4.2 Investigation of Fog and low Clouds Associated with a Coastally Trapped Disturbance

William T. Thompson and Stephen D. Burk
Naval Research Laboratory
Monterey California

John Lewis
National Severe Storms Laboratory and Desert Research Institute
Reno, Nevada

1. INTRODUCTION

The relatively shallow marine boundary layer adjacent to steep coastal topography along the California Coast gives rise to a number of mesoscale phenomena, including coastally trapped disturbances (CTD's), expansion fans, land/sea breezes, low-level jets, and cyclonic eddies*. CTD's occur several times each year during the period from May to early October (Mass and Bond 1996) and are easily identified in satellite imagery due to the distinctive narrow tongue of low clouds and fog propagating to the north along the coast. There have been relatively few investigations of fog and low clouds associated with CTD's. Dorman et al. (1998) utilized a mixed layer model in an investigation of the 10-12 June 1994 CTD event. Results showed that, as the mixed layer cools due to downward heat flux over the cold sea surface along the coast, clouds form when the temperature at the top of the mixed layer is equal to the dewpoint temperature. An important feature of this model is that the switch to southerly flow precedes arrival of the fog by several hours. This timing feature was observed in the June 1994 event by Ralph et al. (1998) and modeled by Thompson et al. (1997).

In the present study, we investigate a CTD event which occurred on 15-16 June 2000. On the afternoon of 15 June, fog in Monterey associated with this event caused a suspension in play at the U. S. Open golf tournament being held at this time. The event is simulated using the Naval Research Laboratory's COAMPS™[1] model. The model 12 h forecast for the period 1200 UTC 15 June to 0000 UTC 16 June reproduces the movement and speed of the fog along the coast north of Pt. Conception. In an effort to understand the evolution and extent of fog and low clouds in this event, several sensitivity studies are performed.

2. MODEL DESCRIPTION

The COAMPS model is a nonhydrostatic mesoscale model, using multiple nests having different horizontal resolution. It features a full suite of physical parameterizations, including schemes for radiation, cloud microphysics, and turbulence. Data assimilation is accomplished using a scheme which, in the absence of observational data, retains horizontal and vertical structure developed in the previous forecast in the initial conditions of a subsequent forecast. Where observational data are available, these data are incorporated into the initial conditions using an increment formed between the observational analysis and the previous forecast. Model forecast water species (vapor, cloud water, cloud ice, rain, snow, and graupel) are carried through the data assimilation into the initial conditions for the subsequent forecast. The model is described in more detail by Hodur et al. (2002). In the present study, the model is run in a triply-nested mode with horizontal resolution of 5 km on the innermost nest. Data assimilation is performed for three days prior to the period of interest using a sequence of 7 12 h forecasts beginning at 0000 UTC 12 June 2000.

---

* Corresponding author address: William T. Thompson, Naval Research Laboratory, Monterey, CA 93943. thompson@nrlmry.navy.mil

[1] COAMPS is a trademark of the Naval Research Laboratory

3. RESULTS

3.1 Synoptic Setting

The event of interest occurred over a 60 h period, from 1200 UTC 13 June to 0000 UTC 16 June 2000. The sea fog first appeared in the California Bight and progressively moved northward to Pt. Arena. A satellite image valid 2100 UTC (1400 LT) 15 June 2000 is shown in Fig 1. Transitory synoptic weather has been shown to influence the generation and longevity of sea fog (Findlater et al. 1989; Koracin et al. 2000; Lewis et al. 2003). Accordingly, we give attention to the larger-scale flow that accompanied this sea fog event.

On June 12-13, a strong pressure ridge built and moved into the Pacific Northwest. Northeast winds in the 850/700 layer were in evidence over the north and central California coast. The subsidence and associated adiabatic warming led to record breaking temperatures in the central valley extending into southern California.

