P4.12 EXPLORING THE TIMING OF FOG FORMATION AND DISSAPATION OVER SAN FRANCISCO BAY AREA USING SATELLITE CLOUD COMPOSITES

Cynthia L. Combs *
CIRA/Colorado State University

Warren Blier
NOAA/NWS Monterey, CA

Walter Strach
NOAA/CWSU Oakland, CA

Mark DeMaria
NESDIS/ORA/RAMMT
CIRA/Colorado State University

1. INTRODUCTION

"The coldest winter I've ever saw was the summer I spent in San Francisco."
- Mark Twain

While there is some debate on whether Mark Twain actually said the above quote, there is no debate on the sentiment behind it for anyone who has visited San Francisco, CA during the summer. While Sacramento, CA can be basking in sunshine and high summertime temperatures at its inland location, San Francisco is often much cooler in its shroud of marine stratus and fog. This layer of low cloud develops from the inversion created by the cold ocean water and the subsidence of the Pacific high that often sits off the California coast during the warm season. The extent and daily progression of this cloud layer is an important forecast for the San Francisco Bay/Monterey area. The effects of the complex terrain features including various bays and coastal mountains ranges add to the challenge. (see figure 1).

In this study, we will investigate whether satellite cloud composites have the potential to aid the Monterey, CA National Weather Service (NWS) office in forecasting the development and extent of fog and low cloud. In a previous study, Connell et al (2001) have shown that hourly cloud frequency composites divided into various wind regime categories are useful in forecasting sea breeze convection in the Florida Panhandle. In another study, Combs et al (2001) showed that wind regime cloud climatologies aided Wakefield, VA forecasters in determining some persistent cloud features leading to convective development under certain wind conditions. Recently, satellite cloud composites have been shown to help Cheyenne, WY forecasters in finding precursor cloud signatures to high wind events in their County Warning Area (Combs et al, 2003). For this study, percent cloud cover composites have been produced over the San Francisco Bay/Monterey area to see if there are any patterns that can be exploited in forecasting the extent of the fog/marine stratus layer.

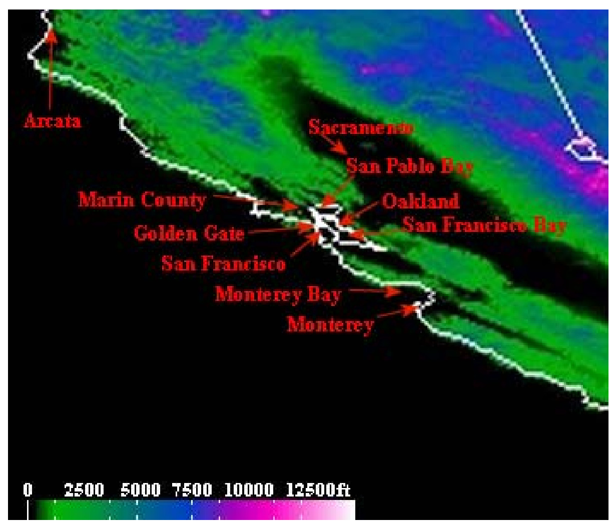

Figure 1: Topography map of study area

2. DATA AND METHODOLOGY

For this project, images for channels 2 (3.6 μm) and 4 (10.7 μm) from the Geostationary Operational Environmental Satellite (GOES) were obtained from an archive collected at CIRA. The GOES 10 images were collected every other hour for May through July, 1999-2003, cover the western U.S., and are sampled to 4-km resolution. Each image was previously quality checked, then sectorized to cover most of California, including the County Warning Area (CWA) for the San Francisco Bay/Monterey office. Then the data were grouped by hour for further processing.

In previous projects, a threshold method using either the visible (channel 1) or the 10.7 μm (channel 4) was

* *Corresponding author address*: Cynthia Combs, CIRA/Colorado State University, W. Laporte Avenue, Foothills Campus, Fort Collins, CO 80523-1375; e-mail: combs@cira.colostate.edu

utilized. Since the clouds being examined were either mid to high level or convective, these methods were appropriate. Unfortunately for this project, we are mainly interested in fog and marine stratus through a twenty-four hour period. Since the visible is only available during daylight hours and the 10.7 μm channel has difficulty detecting low clouds that are close to surface temperature, neither method is ideal for this situation.

To overcome this problem, clouds were determined by a differencing method using the 3.6 μm (channel 2) along with the 10.7 μm bands. The algorithm is similar to one described by Jedlovec and Laws (2003). Basically, the 10.7 μm and 3.6 μm images are matched according to time and are divided into sets for a given month and hour of the day (for instance, all 1200 UTC images for June 2003). For each image pair, a difference value is calculated by subtracting the 3.6 μm brightness temperature value from the 10.7 μm brightness temperature value for each pixel. Then for each pixel location, the largest negative difference and the smallest positive difference is determined for the entire month and hour to form two composite images. In addition, the warmest 10.7 μm temperature value for each pixel location in the set is also determined.

