Identification of turbulence structures above a forest canopy using a wavelet transform

B. J. Turner, M. Y. Leclerc, and M. Gauthier
Department of Physics, University of Quebec, Montreal

K. E. Moore and D. R. Fitzjarrald
Atmospheric Sciences Research Center, State University of New York, Albany

Abstract. The wavelet transform is used to identify scales of large coherent structures present in atmospheric turbulence above the subarctic forest at Schefferville. Individual coherent structures contributing to much of the exchange between the forest and the atmosphere are depicted in terms of both scale and location using contour diagrams of wavelet transform coefficients. Three typical case studies of turbulence and flux observations were selected to examine the physical characteristics of these flux-filled events and their evolution with distance away from the forest canopy. A wavelet transform spectral technique is applied to vertical velocity, temperature, and turbulent heat flux data observed over the sparse coniferous forest to extract the relative importance of each scale present in those data series. The scale of turbulence structures in relation with their characteristic spacing is discussed.

1. Introduction

The recent interest in the emission of biogenic gases from the boreal forest has prompted detailed observations of fluxes above the coniferous forest at Schefferville. While time-averaged mass flux measurements provide information on the total amount of gases emitted per unit time and area, these time-averaged observations do not shed any light on how those gases are transported from the forest environment to the atmosphere. Are those gases transported mostly in a sporadic, intermittent fashion or are they exchanged continuously between the forest and the atmosphere? What scales of eddies are responsible for the bulk of the upward transport of terpenes and isoprenes away from the Schefferville forested environment?

Bergström and Hogström [1989] have found that up to 90% of the flux above a pine forest can be contributed by coherent structures having just over half the record length. The importance of such structures in the gaseous transfer between the forest and its overlying atmosphere therefore explains the interest generated by such phenomena.

But just what is a coherent structure? Coherent structures have been described by Wilczak [1984] as distinct large-scale fluctuation patterns regularly observed in a given turbulent flow. They retain their form much longer than smaller-scale fluctuations and they represent the major events in vertical turbulent fluxes. The appearance of organized structures in laboratory studies [Thomas and Bull, 1983], numerical simulations [McWilliams, 1984], and atmospheric boundary layer turbulence [Antonia et al., 1979] has been well documented. In the canopy region such structures result from the large shear created by the presence of the forest in the flow.

Traditional tools to examine the structure of the turbulence such as Fourier spectra and correlation functions are often difficult to interpret in flows exhibiting intermittency or characterized by the presence of aperiodic structures superimposed on background turbulence, as is the case above a forest. As noted by Mahrt [1991a], the irregular spacing of coherent structures masks their actual scales when a Fourier transform is used. This paper illustrates how such difficulties can be circumvented with the use of wavelet transform techniques. This paper also shows how both size and location of large shear-generated structures carrying the bulk of gases to and away from the canopy to the atmosphere can be identified using a space scale visualization technique based on the use of wavelet transform coefficients.

2. Wavelet Transform

Wavelet analysis is a recently developed local transform method [Grossman and Morlet, 1984; Meyer, 1986; Daubechies, 1988] which has shown promise in the analysis of boundary layer observations [Mahrt, 1991a; Hudgins et al., 1992; Turner and Leclerc, 1992, 1993], laboratory studies [Everson et al., 1990], and computer simulations of turbulence [Meneveau, 1991a, b]. The method's potential for the study of coherent eddy structures was emphasized by Farge and Rabreau [1988]. In this section an introduction to wavelet analysis will be preceded by a brief review of the Fourier transform.

A square-integrable (finite energy) function is one for which the definite integral

\[ \int_{-\infty}^{+\infty} f(x)^2 \, dx \]  

has a finite value. Experimental observations, which must be finite valued and extend over a finite time period, satisfy this condition. The degree of similarity between any two square-integrable functions can be indicated using the scalar product:
The set of such functions forms a vector space [e.g., Edwards, 1967], so a set of basis functions can be chosen. Any function can then be completely described by its scalar product with (i.e., component onto) each of the basis functions chosen.

