Investigation of the Representation of OLEs and Terrain Effects Within the Coastal Zone in the EDMF Parameterization Scheme: An Airborne Doppler Wind Lidar Perspective

Annual Report
Under Grant No.: N000141110450

Covering the Period:
1 July 2011-30 June 2012

Submitted by:

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06 July 2012

REPORT DOCUMENTATION PAGE	*Form Approved* **OMB No. 0704-0188**

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
06July2012	Annual	1 July 2011-30 June 2012

4. TITLE AND SUBTITLE Investigation of the Representation of OLEs and Terrain Effects Within the Coastal Zone in the EDMF Parameterization Scheme: An Airborne Doppler Wind Lidar Perspective	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER N000141110450
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) George D. Emmitt Ralph Foster Stephan De Wekker Steven Greco	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Simpson Weather Associates, Inc. 809 E. Jefferson Street Charlottesville, VA 22902-5131	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) DCMA Manassas-S2404A 10500 Battleview Pkwy, Suite 200 Manassas, VA 20109-2342	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for Public Release, distribution is Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
During Year 1, the current Twin Otter Doppler Wind Lidar (TODWL) data archives were searched to identify cases with (and without) OLEs. We have investigated in detail the TODWL derived wind patterns over and near the coastal zone on several of these days. These analyses, as well as a theoretical model for OLE dynamics developed by the investigators, are also being used to help evaluate numerical simulations utilizing the WRF model. WRF simulations for OLE (and non-OLE) days have been run using various options for BL parameterizations including an EDMF scheme.

In the first year, we have also made progress in improving the retrieval of TODWL derived winds in the bottom 300 m of the atmosphere. We have developed a two-step approach which involves removing high intensity ground returns and identifying and tracking aerosol radial velocities in the layer affected by ground interference. Using this approach for measurements acquired over the Salinas Valley, we showed that additional range gates closer to the surface can be obtained.

We have also collaborated with other participants on the design of the field campaign to be conducted in Year 2, including missions over Monterey Bay and for MATERHORN (Dugway Proving Ground).

INSTRUCTIONS FOR COMPLETING SF 298

15. SUBJECT TERMS OLE, EDMF, Doppler Wind Lidar					
16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT** U	**18. NUMBER OF PAGES** 9	**19a. NAME OF RESPONSIBLE PERSON** George D Emmitt
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U			**19b. TELEPONE NUMBER (*Include area code)*** 434-979-3571

1. Introduction

The main objective of the three-year funded research entitled "Investigation **of the representation of OLEs and terrain effects within the coastal zone in the EDMF parameterization scheme: an airborne Doppler wind lidar perspective" is** to contribute to the evaluation and development of the Eddy Diffusivity Mass Flux (EDMF) parameterization of turbulence and convective mixing, particularly in the presence of Organized Large Eddies (OLEs). During the first year of the proposed effort, this was done by using existing data from the Navy Postgraduate School's airborne Twin Otter Doppler Wind Lidar (TODWL) to investigate lower tropospheric dynamics within the interaction zone of complex terrain and the coastal waters. In addition we utilized a theoretical OLE model as well as numerical simulations from the Weather Research and Forecast (WRF) model to study the atmosphere and to compare EDMF predicted fluxes and spatial/temporal development of the Boundary Layer with those measured by instrumentation on the Twin Otter aircraft. The ultimate goals of the three year study are to determine how OLEs affect turbulent mixing and the surface stress, and to determine via theory, observation and modeling how this differs from the standard PBL parameterizations.

2. Year One Accomplishments

The main task(s) of Year One of this study were, as mentioned above, to use existing TODWL data combined with models such as the WRF to generate one or more approaches to evaluating and modifying the EDMF for the effects of semi-organized boundary layer structures such as OLEs and LLJs. This was broken down to the following individual tasks conducted by Prime Investigator Simpson Weather Associates (**SWA)** and co-Investigators University of Virginia (**UVA**) and University of Washington (**UW**):

Task 1.1 - Sort through existing TODWL data sets (~ 100 hours) and identify those flight legs most useful for the mapping of OLEs and the computation of fluxes for use in the evaluation of the EDMF scheme. (SWA and UW)

Task 1.2 – Analysis of existing TODWL data with a focus on OLEs. (SWA)

Task 1.3 – Development and modification of algorithms for TODWL data retrieval and processing, especially in the bottom 300m. (SWA and UVA)

Task 1.4 - Fluxes will be computed by Emmitt (SWA) from the Twin Otter instrumentation as has been done in prior studies.

