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January 23, 1995

Dr. Dennis Trizna
Space and Remote Sensing Program
ONR 321SR
Room 704
800 N. Quincy St.
Arlington, VA 22217-5660

Dear Dennis:

Enclosed please find a copy of the annual report for our MBL ARI grant number N00014-93-1-0252, "Boundary Layer Coherent Structures" and its AASERT supplement, grant number N00014-93-1-1123. This report has been submitted electronically via e-mail to Ms. Michele Mizuki as requested.

Again accept my apologies for the tardiness of this report.

If you need any additional information, then do not hesitate to contact me.

Best regards,

Hampton N. Shirer
Associate Professor and Associate Head

Boundary Layer Coherent Structures
(MBL ARI)
and
AASERT Supplement

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Long Term Goals

It is apparent that a substantial portion of the air/sea fluxes of heat, moisture, and momentum is accomplished via intermittent processes (Khalsa and Greenhut 1985), processes that are poorly understood at the present time. Recently, Mahrt (1989) has demonstrated that coherent structures in the marine boundary layer (MBL) are responsible for this flux-carrying intermittency. These coherent structure types include such secondary circulations as two-dimensional rolls (cloud streets), three-dimensional convective cells (thermals), and shear-driven eddies (billows) (Brown 1980). These features occur in different atmospheric boundary layer thermal stratification and shear regimes; some are forced primarily by thermal, and others by dynamic, mechanisms.

Our ultimate goal is to determine the mechanisms underlying the intermittency in air/sea fluxes produced by these coherent structure types. As summarized below, we are using a variety of complementary statistical/mathematical approaches to objectively identify the spatial and temporal characteristics of these structures. Our data sources include both the high resolution output produced by the Penn State version of Moeng's Large-Eddy Simulation (LES) code (e.g. Schumann and Moeng 1991) and observations from the MBL ARI experiments performed in 1994 at Risø National Laboratory in Denmark.

Scientific Objectives

Our most immediate scientific objectives are to develop and make operational the algorithms needed to perform the requisite statistical/mathematical analyses of the MBL datasets. To identify the vertical structure of the coherent structures, we have chosen obliquely rotated Principal Component Analysis (PCA; Richman 1986). To capture the contribution of each coherent structure type to intermittency, we have chosen the well-known chaos measure of the correlation dimension (Grassberger and Procaccia 1983; Wells *et al.*, 1994), the recently proposed line-length algorithm of Higuchi (1988), and the capacity dimension (Henderson and

Wells, 1988). Our initial studies of both idealized and archived datasets have revealed that we must properly tailor the PCA and chaos measure algorithms to best capture the coherent structure types within the MBL. In the past year, we have thus concentrated on both techniques development and data analysis of LES output and MBL observations.

Approach

Principal component analysis has been shown to be capable of distinguishing and quantitatively describing multivariate structures within the atmosphere (e.g., Richman 1986; Preisendorfer 1988; White 1989; Alexander *et al.* 1993). Using both standard and newly developed PCA algorithms, we are studying several LES datasets to see which principal components (coherent structure types) are largely independent of the large-scale forcing and which vary sensitively with it (Rinker *et al.*, 1995). The velocity and buoyancy profiles of these components, together with their regime dependence, are being used to quantify the physical processes responsible for forming the different types of coherent structures. These results will then be used to identify, for each forcing regime, the primary physical processes and coherent structure types that are associated with intermittency.

In order to fully quantify the intermittency of coherent structure types, it is necessary to investigate their temporal behavior as well. In recent years, paradigms of complicated temporal behavior have been proposed as the basis for classifying the types of response that may occur in turbulent flows such as those found in the MBL (Henderson and Wells 1988). Nonperiodic, temporal variation is chaotic if the details of a particular time series can not be simulated beyond a few cycles with virtually identical initial conditions, a situation typical of most atmospheric flows. Analyses using such chaos measures as the correlation dimension and the Higuchi (1988) multiscale algorithm are currently being performed on columns of LES data to simulate MBL measurements at a fixed location (Winstead *et al.*, 1995). Both unfiltered LES datasets and coherent structure datasets formed by projecting the unfiltered dataset onto the dominant PCA vertical modes are being considered. By comparing the chaos measures given by these datasets, we will identify the contributions of different types of coherent structures to the intermittency of the MBL. The residual datasets (i.e., the signal not captured by the principal components corresponding to the various coherent structure types) will be tested against the hypothesis of random data, in order to assess the effectiveness of the PCAs in capturing the resolvable structures of the flows. The regime dependency of these contributions will be examined using multiple LES datasets.

We are also applying these chaos measures to observations of the boundary layer, such as those already completed prior to this ARI (Fosmire *et al.*, 1995) and those being conducted by other MBL ARI investigators in the 1994 ARI experiments (RASEX) conducted over Danish waters. By performing similar analyses to both modeled and observed cases, we can develop an objective basis for determining whether similar mechanisms underlie actual and simulated intermittency.

