Thermodynamics of pyrocumulus formation

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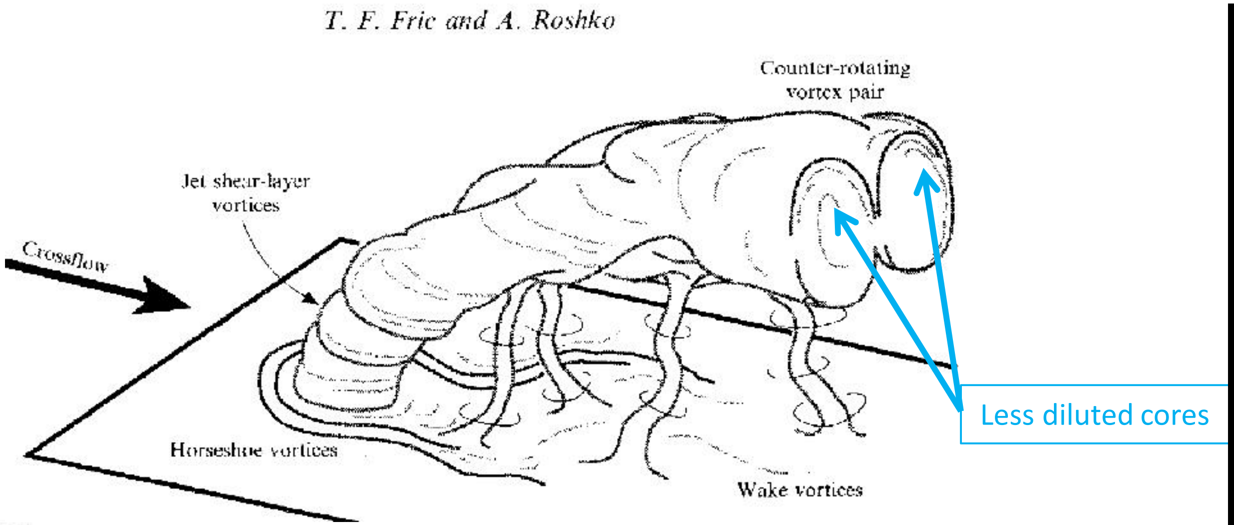
Introduction

- Background
  - ➢ Plume turbulence → entrainment → reduced buoyancy → plume condensation?
- Plume model description
  - ➢ Assumptions
  - ➢ How does it relate to real plumes
- Plume model uses
  - ➢ Identify plume condensation heights
  - ➢ Aid pyroCu/Cb forecasting
- Summary

Background

- Buoyant plumes entrain air from the environment
- Different parts of the plume entrain at different rates
- Entrainment dilutes the plume and reduces its buoyancy
- The buoyancy of individual plume elements reduces with time/height



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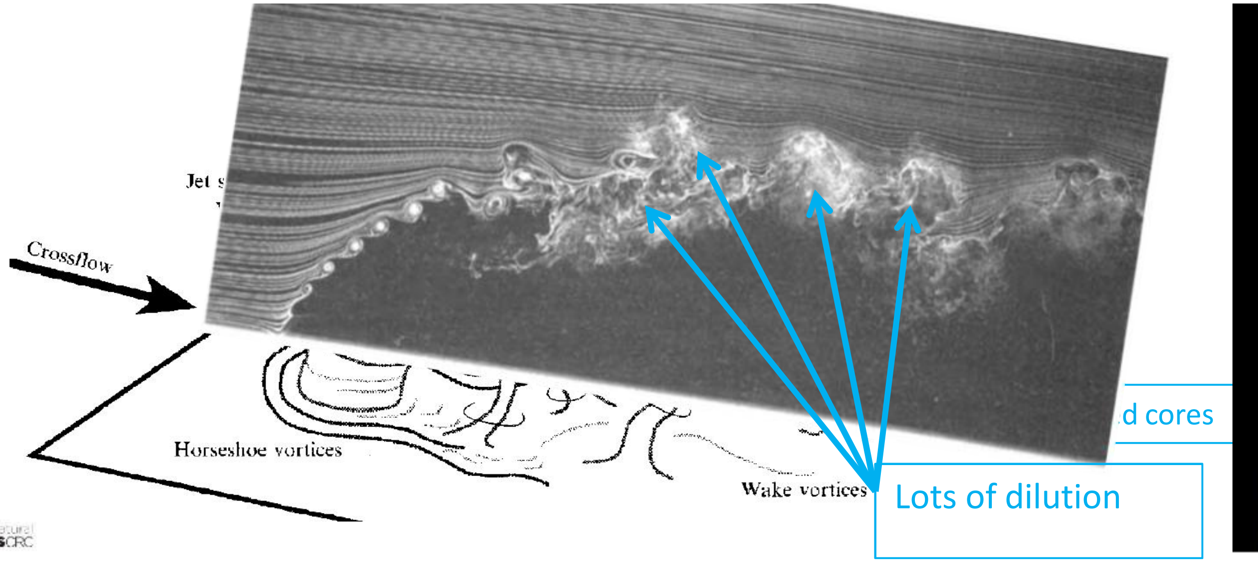


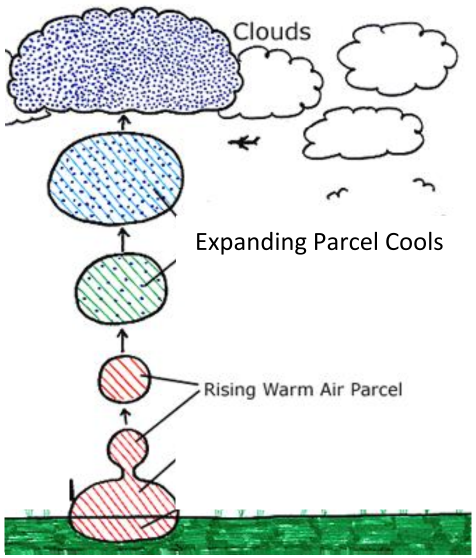
Background

- Fires of varying size, intensity, in varying background wind environments produce plumes that entrain at different rates with height.

Background

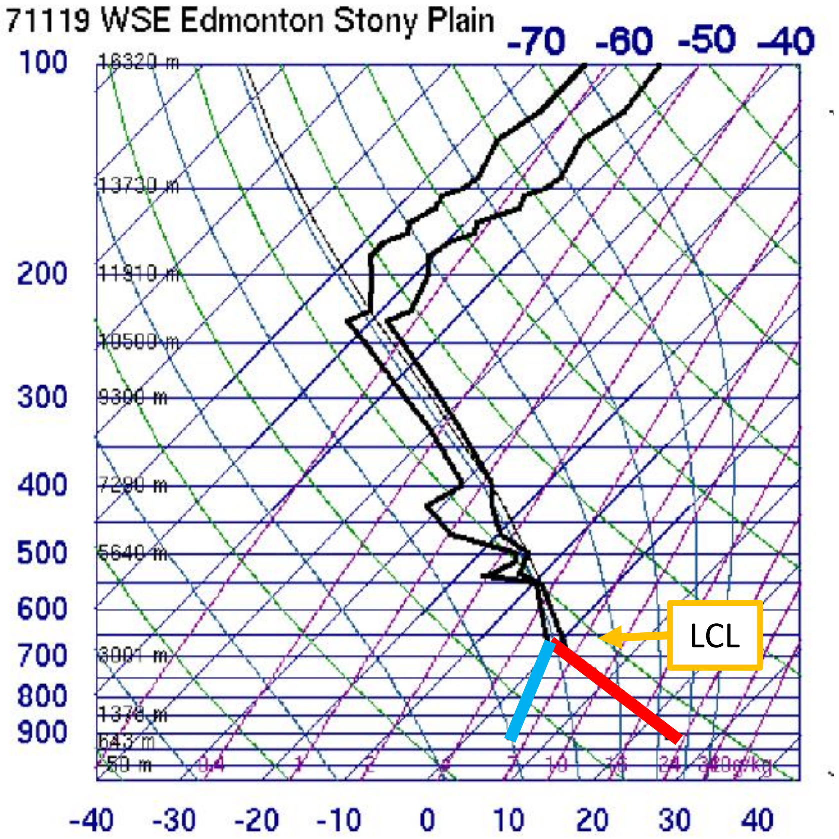
- Adiabatic expansion cools ascending plume elements
- Most plume elements lose buoyancy (~100 % diluted) before condensation occurs
- Some plume elements may cool sufficiently for condensation to occur
- Thus, a condensing plume element must experience "somewhat less dilution" than a non-condensing, ~100% diluted, plume element

- *How much less diluted than 100 %?*
- The plume model was constructed to answer this question



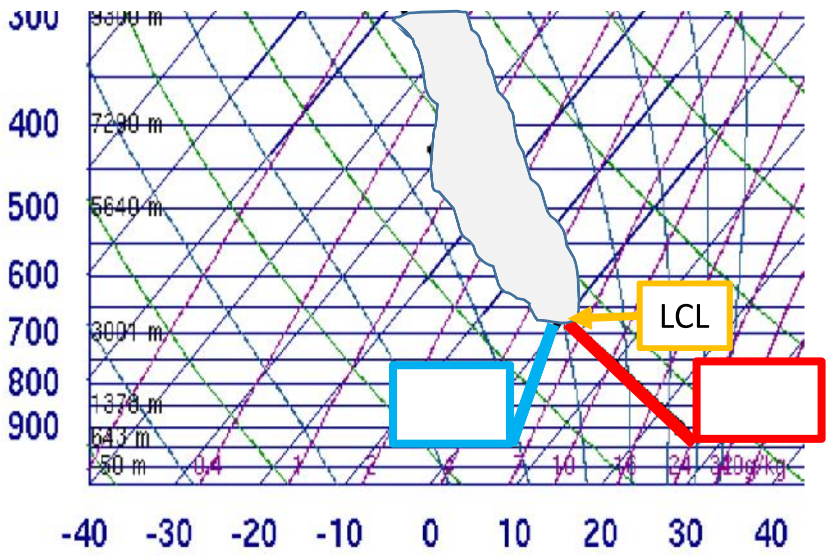
Background

- PyroCb events typically occur in an “inverted-V” environment
  - Well-mixed boundary layer, with constant potential temperature and specific humidity
  - Moist air above the LCL (Lifting Condensation Level)