Once these three composites are produced, two tests are performed. The first is the minimum difference test. If the 10.7 μm - 3.6 μm temperature difference calculated earlier for a given pixel in an image pair is negative, and the difference is less than the negative composite value minus a threshold value (5.1K over land, 4.1K over ocean), it is tagged as cloud. Otherwise, it is considered clear. If the difference is positive, it is tagged cloud if the difference is greater than the positive composite plus 2.0K. After this test is done for all of the pixels in the image pair, a final test is performed on all the 'clear' pixels. If the 10.7 μm temperature for the pixel is 18.5K colder than the warmest 10.7 μm temperature composite value, it is retagged cloud. In addition, each cloud pixel is further identified as 'low' or 'high' depending on whether the 10.7 μm temperature is below or above a threshold of 273K. Once these tests have been completed for a give image pair, a low cloud/high cloud /clear image is produced for future processing. The same procedure is performed on the rest of the image pairs.

Table 1: Surface wind regimes

	Wind regimes
1	Calm (< 5m/s)
2	North
3	Northeast
4	East
5	Southeast
6	South
7	Southwest
8	West
9	Northwest

The next step is to categorize each cloud image by regimes. For this project, three separate regime sets were used. The first takes hourly surface winds measured at Travis Air Force Base from the METAR database. Images were divided into regimes similar to those used with boundary layer winds in previous studies (see Table 1). In order to determine if station location has an effect on the resulting composites, a second set of regimes were based on the surface wind from San Francisco.

A third set of regimes takes a different approach. Instead of wind, it focuses on the difference in Sea Level Pressure (SLP) between Arcata, CA and San Francisco (AcSf), and San Francisco and Sacramento (SfSc). Arcata is roughly north of San Francisco, while Sacramento is northeast. These regimes are described in the Table 2.

For easier reference, each pressure difference regime has been given a descriptive set of initials. Differences greater than 5 mb are called 'Large', between 5 mb and 2.5 mb 'Medium', and less than 2.5 mb are called 'Small'. Thus, 'LS' would signify that the pressure difference between Arcata and San Francisco is greater than 5 mb, while the pressure difference between San Francisco and Sacramento is less than 2.5 mb.

Table 2: SLP pressure difference regimes

Regime	SLP definition
1 (LL)	AsSf > 5mb SfSc > 5mb
2 (LM)	AsSf > 5mb 5mb >SfSc > 2.5 mb
3 (LS)	AsSf > 5mb 2.5mb >SfSc
4 (ML)	5mb > AsSf > 2.5mb SfSc > 5mb
5 (MM)	5mb>AsSf>2.5mb 5>SfSc>2.5mb
6 (MS)	5mb > AsSf > 2.5mb 2.5mb >SfSc
7 (SL)	2.5mb > AsSf SfSc > 5mb
8 (SM)	2.5mb > AsSf 5mb >SfSc > 2.5mb
9 (SS)	2.5mb > AsSf 2.5mb >SfSc

The cloud frequencies within a given wind regime are determined by grouping the images by regime. Then for each pixel location in the image, the number of cloudy pixels is tallied according to cloud height (low, high, and total). Then the number of cloud pixels is divided by the total number of pixels for that location, height and regime to produce a cloud cover percentage.

For this preliminary look, the procedure was implemented for every other hour and wind regime for two summer months (June and July) over a five-year period (1999-2003). Since our main interest is in low clouds like fog and marine stratus, we will focus on the low cloud composites.

3. PRELIMINARY ANALYSIS

3.1 *Travis Air Force base surface wind regimes*

One useful tool for analyzing the success of a given regime set is to look at the number of cases (images) that fall within each regime for a given period. Figure 2 is the graph for the number of cases per hour for each regime based on the Travis AFB surface winds.

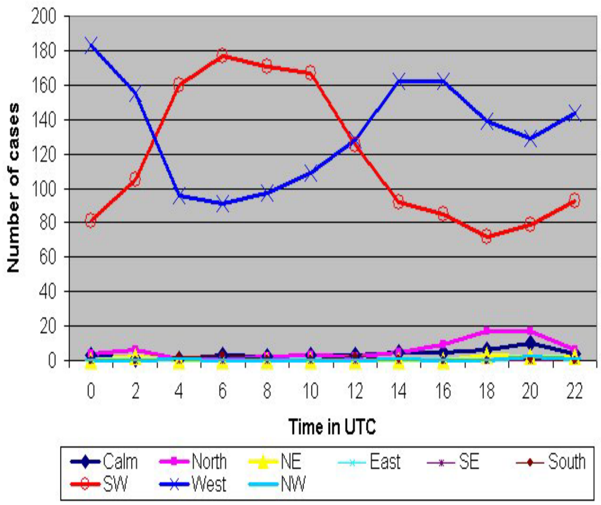

Figure 2: Number of cases per hour for regimes based on Travis AFB surface winds, June and July 1999-2003

It is obvious that most of the cases fall into two regimes, Southwest and West. None of the other regimes have enough cases to provide a good composite, though the North and Calm regimes do come close in the late morning, early afternoon hours (18-20 UTC). It is possible that adding another month to the set (perhaps August) would increase the numbers in these two regimes to provide a better picture. But for now, we will focus on Southwest and West.

