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USING THE LAGRANGIAN METHOD TO TRACK TRAJECTORIES OF FOG AND MIST IN THE MONTEREY BAY

by

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December 2017

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To assist the operational forecaster, this study collects data in the fog-rich environment of Monterey Bay for June and July 2016. Backtracking trajectories via the Lagrangian method provided significant insight as to how air parcels can change characteristics from warm and dry to cool and moist and vice versa. By gathering over 3,500 weather observations for Monterey Bay, the Monterey airport and the Salinas airport, along with tracking 48-hour trajectory data, patterns were identified, and fog formation and dissipation hypotheses were developed.

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USING THE LAGRANGIAN METHOD TO TRACK TRAJECTORIES OF FOG AND MIST IN THE MONTEREY BAY

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ABSTRACT

The military forecaster is challenged with predicting the outcome of the operational atmospheric environment for the warfighter on a daily basis. The caveat is that most operational forecast professionals complete their task without the benefit of an advanced meteorology or atmospheric science degree.

One of the most difficult weather conditions to predict is the onset and the dissipation of fog and low stratus. Coastal California in the summer has one of the highest rates of fog and low stratus in the world, and the United States Navy possesses a large fleet concentration area that operates in the gloomy Eastern Pacific throughout the year. From May through August, training and mission requirements become problematic due to low marine layer cloud decks and diminishing visibility due to fog and mist; all the while, the operational forecaster is expected to provide the best forecast possible during these grim weather conditions.

To assist the operational forecaster, this study collects data in the fog-rich environment of Monterey Bay for June and July 2016. Backtracking trajectories via the Lagrangian method provided significant insight as to how air parcels can change characteristics from warm and dry to cool and moist and vice versa. By gathering over 3,500 weather observations for Monterey Bay, the Monterey airport and the Salinas airport, along with tracking 48-hour trajectory data, patterns were identified, and fog formation and dissipation hypotheses were developed. THIS PAGE INTENTIONALLY LEFT BLANK

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LIST OF ACRONYMS AND ABBREVIATIONS

AG-C1	Aerographer's Mate Forecasting school
ASOS	Automated Surface Observation system
В	Brush, or Eastern Pacific Brush
CA	California
CEWCOM	Cooperative Experiment in West Coast Oceanography and Meteorology
CFSR	Climate Forecast System Reanalysis
CO	Commanding Officer
EPAC	Eastern Pacific
ESRL	Earth System Research Laboratory
FAA	Federal Aviation Administration
Ft	feet (length measurement)
GARP	GEMPAK Analysis and Rendering Program
GOES	Geostationary Operational Environmental Satellite
Kts	knots (speed measurement)
KLM	Koninkliike Luchtvaart Maatschappij Airlines
L	Local wind conditions 15 knots or less
MATLAB	Matrix Laboratory
Μ	meters
Mb	millibar (unit of measurement)
m/s	meters per second
MET	Mobile Environmental Team
MetEd	Meteorological Education
Mi	miles
MRY	Monterey Regional Airport
MSC	maritime stratiform cloudiness
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NDBC	National Data Buoy Network
NEXTOR	National Center of Excellence for Aviation Operations Research
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NPS	Naval Postgraduate School
NWS	National Weather Service
OR	Operational Research Department, Naval Postgraduate School
PDT	Pacific Daylight Time
SFO	San Francisco International Airport
SNS	Salinas Municipal Airport
TAF	Terminal Aerodrome Forecast
TDI	total delay impact
USN	United States Navy
U.S.S.	United States Ship
UNREP	underway replenishment
UTC	Universal Coordinated Time
VERTREP	vertical replenishment
Z	Zulu Time Zone (or UTC)

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I. INTRODUCTION

A. THE RELEVANCE OF FOG FORECASTING

Fog is a mysterious weather phenomenon that becomes the enhancement of dramatic movie scenes; from classic horror cinema to epic battle scenes in war movies, no one really knows what lurks beyond the misty veiled curtain, and that is what intrigues us all.

However, in the real world, military operations and private sector shipping and aviation endeavors can be significantly impacted due to the presence of fog, mist and marine stratiform cloudiness (MSC). Delays, cancellations and potentially hazardous situations can and have occurred because of deteriorating visibility and a lowering of the cloud deck. Given these impacts, forecasting fog is an important task.

The goals of the study are to accomplish two things: predict if fog is going to be in the area, and if it is going to be in the area, when can we expect it to burn off?

This study should enable the Navy forecaster with a quick reference guide in order to provide the warfighter or decision maker an educated initial prognostication concerning fog. By providing the commander an initial assessment, the forecaster and their team may then be able to further investigate the development of current conditions and provide a follow-up forecast at regular intervals. In an operational environment, time is of the essence, and this study fully intends to buy the forecast the precious time needed to provide the best forecast possible.

Why would a Navy forecaster need or use this study? Because forecasting fog in any environment is a challenging task and education, training and experience are the key ingredients for a qualified weather forecaster to accomplish the mission. Traditionally, fog forecasting has always resided on the local weather forecasting expert who has an excellent handle on local conditions, and who relies heavily on understanding the complexity of topography with no true universal fog forecasting scheme (Lundquist and Bourcy 2000).

B. EDUCATION, EXPERIENCE AND RESULTS

Let us compare the education of the National Weather Service (NWS) forecaster and the U.S. Navy forecaster. According to the NWS "Careers in the National Weather Service" (NWS Careers 2017) a weather forecaster requires at a minimum an undergraduate degree in meteorology, atmospheric science or hydrology. Consequently, NWS forecasters are equipped with a solid scientific comprehension of the atmosphere.

Enter the Navy Aerographer's Mate. The Aerographer's Mate is the U.S. Navy's enlisted weather technicians, weather observers and forecasters, tasked with providing operational forecasts worldwide. How does the education of the Navy Aerographer's mate compare to the National Weather Service forecaster? Prospective Navy weather forecasters complete Aerographers Mate C-1 School (AG-C1) in roughly 40 weeks and require no undergraduate degree. The curriculum consists of basic forecasting dynamics, physics, and synoptic weather pattern plotting and satellite interpretation. United States Navy Aerographer's Mate Senior Chief (Mazzulo 2017) Tony Mazzulo is the senior enlisted advisor at Navy AG-C1 School located on Keesler Air Force Base, Mississippi. During an interview with him on September 7, 2017, he said that there is an average of 90 students that graduate AG-C1 school each year, and of those graduates, there is an average of two students that have an undergraduate degree in meteorology or atmospheric science.

C. REAL WORLD FORECASTING CHALLENGES

Is it possible to save time and effort by using this study as a baseline tool for forecasting fog? The National Weather Service Instruction 10-813, November 21, 2016 (Stern 2016), directs that weather stations issue Terminal Aerodrome Forecasts (TAF) at 0000, 0600, 1200 and 1800 Coordinated Universal Time (UTC). On June 1, 2016, Monterey was experiencing low ceilings, mist, limited visibility and fog conditions. The degree of difficulty is much higher when dynamic conditions such as these encroach upon your area of responsibility. As a result, the NWS issued nine (Iowa State University 2016) TAFs verses the standard four required. Imagine the frustration on a day where the foggy weather conditions cause an office to more than double their workload for the day.

Now, let us take the military operational forecaster in the same weather scenario, without the benefit of an undergraduate or advanced degree, and then attempt to provide a forecast for a moving airfield in an area where they may not be the local area subject matter expert.

Clearly, the level of education difference between the NWS and the Navy forecaster is quite vast. As described earlier, the NWS forecaster had at least an undergraduate degree in meteorology or atmospheric science, and was still checkmated throughout the day in an attempt to produce a valid forecast. By providing the operational forecaster some leverage to their fog forecasting approach, they can theoretically bridge the education gap and provide a sound operational forecast. THIS PAGE INTENTIONALLY LEFT BLANK

II. BACKGROUND

Naval operations conducted over land, sea and air have to be carefully planned, coordinated and executed with a high level of precision to ensure mission accomplishment. In an effort to develop a useful tool for the operational forecaster and ensure mission accomplishment in a fog rich environment, it is important to identify the clear and present danger that faces the decision maker at sea and in the air.

A. AVIATION IMPACTS: WHEN FOG KILLS

Of the world's ten most deadly aviation accidents on record, two of these incidents were directly related to fog. In the article "Top 10 Deadliest Weather-related Aviation Accidents on Record" (Burt 2014) the seventh ranked aviation mishap is related to China Air Flight #676 at Chiang Kai-Shek Airport in Taipei, Taiwan, on February 16, 1998, which had a total of 203 fatalities. Peter B. Ladkin, from the University of Bielefeld in Germany is a Professor of Computer Networks and Distributed Systems in the Faculty of Technology, known in Germany as the RVS Group. He specializes in safety and failure analysis of complex systems. Professor Ladkin published an article titled "The Crash of Flight CI676, a China Airlines Airbus A300, Taipei, Taiwan, Monday 16 February, 1998: What We Know So Far" (Ladkin 1998).

