Determining the Risk of Experiencing Severe Turbulence when Flying through an Exhaust Plume

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Abstract— **Several recent incidents have drawn attention to the hazards that exhaust plumes cause to aviation. While exhaust plumes can contain elevated temperatures and reduced oxygen concentrations that are potentially detrimental to rotary aircraft, the upward motion of the plume can cause turbulence to fixed-wing aircraft. This paper presents a model for determining the risk of experiencing severe turbulence when various aircraft types fly through an exhaust plume.**

Keywords- Exhaust Plume; Turbulence; Safety;

I. INTRODUCTION

Exhaust plumes emanating from smokestacks at power plants and other industrial facilities have caused several safety incidents involving both fixed-wing and rotary aircraft flying at low altitudes. Since plumes have garnered recent attention due to some high-profile incidents, it could be beneficial to describe and quantify the risk that plumes pose to local aviation.

Plumes can affect aircraft in several ways including turbulence caused by the upward motion of the plume, the potential for aircraft upset caused by turbulent gusts, elevated temperatures of the effluent exceeding the limits of the aircraft, and low oxygen concentration which limits combustion required by the engines. This paper presents a model to judge the probability of experiencing severe turbulence when flying through an exhaust plume that originates from a single stack or multiple aligned stacks.

II. DESCRIPTION OF EXHAUST PLUMES

In this report, an exhaust plumes is considered to be the effluent from a smokestack at a power plant or other industrial facility that is forced vertically into the atmosphere. These plumes are considered turbulent buoyant jets, as they contain both a momentum-driven jet region near the stack top and a buoyancy-driven plume region further above the stack.

In the literature, a pure jet is defined as effluent that is solely driven by its initial momentum as it exits the stack. There is no density difference between the effluent and the ambient fluid. On the other hand, a pure plume is defined as effluent that has no initial momentum, and the propagation of the effluent is driven solely by density differences. The turbulent buoyant jets considered in this analysis are a combination of both jets and plumes. They have an initial momentum as the effluent exits the stack as well as temperature differences that cause buoyant forces that drive the plume upwards.

In addition to the two distinctive regimes of the exhaust plume, there is an area immediately above the stack on the order of five or six stack diameters where jet flow is not fully established. The internal dynamics of this area have not been modeled, but certain plume models provide an estimate for the length of this Zone of Flow Establishment (ZOFE) [1].

The main regions of the exhaust plume are shown in Fig. 1 for an atmosphere with calm winds. Note that the regions are not to scale, and if an aircraft flies through the effluent, it is most likely encountering the plume region.

III. PREVIOUS WORK ON EXHAUST PLUMES

Over the past 10 years, there has been increased attention

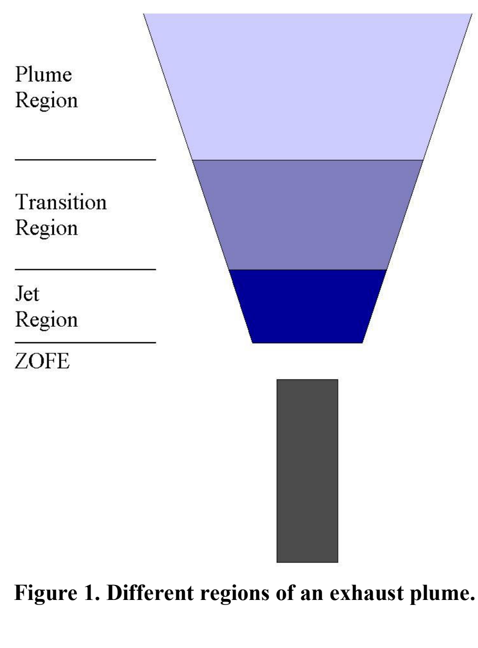

Figure 1. Different regions of an exhaust plume.