Task 1.5 - The mapping of OLEs and LLJs from the lidar data will be used for context for the fluxes and correlations between OLE sectors and fluxes. (SWA and UW)

Task 1.6 - A theoretical model for OLE dynamics will be calibrated against the data and numerical experiments (COAMPS and WRF model runs) and necessary improvements will be developed and implemented. (UW, SWA, UVA).

Task 1.7 - Collaborate with other DRI-funded participants on the design of a field campaign to be conducted in Year 2 (SWA, UW, and UVA).

Task 1.8 – Become familiar with EDMF implementation in WRF and COAMPS (in collaboration with NRL - Doyle) and set up WRF/COAMPS for OLE and non-OLE case studies from previous flights (UVA)

Task 1.9 – Evaluate simulations with past TODWL data (UVA, SWA)

We will define the work done under Tasks 1.1 through 1.5 as Data Analysis and Algorithm Development while the work done under Tasks 1.6, 1.7 and 1.8 to 1.9 will be defined as, respectively, OLE Modeling, Field Campaign Planning, and WRF Modeling and EDMF Implementation. The results to date are provided below.

2.1 Data Analysis and Algorithm Development

Between 2002 and today, more than 100 hours of TOWDL research flights have been conducted over coastal complex terrain in southern California. These missions have provided high resolution wind and aerosol data that may offer an opportunity to study OLE dominated marine BLs and to test EDMF schemes in the presence of significant wind and wind shear and both in the marine and the continental BL. This current TODWL data archive has been searched and analyzed to identify mission cases with (and without) OLEs and Low Level Jets. Several cases of both OLEs and LLJs have been indentified in October 2006, April 2007 and November 2007.

During year 1, we have made progress in improving the retrieval of TODWL derived winds in the bottom 300 m of the atmosphere, a layer that is affected by ground interference (Task 1.3). We developed a two-step approach which involves removing high intensity ground returns and identifying and tracking aerosol radial velocities in the layer affected by ground interference. Using this approach, we showed that additional range gates closer to the surface can be obtained, thereby further enhancing the potential of airborne Doppler lidar in atmospheric applications. We demonstrated the benefits of the two-step approach using measurements acquired over the Salinas Valley in central California. The additional range gates reveal details of the wind field that were previously not quantified with the original approach, such as a pronounced near-surface wind speed maximum.

We also investigated the TODWL derived wind patterns on a day without OLEs (12 November 2007). The airborne Doppler lidar collected four hours of data between the surface and 3000 m MSL along a 40 km segment of the Salinas Valley during this day. The airborne lidar measurements, obtained at a horizontal and vertical resolution of approximately 1500 m and 50 m, respectively, reveal a detailed spatial structure of the atmospheric flows within the valley and their associated aerosol features. Clear skies prevailed on the flight day with northwesterly synoptic flows around 10 m s^{-1}. The data document a shallow sea breeze transitioning into an upvalley flow in the Salinas Valley that accelerates in the upvalley direction. Along with the acceleration of the upvalley wind, the lidar data indicate the presence of enhanced sinking motions. No return flows associated with the sea-breeze or upvalley flows are observed. While synoptic flows are aligned along the valley axis in the upvalley direction, lidar data indicate the presence of a northerly cross-valley flow around the height of the surrounding ridges. This flow intrudes into the valley atmosphere and induces, along with thermally-driven slope flows on the sunlit valley sidewall, a cross-valley circulation that causes an asymmetric distribution of the aerosols. This study demonstrates the large potential of airborne Doppler lidar data in describing flows in complex terrain.

The efforts above have resulted in peer reviewed publications in the Journal of Atmospheric and Oceanic Technology and in the Journal of Applied Meteorology and Climatology (Godwin et al., 2012, and De Wekker et al., 2012).

