Diagnosing tracer transport in convective penetration of a stably stratified layer

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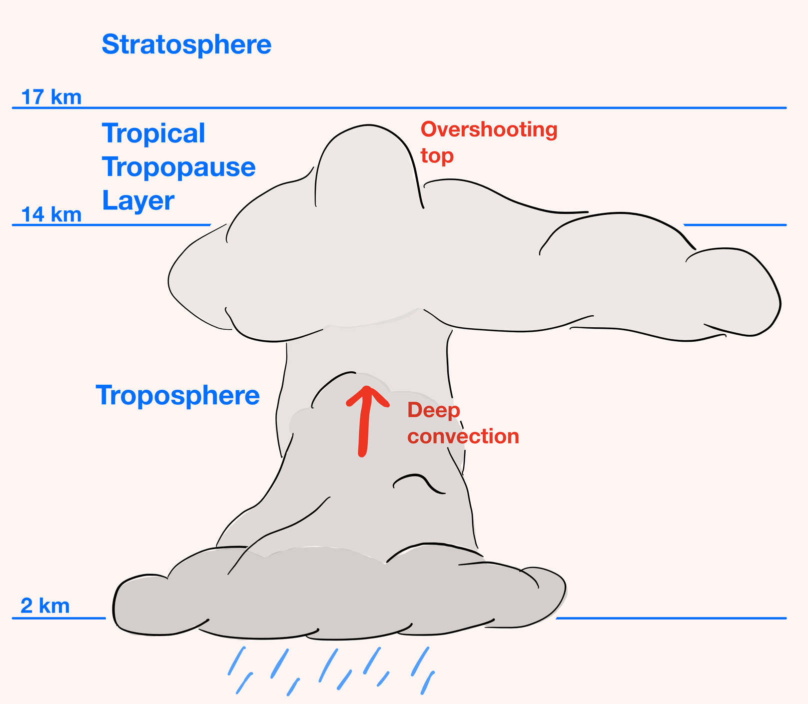
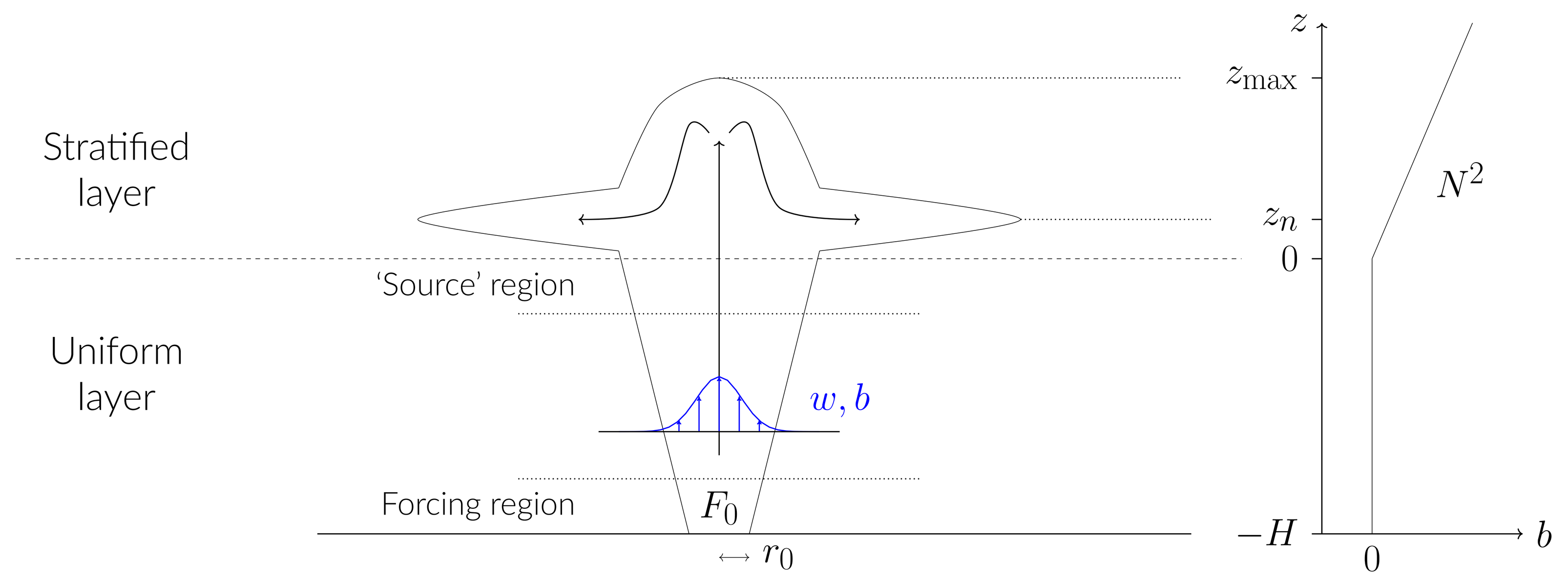
Background