Plume thermodynamic model: *Environment*

- Model assumes an "inverted-V" environment, but considers only the well-mixed boundary layer *below* the LCL
- The environment is described by only two variables: and



Plume thermodynamic model: *Fire*

- The fire releases combustion gases with potential temperature and specific humidity

➢ and are determined by specifying:
(i) a flame temperature, and
(ii) a ratio of moisture to heat production

Plume thermodynamic model: *Plume dilution*

- Each plume element is made up of a mix of combustion gas and environment air specified by a dilution factor

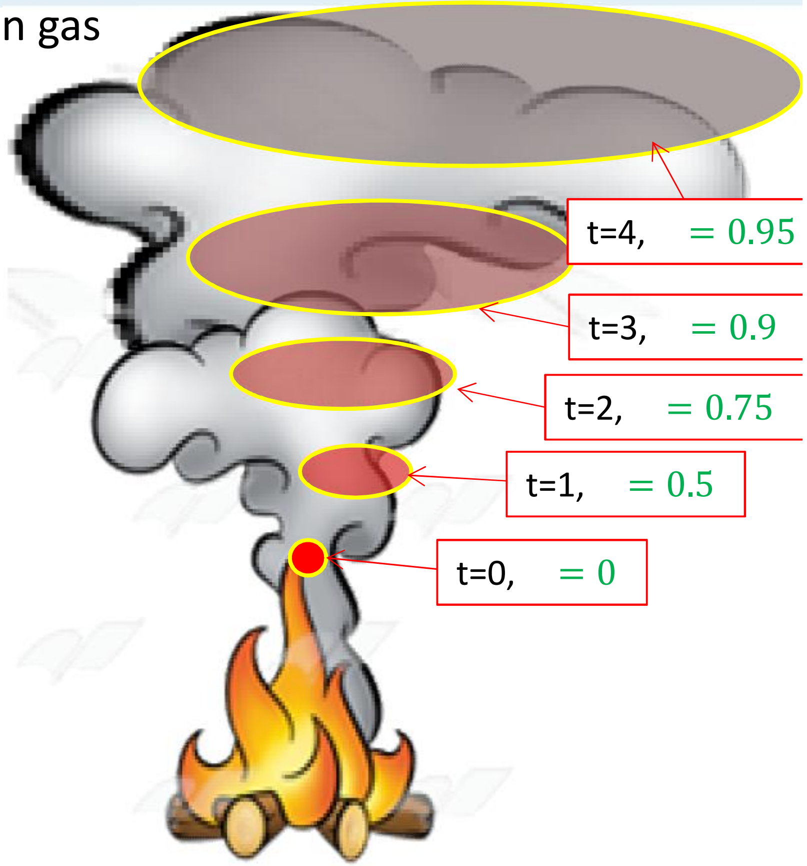
$$= \quad + (1 - \quad)$$
$$= \quad + (1 - \quad)$$

t=0: An element of combustion gas is released which is pure and (i.e., $=0$)

t=1: It rises and entrains environment air (e.g., $=0.5$)

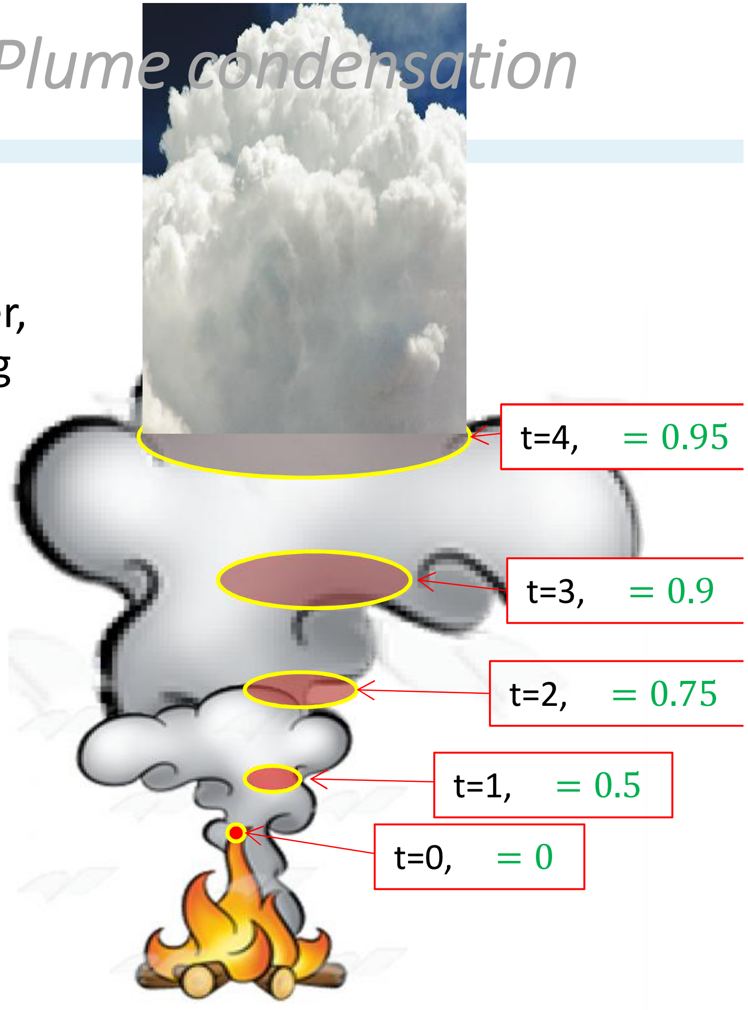
t=2—4: The parcel rises, entrains more, and becomes increasingly diluted.

As $\rightarrow 1$ the plume element loses buoyancy (because $\rightarrow$)



Plume thermodynamic model: *Plume condensation*

- Most plume elements lose buoyancy before rising high enough to condense
- If we could slow down the entrainment rate (e.g., larger, hotter fire) plume elements might rise higher, enabling them to condense
- But how high would each parcel need to rise for condensation to occur?
- Use a thermodynamic diagram to answer this question.



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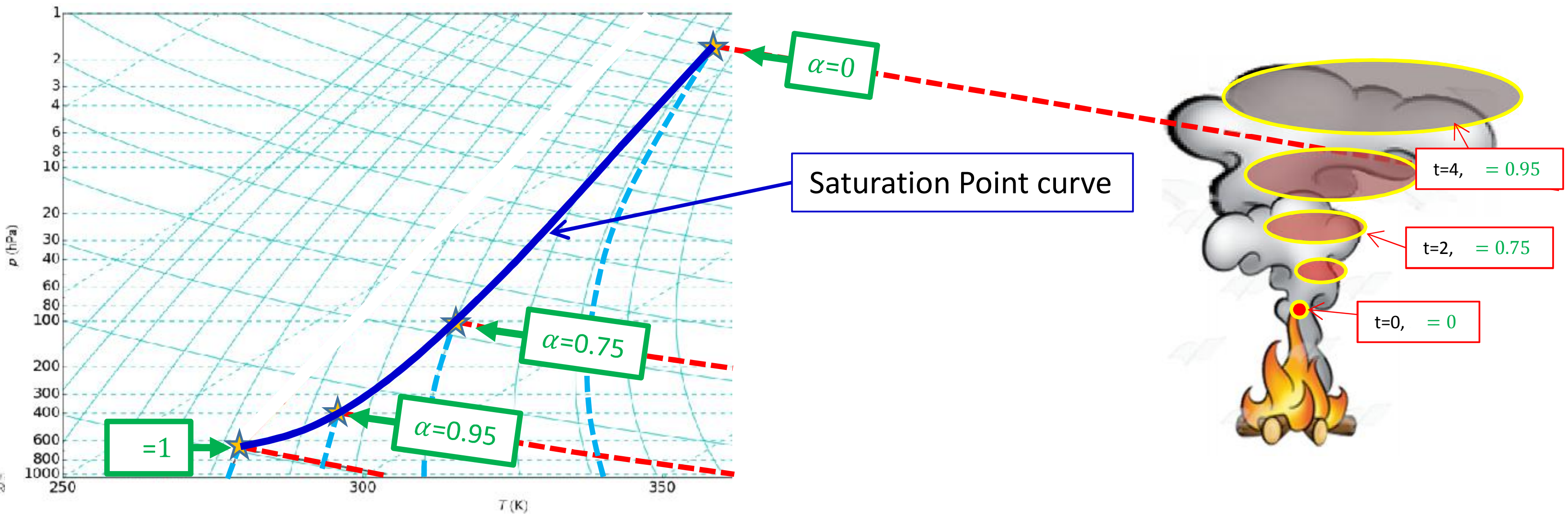
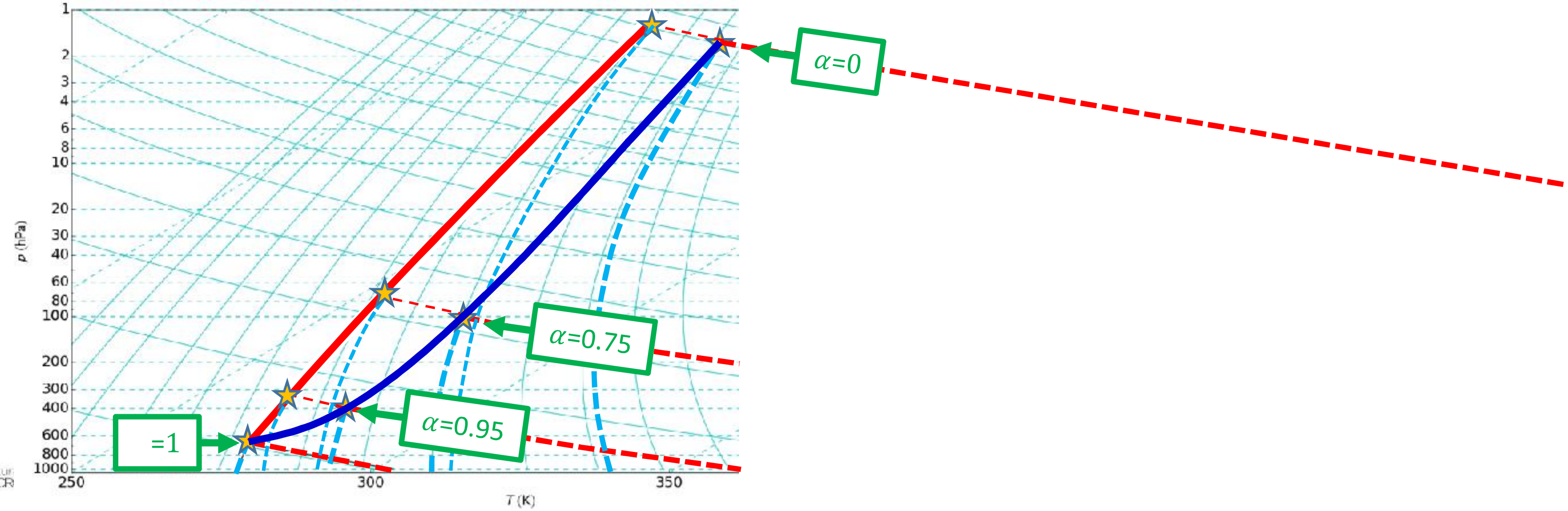
Plume thermodynamic model: *Saturation Point*

