Estimating Mass and Heat Emissions and Near-Field Downwind Pollutant Impacts from Controlled Agricultural Field Burns

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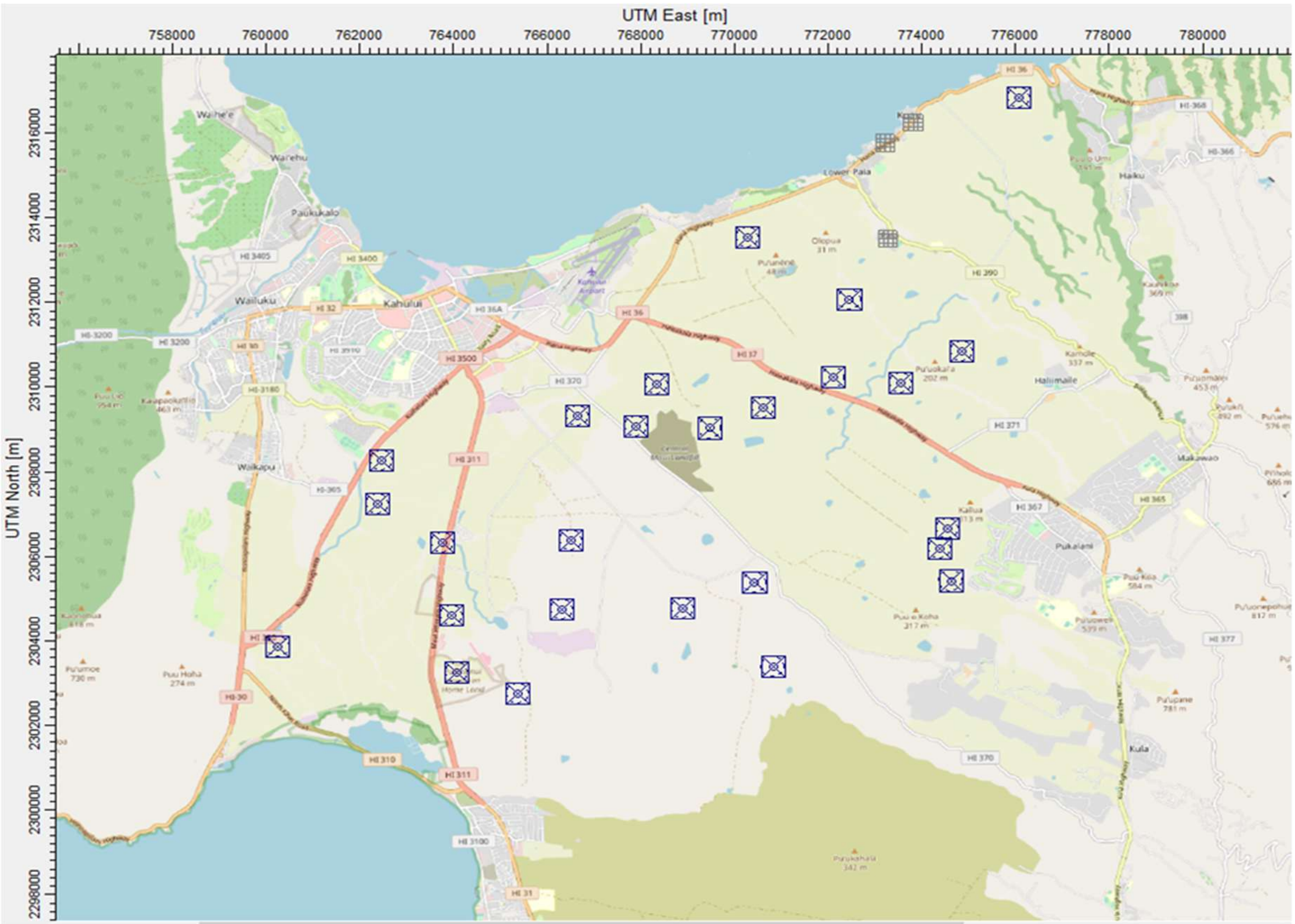
Modeling Driven by Health Effect Concerns

- Many current studies are more concerned about mesoscale and regional effects of wildfires
- My specific project was more concerned with health effects to people living within about 10 m of agricultural field burns
- PM2.5 was modeled

Sugarcane field burn plumes in South Florida (Adegboya 2022)

