Towards a modular superparameterization for Stratocumulus clouds considering unsteady entrainment

H. Schmidt[1,2], J. P. Mellado[3], N. Peters[3], and B. Stevens[4]

[1]Konrad Zuse Zentrum Berlin, Takustr. 9, 14195 Berlin, Germany
[2]Freie Universität Berlin, Institut für Mathematik, Arnimallee 6, 14195 Berlin, Germany
[3]RWTH Aachen, Institut für Technische Verbrennung, ITV, Templergraben. 64, 52064, Aachen, Germany
[4]University of California Los Angeles, Department of Atmospheric and Oceanic Sciences, Box 951565, 7154 MSB, Los Angeles, USA

Motivation

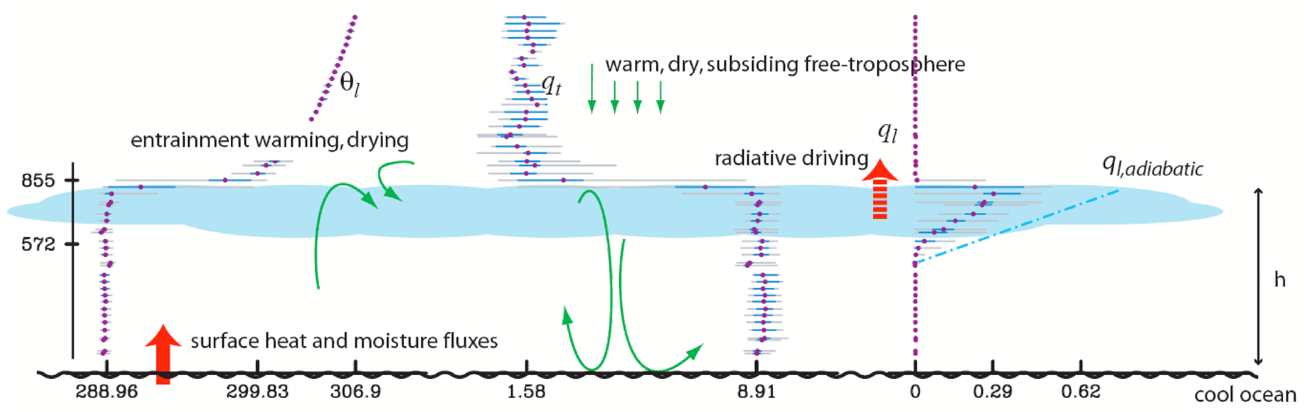
- Low clouds are increasingly recognized as the main source of divergence in model based estimates of climate change [3]
- Model based aerosol/cloud interactions require accurate representation of clouds [1, 2]
- Our best tool for understanding clouds and microphysical interactions is LES, but fundamental issues emerge in precisely those quantities of interest (e.g. Albedo)
- Culmination of more than 10 years of work shows limitations of LES [12] to be fundamental!

