 700 hPa maps, and local experience.

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