According to Ladkin's article, heavy fog was reported at the time of the crash, and the pilot said he was "having difficulty seeing the runway." The ceiling was reported to be between 100 and 200 ft and a runway visual range was 600 m. At some moment close to the runway, the aircraft was well over 1000 ft in the air; this was why he completely missed the runway and asked to come around for another try. As the pilot tried to gain altitude for a go-around, he lost control due to extreme pitch altitudes and speed, resulting in a crash landing 2.3 miles away from the runway and into a residential neighborhood. This tragedy culminated due to the extreme airfield and aircraft weather minimums in reference to ceiling height and visibility. Pilot experience did not seem to be an issue, as both Captain and First Officer had a combined 10,740 flight hours. Had the tower informed the pilots of the deteriorating weather conditions, or if the pilot was able to just see the runway, the outcome may have been different.

Burt's Weather Underground article (Burt 2014) lists the most tragic aviation incident recorded is the deadly collision of two Boeing 747 aircraft on the runway at Los Rodeos Airport in the Canary Islands, Spain on March 27, 1977. Although many factors contributed to the collision, dense fog was a major factor identified. A case study of this incident is located in the Federal Aviation Administration's (FAA) Lessons Learned case study website (Federal Aviation Administration n.d.). The two aircraft involved in the crash were KLM Flight 4805 and Pan Am Flight 1736. According to the case study,

While the aircraft were en route to Las Palmas, a bomb exploded in the passenger terminal building at the airport. Due to the threat of a second explosion, the terminal building was evacuated and the airport closed. Much of the traffic arriving at Las Palmas Airport was diverted to Los Rodeos (Tenerife) Airport on Tenerife Island. For this reason, the parking area at the latter airport was crowded with airplanes.

Upon arrival, Los Rodeos was inundated with a congested taxi-way, which caused very long delays due to the Las Palmas attack. Once the runway became less congested, KLM Flight 4805 was cleared to taxi all the way to the end of the runway, execute a 180 degree turn, and then accelerate and takeoff in the direction they just came from. This is procedure known as "backtracking," and is not an unusual command. The Pan Am flights was ordered to taxi down the runway slowly and follow the KLM flight, and then exit the runway to the left when the pilot located third exit beacon. As the Pan Am flight exits the runway, it would allow the clearance for the KLM flight to takeoff.

Unfortunately, just before the KLM aircraft arrived at the end of the runway and executed the 180 degree turn, a dense fog layer approached, which diminished the air traffic control tower's visibility of the KLM and Pan Am aircraft. A few minutes later, the KLM aircraft reaches the end of the runway, completes its 180 degree turn and is standing by for takeoff; at the same time, the Pan Am aircraft is taxing down the runway searching for the exit beacon, all the while heading in the direction of the KLM aircraft. At this point, runway visibility is completely reduced to less than 100 meters, and when the KLM aircraft reports that they are ready for takeoff to the air traffic control tower, the

control tower gives permission to KLM to takeoff. The KLM aircraft throttles forward in the fog in anticipation of takeoff. The Pan Am aircraft sees the KLM aircraft heading toward them, and tries to pull off the runway and into the grass. The KLM aircraft collides with the Pan Am aircraft as the KLM was in the first stages of liftoff. The collision on the runway was completely devastating, as a total of 583 fatalities were reported. Had there been better visibility on the airfield, it was determined that the tower would have been able to easily spot the locations of both aircraft on the runway, determined that there was no clearance, and notified the KLM pilot that he did not have permission to takeoff. Also, the Pan Am flight would have been able to locate the beacon exit, (see Figure 1) thus completely clearing the runway.



Figure 1. A reconstruction of the collision. Source: Smith (2014).

Fog had a direct impact on two of the ten most deadly aviation mishaps ever recorded. The need for accurate fog forecasts with an emphasis on aviation safety in Central and Northern California is a constant lingering concern every year in the late spring though later summer months.

B. AVIATION IMPACTS: FINANCIAL IMPACTS AND FLIGHT DELAYS

Recognizing that flight delay was a serious and widespread problem in the United States, the Federal Aviation Administration (FAA) sponsored five NEXTOR (National Center of Excellence for Aviation Operations Research) universities and the Brattle Group to conduct an in-depth analysis on total delay impact (TDI). The final report, issued in November of 2010, re-searched all U.S. air transportation flight delays in 2007. The final report from the TDI project team estimates that the total cost (see Figure 2) caused by delays to be a staggering \$31.2 billion (Ball et al. 2010).

Cost Component	Cost (\$ billions)
Costs to Airlines	8.3
Costs to Passengers	16.7
Costs from Lost Demand	2.2
Total Direct Cost	27.2
Impact on GDP	4.0
Total Cost	31.2

Figure 2. Direct cost of air transportation delay in 2007. Source: Ball et al. (2010).

According to the Bureau of Transportation Statistics via the Department of Transportation, weather was the culprit for numerous flight delays for coastal California airports. Figure 3 shows data for San Francisco International Airport (SFO) from April-September 2016 (Buereau of Transportation Statistics, Weather's Share of Delayed Flights San Francisco, CA 2017). During this time frame, 58% of all flights experienced flight delays due to weather.



https://www.transtats.bts.gov/OT_Delay/OT_DelayCause1.asp?pn=1

Figure 3. SFO flight delays due to weather, April–September 2016. Source: Bureau of Transportation Statistics, 2016b.

Figure 4 shows the statistics for Monterey Regional Airport (MRY) during the same time period. During the peak season for fog in the Monterey Bay area, almost 28% of all flights were delayed due to weather (Bureau of Transportation Statistics, 2016a). Based on this evidence, it is clear that forecasting fog and reduced visibility is an extremely valuable skill set that can help reduce both aviation mishaps as well as flight delays.



https://www.transtats.bts.gov/OT_Delay/OT_DelayCause1.asp?pn=1

Figure 4. M RY flight delays due to weather, April–September 2016. Source: Bureau of Transportation Statistics, 2016a.

C. IMPACTS AT SEA

The dangers of fog are clearly not limited to aviation; fog has been a danger to surface ships since the earliest days of sailing. The Commanding Officer of a U.S. Naval warship and the Skipper of an aviation squadron have the highest amount of vested interest in weather conditions, especially when those conditions deteriorate to low ceilings and restricted visibility. Underway replenishments (UNREP), vertical replenishment (VERTREP) and sea and anchor evolutions are just a few of the numerous endeavors which can greatly impact ship centric missions. Aviators have a unique situation where they must be aware of the conditions at sea and be cognizant of the weather conditions at adjacent bingo fields (alternate aviation air fields).

Jeff Kline is a professor of practice in the Graduate School of Operational and Information Sciences (OR) Department at the Naval Postgraduate School in Monterey, California. He is a retired Navy captain and was the Commanding Officer (CO) of the U.S.S. CUSHING (DD-985) from November 26, 1997, until June 29, 1999, while forward-deployed in Yokosuka, Japan. During an interview with Captain Kline, (Kline 2017) he explained the dangers of fog and the importance of having an embedded team of Aerographer's Mates assigned to his ship prior to going out to sea:

As the CO of a Destroyer, I never got underway without them...I demanded them all the time just for that reason. I told the support team that I want a Mobile Environmental Team (MET) every time I get underway, and if I don't have one, then tell me why I can't have them." In reference to fog and his aviation detachment on the CUSHING, he also added, "My Helicopter Detachment never flew in fog. When we were in those situations [foggy conditions] we brought them down.

Throughout the years, improvements have been made to navigation systems, including global positioning systems, radar systems and clear doctrine for international navigation rules of the road. However, no matter how much technology streamlines the rigors of ship driving, fog still remains a constant hazard to those on the sea

On April 27, 2017, the Russian naval spy ship Liman was operating in the Black Sea in the vicinity of the Bosphorus Strait off the coast of Turkey. According to the Turkish news agency Dogan, the area of the collision was completely shrouded in thick fog at the time of the accident. While transiting, the Liman and a Turkish livestock vessel, the Youzarsif H collided. The Russian military reported that a hole had been ripped out of the Liman, causing the spy ship to sink (Telegraph Reporters 2017). According to the Turkish international shipping magazine website SeaNews, a Turkish coastal safety official reported that a total of 78 Russian personnel were rescued from the Liman, but a Russian dispatch reported that there were still 15 Russian military personnel missing (SeaNews Turkey 2017). It is clear by the amount of fog seen in Figure 5 that navigation for both vessels must have been a challenge. Needless to say, this incident was a huge embarrassment the Russian navy.



Figure 5. Russian sailors are rescued from their sinking spy ship. Source: SeaNews Turkey (2017).