Figure 3 below is a low cloud composite for the West wind regime over the California area 0000 UTC (5 pm Pacific Daylight Time). The key to understanding the colors is that cool tones (pinks and blues) are cloud percentages less than 30% (i.e. Mostly clear), while the warmer tones (orange, red, black and gray) are cloud percentages higher than 70%(mostly cloudy). The greens and yellows are in the 40-60% range. As you can see from the image, the general pattern is that there are high cloud percentages over the ocean, and low percentages (ie. mostly clear) over the land. The high percentages over the ocean are due to the marine stratus decks.

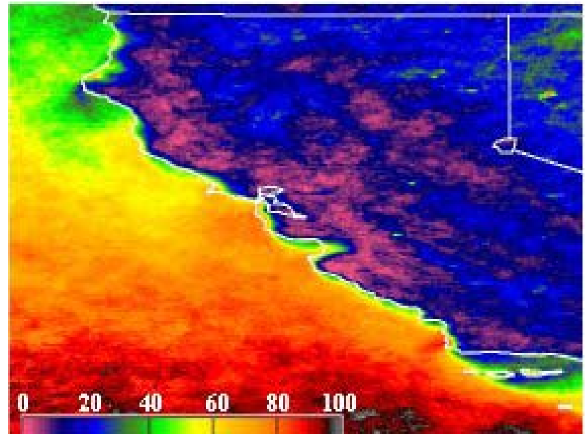

Figure 3: Low Cloud % for the Travis AFB West Wind regime over California, June-July 1999-2003, 0000 UTC, 183 cases.

Now let's zoom in closer to the San Francisco Bay/Monterey area. Figure 4 is for the Southwest regime, while Figure 5 is for the West regime. In viewing the two images, one caveat is the line of high cloud percent along the northern section of the Monterey Bay coastline. It shows up in the afternoon composites, and is an artifact of the processing instead of an actual cloud feature. One possible explanation is that the algorithm is having trouble with the land/sea interface in that particular location.

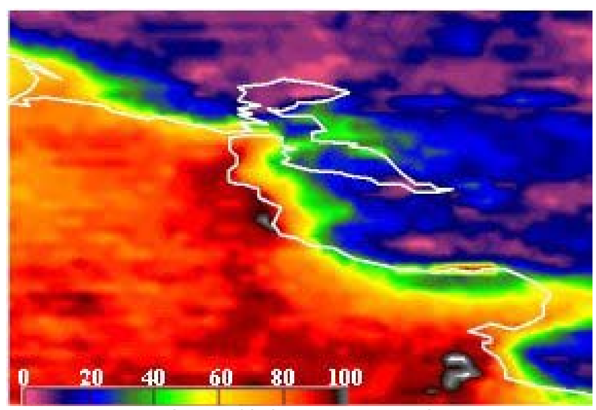

Figure 4: Low Cloud % for the Travis SW Wind regime over the San Francisco Bay/Monterey Bay area, June-July 1999-2003, 0000 UTC, 81 cases.

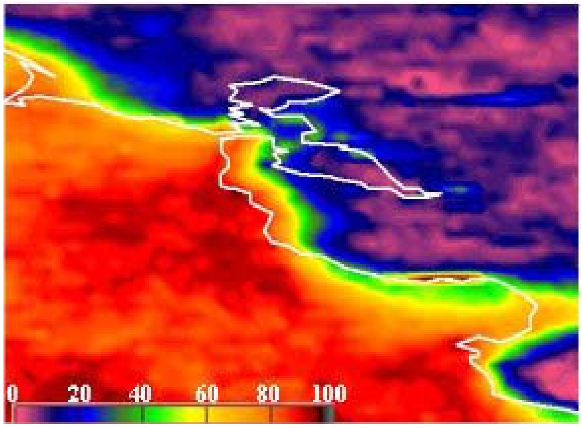

Figure 5: Low Cloud % for the Travis West Wind regime over the San Francisco/Monterey Bay area, June-July 1999-2003, 0000 UTC (5 pm PDT), 183 cases

In comparing the two wind regime composites, the overall patterns are quite similar. Like in the larger sector, high percentages cover most of the adjacent ocean and San Francisco in both regimes. Then there is a rather sharp drop-off to 20-30% on the east side of the San Francisco Peninsula. From there, the San Francisco Bay and San Pablo Bay are down to 10-25% range, as well as most of the land areas.

The scene changes by the early morning hours. Figures 6 and 7 are for the Southwest and West regimes at 1200 UTC (5 am PDT). Cloud percents have increased over the bays and east for the Southwest regime, and cloud percents have increased for most of the area in the West regime. There are more clear areas over Marin county and the land area south of San Francisco Bay.