2.2 OLE Modeling

Observations of boundary layer OLE frequently show strong evidence of rolls coexisting at multiple spatial scales. Shorter wavelength signatures are typically observed nearer to the surface and longer wavelength signatures are detected farther from the surface. Furthermore, it often appears that the longer wavelength OLE modulate the nearer-surface rolls. During the earlier TODWL flights, there was frequently evidence of similar co-existing OLE at different wavelengths. Furthermore, during the ONR-sponsored Impact of Typhoons on the Pacific field program similar evidence of multi-scale OLE was found in synthetic aperture radar imagery of the sea surface in and surrounding tropical cyclones.

A component of our Unified Parameterization research involves validating and calibrating our simple OLE model against data. Previously we have found good agreement between the dominant OLE signatures and the model results. However it was clear that the model needed fundamental improvements in order to study the multi-scale OLE environment that we expect to find during the field program.

To this end we have implemented a basic wave-wave interaction model that couples resonant wave-wave interactions between triads of interacting OLEs. The wave-wave interaction theory is based on the work of Mourad and Brown,who examined 2-D (neutrally-stratified, overturning components only), rolls in the Ekman layer. In the new model, interacting modes are based on the single-wave OLE model described in Foster (2005), which solves for modes such as $\boldsymbol{q}_A = [U_A, V_A, W_A, T_{v_A}]$, i.e. wind components and virtual temperature, in a generalized mean PBL flow that uses variable eddy viscosity to define the smaller-scale eddies. The basic idea is that a single-wave model examines the fastest-growing mode, which will generally dominate the equilibrium solution after a finite time. This mode agrees well with the observed dominant OLE. Modes corresponding to longer or shorter wavelengths, such as seen in the multi-scale OLE PBL, also have positive growth rates; but, they grow so much slower than the dominant modes that they would never play a role in the final solution unless some mechanism can accelerate their growth to catch up to the fast-growing modes.

The multi-scale model starts from our existing nonlinear single-wave model solutions for each of three OLE with wavenumbers α, β and γ and real amplitudes *A*, *B* and *C* respectively and we require α = β + γ. These single-mode solutions are truncated after the first nonlinear Landau coefficient is found. The wave-wave expansion is fairly standard and the derivation can be found in many references. The result is a set of coupled differential equations, analogous to the Landau expansions described in Foster (2005) for the amplitudes (real part) and phases (imaginary part) of the coupled OLE modes:

$$\frac{1}{A}\frac{dA}{dt} - i\frac{d\theta_A}{dt} = \lambda_{0,\alpha} + a_1\frac{BC}{A}e^{i\varphi} + [a_2A^2 + a_3B^2 + a_4C^2]$$

$$\frac{1}{B}\frac{dB}{dt} - i\frac{d\theta_B}{dt} = \lambda_{0,\beta} + b_1\frac{AC}{B}e^{i\varphi} + [b_2A^2 + b_3B^2 + b_4C^2]$$

$$\frac{1}{C}\frac{dC}{dt} - i\frac{d\theta_C}{dt} = \lambda_{0,\gamma} + c_1\frac{AB}{C}e^{i\varphi} + [c_2A^2 + c_3B^2 + c_4C^2]$$

in which a_i, b_i and c_i are higher-order Landau coefficients and are determined as part of the solution through the calculated wave-wave and wave-mean flow interactions of the modes and their harmonics. The zeroth-order Landau coefficients, $\lambda_{0,\gamma}$, are the eigenvalues, which determine the initially exponential growth and phase speed of the modes. The high-order bracketed terms limit the growth and force the modes into the equilibrium OLE state. The new intermediate-order terms proportional to cosines and sines of the imbalance in phase between the modes, $\varphi = \theta_A - \theta_B - \theta_C$, act to couple the modes.