D. CALIFORNIA FOG STUDIES

Up and down the West Coast of the U.S., to include the California coast, low stratus and fog can be found lingering all throughout the summer, developing via complex processes and interaction between the Hadley Cell, coastal upwelling, subsidence of sinking air in contrast with the coastline (Iacobellis and Cayan 2013). During the months of May through September, coastal low cloudiness has the greatest presence. This seasonal feature has been described by Southern Californians as "May Gray" and "June Gloom" because of its dominant effects throughout the region. Over the course of the summer, the coastal low cloudiness migrates from southern California up towards northern California, making July the cloudiest month in northern California (Clemesha et al. 2016). These publications, as well as the peak in aviation flight delays indicate that fog along the California coast in the summer months is significant and poses challenges for operational forecasters

The Calspan Corporation (a component of the Cornell Aeronautical Laboratory) teamed up with the Naval Postgraduate School, Monterey, CA in the early to late 1970s to participate in the Cooperative Experiment in West Coast Oceanography and Meteorology (CEWCOM). The Naval Air Systems Command contributed to the mission as well by supporting data collection and logistical support. During the experiments, ships participated in collecting weather and scientific information throughout the California coast. Over the entire experiment timeline, the group completed a total of seven cruises, and during this time span, over 30 fog occurrences had been documented. Throughout the northern California coast, areas frequented by fog all had common themes: high-pressure dominating the synoptic pattern, coastal upwelling, and strong boundary layer inversions (Koračin et al. 2014).

During these extensive research experiments (Pilié et al. 1979) the role of the Eastern Pacific High was the dominating force in the summertime for the development of fog in the unstable boundary layer. The Eastern Pacific High, usually situated several hundreds of miles to the west and south, produced winds from the west-northwest. During the summer months when these conditions were prominent on the California coast, the destruction of the fog regimes occurred when the Eastern Pacific High migrated over land, creating Santa Ana conditions and easterly offshore flow, which delivered warmer winds and extensive mixing.

While these previous studies clearly identify the basic synoptic patterns associated with fog or no fog days, the actual day to day variability in fog occurrence is considerably more complex than the synoptic pattern suggests based on past scientific studies (Pilié et al. 1979 and Koračin, et al. 2001).

We hypothesize that when the summer Eastern Pacific High delivers wind speeds of 15 kts or less to Monterey Bay, an environment conducive to low stratus and fog will persist, while winds speeds of 16 kts or greater would support the destruction of a coastal fog regime in the Monterey Bay area. This wind speed variation may account for the day to day variability even when the basic synoptic pattern does not change. Clearly, there will be atmospheric dynamics that may occur that will account for windier conditions with fog and other days where Monterey has no ceiling, unrestricted visibility and light and variable winds.

E. TRACKING TRAJECTORIES USING LAGRANGIAN METHOD

When a forecaster has to evaluate synoptic scale weather systems, making an attempt to classify patterns that look similar on satellite and surface pressure charts but produce vastly different weather takes skill and experience to evaluate correctly. In one such case during April of 1999, (Lewis et al. 2003) two migratory Eastern Pacific High-pressure systems had very similar positioning and gradient characteristics, however one system was fog-rich, and the other system was fog-free.

To truly comprehend the processes which take place on similar looking synoptic and mesoscale system weather systems, back-tracking the air sample trajectories of fog and fog free areas have provided scientists important clues and insight into the processes of development and dissipation of California coastal weather on a day-to-day basis. In the study "Transition of Stratus into Fog along the California Coast: Observations and Modeling" trajectories are backtracked during a major fog event from the California/ Oregon border to the Southern California Bight from April 11 through April 16, 1999 (Koračin et al. 2001). The data collection for the experiment also incorporated the use of the National Data Buoy Network (NDBC). These buoys are located all along coastal California, from the California-Oregon border all the way down towards the California Bight in Southern California (Lewis et al. 2003).

Figure 6 provides a visual depiction of the transitioning high-pressure system as it propagated from the West Coast through the Great Basin region. This synoptic scale migratory high and its subsequent weather resulted in major transitions throughout the western United States in just a few days. Ceilings, visibility, temperatures and wind conditions all morphed from one set of extreme variables to the next, prompting scientists to conduct studies into this system from April 1999 to include Koračin et al. (2001), Lewis et al. (2003) and Koračin et al. (2005).



NCEP/NCAR Reanalysis

Figure 6. Sea level pressure chart depicting the location of the transiting highpressure system on April 13 (top) and April 16 (bottom). Source: Koračin et al. (2005). On April 11, 1999, a synoptic scale cyclone pushed through the Northwestern United States. Directly behind this system was a large synoptic scale anti-cyclone which dominated the Eastern Pacific. On April 12, scattered (partly cloudy) stratus conditions were reported from Cape Mendocino in northern California down towards central California. On April 13, as the transitory high-pressure system pressed closer towards the coast, it delivered northwesterly flow, and within a few hours, the skies on the northern and central coast were filled with low-level stratus (see Figure 7). By the evening of April 13, fog conditions were reported in Monterey and Vandenberg Air Force Base in central California and by midnight on April 14, San Diego was completely engulfed in fog and low-level stratus (Koračin et al. 2001).



FIG. 5. Visible images of the stratus clouds along the California coast on 13 Apr 1999, taken from the GOES-10 weather satellite (subsatellite longitude of 135° W). Latitude lines are 35° and 40° N; longitude lines are 115° , 120° , and 125° W.

Figure 7. Visible satellite imagery documenting the intrusion of low stratus and fog to northern and central California on April 13. Source: Koračin et al. (2001).

Figure 8 displays the back trajectories over a 48-hour period. The beginning of the period showcases the initial air parcel off the coast of northern California/southern Oregon on April 13, 0000 UTC. This initial air parcel is embedded within a thick marine layer and may be correlated to the GOES 10 satellite progression in Figure 7. As the trajectories continue to propagate towards the southeast, a correlation with back-trajectories and satellite images show low level stratus and fog, which propagates down the coast toward southern California until April 15 at 0000 UTC.



Figure 8. Back-tracking trajectories of fog and low stratus conditions in Southern California originated 48-hours prior in a fog rich environment on April 13, 0000 UTC off-shore at the California-Oregon border. Source: Koračin et al. (2001).

On April 15, 1200 UTC, the high-pressure system propagated to the east and was in the vicinity of the southern Rockies. This delivered offshore flow to the California coast, which abruptly raised the local temperatures and then dissipated the fog as a result of the intrusion of the warm offshore air combining with the marine layer air parcels (Lewis et al. 2003). Figure 9 provides the back-trajectories that contributed to the dissipation of the fog conditions, ending on April 16, 0000 UTC. The trajectories originate over land, which in turn delivered warm air over the marine fog conditions that dissipated the fog (Koračin et al. 2005).



Figure 11. Horizontal projection of simulated back-trajectories at 10 m (black), 90 m (blue), 270 m (red), and 1000 m (green) that are relevant to fog dissipation. The back-trajectories have their end point at the Point Arguello buoy location on 16 April at 0000 UTC.

Figure 9. Fog dissipation in central California reveals back-trajectories which originated inland, delivering warm air parcels with offshore flow. Source: Koračin et al. (2001).
An important factor to consider; just because trajectories have their origin over land does not mean that they lack properties for fog development in Monterey. Likewise, trajectories that originate over the ocean will not always deliver fog and stratus conditions to Monterey. This study (Koračin et al. 2005) may suggest that the forecast of fog vs. no fog is simply determined by the source of the trajectory (land vs. water).

An example of a high-pressure system that had trajectories originate over water, but produced a cloud-free coastal environment approached the California coast (Lewis et al. 2003) on April 10, 1999. Figure 10 displays a relatively strong high-pressure system in the Central Pacific with coastal winds from the northwest. Figure 11 labels this particular system as Event 1 (fog free). Trajectories for this system originate over water and flow from the west and northwest. The major differences between this anti-cyclonic system, which produced no fog, and the second anti-cyclonic system, which did produce fog, were: 1) the geographic positioning of the high-pressure centers 2) air temperature changes along the trajectories and 3) the strength of low-level subsidence.



Figure 10. Surface pressure chart depicting weak gradient flow over coastal California. Source: Lewis et al. (2003).

Notice from Figure 11 the cloud-free system experienced an increase of air temperatures along the trajectories, weaker subsidence and a high-pressure center in the Central verses the Eastern Pacific. Important to forecasting fog is how two air mass properties evolve along the trajectory. The along-trajectory evolution may provide better

forecast insight concerning fog than simple source regions. We hypothesize that that the along trajectory evolution can be related to synoptic pattern variations that can be identified by the forecaster.



Figure 11. Characteristics of Fog and Fog Free events. Source: Lewis et al. (2003).