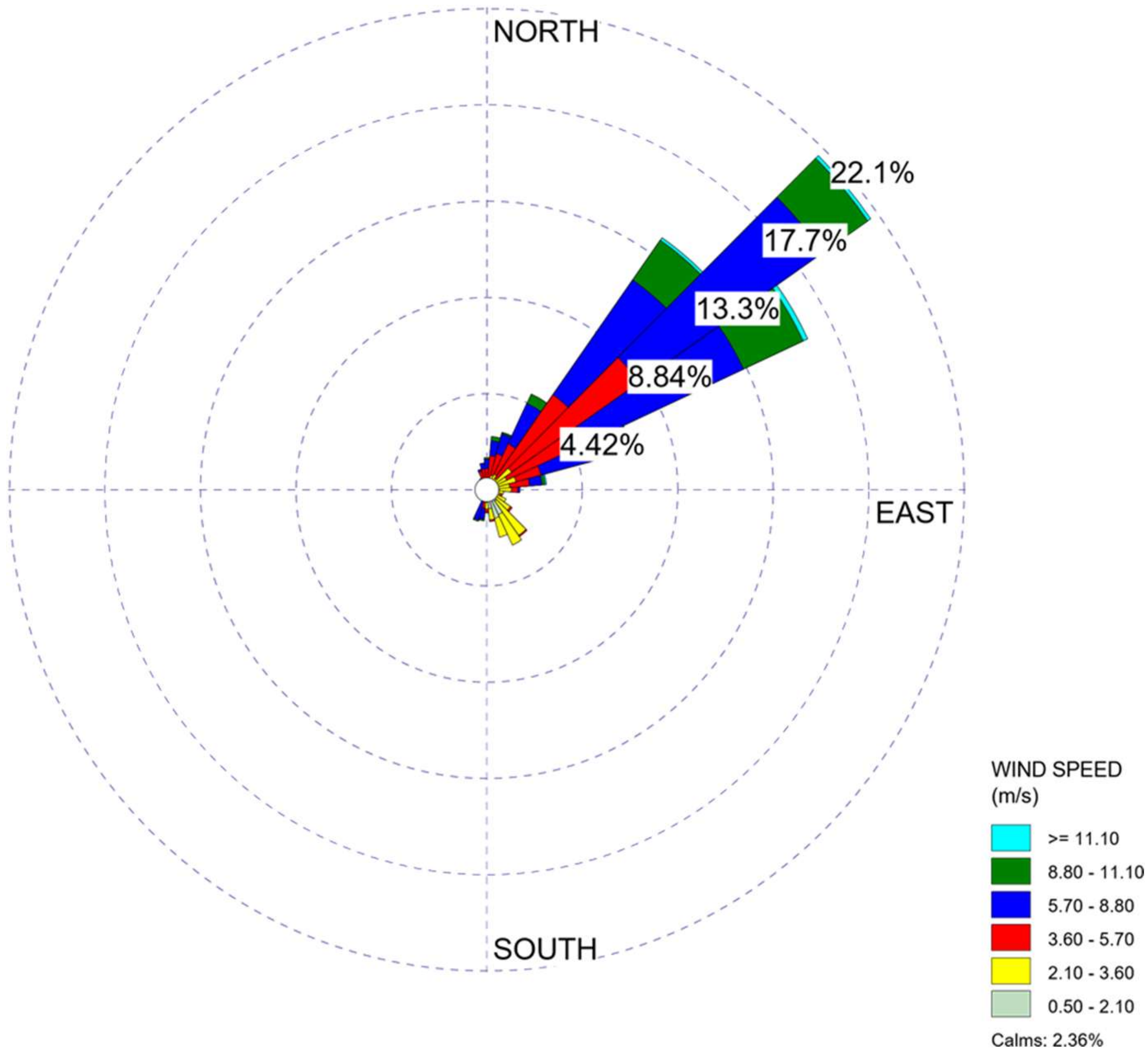
Depending on heat flux and wind speed, the plume could blow along the ground or rise up

Area of sugarcane burning. Airport is in the NW sector. Squares with X's indicate fields that burned in a specific 4 month period. Smaller squares in the top middle right near the coast are where concentrations need to be calculated.



Map is 26 by 18 km

Wind rose from nearby airport for 4 months of interest



Source Emissions Estimation

Standard formula for PM2.5 emissions from burning sugarcane field**:** **E = AFCe**

where **E** is the PM2.5 emissions (kg), **A** is the area being burned (m^2), **F** is the biomass per unit area (kg/m^2), **C** is the fraction of biomass consumed by fire, and **e** is the emission factor (mass of PM2.5 emitted per mass of biomass burned).

