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Plume Mechanics and Stratocumulus Convection

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1. Introduction

The FIRE marine stratocumulus IFO held in July, 1987 produced a data set that is far more comprehensive than data sets from previous stratocumulus experiments. One exciting new development was the use of the 10.6μm lidar system for cloud-top mapping that was available on the NCAR Electra. This system provided a unique look at the small scales of the turbulence in the clouds, images of the turbulent structures that are quantitatively revealed by conditional sampling (e.g., Khalsa and Greenhut, 1987).

The behavior of these updrafts and downdrafts is central to the dynamics of the stratocumulus-topped marine boundary layer. FIRE's objectives of understanding cloud dynamics and how they affect the cloud optical depth — which, in turn, is the crucial factor in determining the clouds' albedo — therefore require the investigation of these drafts. This poster discusses initial results from a simple model capable of simulating moist, entraining plumes that are subject to water phase changes and radiative heating and cooling. The results discussed here are limited to plumes that are not affected by condensation and evaporation but are subject to radiative heating and cooling. These results correspond, therefore, to the "dry cloud" case discussed by Lilly and Schubert (1980). The model's simplicity limits the realism of the results — the plumes are assumed not to interact, for example — but the role of radiative processes in influencing the plume dynamics is clear. Also revealed is the role the plumes play in maintaining the cloud-top inversion.

This poster abstract presents the model equations and methodology used, and discusses qualitative results.

2. Model

The plume model discussed here is based on the work of Telford (1966, 1972) and is basically a simplification of the model discussed by Chai and Telford (1983). The main simplification in the present work concerns the neglect of downdrafts that are explicitly associated with the modeled updrafts. In the Telford (1972) model of a field of convective plumes, updrafts are surrounded by downward (compensating) flow; here, drafts are completely independent.

In the complete model, the physical processes of the drafts include adiabatic expansion, lateral entrainment, buoyant acceleration (due to virtual temperature perturbations induced by boundary conditions, condensation and radiative heating) and parameterized friction. The heating from condensation is the most non-intuitive aspect of the model equations, and this is discussed in detail by Chai (1978) and more briefly in Chai and Telford (1983). Here, it is ignored.

Dependent variables in the model are the plume radius r, vertical velocity w, rms turbulent velocity i, total density ρ, and water content ρ_w. Because condensation is neglected here, the equation for the conservation of water is not needed, and therefore the four equations represent conservation of volume, mass, (vertical) momentum and turbulence kinetic energy. Each plume is assumed to be in a steady state, and therefore these dependent variables are functions of height z. Boundary conditions are applied at the surface or at the inversion, for updrafts and downdrafts, respectively. The plumes are embedded in an environment specified by mean temperature profiles $\overline{T}(z)$ which, hydrostatically, determines the pressure distribution $p(z)$; pressure perturbations associated with the plumes are ignored. The system of equations for the dependent variables is first order and highly non-linear; it is solved numerically using a Runge-Kutta procedure.

The equations can be written as

$$\mathbf{L}(\Gamma)\frac{d\Gamma}{dz} = \mathbf{F}(\Gamma)\,, \qquad (1)$$

where

$$\Gamma(z) \equiv \begin{bmatrix} r(z) \\ w(z) \\ \rho(z) \\ i^2(z) \end{bmatrix}\,. \qquad (2)$$

Assuming a quiescent (non-turbulent) environment and using $\overline{T}(z)$ and $p(z)$ to calculate an environmental density profile $\overline{\rho}(z)$ allows the right-hand side of (1) and the nonlinear operator $\mathbf{L}$ to be written as

$$\mathbf{F} \equiv \begin{bmatrix} 2\lambda i + (1-\kappa)wr^2p^{-1}dp/dz \\ 2\lambda i\overline{\rho w} + rg(\overline{\rho}-\rho) - rw^2\dot{\rho} \\ 2\lambda i\overline{\rho} + r\dot{\rho} \\ 2\lambda i\overline{\rho}\left[(w-\overline{w})^2+i^2\right] - ri^2\dot{\rho} - A/2\,\rho i^3 \end{bmatrix}; \qquad (3)$$

$$\mathbf{L} \equiv \begin{bmatrix} 2w & r & 0 & 0 \\ 2w^2\rho & 2rw\rho & rw^2 & 0 \\ 2w\rho & r\rho & rw & 0 \\ 2w\rho i^2 & r\rho i^2 & r^2wi^2 & r^2w\rho \end{bmatrix}. \qquad (4)$$

The environmental vertical velocity $\overline{w}$ can be deduced from the continuity equation, provided the area of the affected environment is specified. Here, it is assumed to be so much larger that the plume that $\overline{w} \to 0$. The parameter λ is an entrainment coefficient (~0.08, according to Telford, 1966), and A is a dissipation coefficient, taken to be equal to unity. κ is the ratio of the gas constant to the specific heat at constant pressure. The non-adiabatic sources of mass are denoted by $\dot{\rho}$.

In principle, the solution to (1) is given simply by

$$\Gamma(z) = \int_{z_0}^{z} \mathbf{L}^{-1}\mathbf{F}\,dz; \qquad (5)$$

since $|\mathbf{L}| = 2r^4w^4\rho$, the problem is well-posed except for plumes of vanishing radius or density, or plumes that stop. Accordingly, given an environmental temperature profile and boundary conditions, the system (1) can be integrated until the vertical velocity vanishes, at which point, to cite an example in physical terms, an updraft either disappears or becomes a downdraft.