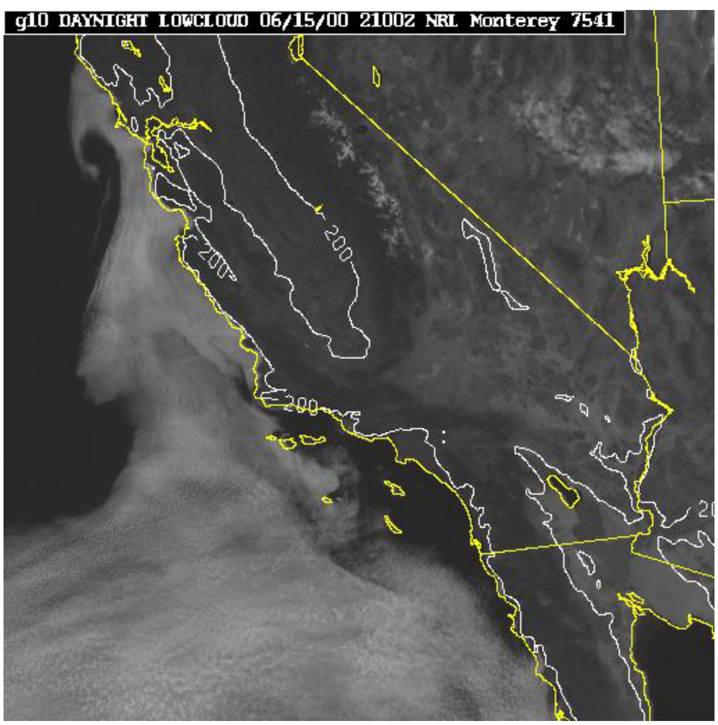

Figure 1. Satellite image valid 2100 UTC 15 June 2000.

The satellite imagery on 14 June showed a wide swath of clear sky off the California coast - a response to the strong subsidence as shown in Fig. 2. In this figure, the instantaneous estimates of the vertical velocity have been found by determining the magnitude of the component of the horizontal wind on the 310 K isentropic surface along the gradient of height on this same surface. We have chosen the 310 K surface since it depicts the flow above the marine layer off the central California coastline. Subsidence as great as .05 m s^{-1} is indicated over northern California, trailing to .01 m s^{-1} in southern California.

During the period of pronounced offshore flow in the 850/700 mb layer (13-14 June), the winds at the ocean surface are out of the north to northwest (off the northern and central California coastline). These winds, typically 7-15 m s^{-1}, are in response to the strong surface pressure gradient. This gradient dramatically weakens over the next 48 h. In the presence of this weakening surface

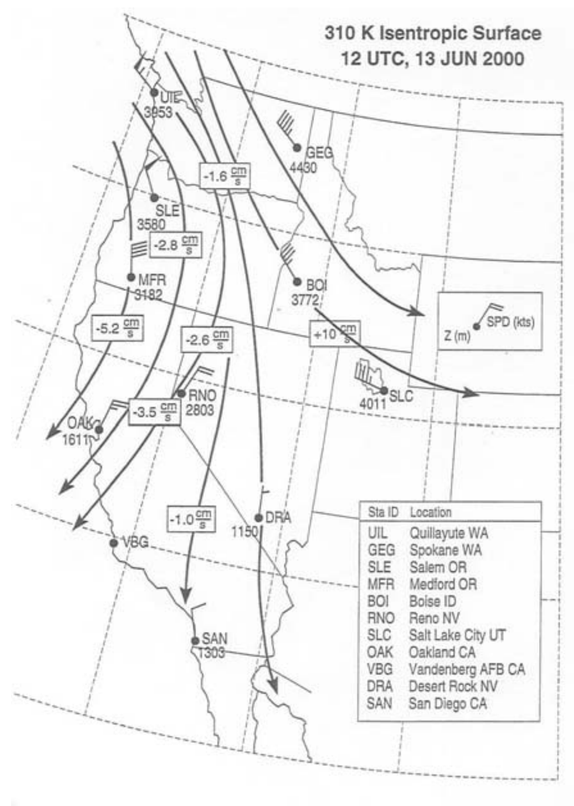

Figure 2. 310 K isentropic surface analysis valid 1200 UTC 13 June 2000.