F. FURTHER TEMPERATURE CONSIDERATIONS

Studying California climatology reveals that in the summertime, migratory highpressure systems which originate over the Eastern Pacific and penetrate inland are not the only type of offshore flow which can deliver inland trajectories and cause coastal low stratus and fog to vanish (Koračin et al. 2001). A prominent feature during the summer is the presence of the strong thermal low-pressure system which resides in the California central valley (Goodman 1977). Figure 12 is a topography map of California. Notice the Great Valley in central portion of the state. The Great Valley is surrounded by mountain regions, and the inland valley experiences extremely high temperatures due to strong solar heating within a very arid environment (Brewer et al. 2012). The thermal low over this region has its greatest effect from June through September, reaching its peak intensity in July and averages a temperature between 40°C and 45°C (Rowson and Colucci, 1992).



Figure 12. Topographic map of California. Source: Wikipedia (2017).

Goodman (1977) discusses the presence of a thermal low and profiles the two separate inland trajectories originating from these thermal lows on July 26 and again on August 5, 1974. The results, which are revealed in Figure 13, show the inland trajectory caused fog and low stratus to dissipate by 0900 PDT on July 26 and at 1200 PDT on August. Lewis et al. (2003), Koračin et al. (2005) and Goodman (1977) discuss the warmer, drier temperatures as a catalyst to the dissipation of fog and stratus due to mixing of air these parcels with cool moist parcels. The results create a weakening of the inversion, which then lifts and eventually erodes the marine layer (Koračin et al. 2005).

Date	Time of fog advection to tower site (PST)	Time of fog dissipation at tower site (PST)	Average fog thickness at tower site (m)	Average temperature range (°C)	Drizzle observed at ground
17-18 July 1974	Fog continuously at tower site for several days; sampling started at 1200.	No dissipation; sampling ended at 1003.	~90	12-14	Yes
20-21 July 1974	1810	1100	~ 80	10-13	Light drizzle at night
26–27 July 1974	1630	Fog lifted at 1030 and by 1200 no stratus at tower site.	~220	12-14	Light drizzle
6-7 August 1974	0130	0900	$\sim \!\! 160$	10-11	No
12-13 July 1975	1730	0915	~220	8.5-11	No
4–5 July 1975	Fog continuously at tower site for several days; sampling started at 1447	No dissipation; sampling ended at 1050.	>220	8–9.5	Light drizzle

Figure 13. Trajectories from a thermal low lead to dissipation of fog and low stratus in July and August 1974. Source: Goodman (1977).

Salinas Municipal Airport (SNS) is located approximately 12 miles inland, and 14 miles away from Monterey Regional Airport (MRY). Based on the impact of thermal lows (Rowson and Colucchi 1992), we consider Salinas Airport a viable indicator for higher temperature intrusions originating from the Central Valley thermal lows. We hypothesize that on days that fog and low stratus are present in Monterey, burn off is possible within a few hours when there is a temperature delta between MRY and SNS of approximately 4–5°F or more due to mixing.

III. DATA COLLECTION AND METHODS

A. OVERVIEW

The time series that will be studied for this thesis will be June and July 2016. The location will be the Monterey Bay area, to include offshore and inland weather stations. We know from previous studies that the California coast is particularly susceptible to fog and stratus conditions in the summer time. June tends to heavily impact southern California; however, July has been noted to invade coastal Central and Northern California (Clemesha et al. 2016).

Utilizing the "Forecaster Funnel" technique (see Figure 14) from the "Climatology for Operational Forecasters" MetEd (Meteorological Education) training course, developing a solid understanding of large scale synoptic weather patterns over coastal California during a two-month time frame will be the first step in analyzing fog and stratus (University Corporation for Atmospheric Research 2013).



The COMET Program

Figure 14. The Forecast Funnel. Source: University Corporation for Atmospheric Research (2013).

Step one will be to analyze the planetary scale patterns in the northern hemisphere to establish long wave trough and ridge patterns. The method for collecting this data will be the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis models from the Earth System Research Laboratory (ESRL) website (Earth System Research Laboratory 2017). Tracking the propagation paths of upper-level ridging can reveal stable conditions and a prolonged period of fog and stratus over coastal California. Identifying upper-level troughs may be an indicator that fog, and stratus will be pushed out of the area, and unstable weather with convective activity can be expected within a few days. We will explore the planetary scale analysis more in the "Results" chapter of this study.

The second step in the data collection process will be to use GARP (GEMPAK Analysis and Rendering Program) as a weather analysis tool to visually display archived data from 200 mb down to the surface in the synoptic scale and mesoscale environment. GARP also enables the user to overlay satellite imagery from the Geostationary Operational Environmental Satellite 15 (GOES 15) onto analysis tools for initialization and verification of weather station reports. By comparing weather station data with surface charts and satellite, we were able to interpret current microscale weather and establish a forensic pattern for future weather development in Monterey Bay. Analysis charts and satellite images will be discussed in further detail in the "Results" chapter.

The third step will be to collect local data. Daily weather data from MRY, SNS, and Monterey Bay will be gathered and analyzed for significant patterns and characteristics. The Climate Forecast System Reanalysis (CFSR) 48-hour back-trajectory data will provide a visual plot that shows where air parcels were located prior to their arrival in Monterey Bay. The fourth and final step will be to analyze the data for trends and relationships into identifiable signatures for exploitation, which should render the operational forecaster very capable in garnering high confidence in future fog predictions.

B. LOCALIZED DATA COLLECTION

As previously discussed, predominate summertime flow, which supports the formation of low stratus and fog in the Eastern Pacific is from a bearing of 330° true

north with winds 15 kts or less (Pilié et al. 1979). Based on this study, the best upstream weather observation data collection point to validate local effects will be from the National Buoy Data Center's (NDBC) Monterey Bay Buoy at station 46042.

The next step will be to collect data from the 48-hour back-trajectory plots. Analyzing the initial physical properties over time will provide important information as to how the weather changed 48 hours later. Calculation of the daily trajectories was determined by conducting an analysis of the CFSR data every six hours, working from the Monterey Bay, and then back to the 48-hour starting point (Nuss, 2017). From the model analysis, the 3D wind-field was determined and then integrated backward in time by 10-minute time-steps.

The third step is to gather downstream weather station information via Automated Surface Observation System (ASOS) weather reports and National Weather Service Weather Service Terminal Aerodrome Forecasts (TAF) for Monterey and Salinas airports from June 1 through July 31.

1. Upstream Data

a. Station 46042 Monterey Bay Buoy

Located in Monterey Bay approximately 36 nautical miles northwest from Monterey airport (Figure 15), the Monterey Bay Buoy is an excellent source of upstream weather. Figure 16 displays the specifications for the buoy. The historical weather data for the June and July, 2016 Monterey Bay buoy are available at the NDBC's historical archive website (National Data Buoy Center Historical Data, 2017).

A total of 720 weather observations were collected for June and 744 for July. Each weather observation's wind speed is measured in meters per second, (m/s) which is ≈ 1.9438 kts (approximately).



Figure 15. The Monterey Bay Buoy provides excellent upstream weather data source for the Monterey. Source: Original map obtained from Google Maps

Station 46042 Monterey Bay Buoy
Location :36.785 N 122.398 W (36°47'5" N 122°23'54" W)
Site elevation: sea level
Air temp height: 4 m above site elevation
Anemometer height: 5 m above site elevation
Barometer elevation: sea level
Sea temp depth: 0.6 m below water line
Water depth: 1645.9 m
Watch circle radius: 1789 yards

Figure 16. Parameters of the Monterey Bay Buoy. Source: National Data Buoy Center, http://www.ndbc.noaa.gov/station_page.php?station=46042

Classification of the buoy wind conditions are separated into two categories: "Local," which is less than 15 kts, and "Brush" conditions, which are winds greater that 15 kts. The naming convention for "Local" suggests that winds less than 15 kts at the buoy occur when that synoptic forcing is not influencing the weather of Monterey Bay. Figure 17 depicts the EPAC High (left) dominating the U.S. West Coast, with winds ranging from 20–30 kts in Central and Northern CA. A close-up image (right) shows winds outside of Monterey Bay near 20 kts, but a table of the Monterey Bay buoy (bottom right) shows winds from the west-northwest and speeds ranging from 2–5 kts. This is an example of "Local" conditions, or "L."



Figure 17. GOES 15 visible satellite with a surface analysis chart and Monterey Bay buoy wind data set highlighted in red; "Local" conditions dominate Monterey.

The term "Brush" refers to a branch of the Eastern Pacific High-pressure system. The geometry of the Central California coast and the positioning of the EPAC High usually spares Monterey Bay from the full force of intense northwesterly flow experienced in coastal Northern California north up to coastal Washington state. Figure 18 shows the location of the EPAC High (left) dominating the U.S. West Coast, with winds ranging from 20–35 kts in Central and Northern CA. A close-up image (right) shows winds outside of Monterey Bay near 30 kts, but these winds are not quite as strong in Monterey Bay. A table of the Monterey Bay buoy (bottom right) shows winds from the northwest and speeds ranging from 16–20 kts. This is an example of "Brush" conditions, or "B."



