ATMOSPHERIC COHERENT STRUCTURES AND BIOLOGICAL INVASIONS

Shane D. Ross*[a)]
*Department of Engineering Science and Mechanics, Virginia Tech, Blacksburg, Virginia, 24061, USA

Summary The language of coherent structures provides a new means for discussion of transport and mixing of atmospheric pathogens, paving the way for new modeling and management strategies for the spread of infectious diseases affecting plants, domestic animals, and humans. Atmospheric dynamical structures have an influence on aeroecology, namely the population structure of airborne microbe species. We report on a recent integration of experimental biology and applied mathematics uncovering how Lagrangian coherent structures and their boundaries, provide a framework for understanding how airborne microbe populations are dispersed and mixed. Applications to identification of frontiers between qualitatively different kinds of behavior in other areas will also be discussed.

Introduction

Many spores, seeds, dust particles and chemical pollutants can be transported across very large distances in the troposphere, sometimes on a continental scale. The atmosphere serves as a medium of transport as well as a reservoir for many of these particles. Several studies show the existence of such long range transport of dust, trace chemicals and biota in the atmosphere [1, 2]. The dynamical systems approach to studying transport in geophysical flows has been around at least since the work of Pierrehumbert [3] and has produced fruitful results. In this paper, we provide a description of sudden temporal changes in the concentration of fungi in the genus *Fusarium* collected with autonomous unmanned aerial vehicles (UAVs) at a single geographic location. In this paper, we explore the possibility that these 'punctuated changes' in concentrations of *Fusarium* are related to the passage of large-scale, moving, transport barriers over the sampling location.

Many *Fusarium* species use the atmosphere to travel from one habitat to another, yet their atmospheric transport is poorly understood. Some members of the genus are important plant and animal pathogens, others saprophytes, and still others are producers of dangerous toxins. Atmospheric transport of *Fusarium* can be broadly categorized into three distinct stages [2] - (1) release and ascent of *Fusarium* into the planetary boundary layer (PBL), (2) long range transport of *Fusarium* in the PBL or above and (3) deposition of *Fusarium* into a new habitat.

In the release and ascent stage, spores of *Fusarium* (or any passively moving particles) have to cross a relatively thin boundary layer that can extend in height up to 50 m, called the surface boundary layer (SBL). The SBL is the lowest 'layer' of the atmosphere and being in contact with the ground, it has very strong vertical gradients in wind speed, temperature and humidity. The flow in this layer is highly turbulent because of the surface effects [4]. The motion of spores in this layer can be approximated as random and indeed the Fokker-Planck equation is one way to describe their motion in this layer. Above the SBL is the PBL, a well-mixed layer in which the turbulence due to the surface forcing decreases. The height of the PBL extends from $\sim$ 50 m to $\sim$ 3 km above the ground, with the upper limit decreasing to as little as 300 m during the night. Once spores manage to cross the SBL and enter the PBL they have the potential to be transported over long distances. Indeed, in the PBL and above, on the meso- to synoptic ($\sim$10-100 km) scale, the motion over time-scales of a day is quasi-2D along constant pressure surfaces which parallel the landscape, following the homogeneous geostrophic equations appropriate to this scale [4].

The first and third stages have received considerable attention in terms of developing computational models, for example in the works of Aylor, Schmale, and co-workers [5, 6]. The long range transport stage has usually been studied using a few sample trajectories [7]. However, the study of individual trajectories cannot fully resolve the complex motion of the atmosphere, nor the resulting changes in the observed concentrations of *Fusarium* in the lower atmosphere. Moreover, studies using individual trajectories may rely on long integration time (days to weeks) for trajectories, which can lead to many uncertainties in trajectory computations. Rather than individual trajectories, the qualitative properties of sets of closely spaced trajectories are more reliable.