- The condensation height for each parcel is determined in the same way we find the lifting condensation level (LCL) of the environment air
- Extend lines of constant and until they meet at the LCL ☆
- Repeat for each , pair, to produce a Saturation Point (SP) curve



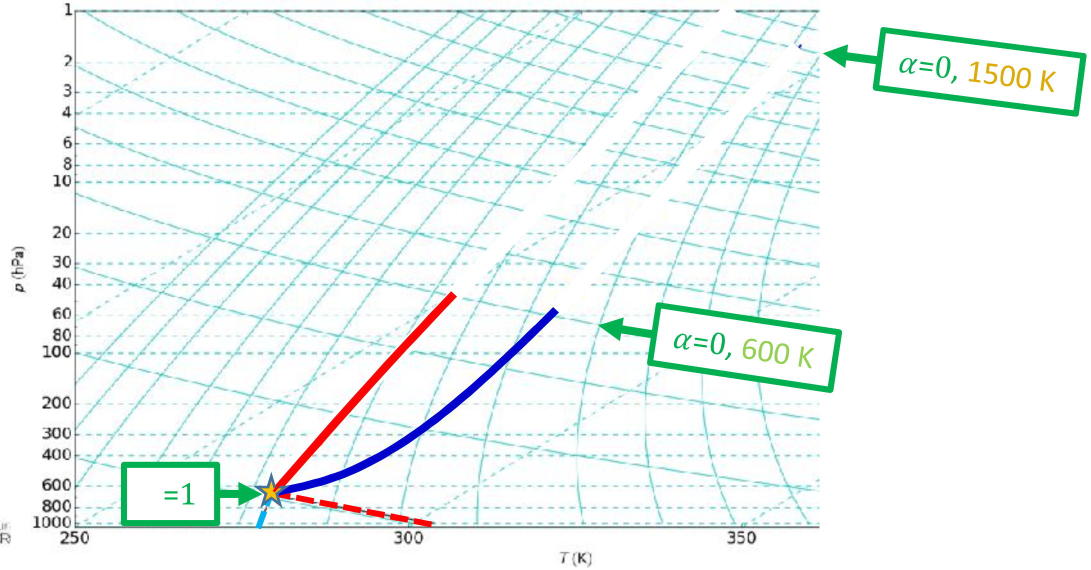
Plume thermodynamic model: *Saturation Point*

- This example assumes:
  - ➢ Combustion gases are released at 1500 K (very hot fire)
  - ➢ Fuel is very moist
- Hot fire with very dry fuel → Steeper SP curve, slightly higher condensation



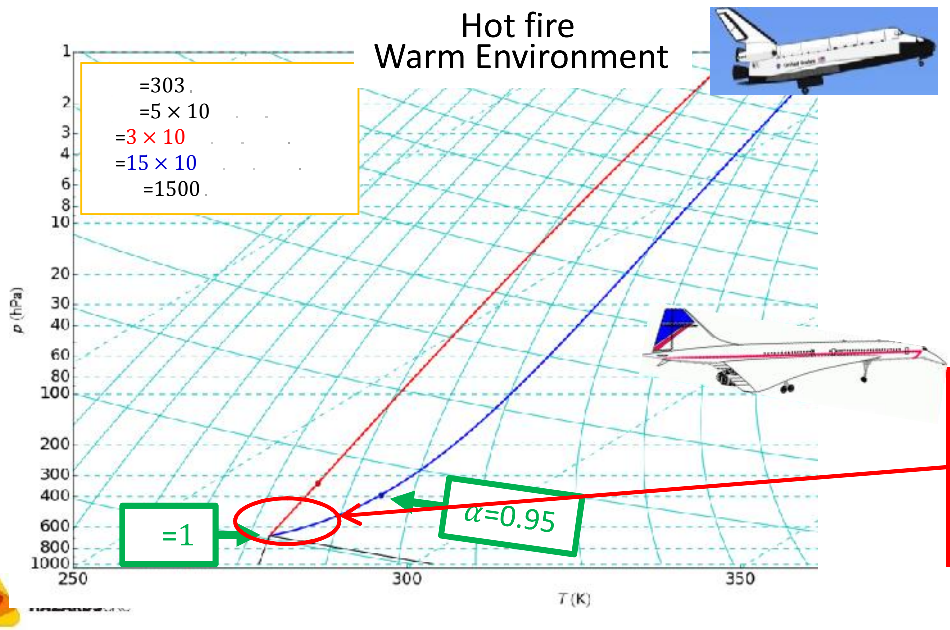
Plume thermodynamic model: *Saturation Point*

- How sensitive are the SP curves to the prescribed combustion gas Temperature?
  - Combustion gases released at 600 K (cool fire)
  - SP curves are *shorter*, but no change in shape
  - Very useful result: SP curves in the lower troposphere are independent of fire T



Plume thermodynamic model: *Saturation Point*

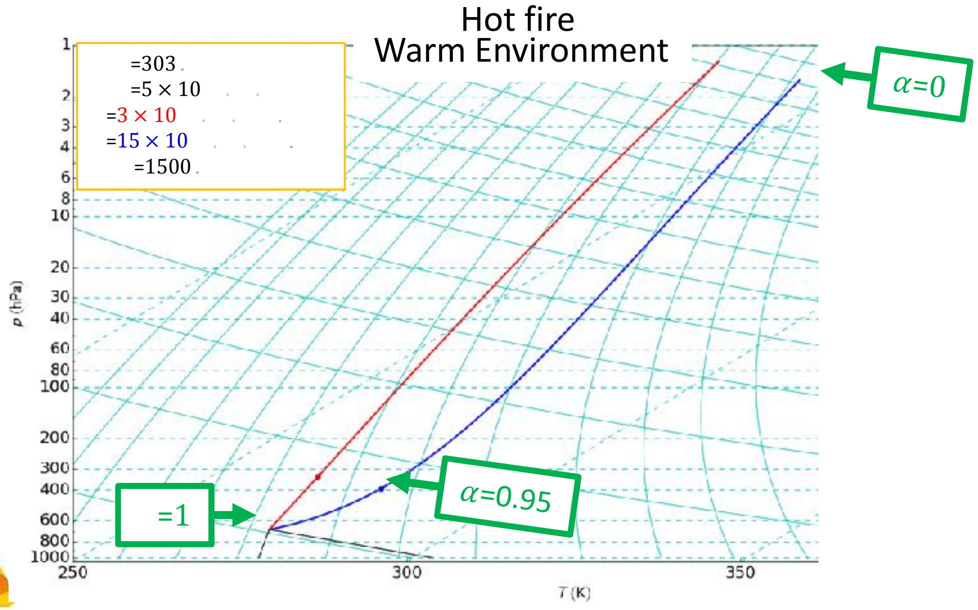
- At what height would an undiluted parcel (= 0) condense?
- Hot fire: ~40 km. Cool fire: ~20 km.
- Hot fire, 95 % dilution: condensation ~7 km.