To understand the effects of the intermediate order terms we examine the quasi-linear growth phase (i.e. dropping the high-order bracketed terms). We assume that mode *C* is slowest growing mode and either *A* or *B* is the fastest-growing mode that generates the dominant OLE mode. We convert the first-order Landau coefficients into polar form (e.g. $a_1 = |a_1|e^{i\varphi_{a_1}}$) and the equations for the amplitude growth and phase changes become

$$\frac{dA}{dt} = a_0 + |a_1| BCcos(\varphi + \varphi_{a_1})$$

$$\frac{dB}{dt} = b_0 + |b_1| ACcos(\varphi - \varphi_{b_1})$$

$$\frac{dC}{dt} = c_0 + |c_1| ABcos(\varphi - \varphi_{c_1})$$

$$\frac{d\varphi}{dt} = \Delta\omega - \left[|a_1| \frac{BC}{A} sin(\varphi + \varphi_{a_1}) + |b_1| \frac{AC}{B} sin(\varphi - \varphi_{b_1}) + |c_1| \frac{AB}{C} sin(\varphi - \varphi_{c_1}) \right]$$

in which $\Delta\omega = \omega_\alpha - \omega_\beta - \omega_\gamma$ is the phase difference of the eigenvalues ($\lambda_{0,\alpha} = a_0 + i\omega_\alpha$). Clearly, if $\varphi - \varphi_{c_1} = 2n\pi$, the initially slow growth rate of mode *C* (i.e. c_0) will be augmented by $|c_1|AB$. For the specified conditions, the 3rd term in the square brackets of the quasi-linear phase imbalance equation will eventually dominate the right hand side. Furthermore, we can assume that the amplitudes are still essentially exponentially-growing. So, the phase imbalance equation becomes

$$\frac{d\varphi}{dt} = |c_1| \frac{A_0 B_0}{C_0} e^{(a_0 + b_0 - c_0)t} sin(\varphi - \varphi_{c_1})$$

This equation can be solved by separation of variables and the $t \to \infty$ behavior shows that $\varphi - \varphi_{c_1} \to 2n\pi$, usually fairly rapidly. Thus, the triad wave-wave interaction tends to accelerate the growth of the initially slowest-growing mode during the quasi-linear growth phase. This behavior can be seen in Figure 1.

The structure of the multi-scale OLE is determined by the sum of

$$q_\alpha = Aq_{0,\alpha} + BCq_{1,\alpha}e^{i\varphi} + A\left[A^2 q_{2,\alpha} + B^2 q_{3,\alpha} + C^2 q_{4,\alpha}\right] + A^2 q_{20,\alpha} + A^3 q_{30,\alpha}$$

$$q_\beta = Bq_{0,\beta} + ACq_{1,\beta}e^{-i\varphi} + B\left[A^2 q_{2,\beta} + B^2 q_{3,\beta} + C^2 q_{4,\beta}\right] + B^2 q_{20,\beta} + B^3 q_{30,\beta}$$

$$q_\gamma = Cq_{0,\beta} + ABq_{1,\gamma}e^{-i\varphi} + C\left[A^2 q_{2,\gamma} + B^2 q_{3,\gamma} + C^2 q_{4,\gamma}\right] + C^2 q_{20,\gamma} + C^3 q_{30,\gamma}$$

and the mean flow modifications, which are just the sum of the individual single-mode mean flow modifications described in Foster (2005).

An example calculation is shown in Figure 2. In this case, mode C is the fastest-growing mode, with a wavelength of 3.5 km and energy is coupled into a weakly-growing 1 km wavelength mode. The final solution clearly shows organization at all three spatial scales, but the intensity of the 1 km mode is modulated by the 3.5 km mode.