Figure 18. An example of EPAC "Brush" conditions from a synoptic and local scale.

The wind data will be analyzed (Figure 19) and then a classification will be determined. Each classification shall be compartmentalized into four six-hour time blocks; 0000, 0600, 1200 and 1800 (all times are in PDT). The classification of the winds for each time block will be an average over the six-hour time frame. On June 1 (Figure 19) the wind speed from meters per second to kts, we can see that the entire day shall be classified as "Local" effects, due to the fact that all of the winds at the buoy are reading less than 15 kts. Once the average is identified, then that classification is annotated on the Monterey Buoy Winds table (Figure 20).

								NBDC I	Buoy Da	ita Jun	ie an	d July 20	16 ~				
#YY	MM	DD	hh	mm	WDIR	WSPD	GST	WVHT	DPD	APD	MWD	PRES	ATMP	WTMP	DEWP	VIS	TIDE
#yr	mo	dy	hr	mn	degT	m/s	m/s	m	sec	sec	degT	f hPa	degC	degC	degC	mi	ft
2016	06	01	00	50	276	4.3	5.7	1.59	16.00	7.16	198	1011.2	12.6	14.0	999.0	99.0	99.00
2016	06	01	01	50	292	3.4	4.8	1.60	16.00	7.19	183	1011.1	12.2	14.0	999.0	99.0	99.00
2016	06	01	02	50	299	2.8	4.1	1.70	14.81	7.72	202	1011.2	12.1	14.0	999.0	99.0	99.00
2016	06	01	03	50	300	2.0	3.5	1.72	16.00	8.08	191	1011.3	11.9	14.0	999.0	99.0	99.00
2016	06	01	04	50	299	3.3	4.9	1.84	16.00	8.30	189	1011.9	11.6	13.9	999.0	99.0	99.00
2016	06	01	05	50	317	3.8	5.1	1.64	14.81	7.47	181	1011.8	11.7	13.9	999.0	99.0	99.00
2016	06	01	06	50	316	2.6	3.7	1.59	14.81	7.29	184	1011.7	11.4	13.9	999.0	99.0	99.00
2016	06	01	07	50	36	0.9	3.1	1.86	16.00	7.80	173	1011.6	11.4	13.8	999.0	99.0	99.00
2016	06	01	08	50	296	0.4	1.2	1.61	14.81	7.70	185	1011.5	11.0	13.8	999.0	99.0	99.00
2016	06	01	09	50	149	0.9	2.2	1.54	14.81	7.43	184	1011.3	11.2	13.7	999.0	99.0	99.00
2016	06	01	10	50	116	1.5	2.4	1.63	14.81	7.66	199	1011.2	11.4	13.7	999.0	99.0	99.00
2016	06	01	11	50	139	2.4	3.8	1.66	14.81	8.02	187	1011.2	11.4	13.6	999.0	99.0	99.00
2016	06	01	12	50	177	2.3	3.9	1.59	14.81	7.85	187	1011.5	11.5	13.6	999.0	99.0	99.00
2016	06	01	13	50	150	2.1	3.0	1.72	13.79	8.36	190	1011.9	11.9	13.6	999.0	99.0	99.00
2016	06	01	14	50	156	3.6	5.2	1.72	14.81	8.36	186	1012.5	11.9	13.6	999.0	99.0	99.00
2016	06	01	15	50	159	3.9	4.9	1.76	17.39	8.47	197	1013.0	12.2	13.6	999.0	99.0	99.00
2016	06	01	16	50	161	3.4	5.0	1.81	13.79	8.39	196	1013.2	12.4	13.6	999.0	99.0	99.00
2016	06	01	17	50	147	3.4	4.3	1.75	14.81	8.49	185	1013.6	12.7	13.6	999.0	99.0	99.00
2016	06	01	18	50	150	3.8	4.8	1.95	14.81	8.78	185	1013.8	13.0	13.7	999.0	99.0	99.00
2016	06	01	19	50	177	3.4	5.3	1.77	19.05	8.19	184	1014.0	13.3	13.9	999.0	99.0	99.00
2016	06	01	20	50	182	4.1	5.1	1.84	16.00	8.14	188	1013.9	13.6	14.0	999.0	99.0	99.00
2016	06	01	21	50	195	3.3	4.2	1.84	14.81	8.10	194	1014.0	13.8	14.1	999.0	99.0	99.00
2016	06	01	22	50	194	3.2	4.3	1.77	17.39	8.27	187	1013.6	13.9	14.3	999.0	99.0	99.00
2016	06	01	23	50	220	1.9	2.8	1.91	14.81	8.67	188	1013.5	14.0	14.2	999.0	99.0	99.00

Figure 19. NDBC data for June 1. Source: National Data Buoy Center Historical Data (2017).

According to Pilié (1979), the ideal conditions for low stratus and fog to form over coastal California in the summertime with winds less than 15 kts. One item to consider is the that just because there are low winds, this fact alone does not mean that one should forecast for fog and stratus. Theoretically, other conditions contributing to fog conditions have to be present, so conducting an analysis of the synoptic and mesoscale charts and models is in order to identify if moisture and inversion characteristics support fog and stratus conditions.

Jun-16										
	1	2								
00L	L									
06L	L									
12L	L									
18L	L									

Figure 20. Annotation of "L" for June 1, which classifies "Local" wind conditions at the Monterey buoy for each six-hour period.

Visible satellite (Figure 21) from May 31, 1700 PDT (June 1, 0000 UTC) shows weak high-pressure in the Eastern Pacific, with a loose gradient and lower wind speeds,

indicating an environment favorable to fog. Although MRY did not report low ceilings or visibility in the mid-afternoon, a clear indicator that MRY may see low fog and stratus in the evening of May 31 and on 1 June is by checking the upstream winds at the Monterey Bay buoy. On Figure 21, (yellow circle is the Monterey Bay) notice that the winds are from the northwest near Monterey and less than 15 kts; the ideal conditions described by Pilié's (1979).



Figure 21. GOES 15 visual satellite, May 31, 1700 PST.

b. Trajectory Data

Utilizing the CFSR back trajectories over a 48-hour period for the Monterey Bay (Figure 22) from June 4 to July 14, critical information into the origin of advected air parcels into the area of interest was created. If trajectories are over land, then fog is not expected, while over water trajectories are more favorable for fog and stratus development. As we can see in Figure 22, the CFSR data field displays an 18z plot for a particular day, and backtracks the air parcel to the source point 48 hours prior.



Figure 22. CFSR back-trajectory analysis for June 29. Source: the Climate Forecast System Reanalysis (CFSR).

We can see that the air parcel trajectory which landed in Monterey Bay was advected in from the northwest and propelled by the Eastern Pacific High. The parcel appears to have stayed over the ocean throughout the 48-hour forecast period and potentially maintained its moist and cool characteristics; a condition directly correlated to low stratus and fog conditions for the Monterey Bay.

2. Downstream Data Collection

a. Monterey and Salinas Airport Weather Observations and Terminal Aerodrome Forecasts (TAF)

MRY will act as ground zero for the major focus of weather conditions for both real time and predicted conditions. SNS will provide a solid inland data point for attempting to predict fog and low stratus burn-off at MRY throughout June and July. Fog burn off is likely to occur first at inland locations and may be used as a potential prediction for burn off at Monterey due to inland stations heating faster than coastal stations. An archive for every single special and routine weather observation for Monterey Airport and Salinas Airport from June 1 through July 31 was collected via the University of Iowa State's Environmental Mesonet "ASOS Network" (Iowa State University, 2016 (1,2)). A routine weather observation is an observation that is recorded at the end of each hour, whereas a special weather observation is recorded when major changes to ceiling height, visibility or actual weather phenomena is occurring on station (Stern, 2016).

For Monterey Airport, a total of 998 weather observations in June and 1056 weather observations in July were analyzed. Standard routine weather observations for June totaled 720, however Monterey registered 998 observations, which indicates that 278 additional special weather observations were included. A total of 744 routine weather observations for July were reported, and additional 312 special weather observations were recorded. In total, Monterey Airport recorded astounding 590 special weather observations between June and July, indicating that the weather patterns were extremely dynamic and complex. Due to these complexities, a graphical depiction for each day must be developed.

Each weather observation was collected and processed into a daily visual representation via MATLAB, version R2015b. Figure 23 represents a graphical depiction of the weather conditions for June 1. This figure represents the sky condition by reporting the ceiling height in blue bars and the visibility with a red line. Both ceiling and visibility values can be determined by the y-axis. The x-axis represents PDT over a 24-hour period.

