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Author(s): Jim Kao
Dan Cooper
Jon Reisner
William Eichinger

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Probing near-surface atmospheric turbulence with lidar measurements and high-resolution hydrodynamic models

C.-Y. J. Kao^a, D. I. Cooper^a, J. M. Reisner^a, W. E. Eichinger^b
and M. Ghil^c

^aLos Alamos National Laboratory, MS C323, Los Alamos, NM 87545

^bIowa Institute for Hydraulic Research, University of Iowa

^cDepartment of Atmospheric Sciences and Institute of Geophysics and Planetary Physics,
University of California at Los Angeles

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ABSTRACT

As lidar technology is able to provide fast data collection at a resolution of meters in an atmospheric volume, it is imperative to promote a modeling counterpart of the lidar capability. This paper describes an integrated capability based on data from a scanning water vapor lidar and a high-resolution hydrodynamic model (HIGRAD) equipped with a visualization routine (VIEWER) that simulates the lidar scanning. The purpose is to better understand the spatial and temporal representativeness of the lidar measurements and, in turn, to extend their utility in studying turbulence fields in the atmospheric boundary layer. Raman lidar water vapor data collected over the Pacific warm pool and the simulations with the HIGRAD code are used for identifying the underlying physics and potential aliasing effects of spatially resolved lidar measurements. This capability also helps improve the trade-off between spatial-temporal resolution and coverage of the lidar measurements.

Keywords: Lidar, hydrodynamic model, water vapor plumes, coherent eddies, ocean surface

1. INTRODUCTION

Lidar (Light Detection and Ranging) remote sensing (Killinger and Mooradian, 1983; Measures, 1992) offers the promise of multi-dimensional atmospheric measurements for ranges of single to tens of kilometers, with spatial resolution of a few meters. This technology provides a unique way to describe atmospheric boundary layer (ABL) phenomena (e.g., Eloranta and Forrest, 1992; Cooper et al., 1994). The lidar system used here is a self-contained field-deployable UV Raman water-vapor lidar (Eichinger et al., 1994) built at the Los Alamos National Laboratory (LANL) and based on the technique pioneered by Melfi et al. (1969). Melfi et al. suggested to compare the backscattered intensities for water and nitrogen in the vibrational Raman band. This permits one to infer the water-vapor concentration, since nitrogen is well mixed in the atmosphere and its concentration is well known.

The LANL water vapor lidar system uses an excimer laser source with 400 mJ/pulse of energy at 200 Hz and wavelengths of 248 nm and 351 nm, respectively, for daytime and nighttime operations. The unique receiver uses a 24" f8 telescope and scanning optics to allow 3-D volumetric imaging of water-vapor mixing ratio. The receiving detector system provides simultaneous measurement of the elastic backscattered UV radiation from aerosols and clouds, as well as the nitrogen and water Raman signatures. The system has a near-field spatial resolution of 0.5 mradian by 1.5 meters and 70-meter far-field resolution.

Water, in its three phases, is of paramount importance in most atmospheric processes; it is involved in competing feedback mechanisms that affect the climate system on all scales. The surface-atmosphere exchange of water, in particular, has received significantly increased attention. However, a fully quantitative understanding of the near-surface distribution of water vapor has yet to be obtained. A basic problem that remains is to determine the water-vapor distribution at the scale of turbulent eddies (Lawford, 1996). The satellite-based data sets upon which present global environmental assessments depend cannot answer this question and neither can conventional ground-based instruments or aircraft platforms. A scanning lidar is useful in this regard because of its high spatial and temporal resolution and the horizontal and vertical cross-sections it can produce.