pressure gradient, sea fog forms in the California Bight and subsequently moves northward. This can best be viewed by recourse to the buoy records (and one C-MAN station - Coastal Marine Automated Network). These records are displayed as time series at each of the stations in Fig. 3 (at the end of this paper), where winds, air temperature (T_a), dew point temperature, and SST are plotted [The C-MAN station (on land) does not record SST and dew point temperature and SST are missing on some of the buoy records]. The salient features from these time series are the following:

(1) A wind shift from northwesterly to southerly is indicated in the buoy and C-MAN records. This shift first appears in the south and moves northward;

(2) the SSTs decrease from south to north - 18/19 ^oC at Catalina Ridge to 9/10 ^oC at Bodega Bay;

(3)When foggy surface air is tracked in a Lagrangian frame (moving with the wind), the temperature is found to decrease;

(4) In the California Bight, the SST>T_a, but to the north at Bodega Bay, SST<T_a .

Based on these features, the cooling of the foggy air appears to have contributions from both the turbulent transfer at the sea surface and the radiation cooling at the top of the fog layer.

3.2 Model Results

At 1200 UTC (0500 LT) 15 June 2000, flow is southerly along the coast from Pt. Conception to Monterey Bay. The shift from northwesterly to southerly at Monterey occurs at 1200 UTC (0500 LT) 15 June 2000 in close agreement with the buoy observations (see fig. 3). Southerly flow continues to propagate to the north, arriving at Bodega Bay at1600 UTC (0900 LT). This is also in good agreement with observations. The speed of propagation of the wind shift from Monterey to Bodega Bay is ~12 m s^{-1}, which is fairly consistent with observations of the 10-11 June 1994 event (11 m s^{-1} ; Ralph et al. 1998).

The tongue of fog has reached Pt. Piedras Blancas at 1200 UTC (0500 LT) and propagates to Monterey by 1700 UTC (1000 LT) and Bodega Bay by 0000 UTC (1700 LT). Shown in Fig. 4 is the region over which the

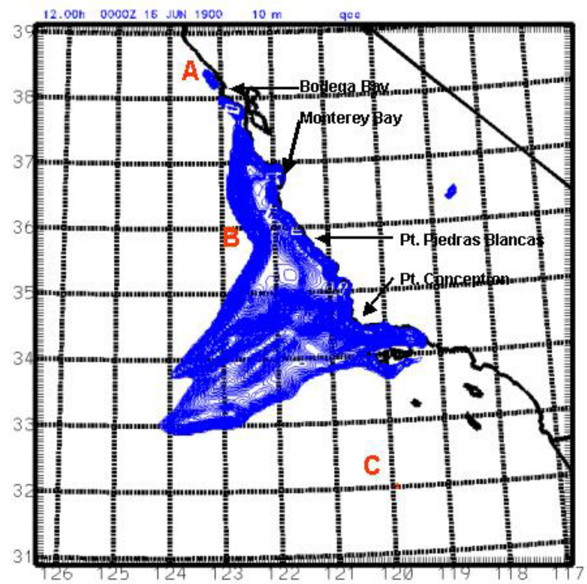

Figure 4. 12 h forecast valid 0000 UTC 16 August 2000 showing fog “footprint” (see text).

cloud liquid water mixing ratio at 10 m elevation exceeds 0.01gm/Kg (the fog “footprint”) at 0000 UTC 1700 LT 15) 16 June. The fog extends from Bodega Bay to the northern portion of the Southern California Bight and offshore to 33^{o}N, 124^{o}W. To the south of the shaded region, fog lifts away from the surface to form low clouds which extend to the southern boundary of the domain and from the coast to the western boundary of the domain.. Also shown in Fig. 4 are the locations of points A, B, and C. Examination of profiles of potential temperature, turbulent kinetic energy (tke), and cloud liquid water mixing ratio (not shown) indicates that, at point A, the boundary layer is quite stable with the potential temperature increasing from 286^{o}K to 296^o in the lowest 100 m. The tke is quite small. At point B near the center of the fog region, the fog extends to 200 m and has a peak water content of 1 gm/Kg. There is a shallow (100 m) mixed layer and the tke peaks near the base of the fog at 1 m^2s^{-2}. At point C in the low cloud regime, the cloud base is at 200 m and the layer is 250 m deep. The peak water content is .3 gm/Kg. There is a 400 m deep mixed layer and the tke peaks in the lower part of the cloud layer at 2.2 m^2s^{-2}.