Tasks Completed

The originally proposed correlation dimension algorithm of Grassberger and Procaccia (1983) is subject to large uncertainties owing to the requirement of estimating slopes from a graph. Recently we have extended the alternative correlation dimension algorithm of Takens (1985), and submitted to *Physica D* a revised draft (Wells *et al.*, 1994) of our initial report (Wells *et. al.*, 1993). Our extended algorithm in principle produces an infinite number of estimates of the correlation dimension; as a consequence, the robustness of the estimates from an MBL time series can be assessed. We have tested our new algorithm extensively using *ad hoc* cases to determine the sensitivity of the results to noise or undersampling and to a phenomenon known as lacunarity (Theiler 1988). Application of this algorithm to a several-week boundary layer time series has been summarized in Fosmire *et al.* (1995). Finally, graduate student Laura Suciu has begun work on extending in a similar way the capacity dimension algorithm of Henderson and Wells (1988).

The multiscale algorithm proposed by Higuchi (1988) was coded and tested by Harry Henderson, both on time series of known properties and on several archived datasets. The results indicated that there were benefits to be obtained from the approach that went beyond those discussed in the original paper (Henderson and Thomson 1994). The algorithm has been applied to LES time series by AASERT student Nathaniel Winstead, and preliminary discussion of the coherent structure identified in this preliminary analysis is given in Winstead *et al.* (1995).

Three graduate students (AASERT students Don Rinker, Joe Rohrbach and Todd Sikora) under the guidance of George Young have become familiar with the obliquely rotated PCA algorithm through extensive testing using a wide range of datasets. Application of this algorithm to snapshots of LES data is being performed by Don Rinker, with preliminary results reported in Rinker *et al.* (1995). Finally, George Young during the initial months of his sabbatical at Risø National Laboratory in Roskilde, Denmark has extended the standard PCA algorithms described in Richman (1986) by considering alternative rotation techniques; these techniques are able to capture a coherent structure type that might require combination of several principal components.

Results/Conclusions

Our investigations using idealized chaotic cases have demonstrated that we can identify the signatures of noise contamination or undersampling and lacunarity in the results by calculating a large number of independent estimates of the correlation dimension with our new method (Wells *et al.*, 1994). As a result, we can determine which estimate of the dimension is the most likely to best approximate the correlation dimension. This algorithm, which has proved to be quite successful when applied to the Henon (1976) and Lorenz (1963) attractors, is now ready to be applied to MBL datasets. For example, Fosmire *et al.* (1995) has demonstrated that more robust correlation dimension estimates are produced when the time series for horizontal kinetic energy is used rather than a series for an individual wind component; in the sense of Lorenz (1991), the horizontal kinetic energy seems to be more closely coupled to the underlying dynamics than is any one of the wind components.

The multiscale Higuchi algorithm has been checked for accuracy, and it was determined that three-digit accuracy for the dimension was obtainable using relatively small datasets of length typical for the MBL (Henderson and Thomson 1994). It was also found that the approach was a sensitive indicator of imposed periodic signals, and that it was able to detect such signals even when the signal-to-noise ratio was as low as 1 to 1000. Analysis of aircraft–measured and LES data sets revealed similar results over the range of validity of the data. The most significant result is that the multiscale information from the algorithm offers an alternative method to the measurement of power spectra, and so provides a method to verify the detection and separation of coherent structures from a noisy signal via the PCA approach.

The application of the PCA algorithm to idealized data tests has shown that the method is able to distinguish multiple coherent structure types under several realistic conditions. These tests provide proof that PCA can yield valid results without having an *a priori* conceptual model, as required of previous (conditional sampling) methods. Preliminary analysis of multivariate profiles from LES data sets reveals that mixed-layer convection can be separated from gravity waves of the free atmosphere (Rinker *et al.* 1995). Further work is needed to document the ability of PCA to identify the structures produced by LES.

Impact for Science

The observational and modeling studies currently underway will lead to improved understanding of the flux intermittency commonly observed in the MBL. This will help advance our overall understanding of processes that affect the state of the sea surface.

Relationships to Other Programs or Projects

Our work using LES data is made possible through our close collaboration with our colleague John Wyngaard, who is also supported by the MBL ARI. The work being performed by us on this ARI project is closely related to our work being performed on our HI-RES project to determine the stress variability at the sea surface caused by the boundary layer coherent structure types of two-dimensional rolls and three-dimensional cells. As this stress variability is produced by intermittent vertical momentum transports by these coherent structures, better understanding of the sea surface stress patterns requires a better understanding of the actual momentum transports by these structures. Finally, the development of the improved correlation dimension algorithm of Wells *et al.* (1994) for estimating the correlation dimension was begun under our HI-RES project and then completed under our MBL project.

