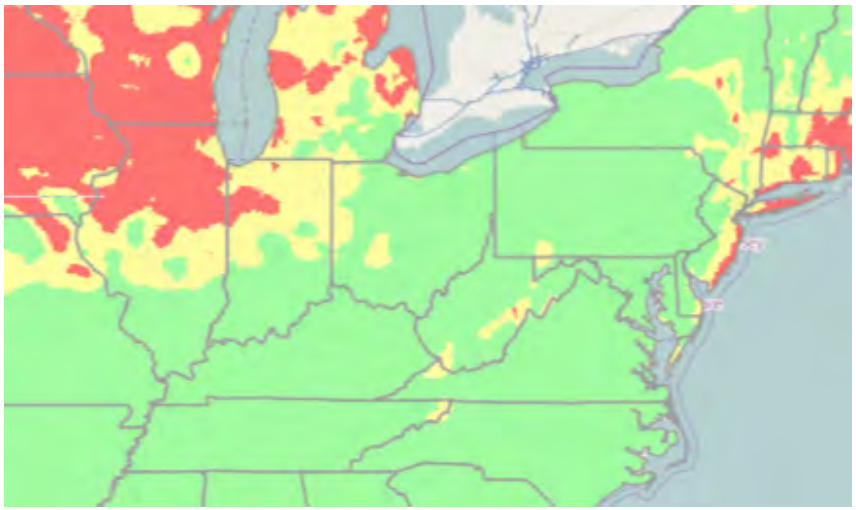
Atmospheric coherent structures and aerobiological invasions

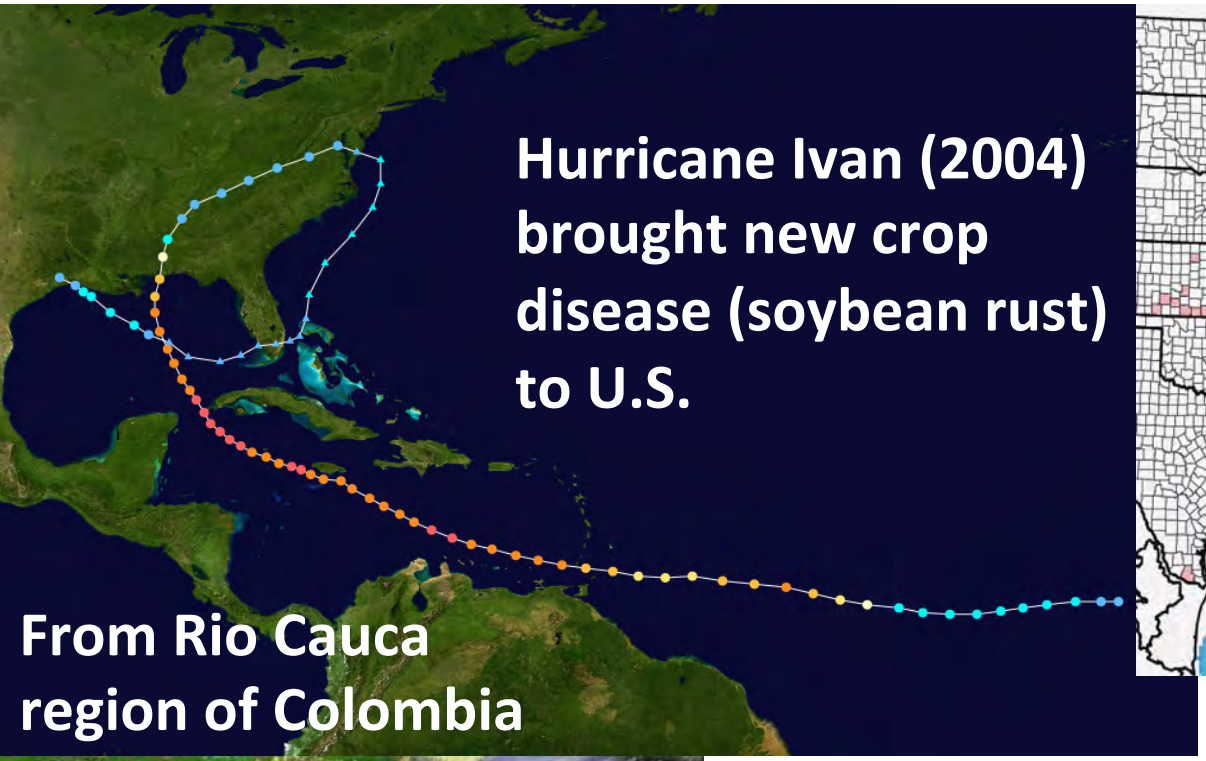
Shane Ross

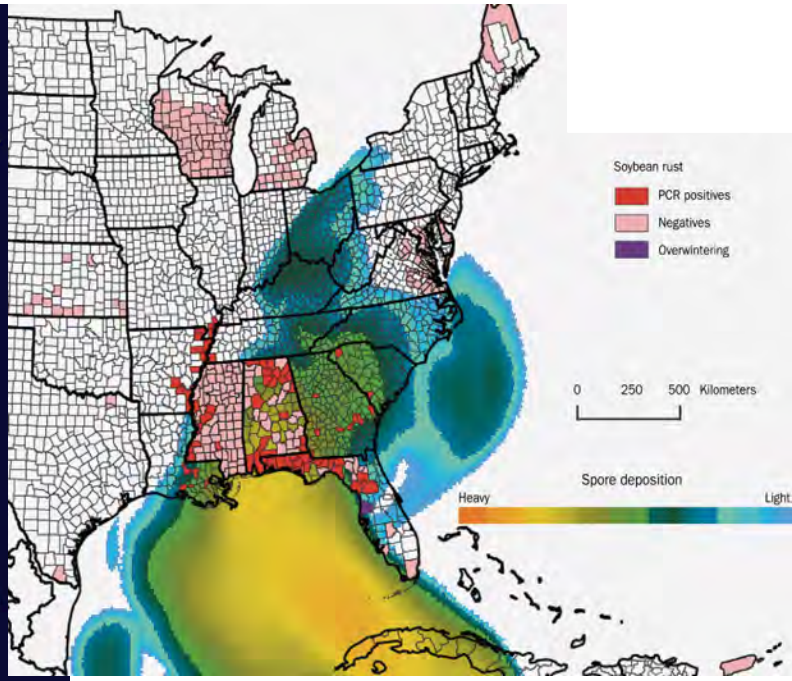
Joint with Amir BozorgMagham, Phanindra Tallapragada, Binbin Lin, A.J. Prussin, David Schmale

Virginia Tech, Department of Engineering Science and Mechanics



Invasive species riding the atmosphere





Red=infected US regions

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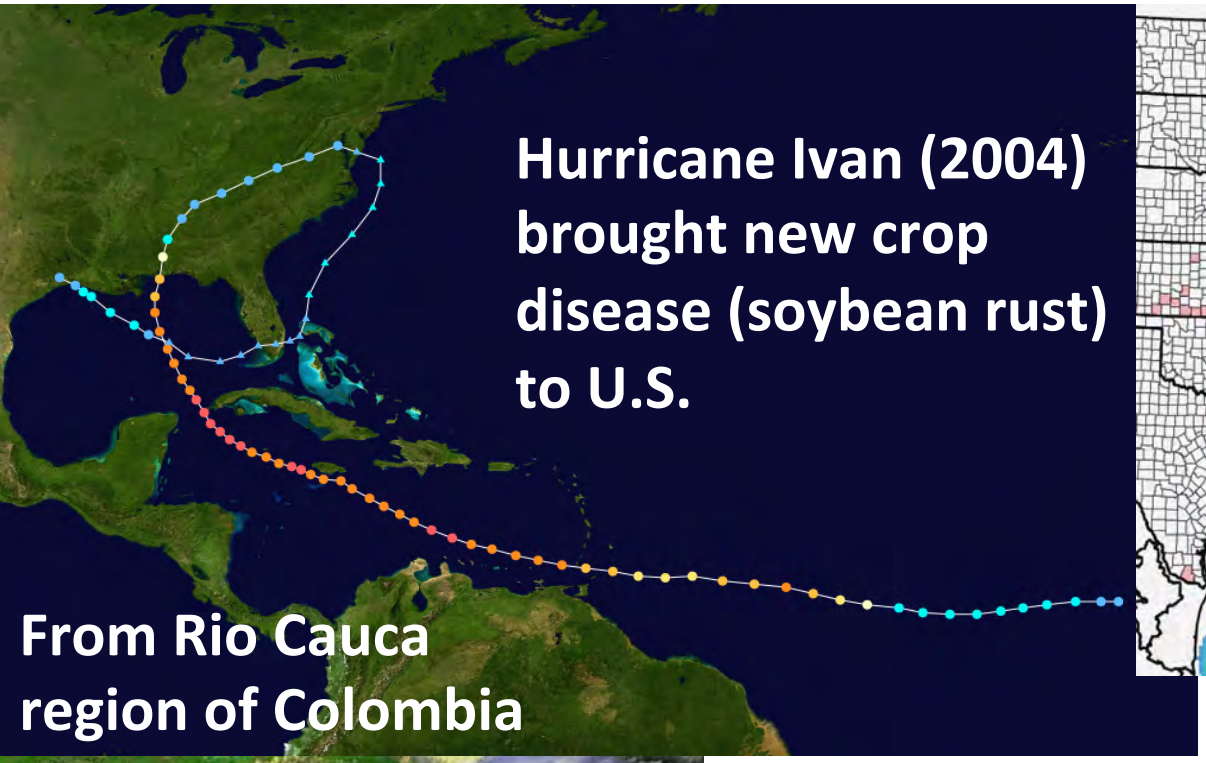
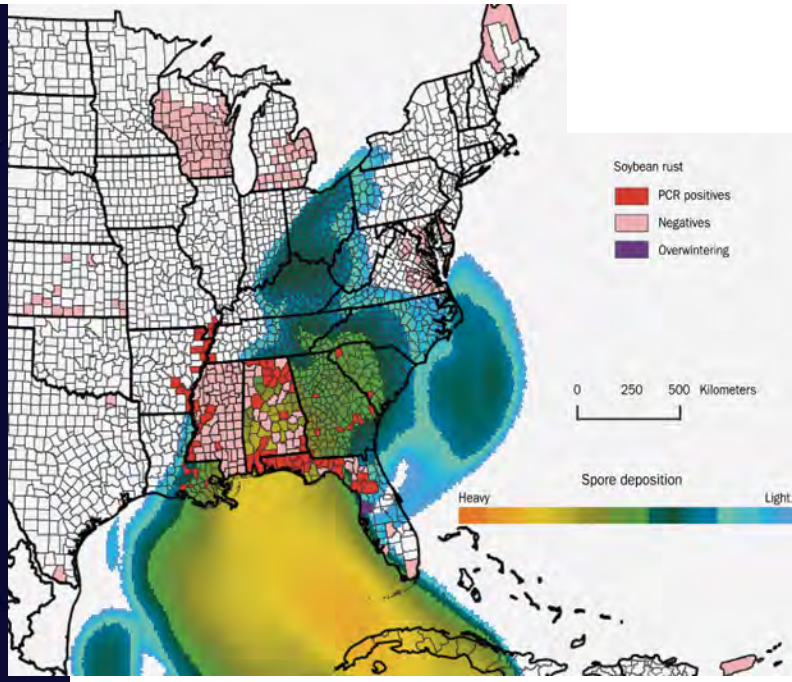
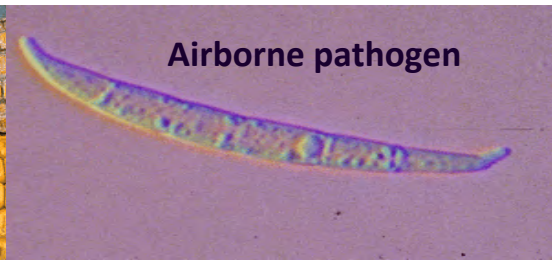