Problem

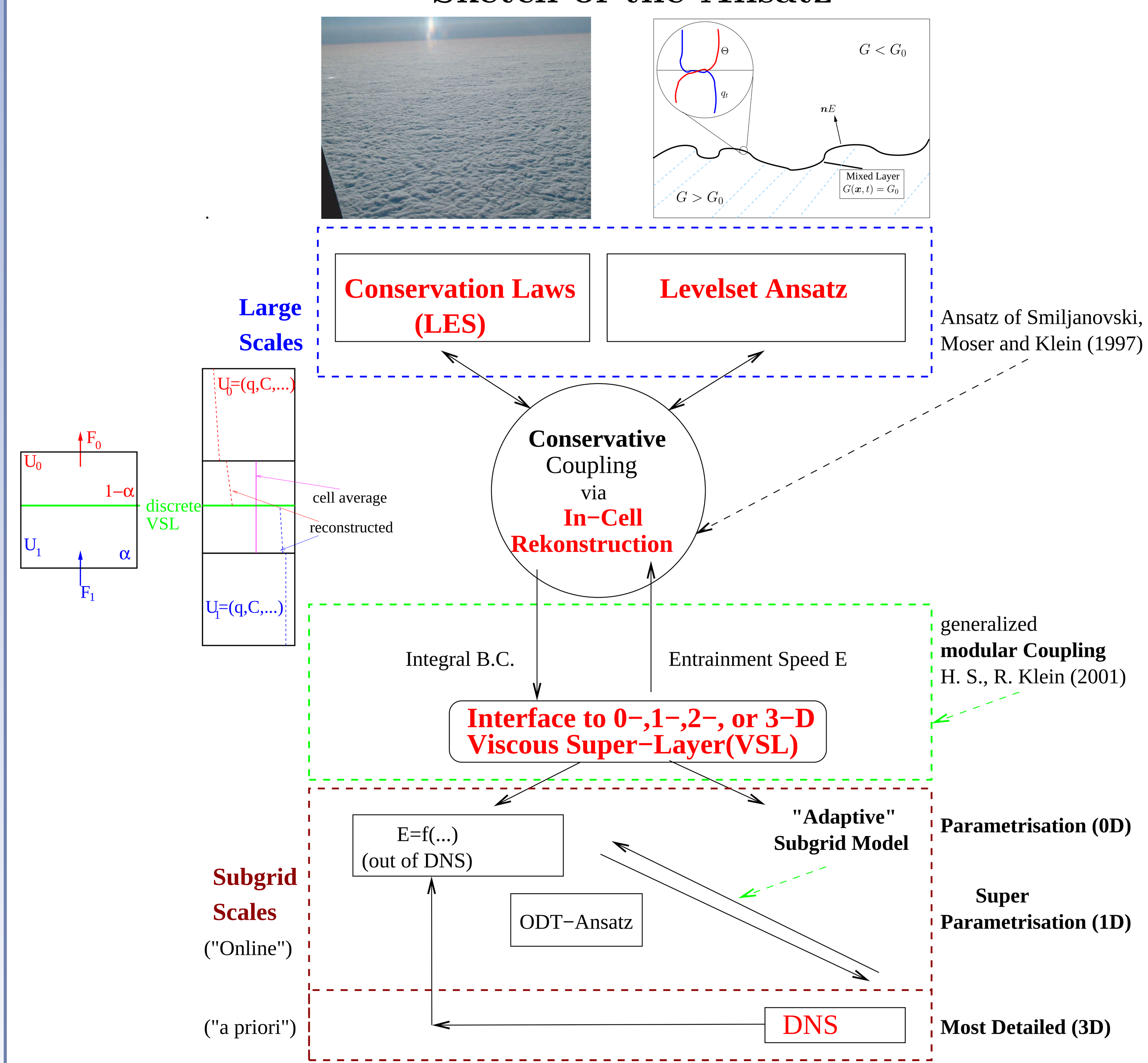
1. **Numerical vs. Physical**
   - Current LES cannot resolve the interface physics due to insufficient resolution
   - Elaborate physically based subgrid models are numerically smeared out (fed wrong)
   - Distinction between numerical and physical effects is impossible
2. **Small vs. Large Scale**
   - Interface motion is driven by large scales.
   - But mixing across the interface is a small scale phenomenon.
   - The coupling between both is not trivial.

Key Ideas

1. **Separation of Numerical and Physical Issues**
   - Interface method to avoid numerical smearing, [9, 10]
   - Consistent embedding of entrainment physics [6]
2. **Separate Treatment of Small and Large Scales**
   - VLES + front tracking for large scales
   - DNS, one dimensional turbulence (ODT), and lower order models for small scale
   - Modular coupling procedure [9], which has been developed for combustion and two phase flow problems, helps to combine both scales in a consistent manner.



Sketch of the Ansatz



Large Scales and Modular Multi Scale Coupling (ZIB)

Characteristic Scales

Large Scales:
Fluctuation of key values over a large scale eddy ($l \approx 800m$): $\Theta' \approx 0.08K$, $q_t' \approx 4 \cdot 10^{-5} g/kg$, and $\tau_l = 600s$. Large scale turbulence is driven by radiation on top of the cloud, since cloud is opaque.

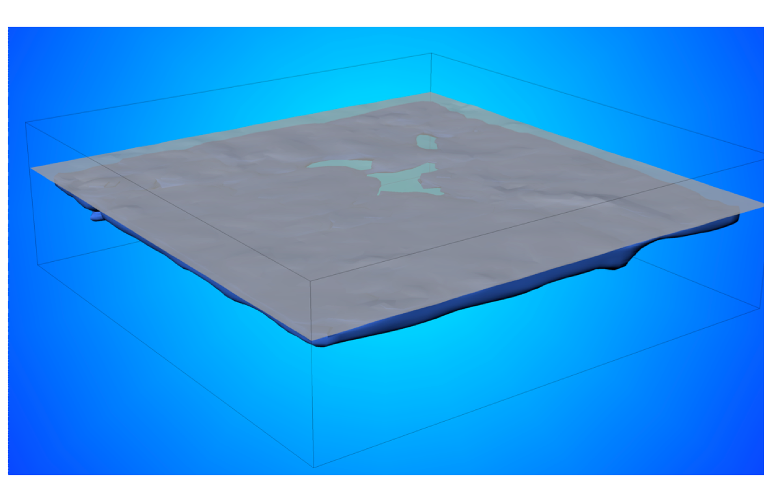
Small Scales:
Changes across the viscous super layer $\leq 10m$: $\Delta\Theta \approx 10K$ and $\Delta q_t \approx 8g/kg$