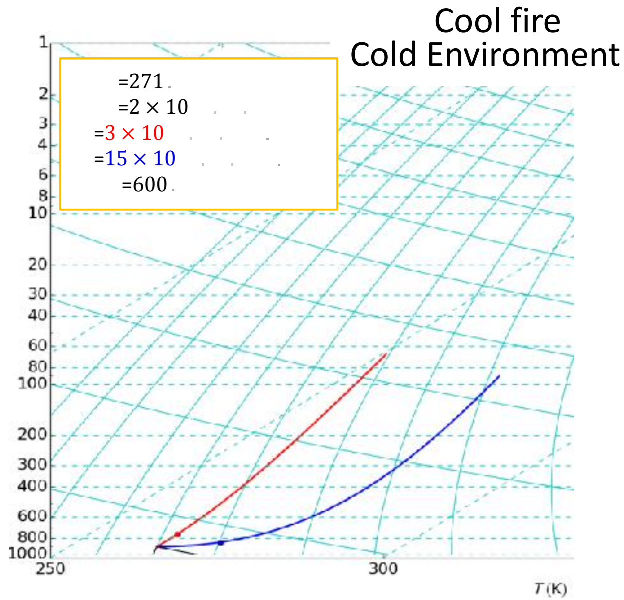


Q: How much "*less diluted*" does a realistic condensing plume element need to be?
A: *Not much less than 100%*

Plume thermodynamic model: *Saturation Point*

- How do the SP curves vary in different environments, different fires?
- Cooler fire: shorter SP curves
  - *Fire temperature only affects the SP curve length (not important for pyroCb prediction).*
- Colder and drier environment: flatter SP curves
  - *Can be important for pyroCb prediction*

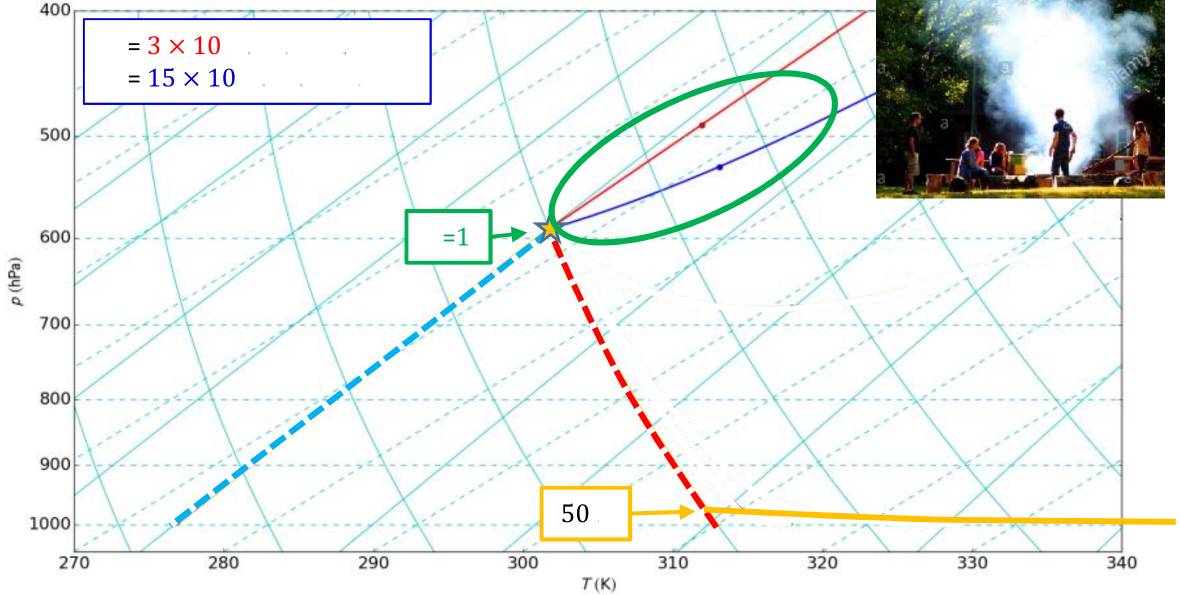




Plume thermodynamic model: *PyroCb prediction*

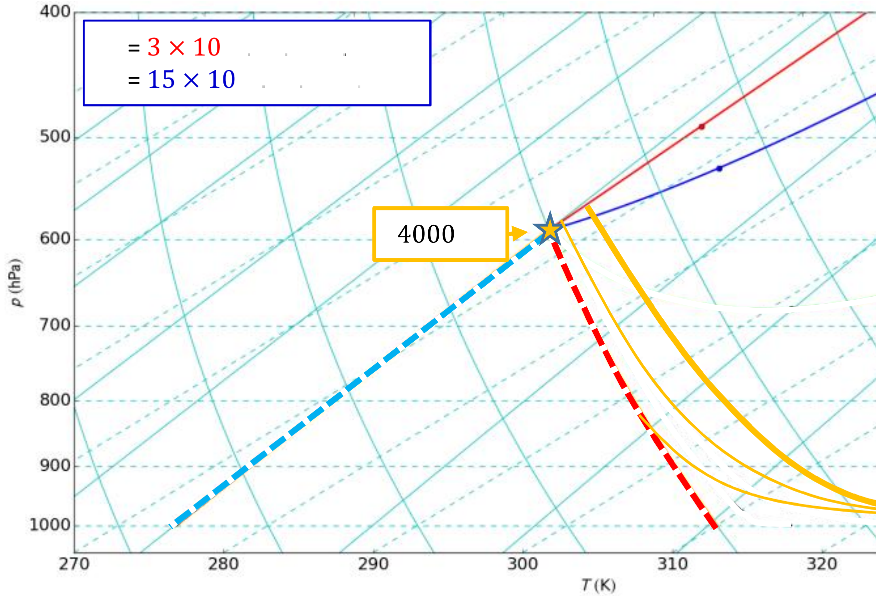
- What can we learn from the model?
- Focus closer to the LCL (near where $\sim$1).
- How might vary with height?
- Camp fire:
- = 600 K at flame tips,

  , = at ~50 m.
- *Loses buoyancy at ~50 m*
- *No Condensation*



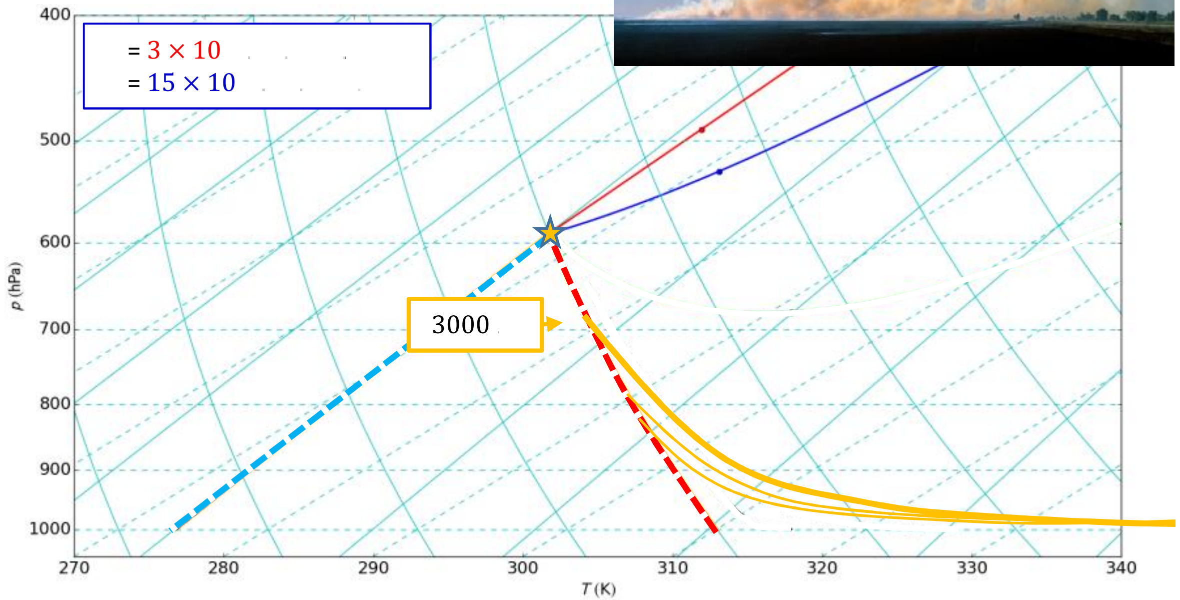
Plume thermodynamic model: *PyroCb prediction*

- What can we learn from the model?
- Focus closer to the LCL (condensation occurs where ~ 1).
- How might vary with height?
- Wild fire, light winds:
- = 600 K at flame tips,
  , = $+4$ at ~4000 m
- *Condensation at* ~4000 m
  between SP curves
- Elements near the plume edge
  might not condense.
- A broad spectrum of traces
  is likely



