giving a slightly larger value for divergence, i.e.,

$$\delta_3 = \nabla\cdot\bar{V} \approx -2.5\frac{\bar{u}}{x}\frac{\Delta T}{T}.$$

The largest adiabatic temperature change experienced by a wind is probably in a Föhn. If it warms by 30°C in its descent over a distance x, the standard Gaussian concentration calculation is increased by a factor of

$$\exp\left(-\frac{\delta_3 x}{\bar{u}}\right) \approx \exp(+0.26) = 1.3.$$

These examples represent typical as well as extreme meteorological conditions. If meteorological and surface conditions are such that Roberts' equation is applicable ($\bar{u}$ and δ are constant), then it seems that the effect of total divergence, or compressibility, can usually be neglected. In the case of extreme conditions in which total divergence is non-negligible, there is probably a much greater error due to uncertainties in $\bar{u}$, σ_y, and σ_z than in the omission of divergence effects.

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AUTHORS' REPLY

We thank Matthias for commenting on our paper. His criticism provides an opportunity for us to clarify two key points that were not fully discussed in our manuscript.

First, our intent was to explore the mechanism for systematic or organized effects of complex topography on the dispersion coefficients σ_y and σ_z, and secondly to suggest that two-dimensional divergence might be used as an index of the organized flow effect. Clearly, as Matthias correctly states, the three-dimensional divergence must be zero or nearly so for any realistic tropospheric dispersion applications. Our notation in the original paper was misleading in this regard. To rectify this confusion, consider the following definition of a velocity field:

$$\mathbf{V} = \bar{\mathbf{V}} + \hat{\mathbf{V}} + \mathbf{V}' = (\bar{u} + \hat{u} + u',\ \hat{v} + v',\ \hat{w} + w') \quad \text{(a)}$$

where

$\bar{\mathbf{V}}$ = ensemble mean velocity without topography $= (u, 0, 0)$,

$\hat{\mathbf{V}}$ = mean topographically induced variation from $\bar{\mathbf{V}}$,

$\mathbf{V}'$ = remaining small-scale variations from the ensemble mean, generally considered turbulent fluctuations.

The presence of topography, for the purpose of this discussion, leads to the $\hat{\mathbf{V}}$ field, which is not approximated as homogeneous and/or isotropic as are the $\mathbf{V}'$ turbulence terms, but represents a larger scale (in space) effect on plume dynamics. Clearly, when averages are taken over space scales much larger than the topographic variation, the contribution of $\hat{\mathbf{V}}$ becomes less significant. Introduction of (a) into the conservation of mass expression from the original paper, after performing an ensemble average, yields:

$$\frac{\partial}{\partial t}\bar{\chi} + \nabla\cdot(\bar{\chi}\bar{\mathbf{V}}) + \nabla\cdot(\bar{\chi}\hat{\mathbf{V}}) = \nabla\cdot(K\cdot\nabla\bar{\chi}) \quad \text{(b)}$$

which, since $\nabla\cdot\bar{\mathbf{V}} \approx 0$, becomes

$$\frac{\partial\bar{\chi}}{\partial t} + \bar{\mathbf{V}}\cdot\nabla\bar{\chi} + \bar{\chi}\delta = \nabla\cdot(K\cdot\nabla\bar{\chi}) \quad \text{(c)}$$

if δ is defined as

$$\delta = \nabla\cdot\hat{\mathbf{V}} + \frac{\hat{\mathbf{V}}\cdot\nabla\bar{\chi}}{\bar{\chi}}. \quad \text{(d)}$$

We considered that the lead term in (d) is in fact the two-dimensional divergence $\partial\hat{v}/\partial y + \partial\hat{w}/\partial z$, that the $\partial\hat{u}/\partial x$ contribution is overwhelmed by the $\bar{u}$ transport as are the x diffusion terms, and that advection by the $\hat{\mathbf{V}}$ field could be neglected. We did this to calculate the magnitude of the correction, since estimates of two-dimensional divergence were available.

Because this last consideration is questionable, we can alter the form of our solution to include the advection effect. However, the main point of our paper is to illustrate that the contribution of the $\hat{\mathbf{V}}$ field to σ_y and σ_z is through

$$\left(\frac{\partial\hat{v}}{\partial y} + \frac{\hat{v}}{\bar{\chi}}\frac{\partial\bar{\chi}}{\partial y}\right)$$

and

$$\left(\frac{\partial\hat{w}}{\partial z} + \frac{\hat{w}}{\bar{\chi}}\frac{\partial\bar{\chi}}{\partial z}\right)$$

which, as we showed in equation (3) of the original paper, can be formally incorporated into the conventional Gaussian solution.

Equation (3) in the original paper provides a formal illustration that diffusion from point sources in complex terrain can be treated using a Gaussian model. But the conventional σ_y and σ_z coefficients, designed to parameterize the turbulent diffusion process, must be supplemented with contributions from the $\hat{\mathbf{V}}$ field, the organized circulation patterns induced by the terrain. We imply that the following two alternatives are available for modeling point source dispersion in complex terrain:

(1) Direct measurement or simulation through use of a meteorological wind field model to determine $\bar{\mathbf{V}} + \hat{\mathbf{V}}$, coupled with conventional Gaussian calculation or other 'turbulent' diffusion approximation.

(2) Direct measurement of σ_y and σ_z, which contain the dispersion on a sufficiently large space scale to incorporate the organized $\hat{\mathbf{V}}$ flow field created by the topographic forcing.

It seems necessary to reiterate that the $\hat{\mathbf{V}}$ field is due to differential thermal convection from mountain slope surfaces, coupled with mechanical interactions of the terrain with the mean meteorological winds. This suggests the terrain-augmented σ's will be strongly dependent on insolation (stability) and on terrain form. While the former effect has already been noted in the literature, the latter has prevented generalization of mountain dispersion data. We strongly support the need for more comprehensive field experimentation to develop terrain-influenced dispersion parameters.

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