Here we discuss a more systematic, geometric framework for discussing the changes in atmospherically advected microorganism concentrations, based on computations of atmospheric transport barriers (ATBs). The ATBs are approximated as Lagrangian coherent structures boundaries (LCSBs) extracted as ridges from the finite-time Lyapunov exponent (FTLE) field. The LCSBs serve as the most important material surfaces within the flow which effectively separate air masses of qualitatively different dynamics, and hence are distinguished transport barriers. We hypothesized that punctuated changes in the concentration of *Fusarium* at a single geographic location are correlated with the passage of atmospheric LCSBs. We test this hypothesis by integrating with experimental measurements of the concentration of dynamical systems framework for computing LCSBs during periods surrounding our *Fusarium* collections.

Hypotheses on role of ATBs in punctuated changes

The role of transport barriers as separatrices that influence both mixing and separation processes has been investigated in many problems of geophysical flows [8, 9]. However, the relationship between the movement of atmospheric LCSBs over the landscape and punctuated changes in concentration of microorganisms at a fixed geographic locations has not yet been investigated. We present hypotheses on the role of LCSBs in punctuated changes in atmospheric concentrations of the fungal genus *Fusarium*. Microbes belonging to the genus *Fusarium* were selected for this study because of the relative abundance of *Fusarium* in the atmosphere and the existence of reliable methods for selectively collecting *Fusarium* in

[a)] Corresponding author. E-mail: shane.ross@vt.edu.

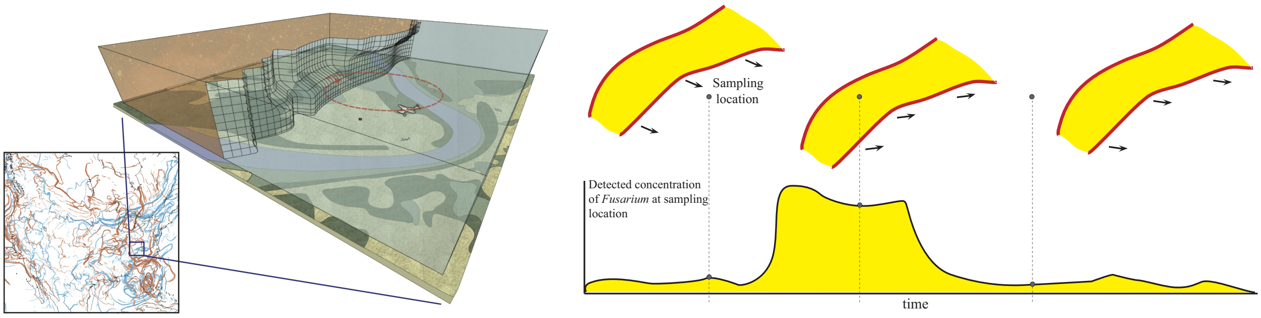

Figure 1. (a) Atmospheric LCSBs are large-scale features with local effects. An LCSB (shown as undulating mesh) separates two volumes of air as it moves over topography, shown schematically on a scale of several kilometers near our sampling site at Virginia Tech's Kentland Farm in Blacksburg, Virginia, USA. We use autonomous UAVs to collect *Fusarium* in the lower atmosphere. We hypothesize that mixed populations of *Fusarium* in the lower atmosphere are mediated by LCSB, as an LCSB is a highly repelling material surface separating two relatively well-mixed air masses. This LCSB is just one of a large-scale network of repelling and attracting LCSB on the continental scale (left). (b) Movement of a 'cloud' of relatively high concentration of *Fusarium* bracketed by repelling LCSBs (upper panel, three time snapshots going from left to right) and the corresponding abrupt changes in detected concentrations of *Fusarium* at a geographically fixed sampling location (below). The continuous signal with time is hypothetical. Sampling yields only a discrete number of observations, as sampling takes a finite duration and the time between samples can be significant. In this example, two punctuated changes are shown (an abrupt increase followed by an abrupt decrease), which are a consequence of the particular LCSB movement with respect to the sampling location.

the lower atmosphere [10]. Moreover, many members of this genus cause important diseases in animals and crops with serious economic consequences, as discussed in the introduction.