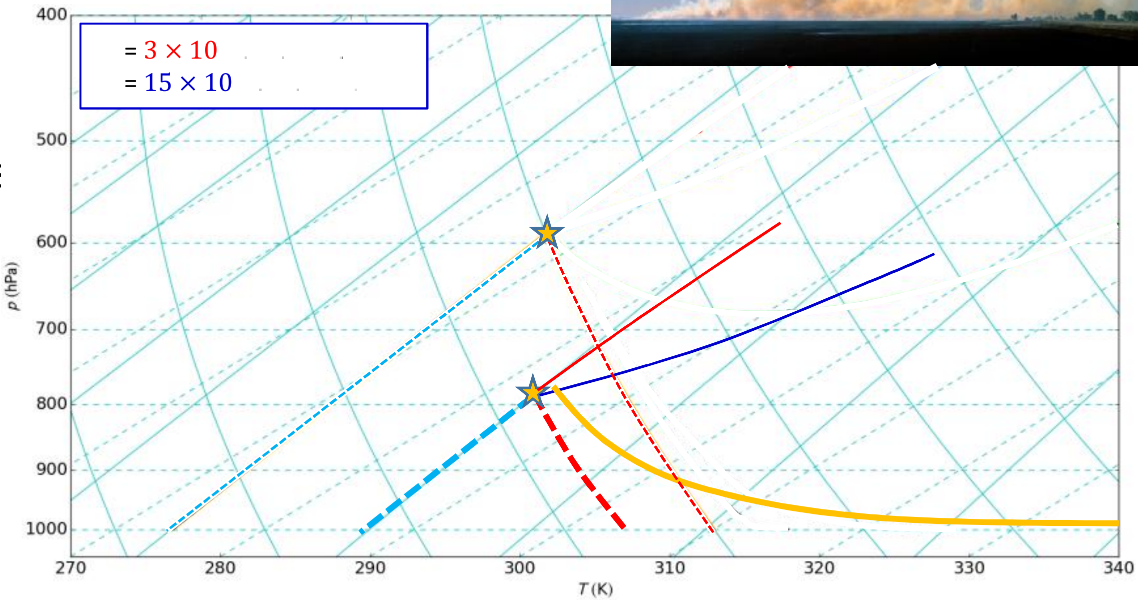
Plume thermodynamic model: *PyroCb prediction*

- What can we learn from the model?
- Focus closer to the LCL (condensation occurs where ~1)
- How might vary with height?
- Wild fire, strong winds:
- = 600 K at flame tips,
  , = at ~3000 m
- *No Condensation*
- A broad spectrum of traces is likely



Plume thermodynamic model: *PyroCb prediction*

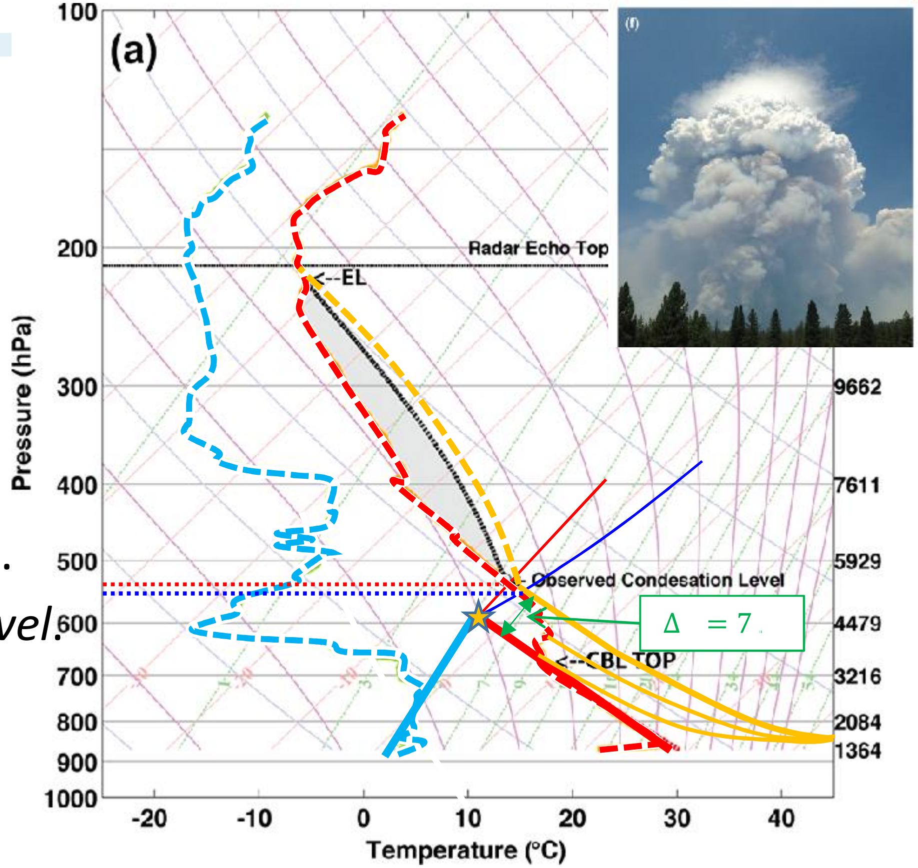
- What can we learn from the model?
- Focus closer to the LCL (condensation occurs where ∼1)
- How might vary with height?
- Wild fire, strong winds:
- In a cooler, moister environment (lower LCL) this plume condenses



Plume thermodynamic model: *PyroCb prediction*

- How can the model be applied to a real fire?
- Env Temperature (red dashed line)
- Env Moisture (blue dashed line)
- Find the mixed layer LCL
- Add SP curves
- Lowest possible condensation height:

  Intersection of SP curve and Env Temperature.
- Slightly lower than *Observed Condensation Level*.
- Condensing plume elements need to be > 7 K warmer than , (Δ = −)
- FireCAPE estimates possible



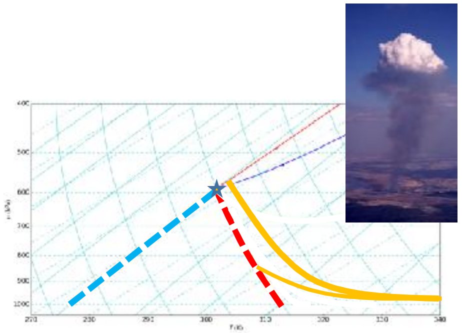
Lareau and Clements (2016) Fig. 9a

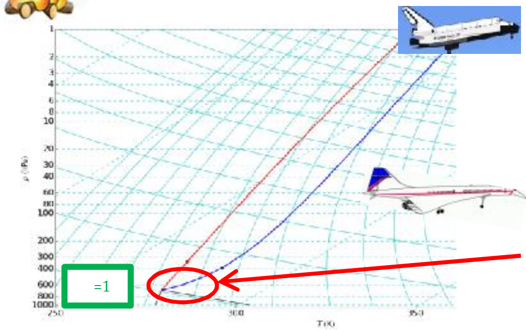
Summary

- Plumes entrain → become diluted → buoyancy reduces
  Some plume elements become ~100% diluted (lose buoyancy)
  Others rise and condense somewhat less than 100% diluted
- *How much less?*

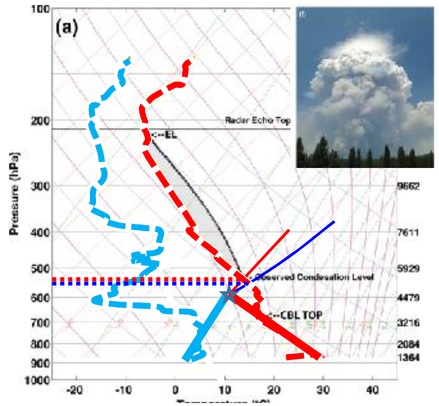
  Not much less than 100% diluted

- Plume model introduces SP curves to thermodynamic diagrams
  Plume element loses buoyancy
  Plume element condenses





- Add SP curves to real thermo diagrams for pyroCb prediction
  Identify: Lowest condensation level
  PyroCu/Cb formation inhibition (magnitude of Δ)



