Vertical distribution of emissions from Freitas model

1. **Retrieve the stand alone Freitas plume rise code (Mallia et al., 2018)**
    - https://github.com/tartanrunner25/Plume-model
    - Make alteration to plume_alone.f90 described below
    - Compile

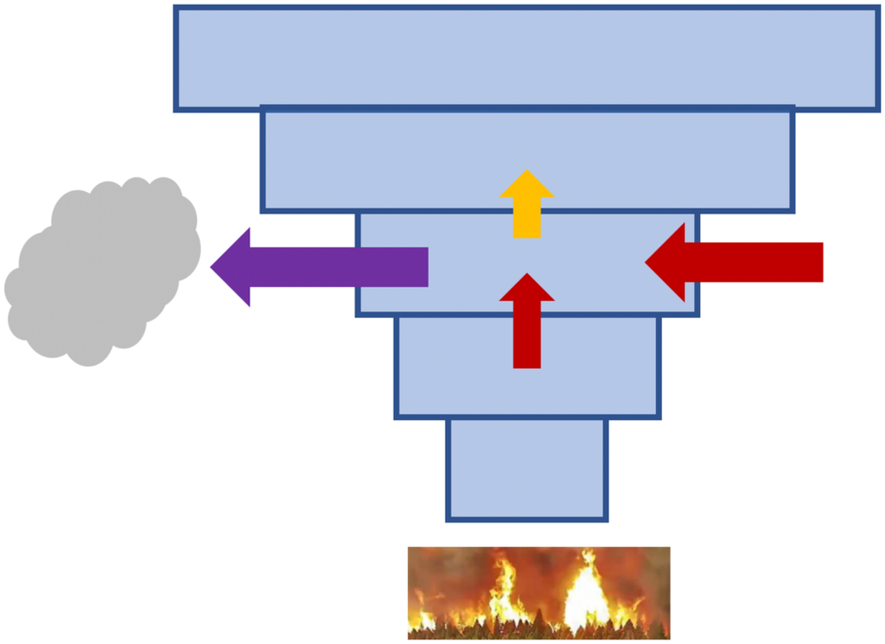
2. **Update plume_alone.f90 script**
    - Add necessary variables to the output thermodynamic profiles to use entrainment and mass balance under a steady state solution to estimate detrainment

```
IF(finalout == 1) then
   WRITE (5, 400) zt(KO)/1000., PEA, W (KO), BTMP, ETMP, VAP1, &
    VAP2, GPKC, GPKH, GPKI, rbuoy(KO)*100., radius(KO)/1000., dwdt_entr(KO), T(KO),TE(KO)
endif
```

    - Added the layer radius, the entrainment acceleration (eq. 11; Freitas et al., 2010), and the plume and environmental temperatures

3. **Perform mass balance on individual plume layers**
    - Freitas model conceptualizes the plume as stacked cylinders of varying radius
    - For each layer (top layer varies slightly) the following equation is used:
      $D_{mass,Z} = E_{mass,Z} + (\overline{\rho_{Z,Z-1}})(\overline{W_{Z,Z-1}})(\overline{A_{Z,Z-1}})$ - $(\overline{\rho_{Z,Z+1}})(\overline{W_{Z,Z+1}})(\overline{A_{Z,Z+1}})$

    where $D_{mass,Z}$ is the mass of in plume air detrained from vertical level Z, $E_{mass,Z}$ is the mass of environmental air entrained into the plume at vertical level Z, and the remaining terms characterize the vertical flux of mass into the layer from the layer below and the vertical flux of mass out of the layer to the layer above, respectively (left-to-right). The vertical mass flux between any two layers was taken to be a product of their mean density ($\bar{\rho}$), mean vertical velocity ($\overline{W}$), and mean plume horizontal area ($\bar{A}$), ideally characterizing the interface between layers (Wilmot et al., 2022).



- For the plume top layer (defined as the layer in which the vertical velocity drops below 1 m/s) the vertical mass flux to the layer above is redirected as horizontal detrainment from the plume.