If the burn time is $\mathbf{t_d}$, then the average emission rate is $\mathbf{E/t_d}$, with units kg/s. It is assumed that the burn rate is identical across the entire area of the field, and across the burn time period $\mathbf{t_d}$.

The biomass of sugarcane per unit area is **F** =1.065 kg/m^2 for South Florida fields, with an uncertainty of about +/- 20 to 50 %. Studies suggest that **F** is twice as large in Hawaii (i.e., 2.13 kg/m^2).

The general consensus is that the fraction of biomass consumed by fire **C** is 0.65. The mass emission factor **e**, is quoted to be about 0.004 to 0.005.

With the above assumptions, the PM2.5 emissions per unit area, **FCe**, in Hawaii is about 0.007 kg/m^2.

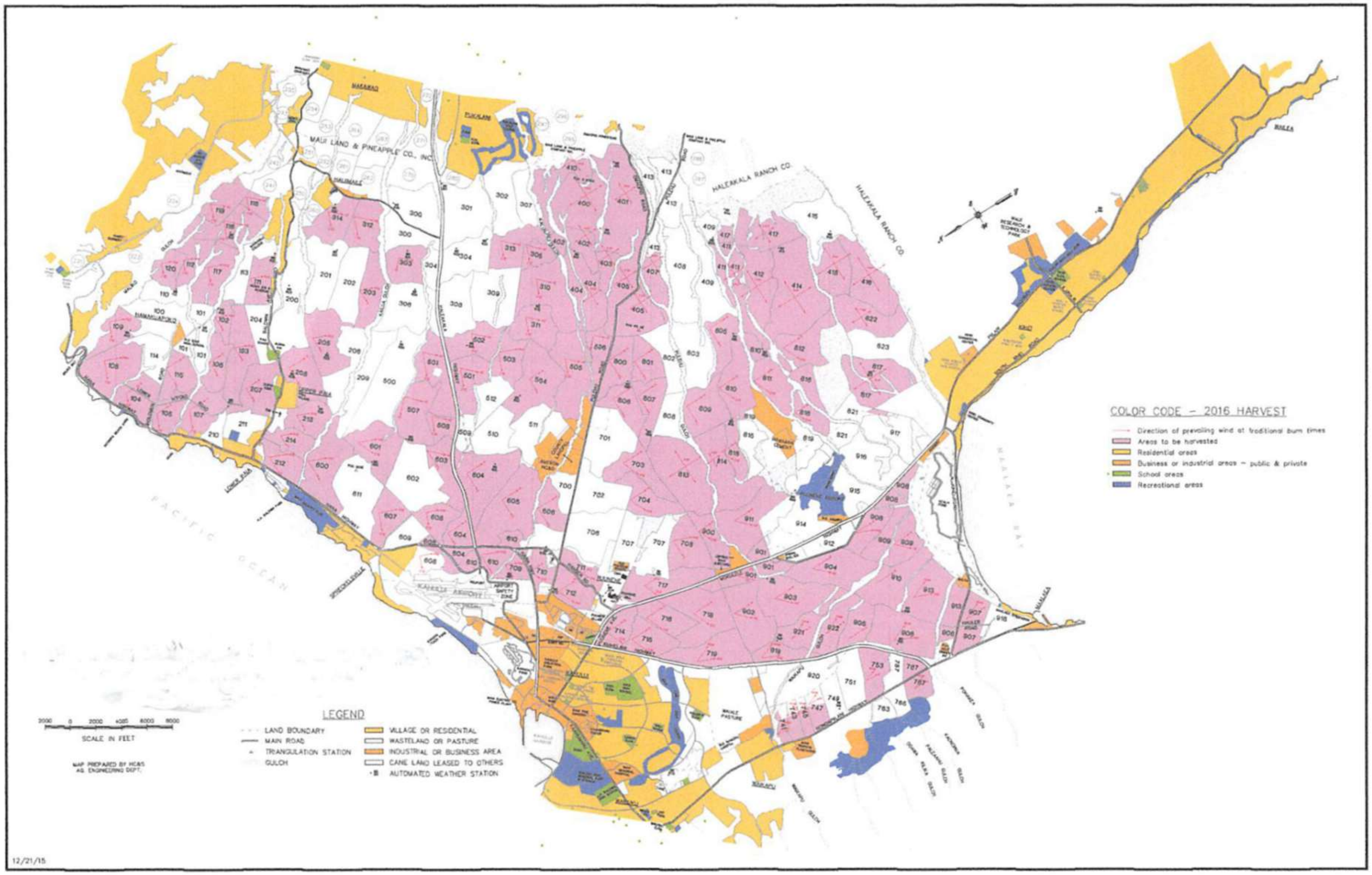
A typical sugarcane field being burned has an area **A** of about 250,000 m^2, equivalent to about 63 acres. Thus, the total PM2.5 emissions from the field is about 1,750 kg.