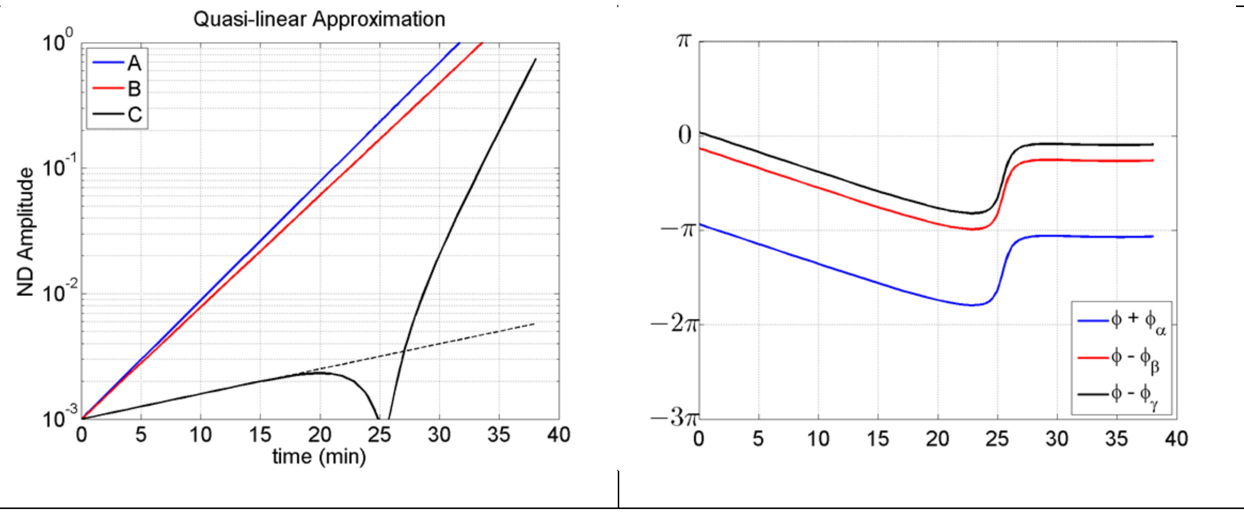

Figure 1: (a) Nondimensional amplitude as a function of time for three interacting modes for the quasi-linear growth approximation. (b) As in (a), but for the phase imbalance relative to the phases of the the first Landau coefficient for each mode. Note that the growth of mode C accelerates when $\varphi - \varphi_{c_1} \rightarrow 2n\pi$ and that it is reduced when $\varphi - \varphi_{c_1} \rightarrow -\pi$.

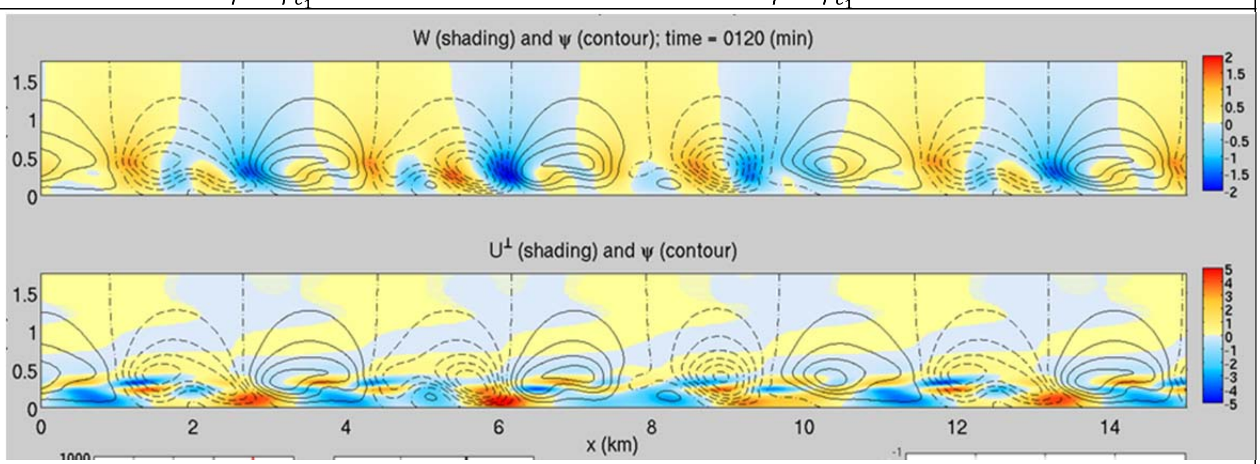

Figure 2: Multiscale OLE for the triad λ_A =1.05 km, λ_B =1.5 km and λ_C =3.5 km. In both panels the contours show the overturning motion streamfunction. In th eupper panel, the color shading is the vertical velocity. In the lower panel, the color shading is the along-roll perturbation velocity.