We consider the problem of a buoyant plume, generated in an unstratified region, impinging on a region with strong stable stratification. This is a simple representation of the tropical upper troposphere and lower stratosphere, where convective plumes generated by strong thunderstorm complexes can penetrate into the lower stratosphere. Stratospheric composition is largely set by cross-tropopause transport in the tropics as tropospheric air predominantly enters the stratosphere in the tropics (Fueglistaler et al., 2009). Detailed numerical simulation of entire thunderstorm complexes is computationally expensive (Dauhut et al., 2015, 2018); the working hypothesis here is that it is useful to study the idealised setup of penetration of a single artificially generated plume into a stably stratified layer.



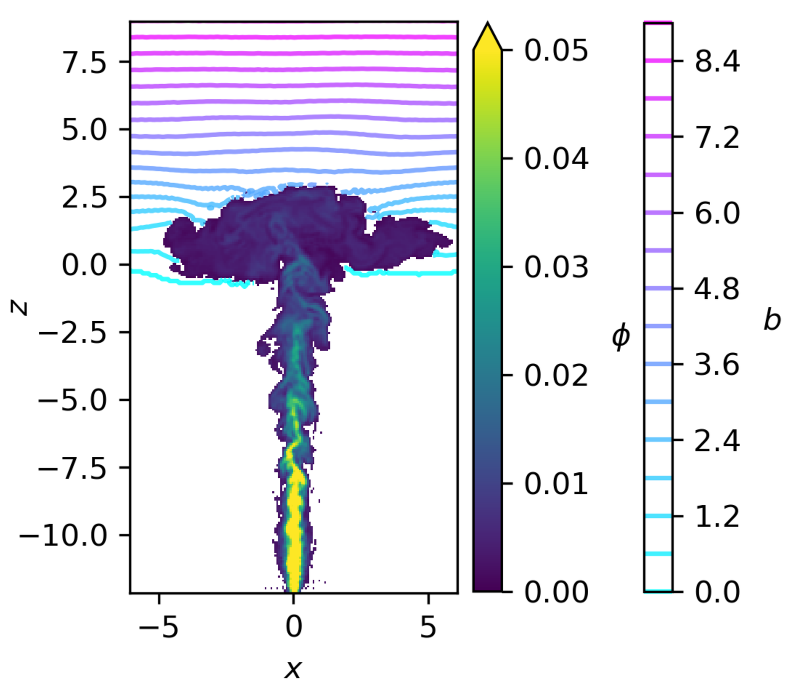
Idealised numerical simulations

We perform large eddy simulations of the incompressible Navier-Stokes equations in a doubly periodic domain. A plume with a fixed integral source buoyancy flux F_0 and source radius r_0 is generated by relaxing the buoyancy towards the analytic buoyancy profile of a forced plume in a thin forcing region at the bottom of a uniform layer of depth H. The plume carries a passive tracer with concentration $\phi(\boldsymbol{x}, t)$ and the buoyancy field is $b(\boldsymbol{x}, t)$. Turbulence is initiated with a random 5% perturbation of all velocity components in a thin layer above the forcing region. A linear stably stratified layer with fixed buoyancy frequency N lies above the uniform layer. Latent heating and other complicating factors are neglected. All quantities shown are non-dimensionalised using F_0 and N. The characteristic lengthscale is $F_0^{1/4}N^{-3/4}$ and the characteristic timescale is N^{-1}.