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brought to the issue of how exhaust plumes affect aviation safety. In 2004, Australia's Civil Aviation Safety Authority (CASA) released an Advisory Circular (AC) to provide guidance on the hazards of exhaust plumes on aircraft operations. AC139-05 declares that the hazardous region around an exhaust plume includes every location where the average vertical velocity of the plume is greater than 4.3 m/s [2].

Following CASA's research on exhaust plumes, the Federal Aviation Administration (FAA) published a report to determine the safety risk of exhaust plumes on aircraft operations. In this report, it was concluded that the risk of an aircraft accident or incident caused by an exhaust plume was lower than the Target Level of Safety (TLS) of 1 x 10^{-7}, meaning that the risk was considered small enough to be acceptable [3].

In both the United States and Australia, there have been many formal studies on existing or proposed power plants to determine if they are hazardous to aircraft operations. In most of the studies, the CASA standard has been used to determine how the plumes affect local aviation [4-7].

IV. Hazards Caused by Exhaust Plumes

There have been several reported aviation incidents involving plumes around the globe for both fixed-wing and rotary aircraft. In the United States, the most highly visible exhaust plume-related incident occurred on December 18, 2008 as United Express flight 6922 (operated by Colgan Air) was on final approach into Morgantown Municipal Airport (KMGW) in West Virginia. This flight experienced severe turbulence as it flew over the Fort Martin Power Station on the Instrument Landing System (ILS) final approach to Runway 18, which caused the flight to execute a missed approach and divert to its final destination of Washington Dulles International Airport (KIAD).

The Director of Operations for Colgan Air wrote a letter to the FAA requesting a full investigation of the risk involved with an aircraft flying through the exhaust plume, a Notice to Airmen (NOTAM) be issued to all flights operating in the vicinity of KMGW, and notes be appended to the airport diagram about the possible turbulence caused by the plume at the power station [8].

A literature review of this and other incidents [9-12] was conducted and conclusions are listed here:

- Exhaust plumes from power plants and other industrial facilities can create hazards for both fixed-wing and rotary aircraft flying at low altitudes
- Turbulence caused by the upward motion of the plume is a hazard for lighter fixed-wing aircraft on final approach
- Elevated temperatures exceeding the operational limits and/or reduced oxygen concentration associated with exhaust plumes can be hazardous to helicopters flying very slowly through plumes or hovering close to the top of the stack. The area of elevated temperatures around the plume was examined, and it was found that this area is much smaller than the area of risk for severe turbulence.
- Plumes can be visible or invisible. Even though they may not appear to be in operation, stacks could be producing hazardous exhaust plumes
- Plumes can emanate from a single stack, but they can also be exaggerated when multiple operational stacks are placed in close proximity to each other

V. Model Description

Determining the risk of experiencing severe turbulence when flying through an exhaust plume relies on multiple models pieced together. First, a plume model is required to estimate the trajectory and mean flow of the plume as it rises into the atmosphere. Once the mean behavior of the plume is computed, a turbulence model is introduced which accounts for the turbulent gusts produced inside of the plume. Finally, an aircraft response model is required to evaluate how various aircraft types are affected by the turbulent gusts caused by the exhaust plume. Fig. 2 shows how the different models are structured to compute the area of risk of severe turbulence around exhaust plumes.

A. Mean Plume Model

The plume model uses stack and environmental inputs to estimate the trajectory and time-averaged flow of the exhaust plume which rises above the stack. Three different plume models from literature were considered for this purpose, and they are the Jirka model [1] used by Science Applications International Corporation (SAIC) for plume research [13], The Air Pollution Model (TAPM) [14] recommended for use by Australia's CASA, and the Spillane model [15] which has also been previously used for aviation purposes.