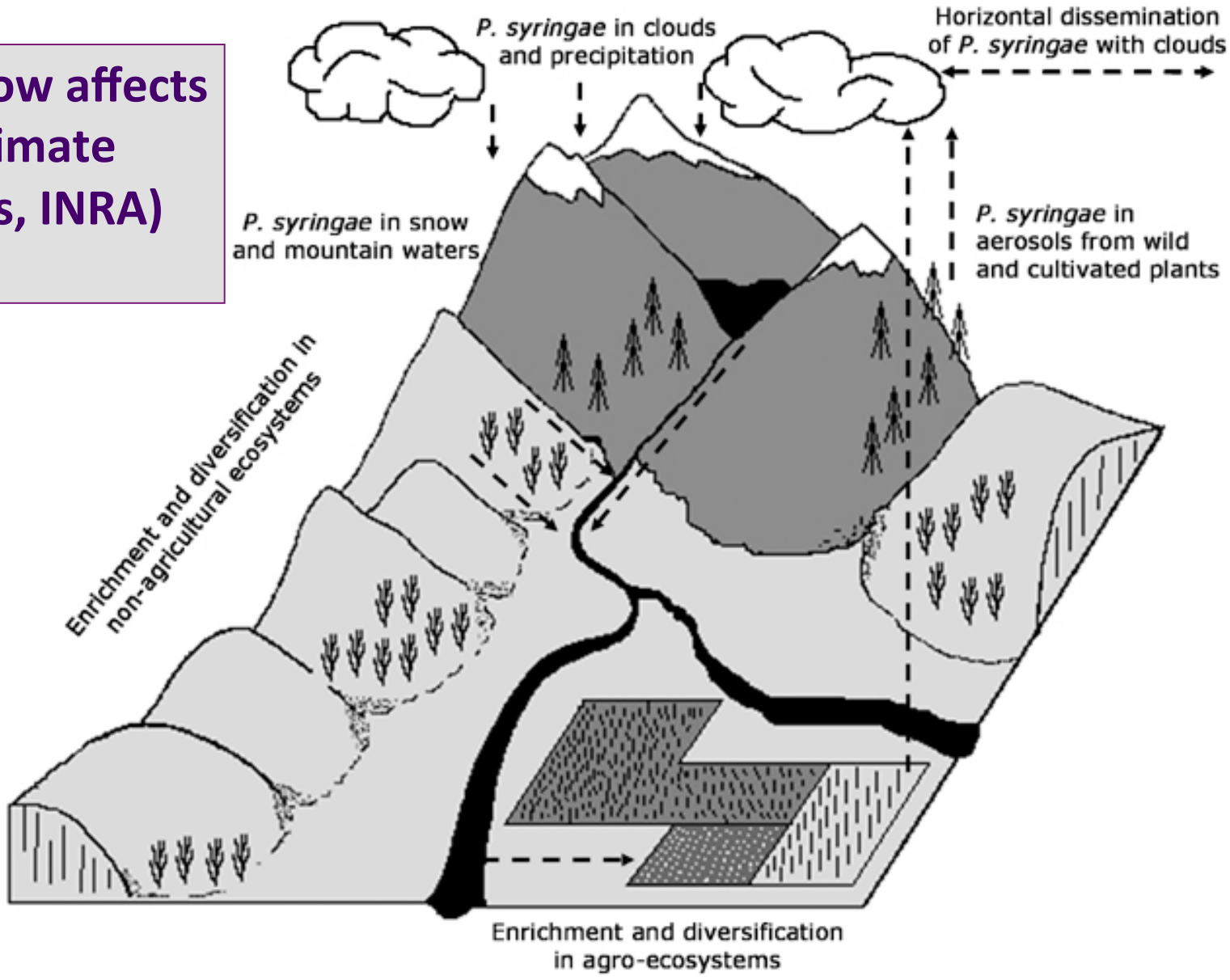


Cost of invasive organisms is ***>$100 billion*** **per year in U.S.**

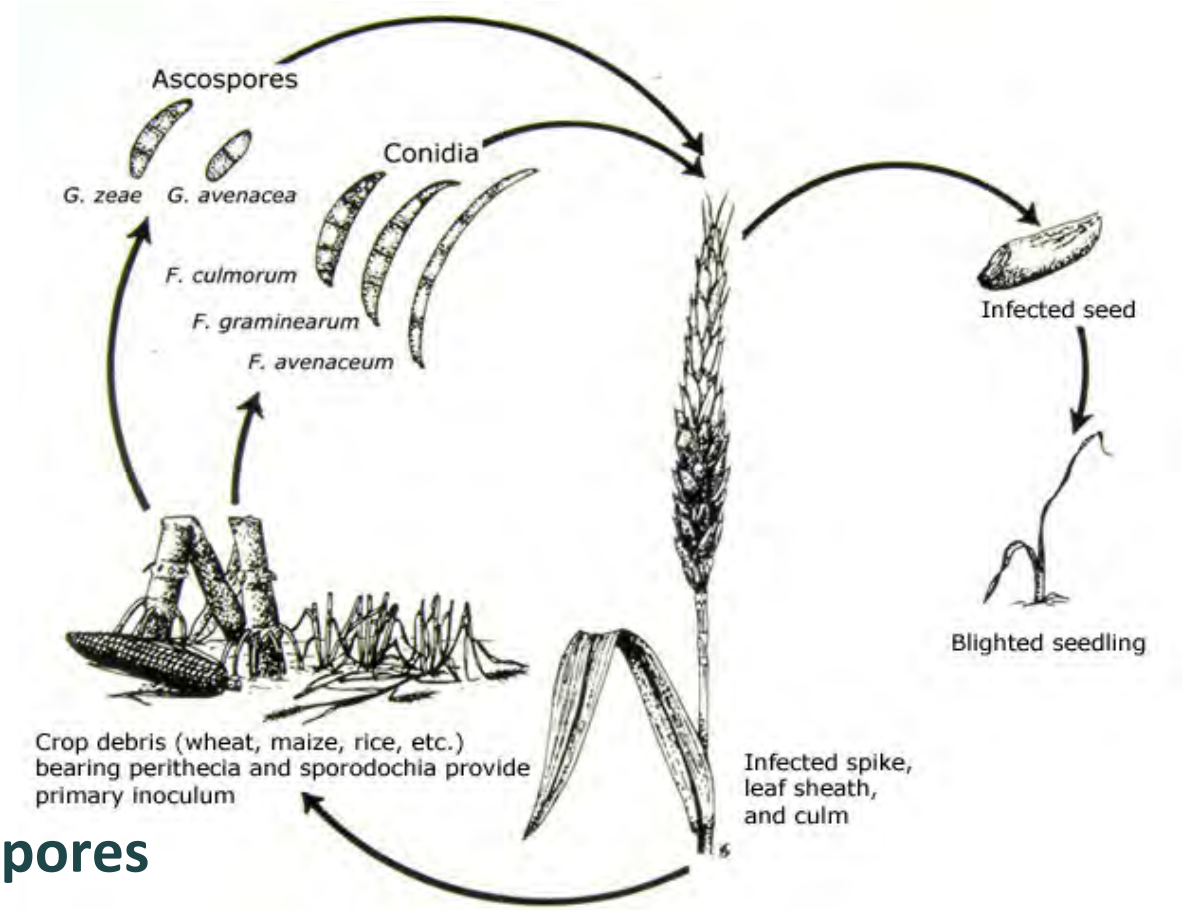


Plant pathogens linked to water cycle

What you grow affects local microclimate (Cindy Morris, INRA)



Atmospheric transport of microorganisms



e.g., *Fusarium* fungal spores

- **Spore production, release, escape from surface**
- **Long-range transport (time-scale hours to days)**
- **Deposition, infection efficiency, host susceptibility**

Schmale & Bergstrom [2003]

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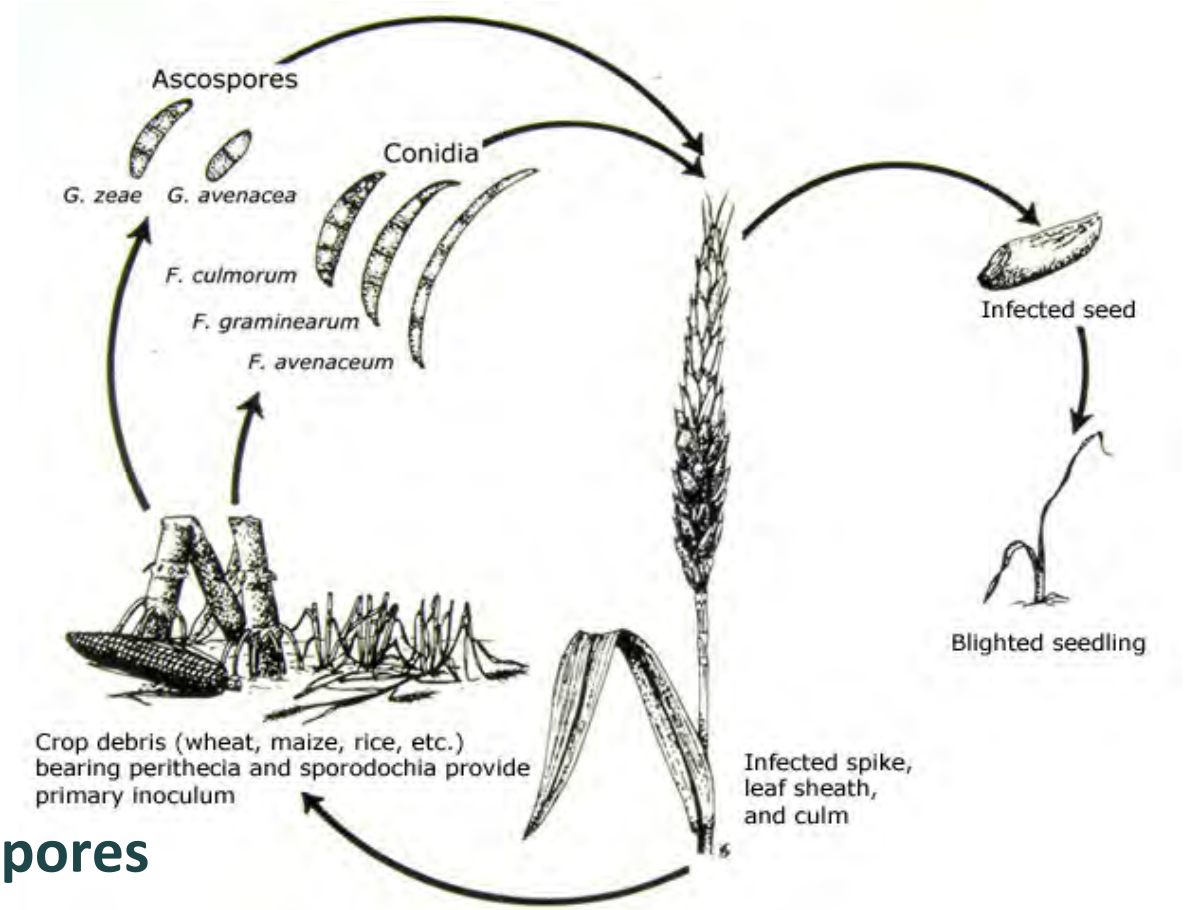

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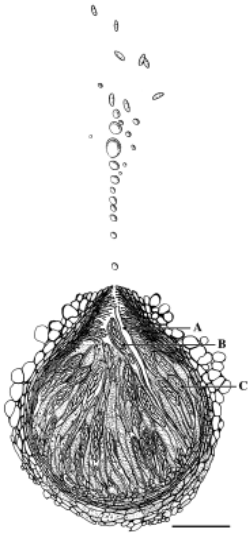
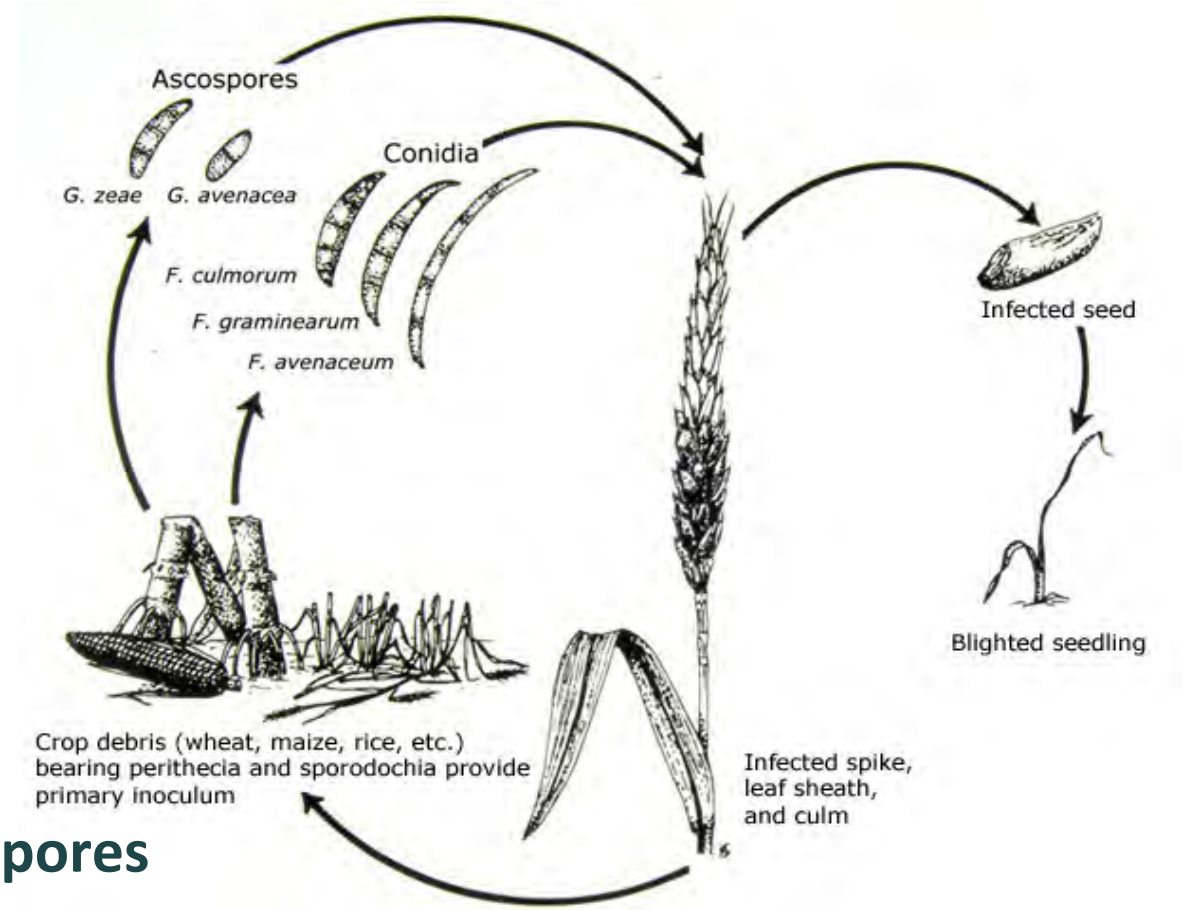


$a \approx 10^6 g$



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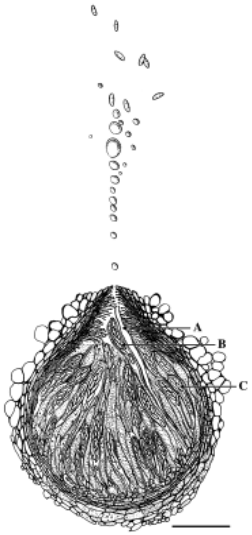
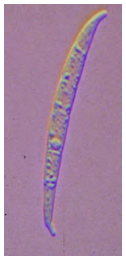
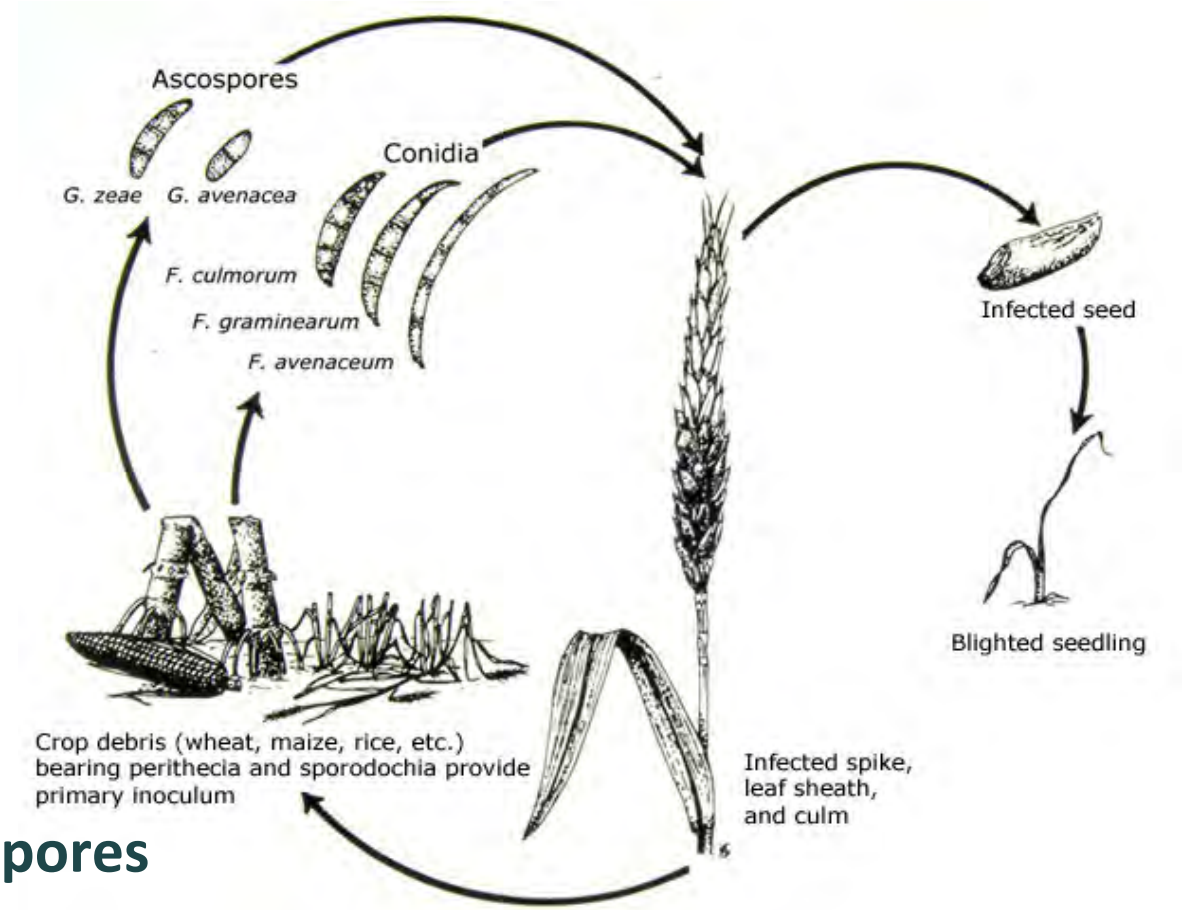