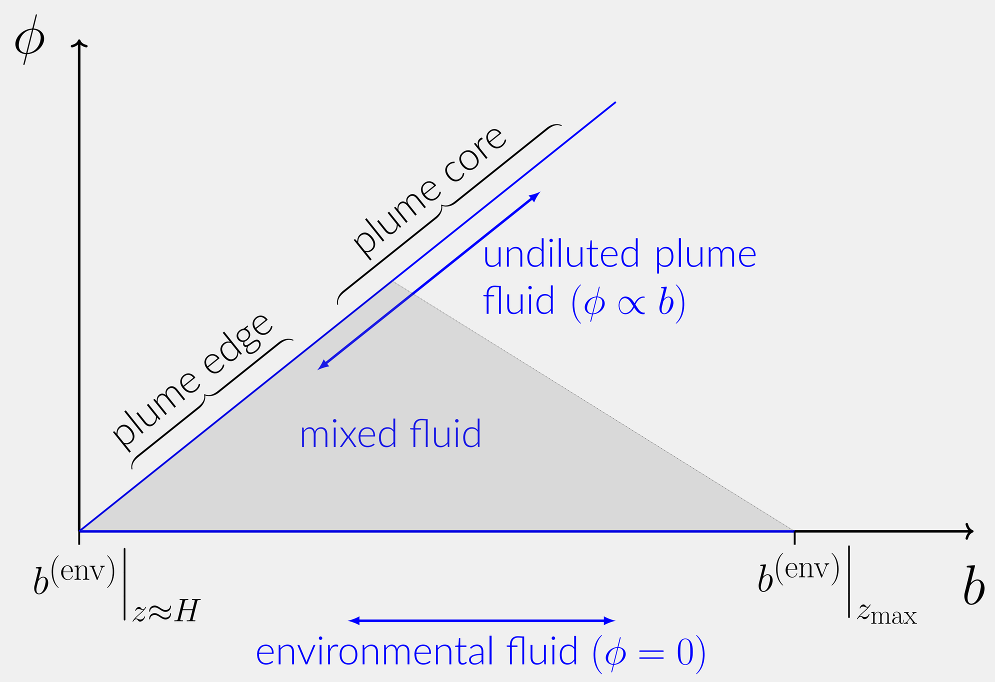
Plume dynamics

The plume becomes turbulent as it rises through the uniform layer and penetrates the stably stratified layer. As the plume cap encounters more buoyant fluid, it decelerates and overturns at $z_{\max}$, subsides to the equilibrium height z_n, and forms a radially-spreading intrusion. Irreversible transport of tracer to a given buoyancy surface depends on the environmental buoyancy accessed via mixing during the transient rise of plume fluid deep into the stratified layer. All plots and data shown are from a simulation with $N = 1\,\mathrm{s}^{-1}$ and $F_0 = 8 \times 10^{-8}\,\mathrm{m}^4\mathrm{s}^{-3}$.