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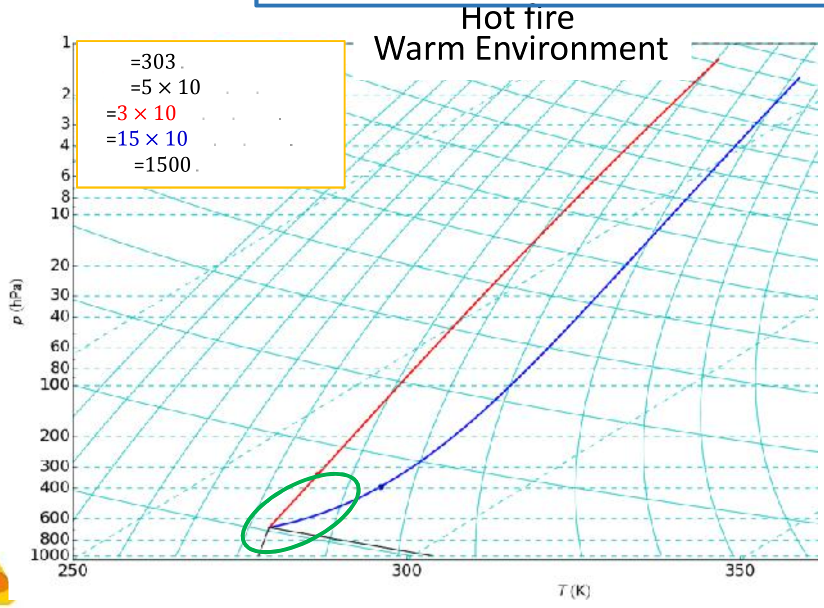
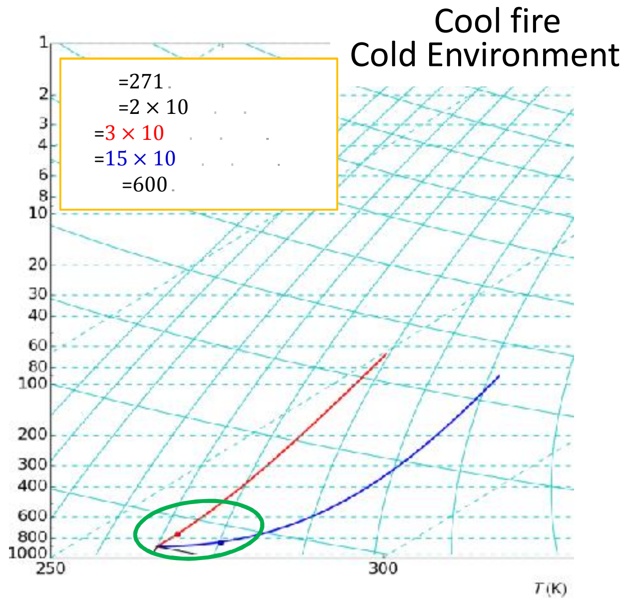
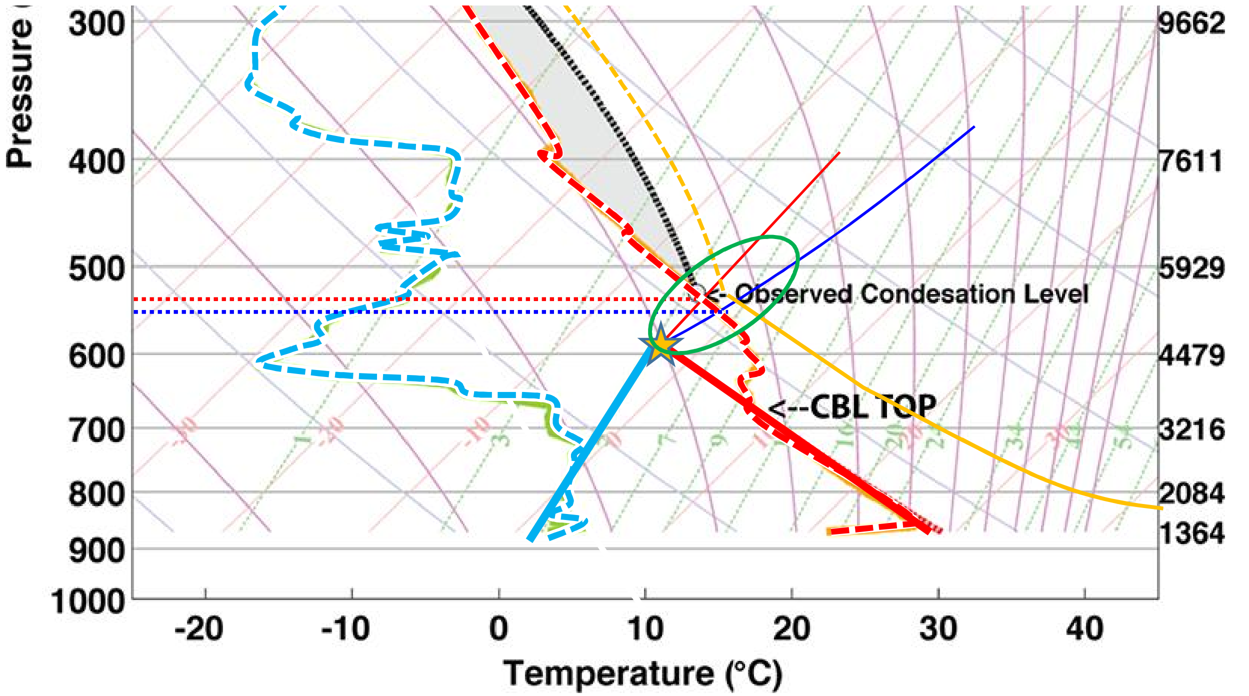




Plume thermodynamic model: *PyroCb prediction*

- Different SP curve gradients due to different environment conditions can impact the condensation level height



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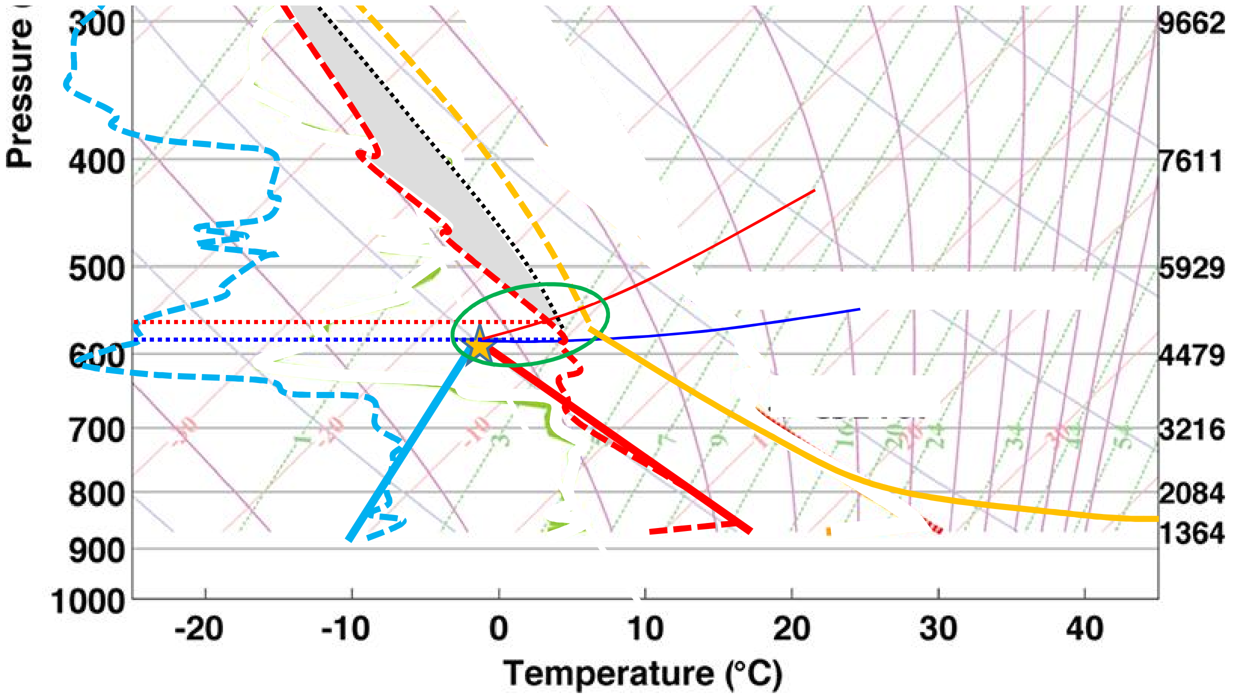


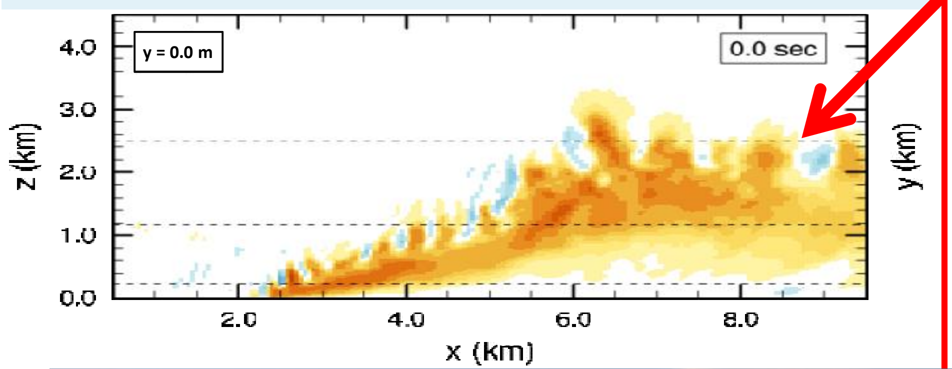
Plume dynamics – 15 m s^{-1} wind

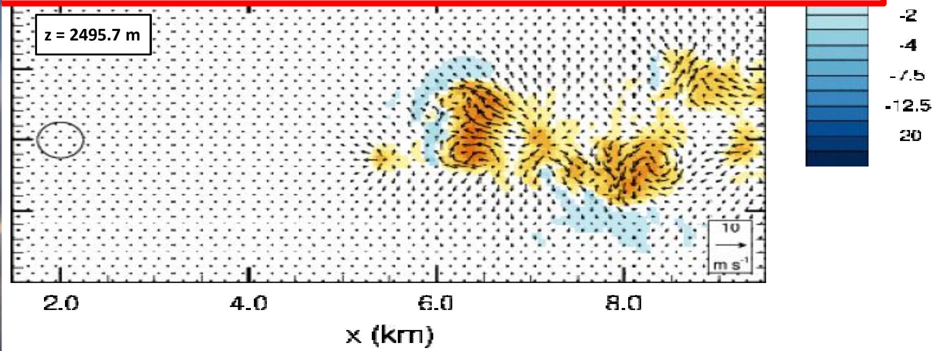
Imagine if the LCL was about 2500 m above the surface

We would expect condensation to occur some distance downstream from the fire source

Condensation might be expected wherever there is yellow shading (and beyond) in the panel below

Ascent area is *much* larger than the fire source





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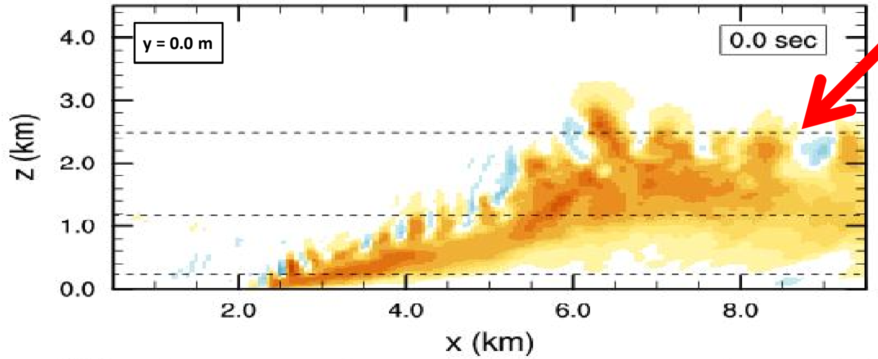