Scale Relation:
$\frac{\Delta q_t}{q'} \gg 1$ and $\frac{\Delta\Theta}{\Theta'} \geq 100$ $\Rightarrow$ Looks like an interface!

Accurate large scale control of the progress variable is important! This is a necessary condition for embedding a subgrid scale model that is driven by the large scales and has significant feedback on them at the same time. There are analogies to combustion and two phase flow modelling, but poorly explored!

Evolution of the Interface

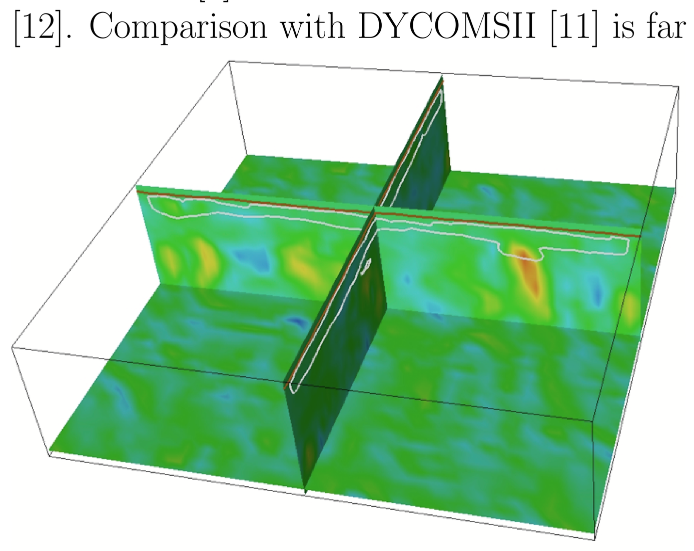
$$\frac{\partial}{\partial t} G + (\boldsymbol{v} + E\boldsymbol{n}) \cdot \nabla G = \text{sign}(G)\,(1 - |\nabla G|)\frac{|G|}{\zeta} \qquad (1)$$



Steps to a Sc simulation (UCLA-LES) including a tracked viscous superlayer: Isosurface of liquid water (blue) and zero levelset (gray)

Flow Equations and Codes

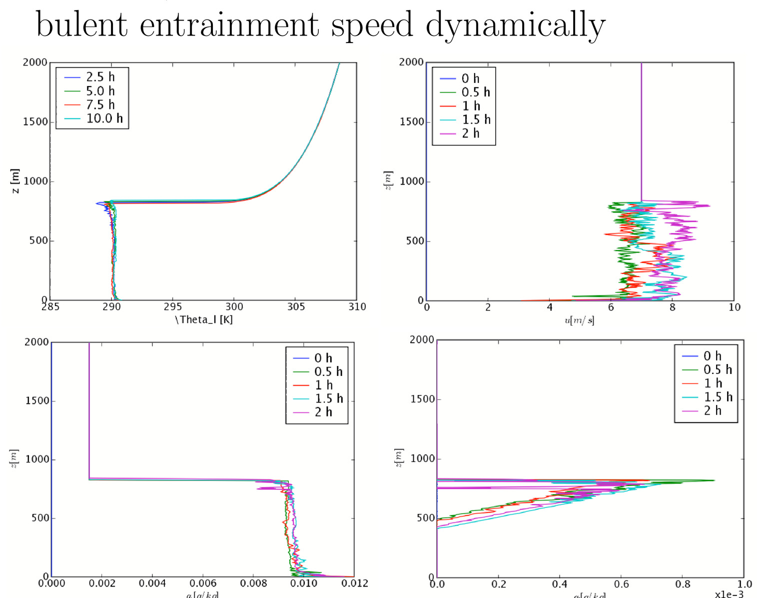
We are implementing the Heterogeneous Multiscale Model from [9] into the anelastic UCLA-LES solver [12]. Comparison with DYCOMSII [11] is far goal.