spore
~100 μm

$a \approx 10^6 g$



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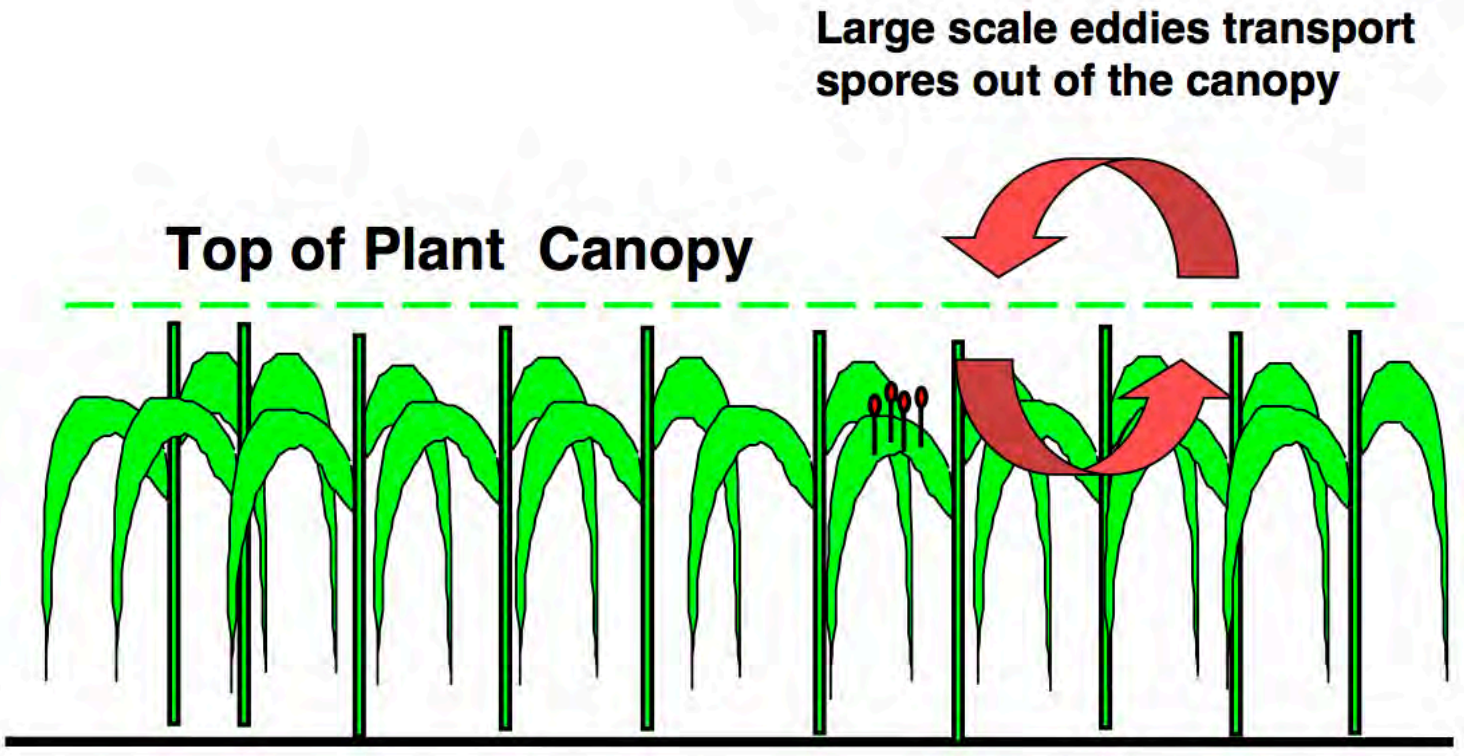

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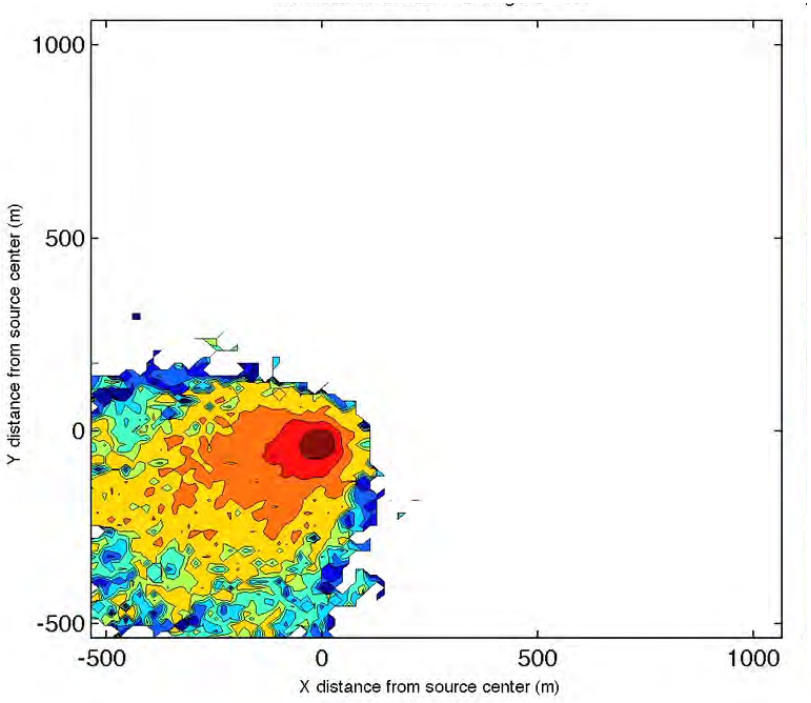
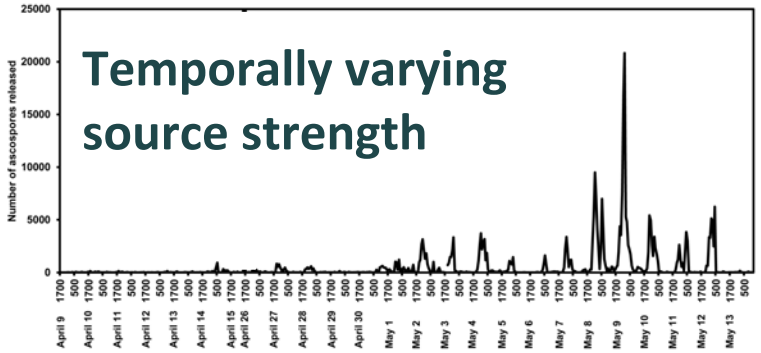
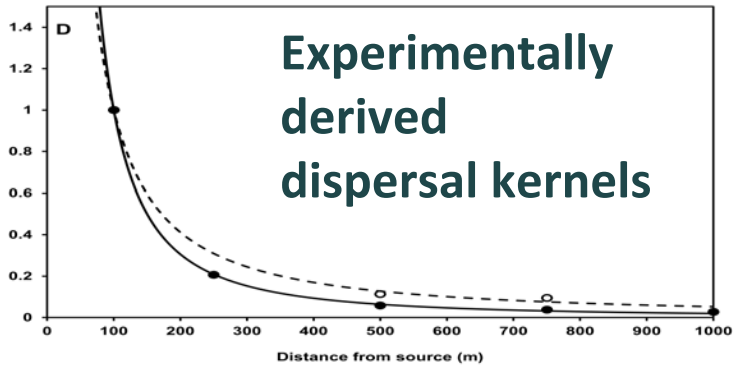
Aylor [1999]

Atmospheric transport of microorganisms

Plume follows changing wind direction







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Prussin et al. [2014a,b] *Plant Disease*

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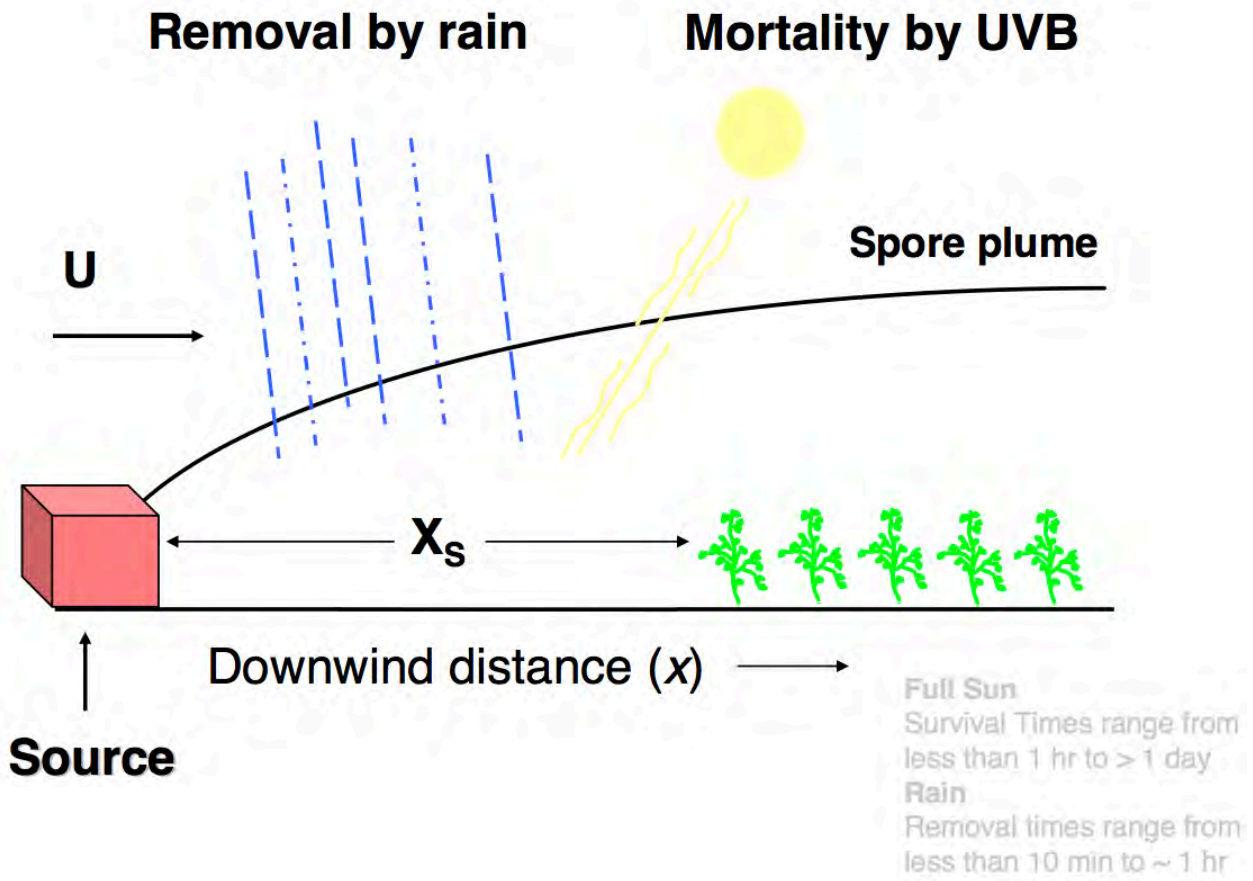

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Aylor [1999]; Prussin et al [2014]

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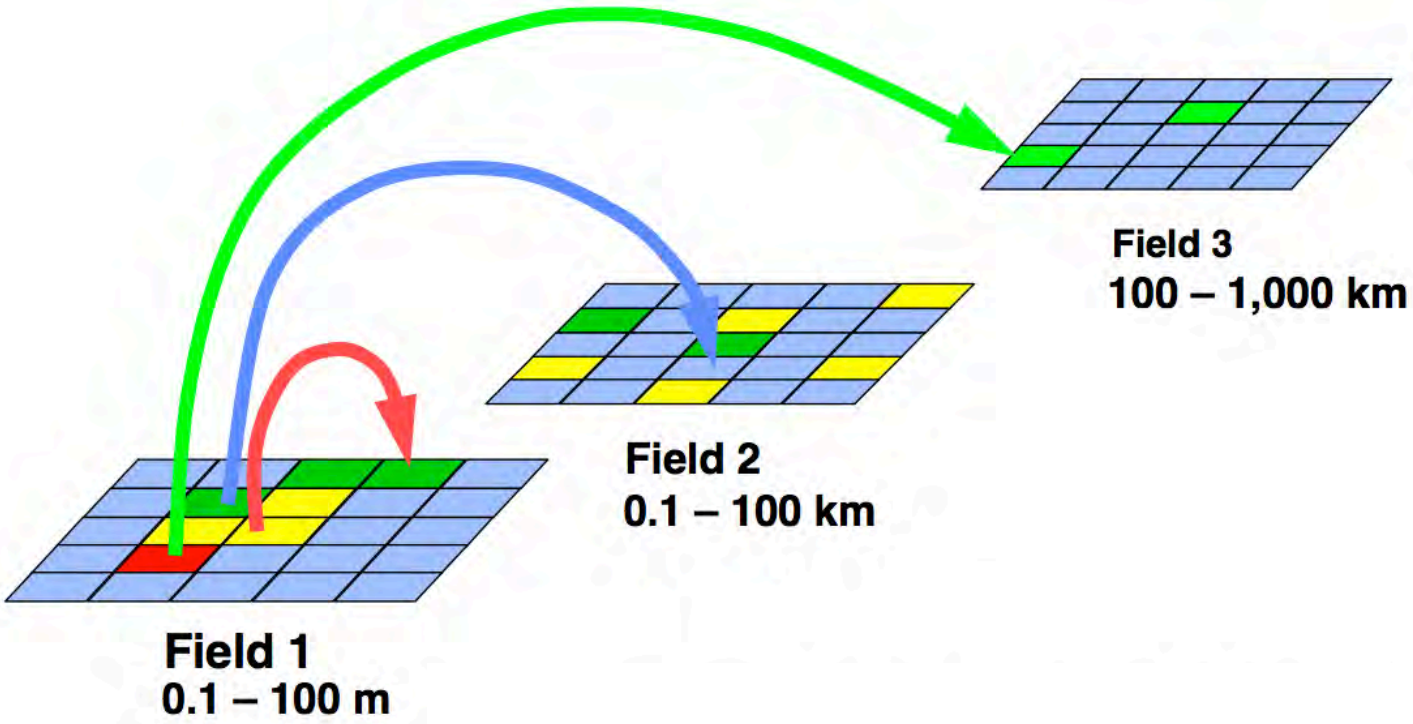


Deposition patterns can be patchy

- Spore production, release, escape from surface
- Long-range transport (time-scale hours to days)
- Deposition, infection efficiency, host susceptibility

Aylor [1999]

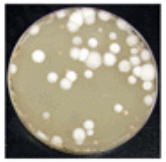
Aerial sampling drones:
40 m – 400 m altitude
(David Schmale's group)