Table 2.

Burn Field	No. of Burns
108	1
202	3
209	2
302	4
306	4
307	2
405	1
409	4
410	2
501	1
511	2
512	2
605	1
611	3
700	1
706	3
719	2
803	5
813	4
815	1
821	1
902	2
906	3
911	2
914	3
915	2
Total	61

During Sept-Dec 2015, records indicate that 61 field burns took place, each of duration one hour, and each in the early morning. Burns are allowed only at certain times of day and wind speeds.

Fields are all shown and numbered on map below. Width is about 30 km. North is down and to left.



Source Emissions Rate (for input to model)

For the assumed 63 acre (250,000 m) field, the emission rate of PM2.5 is 1750 kg/t_d

The fields are required by the State to be extinguished after 1 hr, which is therefore the assumed t_d.

Although the emissions vary with space across the field and with time within the 1 hr burn period, we assume constant emissions.

Thus, the emission rate is 1750 kg/3600 s = 0.486 kg/s

Heat Flux

- To estimate the heat flux $\mathbf{Q_H}$ (in MW) from a burning sugarcane field, we need to know the heat released by burning a specific mass of sugarcane. Several references state that about 8 MJ of heat is released by burning one kg of sugarcane. Note that J refers to Joule, a measure of energy, and that 1 J = 1 kg m^2/s^2. Recall that the mass of sugarcane biomass per m^2 is about 2 kg in Hawaii. Assume, as before, that the field area is 250,000 m^2. Therefore, 4,000,000 MJ are released from the entire field over the course of the burn. However, to calculate plume rise, we need to know the heat flux, which is Joules per unit time, or power. Note that 1 watt (W) equals 1 J/s, and 1 megawatt, MW = 10^6 W. Let's assume the 4,000,000 MJ heat release, and use the one hour burn time (t_d =3600s).

- For $\mathbf{t_d}$ = 3,600 s, the heat flux from the burning field $\mathbf{Q_H}$ is 1111 MJ/s or MW.

- This is about 20 times the natural sensible heat flux from a field on a summer afternoon

Briggs plume rise for the sugarcane field scenarios described above

Briggs' formula for the rise of the buoyant plume above the source at distances less than about 1 or 2 km, when the plume is still rising, is: $\mathbf{h = 1.6\ F_o^{1/3}\ x^{2/3}\ /u}$ where **h** (in m) is the height above ground of the plume centerline, $\mathbf{F_o}$ is the initial buoyancy flux in m^4/s^3, **x** is downwind distance in m, and **u** is ambient wind speed in m/s. Briggs $\mathbf{F_o}$ and the heat flux in MW are related by: $\mathbf{F_o}$ (in m^4/s^3) = 8.63 $\mathbf{Q_H}$ (in MW). For the heat flux derived on a previous slide, the plume rise calculated using Briggs' formula, assuming **u** = 5 m/s, for a distance of 100 m, is about 100 m. However, the Briggs formula is for industrial sources with much smaller areas, such as a stack. Also, as mentioned earlier, the sugar cane fire is variable in time and across the area of the field, and photographs suggest there is not an obvious "plume rise median height", since there are parts of the fire area with less intensity and thus minimal plume rise.

Calculating plume rise from burning sugarcane fields

Plume rise in the atmosphere from stack plumes has been widely studied and standard methods developed for estimating plume rise (Briggs 1969 and 1984, Hanna et al. 1982). The Briggs formulas are incorporated in many wildfire models (e.g., Lavdas 1996, Nowell et al., 2022). However, the simplest formulas assume a constant wind speed **u** and temperature gradient with height **dT/dz**.