Field applications of the LANL Raman lidar have been successful over both ocean and land surfaces in helping understand the water vapor's variability and in estimating its surface flux. Some of the more recent lidar projects conducted by LANL include (i) the Maricopa, Corrales and Socorro (MCS), NM, Evapotranspiration (ET) Experiments, (ii) the Lake Mead Land-Water Interface Experiment, (iii) the Yucca Mountain Surface Evaporation Experiment, (iv) the Central Equatorial Pacific Experiment (CEPEX), and (v) the Combined Sensors Program (CSP) over the Pacific warm pool. Descriptions of these projects are given below. The MCS ET studies with the Raman system showed great temporal and spatial variability of water and energy fluxes even over uniform canopies. The Lake Mead Experiment was the first investigation of energy-mass transport at a land-water interface with a high spatial resolution. The Yucca Mountain project extended the lidar application to surface-atmosphere interaction over a complex-terrain region with mixed vegetation. CEPEX was part of an international climate research effort to address the "thermostat hypothesis," a feedback mechanism between water vapor and ocean sea surface temperature purported to limit global warming (Ramanathan and Collins, 1991). Our lidar results during CEPEX show the agreement with the coincident radiosonde water-vapor data within 0.25 g/kg (Cooper et al., 1996). The CSP project (Post et al., 1997) employed a whole suite of meteorological sensors to quantify processes associated with ocean-atmosphere interactions in the tropics, and to help understand the small-scale processes in the ocean-atmosphere exchange of water and heat.

The lidar data shown in this paper were collected during CSP on 26 March 1996. Cooper et al. (1997) and Hagelberg et al. (1998) have shown that the LANL lidar system is a highly accurate and reliable probe of turbulent ABL processes during CSP. However, to better help describe and understand these processes, we need to demonstrate the actual representativeness, as opposed to the mere quantitative accuracy of the lidar data.

Like all volume-imaging sensor systems, lidars require an advanced methodology to make the best use of their measurements' temporal and spatial properties. Over the last decade, experimentalists have made every effort to make the lidar scan as fast as its laser power and detector's efficiency allow, while retaining a good signal-to-noise ratio. Faster scanning, however, does not necessarily improve the lidar imagery's value in terms of better dynamical insight as long as the features of interest still evolve significantly over the faster scans' duration. It is difficult, therefore, to determine the scanning strategy from first principles, since the atmosphere evolves continuously over the entire range of spatial and temporal scales. This study uses a state-of-the-art turbulence-resolving model to help synthesize the ABL phenomena observed through the LANL scanning Raman water-vapor lidar system.

2. LIDAR DATA

In general, the oceanic ABL is characterized by the presence of both vertical wind shear and thermal instability (Stull, 1988). As a result, it can be subdivided into a surface layer, a free-convection layer, and a mixed layer; in each of these sublayers, the balance of heat, momentum, and moisture fluxes is different. The characteristic height of the surface layer is the Monin-Obukhov (Kaimal and Finnigan, 1994) length of a few tens of meters. The free-convection layer extends up to about $0.1 Z_m$, where Z_m is the height of the first temperature inversion at about 1 km above the surface; Z_m is also the characteristic height of the mixed layer. Field experiments using aircraft (William and Hacker, 1993) and numerical studies (Schmidt and Schumann, 1989) show, in fact, that these sublayers are not well separated from each other: small-scale

plumes formed in the surface layer rise and combine into larger-scale thermals in the free-convection layer, while sinking air from the mixed layer penetrates into the free-convection and surface layers.

When a lidar operates at a fixed azimuth angle and scans over a range in elevation with time, the resultant image covers a vertical slice of the atmosphere (see Fig. 1A). At a fixed height with a zero elevation angle, the lidar can be operated to scan over a horizontal slice of the atmosphere (see Fig. 1B). Neither of the above slices represent a truly instantaneous field of water vapor, simply because each lidar line-of-sight collects data at a different instant in time. The water-vapor mixing ratio shown in Fig. 1A is a portion of a vertical slice observed during the CSP project. The slice covers 40 degrees of elevation angle and is made up of 81 lines-of-sight, with an angular resolution of 0.5 deg. Each line-of-sight took 0.75 s and the total scanning time was 60 s. The 0.75-s delay between scans should not affect the general flow features being observed: the rising motion of moist air (in red, yellow, and green) and the descending motion of dry air (in purple and blue). The regrouping of near-surface coherent plumes into larger and more organized eddies as they rise through the surface layer and the accompanying descent of dry eddies from the well-mixed layer toward the surface have been proposed by earlier studies (Wyngaard et al., 1988, William and Hacker, 1993). Such organized exchanges between the surface layer and the rest of the ABL above contradict the classical Monin-Obukhov similarity theory (Kaimal and Finnigan, 1994), which assumes the two to be independent of each other. Simple curve fitting of the data shown in Fig. 1A reveals that Monin-Obukhov similarity theory consistently overestimates, in fact, the moisture in the upper part of the surface layer.