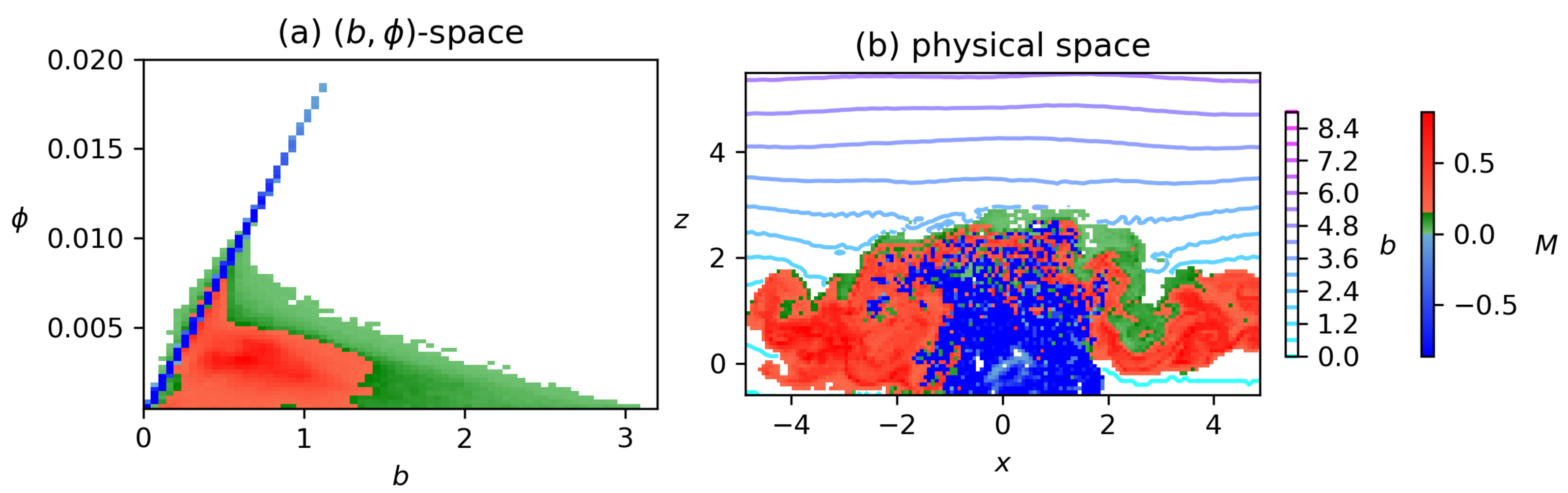
Buoyancy-tracer volume distribution

To diagnose tracer transport, we consider the joint distribution $W(b, \phi; t)$ of volume in (b, ϕ)-space, where W is defined such that $W(b', \phi'; t)\,\mathrm{d}b\,\mathrm{d}\phi$ is the volume of fluid within the stratified layer with buoyancy between b' and $b'+\mathrm{d}b$ and tracer concentration between ϕ' and $\phi'+\mathrm{d}\phi$. The distribution W is independent of advection within the stratified layer; only fluid entering the domain and diffusive mixing within the domain result in changes to W. Moreover, the mixture of a set of fluid parcels lies within the convex envelope of those parcels. It is therefore possible to diagnose the mixing process in convective penetration by identifying regions that mix in (b, ϕ)-space and assessing volume averages of mixing diagnostics within the corresponding regions of physical space.



Undiluted plume fluid that enters the stratified layer has a compact distribution along a line in (b, ϕ)-space. This occurs since turbulent mixing & entrainment in the rising plume gives b and ϕ Gaussian radial profiles with the same characteristic width, so $\phi \propto b$. At the edges of the plume, b and ϕ are small, whilst b and ϕ are maximised on the plume centreline. The environmental fluid surrounding the plume is represented by the $\phi = 0$ axis as it contains no tracer but a range of buoyancies. Mixtures of plume and environmental fluid lie within the convex envelope of the 'source' line where plume fluid enters and the $\phi = 0$ axis up to the environmental buoyancy corresponding to the maximum penetration depth. Extreme values of b and ϕ in the plume do not mix with the environment due to shielding by the intrusion until overturning near $z_{\max}$.

Input, transport and accumulation regions



The cumulative change of volume $M(b, \phi; t)$ in (b, ϕ)-space that results from mixing is calculated by subtracting the cumulative input to the volume distribution up to time t, denoted S but not shown, from W. The resulting distribution M can be partitioned into three regions. M is negative where volume is lost due to mixing, which corresponds to (b, ϕ) regions where undiluted plume fluid continuously enters the stratified layer and moves away due to mixing with the environment. M is large and increasing in time where significant volume accumulates in (b, ϕ)-space, corresponding to the intrusion, where mixtures of environmental and plume fluid homogenise and become well-mixed. M is small and non-increasing in the (green, class T) 'transport' region of (b, ϕ)-space where undiluted plume fluid first mixes with the environment and moves from the (blue, class U) 'input' region to the (red, class A) 'accumulation' region where M is large. In physical space, fluid in class T lies in the plume cap, where the plume overturns and undiluted plume fluid is first exposed to – and mixes with – the environment.