Briggs does provide the plume rise formula in differential form, which allows calculations to be made for any vertical profiles of u and T, and several modelers include that solution (see next 2 slides). Other persons have proposed a similar differential formula. Briggs also suggests corrections for plumes from area sources of radius **R**, since plume rise from an area source (such as a sugarcane fire) would be less due to the increased entrainment of ambient air into the broader initial cloud perimeter.

Briggs also developed parameterizations for ground-based plumes during high winds, where the wind speed can be strong enough to keep the plume from lifting off.

Of course, CFD models with high resolution can directly simulate the rise and spread of a plume in an arbitrary boundary layer, itself possibly simulated by a CFD model.

Calculating plume rise by solution of governing equations (Briggs). Similar to what many others do.

Definition of volume flux $\mathbf{V}$ (ignores π): Vertical $\mathbf{V = wR^2}$;
Bent over: $\mathbf{V = uR^2}$, where $\mathbf{w}$ is vertical velocity, $\mathbf{u}$ is horizontal velocity, and $\mathbf{R}$ is plume radius. Initial volume flux is $\mathbf{V_o = w_o R_o^2}$, where subscript $\mathbf{o}$ is at start point of plume.

Definition of Initial Momentum Flux: $\mathbf{M_o = (\rho_{po}/\rho_{eo}) w_o V_o}$, where $\boldsymbol{\rho_{po}}$ and $\boldsymbol{\rho_{eo}}$ are initial plume and ambient air density

Definition of Initial Buoyancy Flux: $\mathbf{F_o = g((T_{po} - T_{eo})/T_{po}) V_o}$, where $\mathbf{T_{po}}$ and $\mathbf{T_{eo}}$ are initial plume and ambient air temperature (K)

Definition of environmental stability $\mathbf{s = (g/T_e)(dT_e/dz + 0.01^oC/m)}$

Calculating plume rise by solution of governing equations (Briggs), page 2.

Equation for buoyancy conservation: Vertical plume: **dF/dz = -sV**; Bent-over plume: **dF/dz = -sV/S** where **S** = 2.3

Equation for momentum conservation: Vertical plume and Bent-over plume: **dM/dz = F/w**

Closure by Taylor entrainment assumption: $\mathbf{dV/dz = 2Rv_e}$, where entrainment velocity $\mathbf{v_e}$ is $\boldsymbol{\alpha}\mathbf{w}$ for vertical plumes and $\boldsymbol{\beta}\mathbf{u}$ for bent-over plumes. Lab and field experiments suggest $\boldsymbol{\alpha}$ is about 0.08 and $\boldsymbol{\beta}$ is about 0.6. Thus, for Vertical plume: $\mathbf{dV/dz = 2\alpha M^{0.5}}$; Bent-over plume: $\mathbf{dV/dz = 2\ \beta Ru}$

These equations can handle variations of **u** and **s** with height. Terms can be added for evaporation, condensation, and chemical reactions.

Plume rise methodology in HPAC/SCIPUFF, used in IMAAC

SCIPUFF (Second-Order Closure Puff) is a member of the Lagrangian puff model group. The transport and dispersion of individual puffs (released sequentially) is calculated. For a continuous source with constant ambient **dT/dz** gradient and wind speed **u** across the domain, the model reduces to the Briggs model.

However, SCIPUFF can accommodate time and space variable (gridded) input meteorology, such as from WRF, HRRR or ECWMF. In this case it uses the basic differential equations for buoyant plume or puff rise, similar to those in the previous 2 slides. See Section 16.3 (Dynamic Rise Effects) in the on-line manual for SCIPUFF 2-8.

In general, any plume rise model is designed to “fit” the basic Briggs model in the limit of constant wind speed and temperature gradient. The “constants” in the Briggs formulas themselves were determined from comparisons with numerous lab and field data.

Briggs plume rise for the sugarcane field scenarios described above

Briggs' formula for the rise of the buoyant plume above the source at distances less than about 1 or 2 km, when the plume is still rising, is: $\mathbf{h = 1.6\, F_o^{1/3}\, x^{2/3} / u}$ where **h** (in m) is the height above ground of the plume centerline, $\mathbf{F_o}$ is the initial buoyancy flux in m^4/s^3, **x** is downwind distance in m, and **u** is ambient wind speed in m/s. Briggs $\mathbf{F_o}$ and the heat flux in MW are related by: $\mathbf{F_o}$ (in m^4/s^3) = 8.63 $\mathbf{Q_H}$ (in MW). For the heat flux derived on a previous slide, the plume rise calculated using Briggs' formula, assuming **u** = 5 m/s, for a distance of 100 m, is about 100 m. However, the Briggs formula is for industrial sources with much smaller areas, such as a stack. Also, as mentioned earlier, the sugar cane fire is variable in time and across the area of the field, and photographs suggest there is not an obvious "plume rise median height", since there are parts of the fire area with less intensity and thus minimal plume rise.