Based upon classification criteria for visibility and ceiling (Figure 23), the first and second six-hour time block would be color-coded as "red" due to the poor visibility and low ceiling height (Figure 24). However, we do see that the conditions cleared by 1300 PDT (Figure 23) and remain that way throughout the evening. These criteria which would indicate that the final two six-hour time blocks would be classified as "green" (Figure 24). All 998 observations for June and 1056 observations for July were processed and then represented in a daily image, like Figure 23. Next, sky condition and visibility measurements for Monterey Regional Airport were annotated to the Monterey Bay weather assessment table (Figure 24) using the same six-hour time block. Classifications for sky condition and visibility are as follows; if the ceiling is less than 1000 feet, then the classification is red. If visibility is less than 7 mi, classification is red. If the sky condition is 1000 feet or greater and visibility is greater than 7 mi, the classification is green. The visibility and sky condition criteria are likewise for the same six-hour time frame as the buoy data. If there are two "red" sky or visibility events in a six-hour time block, the entire block is considered "red."



Figure 23. A MATLAB graphical depiction of Monterey Airport ceiling height and visibility for June 1.

	Jun-16										
	1	2									
00L	L										
06L	L										
12L	L										
18L	L										

Figure 24. An example of Monterey Bay weather data with Monterey Airport ceiling and visibility.

b. Monterey and Salinas Airport temperature data collection for low stratus and fog dissipation

Lewis et al. (2003), Koračin et al. (2005) and Goodman (1977) discuss the warmer, drier air temperatures as a catalyst to the dissipation of fog and stratus due to

mixing of air these parcels with cool moist parcels. We hypothesize that there is a correlation in temperature differences between MRY and SNS, specifically if the temperatures at SNS (downstream along the trajectory) rise above MRY.

By collecting the routine weather observations for Monterey and Salinas on days that Monterey has fog and stratus with eventual dissipation, we can compare the temperature between both stations and determine if there is a correlation for dissipation. The first step is to check the Monterey Bay weather data chart (Figure 25) on June 1; we see that there are "red" conditions, meaning low visibility and ceilings early in the day, but we also see that the conditions are "green," meaning dissipation occurred later in the day. Next, we verify the time of the dissipation (Figure 26) and see that it was around 1300 PDT.

	1	2	Γ
00L	L	L	L
06L	L	L	1
12L	L	L	I
18L	L	L	L

Figure 25. June Monterey Bay weather data.



Figure 26. The Monterey daily weather chart shows a close-up of the ceiling and visibility conditions improving on June 1 near 1300 PDT.

After the Monterey weather chart is verified, the weather observations for Monterey and Salinas are compared and archived for June 1. Figure 27 shows "MRY" which represents Monterey airport. The first observation displayed is 0954 PDT, where we notice the temperature is 12°C. Next, we see that the time of dissipation (sky condition went from overcast to scattered) was at 1227 PDT, and the temperature difference was over 5°F (12°C is 53.5°F) from 0954 and continued to be over 5°F through 1254 PDT. We hypothesize that given the proper atmospheric conditions, when the downstream inland temperature is over approximately 4–5°F above Monterey, dissipation may occur within two hours of the temperature difference from Salinas to Monterey. Figure 28 displays a Monterey fog and temperature analysis breakdown. For June 1, we acknowledge that there was fog present, that the fog did burn off, the time it dissipated, what the temperature difference was, whether our hypothesis was supported and the time difference. We annotate the time difference as a point of interest; how long after the temperature difference will the weather station in Monterey experience dissipation? This question is important; it may be able to assist the operational forecaster by providing a useful tool for predicting a time for the warfighter to move on a mission.



Figure 27. Observations for Salinas and Monterey Airport on June 1

June	Fog/Mist	Burn Off	Time B/O	Temp Dif.	Hypoth	Dif. Time
1	Yes	Yes	1227	7F	Yes	1000

Figure 28. Annotation of temperature differences as it relates to dissipation of stratus and fog.

IV. RESULTS

A. OVERVIEW

The intent of this study is to accurately predict when low stratus and fog would occur at Monterey Regional Airport by observing wind conditions at the Monterey Bay buoy. After predicting said fog and low stratus, the focus was to predict what time Monterey airport would experience dissipation of those conditions. The results of this prediction series will be separated into two categories; 1) Analysis of the Monterey Bay and Monterey Airport weather conditions and 2) Analysis of Monterey Airport fog and low stratus dissipation using upstream temperatures.

Revisiting the concept of the "Forecast Funnel," the planetary scale upstream of coastal California will be studied. Utilizing the NCEP/NCAR, analysis of the 200 mb long wave and short-wave flow in the northern hemisphere with focus over the Central/Eastern Pacific and U.S. West Coast region will lay a foundation for expected weather patterns.

B. PLANETARY SCALE ANALYSIS 200MB PLANETARY LONG WAVE ANALYSIS

1. June 2016

June 1–10: The planetary long wave pattern over the far Eastern Pacific is dominated by an upper-level high center from June 1–4 (Figure 29) and then a major long wave ridge propagates from the Eastern Pacific towards the Rockies from June 5–10. Directly behind this ridge is a deep long wave trough extending from Alaska south towards the Central Pacific on June 6 and propagates eastward over the U.S. West Coast by June 10. This evolution suggests that low clouds and stratus might dissipate when the trough approaches.



Figure 29. An upper-level ridge dominates the Eastern Pacific on June 3 (left), and a long wave trough influences the U.S. West Coast on June 10. Source: Earth System Research Laboratory (ESRL) (2017).

June 11–20: The long wave trough which arrived on the west coast on June 10 continues to stall and linger (Figure 30) until June 19. An upper-level height center begins to form near the Four Corners region on June 18, and ridging begins to extend westward towards the West Coast by June 20. This evolution indicates that any dissipation of fog by the trough will end and fog should return by June 19 or so.



Figure 30. A closed upper-level circulation ranges from Victoria, British Columbia, towards northern Oregon on June 15. Source: Earth System Research Laboratory (ESRL) (2017).

June 21–30: Figure 31 shows the upper-level ridging beings to flatten by June 22 but lacks notable dynamic movement through June 30. This would favor persistence of fog conditions through the end of June.



Figure 31. On June 24, the upper-level ridge flattens out and becomes stationary. Source: Earth System Research Laboratory (ESRL) (2017).

2. July 2016

July 1–10: Upper-level ridging continues to linger until July 4, as it slowly begins to propagate eastward, making way for a short-wave trough from British Columbia Canada. On July 5 the trough slowly moves toward California, becoming stationary by July 10 (Figure 32). Again as the trough moves in overhead by July 5 to beyond July 10, fog may be dissipated by the trough.



Figure 32. Upper-level ridging maintains a strong presence on July 10 over the California coast.

July 11–31: The short-wave trough flattens out by July 12, making way for a weak upper-level height center to ridge into California from the southwest from July 13–31 (Figure 33). This sets the stage for prolonged fog conditions from July 13 to months end. These long-wave patterns provide background conditions for fog verses no fog. However, to gain more insight the synoptic and mesoscale conditions are examined in the next section.



Figure 33. Upper-level ridging continues to predominate all throughout the Eastern Pacific and West Coast region on June 28. Source: Earth System Research Laboratory (ESRL) (2017).

C. SYNOPTIC AND MESOSCALE ANALYSIS USING GARP

1. June 2016

June 1–10: From June 1–4, a 1022 mb high-pressure system dominates the synoptic pattern throughout Eastern Pacific and West coast, delivering north-northwesterly flow from Washington state to central California. On June 5, the high-pressure system slowly propagates to the north, weakening northwesterly flow and slackening the pressure gradient over California, which permits mesoscale local effects to dominate the central coast region until June 10 (Figure 34). This pattern is consistent with the upper trough approaching the coast after June 5 but did not result in dissipating coastal clouds and fog.



Figure 34. High pressure influencing coastal California on June 2. Source: GARP Sea Level Pressure Analysis and GOES 15 satellite imagery.

June 10–15: A strong 1032 mb high-pressure system develops over the Central Pacific and establishes northwesterly flow over the West Coast once again. Late on June 15, a deep upper-level trough at 500 mb is deepening off the coast of Oregon. The deep trough results in coastal clearing as we can see in Figure 35.



Figure 35. A 1032 mb high-pressure center in the Central Pacific on June 14. Source: GARP Sea Level Pressure Analysis and GOES 15 satellite imagery.

June 16–19: A closed upper-level pressure center at 500 mb deepens off the coast of Oregon by June 16. An associated trough extends from the Oregon coast towards the southwest by June 17 (Figure 36). Infrared satellite and depicts the development of an unstable upper-level front on June 17 (Figure 37). This frontal system and associated frontal system is present via visible satellite imagery on June 17 and 18. Even though low clouds are present in the pre-frontal environment, this is not a typical summertime fog pattern. This system quickly dissipates as it decays near the western Rocky Mountains. Another Eastern Pacific High-pressure system soon establishes a foothold in the wake of the frontal system by June 19, which sets up a more typical fog pattern.