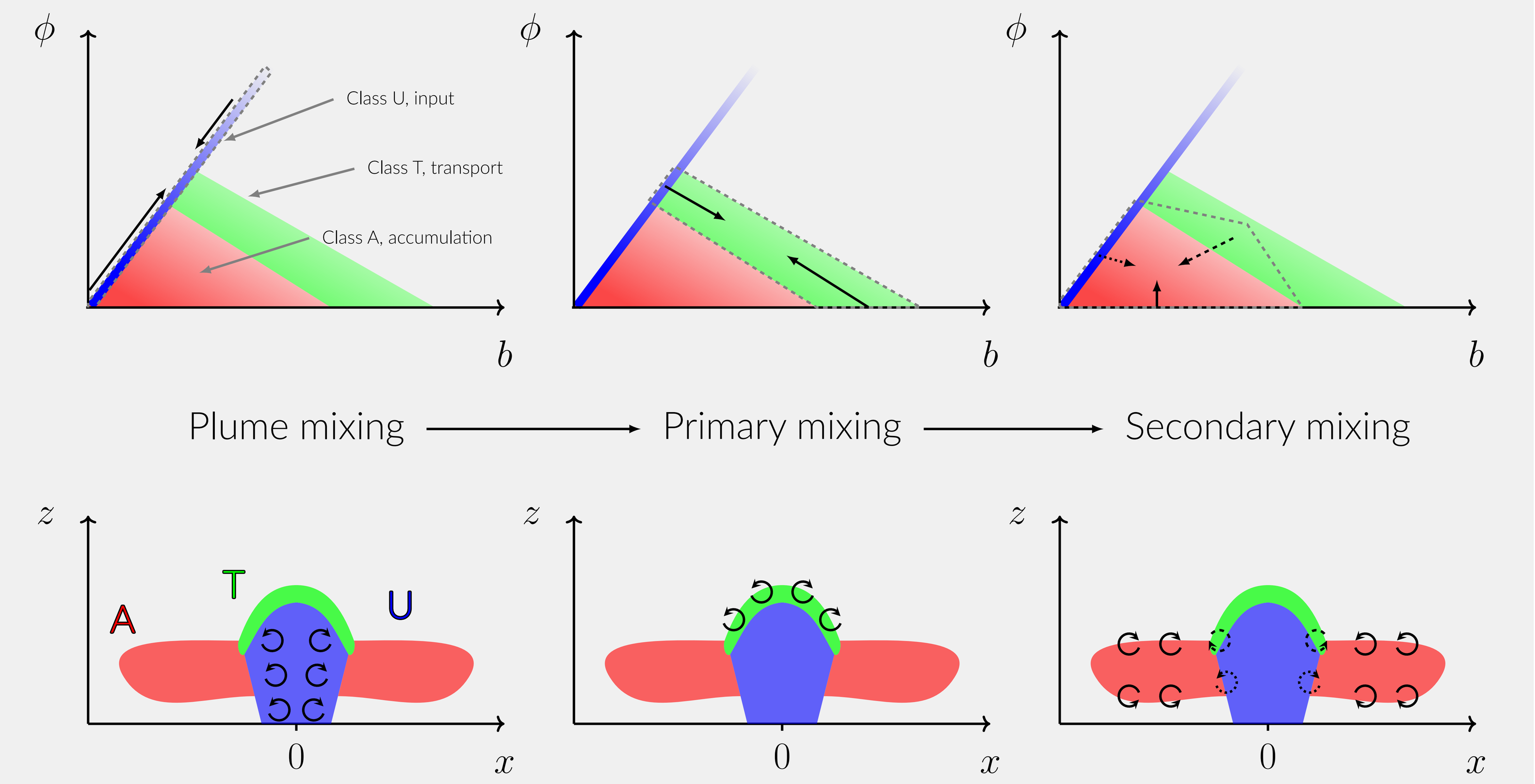
Mixing diagnostics

The partitioning of the distribution M distinguishes three classes of fluid. To examine the mixing in each class, we consider the volume average (denoted with a bar) of four mixing diagnostics: the turbulent kinetic energy dissipation rate ε, the potential energy dissipation rate χ, the local vertical buoyancy gradient $\partial_z b$, and a dimensionless activity parameter $I = (\varepsilon/\nu)/\partial_z b$ which quantifies the balance between the timescale for turbulence to develop and the local buoyancy timescale. The instantaneous mixing efficiency is calculated as $\eta = \overline{\chi}/(\overline{\chi} + \overline{\varepsilon})$, which quantifies the fraction of energy dissipated via turbulence that leads to diffusive mixing.

	Full plume	Input	Transport	Accumulation
Volume %	100	9.73	17.3	73
$\overline{I}$	33.8	186	28.3	22.7
$\langle\lvert\partial_z b\rvert\rangle$	1.05	0.603	2.09	0.859
$\overline{\varepsilon}$	0.0534	0.186	0.0966	0.0255
$\overline{\chi}$	0.0302	0.0158	0.117	0.0115
η	0.361	0.0783	0.548	0.311

Stages of mixing

The results suggest a three-stage mixing process in convective penetration. Undiluted plume fluid rises upwards, with the largest ε by an order of magnitude, and relatively weak buoyancy gradients. As fluid overturns and impinges on the surrounding environmental fluid, intense buoyancy gradients are established as indicated by a thin layer of very large χ in class T. Here, mixing is the most efficient. In the spreading intrusion, there is some continued efficient mixing as fluid homogenises and entrains environmental fluid at the bottom of the stratified layer, but buoyancy gradients and turbulent dissipation are both weak.



Summary

- We provide a framework for quantifying the mixing effect of a buoyant plume with a passive tracer as it penetrates into a stably stratified environment. In particular, we identify a transport region in which much of the transition from the undiluted plume to mixed intrusion takes place.
- Future work is focussed on establishing the dependence of these results on F_0, N, and the configuration of the plume at penetration – offering a possible approach to parameterisations of tracer transport and mixing.
- Results that are more relevant to the atmospheric problem can be extracted by including vertical shear and buoyancy-dependent tracer concentration, which captures the effect of saturation.

References

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