Use of Observations to Estimate Plume Rise

- In view of uncertainties in estimating plume rise with formulas, sometimes it is preferable to rely on observations, by on-site persons or by videos or by remote sounders or other methods.

- For wildfires, observations are used by a few modelers, distributing the plume material into several “layers” for input to the dispersion model. This was also done by the US DTRA and by the Swedish FOI for a large sulfur fire. This was also done by some modelers of the East Palestine train wreck fire where numerous photos and videos of the burning materials were available.

- Sometimes photos of a plume are ambiguous (see next slide)

- However, since we were using AERMOD, we had to conform to its allowed input specifications for plumes from area sources

Iceland's Eyjafjallajokull volcano April 16, 2010
What is your estimate of the initial plume rise?
There are multiple layers

Assumed initial plume shape

- The state required the sugarcane burn to be extinguished after an hour. But smoldering occurred after that time

- Observations of sugarcane burn plumes often show that part of the smoke plume remains near the ground

- The state also required sugar cane companies to have a person driving around the area during and after the fire and reporting what he observed regarding plume shape and presence at the ground of smoke or ash. There were often reports of smoke and ash at the ground.

- Therefore, to be conservative, we assumed that the base of the plume remained near the ground.

Why use the AERMOD dispersion model?

- The source of the emissions is in the U.S. and AERMOD is EPA's approved regulatory model.

- The pollutant being modeled is PM2.5, which is one of the pollutants with a NAAQS (National Ambient Air Quality Standard).

- Therefore, any modeling with AERMOD will not be questioned as much as if another model is used.

- Concentrations of many components of PM2.5 can also be modeled by just multiplying by the mass fraction.

AERMOD options for initial ground-based cloud specification (for one hour release)

- We are not using the Briggs buoyant plume rise option.

- AERMOD Option 1: Circular area source specifications:

  PM2.5 Emission rate: 0.00194 g/s-m^2

  Radius of circular area: 285 m

  Release height: 0 m

- AERMOD Option 2: Volume source specifications:

  PM2.5 Emission rate: 486 g/s

  Square horizontal area with side: 500 m

  Initial lateral dimension: 116.28 m (automatically calculated by AERMOD View)

  Initial vertical dimension: 0, 50, or 100 m.

AERMOD Predictions of Max 24-hr PM2.5

- The AERMOD calculations of maximum 24-hr PM2.5 concentration for the three receptors and the Sept-Dec 2015 period are:

Circular area source, release height = 0 m	16.30 $\mu g/m^3$
Volume source, initial vertical dimension = 0 m	8.60 $\mu g/m^3$
Volume source, initial vertical dimension = 50 m	8.46 $\mu g/m^3$
Volume source, initial vertical dimension = 100 m	8.08 $\mu g/m^3$

- Of the above options for specifying the initial source, we believe that the circular area source with release height of zero is the most scientifically reasonable, since it most closely matches the observed burning fields. For this option, maximum 24 hr PM2.5 concentration is 16.3 $\mu g/m^3$ (meaning that the one hour maximum concentration was 24 * 16.3 = 391 $\mu g/m^3$).

- Other outputs could be listed, such as the max annual average PM2.5 concentration, which can be converted to an annual total exposure. Also, as mentioned earlier, maps of the area with contours of predicted concentrations could be generated.

Check AERMOD with simple screening model

- We also made calculations for a year when there was no information on the actual day and hour of the field burns. We ran a simple conservative screening model, assuming the wind would blow the center of the smoke plume from the closest field over the given receptor. The screening model is a box model, similar to the model recommended in Hanna et al. in their 1982 text: **C = Q/(uWH),** where **C** is concentration (µg/m^3), **Q** is total emission rate (g/s), **u** is wind speed, **W** is the cloud cross-wind width and **H** is the cloud depth. **C** is assumed to be constant over the rectangle defined by **W** and **H**.