Figure 36. Upper-level circulation at 500 mb, June 17. Source: GARP 500 mb analysis and GOES 15 satellite imagery.



Figure 37. Frontal system at the surface, June 17. Source: GARP Sea Level Pressure Analysis and GOES 15 satellite imagery.

June 20–30: The Eastern Pacific High-pressure system remains stationary throughout the next 10 days (Figure 38), becoming progressively stronger during the early periods (June 20–23), slightly weaker (June 24–26) and then gaining strength as it builds to a 1032 mb high June 30. During this synoptic regime, coastal fog becomes more widespread along the California coast.



Figure 38. A strong Eastern Pacific high-pressure system dominates the region; low stratus and fog smothers the California coast. Source: GARP Sea Level Pressure Analysis and GOES 15 satellite imagery.

2. July 2016

July 1–7: The Eastern Pacific High continues to dominate the west coast, however the by late July 7, the gradient flow which initially influences the coastal region begins to loosen as the system meanders west and weakens (Figure 39). The EPAC High gives persistent fog during this period.



Figure 39. High pressure continues to dominate coastal California on July 3. Source: GARP Sea Level Pressure Analysis and GOES 15 satellite imagery.

July 8–10: The Eastern Pacific High retreats as a mature low-pressure system from the north near coastal Washington state propagates south and begins filling to the point of dissipation by late July 10 (Figure 40). While not completely dissipating low clouds, the low-pressure system does tend to break up clouds offshore and to the north of MRY.



Figure 40. A decaying frontal system off the coast of Washington state breaks down the influence of high pressure in the Eastern Pacific on July 9. Source: GARP Sea Level Pressure Analysis and GOES 15 satellite imagery.

July 11–18: The Eastern Pacific High forms directly behind the low-pressure system on July 11 and establishes influence upon the California coastal region (Figure 41). Visible satellite imagery displays thick coastal stratus along Central and Northern California throughout this time.



Figure 41. Thick low-level stratus and fog along the Central California coast on July 18. Source: GARP Sea Level Pressure Analysis and GOES 15 satellite imagery.

July 19–23: The influence of the Pacific High on the western U.S. begins to wane as it retreats slightly westward toward the central Pacific, loosening the gradient along coastal California (Figure 42). Slight clearing of coastal stratus is evident via visible satellite along the central coast during this period. On July 22, the Pacific High is beginning to reemerge and gain strength, and slowly propagate from the Central to the Eastern Pacific.



Figure 42. High pressure retreats towards the Central Pacific, loosening up the gradient along coastal California; local effects influence the weather as a result on July 20.

July 24–31: Figure 43 shows the Eastern Pacific High builds and finally begins to exert its influence upon coastal California; stratus engulfs central and northern California. This is consistent with the ridging aloft noted in the previous section.



Figure 43. High pressure and coastal fog a low cloudiness on July 28 from Washington state south down to the Channel Islands off the Southern California coast.

D. ANALYSIS: MONTEREY BAY BUOY AND AIRPORT WEATHER

Observing the overall data for Monterey, both at the airport and at the bay buoy, 21 of 30 days in June experienced low stratus and fog conditions, with the predominate synoptic feature being the Eastern Pacific high-pressure system. In the middle of the month, the fog conditions were cleared out by a fast moving upper-level low-pressure system which eventually made its way to the surface and slightly disrupted the stability of the region.

Figure 44 displays the wind speed for each six-hour time frame at the Monterey Bay buoy. Recall from "Data Collection and Methods" that "L" represents winds less than 15 kts and "B" represents the Eastern Pacific Brush or EPAC Brush, for winds 16 kts or greater. The color scheme represents two weather conditions at Monterey airport: sky condition or ceiling in ft and the visibility in mi. Red conditions mark the presence of a ceiling less than 1000 feet and/or visibility of less than 7 mi in fog/mist with low stratus. Green represents the lack of fog and low stratus or the dissipation of those conditions.

		Monterey Airport/Monterey Buoy Weather Comparison 2016																													
	June 2016																														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
00L	L	L	L	В	L	L	L	L	В	В	В	L	L	В	В	L	L	L	В	В	В	В	В	В	В	В	В	В	В	L	
06L	L	L	L	L	L	L	L	L	В	В	В	L	L	В	В	L	L	L	L	В	В	В	В	В	В	В	В	В	В	L	
12L	L	L	L	L	L	L	L	L	В	В	В	L	L	В	В	L	L	L	В	В	В	В	В	В	В	В	В	В	В	L	
18L	L	L	L	L	L	L	L	L	В	В	L	L	В	В	L	L	L	В	В	В	В	В	В	В	В	В	В	В	В	L	

Figure 44. Results of the data collection for June 2016.

Of the 21 days in June which had fog and low stratus, 16 days experienced dissipation, while five days experienced no clearing at all. Of the 16 days that had dissipation, six of these days had dissipation after 1200 PDT.

Next, we analyze winds in Monterey Bay and their correlation to Monterey Airport low fog and stratus. Recall that Pilié (1979) discusses optimum winds for enhancing fog and low stratus in coastal California to be from a northwest direction and less than 15 kts; the results using this factor alone for June were marginal at best, whereas the results for July were more promising.

Predicting that fog and low stratus in June was possible simply based on the wind direction at the Monterey Bay buoy provided us with a relatively low percentage; 43% of fog occurrence (Figure 45). For an operational forecaster, a method of prediction that garners 43% is simply used as a data point or additional tool. The forecaster and his/her team will be required to analyze additional data to render a solid forecast.

		June 201	6	Local Conditions Lead to Red Conditions								
	Red Green		Total	120/								
Local	24	32	56	4370								
EPAC Brush	31	33	64									
Total	55	65	120									

Figure 45. Prediction results of fog and low stratus for June.

The presence and continuity of low stratus and fog increase in July, as the Monterey area experienced 29 of 31 days with low ceilings and visibility (Figure 46). Of the 29 days where fog and low stratus were present, 20 days experienced dissipation. Of these 20 days, nine experienced dissipation after 1200 PDT.



Figure 46. Results of the data collection for July 2016.

We see a significant rise in percentage of low level fog and stratus as it correlates to the wind direction of the Monterey Bay buoy, an impressive 75% (Figure 47). This high percentage of occurrence may be aided by the overall greater percentage of fog days under all flow patterns.

		July 201	6	Local Conditions Lead to Red Conditions								
	Red	Green	Total	750/								
Local	69	23	92	1370								
EPAC Brush	17	15	32									
Total	86	38	124									

Figure 47. Prediction results of fog and low stratus for July.

The fact that July was clearly a more robust month for low stratus and fog correlates to "The northward march of summer low cloudiness along the California coast," where Clemesha (2016) tracks coastal level cloudiness (CLC) which inundates Baja Mexico and Southern California in May and June (Figure 48). As June turns into July, the CLC propagates from Southern to Central and Northern California. This propagation occurs due to a slow expansion of the Hadley Cell; as the Hadley Cell expands poleward, it meanders in a northwesterly direction, creating more subsidence along its area of influence throughout the summer by increasing temperatures and upwelling along the coast.

We know that based on the shifting of the Hadley Cell and positioning of the Eastern Pacific High that we had more cloudiness in July, but an analysis of the 48-hour trajectories also provides insight.


Figure 48. Summer CLC values for coastal California. Source: Clemesha et al. (2016).

An example of three different trajectories plots of the 48-hour trajectory data from CFSR on June 6, 12 and 22 (Figure 49) illustrates flow that originated over the ocean, but propagated over inland areas during the time series, thus changing the characteristics more conducive to drier and warmer properties; the result provides a climate that has fog and stratus tendencies, but also lacks continuity for prolonged and sustained fog and stratus conditions. June 6 trajectories began over the ocean, and when they arrived 48-hours later (18z) in Monterey, the fog and stratus was still lingering. Dissipation did not occur until 1400 PDT. June 12 trajectories began over the ocean, traveled over land and then back over the ocean. When they arrived in Monterey Bay from the ocean, fog and stratus were still present. Dissipation did not occur until 1300 PDT. June 22 trajectories were like June 12, but drier conditions persisted as dissipation occurred at 1000 PDT.



Figure 49. The 48-hour trajectories with weather analysis on June 6, 12 and 22.

Most trajectories in July begin over the ocean and arrive into the Monterey Bay from the north or northwest. Most of these trajectories began in a stratus rich environment, and maintained these characteristics upon arrival.

