Wind Shear due to the California Marine Layer

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November 2016

Abstract

A. The purpose of this paper is to estimate the magnitude of the wind shear at the edge of fog banks. The hypothesis is that the effect will be 0.5-1 m/s in the direction perpendicular to the fog bank. Multiple methods of estimation will be used to ensure consistency of results. First a qualitative view of the effect will be given, based on both personal observation and the weather trends of the California coast. This will be followed by an application of Bernoulli's principle, that will estimate the effect of the shear to be 0.31-0.62 m/s at altitudes of 5m to 10m.

I. Introduction

The California coastline is commonly thought of as the quintessential coast line, with travelers from all over the world coming to witness the unique natural phenomena that occur daily. Much of what makes the California coast so unique is the meteorological phenomenon of the marine layer.

The marine layer is a layer of cold air that forms over the Pacific Ocean, and since cold air is denser than warm air, it is trapped at low altitude. Normally, this layer of cold air leads to fog due to the humid air mass being cooled to it's saturation point. It is a common misconception that the marine layer is the fog bank, when really fog is a byproduct of the marine layer.

The whole process is primarily a wind driven phenomenon. The predominant wind direction in California is west-northwest. This is due to north pacific high, a semi-permanent weather phenomenon west of California. For the purposes of this paper, the wind direction will always be assumed to be consistently from this prevailing wind direction. We can safely make this assumption since it is only under these prevailing conditions that the marine layer will form. Under other wind directions, such as a Santa Ana wind from the east for example, there is not enough moisture in the air for fog to form.

Lastly, since there is a saying in Southern California that the month of June should be called "June Gloom", this paper will arbitrarily use data from the month of June while estimating the magnitude of the "Fog Shear" effect.

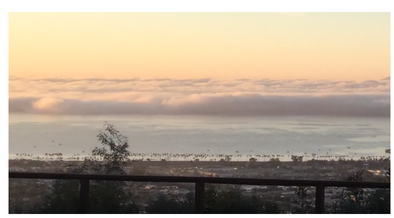

Figure 1: *Fog Bank, Santa Barbara*

II. Fog Formation

The winds due to the north pacific high play two important roles in the formation of fog along the California Coast. First it brings warm

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humid air from the middle of the pacific to the coast. This is crucial since without humid air, the fog bank can't form. Second the wind drives coastal upwelling along the coast, which causes the SST (Sea Surface Temperature) to drop. This SST drop cools the low-level air mass, thereby creating the marine layer.

Fog that forms along the California coast is a type of fog known as advection fog. Advection fog forms due to a warm and humid air mass moving over a cold surface. This forms fog as the warm air is cooled to it's saturation point. It is important to note that the fog is not formed by evaporation from the water beneath it.

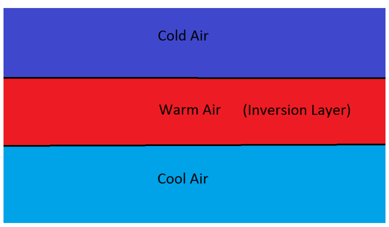

Figure 2: *Inversion Layer*

Since air cools close to the sea surface but remains warm higher in the altitude, a large vertical temperature difference develops. The interface between the warm air mass and the cool one is called the inversion layer (Figure 2). This inversion of the standard air being cooler with height, prevents mixing of air within the marine layer with the air above.

III. Geographic Effects

For the wind shear effect to occur there must be a humid to dry air interface. The primary reason for the formation of fog banks over certain parts of the ocean and not others, and hence the formation of fog/dry air boundaries, is due to the coastal geography. Warm winds from the north pacific high are oftentimes blocked by landmasses and points along the coast. This allows fog to form over the areas where the wind flows uninhibited, while not forming where the wind is blocked.

The following two maps (Figures 3 & 4) illustrate this, the striped red areas are where fog will be slower to form, or will not form at all:

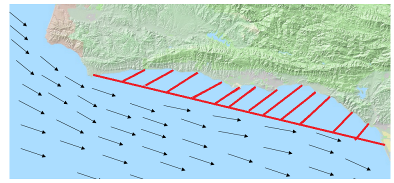

Figure 3: *Map of Point Conception (OSM)*

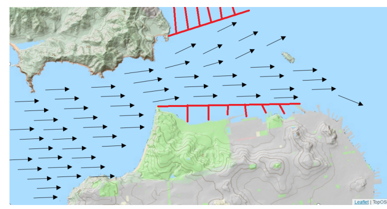

Figure 4: *Map of San Francisco(OSM)*

IV. Estimation of the Humid to Dry Air Interface

I. Temperatures

A good estimate of temperature within a fog bank is the mean air temperature of "Station 46063" located off the coast of Point Conception (red buoy in Figure 5) . This buoy during the month of June will typically consistently be in advection fog. The mean historical air temperature for the month of June is $T = 13\,^{\circ}\mathrm{C}$ (NDBC-NOAA)

