# Subfilter Scale Fluxes in the Marine Surface Layer

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## LONG-TERM GOALS

A goal of marine surface layer research is to identify and quantify coupling mechanisms that connect the atmospheric boundary layer and surface waves. Large-eddy simulation (LES) plays a role in this research and has provided insight into the interactions between imposed waves and turbulence (Sullivan *et al.*, 2004; Sullivan *et al.*, 2006). However, the fidelity of subfilter-scale (SFS) parameterizations used in LES for flows over complex geometry, *e.g.,* a moving surface gravity wave field, is untested. Recent field campaigns such as the Horizontal Array Turbulence Study (HATS) conducted over land have provided new impetus to improve parameterizations in LES codes (*e.g.,* see Sullivan *et al.*, 2003; Chen & Tong, 2006; Hatlee & Wyngaard, 2006). A natural progression in these investigations is then to study increasingly complex flows. In the present work we present results from a new field campaign, the Ocean Horizontal Array Turbulence Study (OHATS), specifically directed at the measurement of SFS variables in the marine surface layer in the presence of surface waves. These observations can be used to examine and improve the SFS parameterization in LES codes, and more broadly, the impacts of water waves on surface layer turbulence under a variety of atmospheric stability conditions and wave states. Ultimately, the dataset and derived improvements to LES can benefit surface-layer parameterizations in mesoscale and numerical weather prediction models. Partners in OHATS are Applied Ocean Physics & Engineering at Woods Hole Oceanographic Institute (also U. Connecticut), the Earth Observing Laboratory at the National Center for Atmospheric Research, and the Department of Meteorology at Pennsylvania State University. The OHATS field campaign was conducted in 2004 off the coast of Martha's Vineyard using a low-profile Air-Sea Interaction Tower (ASIT). The ASIT is an integral component of the Martha's Vineyard Coastal Observatory operated by Woods Hole Oceanographic Institute. See http://www.atd.ucar.edu/rtf/projects/OHATS04 for additional information.

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## OBJECTIVES

The immediate goal of our research is to carry out an extensive analysis of the large database collected during OHATS. Bulk and SFS variables (*e.g.,* momentum and scalar fluxes) will be computed as function of atmospheric stratification and wave age. These findings can then readily be compared with previous results obtained over land.

## APPROACH

Large-eddy simulation faces a closure problem similar to that in traditional Reynolds average modeling (RANS) (*e.g.,* see Pope, 2000). In LES the unknowns are the SFS fluxes for momentum, defined as

$$\tau_{ij} = \overline{u_i u_j} - \overline{u_i}\;\overline{u_j} \ , \tag{1}$$

and the SFS flux for an arbitrary scalar $c$ defined as

$$f_i \ = \overline{u_i c} - \overline{u_i}\;\overline{c} \ . \tag{2}$$

In the above the overbar $\overline{(\ )}$ denotes *spatial* filtering.

The scientific approach adopted here is to obtain field measurements of the total fields $(u_i, c)$ from which we can construct SFS momentum and scalar fluxes in (1) and (2) over a wide range of stratification and wave states. The data needs to be gathered at a sufficient number of spatial locations to permit spatial filtering of the total fields.

OHATS utilizes the horizontal array technique first proposed by Tong *et al.* (1998, 1999) which has since been utilized in several investigations of SFS motions in atmospheric boundary layers over rough land surfaces (Porté-Agel *et al.*, 2001; Horst *et al.*, 2004; Sullivan *et al.*, 2003). Two arrays (or lines) of sonic anemometers are positioned crosswind to the primary wind direction with the horizontal spacing between individual sonic anemometers selected to achieve a specific spatial filter width. The two sonic lines are located at different heights above the surface to allow for measurement of vertical gradients. Under the assumption of Taylor's hypothesis in the alongwind direction, we are in essence able to measure a 2-D $(x - y)$ plane of winds and temperature fluctuations at two levels in the atmospheric surface layer. The use of a dense array of sonic anemometers allows both single and double spatial filtering. In addition to the surface layer winds in OHATS, wave height information and wave propagation direction were obtained using three downward pointing laser altimeters mounted on the ASIT diving board.

