A TECHNIQUE
USING THE WAVELET TRANSFORM TO IDENTIFY AND ISOLATE
COHERENT STRUCTURES IN THE PLANETARY BOUNDARY LAYER

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A TECHNIQUE USING THE WAVELET TRANSFORM TO IDENTIFY AND ISOLATE COHERENT STRUCTURES IN THE PLANETARY BOUNDARY LAYER

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1.0 INTRODUCTION

A dominant feature of the convective planetary boundary layer (PBL) is the presence of coherent structures often referred to as thermal plumes. These are regions of buoyant, rising air whose maximum height is limited by the capping inversion at the top of the mixed layer. They range in diameter from 0.05 to 5 km or more, scale with the height of the mixed layer (Zi), are the large-scale source of energy input to the turbulence spectrum (Stull, 1989), and provide the mechanism for transferring energy from the surface through the mixed layer and into the capping inversion. When conditions are appropriate, fair-weather cumulus clouds develop at the tops of the thermal plumes. In this sense, small cumulus clouds provide a visual description of the size, location, and lifetime of mature, active thermal plumes in a deep mixed layer.

Plume development is not limited to plumes associated with cumulus clouds. Although the horizontal pattern of thermals is often apparently randomly oriented, Ferrare et al. (1991) showed that thermals can be organized into "thermal streets," similar to cloud streets, but without clouds. The authors also used scanning lidar data to show that the horizontal cross section of thermals is roughly elliptical, with the major axis along the direction of the wind shear vector. Traveling with the mean wind, thermal plumes act as a conduit for heat and moisture between the surface and the lower troposphere.

Thermal plumes can be defined either by patterns of rising air or as organized regions of enhanced "thermal turbulence" that can be depicted by large values of the temperature structure parameter, $C_T^{-2}$, which can be evaluated with remote sensing instruments such as radar profilers and sodars. This more general description includes some regions of downward moving air and entrainment into the plume (Coulter et al., 1993).

Detection of thermal plumes is done most easily with remote sensors that provide either a vertical time section of PBL structure (sodars or radar profilers) or a horizontal cross section of the PBL (scanning lidars or radars). Although thermal elements thus sampled can usually be identified visually from a computer graphics display, their objective definition is more difficult. Conditional sampling and associated techniques usually require some threshold and time-averaging criteria (Gao and Li, 1993).

Wavelet analysis has recently shown great promise as a mathematical tool for the detection and study of these structures. Wavelet analysis provides a mechanism for determining scale and temporal information independently and thereby for isolating singular, nonperiodic events within a time series (Daubechies, 1988; Argoul et al., 1989; Farge, 1992; Gao and Li, 1993). A weighting function whose shape changes with scale is applied repeatedly to a time series. The relative importance of any given scale can be determined at each time. Computing the variance of the transform coefficients calculated over all times allows the overall contributions of different scales to be determined, as is done with Fourier analysis.

2.0 ANALYSIS TECHNIQUE

The wavelet transform can be written

$$ W_{\psi f}(a,b) = \frac{1}{a^{1/2}} \int f(t) \psi \left( \frac{t-b}{a} \right) dt $$

where $f(t)$ is the raw signal. The function $\psi[(t-b)/a]$, called the mother wavelet, is the weighting function applied to all the data; the parameters $a$ and $b$ represent scale size and temporal location, respectively; and the $|a|^{-1/2}$ term maintains constant energy. We have chosen for these analyses

$$ \psi(t) = (1 - 16t^2) \exp(-8t^2), $$

where $t' = (t-b)/a$, similar to Gao and Li (1993). This function has a narrow, strong

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weight near $t = b$ for small $a$ and a broader, weaker central weight with increasing values of $a$. The digital form of (1) was applied to sodar and profiler data with $a$ varying from 1 (a single sample) to 900 (sodar) or 150 (profiler).

The variance of the wavelet transform was then calculated over the complete time series. The scale size with maximum variance ($\hat{a}$) was chosen by inspection; the magnitude of the variance at this scale was used to define a threshold value. Time periods when the magnitude of $\hat{a}$ exceeded the threshold were selected as periods when coherent structures were passing above the sensor.