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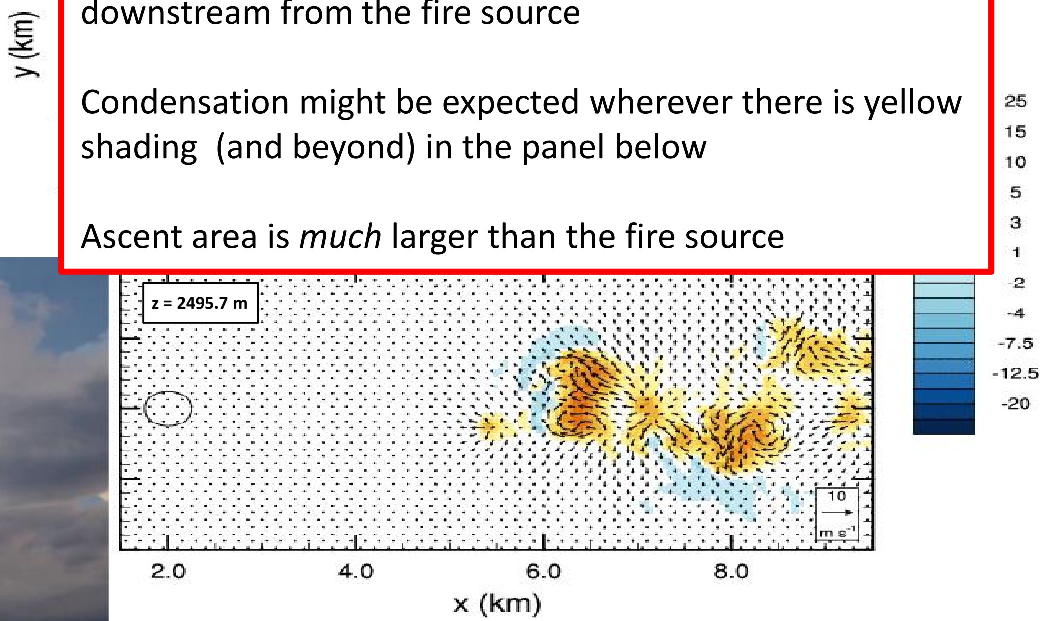

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Entrainment in a thermal

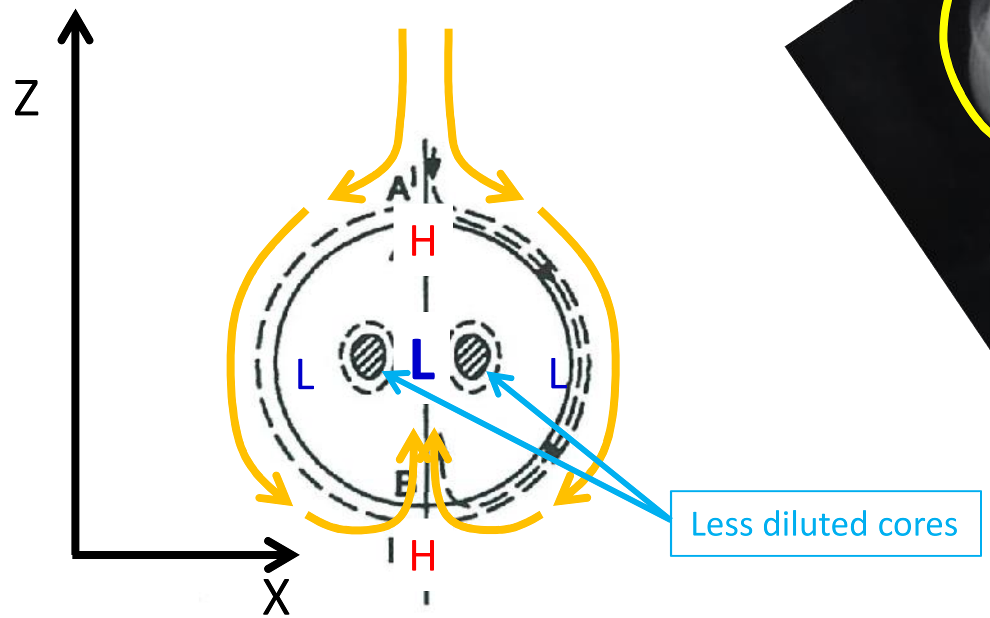
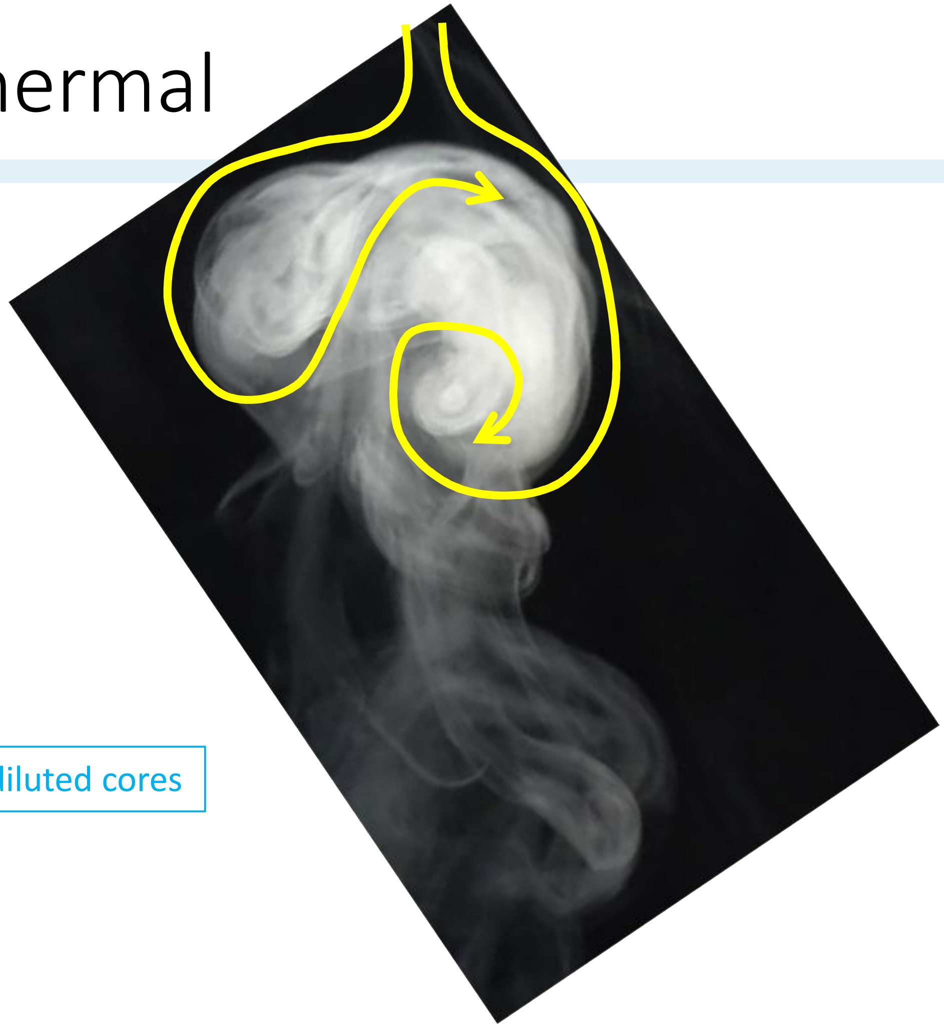


Figure 5. Entrainment into a thin-ring vortex in which the core thickness diffusively in Δt from the continuous to the dashed core and the advected fluid grows from the continuous to the dashed envelope.