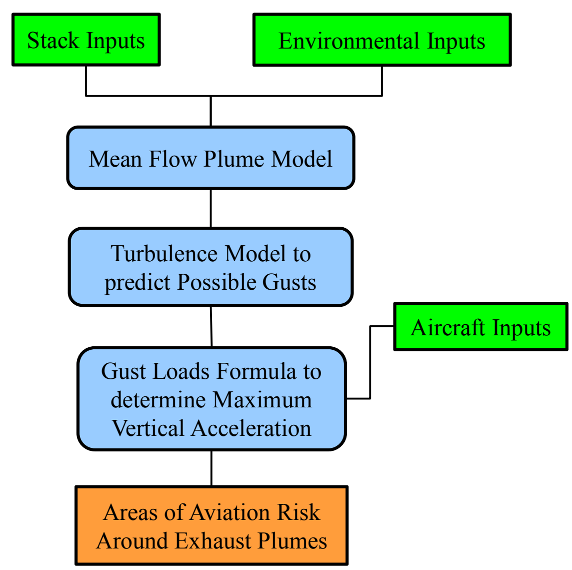

Figure 2. Overview of the various models required to produce severe turbulence risk maps. The green boxes represent the inputs, the blue boxes are the models from literature, and the orange box is the output.

Table 1. Plume rise error associated with each plume model for single stack operation.

Plant Name	Number of Observations	Spillane Single Stack	TAPM Single Stack	Jirka Single Stack
Paradise	30	17.5%	20.1%	27.2%
Gallatin	31	24.6%	25.6%	46.2%
Widows Creek	10	27.4%	26.6%	31.4%
Overall Median	71	22.7%	23.6%	33.6%

All three models rely on a system of Ordinary Differential Equations (ODEs) to model the propagation of the plume under given atmospheric conditions. Outputs of these models include vertical and horizontal coordinates of the plume centerline, mean centerline velocity, mean centerline temperature, and plume width. Furthermore, they provide equations for estimating the mean velocity and temperature at any point inside of the plume.

To select a plume model for this research, outputs from the various models were compared against empirical data in terms of trajectory coordinates and mean centerline velocity. Trajectory data gathered by the Tennessee Valley Authority (TVA) was used to compare against the model outputs. The TVA data consists of detailed trajectory measurements of plumes from several power plants under many different environmental conditions. This is an important data source because it is a full-scale study and not performed inside a laboratory environment [16]. The plume rise error for each model is shown in Table 1. Overall, the Spillane model was significantly more accurate than the Jirka model and slightly more accurate than TAPM in terms of the trajectories of the plumes compared to the TVA data.

In terms of centerline velocity measurements, the three

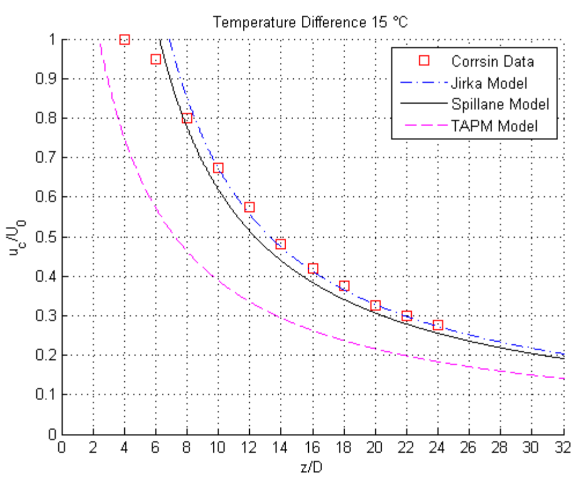

Figure 3. Centerline velocity comparison for different plume models when compared to experimental data with a temperature difference of 15°C between the plume and the environment.