Figure 1B shows the horizontal distribution of water-vapor mixing ratio measured by the lidar at a 10-m elevation above sea level during CSP, based on the same measurement specifications used in Fig. 1A. Using a two-dimensional wavelet technique (Hagelberg et al. 1998), we identified a dominant radius of 10 m for the coherent eddies (in red and yellow) shown in Fig. 1B. The drying effects due to the organized downward air flow (in purple and blue) are also present. The 0.75-s delay between scans used in Fig. 1B may, however, introduce some aliasing effects in the number and position of small-scale turbulent water-vapor plumes near the surface, since the plumes' recycling time scale at the 10-m level is rather small (at the order of 10 s) (Kaimal and Finnigan, 1994). The spatial structure of the resulting mixed-layer eddies may also be aliased due to the relatively long total duration of the scan. To help provide a more rigorous interpretation of lidar images such as those in Fig. 1, we use a hydrodynamic modeling approach to see to what extent lidar imagery does correctly represent ABL turbulence.

3. MODEL AND SIMULATION DESIGN

The hydrodynamic model used for the current study is an outgrowth of the numerical modeling framework of Smolarkiewicz and Margolin (1993). It is based on a nonoscillatory forward-in-time advection scheme which has the advantage of preserving local extrema, as well as the sign of the transported scalar properties. The scheme has been shown to yield numerical solutions that are consistent with known analytic properties of the modeled flows Smolarkiewicz and Margolin (1998). The model minimizes the need for artificial viscosity, while suppressing nonlinear computational instabilities. Overall, the model is designed to accurately simulate small-scale atmospheric dynamics with high-gradient features; hence it is referred to as HIGRAD. A radiation package is included in the model to simulate the radiative effects in the atmosphere (Smith and Kao, 1996).

In order to match the effective range of the lidar⁴ we use a three-dimensional (3-D) model domain with a size of 560 m by 560 m in the horizontal and 1000 m in the vertical. The vertical extent being about twice the horizontal extent allows the model to simulate the interaction between the free atmosphere and the ABL. Even though the lidar provides data at a 1.5-m resolution in the radial direction, a 2.5-m resolution was chosen the grid size in the horizontal x and y directions, based on a trade-off between accuracy and computing resources. In the vertical direction, a stretched coordinate is used: the first grid point is 0.18 m

⁴ The effective range of the existing LANL water-vapor lidar is from 100 to 650 m; over this range the nitrogen and water-vapor signals coincide, thus insuring the accuracy of the measurements.

above the surface to better resolve the surface layer and the largest grid increment near the upper boundary is about 25 m. The total number of grid cells is 225 by 225 by 81 (~ 4.1 million). The time step for the model integration is 0.125 s, to match the ultra-fine vertical spatial resolution near the surface. It takes 50,000 node-hours of CPU time on the 128-node SGI super-clustered Blue Mountain computer at LANL to perform a one-hour model simulation.

All the subgrid transports use a very small diffusivity coefficient with a constant value of $10^{-7} \text{ m}^2 \text{ s}^{-1}$. Our ABL simulation is thus similar to direct numerical turbulence simulations at least in terms of the very small grid size near the surface and the small diffusivity coefficient. A recent study by Margolin et al. (1999) demonstrates that a nonoscillatory advection scheme such as MPDATA used in our model can accurately reproduce the dynamics of an atmospheric convective boundary layer without incorporating an explicit sub-grid scale (SGS) diffusion scheme. Other researchers (e.g., Linden et al., 1994) reached similar conclusions for different flow regimes. It appears that the implicit diffusion built in nonoscillatory advection schemes serves well as an explicit SGS module.