3.0 DATA AND RESULTS

Figure 1 shows the vertical velocity field sampled by a minisodar (Coulter and Martin, 1987) over a desert steppe during the Boardman ARM Regional Flux Experiment (BARFEX) in June 1992 (Doran et al., 1993). The conditions are representative of a convective PBL with strong surface heating that generates well-defined thermal plumes. Contours of the wavelet transform coefficients (Fig. 2) as a function of scale size and time are derived from the time series of vertical velocity ($w$) at range gate 11 (84 m above the surface) from data shown in Fig. 1. The scale size shown represents the number of time steps to which the scale corresponds. Because typical wind speeds were less than 3 m s$^{-1}$, the maximum scale size (900) corresponds to a horizontal scale of about 1.5 km. A rough correspondence is apparent between periods of strong positive wavelet coefficient and organized positive vertical velocities.

Figure 1. Vertical time section of minisodar-derived vertical velocities. Each range gate corresponds to 8 m. Increasing darkness indicates stronger upward motion.

Figure 2. Contours of wavelet transform coefficients for vertical velocity data at range gate 11 in Fig. 1. Contour interval is 2 m s$^{-1}$; negative values are dashed lines.

Similar analyses can be made from 915-MHz profiler data from the Southern Great Plains Cloud and Radiation Testbed (SGP CART) site of the Department of Energy (DOE) Atmospheric Radiation Measurements (ARM) Program. In these cases, samples of the profile of vertical velocities were obtained every 15 s rather than every second; however, in light winds this sample rate is still sufficient to identify coherent structures.

Figure 3 is an example of wavelet variance determined from profiler data on days with contrasting conditions. Both curves have distinct maxima that were chosen to define...
both the principal scale of coherent activity and the threshold value. In some other cases

a peak is not isolated; however, a flat "saddle point" or inflection invariably appears at the appropriate scale. The saddle point is chosen if no well defined peak is present. The threshold value, \( C_{th} \) was chosen as

\[
C_{th} = 0.5(V_{\alpha})^{1/2}
\]  

where \( V_{\alpha} \) is the variance at the chosen principal scale.

Analysis of the wavelet transform field to identify times when the size of the wavelet transform coefficient at the principal scale exceeds \( C_{th} \) is straightforward. Figure 4 shows examples of vertical velocities on convective afternoons above desert steppe (sodar) and Oklahoma grass and wheat fields (profiler). The regions of coherent structure (defined by time periods with predominantly positive \( w \)) correspond well with the time periods selected by the objective-analysis scheme. We note the fairly well defined

character of elevated vertical velocities at both 44 and 520 m (The thermal structure is more apparent when multiple heights are analyzed). The velocities in the wavelet-defined thermal regions at 520 m are approximately twice those at 44 m, even though the minisodar data over the desert are associated with heat fluxes roughly 50% larger than those over grassland (320 W m\(^{-2}\) vs. 220 W m\(^{-2}\)).

Data were analyzed objectively as described above using 12 afternoon periods (4 h each) at the SGP CART site with profiler vertical velocities and from a single hour above desert steppe and nearby heavily irrigated farmland during BARFEX 1992 with minisodar-measured vertical velocities. The distribution of the average in-thermal vertical velocity from all time periods is shown in Fig.

5. The negative values in Fig. 5 were produced primarily above the heavily irrigated farmland (the sensible heat flux was often negative because of the very large latent heat fluxes caused by the heavy irrigation) and during two days at the SGP CART site when thick clouds largely eliminated surface heating. In these cases the objective procedure sometimes selects short time periods with negative velocities that are obviously not true thermal plumes. Imposition of a requirement for vertical continuity among selected coherent structure regions will likely correct this problem. Future work will eliminate these cases by requiring vertical continuity in the selected time periods.
Figure 5. Distribution of vertical velocity averaged over coherent structures selected with the wavelet transform. Source data vary over surfaces and conditions as described in the text.

4.0 CONCLUSION

A technique has been developed for objectively defining coherent structures in the PBL by using the wavelet transform. Determination of the peak or inflection point in the variance as a function of scale and use of the magnitude of the variance at the peak as a threshold allowed the time periods for thermal plumes in convective conditions have been determined objectively. Analysis of coherent structures is being used in ongoing work to determine area-averaged energy budgets at the ARM CART site.

5. Acknowledgement

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6.0 REFERENCES