The Fourier transform gives the components of a function onto a basis of sines and cosines of each wavenumber \( k \). In complex notation

\[
F(k) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} f(x) e^{ikx} \, dx
\]

(3)

For any series of measurements the integral in (3) will be finite. A Fourier power spectrum \( S_F(k) \) can be defined such that

\[
\frac{1}{2\pi L} \int_{s_0}^{s_0+L} f(x)^2 \, dx = \frac{1}{L} \int_{-\infty}^{+\infty} |F(k)|^2 \, dk = \int_{0}^{+\infty} S_F(k) \, dk
\]

(4)

where \( L \) is the record length, \( F(k) \) is the Fourier transform, and the asterisk denotes the complex conjugate. The Fourier power spectrum gives a measure of the prevalence of periodicities of each wavenumber in the series of observations. The frequency-weighted Fourier power spectrum \( kS_F(k) \) gives a similar power spectral density per logarithmic interval of \( k \).

The basis functions of sines and cosines are precise in frequency and extended in space. Consequently, the Fourier power spectrum gives precise frequency information but conceals information about where individual features appear or how they are distributed. This becomes crucial in highly intermittent turbulent flows. As well, \( S_F(k) \) responds strongly both to scales and to spacing of individual features [Gamage, 1990].

With the wavelet transform, basis functions are constructed from a normalized pulse, called a wavelet, which is more localized in space but less localized in frequency than a sine or cosine. The simplest wavelet is the Haar wavelet:

\[
\psi^0(x) = \begin{cases} +1, & -\frac{1}{2} \leq x \leq 0 \\ -1, & 0 \leq x \leq +\frac{1}{2} \\ 0, & \text{otherwise.} \end{cases}
\]

(5)

Dilations of the basic wavelet to different scales are defined by

\[
\psi^m(x) = 2^{-m/2} \psi^0(2^{-m} x)
\]

(6)

(\text{where } m \text{ is an integer}). For each scale index \( m \) this gives normalized wavelets of length \( 2^m \).

The wavelet transform coefficient for an interval of length \( 2^m \) centered at position \( x \) is given by

\[
W(x, m) = \frac{1}{L} \int_{s_0}^{s_0+L} f(z) \psi^m(z-x) \, dz
\]

(7)

Wavelet coefficients for each scale can be taken to represent the features lost when the resolution of \( f(x) \) is smoothed by a factor of 2 [Mallat, 1989]. This leads to an efficient fast wavelet transform algorithm which is well described in Appendix A of Meneveau [1990].

We can now represent a function in terms of its wavelet coefficients:

\[
f(x) = \sum_m \sum_i W(2^m(i + \frac{1}{2}), m) \psi^m(x - 2^m(i + \frac{1}{2}))
\]

(8)

(\text{where } i \text{ is an integer}). The wavelet coefficients are related to the variance by

\[
\frac{1}{L} \int_{s_0}^{s_0+L} f(x)^2 \, dx = \frac{1}{L} \sum_m \sum_i W(2^m(i + \frac{1}{2}), m)^2
\]

(9)

In this study, wavelet coefficients for each scale are determined at each position for each \( m \). In the limit, a wavelet power spectrum can be defined as

\[
S_w(m) = \frac{1}{L} \int_{s_0}^{s_0+L} 2^{-m} W(x, m)^2 \, dx
\]

(10)

This quantity, with slightly different notation, is the "wavelet variance" investigated by Mahrt [1991a]. \( S_w(m) \) is a measure of the importance of features at length scales near \( 2^m \), in a power of 2 wavenumber interval (an "octave").

A frequency-weighted Fourier spectrum gives a spectral density per (natural) logarithmic interval of \( k \), whereas the wavelet spectrum gives a spectral density per octave (factor of 2 interval) of \( k \). One must therefore apply a normalization factor such that

\[
(\log 2)kS_f(k) \sim S_w(m)
\]

(11)

for a meaningful comparison of the two spectra.

This study will also examine a wavelet flux spectrum, an example of which is the wavelet vertical heat flux spectrum:

\[
S_w^{wT}(m) = \frac{1}{L} \int_{s_0}^{s_0+L} 2^{-m} W^w(x, m) W^T(x, m) \, dx
\]

(12)

where \( W^w \) and \( W^T \) are the wavelet coefficients, respectively, of vertical velocity and temperature. A similar wavelet cospectrum was introduced by Mahrt [1991b]. Values of \( S_w^{wT}(m) \) can be positive or negative, reflecting whether the net flux at each scale is upward or downward.