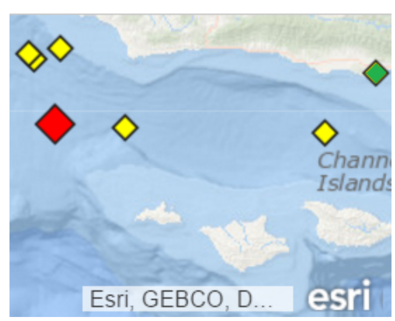

Figure 5: *Buoy Locations (NDBC-NOAA)*

An estimate of temperature outside the fog bank is more difficult. I propose that "NTBC1 Buoy", $T_{mean} = 15\,^{\circ}C$ in June (NDBC-NOAA), located near the Santa Barbara Harbor (green buoy in Figure 5), gives a good estimate. While this buoy may experience some fog, I believe that this cooling is offset due to it's proximity to land. While this is a very ad hoc reasoning, it does agree with the $\Delta T = 1 - 2\,^{\circ}C$ observed by the R/V *Acania* sea fog expedition (Pilié et al.). Since it is ΔT that we are worried about anyways we will accept the ansantz that $T = 15\,^{\circ}C$ is a good estimate for the temperature outside the fog bank.

II. Air Density

The most important values, to understand the fog shear phenomenon, are the densities of the air within the fog bank and outside it. It is this density gradient that drives the flow of air. To calculate these densities we turn to the ideal gas law.

$$P = \rho R_{specific} T \tag{1}$$

Thus the density of humid air can be expressed as:

$$\rho = \frac{P_{air}}{R_{air}T} + \frac{P_{vapor}}{R_{vapor}T} \tag{2}$$

The next step is to convert this equation into a form dependent on absolute pressure rather than partial pressures.

$$P_{vapor} = \phi P_{saturation} \tag{3}$$

By using the Tetens' Formula (Tetens) , an approximation of the Clausius-Clapeyron relation for water vapor, we can estimate P_{vapor}. Note that in this equation, temperature is in degrees Celsius. It is also a good time to note that fog is typically at 100% so the relative humidity term ϕ will be equal to 1.

$$P_{vapor} = \phi * 610.78 * 10^{\frac{7.5T}{T+237.3}} \tag{4}$$

The partial pressure of air is simply the absolute pressure minus the partial pressure of the water vapor

$$P_{air} = P_{abs} - P_{vapor} \tag{5}$$

The equation for air density in fog is thus:

$$\rho = \frac{P_{abs}}{R_{air}(T+273.15)} - \frac{610.78 * 10^{\frac{7.5T}{T+237.3}}}{R_{air}(T+273.15)} + \frac{610.78 * 10^{\frac{7.5T}{T+237.3}}}{R_{vapor}T} \tag{6}$$

This is now dependent solely on T and P_{abs}. As discussed previously:

$$T_{outside} = 15\,^{\circ}C\,,\ T_{fog} = 13\,^{\circ}C \tag{7}$$

Using these temperatures, the appropriate specific gas constants, and $P_{abs} = 1atm = 101325Pa$:

$$R_{air} = 287.058 \quad J/(kg * K) \tag{8}$$

$$R_{vapor} = 461.495 \quad J/(kg * K) \tag{9}$$

$$\rho_{fog} = 1.26311 \quad and \quad \rho_{dry} = 1.22498 \tag{10}$$

III. Suspended Water Droplet Correction to Fog Density

It should be said that fog is not completely a gas, and therefore the density of fog should take into account the effect of the liquid water suspended within it. The liquid water content (LWC) can be determined by performing a latent heat calculation

$$L = \frac{Q}{m}\,,\ m = \frac{Q}{L} \tag{11}$$

$$Q = m_{fog} * C_p * \Delta T \tag{12}$$

We set $m_{fog} = 1.26311Kg$ so that we get an estimate of the m_{water}/m^{-3}, i.e the LWC. For water vapor at STP: $C_p, \approx 2Jg^{-1}K^{-1}$. We also assume $\Delta T = -2\ ^{\circ}C)$ as discussed previously. $L = -2444Jg^{-1}$ (Marsh)

$$m_{water} = \frac{(1.26311kg) * (2Jg^{-1}K^{-1}) * (-2\,^{\circ}C)}{-2444Jg^{-1}} \tag{13}$$

$$m_{water} = 0.0020kg \tag{14}$$

So the calculated LWC is equal to $2000\,mg/m^{-3}$.

However, mixing effects below the inversion layer cause the observed LWC to be even lower, so we must turn to field data. According to observations from the R/V Acania, measured LWC was between 100 and 350 mg/m^{-3}. (Pilié et al) This corresponds to at most a 0.00035 Kg/m^{-3} increase in fog density. Overall, there is at most a negligible increase from $\rho_{fog} = 1.26311$ to $\rho_{fog'} = 1.26346$.