Kentland Farm

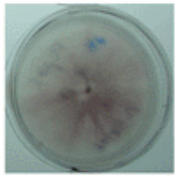
Samples collected over 10-30 minute intervals at constant elevation (e.g., 400m) above ground leve

Collect spores, identify species

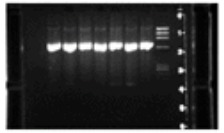
UAVs and ground-level sampler



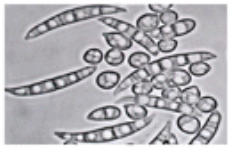
Colonies of *Fusarium*



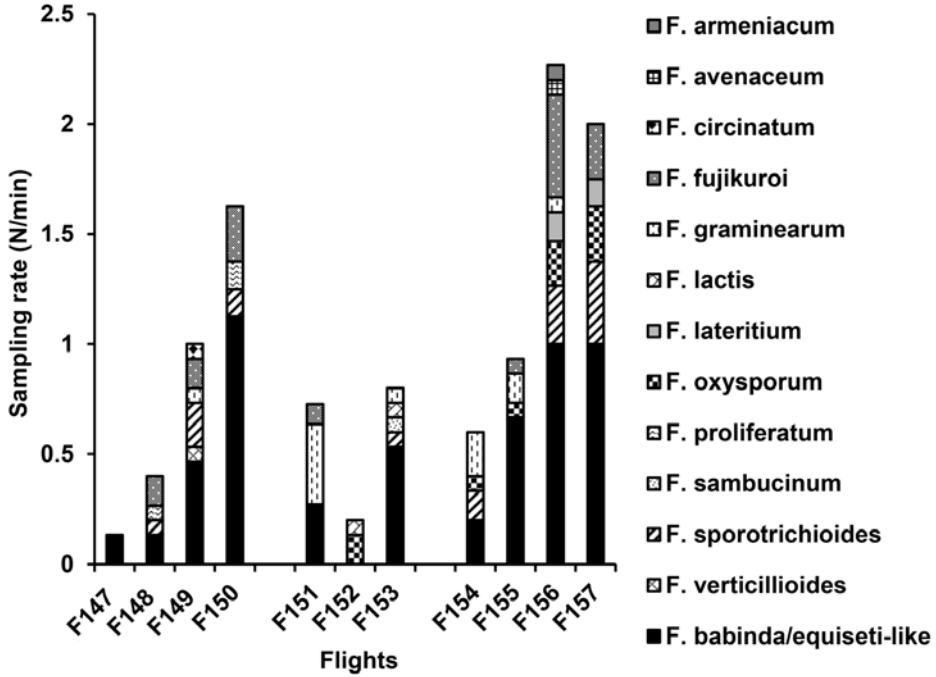
Single-spored cultures



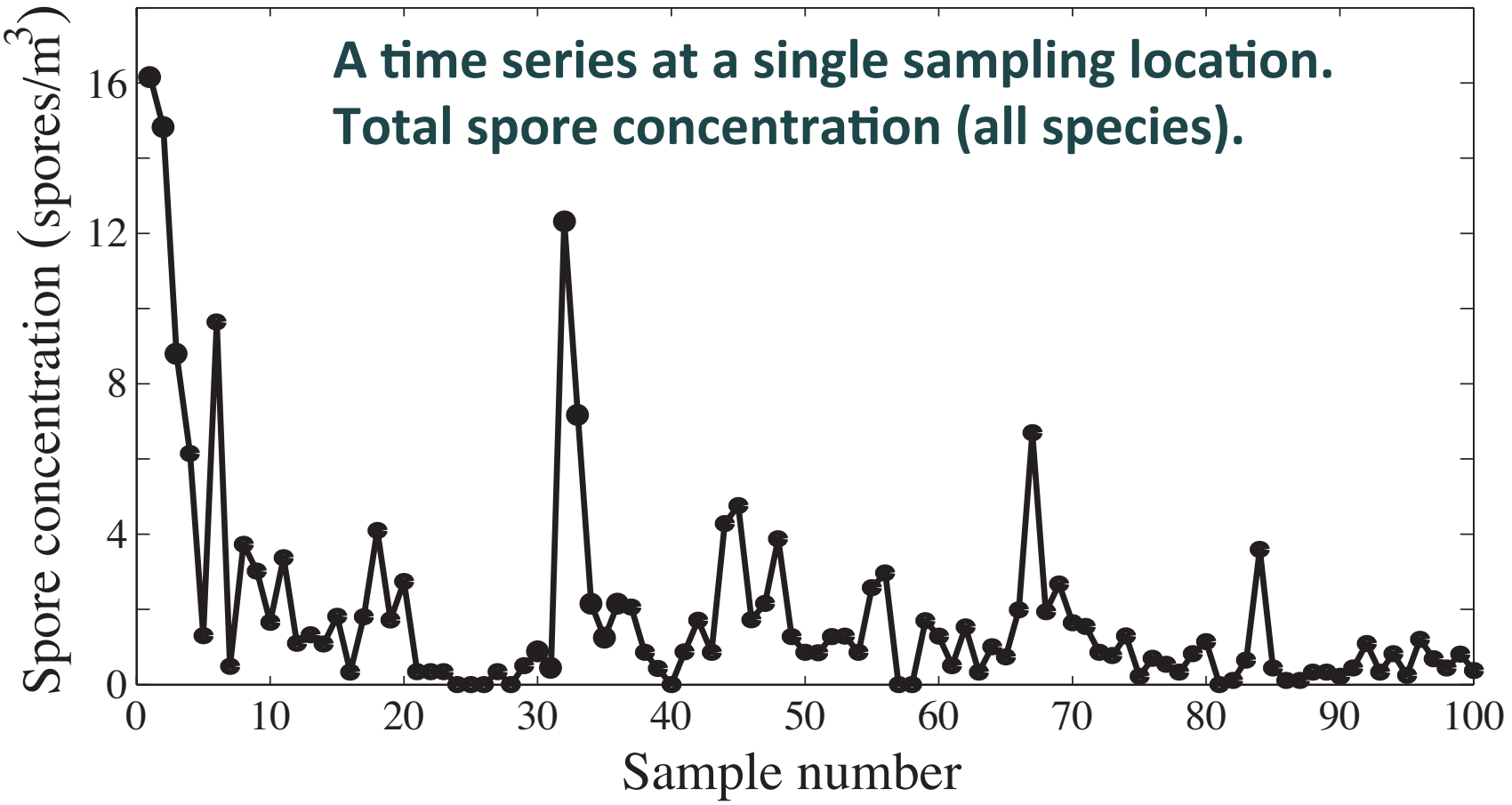
PCR, sequencing, and BLAST searches against FUSARIUM-ID and GenBank



Morphology-based verification



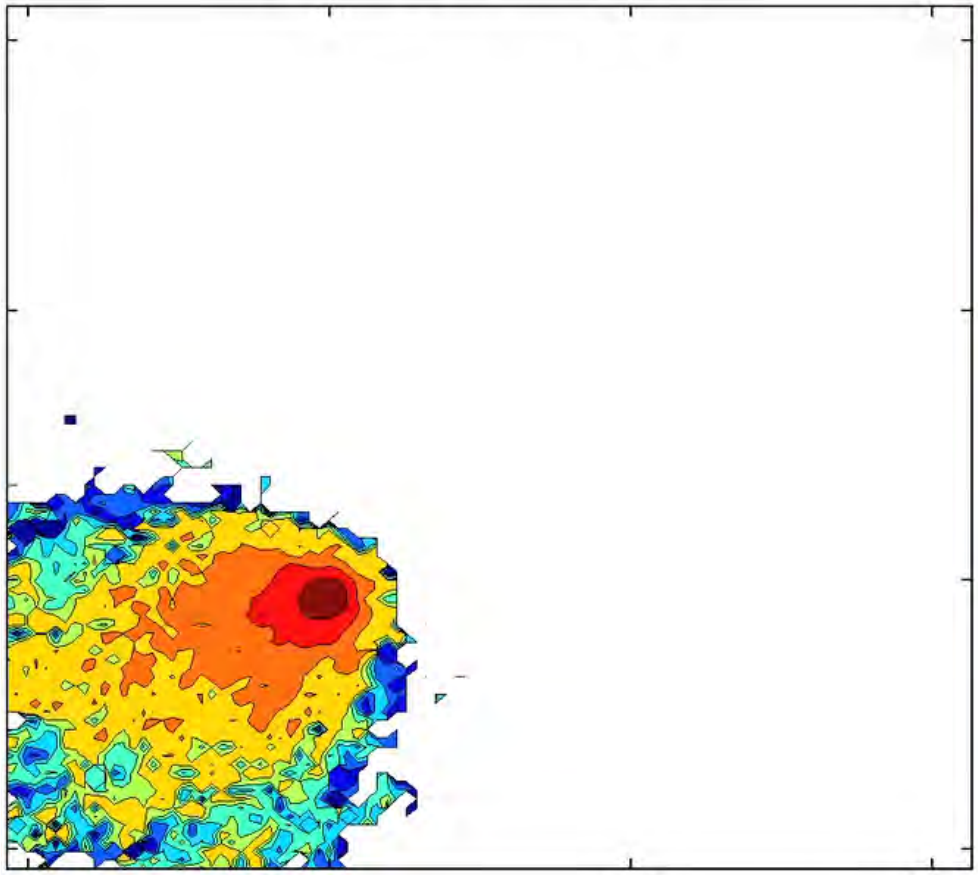
Fluctuations in fungal spore concentration



Concentration of *Fusarium* spores (number/m^3) for samples from 100 flights conducted between August 2006 and March 2010.

Sources are unknown

If sources were known, could model plume



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We are sampling a superposition of plumes from various distant sources (e.g., diseased fields)

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e.g., can imagine 'invisible' smoke plumes

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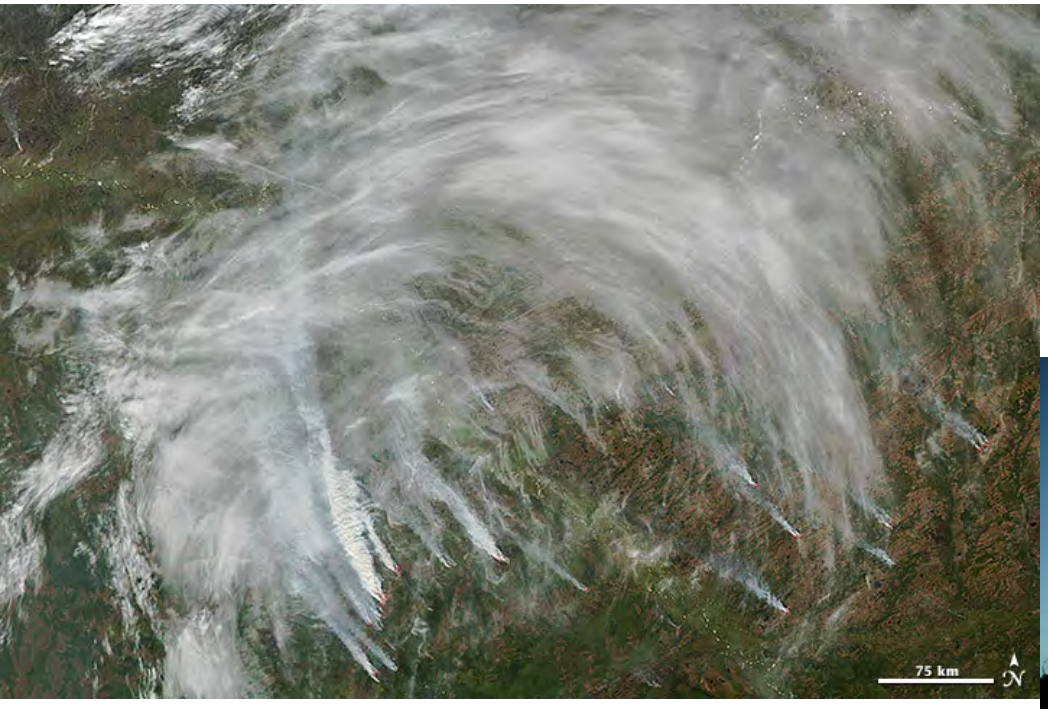

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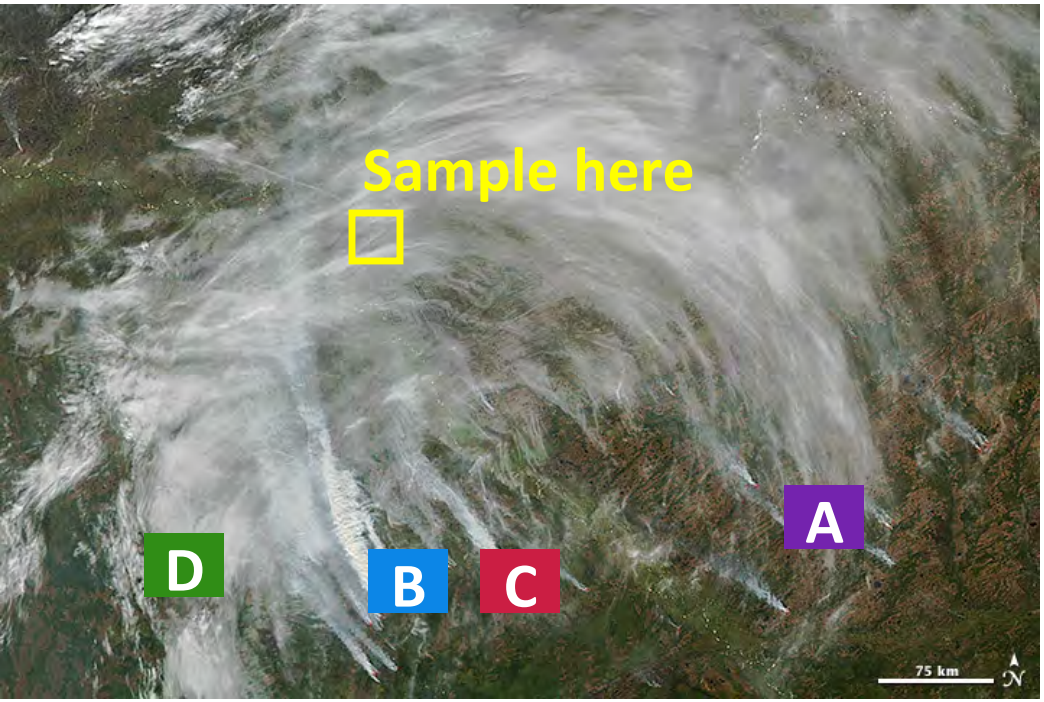