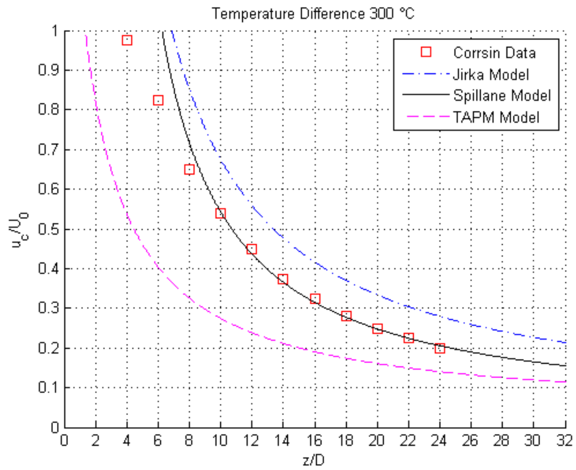

Figure 4. Centerline velocity comparison for different plume models when compared to experimental data with a temperature difference of 300°C between the plume and the environment.

models were compared to data from Corrsin [17]. This data was collected from a laboratory environment with varying effluent temperatures. The first data comparison is shown in Fig. 3, where the temperature difference between the effluent and the environment is only 15°C. The ratio of the centerline velocity (u_c) to the initial exit velocity of the plume (U_0) is plotted against the ratio of the height above the stack (z) to the diameter of the stack (D). In this case, the Jirka model provides an excellent estimate for the centerline velocity of the plume, and the Spillane model is also fairly accurate. On the other hand, TAPM under-predicts the centerline velocity rather significantly. This is largely due to TAPM not accounting for the ZOFE as the other two models do.

The next data comparison is shown in Fig. 4 where the temperature difference between the effluent and the environment is raised to 300°C. TAPM again significantly under-predicts the centerline velocity of the plume. In this case, the Spillane model is very accurate, while the Jirka model tends to over-predict the centerline velocity. The Jirka model relies on the Boussinesq approximation, which states that when density differences between two fluids are small, they can be neglected, except when they are being multiplied by g, the acceleration due to gravity. This approximation greatly simplifies the Navier-Stokes equations, from which the Jirka model is derived. Since power plant smokestacks can emit effluent that is hundreds of degrees hotter than the atmosphere with a corresponding density that is much lower than the surrounding atmosphere, the Jirka model could be inaccurate at high exhaust temperatures.

The Spillane model has been shown to produce more accurate predictions for the plume trajectory and the centerline velocity of the plume at high temperature differences. Since industrial smoke stacks are expected to produce high temperature exhaust, the Spillane model has been chosen to represent the exhaust plume.

The Spillane model can approximate plumes emanating from a single stack or multiple aligned, uniform stacks. It requires stack inputs including diameter of the stack, height of the stack, temperature of the effluent, and initial velocity of the effluent. Atmospheric inputs include ambient temperature, wind, and lapse rate.

B. Turbulence Model

While the Spillane model was chosen for estimating the mean flow behavior of the plume, the velocity of the plume at a given point is not constant, and it will fluctuate with time. The model should account for these velocity fluctuations, or turbulent gusts, when considering the risk to aviation. It is assumed that the velocity fluctuations follow a normal distribution centered on the mean velocity. Consequently, half of the velocity fluctuations will be less than the mean velocity and half will be greater than the mean velocity.

The Root-Mean-Square (RMS) of the centerline velocity provides a measure of the intensity of the fluctuations. Experimental data from Papanicolaou and List show that the RMS of the centerline velocity of the plume (U_{rms}) is equal to 0.25 of the mean centerline velocity (U_C) [18]. The total vertical gust experienced by the aircraft will be equal to the sum of the mean centerline velocity as calculated from Spillane and the RMS value multiplied by a factor, n, as shown in (1).

$$U_{gust} = U_C + nU_{rms} \tag{1}$$

Since a normal distribution is assumed, the probability of experiencing a vertical gust greater than the mean centerline velocity is 0.5. When the amplitude of a gust is greater, the probability of experiencing that gust decreases. Following the Cumulative Distribution Function (CDF) of a normal distribution, the probability of experiencing a gust with amplitude U_{gust} can be easily computed.

By coupling the mean velocities produced by the Spillane model with the gust produced from the turbulence model, a coordinate grid of gust amplitudes was produced throughout the trajectory of the plume. This grid of possible gust amplitudes was used as input into the aircraft response model.