In practice, integration of (1) must be accomplished numerically because of the nonlinearity of $\mathbf{F}$ and $\mathbf{L}$. This is simplified by defining a *density perturbation* (which is also a temperature perturbation, due to the hydrostatic assumption and neglect of pressure perturbations within the plume)

$$\delta \equiv (\overline{\rho}/\rho - 1) = (T/\overline{T} - 1), \qquad (6)$$

where T is the plume temperature. Defining an entrainment (inverse) length scale $\Lambda \equiv \frac{2\lambda i}{rw}(1+\delta)$; a static stability

$S \equiv (g/c_p + d\overline{T}/dz)/\overline{T}$; and the parameters $\beta \equiv g\delta/w^2$ and $\sigma \equiv -(1-\kappa)p^{-1}dp/dz$, where g and c_p are gravitational acceleration and the specific heat of air at constant pressure, respectively; and the appropriate heating rate Q (this is discussed further below), the equations take the form

$$\frac{d(r^2)}{dz} = \left[\Lambda\frac{2+\delta}{1+\delta} + \sigma - \beta\right] r^2 \; ; \tag{7a}$$

$$\frac{dw}{dz} = \left[-\Lambda + \beta\right] w \; ; \tag{7b}$$

$$\frac{d\delta}{dz} = -\Lambda\delta - (S - Q/w)(1 + \delta) \; ; \tag{7c}$$

$$\frac{d(i^2)}{dz} = -\left[\Lambda(1-\frac{w^2}{i^2}) + \frac{A}{2}\,\frac{i}{rw}\right] i^2 \, . \tag{7d}$$

The parameter σ acts as an adiabatic expansion term, and β represents a sort of Bernoulli effect, through which accelerating plumes become smaller. The heating Q is related to the radiative flux divergence by

$$Q \equiv -\frac{1}{\overline{\rho} c_p \overline{T}} \frac{dF_{rad}}{dz}. \tag{8}$$

In deriving (7c), it has been assumed that the radiative heating is horizontally homogeneous, a reasonable first-orcer approximation for stratocumulus clouds. In the case of isolated cumulus, this is clearly invalid, and future work with stratocumulus convection will also use differential heating rates. It is important to stress that radiative heating has a distinct influence on the plume's perturbation temperature (and therefore its dynamics, through the coupled system) *even though the heating rates are assumed to be horizontally homogeneous*. The results discussed in this poster use radiative fluxes calculated with the parameterizations developed by Hanson and Derr (1987). Various assumptions about the (implicit) cloud liquid water and solar zenith are used to investigate the sensitivity of plumes to the heating.

3. Discussion

The main purpose of this abstract is to present the equations of the plume model and briefly to discuss the model's behavior in qualitative terms. Numerical solutions will be presented on the poster itself. Even without integrating the set of equations (7), however, it is possible to infer several aspects of the model's behavior from the governing equations.

Note, first, that, with the exception of the term $-(S-Q/w)$ on the right-hand-side of (7c), the equations are homogenous and, further, take the general form

$$\frac{d\ln\hat{\Gamma}}{dz} = \hat{F}(\hat{\Gamma}) \, , \tag{9a}$$

where $\hat{\Gamma}$ and $\hat{F}$ are analogous to Γ and F in (2) and (3). This suggests, in cases of neutral stability with no heating, that small departures from boundary conditions can by deduced analytically with

$$\hat{\Gamma}(z) = \hat{\Gamma}_0 \exp\left[-\hat{F}_0(z-z_0)\right] \, , \tag{9b}$$

where $(\;)_0$ is a boundary value. For realistic plumes, $|\delta| \ll 1$ and $|w| < i$, and w and δ can take both positive and negative values. The behavior of the solutions (9b) can then be classified entirely according to the energetics of the plume in question. Energy-producing plumes — that is, *direct circulations* — behave identically, be they (warm) updrafts or (cold) downdrafts. Similarly, energy consuming plumes (*indirect circulations*) exhibit the same symmetry.

The behavior of a warm updraft that encounters an abrupt increase in stability is also apparent from Eqs. (7). The term $-S(1+\delta)$ on the right-hand-side of (7c) will immediately cause the temperature perturbation to decrease, eventually to become negative. When this happens, β changes sign and the plume decelerates and widens [see (7a) and (7b)]. The point at which $w \to 0$ signals the termination of the integration.

Note also that the effect of radiative cooling on updrafts will be exacerbated tremendously by this behavior within an inversion. As the plume slows, the term Q/w in (7c) will become disproportionately large and will apply positive feedback to the the deceleration. The role of radiative cooling in decelerating updrafts in the presence of clouds may thus explain the relatively sharper inversion structure observed atop the cloud-topped boundary layer when compared to the un-cloudy boundary layer. In the latter case, updrafts are slowed by lack of positive buoyancy, and this causes them to spread out and stop. In the cloud-topped case, the radiative cooling acts as a braking mechanism for the updrafts, stopping them nearer the inversion base. The net effect of this on many plumes is a thinner inversion layer.

Finally, it can be seen that, in cool downdrafts, this behavior works in the opposite sense, to accelerate the downdraft, but with *negative* feedback. This suggests that, near the cloud top, at least, the role of energetic downdrafts should be much stronger in stratocumulus than in the clear boundary layer. It also suggests that solar heating will affect the different drafts in quite different fashions. It is this assymetry of updrafts and downdrafts of the same sense of circulation (i.e., both direct) in the presence of radiative heating that causes the dynamics of stratocumulus convection to differ so dramatically from the clear boundary layer heated from below. Further discussion, with quantitative results of the cases discussed here, will be included on the poster.

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