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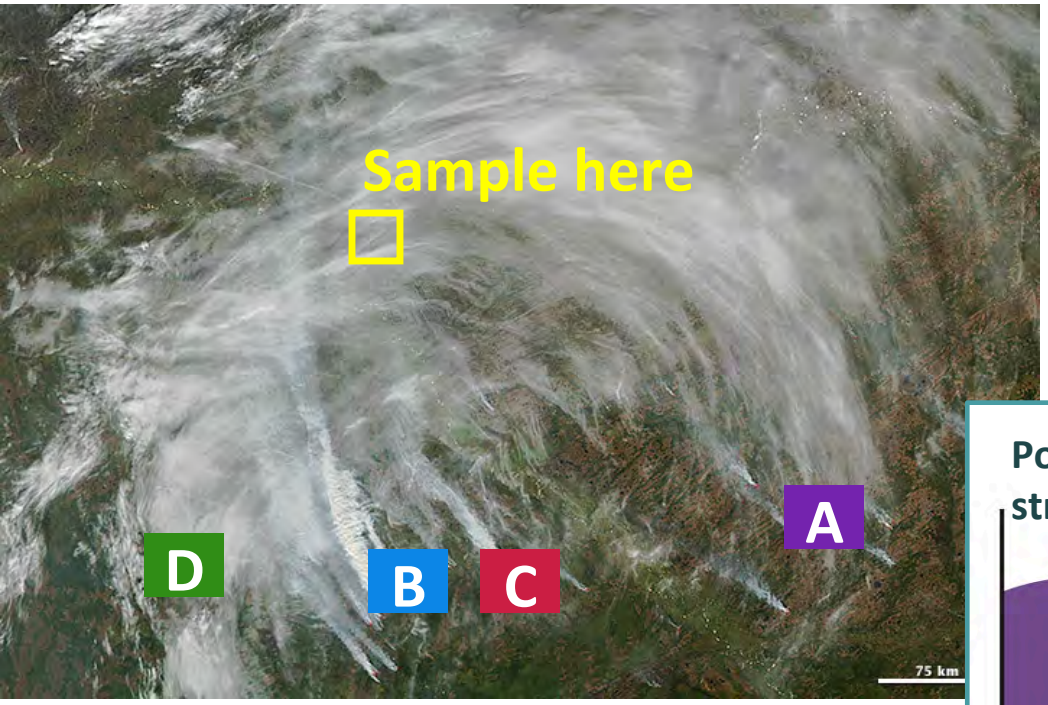

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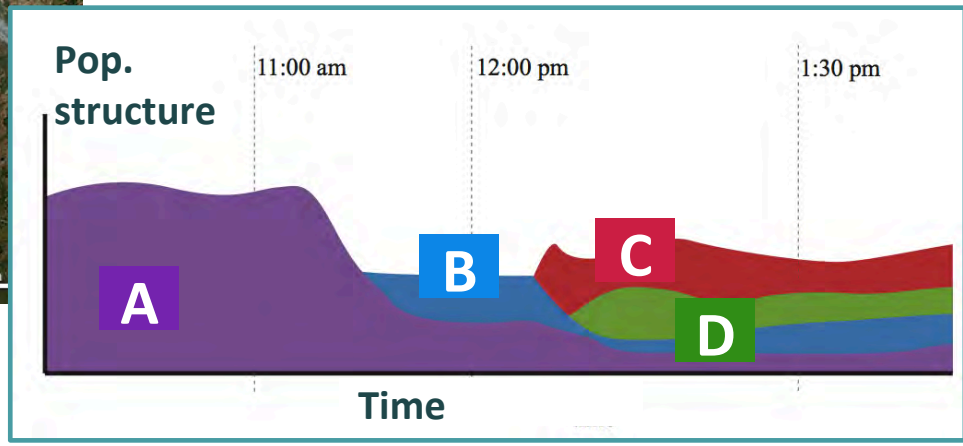
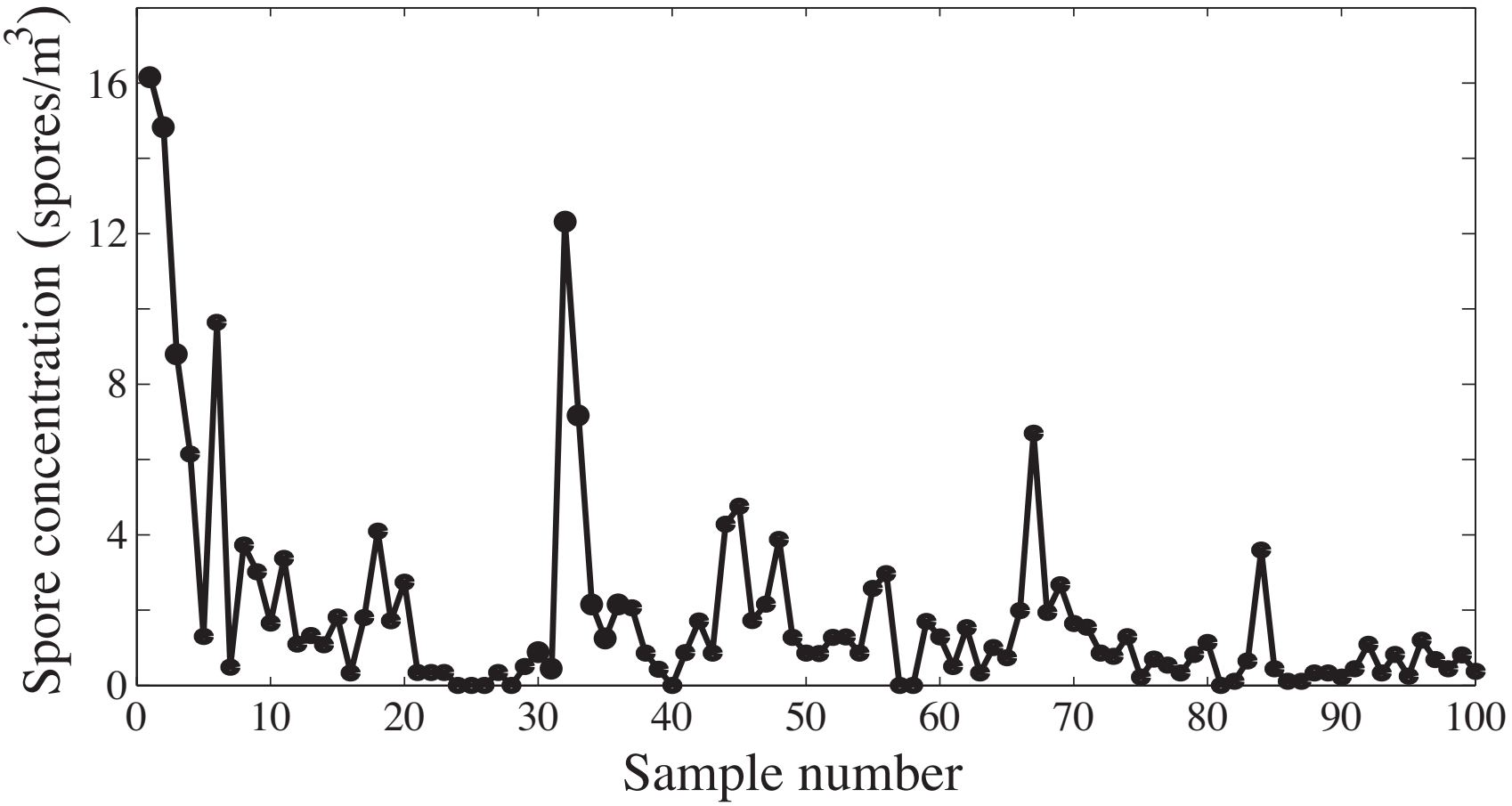


Fluctuations in fungal spore concentration



Concentration of *Fusarium* spores (number/m^3) for samples from 100 flights conducted between August 2006 and March 2010.

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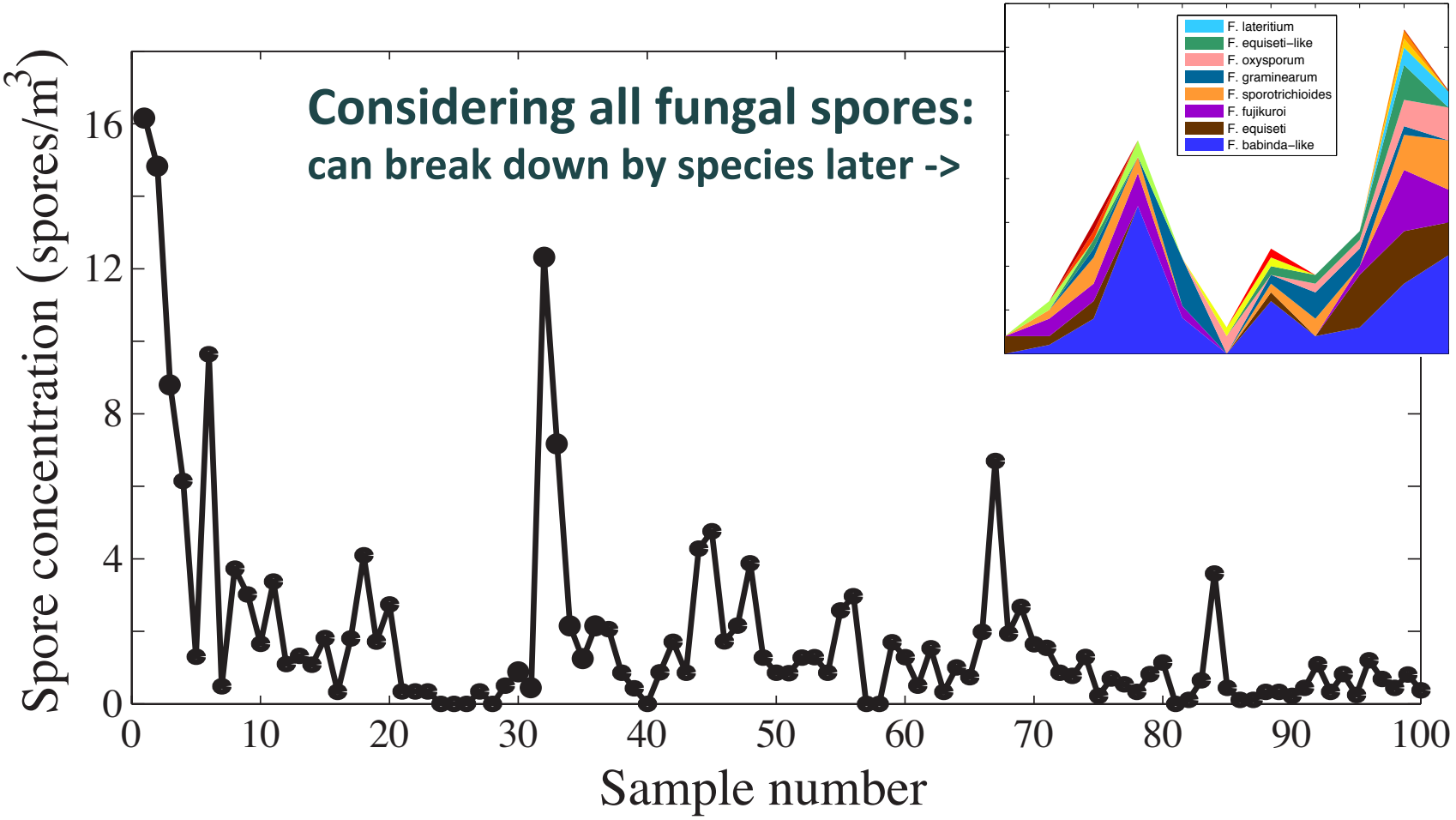

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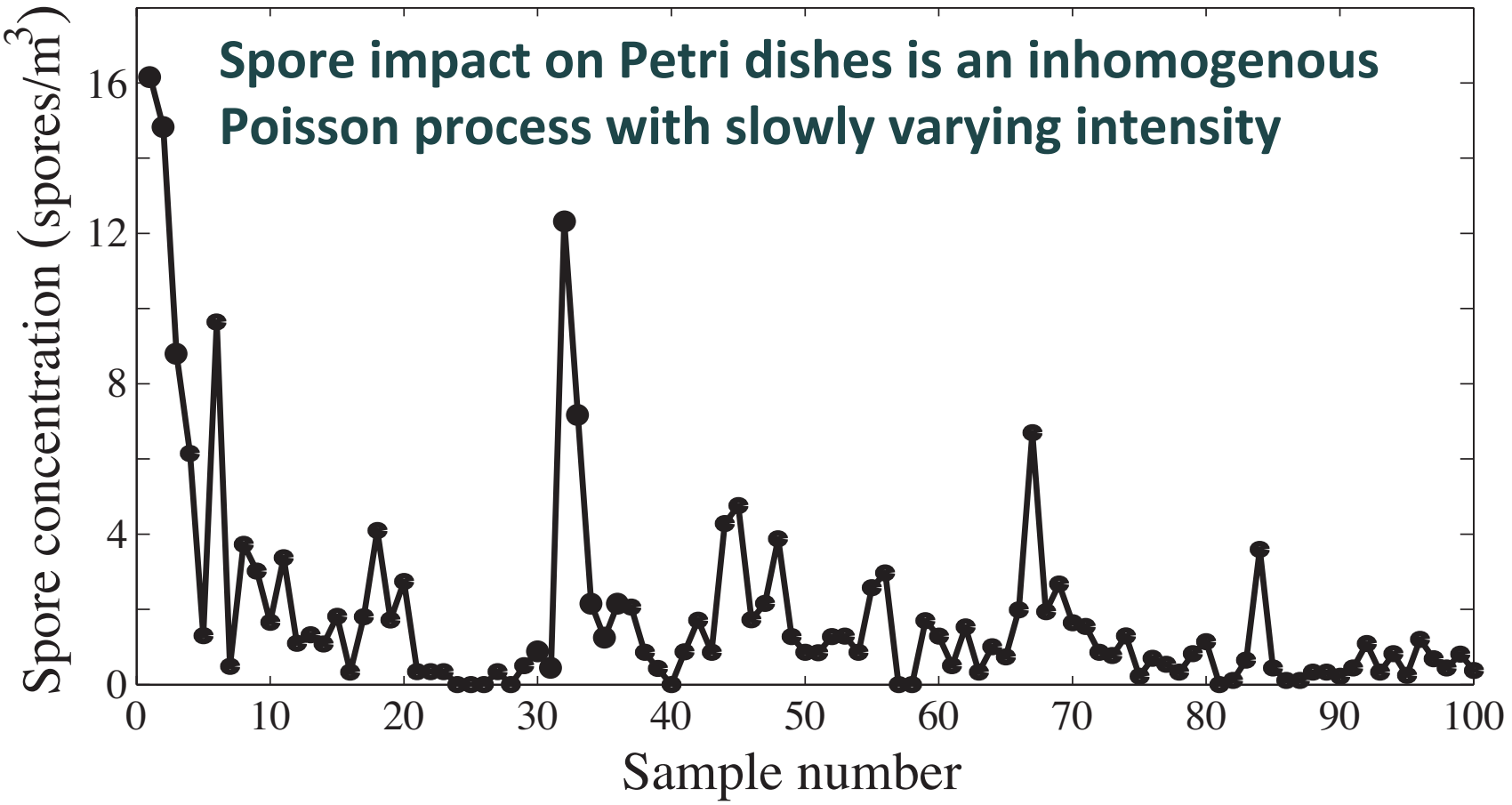