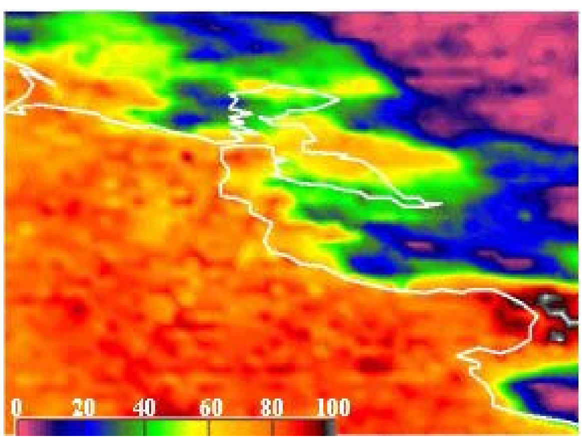

Figure 6: Low Cloud % for the Travis SW Wind regime over the San Francisco/Monterey Bay area, June-July 1999-2003, 1200 UTC (5 am PDT), 125 cases

If we zoom out again for the West regime in Figure 8, it is obvious that while the inland areas are even less cloudy than before (< 10%), many coastal areas are covered in low cloud. Terrain effects are obvious in some areas, like the Salinas River valley southeast of

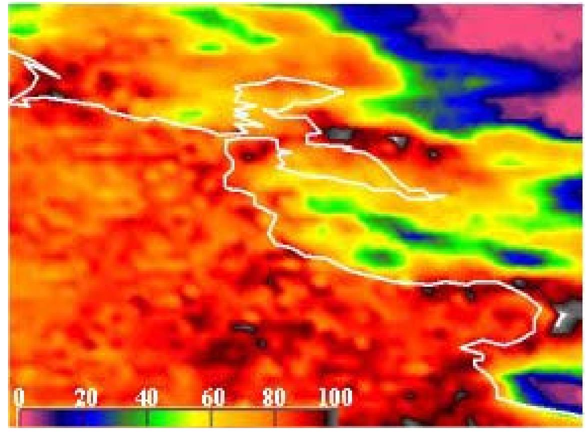

Figure 7: Low Cloud % for the Travis West Wind regime over the San Francisco/Monterey Bay area, June-July 1999-2003, 1200 UTC, 128 cases.

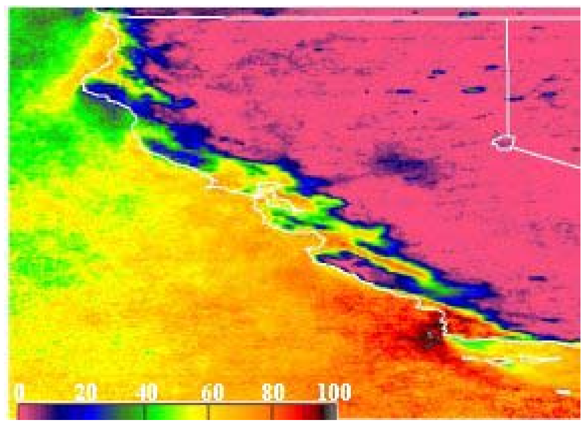

Figure 8: Low Cloud % for the Travis AFB West Wind regime over California, Jun-Jul 1999-2003, 1200 UTC, 128 cases.

Monterey Bay, and clearer areas in around the Santa Cruz mountains between San Francisco Bay and Monterey Bay. From the time loops of the composites, the progression of high cloud percentages from close to the shore in the 5 pm composite out to low areas inland by 5 am composite and back again can be traced. (To see the time loops, go to website http://www.cira.colostate.edu/RAMM/clim/Monterey/fogMS.html)

This confirms what climatology tells us. However, while there are some subtle differences between the Travis AFB Southwest and West regimes, there is a need for a stronger distinction. So we will see if a change in surface station location will help.

3.2 *San Francisco surface wind regimes*

In comparison to Travis AFB, the San Francisco station has more regimes with significant number of cases. Figure 9 below displays the number of cases per hour per regime. The West regime still has the highest values, but the Southwest remains respectable, as is several of the hours for Calm and Northwest regimes.

Two hours of the North regime (1800 and 2000 UTC) also have decent numbers.

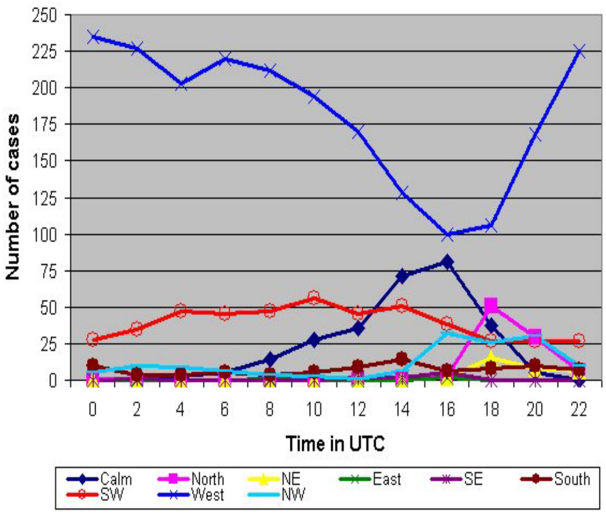

Figure 9: Number of cases per hour for regimes based on San Francisco surface winds, June & July 1999-2003

To see what effect the larger spread of regimes would have, the hour of 1800 UTC (11 am PDT) was chosen for closer scrutiny. Figures 10-14 are composites based on San Francisco surface wind. The first obvious difference is between the Calm case (figure 10) and the rest of the figures. Not only are the cloud percentages over the bay area mostly in the 30% or less category, but the cloud percent over much of the adjacent ocean is also 50% or less. At the other end of the spectrum, the Southwest regime shows the strongest cloud signal. It is seen not only through Golden Gate and over San Francisco, but well into the Oakland, Berkley and the San Francisco Bay areas as well. Subtle differences in low cloud coverage can also be seen in the North, Northwest, and West regimes.