3.3 Sensitivity Studies

Two important characteristics of the cloud field in this event are 1) the areal extent of fog as compared to the extent of low clouds and 2) the location of the northern end of the tongue. Given the relatively cold ocean surface temperature along the coast north of Point Conception and the somewhat warmer ocean surface temperature in the southern California Bight, it seems plausible that surface latent and sensible heat fluxes may play an important role in determining the extent of fog and low clouds. In an effort to understand the relative importance of these fluxes, sensitivity studies are performed. In each of several 12 h simulations, the initial conditions are identical to the control. In the first of the sensitivity studies, both latent and sensible surface heat fluxes are removed at all ocean grid points. In the second, latent heat flux is removed at all ocean grid points, and, in the third, sensible heat flux is removed.

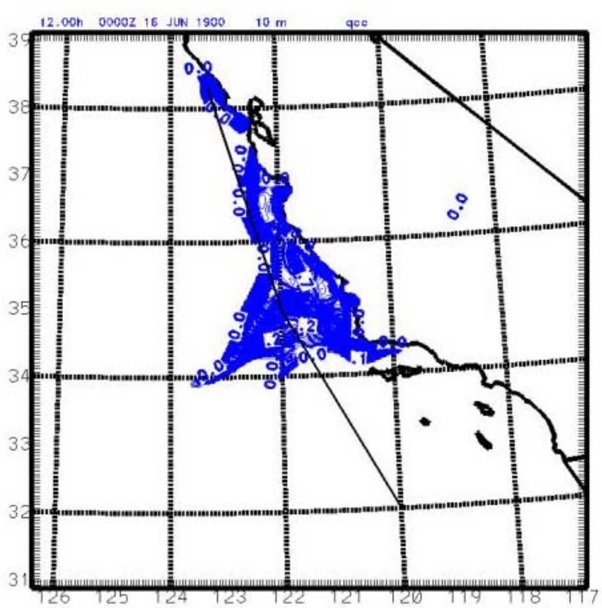

Figure 5. (a) as in Fig 4 but for the simulation in which surface latent heat flux over water is excluded (b) as in Fig 4 but for the simulation in which surface sensible heat flux is excluded.

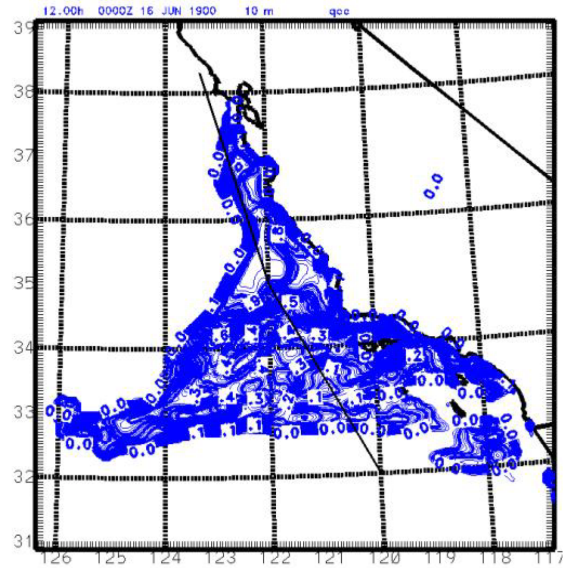

Figure 5 (b).

The results of the simulation in which both fluxes are removed are remarkably similar to the control, at least in terms of the coarse structure, indicating that boundary layer moistening due to latent heat flux (tending to enhance cloudiness) and warming due to sensible heat flux (tending to reduce cloudiness) are nearly compensating one another.