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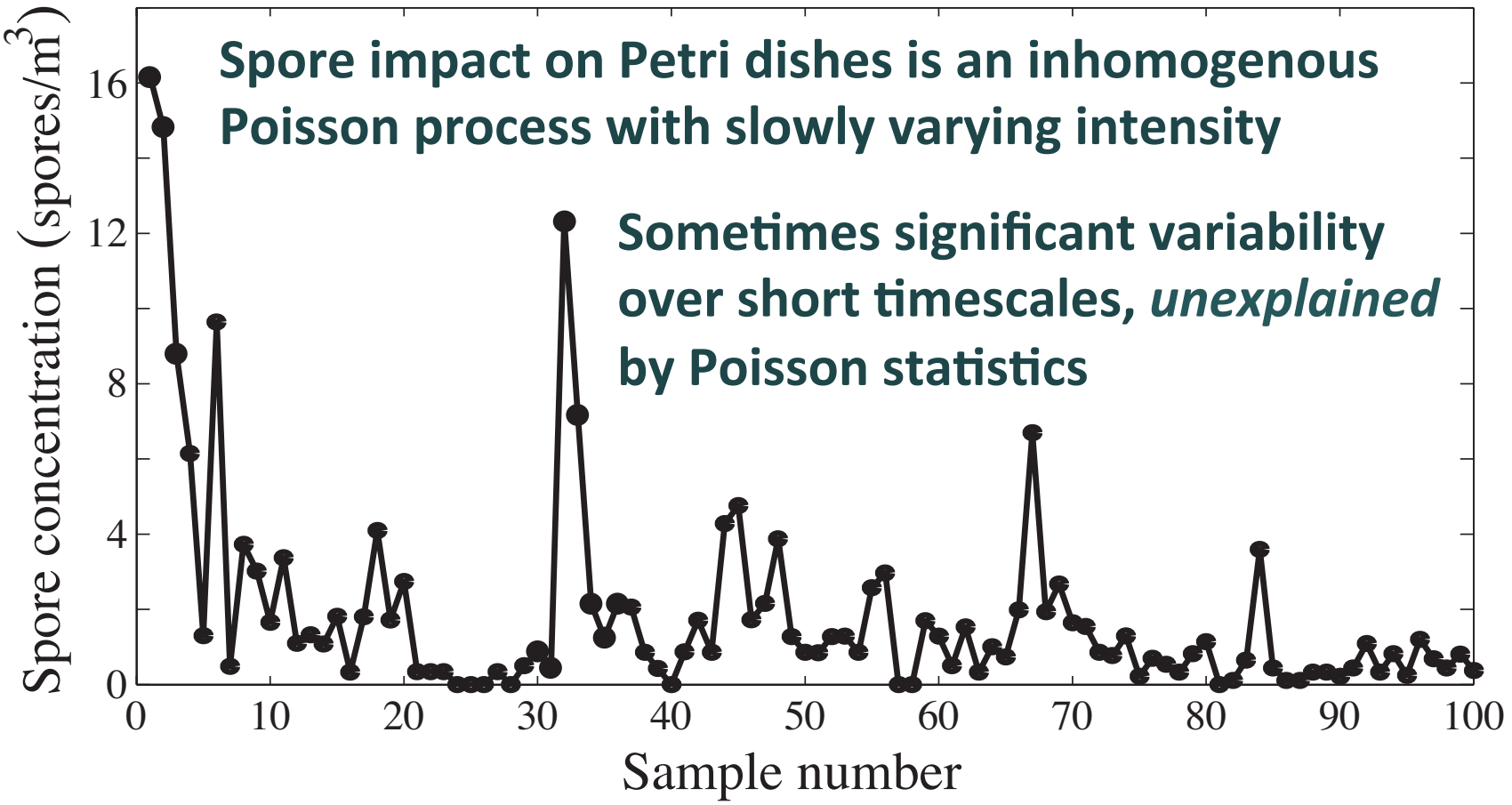

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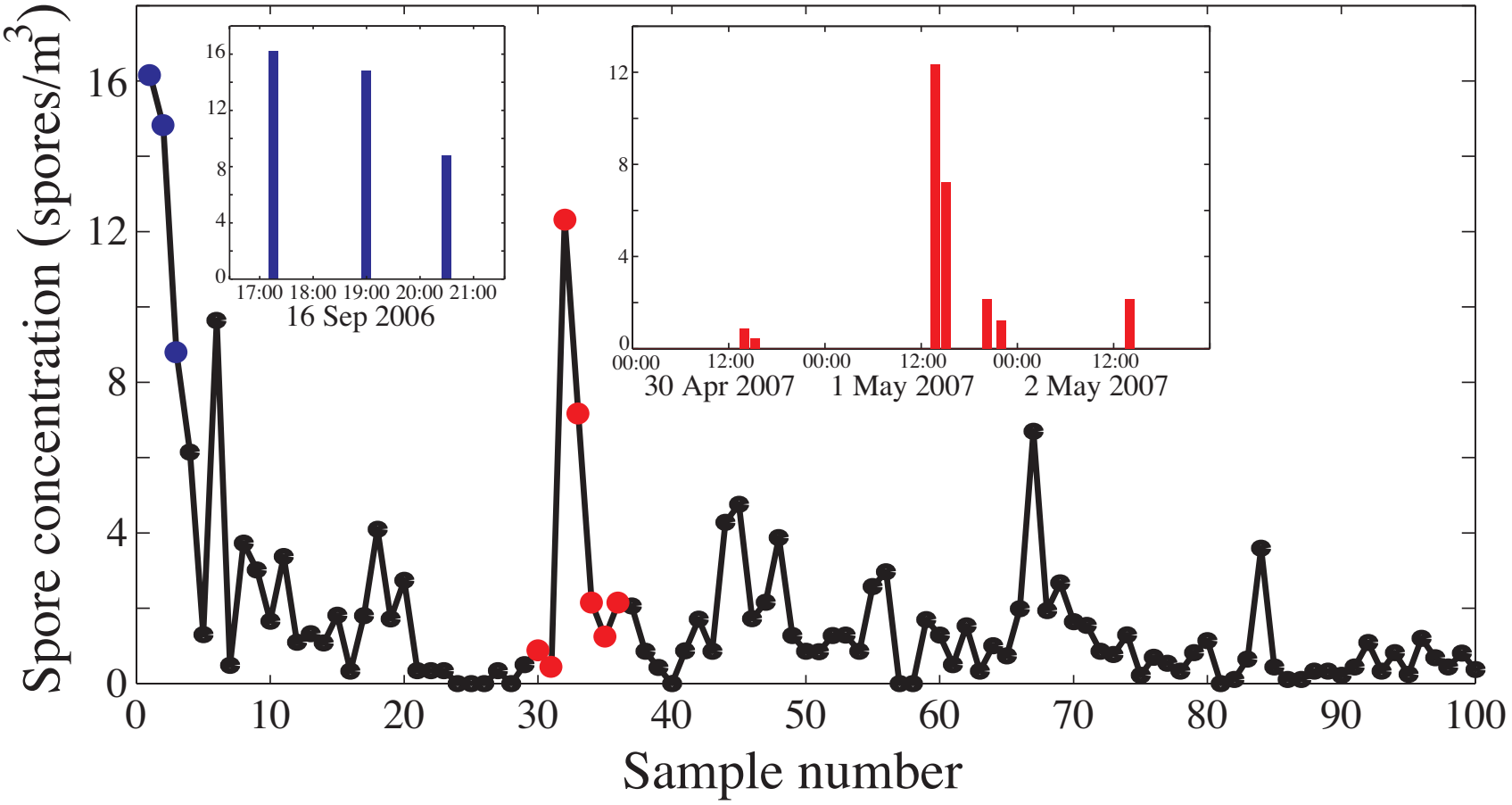
Punctuated changes in fungal spore concentration



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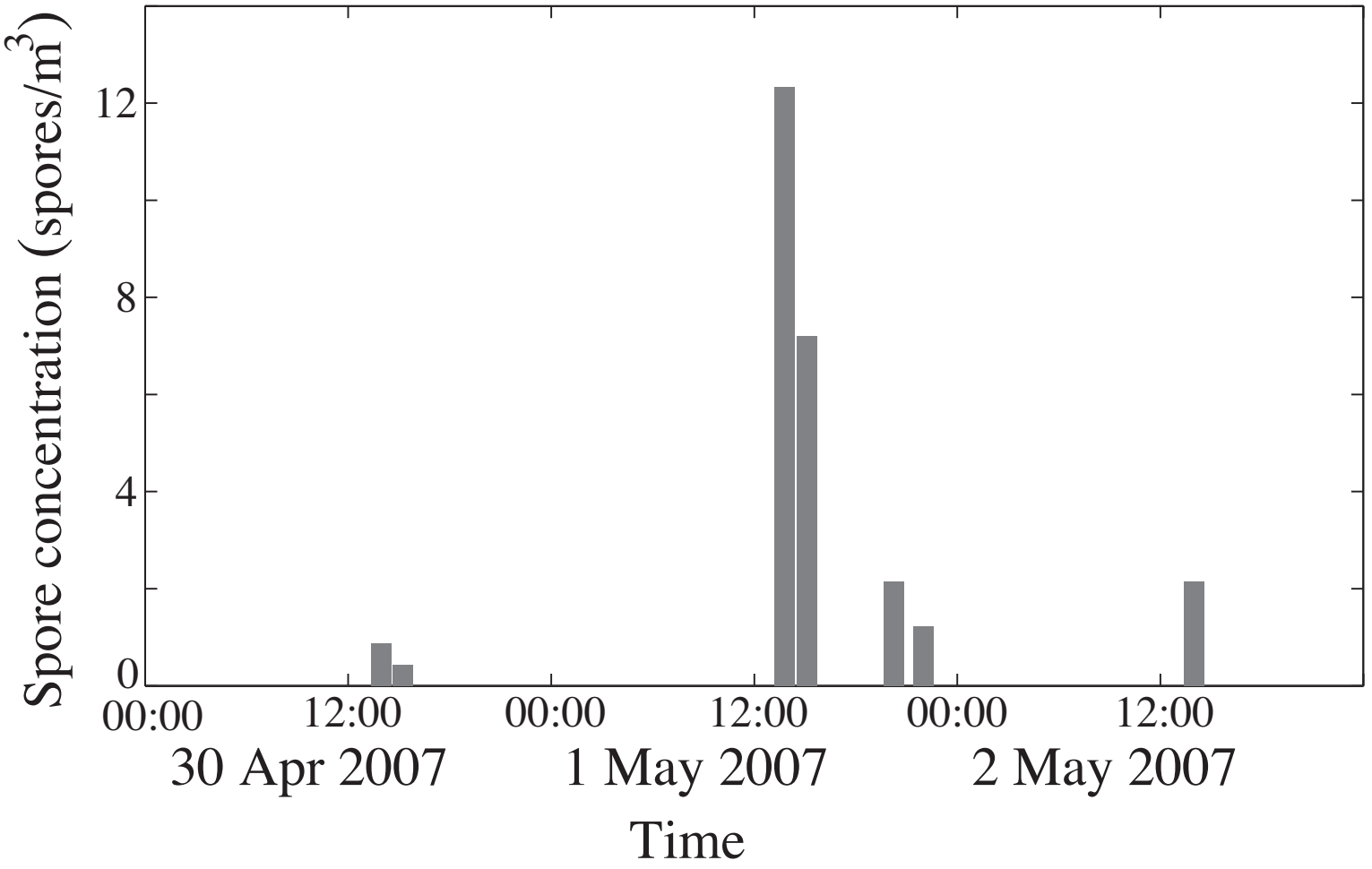
A classic punctuated change



Time series of concentration $\{(t_0, C_0), \ldots, (t_{N-1}, C_{N-1})\}$

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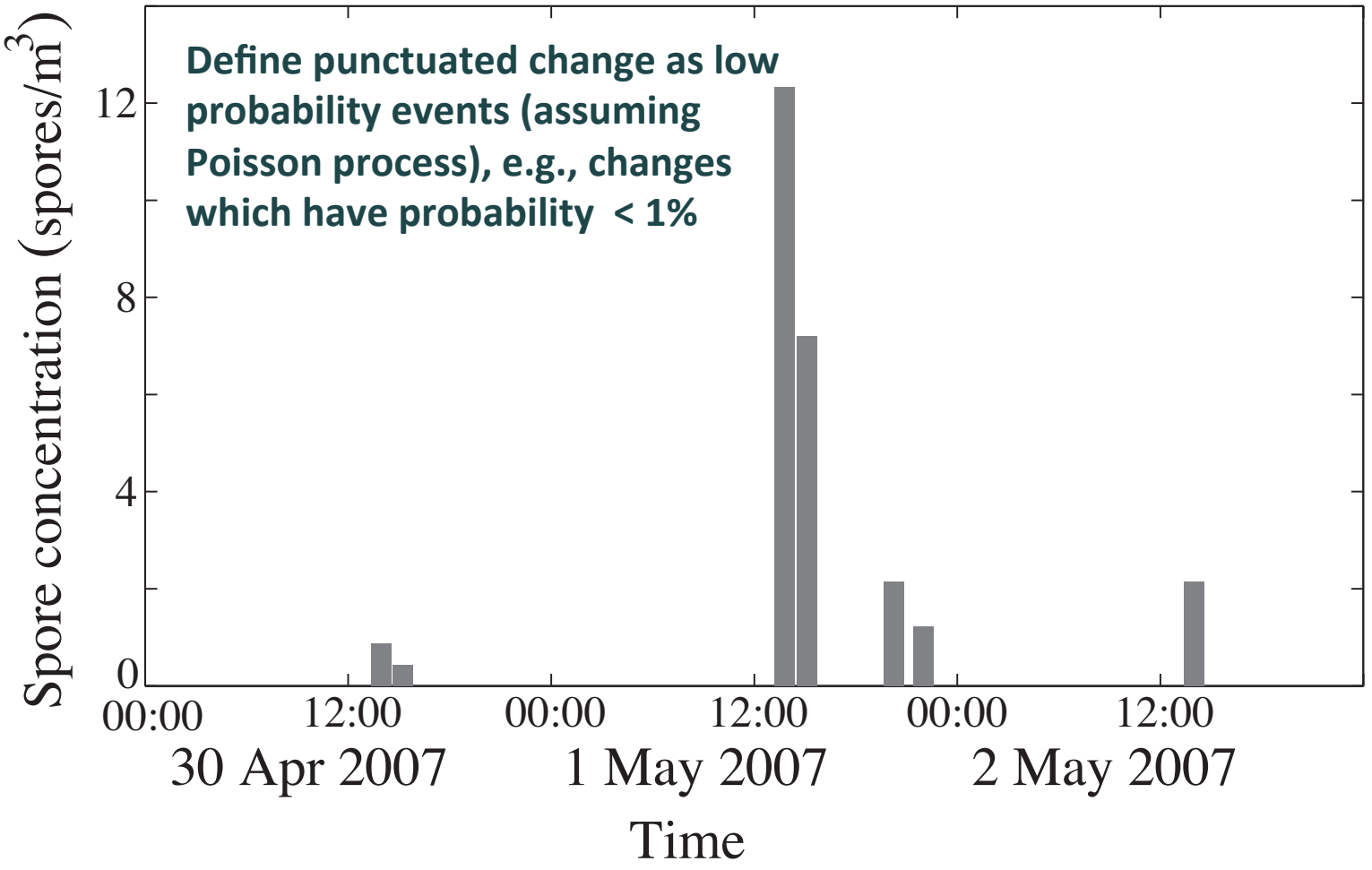

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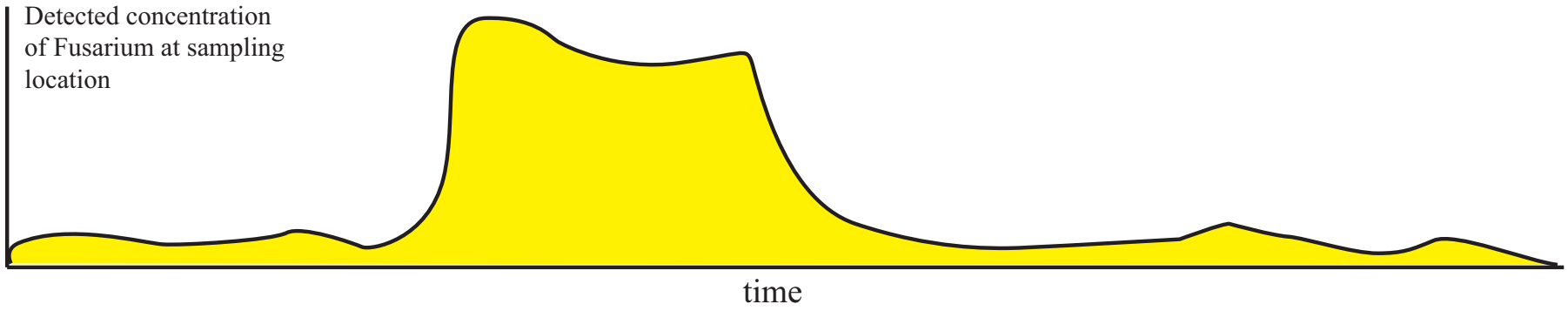
Punctuated changes:
How to understand cloud edges?