Other examples for trajectories can be seen in Figure 50, where the 48-hour start point on July 1 was inland over San Diego, CA. Tracing the plot, the trajectory continues to meander inland and eventually traverse over water, landing in the Monterey Bay by July 3 at 1800 UTC. Conditions in Monterey in the early morning of July 3 contained low stratus, and although the air parcel originated inland, low stratus and fog properties morphed these trajectories from warm and dry parcels to cooler and moist characteristics; the result was a thick layer of stratus which did not dissipate until mid-afternoon.

A typical trajectory plot for July is depicted in Figure 51, where we witness the GOES 15 visible satellite pictures for July 5, which reveals a stratus rich environment. The star on the satellite picture to the left indicates the beginning of the 48-hour trajectory plot. Notice in the middle of Figure 51, we can see the path of the trajectory plot; it originates over the ocean, and maintains the cool and moist properties throughout the period. The satellite image on the right is from July 7, and depicts the path and its ultimate destination in the Monterey Bay. Conditions in Monterey on July 7 were characterized with ceilings at 600 feet and visibility less than 6 miles in mist.



July 1 GOES 15 VIS

July 3 GOES 15 VIS

Figure 50. GOES 15 visible satellite pictures on July 1 and 3 with 48-hour trajectory plots for July 3



July / GOES IS

Figure 51. GOES 15 visible satellite pictures for July 5 and 7, with the 48-hour trajectory plot for July 7.

E. TEMPERATURE DIFFERENCE RESULTS FOR SALINAS AND MONTEREY RESULTING IN DISSIPATION

Finally, we review the prediction of fog and stratus dissipation based on the temperature differences within the typical trajectory from Monterey to Salinas. We hypothesized that if there is a difference in temperature of approximately 4°F-5°F on a day where there was fog and stratus in Monterey, there should be the potential for dissipation.

The hypothesis that the temperature difference from Salinas to Monterey would provide a solid indicator for dissipation in Monterey garnered poor results. Each column of the Temperature Comparison chart for July (Figure 52) represents an analysis question of each day; was there the presence of fog/mist? Was there "Burn Off" (dissipation)? What time was "Burn Off"? What was the temperature difference between Salinas and Monterey? Was the hypothesis supported? If it was supported, when did we see the temperature difference occur?

June prediction results for dissipation were quite disappointing (Figure 53), but expected. As discussed earlier, although low stratus and fog conditions were present, drier inland trajectories introduced more variability in flow characteristics. The hypothesis/prediction rate was only 31% (Figure 53); of the 16 times where dissipation occurred in Monterey, the temperature difference of 4–5°F only played a role five times.

As previously notes, June had more "Brush" days (higher winds) and therefore stronger onshore advection. This may limit the ability for the temperature to rise at SNS and prevent it from being a valuable predictor in higher wind conditions.

June	Fog/Mist	Burn Off	Time B/O	Temp Dif.	Hypoth	Dif. Time	
1	Yes	Yes	1227	7F	Yes	1000	
2	Yes	Yes	1000	OF	No		
3	Yes	Yes	800	1F	No		
4	Yes	Yes	200	2F	No		
5	Yes	Yes	1100	4F		1000	
6	Yes	Yes	1400	1F	No		
7	Yes	Yes	1400	5F		1100	
8	Yes	Yes	1300	3F	No		
9			Fog F	ree Day			
10	Yes	Yes	900	OF	No		
11			Fog F	ree Day			
12	Yes	Yes	1300	3F	No		
13	Yes	Yes	1200	OF	No		
14							
15							
16					-		
17			Fog Fr	ee Day	S		
18	Yes	Yes	800	OF	No		
19							
20					~		
21		Fog Free Days					
22	Yes	Yes	1000	6F	Yes	1000	
23	Yes	Yes	600	OF	Νο		
24	Yes	Yes	1100	6F	Yes	1100	
25	Yes		Fog Re	mained, N	o Burnoff		
26	Yes	Yes	1100	10F	Yes	1000	
27	Yes						
28	Yes						
29	Yes	Fo	a Boma	ainad M		off	
30	Yes	es Fog Remained, No Burnon					

Figure 52. June temperature comparison chart.

Ceiling and temp chart results	
Days with Fog/Mist and Burn Off	16
Days temp diff was a factor	5
Result	31%

Figure 53. June prediction results for dissipation via temperature differences.

The July temperature comparison chart in Figure 54 represents a stark contrast from the results we initially had in June; the prediction rate is an impressive 70% (Figure 55). Of the 20 days that had fog/stratus and experienced dissipation, 14 of these days also had a temperature difference of at least $4^{\circ}-5^{\circ}F$ between Salinas and Monterey. We believe that the dissipation occurred on these 14 days were due to progressively warmer July temperatures in Salinas (inland) coupled with weaker flow along the coast which created mixing, breaking the inversion and lifting the marine layer (Goodman 1977).

July had 92 of 124 days where "Local," or L" conditions dominated. Because of this lack of major synoptic influence, there is a high probability that inland temperatures

rose at a much faster rate at SNS, allowing sufficient time to deliver warmer temperatures and mixing from SNS to a cool and moist MRY atmosphere; this would cause a break in the inversion and dissipation of fog in the area.

r						1
July	Fog/Mist	Burn Off	Time B/O	Temp Dif.	Hypoth	Dif. Time
1			1200	7F		1100
2			1300	4F		1200
3			1400	ЗF		
4			1400	1F		
5			1500	6F		1400
6			1200	6F		1000
7			1200	7F		1100
8			1100	5F		1100
9			830	2F		
10			Fog Fre	ee Day		
11			1000	6F		1000
12			1100	5F		1000
13		Fo	g Remaine	d, No Burn	off	
14			900	3F		
15			1100	6F		1000
16			1100	4F		900
17			1340	5F		1130
18			1300	5F		1300
19			1100	8F		1000
20			Fog Fre	ee Day		
21			900	OF		
22			1000	7F		900
23			600	OF		
24						
25						
26						
27						
28						
29						
30		-	Dowe			
31		Fog	s Rema	inea, N	jo buri	

Figure 54. July temperature comparison chart

Ceiling and temp chart results	
Days with Fog/Mist and Burn Off	20
Days temp diff was a factor	14
Result	70%

Figure 55. July temperature comparison prediction results

V. CONCLUSION AND RECOMMENDATIONS

A. OVERVIEW

For the operational forecaster, making a quick decision in crisis is always going to make for a challenging situation. The purpose of this study was to provide a quick decision aid to assist forecasters operating in a fog potential environment, i.e., an environment which would hinder the maneuverability of the warfighter. All forecasters have a basic understanding of atmospheric dynamics and physics when dealing with fog conditions, but the ability to accurately forecast the onset and then the dissipation has continually remained a challenge.

B. LESSONS LEARNED

Hypothesis One: Wind Component for Predicting Fog in June

Winds alone are not a good predictor of fog and stratus in June for Monterey (Figure 56). There were more EPAC Brush days (higher winds) that had fog and stratus conditions verses "Local" conditions. Other dynamics were at work, and would have to be studies further.



Figure 56. Hypothesis results for using winds to predict fog and stratus in June.

Hypothesis One: Wind Component for Predicting Fog in July

Winds were a very good indicator for fog and stratus prediction for Monterey in July. Clemesha (2016) shows high percentages of fog in Central and Northern California during July. MRY experienced 92 of 124 "Local" conditions and overall fog prediction was 75% in July (Figure 57). Throughout the month, all the ingredients are present for fog and stratus to include the northwest shift of the EPAC High (which loosened the gradient), warmer temperatures aloft and cooler temperatures at the sea surface, strong inversions, and lighter winds.



Figure 57. Hypothesis results for using winds to predict fog and stratus in July.

Hypothesis Two: Temperature Component for Predicting Dissipation in June

Using the temperature differences between SNS and MRY to predict fog dissipation in Monterey did not work very well in June (Figure 58). We believe that because there were more EPAC Brush conditions in June, there was not enough time to allow for sufficient warming at SNS. This lack of warming at SNS thus rendered the temperature component useless for the majority of the month (31%).



Figure 58. Hypothesis results for using temperature difference to predict fog and stratus dissipation in June.

Hypothesis Two: Temperature Component for Predicting Dissipation in July

Using temperature differences between SNS and MRY in July for predicting dissipation of fog and stratus enjoyed a 70% prediction rate (Figure 59). We believe that because there were more days without a major synoptic presence, local inland weather stations (SNS) were able to warm at a faster rate.



Figure 59. Hypothesis results for using temperature difference to predict fog and stratus dissipation in July.

A by-product of this study exposes the challenge operational planners would have for military exercises in June in Southern California, or the same exercises for July in Central or Northern California. Unless the desire was to sharpen the skills of the warfighter and the weather forecast teams, these two months in the summer could hinder operations due to dangerous conditions and potential flight delays.

We also recommend a similar study be conducted in a Southern California city with a large military presence like San Diego. Finding the appropriate upstream and downstream weather stations would not be difficult to find, and if actual operational forecasters could participate, perhaps the next study could make use of their experiences.

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