V. Bernoulli's Principle

I. Conditions to the use of Bernoulli's Principle

Since Bernoulli's equation is fundamentally a statement of energy conservation, it must be shown to a reasonable extent, that energy is conserved in the marine layer system. The first statement is that the inversion layer is strong enough to act as a barrier, such that the fog does not move through it. This allows us to visualize the fog bank as being confined by the inversion layer, as illustrated in the following figure (Figure 6):

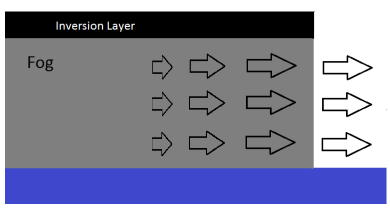

Figure 6: *Inversion Layer Confinement*

The next possible problem lies in energy contributions due to phase changes. Since the fog bank is formed near exclusively via advection and not evaporation, there is a negligible energy contribution from the vaporization of water. There is also an energy contribution from the condensation of water. However, as discussed in the subsection "Suspended Water Droplet Correction to Fog Density", the liquid water content of the fog bank is quite low, so liquid water makes a negligible energy contribution.

Incompressibility is another condition required for the application of Bernoulli's equation. Therefore we must show that the flow from the fog bank to the outside is a relatively incompressible flow. This may seem counterintuitive since the process is driven by a difference in densities, therefore disproving that the air is incompressible. Luckily, the effects of compressible can be ignored at low Mach numbers (Shaughnessy et al, p. 512). The expected velocity of the effect is Mach 0.003, well within Mach 0.3, the incompressible flow regime.

Lastly, we must make the idealization that the process is isobaric. Since the effect is localized and subject to the same non-local phenomenon of the pacific high, I believe that this is a reasonable assumption

In conclusion, we make the assumptions that energy is conserved in the system, flow is incompressible, and the process is frictionless and adiabatic. These conditions allow the use Bernoulli's principle to make an estimate of the wind velocity.

II. Solving for Wind Velocity

The starting point is Bernoulli's equation:

$$P_1 + \frac{1}{2}\rho_1 v_1 + \rho_1 g h_1 = P_2 + \frac{1}{2}\rho_2 v_2 + \rho_2 g h_2 \tag{15}$$

We assume that $v_1 \approx 0$ within the fog bank and solve for v_2

$$P_1 + \rho_1 g h_1 - P_2 - \rho_2 g h_2 = \frac{1}{2}\rho_2 v_2 \tag{16}$$

$$v_2 = \frac{2}{\rho_2} * (P_1 - P_2 + \rho_1 g h_1 - \rho_2 g h_2) \tag{17}$$

Since we are assuming that the process is isobaric $P_1 - P_2 = 0$

$$v_2 = \frac{2}{\rho_2} * (\rho_1 g h_1 - \rho_2 g h_2) \tag{18}$$

$$v = \frac{2}{\rho_2} * (\rho_1 g - \rho_2 g) * h \tag{19}$$

$$v = 0.06225h \tag{20}$$

So the final results are dependent on height, which makes logical sense, as wind is normally faster the higher up you are:

$$v_{5\ meters} = 0.31127\ m/s \tag{21}$$

$$v_{10\ meters} = 0.62254\ m/s \tag{22}$$

$$v_{100\ meters} = 6.22\ m/s \tag{23}$$

VI. Discussion

At higher altitudes the results for velocity are way too large, ex. $v_{100\ meters} = 6.22\ m/s$. However, this can be explained by our assumption of uniform cooling. In reality, there is a vertical temperature gradient within the fog bank due to the radiative heating at the top of the fog bank, and the cooling from the sea surface at the bottom of the fog bank.

If we were to assume a linear temperature gradient of 2 degrees from 0m to 200m, $v_{100\ meters}$ would equal 2.69 m/s, a more than reasonable result. 200m was chosen since the Golden Gate Bridge is 227 meters high (Goldengatebridge.org) and the bridge typically sticks out above the fog bank.

Figure 7: *Golden Gate Bridge in Fog (Erturk)*

To improve upon these results, more field data would be useful. Measurements such as temperatures at varying heights, and precise temperature differences in and out of the fog bank, would strengthen the results. Pressure measurements would also be very useful since the dependence on the process being isobaric, is crucial to the results obtained via Bernoulli's equation to hold.

VII. Conclusion

Overall, I'm very satisfied with the result of 0.31127 m/s to 0.62254 m/s in the 5-10m altitude. While sailing, I've always estimated there to be a 5-10 degree wind shift when near a fog bank. The normal wind in Santa Barbara is $\approx 5m/s$ so a shear of 0.31127 m/s to 0.62254 m/s corresponds to a 3.56° to 7.01° wind shift, via vector addition and trigonometry:

$$tan^{-1}(\frac{0.31127}{5})\ to\ tan^{-1}(\frac{0.31127}{5}) \tag{24}$$

This result of an approximately 5° wind shift agrees remarkably with the observed phenomenon. Even though we used a very idealized model presented in the paper, the result was spot on. It really goes to show the power of a simple equation, like Bernoulli's equation.

VIII. Citations

References

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