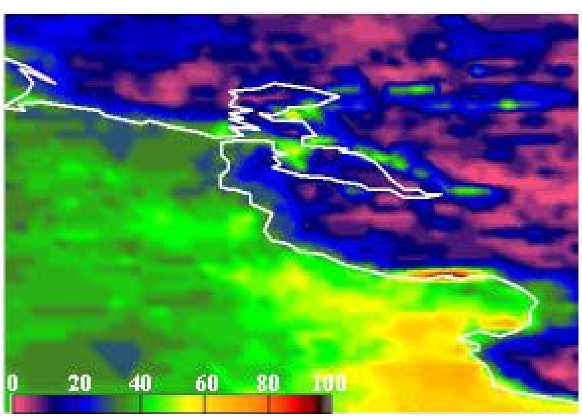

Figure 10: Low Cloud % for the San Francisco Calm Wind regime, Jun-Jul 1999-2003, 1800 UTC (11am PDT), 37 cases

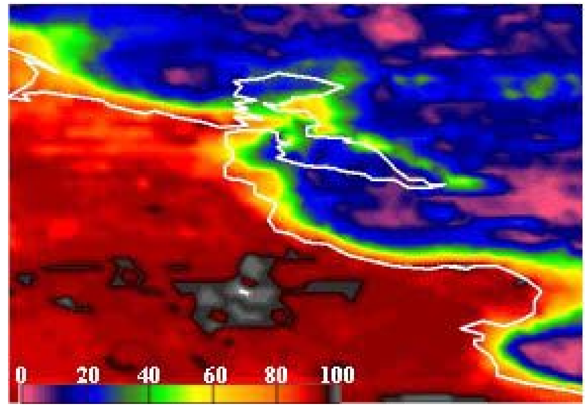

Figure 11: Low Cloud % for the San Francisco North Wind regime, Jun-Jul 1999-2003, 1800 UTC, 51 cases

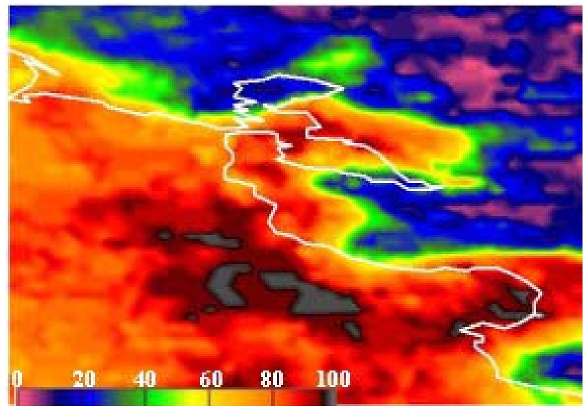

Figure 12: Low Cloud % for the San Francisco Southwest Wind regime, Jun-Jul 1999-2003, 1800 UTC, 27cases

Unfortunately, all of these regimes do not have significant amounts of data for the entire day. The Calm regime only has enough cases for 800-1800 UTC, while the North only has enough data for 1800 and 2000 UTC. Only the West and Southwest regimes provide a good, 24-hour look. Perhaps adding another month of data for the five-year period would help, but there is no guarantees. It is time for a new approach.

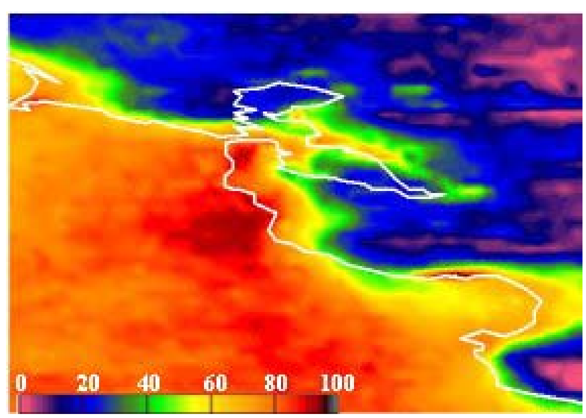

Figure 13: Low Cloud % for the San Francisco West Wind regime, Jun-Jul 1999-2003, 1800 UTC, 106 cases.

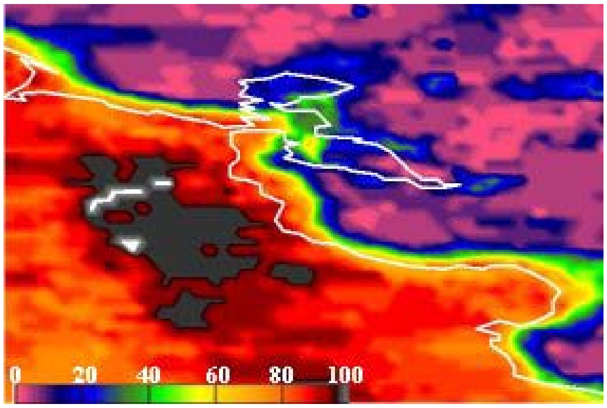

Figure 14: Low Cloud % for the San Francisco NW Wind regime, Jun-Jul 1999-2003, 1800 UTC, 26 cases.