Shown in fig 5 are the fog footprints for the simulation in which latent heat flux is removed (Fig. 5 a) and the simulation in which sensible heat flux is removed (Fig 5 b). Comparison of Fig 4 for the control and Fig 5 indicates that the removal of the individual fluxes has a dramatic impact on the distribution of the fog, both in terms of areal extent and the location of the northern edge. Somewhat paradoxically, the simulation in which latent heat flux is removed has both the smallest areal coverage and the <u>greatest</u> northern extent while the simulation in which sensible heat flux is removed has both the largest areal coverage and the <u>smallest</u> northern extent.

4. DISCUSSION AND CONCLUSIONS

Investigation of the CTD event of 15 June 2000 has shed light of several aspects of cloud liquid water field associated with the CTD. The synoptic features leading to the “heat wave” which typically precedes CTD’s are identified using isentropic analyses. Using the COAMPS model, the distribution of fog and low clouds is documented and the boundary layer structure within the tongue of low clouds and fog is investigated. Model results are shown to be in reasonable agreement with satellite imagery and buoy observations.

Analysis of the results of the sensitivity studies reveals some of the aspects of the roles of surface sensible and latent heart fluxes in this CTD event. Along most of the coast in the fog and low cloud regime, both surface sensible and latent heat flux are upward. Upward sensible heat flux warms the boundary layer and enhances entrainment of dry air, tending to reduce cloudiness. Upward latent heat flux tends to moisten the boundary layer and promotes cloudiness. North of San Francisco, the ocean surface temperature is particularly cold and latent and sensible heat fluxes are downward. Downward sensible heat flux results in cooling of the layer, promoting cloudiness while downward latent heat flux leads to drying, tending to reduce cloudiness. The results of the simulation in which both sensible and latent heat flux are removed indicates that the effects nearly balance one another. When latent heat flux is removed, it no longer promotes cloudiness over the bulk of the footprint and thus the size of the footprint is reduced. North of San Francisco, it no longer tends to reduce cloudiness so the tongue extends further to the north. A similar interpretation applies for the removal of sensible heat flux: over the bulk of the footprint, warming and dying of the layer are eliminated and the footprint gets larger. To the north, downward heat flux promoting cloudiness is eliminated and the tongue does not extend as far to the north.

Several issues remain to be addressed. These include the processes modifying the thermodynamics in the region of southerly flow in advance of the northern edge of the tongue of fog as it propagates along the coast and the role of radiative flux divergence in cooling the fog boundary layer.

Acknowledgements. This research was supported by the Office of Naval Research Program Element 0601153N.

REFERENCES

Dorman, C. E., L. Armi, J. M. Bane, and D. P. Rogers, 1998: Sea surface mixed layer during the 10-11 June 1994 California coastally trapped event. *Mon. Wea. Rev.*, **126**, 600-619.

Findlater, J., Roach, W., and McHugh, B.,1989: The haar of north-east Scotland. *Quart. Jour. Roy. Meteor. Soc.*, **115**, 581-608.

Hodur, R. M., J. Pullen, J. Cummings, X. Hong, J. D. Doyle, P. Martin, and M. A. Rennick, 2002: The coupled ocean/atmosphere mesoscale prediction system (COAMPS). *Oceanography,* **15,** 88-89.

Koracin, D., J. Lewis, W. T. Thompson, C. E. Dorman, and J. A. Businger, 2001: Transition of stratus into fog along the California Coast: Observation and Modeling. *J. Atmos. Sci***.,** **58**, 1714-1731.

Lewis, J., Koracin, D., Rabin, R., and Businger, J. 2003: Sea fog along the California coast: Viewed in the context of transient weather systems. [Accepted Jour. Geophys. Res. (Atmospheres)]

Mass, C. F. and N. A. Bond, 1996: Coastally trapped wind reversals along the United States west coast during the warm season. Part II: Synoptic evolution. *Mon. Wea. Rev.*, **124**, 446-461.

Ralph, F. M., L. Armi, J. M. Bane, C. Dorman, W. D. Neff, P. J. Neiman, W. Nuss, and P. O. G. Persson, 1998: Observations and analysis of the 10-11 June 1994 coastally trapped disturbance. *Mon. Wea. Rev.*, **126**, 2435-2465.