C. Aircraft Response Model

To determine the effects that the plume has on an aircraft flying over it, the outputs from the plume and turbulence models were fed into an aircraft response model, which calculates the vertical acceleration, or load factor, of the aircraft caused by the gust. The gust was assumed to have a One-Minus Cosine form as described in Schmidt and Hoblit [19,20].

A formula developed initially by the National Advisory Committee for Aeronautics (NACA) calculates the maximum load factor response of an aircraft in g-force when experiencing a gust of a One-Minus Cosine form [21]. This formula, shown in (2), was chosen because it is widely accepted in the aviation community and appears in the Federal Aviation Regulations (FAR) Part 23.341 [22]. In (2), $load_{max}$ is the maximum load factor, K_g is a derived gust alleviation factor, $C_{L\alpha}$ is the lift-curve slope, ρ is the air density, V is the aircraft speed, W is the aircraft weight, S is the aircraft surface area, and U_{gust} is the vertical gust impacting the aircraft.

$$\mathrm{load}_{max} = K_g \left[C_{L\alpha} \frac{\rho V}{2} \frac{U_{gust}}{(W/S)} \right] \tag{2}$$

Although exhaust plumes are expected to impact smaller, lighter General Aviation (GA) aircraft much more significantly than larger aircraft types, three types of aircraft with different sizes were examined. Aircraft parameters were taken from Schmidt's "Introduction to Aircraft Dynamics" [20] for a North American Navion GA aircraft, a Lockheed Jetstar business jet, and a Convair CV-880M jet, and they are shown in Table 2.

The National Oceanic and Atmospheric Administration (NOAA) created a table that defines limits for light, moderate, severe, and extreme turbulence relative to the vertical acceleration of the aircraft [23]. Note that there is no US standard for how vertical acceleration can be used to judge the intensity of turbulence. This NOAA table also provides qualitative descriptions for the different levels of turbulence. Severe turbulence is described as possibly causing the pilot to momentarily lose control of the aircraft. Therefore, the probability of experiencing a gust that causes the aircraft to have a vertical acceleration of greater than the threshold for severe turbulence (1g) was calculated for the area around a smokestack.

D. Impact of Environmental Parameters

For each environmental data input, the model is deterministic, i.e. the same inputs will yield the same output. Atmospheric conditions can drastically affect the propagation of a plume into the atmosphere, and the model depends primarily on three parameters: ambient temperature, lapse rate, and the ambient wind.

Since the buoyancy of the plume is driven by the temperature difference between the effluent and the

Table 2. Aircraft parameters used in aircraft response model.

Parameter	North American Navion GA Aircraft	Lockheed Jetstar	Convair CV-880M Jet	Units
Surface Area, S	16.72	50.40	185.81	m^2
Wingspan, b	10.18	16.38	36.58	m
Mean Chord Length, $\bar{c}$	1.74	3.33	5.77	m
Mass, M (converted to weight in equation, W)	1,247	10,843	57,150	kg
Lift-Curve Slope, $C_{L\alpha}$	4.44	5	4.66	$radians^{-1}$
Rolling moment of Inertia, I_x	1,421	59,690	1.36×10^6	$kg\text{-}m^2$
Approach Airspeed, $V_{approach}$	72 (taken from discussions with pilots)	132	135	knots

atmosphere, a colder ambient temperature will increase the buoyancy effects of the plume.

The lapse rate is defined as the derivative of potential temperature with respect to height, and it is an indicator of how the density of the air changes at different altitudes. In most situations, the density of the air will decrease with altitude, which limits the buoyancy of the plume. In rare cases such as an inversion layer, the density of the air could increase with height, causing enhanced buoyancy of the plume.

The biggest environmental factor affecting plume propagation, however, is the ambient wind. In calm wind scenarios, the plume can rise vertically to a maximum height. On the other hand, even with a light wind, the plume will turn over and dissipate fairly rapidly. The effect of ambient wind can be seen in Fig. 5 and Fig. 6, which show the trajectory and mean velocity of a plume with the same initial conditions subject to calm winds and a four knot wind respectively.