3. Data Analysis

3.1. Schefferville experiment. The data were collected during the 1990 NASA Arctic Boundary Layer Expedition 3B (ABLE 3B) field campaign to provide micrometeorological information to support observations of trace gases emanating from the boreal forest ecosystem. The data were collected near Schefferville, Québec, Canada (54°48'N, 66°49'W), in the summer of 1990 above a coniferous forest. This forest is a typical sparse and short (with mean tree
height of 6.3 m) subarctic forest. It is composed primarily of
black spruce (*picea mariana*) and tamarack (*larix laricina*)
with some white spruce (*picea glauca*) and balsam fir (*abies
balsamea*). A thick layer of lichens covers the ground. The
zero-plane displacement was estimated to be 0.40 m [Fitz­
jarrald and Moore, this issue].

Measurements were made at three levels above the forest
on a 30-m tower on reasonably level terrain. One triaxial
sonic anemometer (Applied Technology, Boulder, Colorado)
was placed at 29.8 m and two single-axis (vertical) sonic
anemometers (Campbell Scientific, Logan, Utah) were
located at 8.7 and 13.1 m. Fast response thermocouples
Campbell Scientific, Logan, Utah) were installed at the
highest and lowest levels (29.8 and 8.7 m). The location of
these fast response instruments provides eddy correlation
estimates of sensible and latent heat fluxes at three and two
levels, respectively. The sampling frequency was 10 Hz and
results presented here are based on a 1-s grab sampling
interval.

Observations used in this paper were made on August 11,
1990. Wavelet contour analyses were made on two (typical)
individual case studies (section 3.2.2). One period with unstable
atmospheric conditions, beginning at 1456 eastern daylight time
(EDT), was chosen as it contained temperature ramps, a
manifestation of coherent structures in the measured signal.
A transition period during the early evening at 1942 EDT was
also selected for analysis since it contained both locally
upward and downward heat flux events. Wavelet spectra
(section 3.3) are also examined over a 2-hour (unstable
conditions) period beginning at 1214 EDT of the same day.
This particular period was selected because of its steady
windspeed and stability conditions over that long record
length.

3.2. Wavelet Contours

The wavelet contour diagrams presented in this section
are contours of $2^{-m} W(x, m)^2$ on a phase plot of horizontal
scale versus position. This is the integrand of expression (10)
which defines $S_W(m)$ and describes the contribution to the
variance of features with length scales near $2^m$.

The Fourier transform of a function gives broad spectral
information. The wavelet transform gives information on
how much different frequency intervals are present in the
function at different positions. Thus the wavelet contour
diagram capitalizes on this combination, delineating regions
of strong activity in phase space of scale versus position.
Examples of similar wavelet phase plots are found in the
work of Argoul [1989] and Mahrt [1991a].

In a similar fashion, wavelet flux contour diagrams (using
heat flux as an example) are contours of the integrand of (12)
defining $S_{Wf}^T(m)$:

$$2^{-m}W^f(x, m)W^T(x, m)$$

This describes the contribution, whether positive or nega­
tive, of features with length scales near $2^m$ and position near
x to the covariance.

In this paper, wavelet contour plots will be used to express
the size of structures as a function of location using the space
scale representation. The term structures used here signify
an abrupt and short-lived change in the signal corresponding
physically to the passage of a large coherent fluid parcel.

Figure 1. Artificial time series and associated wavelet con­tours: (a) and (b) for three features and (c) and (d) with
added fluctuations. Contour levels are 0.02 and 0.10 m$^2$/s$^2$
per octave (power of 2 of scale).

3.2.1. Wavelet contours on artificial time series. Figure
1 shows a synthetic data series with its associated wavelet
contour diagram. Two contour levels are depicted, with the
higher-level contours corresponding to the largest squared
wavelet coefficients. These correspond to the scales and
positions contributing most to the variance, while the lower­
level contours outline space scale regions of smaller but still
significant squared wavelet coefficients and contributions to
the covariance. The first feature, a "top hat," is detected first
at large scales for positions before the feature itself. As the
leading edge of the top hat feature is approached, the feature
is detected strongly by increasingly finer scales of wavelets
(Figure 1b, until the initial discontinuity gives a strong
contour level for the smallest scale on the contour plot.
Similar contours are formed near the position of the sharp
trailing edge of the feature.

The second event in Figure 1a is a simulation of a ramp, a
manifestation of a coherent structure. Its wavelet contour
signature is similar to that of the top hat, with the first half
weakened and the contours shifted to smaller scales. The
third feature in Figure 1a is an inverse ramp, typically
encountered near the forest-atmosphere interface in a thermally stratified boundary layer.