## WORK COMPLETED

During fiscal year 2005 we completed the deployment for OHATS and successfully carried out the field campaign. The intensive observation period for OHATS extended from August to October, approximately 85 days. A description of the data collection procedures, the available data, and software tools used to analyze the database are described in our FY05 progress report. In FY06 we began a detailed analysis of the OHATS data. This includes computation of bulk surface layer variables, SFS momentum and scalar fluxes, and transfer rates between resolved and SFS fields. Also, wave height spectra were computed using data collected from the laser altimeters. The availability of the wave height information provides an opportunity to correlate motions in the air with the underlying sea surface. The wave-induced motion algorithm used in OHATS was provided by Dr. Tihomir Hristov (Johns Hopkins University) and is described in Hristov *et al.* (1998). An overview of the data analysis procedures and software is given in Sullivan *et al.* (2006).

## RESULTS

The OHATS database provides an opportunity to perform a variety of analysis on SFS variables and the underlying wave fields. Recently, we analyzed the SFS momentum and scalar fluxes with a goal of evaluating different SFS parameterizations. Here we concentrate on the the SFS scalar flux and examine the similarities and differences for flow over stationary roughness and moving water waves.

Wyngaard (2004) proposed a new class of subfilter-scale models that are intended to be applicable across a range of scales spanning the gap $l \sim \triangle_f$ between the "LES limit" $l/\triangle_f >> 1$ and the "mesoscale limit" $l/\triangle_f << 1$ with $l$ the scale of the dominant turbulence and $\triangle_f$ the filter width. The mathematical steps outlining the methodology are fully described by Wyngaard (2004). The basis of these simplified rate-equation models is rational truncation of the full transport equations for SFS fluxes based on scale analysis. These SFS prescriptions offer improvements to simple eddy viscosity closures, but have not yet been fully implemented and evaluated in simulation codes. Using a subset of the HATS database (Sullivan *et al.*, 2003), Hatlee & Wyngaard (2006) tested variants of these SFS closures for scalar flux. One of the important results from their investigation is the proper prediction of all components of SFS scalar flux. For a conserved scalar $c$ the components of the SFS scalar flux $f_i$ are modeled using a rate equation of the form

$$\frac{\partial f_i}{\partial t} \;=\; -f_j \frac{\partial \overline{u}_i}{\partial x_j} \;-\; \tau_{ij}\frac{\partial \overline{c}}{\partial x_j} - \frac{f_i}{T}\;. \tag{3}$$

This truncated model includes only time change, tilting and production terms and models pressure destruction via a sink of the form $-f_i/T$ with the time scale of the SFS turbulence

$$T \;=\; C\,\triangle_f\,/E^{1/2}\;. \tag{4}$$

In the above expressions, $\overline{u}_i$ is the resolved (filtered) velocity, $\tau_{ij}$ is the SFS momentum flux, $E = \tau_{ii}/2$ is the SFS kinetic energy, and the modeling constant $C \approx 0.3$ is chosen to match the HATS data.

Algebraic stress models with some structural similarity to (3) have been proposed for stratified flows (Findikakis & Street, 1979) and implemented in RANS codes (*e.g.,* Hanjalic, 2001), but only recently have these types of models been validated against geophysical data in the context of LES. Here we test the applicability of (3) and (4) for scalar transport in turbulent flow over water waves.

The OHATS database possesses all the ingredients necessary to evaluate the SFS closure given by (3) using virtual temperature $\theta$ as the conserved scalar $c$. Our algorithm advances (3) in time with a second-order Adams-Bashforth method. The observed values of SFS momentum fluxes and energy, resolved velocity and scalar gradients, which appear on the right-hand-side, are spline interpolated to increase their temporal resolution and thereby eliminate errors due to finite differencing. We performed an independent test of our algorithm using all the acceptable cases in the HATS database. Figure 1 shows the observed and modeled components of average scalar flux $\langle f_1\rangle, \langle f_3\rangle$; these results are in agreement with Hatlee & Wyngaard (2006) and verify the correctness of our algorithm. The findings illustrate that (3) is a good predictor for SFS scalar flux over a range of stratifications and filter widths over land. An important attribute of (3) is the prediction of a finite average value of horizontal scalar flux $\langle f_1\rangle$ even in a horizontally homogeneous flow $\langle \partial\overline{c}/\partial x, \partial\overline{c}/\partial y\rangle = 0$. An eddy-viscosity scalar-gradient closure leads to $\langle f_1\rangle = 0$. We mention that a dynamic evaluation of the eddy viscosity (*e.g.,* Germano *et al.*, 1991) cannot overcome this deficiency since production from "scalar tilting" $f_j \partial\overline{u}_i/\partial x_j$ in (3) is not present in eddy viscosity models (see also Wyngaard *et al.*, 1971).