Observed changes in the atmospheric concentrations of *Fusarium* suggest that we are sampling masses of air that differ not only in the relative amount of *Fusarium*, but also in their composition of different species and/or strains of *Fusarium*. We hypothesize that moving three-dimensional atmospheric LCSBs are partitioning large-scale air masses, a small portion of which we are sampling with UAVs, as illustrated in Fig. 1. We summarize the hypothesis as: *Punctuated changes in the atmospheric concentration of Fusarium imply the movement of a LCSB over the sampling point, between the two sampling times.*

Results, Conclusions, and Future Work

To summarize the results of the hypothesis testing, our analysis suggests that punctuated changes in the atmospheric concentrations of *Fusarium* are associated with the movement of LCSBs, and particularly repelling LCSBs, in a one-way correlation [11]. That is, when a punctuated change occurs between two sampling times, there is a high probability that a repelling LCSB passed over the sampling location between the two sampling times. We are not suggesting a two-way correlation, i.e., the movement of every repelling LCSB does not lead to a punctuated change. There are two potential explanations for this. First, the chaotic nature of atmospheric flow ensures that many trajectories have a high local repulsion. Second, we did not discriminate between ridges in the FTLE field of high and low magnitude above the threshold. It is possible that the magnitude of punctuated changes can depend on 'repelling strength' of the repelling LCSB. Furthermore, the results of our hypotheses testing are influenced by several parameters: the time-scale used to determine punctuated changes, (12 or 24 hours), the baseline concentration of spores, the threshold value of ΔC which determines whether a change is significant, and other factors. Future studies are expected to systematically investigate the influence of these factors. The role of coherent fluid structures in biological invasion in other contexts should be considered, as well as the role of dynamic barriers in shaping the large-scale migration of organisms more generally.

References

[1] D. E. Aylor. A framework for examining inter-regional aerial transport of fungal spores. *Agricultural and Forest Meteorology*, 38:263–288, 2002.

[2] S. Isard and S. H. Gage. *Flow of Life in the Atmosphere: An Airscape Approach to Understanding Invasive Organisms*. Michigan State University Press, East Lansing, MI, 2001.

[3] R. T. Pierrehumbert. Chaotic mixing of tracers and vorticity by modulated travelling Rossby waves. *Geophysical and Astrophysical Fluid Dynamics*, 58:285–320, 1991.

[4] W. Zdunkowski and A. Bott. *Dynamics of the atmosphere; a course in theoretical meteorology*. Cambridge University Press, 2003.

[5] D. E. Aylor and T. K. Flesch. Estimating spore release rates using a Lagrangian stochastic simulation model. *Journal of Applied Meteorology*, 40:1196–1208, 2001.

[6] D. G. Schmale and G. C. Bergstrom. Spore deposition of the ear rot pathogen, *Gibberella zeae*, inside corn canopies. *Canadian Journal of Plant Pathology*, 26:591–595, 2004.

[7] J. M. Davis. Modeling the long-range transport of plant pathogens in the atmosphere. *Annual review of phytopathology*, 25:169–188, 1987.

[8] C. Coulliette, F. Lekien, J. D. Paduan, G. Haller, and J. Marsden. Optimal pollution mitigation in Monterey Bay based on coastal radar data and nonlinear dynamics. *Environmental Science and Technology*, 41:6562–6572, 2007.

[9] F. Lekien and S. D. Ross. The computation of finite-time Lyapunov exponents on unstructured meshes and for non-Euclidean manifolds. *Chaos*, 20:017505, 2010.

[10] D. G. Schmale, B. R. Dingus, and C. Reinholtz. Development and application of an autonomous unmanned aerial vehicle for precise aerobiological sampling above agricultural fields. *Journal of Field Robotics*, 25:133–147, 2008.

[11] Tallapragada, P., Ross, S. D. and Schmale, D. Lagrangian coherent structures are associated with fluctuations in airborne microbial populations. *Chaos*, 21:033122, 2011.