The initial state of the model simulation was constructed based on the balloon soundings, ship measurements, and the lidar profiles collected by CSP on 26 March 1996. The initial ABL structure in the model simulation is assumed to be vertically well mixed with a constant water-vapor mixing ratio of 19.5 g kg^{-1} and a potential temperature of 301.5 K. The sea surface temperature is set at 302.5 K and the surface water-vapor mixing ratio at 22.5 g kg^{-1} , based on the surface observations from CSP. To excite an initial disturbance, a random temperature perturbation with a magnitude of 0.01 K is imposed at the surface. The initial momentum field is set to be identically zero. A large-scale subsidence rate of 0.01 cm s^{-1} is prescribed to help maintain the height of the mixed layer. No-slip and cyclic boundary conditions are, respectively, used in the vertical and lateral directions.

We wish to compare the model results directly with the lidar data. Since the model output of any variable at a specific time represents an instantaneous 3-D field, it cannot readily be compared with the lidar imagery. We designed a simple visualization code called VIEWER, which mimics the actual lidar scanning geometry and resolution, to "view" the model output that is generated every 0.75 s. Each modeled line-of-sight in VIEWER is thus extracted from a different instantaneous output file and represents the data within an angle of 0.5 deg, out to the radial distance of 560 m. To render more faithful the representation of the actual lidar's coverage as a function of radial distance, we further divide each 0.5-deg viewing angle in VIEWER evenly into ten sub-angles. We then map the simulated data from Cartesian onto the polar coordinates given by each modeled sub-line-of-sight, with a radial resolution of 2.5 m. The final image is then plotted back in Cartesian coordinates. Our VIEWER code thus provides an objective comparison between the simulations and the observations from a scanning lidar.

4. MODEL RESULTS

A quasi-stationary state is reached after 10 model hours into the simulation. It is due to the three-way interaction between radiative forcing, large-scale subsidence, and turbulent mixing. The main features of ABL dynamics are well captured by the simulation's quasi-steady state. At hour 10, the mixed layer is, on the average, moister by about 1.5 g kg^{-1} than the initial value, suggesting vigorous moistening caused by the plumes rising from the warm and wet ocean surface. A towering thermal extends from the surface into the free-convection layer, whose top lies for the given model parameters at about 150 m. The entrainment of dryer and warmer air from the free atmosphere, above the first inversion, downward into the mixed layer is also successfully reproduced (not shown).

The HIGRAD simulation results at 12 hr are shown, using the VIEWER visualization procedure, in Fig. 2. Despite the discrepancies between the two figures caused by the different data textures, the simulated structure and variability of the water-vapor plumes are in fair agreement with the observations shown in Fig. 1. The regrouping of the surface-layer plumes into larger moist eddies is clearly simulated in Fig. 2A. The accompanying downward dry eddies that counterbalance the upward mass and momentum fluxes are

* Correspondence: e-mail: kao@lanl.gov, Tel: 505-667-9226

also well captured. The model, however, appears to produce a larger area of downward dry eddies (Figs. 2A,B) than seen in the observations (Figs. 1A, B). Suggested refinements of the Monin-Obukhov theory for the surface-layer structure include the drying effects of the mixed-layer intrusions (Williams and Hacker, 1993). Our model results (Fig. 2) strongly support the idea that dynamic interactions between the surface layer and the mixed layer are a major mechanism in maintaining the structure of a convective ABL, in good agreement with the lidar observations (Fig. 1).

The HIGRAD-plus-VIEWER system also helps us understand how the transient features may contribute aliasing effects in the data images (e.g., Fig. 1) collected from a scanning lidar. By comparing the scanned VIEWER imagery with the instantaneous model output, we found that the overall ABL structure observed through vertical scans (Fig. 2A) does resemble individual snapshots of the ABL (not shown). The ABL is characterized, within a typical scanning period, by a gradually evolving upward moist branch (left half of Fig. 2A) and a quasi-stationary downward dry branch (right half of Fig. 2A) that change but little between scans.