Results from our analysis of the OHATS data are depicted in figure 2. These findings show that the prediction of horizontal scalar flux over waves is slightly below but closely follows the trend from HATS. However, (3) noticeably over predicts the SFS vertical scalar flux $f_3$ especially in cases with larger waves and scalar surface flux. Cases with significant wave heights greater than 1 m and at the same time surface convection exhibit the greatest departure from the HATS observations and predictions given by (3). The trends in figure 2 seem clear and hence the surprising result for $f_3$ merits further interrogation.

Inspection of (3) suggests the approximate balance $\tau_{ij} \partial \overline{c} / \partial x_j \approx -f_i/T$, *i.e.,* the production of SFS flux is balanced by pressure destruction. Then a simple (*ad hoc*) modification is to introduce separate pressure destruction modeling constants $(C_H, C_V)$ in the horizontal and vertical directions, respectively. The physical motivation for this model is the speculation that the wave field modifies the production of SFS scalar flux and hence the pressure destruction needs to respond accordingly. A test of this modified scalar flux model is shown in figure 3 using best constants $(C_H, C_V) = (0.3, 0.06)$. The model predictions closely follow the observations; note the predictions with this modified model improves both the horizontal and vertical scalar flux estimates. An important ingredient of any SFS model is to transfer squared scalar variance $\overline{c^2}$ between resolved and SFS fields, *i.e.,* establish a proper cascade to smaller scales. The variance transfer rate for scalars is (Wyngaard, 2004)

$$\mathcal{P} \;=\; 2\, f_i \frac{\partial \overline{c}}{\partial x_i} \; . \tag{5}$$

In the LES regime, $\mathcal{P}$ is a stochastic variable and not constrained to be positive definite, *i.e.,* the instantaneous transfer can be from the SFS field to the resolved field (backscatter) or from the resolved field to the SFS field (forwardscatter). However, the ensemble average $\langle \mathcal{P} \rangle$ is forwardscatter. In figure 4 we compare estimates of mean scalar variance transfer from our model to the OHATS observations. The close agreement indicates that the modified rate equation (with 2 pressure destruction constants) performs well using the scalar transfer rate as a metric.

These results for SFS scalar flux suggest that the wave field plays a role in setting the SFS fluxes that is unique compared to flow over stationary roughness. A next step is to closely examine the phase relationship between the wave induced pressure and scalar fields. In order to explore this speculation we need to identify the wave correlated motions in the velocity, pressure, and scalar fields, as described earlier. In addition, we can use the direct numerical simulation (DNS) results for stratified flow over waves described by Sullivan & McWilliams (2002) to gain insight into the present results.

## IMPACT/APPLICATIONS

The OHATS field enhances our current understanding of air-sea interaction processes, provides insight into the couplings between surface waves and turbulence, and sheds new light on SFS modeling for LES. The research also compliments the CBLAST program sponsored by the Office of Naval Research. In addition the OHATS dataset can be used to further our understanding of LES of swell driven marine boundary layers (Sullivan *et al.*, 2004; Sullivan *et al.*, 2006; Edson *et al.*, 2006).

## TRANSITIONS & RELATED PROJECTS

We are currently engaged in using large-eddy simulation to model air-sea interaction processes in both the atmospheric and oceanic boundary layers. In particular, we are using LES to assist in the interpretation of field measurements taken during the recent low-wind (Edson *et al.*, 2006) and hurricane Coupled Boundary Layer Air-Sea interaction Transfer (CBLAST) field campaigns. OHATS provides an additional data source for understanding air-sea interaction processes. A web site describing CBLAST and the Martha's Vineyard Coastal Observatory can be found at:

http://www.whoi.edu/science/AOPE/dept/CBLASTmain.html
http://mvcodata.whoi.edu/cgi-bin/mvco/mvco.cgi