3.2 ***Sea Level Pressure difference regimes***

Instead of basing regimes on surface winds, the focus will shift to SLP. The basic idea is to gain a rough idea of the strength and/or position of the eastern Pacific high and how it may effect the penetration of the marine stratus inland during the day.

The first good sign for this set is the graph of the number of cases per regime per time of day (Figure 15). While the number of cases can vary quite a lot during the day for a given regime, all but two regimes have significant number of cases for some part of the day. In addition, five regimes had significant numbers throughout the day. This will provide good time series as well as snapshots during specific times.

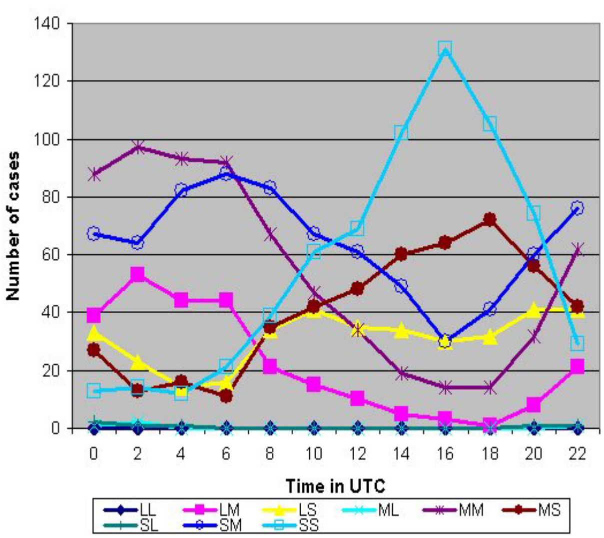

Figure 15: Number of cases per hour for regimes based on pressure differences Arcata - San Francisco and San Francisco - Sacramento, June and July 1999-2003

First, we will compare the composites from six of the SLP regimes at 1000 UTC (3 am). The first two regimes (Figures 16 and 17), where the north/south pressure difference is large, show less than 30% cloud cover for most of the Bay area. While the LM regime shows more clouds over the adjacent ocean than LS, and the LS regime shows more cloud over the Monterey Bay, both display significantly less clouds than the other four regimes shown. Time series show this trend continues for the 24-hour period, though the LM regime is lacking cases during the 1400-2000 UTC period.

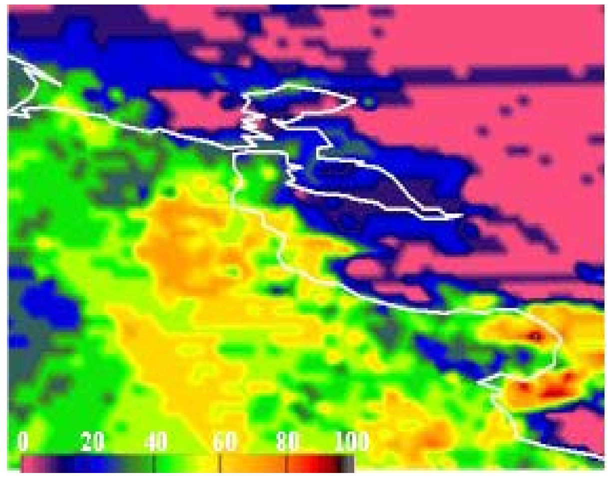

Figure 16: Low Cloud % for SLP regime 2 (Large/ Medium), Jun-Jul 1999-2003, 1000 UTC, 15 cases

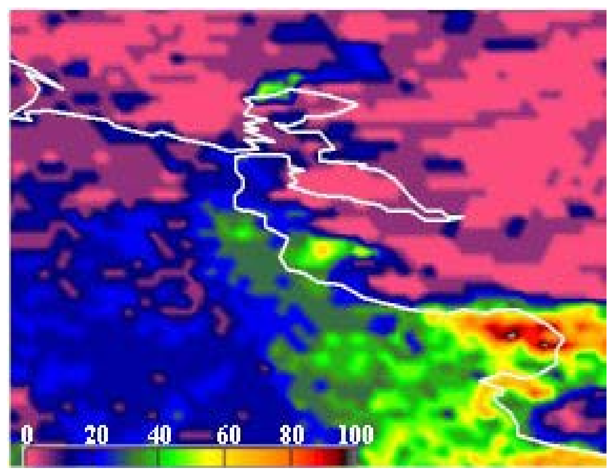

Figure 17: Low Cloud % for the SLP regime 3 (Large/Small), Jun-Jul 1999-2003, 1000 UTC, 41 cases

The MM regime (figure 18) shows more clouds than LM and LS, especially over the San Francisco Peninsula and through the Golden Gate channel across to Oakland. The San Pablo Bay and Marin county to the north continue to show low cloud percents(< 30%), as well as the area directly south of San Francisco Bay. The MS regime (figure 19) shows a similar pattern, only with slightly higher cloud percents in the San Pablo Bay and a general 'widening' of higher cloud percents.

The SM and SS regimes (figures 20 and 21) show not only very high cloud percentages (> 70%) in most areas, but areas of 50% and above are more widespread. The only areas that seem to remain lower than 30% are over the Santa Cruz mountains and the Gabilan Range.