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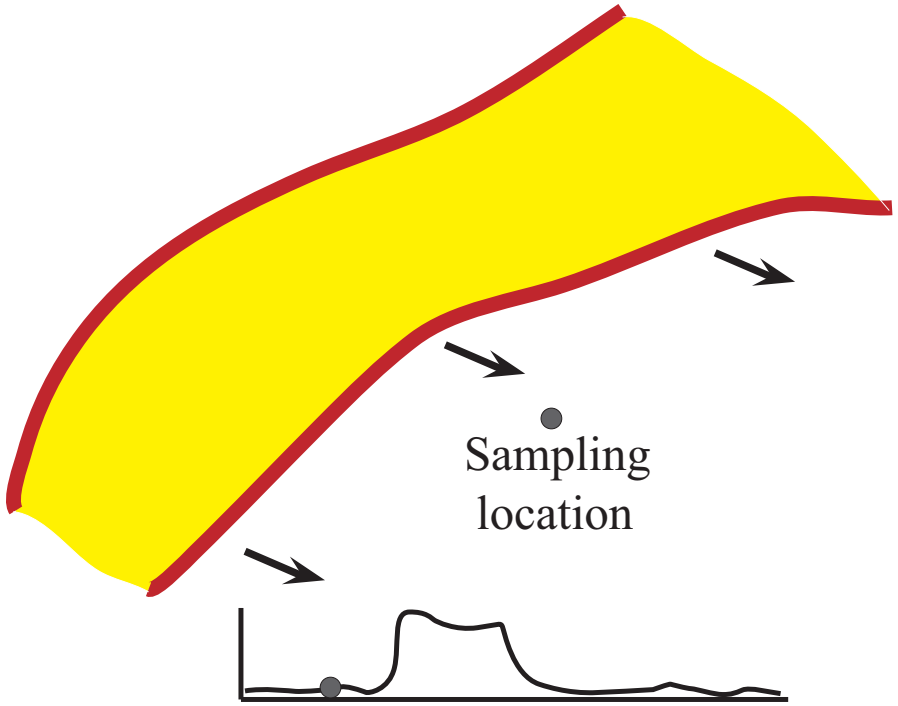

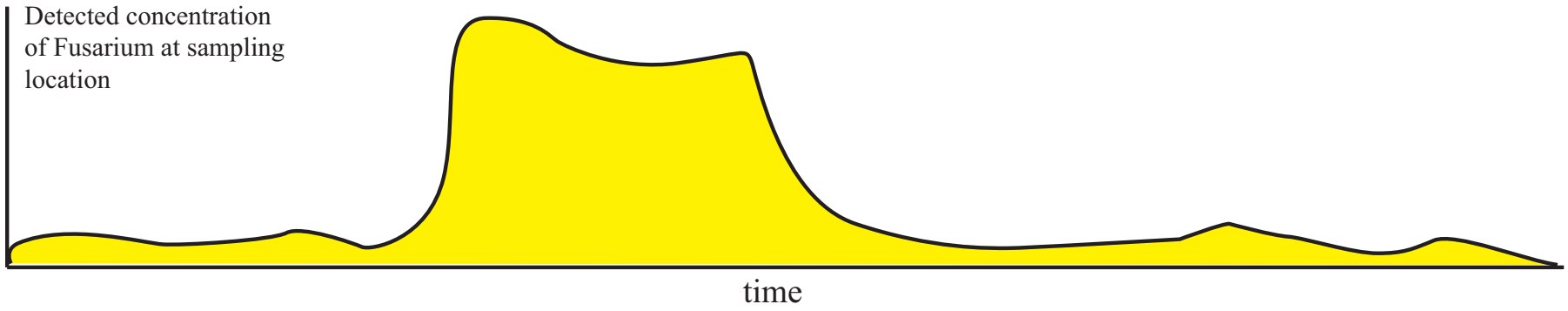

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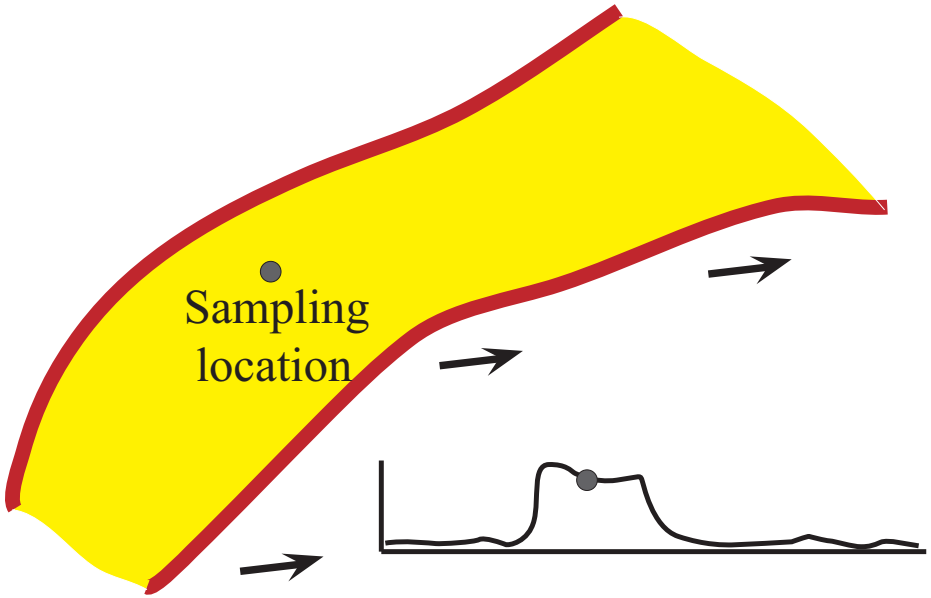

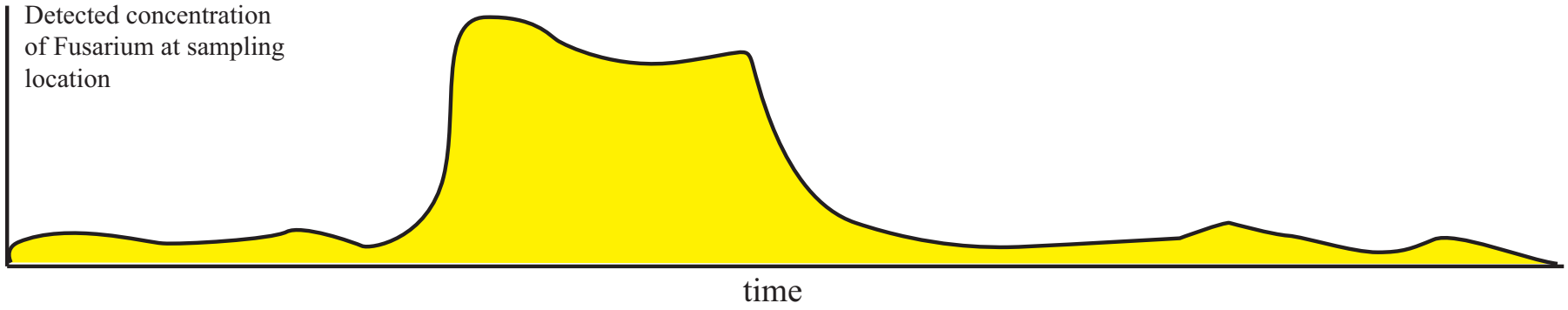

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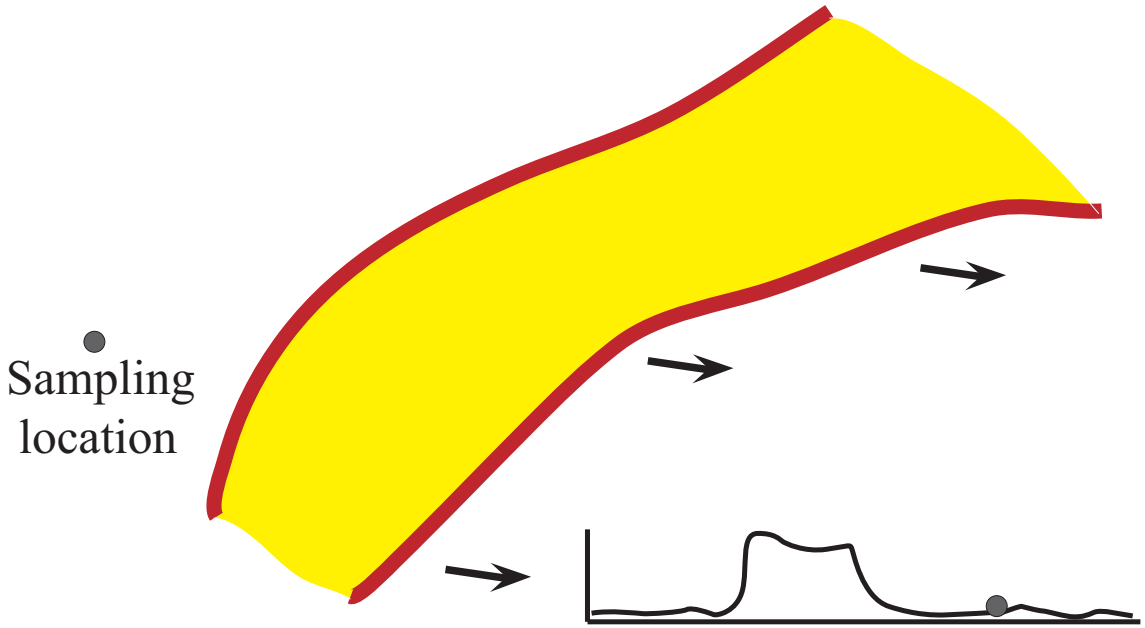
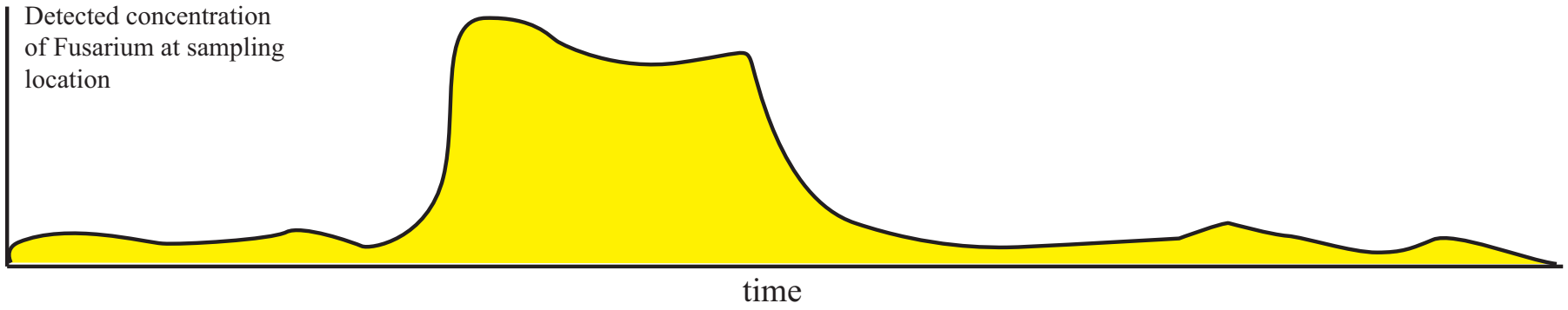


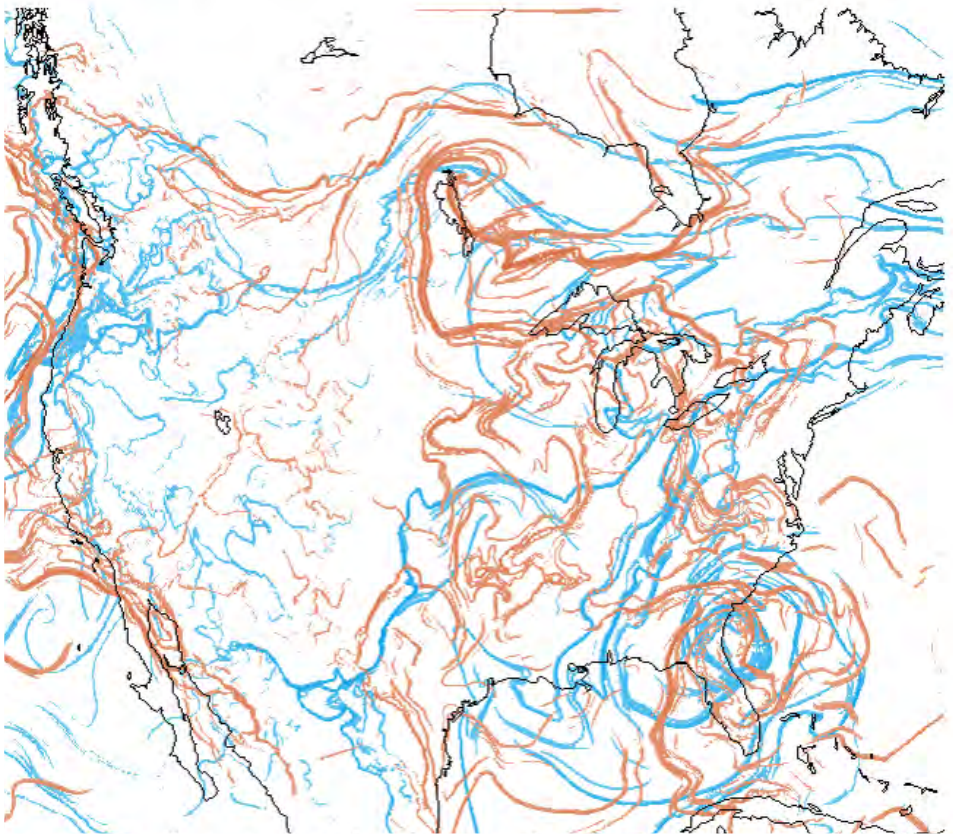


Atmospheric transport network

LCS, repelling (orange) and attracting (blue)