- **W** and **H** are defined using their initial values at the downwind edge of the field (subscript o) and a measure of the dispersion: $\mathbf{W = W_o + 0.16x}$ and $\mathbf{H = H_o + 0.04x}$. The dispersion components of **W** (0.16**x**) and **H** (0.04**x**) follow the P-G $\boldsymbol{\sigma_y}$ and $\boldsymbol{\sigma_z}$ curves for rural neutral conditions (class D). However, since $\boldsymbol{\sigma_y}$ describes only one side of the plume and **W** refers to entire width, we multiply the P-G $\boldsymbol{\sigma_y}$ by 2.

Screening model, continued

- The initial cloud width, $\mathbf{W_o}$, is assumed to be 500 m, as discussed earlier. This is the median over all the fields. The initial cloud depth, $\mathbf{H_o}$, is assumed to be 50 m, which is approximately what it would be at the downwind edge of the source area. This screening model makes the conservative assumption that there is no plume rise (i.e., the base of the smoke cloud remains at the ground). As before, we assume **Q** = 486 g/s.

x = 100 m, **C** (1 hr) = 5810 μg/m^3, **C**(24 hr) = 242 μg/m^3
x = 1 km, **C** (1 hr) = 2730 μg/m^3, **C**(24 hr) = 114 μg/m^3
x = 5 km, **C** (1 hr) = 498 μg/m^3, **C**(24 hr) = 20.8 μg/m^3
x = 10 km, **C** (1 hr) = 171 μg/m^3, **C**(24 hr) = 7.1 μg/m^3

- These predicted concentrations at 5 and 10 km are in the range of the wildfire and Maui routine monitoring numbers. Also, since the nearest upwind field burned the AERMOD scenario, Field 108, was about 5 to 10 km upwind of the receptors, the maximum 24 hr AERMOD prediction of 16 μg/m^3 agrees with the screening model predictions.

U.S. PM2.5 NAAQS (standard)

- The emissions are assumed to apply over one hour (i.e., all burning takes place over a one hour period) and AERMOD produces a minimum one hour average. National Ambient Air Quality Standards (NAAQS) exist for PM2.5. They are: 1 year avg = 9 μg/m^3 1 day avg = 35 μg/m^3

- Because the minimum averaging time for the PM2.5 NAAQS is one day, the model produces maps and data summaries for one day averages. However, as stated above, the burn time for a field is about one hour. The model calculates non-zero concentrations only for that hour. For example, if the AERMOD-predicted concentration is 100 μg/m^3 during the one hour burn period, and zero for the other 23 hours in the day, the 24 hour average will be 100/24 = 4.2 μg/m^3.

- Health experts must be able to determine the effects of exposure times that are less than the minimum NAAQS exposure time.

State PM Monitoring

The State Department of Health (DOH) established air quality monitoring stations at three locations. One is only a few km from one of the three receptor locations. Over all the monitoring sites, the highest observed PM2.5 daily concentrations for each year are often above 20 $\mu g/m^3$ and the highest PM10 daily concentrations for each year are often above 100 $\mu g/m^3$. For daily averages, these monitored maximum PM2.5 and PM10 concentrations are slightly less than the NAAQS. However, as mentioned earlier, the burn duration for a sugarcane field is only about one hour, implying that the emissions from the burning fields will be heaviest for about an hour. Thus, a daily concentration of 20 $\mu g/m^3$ implies an hourly concentration (during the burn) of 480 $\mu g/m^3$.

Observations Elsewhere of PM near Wildfires

Another comparison can be made using observed daily averaged PM2.5 concentrations from major wildfires. At downwind distances of 10 or 20 km, these have been observed to be in the range from 100 to 500 μg/m^3.

The wildfire references mention that, in the initial smoke plume, there are "soot" particles as well as some "ash" particles. Close to the fire, larger ash particles can be present, which settle out near the source. Note that the gravitational settling velocity of particles increases rapidly with diameter. For example, a particle with diameter of 10 μm has a settling velocity of about 0.5 cm/s, while a particle with diameter of 100 μm has a settling velocity of 35 cm/s.

Key point regarding modeling PM2.5 from agricultural fires

- Estimating pollutant concentrations C within 1 or 2 km of a major fire requires knowledge of the initial plume and whether parts of the smoke plume remain near the ground.
- If you assume "classical" plume rise, nearfield predicted C's can be minimal.
- If you assume that a significant portion of the plume remains near the ground, predicted C's can be unhealthful.