Another interesting note is that there seems to be a stronger connection to the north-south pressure difference (San Francisco - Arcata) than the east-northeast difference (San Francisco - Sacramento). When the SLP difference is high, there appears to be significantly less cloud over the San Francisco Bay/Monterey area. When the difference is low, there is more penetration of the marine stratus layer into the low-lying areas.

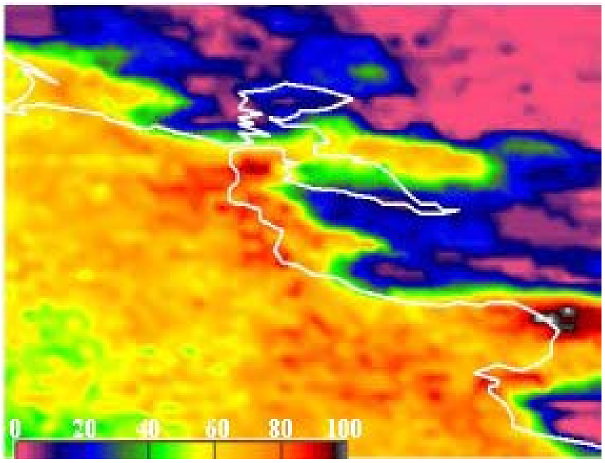

Figure 18: Low Cloud % for the SLP regime 5 (Medium/Medium), Jun-Jul 1999-2003, 1000 UTC

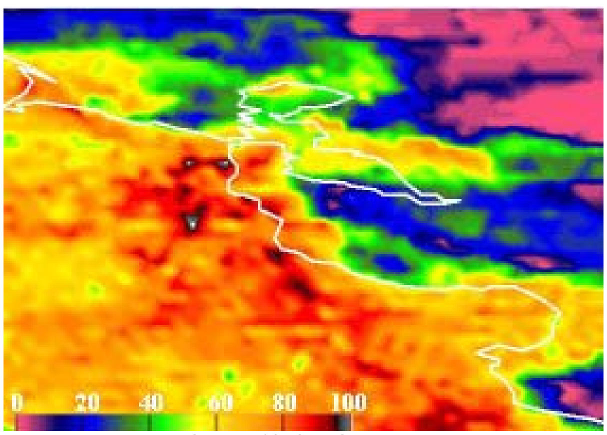

Figure 19: Low Cloud % for SLP regime 6 (Medium/ Small), June-July 1999-2003, 1000 UTC, 42 cases

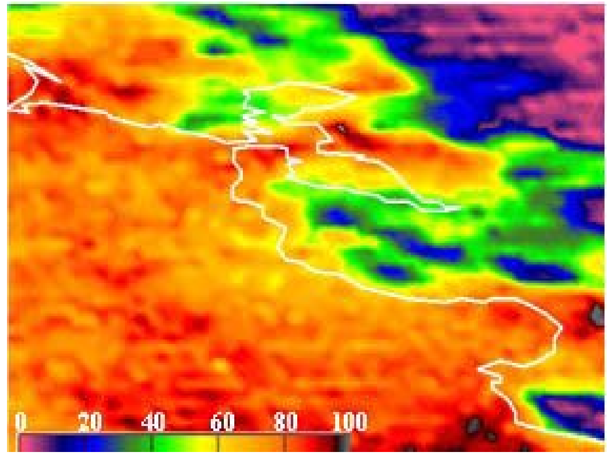

Figure 20: Low Cloud % for SLP regime 8 (Small/ Medium), Jun-Jul 1999-2003, 1000 UTC, 67 cases

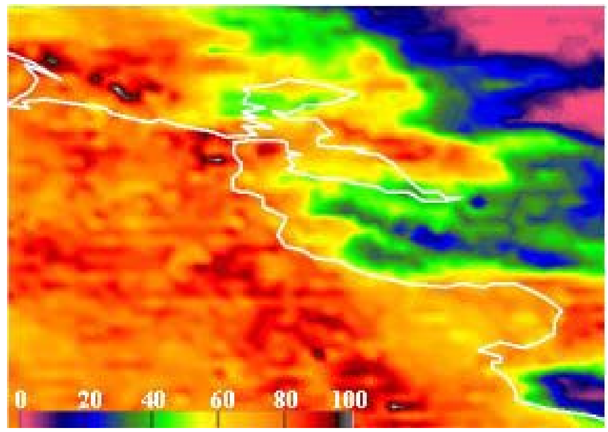

Figure 21: Low Cloud % for SLP regime 9 (Small/Small), June-July 1999-2003, 1000 UTC, 61 cases

With this in mind, for the evening hour of 0000 UTC (5 pm), we'll compare the LS (Figure 22), the MM (Figure 23) and the SM (Figure 24). The LS regime, like its 1000 UTC counterpart, is still quite clear for most of the composite. The MM regime is less than 30% through the area over Oakland and to the east where its 1000 UTC counterpart was over 50%. The west side of the San Francisco peninsula still has high cloud percentages. The SM composite is similar in pattern to the MM, but compared to its 1000 UTC counterpart shows considerably lower cloud percentages.