More severe aliasing, however, can be found in a modeled horizontal scan near the ocean surface, as shown in Fig. 3. Figure 3A shows the modeled imagery of a 90-degree horizontal scan 10 m above the surface, with 81 lines-of-sight in a 60-s scanning time (i.e., an azimuthal resolution that is coarser by a factor of two than the earlier case). Shown in Figs. 3B–3D are the instantaneous water-vapor fields simulated at 1, 30, and 60 s and included in the VIEWER scanning of Fig. 3A. The background contrast between wet and dry zones remains the same throughout the 60-s interval. It is dominated by the more persistent larger-scale dynamics, as described previously. At this scale, the spatial-pattern correlations between the vertical-motion field and the water-vapor concentrations are quite high. The distribution of small-scale plumes and their intensity, however, are highly transient within this interval. As a result, the modeled lidar imagery (Fig. 3A) is heavily biased toward the later time instants in representing the near-surface plumes.

This problem can be handled either by improving the lidar's performance or by adding data assimilation capabilities to our modeling system, or both. Improving lidar performance further requires increasing the instrument's scanning speed while maintaining accuracy and coverage. Data assimilation is a numerical approach to combining measurements that are unevenly distributed in space and time with a model that simulates the flow being observed (Daley, 1991). Near-optimal and computationally feasible methods exist to deal with trade-offs between observing pattern and accuracy, like the one at hand (Ghil and Malanotte-Rizzoli, 1991).

5. CONCLUDING REMARKS

In summary, high-resolution hydrodynamic modeling complements scanning-lidar measurements in an integrated approach for probing atmospheric turbulence. On the one hand, our Raman lidar provides highly accurate data profiles to help initialize model simulations. Lidar scans also provide the necessary information to test model performance, such as the size of surface plumes and the scale of the organized exchange between the surface layer and the atmosphere above. The model simulations, on the other hand, are a primary means of accumulating and crystallizing knowledge required to interpret the lidar data and validate measurement strategies. The model also provides the only means of applying near-optimal assimilation methods to the lidar data. This will allow us to identify future needs for both model and instrument improvements in studying the small-scale variability and surface-air exchange processes over various regions.

We demonstrated here that our integrated model-instrument approach could resolve the plume-scale turbulent features associated with water vapor over a warm ocean surface. The essence of correctly and robustly parameterizing the surface-air exchange in large-scale climate models is to resolve and describe the scales and mechanisms that govern the surface evaporation. We showed that, over warm ocean surfaces, rate-limiting exchange processes occur in turbulent and convective motions at scales of a few meters. The surface plumes and their transport properties are modulated and counterbalanced by larger dry eddies that penetrate downward from the mixed layer. Existing parameterizations of the surface layer have not yet successfully included these processes, not even by using a curve-fitting approach based on Monin-

Obuhkov theory (Brutsaert, 1999). Over land surfaces, near-surface inhomogeneities — due to variable terrain and vegetation — are critical to the variability of water-vapor plumes and to the exchange processes they mediate. This renders fine-scale ABL exploration by the powerful approach described here even more imperative.

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Fig.1. Lidar data collected during CSP: (A) A portion of a vertical Raman lidar scan of water-vapor mixing ratio acquired on 26 March 1996 at 0420 UTC (1820 local time), with horizontal distance on the abscissa and height above sea level (ASL) on the ordinate. The scan reveals near-surface small-scale convective plumes (in red), as well as organized upward (in red, yellow, and green) and downward eddies (in purple and blue). (B) A portion of a horizontal Raman lidar scan of water-vapor mixing ratio acquired at 10 m above the ocean surface on 26 March 1996 at 0440 UTC (1840 local time). The x- and y-axes are two perpendicular directions in the horizontal. Sinking air with low water-vapor concentration surrounds isolated convective plumes. Color bars are shown below each panel.

A

B

Fig. 2. Same as Fig. 1, except for model results from the HIGRAD and VIEWER codes. The simulated scans are from the x-axis toward the y-axis, as in Fig. 1. The two panels are both derived from the same one-minute chunk of model output taken 12 hr after the initial time, while the two panels from Fig. 1 were, by necessity, 20 minutes apart.

Fig. 3. (A) is the modeled horizontal scan with a coarser resolution in azimuth but for a larger scanned area in comparison with Fig. 2B; (B), (C), and (D) are the instantaneous water-vapor fields at 1 s, 30 s, and 60 s, respectively, into the scanning interval used in Fig. 3D.