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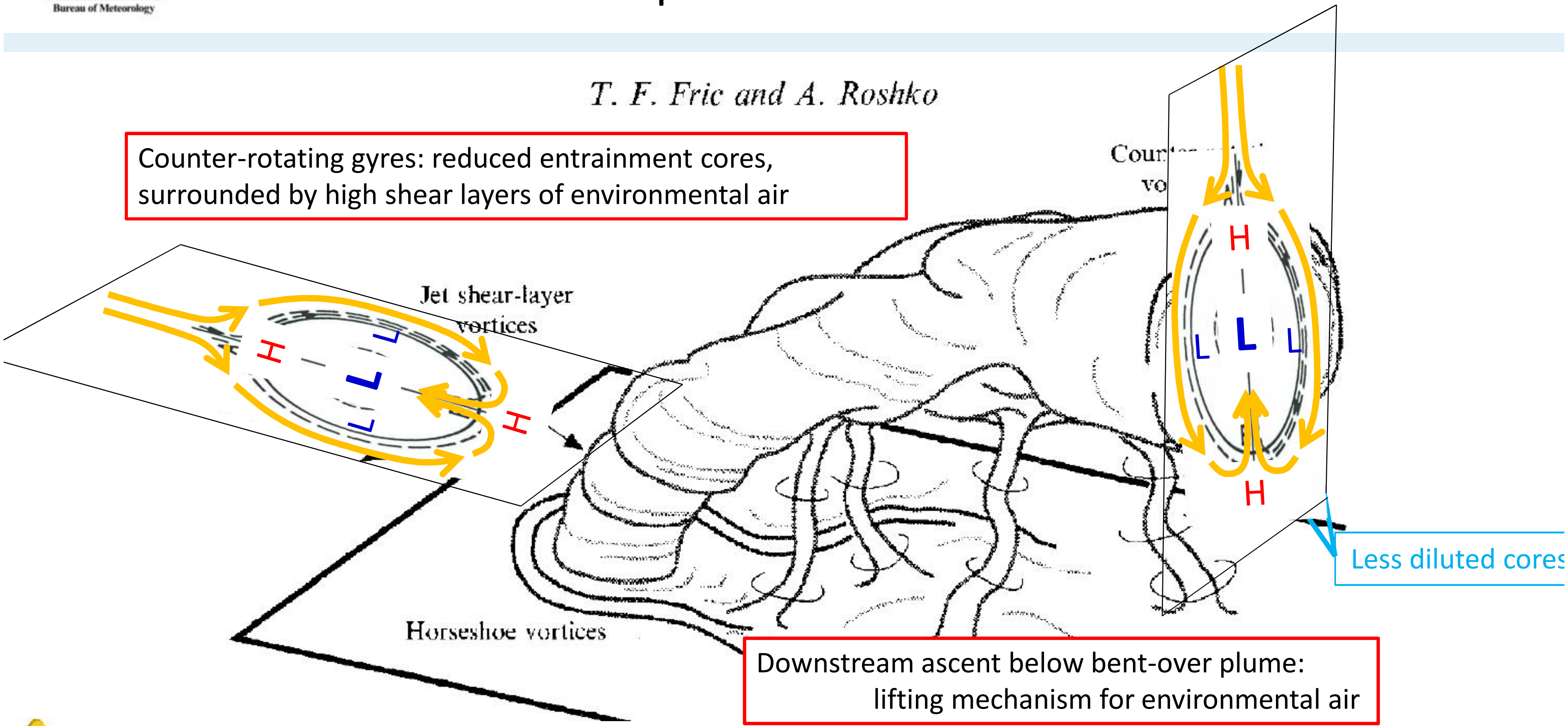
Entrainment in a plume in a cross flow



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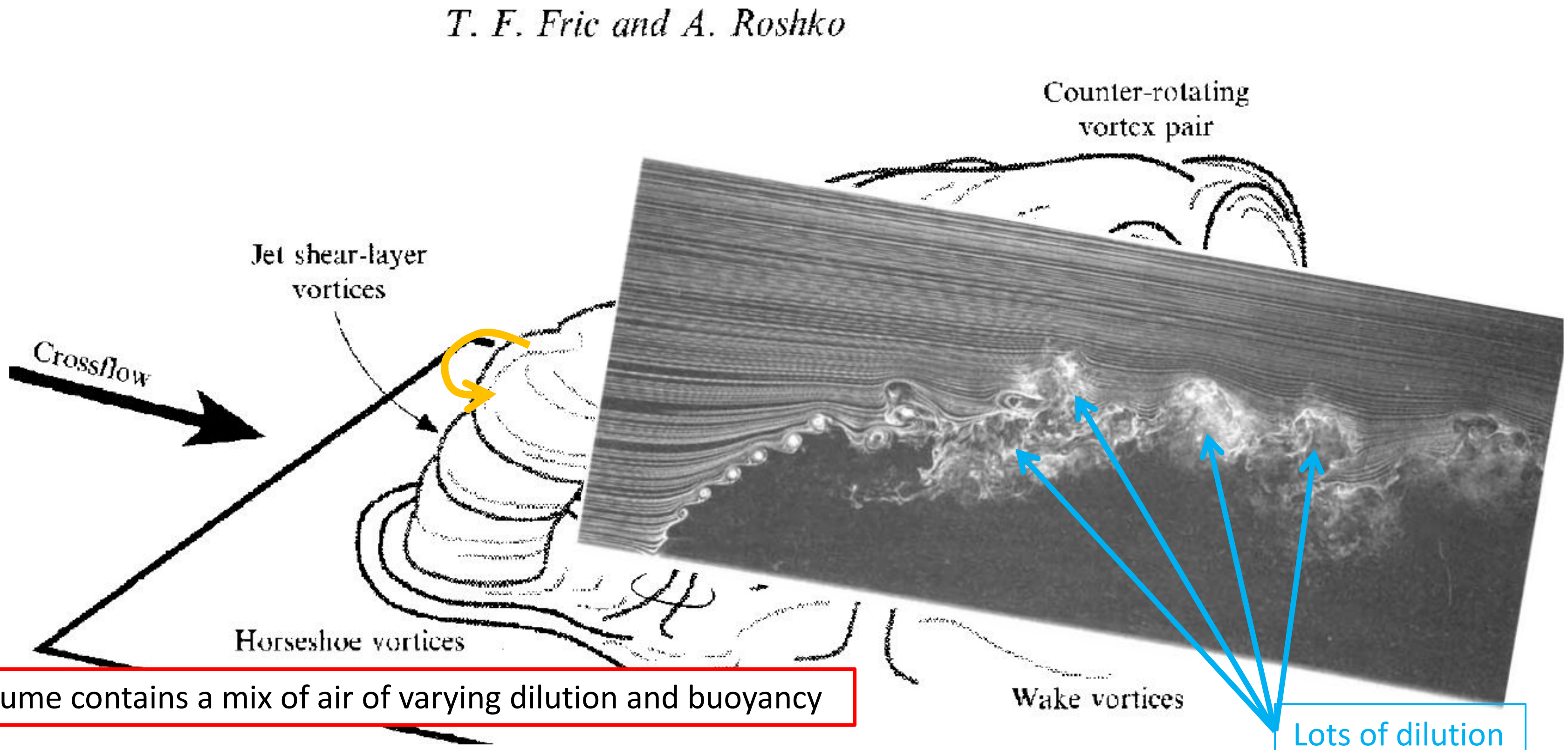


Plume contains a mix of air of varying dilution and buoyancy

Plume thermodynamic model: *Fire*

- The fire releases combustion gases, with potential temperature and specific humidity: and

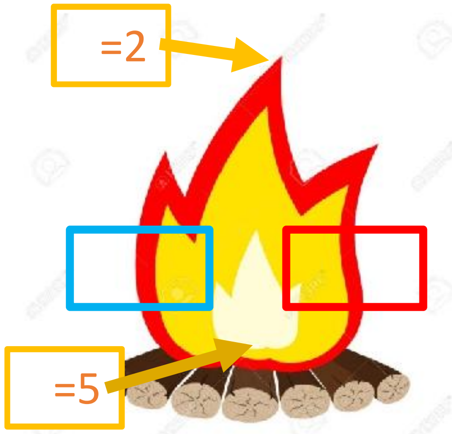
  which are completely unknown.
- Forest fire temperature measurements range from 1500 K at the fire base to 600 K at the flame tips.
- Expressed as a multiple of :

  $$\boxed{\quad = \quad}$$
- Heat released by the fire:

  $$\Delta \quad = (\quad - 1)$$
- Ratio of moisture to heat released by the fire:

  $$\Delta \quad = \quad \Delta$$
- Combustion: 6:1 air to fuel ratio thus contribution to :

  $$\boxed{\quad = \Delta \quad + 0.86}$$



Plume thermodynamic model: *Plume*

- The plume is made up of a mix of ***fire*** and ***environment*** heat and moisture specified by a dilution factor

$$= \quad + (1 - \quad)$$
$$= \quad + (1 - \quad)$$

- The plume is defined by five parameters, however the fire intensity and dilution can be replaced by a single buoyancy parameter:

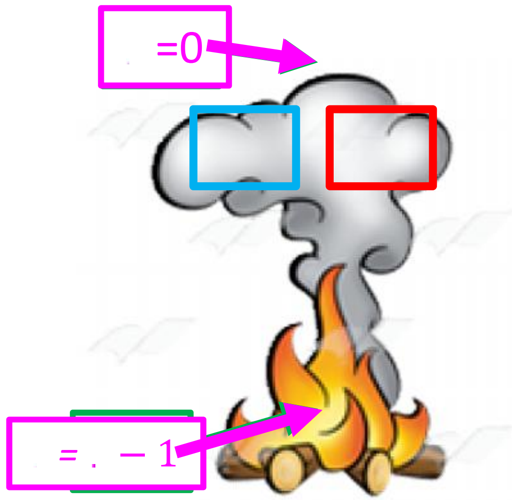
$$= \left(\frac{\quad}{\quad} \right) = (1 - \quad)(\quad - 1)$$

Then $= (\quad + 1)$

$$= (0.86 + 0.14 \quad) \quad +$$

- Plumes condense for ~ 1 hence:

$$\cong \quad +$$



Plume thermodynamic model: *Plume* (cont.)

$$= (\quad + 1)$$

$$= (0.86 + 0.14 \quad) \qquad + \qquad\qquad \text{1.}$$

$$\cong \qquad + \qquad\qquad \text{2.}$$

- When the full range of is considered, Eq. 1 is used for
- For most of our plume analysis ~ 1, and Eq.2 can be used, which reduces our parameter space to four variables:

  Two environment variables and

  Two fire/plume variables and

- is unknown but expected to range from $3 \rightarrow 15 \times 10$

In theory could be determined from plume observations since

$$\cong \frac{\quad}{\quad}$$

- is influenced by fire size, intensity and atmospheric factors that impact

plume entrainment (e.g., wind, stability): **Biggest Unknown!!!**