Transitions Accomplished or Expected

Improved understanding of air/sea flux intermittency will lead to improved means for interpreting sea surface roughness patterns on SAR imagery. This improvement will become possible as we obtain an improved understanding in this ARI project of the vertical momentum transports by the various coherent structure types.

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PUBLICATIONS/PRESENTATIONS/AWARDS—FY93/FY94
HAMPTON N. SHIRER AND GEORGE S. YOUNG, PI
DECEMBER 1994

Refereed Papers

Wells, R., H.N. Shirer, and C.J. Fosmire, 1994: Extension and convergence of the Takens estimators for the correlation dimension. *Physica D*, submitted.

Non-refereed Papers

Fosmire, C.J., H.N. Shirer and R. Wells, 1995: The chaotic structure of low frequency boundary layer time series. *Preprints, 11th Symposium on Boundary Layers and Turbulence*, Charlotte, NC, American Meteorological Society, in press.

Henderson, H.W. and D.W. Thomson, 1994. Fractal dimensions of remotely sensed atmospheric signals. *Proc. of the Second Experimental Chaos Conference*, Oct. 6-8, 1993, Arlington, VA. World Scientific Publishing Company, in press.

Rinker, D.K., T.D. Sikora, and G.S. Young, 1995. Use of obliquely rotated principal component analysis to identify coherent structures. *Preprints, 11th Symposium on Boundary Layers and Turbulence*, Charlotte, NC, American Meteorological Society, in press.

Winstead, N.S., H.N. Shirer, H.W. Henderson and R. Wells, 1995: Diagnosing chaotic behavior in time series produced by large eddy simulation. *Preprints, 11th Symposium on Boundary Layers and Turbulence*, Charlotte, NC, American Meteorological Society, in press.

Number of Graduate Students

Supported by MBL and AASERT	6

Patents

None

Presentations and Briefings

Shirer, H.N., R. Wells, P.J. Bromfield, L.V. Zuccarello, and B.A. Lambert, 1994: Sea surface stress variability caused by kilometer-scale boundary layer circulations Spring 1994 HI-RES Workshop, Ann Arbor, MI, May 1994

Shirer, H.N., R. Wells, H.W. Henderson, C.J. Fosmire, N. S. Winstead, 1994: Diagnosing chaotic behavior in boundary layer time series. Third Marine Boundary Layer Accelerated Research Initiative Workshop, Scripps Oceanographic Institute, La Jolla, CA, July 1994.

Sublette, M.S. and G.S. Young, 1994a: An analysis of the Gulf Stream Atmospheric Front during HI-RES. HI-RES Workshop, Ann Arbor, MI, May 1994.

Sublette, M.S. and G.S. Young, 1994b: An analysis of the Gulf Stream Atmospheric Front during the summer season. Sixth Conference on Mesoscale Processes, Portland, OR, July 1994, American Meteorological Society.

Young, G.S, 1993: Spatial variations in air/sea interaction: Observed phenomena and expected signatures. Hi-RES workshop, Woods Hole Oceanographic Institute, November 1993.

Young, G.S., 1994a: Meteorology of the convective boundary layer. Invited presentation at Woods Hole Oceanographic Institution, Summer, 1994.

Young, G.S., 1994b: Air/sea interaction in convective wakes. Invited presentation at Woods Hole Oceanographic Institution, Fall 1994.

Young, G.S., 1994c: Meteorology of thunderstorms. Invited presentation at Woods Hole Oceanographic Institution, Fall 1994.

Young, G.S., 1994d: Statistical approaches to quantifying coherent structures (RASEX). Invited presentation at Risø National Laboratory, Roskilde, Denmark, Fall 1994.

Young, G.S. and H.N. Shirer, 1993: Contributions of coherent structures to intermittency of air/sea fluxes. Second Marine Boundary Layer Accelerated Research Initiative Workshop, Scripps Oceanographic Institute, La Jolla, CA, March 17, 1993.

Young, G.S., D.K. Rinker, T.D. Sikora, 1994: Coherent structure identification using obliquely rotated principal component analysis. Third Marine Boundary Layer Accelerated Research Initiative Workshop, Scripps Oceanographic Institute, La Jolla, CA, July 1994.

Awards/Honors

H.N. Shirer, co-PI

Promoted to Associate Head of the Department of Meteorology, October 1, 1993.

G.S. Young, co-PI

Awarded sabbatical leave for '94-'95 academic year; majority of time to be spent at Risø National Laboratory, Roskilde, Denmark, in part to collaborate on MBL ARI-funded RASEX field project

Committee or Panel Service

H.N. Shirer, co-PI

Associate Editor, *Journal of the Atmospheric Sciences*, August 1992-December 1993.

G.S. Young, co-PI

TOGA Surface Processes Group (1991-present)
UCAR University Relations Committee (1991-1994)
Mountain Meteorology Committee (1992-present)
ASTEX Science Team (1992-present)

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