Previous studies [e.g., Liandrat and Moret-Bailly, 1990] have used the wavelet transform, particularly the Haar wavelet, as a method of edge detection in turbulence measurements. Although these contour diagrams are also useful in edge detection, they do reveal strong fluctuations of all scales. The wavelet contour diagram can help identify localized structures with superimposed smaller-scale turbulence. This is shown in Figure 1c, in which a rapid fluctuation of large amplitude has been superimposed on the time series.

Limitations of such contour diagrams should be noted when interpreting them. The exact shape of contours for a given feature depends on the choice of contour levels and to some extent on the wavelet functions used. Also, the wavelet transform algorithm used only calculated wavelet coefficients for wavelet lengths of $2^m$, where $m$ is an integer. The effect of the contouring routine's interpolation is that a region of high contour levels is often "lumpy" and sometimes broken into several smaller localities.

In Figures 2a–2d, the behavior of wavelet flux contour diagrams using several aspects of artificial time series is presented. The first two events, while seemingly identical in the $w'T'$ time series differ in the individual series of $W$ and $T$ (Figures 2a and 2b). This difference in scale leads to markedly different flux contour patterns, revealing the scales of turbulence responsible for the flux. The third event of Figures 2a–2d is similar to the first except that $w'$ and $T'$ fluctuations are exactly out of phase. The resulting downward heat flux appears as negative (dotted curve) contours in Figure 2d.

Figure 2. Artificial time series for (a) vertical velocity, (b) temperature fluctuations, (c) instantaneous heat flux $w'T'$, and (d) wavelet flux contours. Contour levels are $-0.10$ and $+0.10 \text{ °C m/s per octave}$.

3.2.2. Wavelet contours of coherent structures above the sparse coniferous Schefferville forest. Observations from 1456 to 1506 EDT at 30 m are depicted in Figure 3. The Richardson flux number was $-0.12$ and the mean horizontal wind speed near 30 m was $4.0 \text{ m/s}$. The time series and wavelet contour diagram of vertical velocity fluctuations are shown in Figure 3a and the time series and wavelet contour diagram of temperature fluctuations in Figure 3b. The spatial scale of features was obtained using Taylor's hypothesis. Two contour levels are used, with the higher-level contours embedded in the lower-level contours.

This period was selected because of the presence of

Figure 3. Time series and wavelet contours of measurements on August 11, 1990, from 1456 eastern daylight time (EDT) to 1506 EDT: (a) vertical velocity, with contour levels of $0.06$ and $0.20 \text{ m²/s² per octave}$ and (b) temperature fluctuations, with contour levels of $0.010$ and $0.025 \text{ °C² per octave}$.
several coherent structures in the temperature time series. Ramp features in the temperature data occur with microfronts near 180, 320, and 440 s. The temperature wavelet contours detect the presence of large coherent structures with scales ranging from roughly 70 to 400 m. These structures originate well above the roughness sublayer of the forest, as suggested by the several strong vertical temperature drops depicted in Figure 3. The corresponding vertical velocity wavelet contours suggest coincident but slightly smaller characteristic length scales of the observed structures. A visual inspection of the vertical velocity time series indicate less coherent activity than in the temperature data with more high-frequency fluctuations. This is reproduced in the wavelet contours.

Figures 4a–4f show time series and its associated wavelet heat flux contour diagrams at 30, 13, and 9 m during the same period. Here again, the two outer and inner contour levels used are the same at each observation level. As expected, the size and persistence of the observed structures decreases with decreasing distance from the treetop. Upon approaching the canopy, it can be seen that the signal becomes noisier, indicating the breakup of larger flow structures. This likely reflects the influence of the strong wind shear created by the presence of the canopy in the flow. The coherence of the dominating structures over the vertical separation between the three observation levels is apparent (at 30, 13.1, and 9.3 m), with the large features in the heat flux wavelet contours seen simultaneously at all levels.