To ultimately determine the likelihood of experiencing severe turbulence, the model needs to be run over several years of environmental data. For a given plume, the final output will show the likelihood of experiencing severe turbulence for a particular aircraft type in the airspace above the plume.

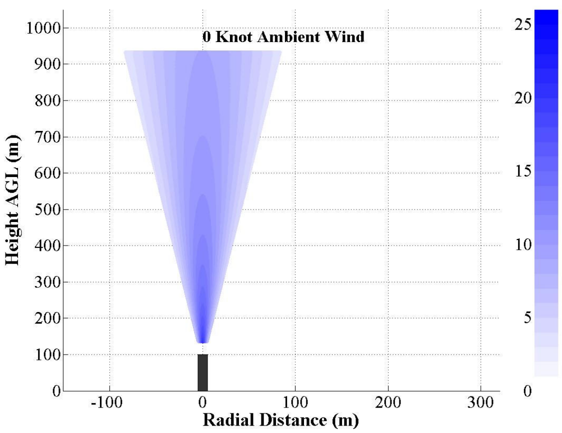

Figure 5. Velocity of a plume with a 0 knot ambient wind.

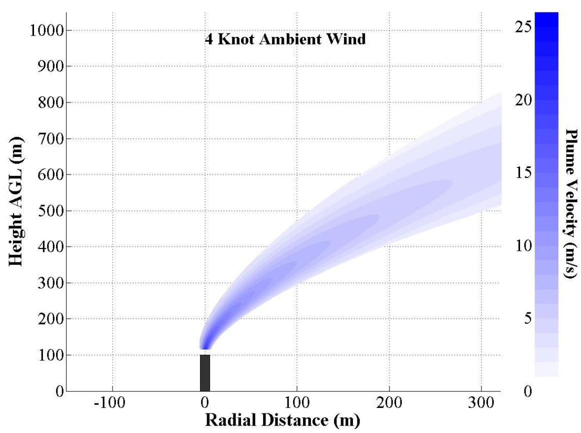

Figure 6. Velocity of a plume with a 4 knot ambient wind.

VI. CASE STUDIES

Since the severe turbulence event at KMGW was the most publicized incident, this particular stack was selected for examination. The smokestack is 168 meters tall with a diameter of 10.7 meters. The effluent has a velocity of 18.1 m/s and a temperature of 55°C. The model was run against nearly three years of environmental data sampled hourly for a total of 25,315 measurements. The weather data was taken from NOAA's Rapid Update Cycle (RUC) historical dataset, which considers measurements from weather stations, aircraft, weather balloons, and other sources to archive historical weather data and produce short-term forecasts. RUC data is gridded over the continental US with a resolution of 13 km at various altitudes in the atmosphere [24].

Fig. 7 shows the risk of experiencing severe turbulence when flying through the plume near KMGW for a Navion GA aircraft. The stack itself is represented by the grey rectangle while the varying levels of risk are displayed in different colors, with the darker shades representing the areas of higher risk. As expected, the highest risk of experiencing severe turbulence occurs in the region closest to the top of the stack. As the plume rises further above the stack, the probability of experiencing severe turbulence continues to decrease. Above 600 meters Above Ground Level (AGL), the risk decreases to less than 10^{-7}. The vertical component of the risk associated with the plume is much larger than the horizontal component, as the risk drops below 10^{-7} at about 100 meters to the side of the stack.

The plume model was also run against the 25,315 hourly weather measurements for the two other aircraft types in Table 2, and their risk plots are shown in Fig. 8 and Fig. 9. It is clear that as the size of the aircraft increases, the risk of experiencing severe turbulence decreases. For example, the riskiest area for the Convair jet is only 10^{-3}; in other words, if the Convair flew through the plume 1000 times in this area, it would experience severe turbulence once.