2.3 Field Campaign Planning

We have been collaborating with other DRI-funded participants on the design of a field campaign to be conducted in Year 2. In field campaigns planned for the Monterey Bay area in August/September 2012, and for MATERHORN at the Dugway Proving Ground (DPG) in September/October 2012, radiosondes will be launched. Many additional instruments including flux sensors will also be deployed during MATERHORN which will allow a thorough evaluation of the EDMF scheme during OLE and non-OLE events

2.4 WRF Modeling and EKMF Implementation

Flight experiments over Monterey Bay and the local complex terrain have been executed within the context of the WRF model run in order to understand and visualize the interaction between winds at different spatiotemporal scales. We have started performing WRF simulations for the non-OLE day and will continue with an observational and numerical OLE case study. The WRF simulations are run using various options for the boundary layer parameterizations including an EDMF scheme.

A student that we hired in 2011 at the start of the project to assist in performing the simulations and evaluate the simulation with past TODWL data (Task 1.9) has left UVA. Steve Greco (SWA) and Stephan De Wekker (UVA) are now performing the necessary simulations on a 64 processor cluster at UVA. A preliminary result is shown in Figure 3.

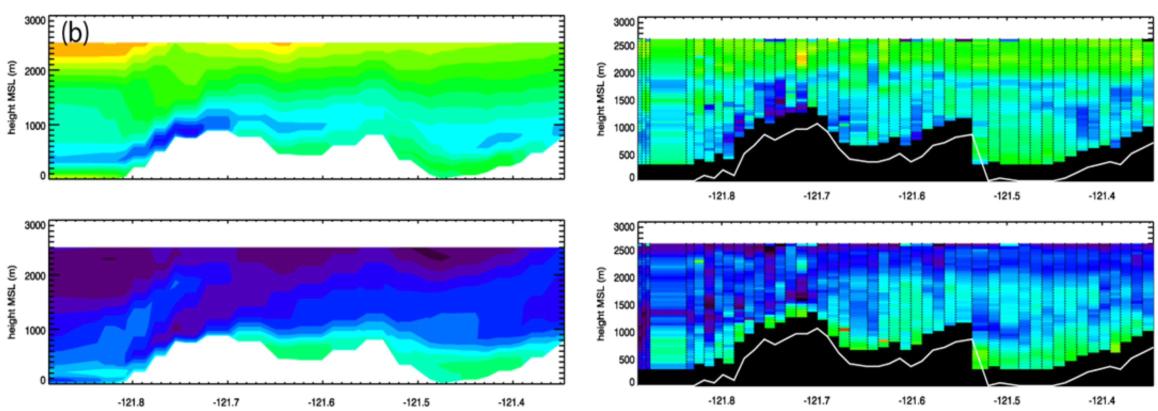

Figure 3: Comparison between simulated (left panel) and Doppler Lidar derived U wind (top) and V wind (bottom) for leg 1 on ~ 22 UTC on November 12, 2007. Topography, determined from the signal-to-noise ratio, is indicated by the white line. Warmer colors indicate more positive wind components.

A comparison of the winds in a cross section shows that some important features of the observed winds are captured by WRF. A more detailed analysis and evaluation of the mesoscale model in which an EDMF scheme is implemented is planned for a journal paper that we plan to submit later in 2012.

Additionally, we are currently performing idealized numerical simulations using WRF-LES to simulate OLE's (in particular rolls) that will be used to test a theoretical model for OLE dynamics that has been developed by collaborator Foster (Task 1.6).

3. References

Foster, R., 2005: Why rolls are prevalent in the hurricane boundary layer. *J. Atmos. Sci.*, 62, 2647-2661.

4. Publications

Godwin, K.S., S.F.J. De Wekker, and G. D. Emmitt, 2012: Retrieving winds in the surface layer over land using an Airborne Doppler lidar. *J. Atm. Ocean. Tech*. **29**, 487–499. doi: http://dx.doi.org/10.1175/JTECH-D-11-00139.1

De Wekker, S.F.J., K.S. Godwin, G. D. Emmitt, and S. Greco, 2012: Airborne Doppler lidar measurements of valley flows in complex coastal terrain. *J. Appl Meteor. Climat*. doi: http://dx.doi.org/10.1175/JAMC-D-10-05034.1.