Figures 5a–5f displays time series and wavelet heat flux contour diagrams (at all three levels) for a 200-s interval beginning at 1942 EDT. The Richardson number was 0.43 and the horizontal wind speed was 3.5 m/s at 30 m. Contour levels illustrated with solid curves depict positive heat flux contributions by the corresponding scales while those drawn using dotted curves depict negative heat flux contributions. The atmosphere is stable in this 1942 EDT period and, as expected, the coupling between the different layers of fluid is weaker than in the previous example. The magnitude of heat flux scales and their intensity are smaller than in the above example, with a more random, homogenous scale distribution with both height and time. This is likely attributed to the gradual vertical thermal stratification due to radiational cooling. In this case study, positive and negative wavelet heat flux contours delineated using different symbols (Figures 5b, 5d, and 5f) detect the scales at which individual upward and downward flux events actually occur. Observations of the heat flux data at several times the forest height (30 m) show instantaneous heat flux values to be mostly negative. Approaching the canopy (at 13.1 m), the effect of thermal stratification and the strong cooling of the forest is more noticeable, with stronger downward heat flux events. This effect is most dramatic with vigorous downward heat flux events dominating the signal at the treetop (9.1 m). In addition, upward flux events become more important with increasing proximity of the canopy. Those may be attributed to the presence of blobs of warm air released right after sunset as a result of the canopy thermal storage accumulated throughout the day (tree trunks, soil, etc.). Thus even though the turbulent heat flux is, on average, negative, these
intermittent small-scale convective structures would still show up as positive heat flux events. Since these originate within the forest and would be restricted in their upward motion by the mean temperature inversion, their effects would be most pronounced near the canopy. The observed timescales of positive heat flux structures in this stable atmosphere are significantly smaller than those in convective conditions seen previously. While these case studies provide valuable insight into the interaction between the forest and the atmosphere and into the evolution of this exchange throughout the day, further work is necessary to infer how these large-scale eddies contribute to the transport of biogenic gases.

3.3. Wavelet Spectra

While wavelet contour diagrams are instrumental in the detection of coherent structures and in the determination of their scales and position, an indication of the spectral contribution of those scales to the variance is most useful.

The spectral contribution of turbulent events to the variance of turbulence variables is, in aperiodic signals such as those often observed in the atmosphere near the forest environment, best evaluated using alternatives to the Fourier spectral decomposition. This is because in a nonperiodic signal, the Fourier decomposition responds primarily to the spacing of structures [Kharkevitch 1960] and thus contains information which differs from the wavelet spectrum [Gamage, 1990].

In an effort to quantify the scales of the coherent structures and their spacing, frequency-weighted Fourier and wavelet spectra are shown in Figure 6. The wavelet spectrum is smoothed by power of two units of wavenumber (octaves). This somewhat limits the precision in identifying the location of the spectral peak. Both types of spectra are normalized by the variance or covariance of the variable(s) of vertical velocity, temperature, and heat flux observations over a 20-min period at 30 m. The mean wind speed at that level averaged 5.2 m/s, with a Richardson number of −0.2.

Figures 6a, 6b, and 6c shows that for a 20-min period (1200 data points), each Fourier spectrum exhibits two peaks. This bimodal behavior is not the representation of a physical process but constitutes an artifact of the insufficient record length (1200 points) used to compute a stable Fourier spectrum. This artifact is notable in the wavelet spectrum. As expected, when 2-hour Fourier spectra are computed (Figures 6d, 6e, and 6f), the Fourier spectral bimodal behavior disappears.

The relatively short data runs lead to much scatter in the spectra and thus warrant caution in their interpretation. Wavelet spectra appear to have spectral peaks occurring at slightly higher frequencies than those of Fourier spectra. The wavelet spectra in Figure 6a, 6b, and 6c exhibit a broad peak for T, W, and WT at dimensionless event scales of about 0.03, 0.8, 0.03, respectively. The wide peak in the wavelet spectrum suggests the presence of more than one size of events contributing to the variance of the record. Fourier spectra extrema suggest, for the illustrated 20-min record, characteristic event spacings of 0.02, 0.05, and 0.02 for temperature, vertical velocity, and turbulent heat flux. While the amount of experimental evidence presented here is small, these results are nevertheless in broad agreement with the results of Jensen and Lenschow [1978] in which the spacing between the structures observed from aircraft observations to be about twice the size of the events in penetrative convection.

However, in spite of the indication above that wavelet spectra peak at a higher frequency than the Fourier spectra, those two spectra are not fundamentally different from one
another for the six contiguous 20-min runs presented in Figures 6d, 6e, and 6f.