In this model, it is assumed the wind is blowing from the

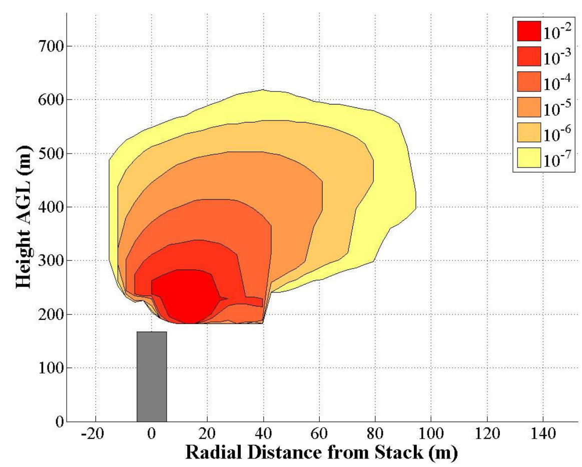

Figure 7. Risk of experiencing severe turbulence in a Navion GA aircraft at the smokestack north of KMGW.

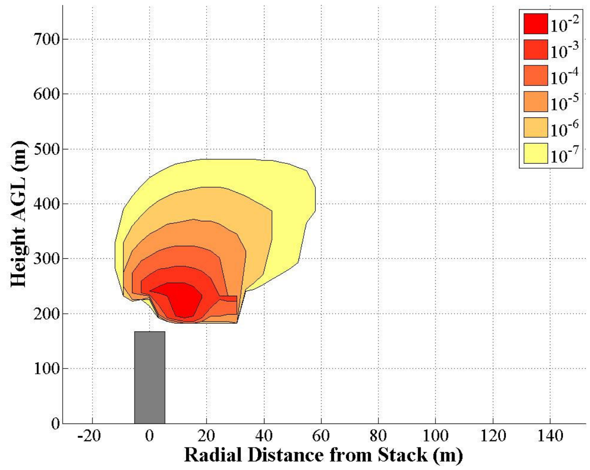

Figure 8. Risk of experiencing severe turbulence in a Lockheed Jetstar aircraft at the smokestack north of KMGW.

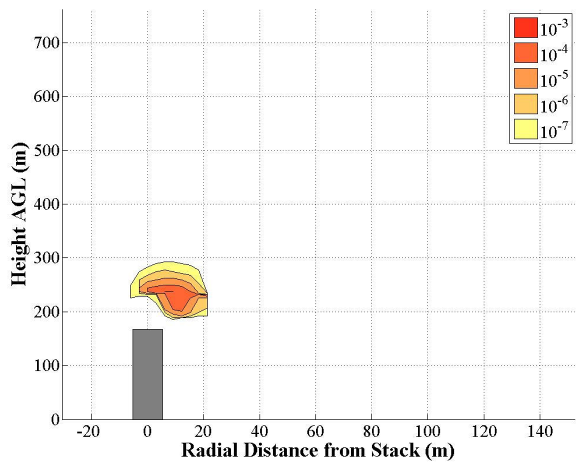

Figure 9. Risk of experiencing severe turbulence in a Convair CV-880M aircraft at the smokestack north of KMGW.

same direction in each hourly measurement; hence the area of risk above the plume is not symmetrically displayed above the stack. To convert these plots to a three-dimensional airspace, the areas of risk should be rotated around the stack to create cylinders.

After reviewing the KMGW case as well as a few others, it can be shown that exhaust plumes present some risk to low-flying aircraft. Smaller aircraft flying in a cold atmosphere with calm winds have the largest area of risk of experiencing severe turbulence.

VII. Conclusions

This paper presented a model for quantifying the hazards to aviation that are caused by exhaust plumes. The upward motion of exhaust plumes has the potential to cause low-flying aircraft to experience severe turbulence, particularly in a cold environment with calm winds. Output from this model includes contour maps showing the level of risk of experiencing severe turbulence in the vicinity around an exhaust plume. Although smaller, lighter aircraft tend to be more at risk of experiencing severe turbulence, some risk could still be present at particular plumes for larger aircraft types.

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