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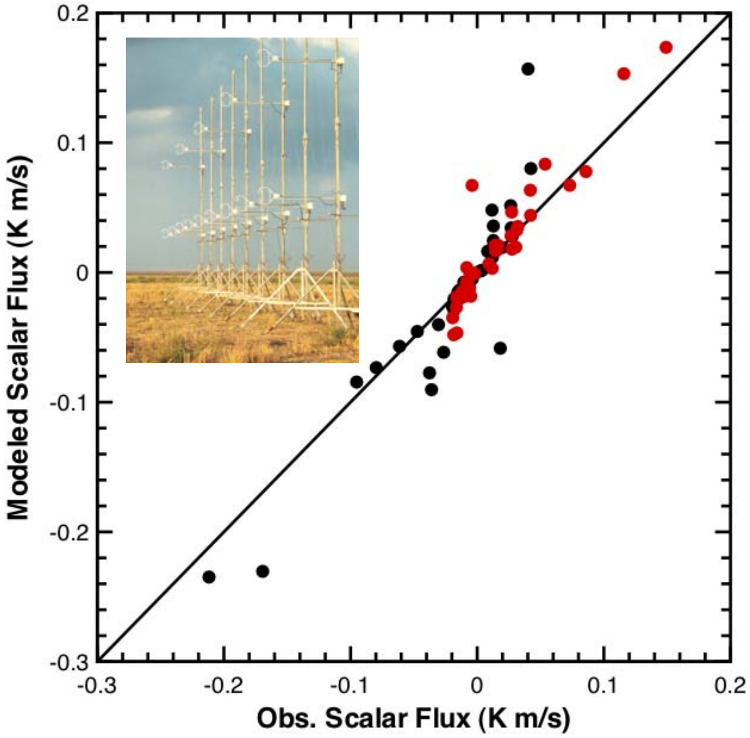

**Figure 1:** Comparison of modeled and observed SFS scalar flux in the atmospheric surface layer over a stationary rough surface from the field campaign HATS (Sullivan *et al.*2003). $\langle f_1 \rangle$ and $\langle f_3 \rangle$ are indicated by black and red dots respectively. The inset photograph shows the HATS field deployment of an array of sonic anemometers above a fallow field in California.

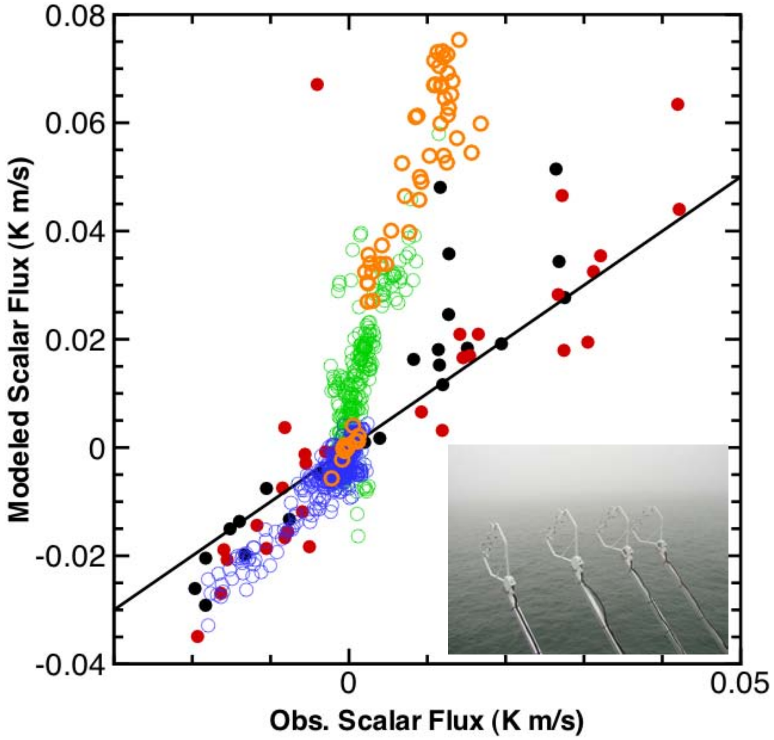

**Figure 2:** Comparison of modeled and observed SFS scalar flux in the marine surface layer over moving waves. Horizontal scalar flux $\langle f_1 \rangle$ is indicated by open blue circles. Vertical scalar flux $\langle f_3 \rangle$ is indicated by open green and orange circles; cases with significant wave height greater than 1 m are shown in orange. The results from HATS are the black and red dots. Note the difference in vertical and horizontal scales compared to figure 1. The inset photograph taken from the ASIT shows sonic anemometers before final positioning in OHATS.