Thompson, W. T., T. Haack, J. D. Doyle, and S. D. Burk, 1997: A nonhydrostatic mesoscale simulation of the 10-11 June 1994 coastally trapped wind reversal. *Mon. Wea. Rev.*, **125**, 3211-3230,

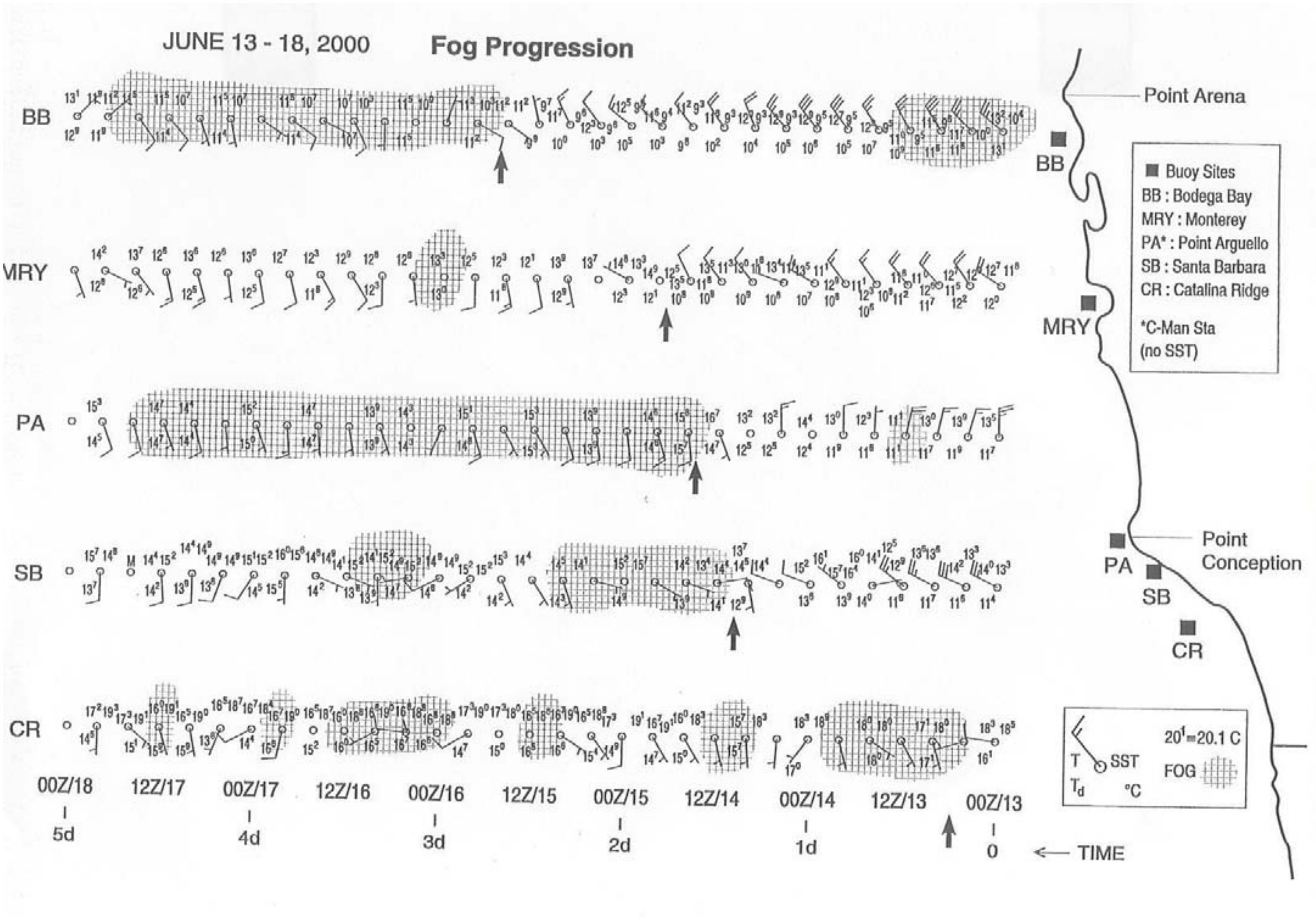

Figure 3. Time series of buoy observations.