Those spectra depict the turbulence characteristics at a vertical distance of nearly 5 times the canopy height, away from the influence of the forest. These spectra are thus likely to better reflect the turbulence characteristics observed in slightly convective boundary layers. This preliminary investigation into the properties of wavelet spectra and of their fundamental difference with the Fourier spectra is, for the physical system described here, reassuring since the difference between the two is small. It is clear that this is a topic worthy of more in-depth investigation.

4. Conclusions

Information concerning the organized structures present in the flow in the atmospheric surface layer above a forest canopy has been pointed out using a novel and promising data analysis tool. Three case studies were used to illustrate the relevance, applicability and usefulness to forest turbulence and flux data in intermittent flows characterized by both intermittency and by the presence of large-scale events contributing to the transport of heat and mass. Wavelet contour diagrams, as described in this paper, provide a method to examine scales, location, and duration of flow structures in turbulent velocity, temperature, and flux records. Tests with artificial time series confirm that structures embedded in less organized turbulence can still be detected by their wavelet contours.

In the case study examining the structure of the turbulence above the forest in unstable conditions (Figure 3a), wavelet contours of vertical velocity, temperature, and heat flux suggest that although there are large-scale coherent eddies, most eddies have scales of tens of meters. Temperature structures tend to have slightly longer length scales, up to 300 m, as seen in Figure 3b.

Wavelet contour plots for heat flux at the three observation levels (Figures 3 and 4) show coherence in intense flux events at each level. Examples of this vertical organization of the flux are seen near 180, 275, and 320 s. Approaching the forest top, the average duration of flux events becomes smaller. The wavelet contours document well the breakdown of eddies in the increased wind shear present closer to the rough and sparse forest canopy.

Furthermore, heat flux wavelet contours obtained for data collected at sunset during the transition from unstable to stable conditions during an early evening period with overall net negative heat flux identify both the scales and the position of negative and positive heat flux structures in the same record. The positive heat flux events appear to originate at low levels as blobs of ascending warm air to later break up and dissipate as they attempt to rise against the inversion. The flow at 30 m in this case was mostly decoupled from the lower levels.

Wavelet spectra computed on several short records suggest the dominant scales of events observed above the forest at nearly 5 times the canopy height in slightly unstable conditions, not significantly different than those computed by a Fourier spectrum, even though, from the scatter present among the different runs, a slight shift to higher frequencies appears to emerge from the wavelet spectra. For the case studied here, the spacing of the structures was found to be generally around one and a half times the event scales for the period in which wavelet and Fourier spectra were computed. More spectra and on longer records should, however, be used to clearly separate the noise from the signal. Of particular interest, wavelet and Fourier spectra should be computed in the immediate vicinity of the canopy and within, where flows are dominated by aperiodic coherent structures.

While this paper looked at how this wavelet transform could be used to detect the characteristic scales at which heat is exchanged in the forest environment, further work should be done to examine the contribution of such structures to total heat, mass (biogenic emissions), and momentum fluxes. A much more exhaustive evaluation of the forest-atmosphere interaction and of the resulting turbulent exchange taking place at the interface should be pursued using the tools presented above. In particular, a study of the modulation by the forest of the scale distribution and of the
scale-scale spacing ratio with increasing proximity of the canopy and inside the canopy should be done. We also suggest a more exhaustive evaluation of the scales and scale-spacing study to identify the effect of shear from that of surface heating.

Since the above techniques are still in their infancy, we suggest that further study should be extended using bases other than Haar. In future work, comparison with results using a continuous wavelet that is more localized in frequency space is desirable, although computationally more expensive and requiring longer records. The effects of changes in the wavelet basis on contours and spectra constitutes a topic needing further research.

Acknowledgments. We are thankful to the comments provided by the reviewer. This work was funded by a grant from the Formation de Chercheurs et l'Aide à la Recherche and the National Science and Engineering Research Council. NASA provided the funding to collect the micrometeorological observations.

References


Farge, M., and G. Rabreau, Transformée en ondelettes pour dé­


McWilliams, J. C., The emergence of isolated coherent vortices in turbulent flow, J. Fluid Mech., 146, 21-43, 1984.


Turner, B. J., and M. Y. Leclerc, Conditional sampling of coherent structures using the wavelet transform, in Turbulence and Diffu­


Wilczak, J. M., Large-scale eddies in the unstably stratified atmo­


(Received December 9, 1992; revised August 6, 1993; accepted August 6, 1993.)