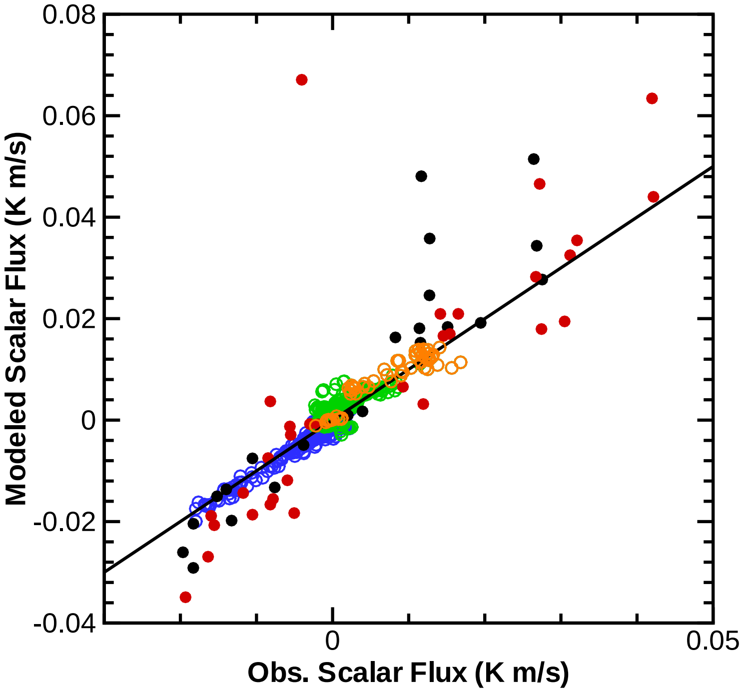

**Figure 3:** Comparison of modeled and observed SFS scalar flux in the marine surface layer over moving waves as in figure 2 but using a modified rate equation with separate constants in the pressure destruction model for horizontal and vertical scalar flux, $(C_H, C_V) = (0.3, 0.06)$, respectively.

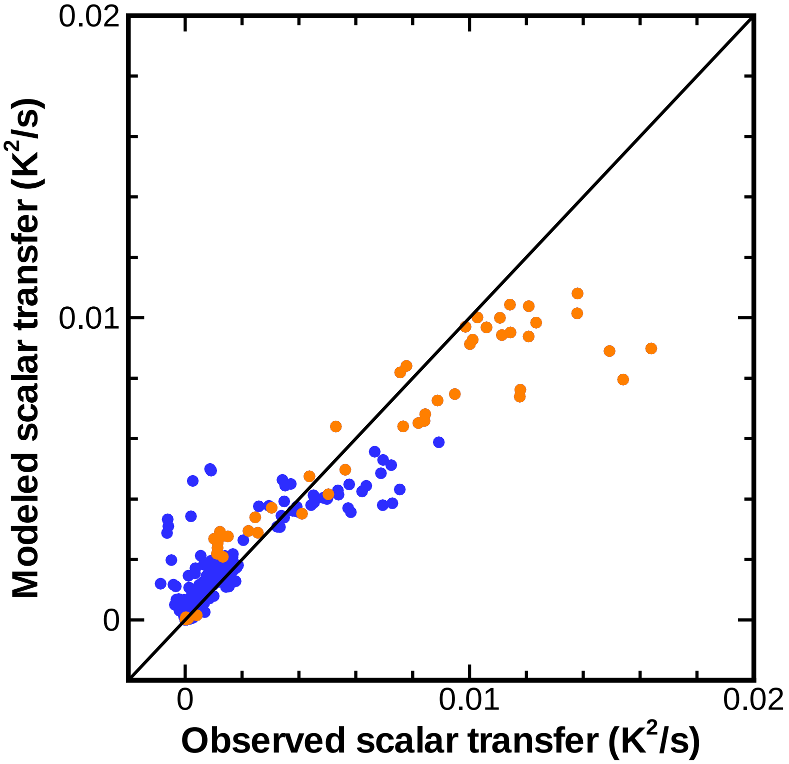

**Figure 4:** Comparison of modeled and observed mean scalar transfer $\langle f_i \frac{\partial\bar{\theta}}{\partial x_i}\rangle$ in the marine surface layer over moving waves. Orange dots indicate results for cases with significant wave heights greater than 1m and convective conditions. Blue dots are all other cases.