UCLA-LES: Vertical velocity, contour of q_l (white) and $G = 0$ (red).

Subgrid Scale Entrainment Modeling

- One Dimensional Turbulence Model [7]
- Towards an extension of a Sc Code (Wunsch, Kerstein, Krueger [8]) to be used as "online" SGSM
- The goal is to feed the model (attached to the Interface) by LES Fluxes and to extract the turbulent entrainment speed dynamically

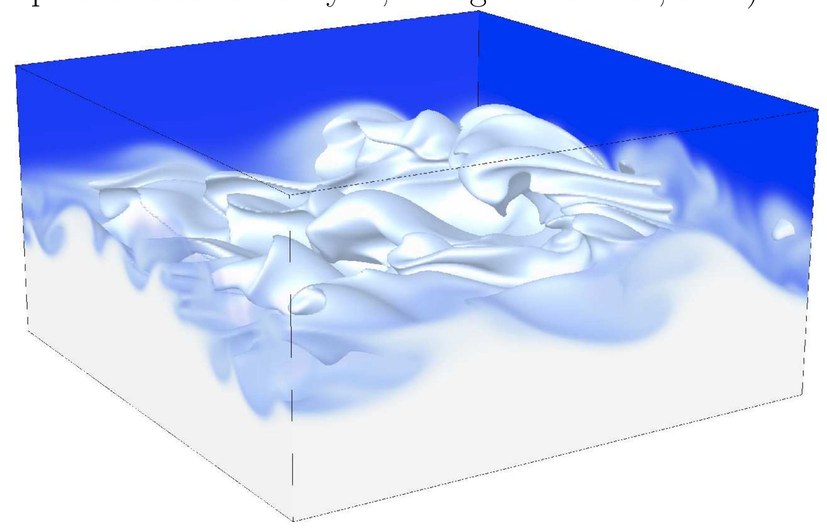


Sc boundary layer simulation as starting point for a small scale entrainment model moving with the entrainment layer

DNS and Entrainment Modeling (ITV)

Stratified Mixing Layer

Temporally-evolving shear layers are simulated. Focus is on the nonturbulent/turbulent transition region, e.g. viscous superlayer based on vorticity (Corrsin, 1955). Water equilibrium conditions are assumed and an Eulerian-Eulerian (two-fluid) formulation is used. Latent heat effects will be investigated by looking at the large- (e.g. scalings) and small-scale phenomena (e.g. local structure, dissipation element analysis, Wang and Peters, 2006).



Vertical shear layer with total specific humidity field. Initially there is hot dry air on top of cold moist air.

Entrainment Model

Global entrainment velocity is defined as temporal change of a mixing region thickness δ_ω,

$$E = \frac{d\delta_w}{dt}. \qquad (2)$$

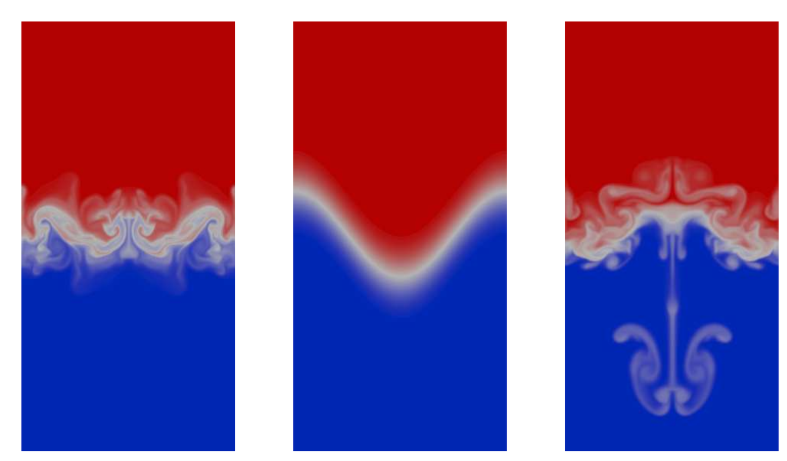
We need to know the dependence of E on the nondimensional parameters of the problem, possibly:

$$E = E(Ri_g, \delta_{w,0}/\delta_{T,0}, Q) \qquad (3)$$

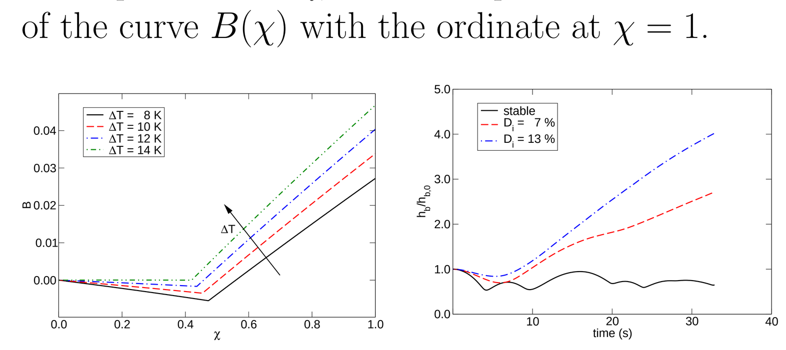
- Ri_g, gradient Richardson number
- $\delta_{w,0}/\delta_{T,0}$, ratio of initial velocity and temperature thicknesses of the layer.
- $Q = q_{l,0}L/(C_{p,0}\Delta T)$, ratio of the available latent heat and enthalpy difference across the layer.

Buoyancy Reversal

The two-layer system of hot/dry air on top of cold/moist air can have buoyancy reversal instability due to evaporative cooling. Central figure below represents the perturbed initial condition: the stable mode develops a turbulent mixing region around the central position due to baroclinic production of vorticity (left); if buoyant reversal, an additional downdraft might be formed (right).



Study normally done in terms of buoyancy B as a function of the mixture fraction χ ($\chi = 0$ lower layer, $\chi = 1$ upper layer), as shown in figure below (left). One important quantity is the buoyancy reversal parameter D_i, which compares the minimum of the curve $B(\chi)$ with the ordinate at $\chi = 1$.



As D is increased, the downdraft develops faster, as shown in figure above (right). The finger length h_b is measured by the distance between the falling front and the mean position of the oscillating mode.

What is the relevance of buoyancy reversal in the turbulent configuration?

References

[1] Albrecht, B. A. Aerosols, cloud microphysics and fractional cloudiness. *Science*, **245**, 1227–1230, (1989).

[2] Bony, S., J.-L. Dufresne, H. Le Treut, J.-J. Morcrette, and C. Senior On dynamic and thermodynamic components of cloud changes. *Climate Dynamics*, **22**, 71–86, (2004).

[3] Bony, S., J.-L. Dufresne Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models. *Geophysical Reasearch Letters*, **32**, (2005).

[4] Corrsin, S. and Kistler, A.L. Free-stream boundaries of turbulent flows *NACA Technical Report*, **1244**, 1033–1064 (1955).

[5] Druzhinin, O.A. and Elghobashi, S. Direct numerical simulation of bubble-laden turbulent flows using the two-fluid formulation *Phys. Fluids*, **10:3**, 685–697 (1988).

[6] Effelsberg, E., Peters, N. A composite model for the conserved scalar pdf. *Comb. and Flame*, **85**, 206–214, (1983).

[7] Kerstein, A.R. One-dimensional turbulence: Model formulation and application to homogeneous turbulence, shear flows, and buoyant statistical flows. *J. Fluid Mech.*, **392**, 277–334, (1999).

[8] Kerstein, A.R.; Wunsch, S., and Krueger, S.K. A strategy for improvement of LES prediction of stratocumulus entrainment using the 'one-dimensional turbulence' simulation method. *12th Conference on Cloud Physics*, **P1.38**, 1–9, (2006)

[9] Schmidt, H., Klein, R. A generalized level-set/in-cell-reconstruction approach for accelerating turbulent premixed flames. *CTM*, **7**, 243-267, (2003).

[10] Smiljanovski, V., Moser, V., Klein, R. A Capturing-Tracking Hybrid Scheme for Deflagration Discontinuities. *CTM*, **2**(1), 183-215, (1997).

[11] Stevens, B. et al. DYCOMS-II: The Second Dynamics and Chemistry of Marine Stratocumulus field study. *Bull. Amer. Meteor. Soc.*, **84**, 579–593 (2003).

[12] Stevens, B. et al. Evaluation of large-eddy simulations via observations of nocturnal marine stratocumulus *Monthly Weather Review*, **133**, 1443–1462 (2005).

[13] Wang, L. and Peters, N. The length-scale distribution function of the distance between extremal points in passice scalar turbulence *NA*, **554**, 457–475 (2006).