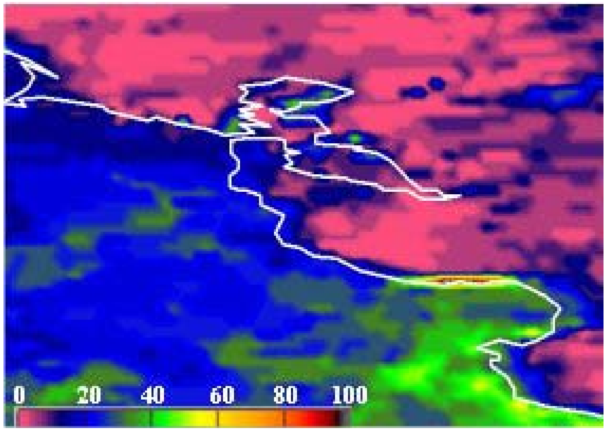

Figure 22: Low Cloud % for the SLP regime 3 (Large/Small), Jun-Jul 1999-2003, 0000 UTC

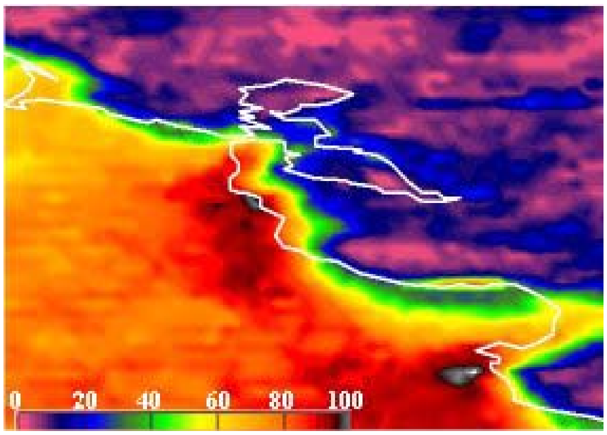

Figure 23: Low Cloud % for the SLP regime 5 (Medium/Medium), Jun-Jul 1999-2003, 0000 UTC

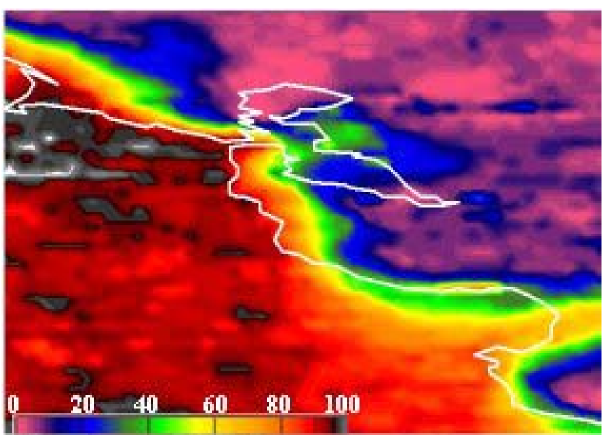

Figure 24: Low Cloud % for the SLP regime 8 (Small/Medium), Jun-Jul 1999-2003, 0000 UTC

4. CONCLUSIONS AND FUTURE WORK

While the Travis AFB wind set did not appear to show much difference between its two main regimes, both the San Francisco wind set and the SLP pressure difference set show promise. The results from the SLP set seem to suggest that more inland penetration occurs when there is a weaker pressure difference between Arcata and San Francisco. While there are subtle differences in the regimes where the San Francisco/Sacramento difference is taken into account, it may be interesting in the future to see if the SLP difference from another station like Fresno or Barstow would have a greater effect. More analysis of the terrain structure effects on the various composites would also be of interest.

For the San Francisco wind regime, more cases would be helpful, especially if they would add to regimes hours with low case counts. In the near future, August 1999-2003 will be added to the data set.

5. ACKNOWLEDGMENTS

The authors would like to thank Adam Kankiewicz for his helpful discussion on California weather. This work was funded by NOAA grant number NA67RJ0152. The views, opinions, and findings in this report are those of the authors, and should not be construed as an official NOAA and or U.S. Government position, policy, or decision.

6. REFERENCES

Combs, C. L., N. A. Stuart, M. DeMaria, and T. H. Vonder Haar: Wind regime GOES cloud cover composites for the Wakefield, VA county warning area. Preprints, *11th Conf. On Satellite Meteorology and Oceanography,* Madison, WI, Amer. Meteor. Soc., 165-167.

Combs, C. L., M. Weiland, M. DeMaria, and T.H. Vonder Haar: Examinging high wind events using satellite cloud cover composites over the Cheyenne, WY region. Preprints CD, *12th Conf. On Satellite Meteorology and Oceanography*, Long Beach, CA, Feb 2003, Amer. Meteor. Soc., P2.25

Connell, B. H., K. J. Gould, and J. F. W. Purdom, 2001. High resolution GOES-8 visible and infrared cloud frequency composites over northern Florida during the summers 1996-1999. *Wea. Forecasting*, **16**, 713-724.

Jedlovec, G.J., and K. Laws:GOES cloud detection at the global hydrology and climate center. Preprints CD, *12th Conf. On Satellite Meteorology and Oceanography*, Long Beach, CA, Feb 2003, Amer. Meteor. Soc., P1.21.