4. **Using the thermodynamic profile to calculate these fluxes**
    - <u>Vertical mass fluxes:</u>
        i. Calculate plume layer average density using output pressure and temperature values within the equation of state
        ii. Calculate plume layer areas from output plume radius values
        iii. Assume the flux between layers is best characterized using the average density, area, and vertical velocities of the layers as opposed to selecting the values from one of the layers (goal here is to approximate conditions at the interface between layers despite having a step function in values between the layers)
    - <u>Entrainment flux:</u>
        i. From equation 11 (Freitas et al., 2010), we can get at the sum of the lateral and dynamic entrainment coefficients for a given layer by dividing the entrainment acceleration by negative one and the layer vertical velocity

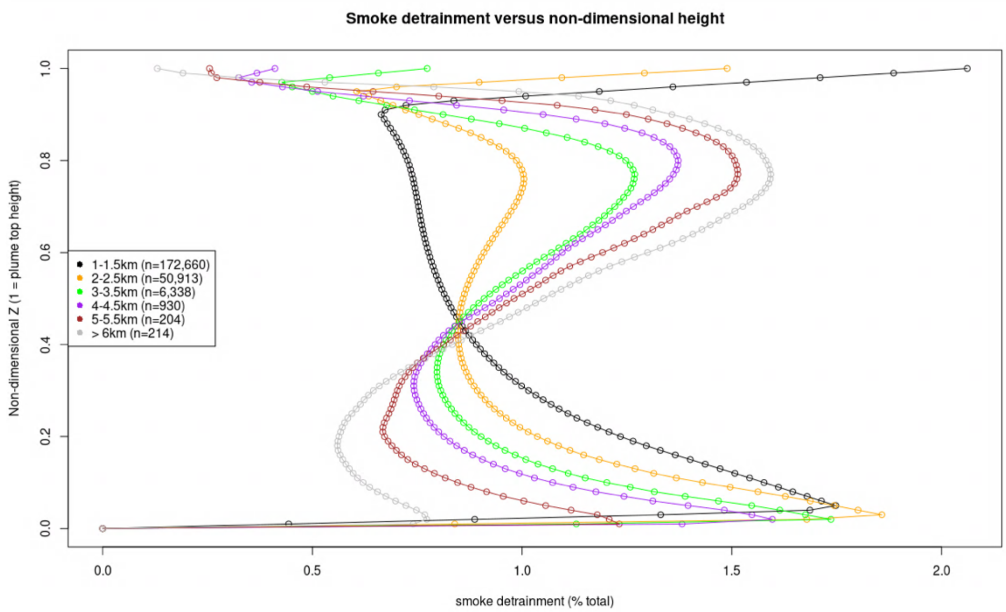
$$\mathrm{E_a} = -(\lambda_{\mathrm{entr}} + \delta_{\mathrm{entr}})w \tag{11}$$

        ii. Using equation A3 (Freitas et al., 2010) we see that the mass flux for a layer is equal to the entrainment coefficients multiplied by the mass of the layer

$$\delta_{\mathrm{entr}} = \frac{1}{m}\frac{\Delta m}{\Delta t}$$

iii. Calculate the layer mass given the layer average density and ability to calculate layer volume (100 m vertical levels and information on radius)

5. **Vertical profile of emissions from layered detrainment values**
    - From layered detrainment values, the fraction of emissions detrained within each vertical level is calculated by normalizing the layered detrainment values by the plume summed detrainment (all layers)
    - For interpolation to finer vertical resolution, detrainment at the surface and the top of the plume top layer are assumed to be zero (note: treat the layer detrainment value as representative of the middle of that layer for this interpolation). Be sure to once again normalize the vertical profile if you perform an interpolation.
    - Averaged over many simulations and put into non-dimensional space, such interpolations have the following shape:



6. **Coding the vertical distribution of emissions from Freitas output**
    - An R script (vertical_profile.R) that produces the vertical profile of emissions below plume top is provided alongside this document.
    - We hope to provide this calculation as a FORTRAN subroutine at some point as well

Further description is provided in:

Wilmot, T.Y., Mallia, D.V., Hallar, A.G. et al. Wildfire plumes in the Western US are reaching greater heights and injecting more aerosols aloft as wildfire activity intensifies. Sci Rep 12, 12400 (2022). https://doi.org/10.1038/s41598-022-16607-3

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