Atmospheric Superhighway, a skeleton of large-scale horizontal transport

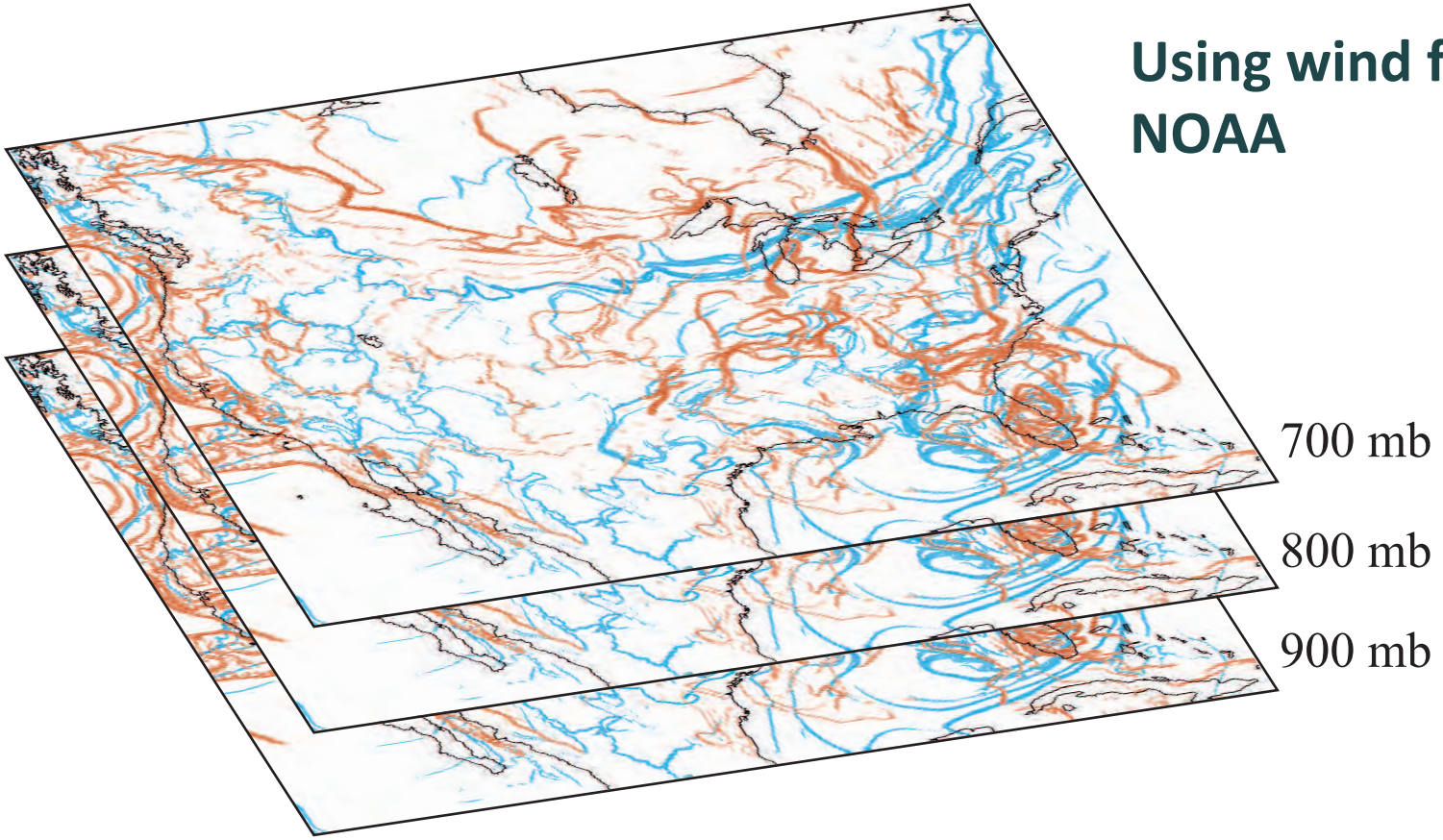
Relevant for large-scale spatiotemporal patterns of pollution but also **biological agents**



orange = repelling LCSs, blue = attracting LCSs

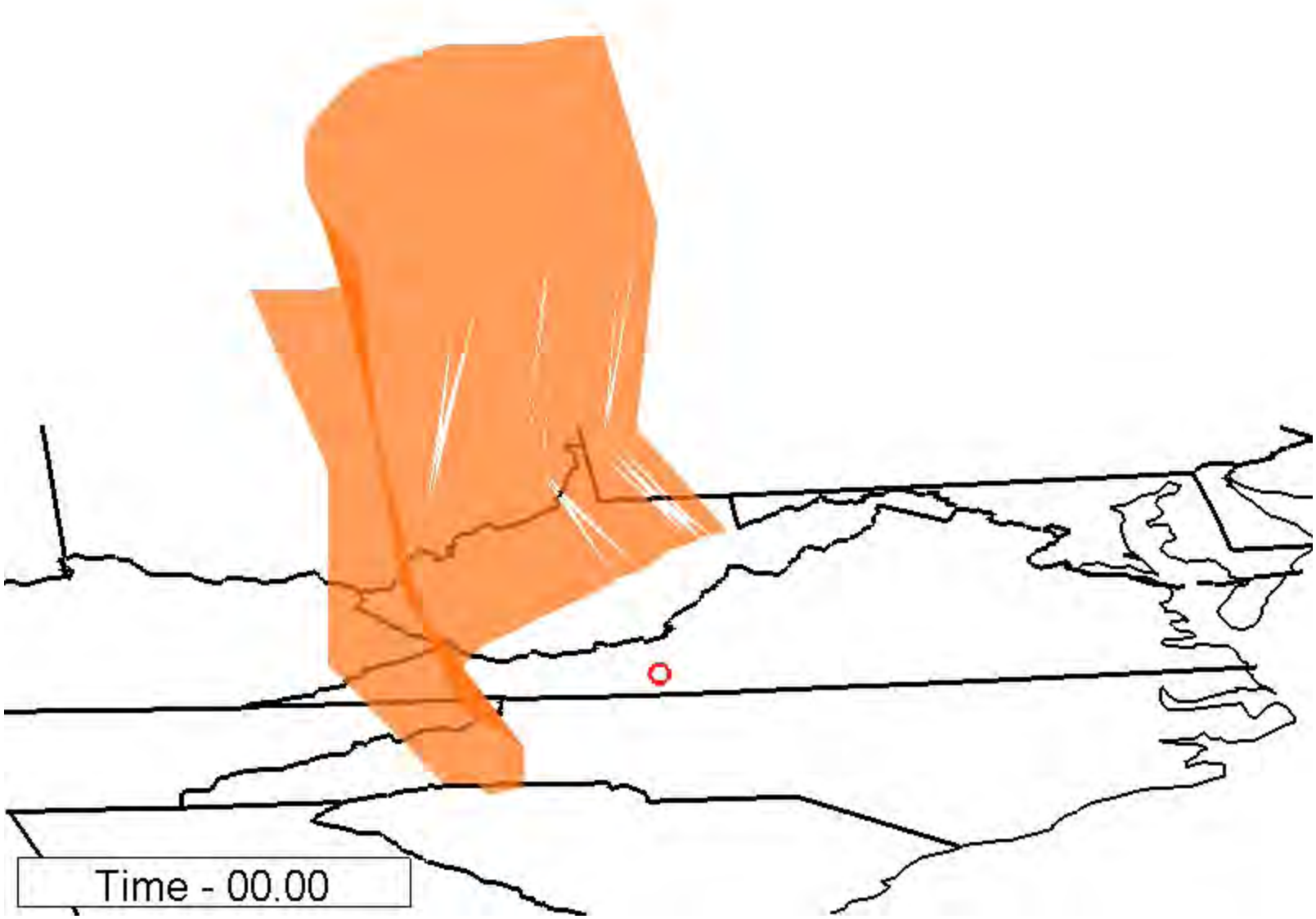
Mesoscale to synoptic scale motion

- **Consider first 2D motion, then fully 3D**
- **Quasi-2D motion (isobaric) over timescales of interest, < 12-24 hrs, given by fungal spore viability**



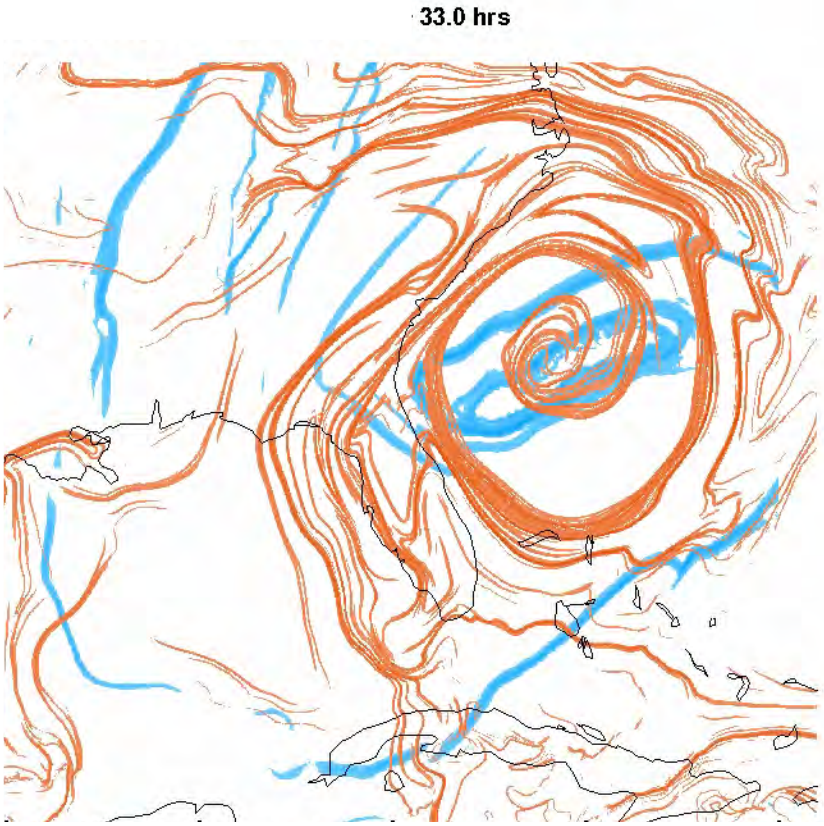
Using wind fields from NOAA

Curtain-like partitions moving over landscape

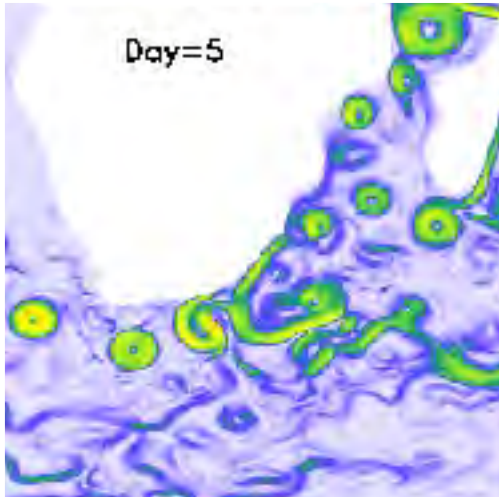


Identify coherent structures

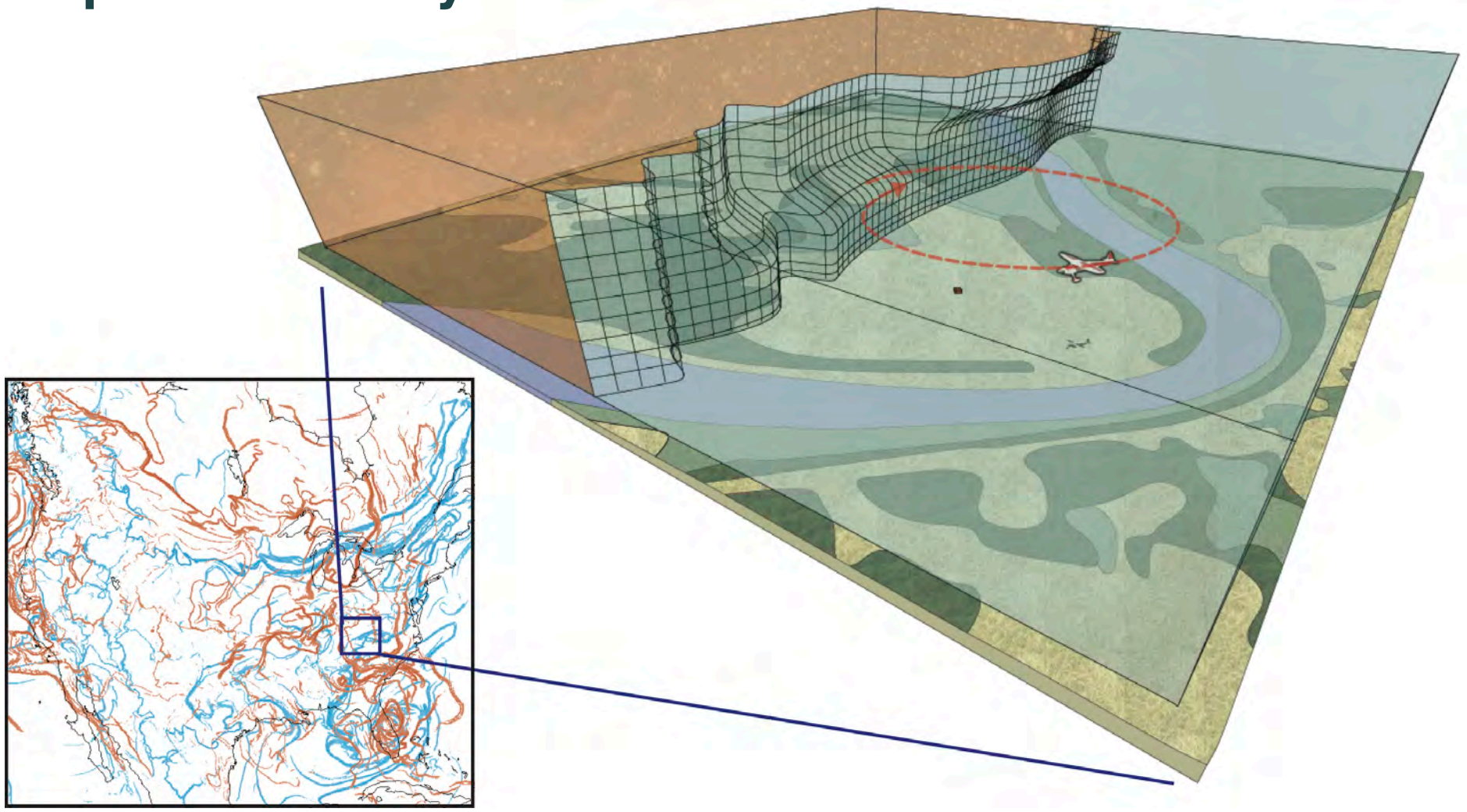
- **Coherent atmospheric filaments or vortices mix little with surroundings, analogous to ocean eddies**



- **Temporarily isolated sub-systems**

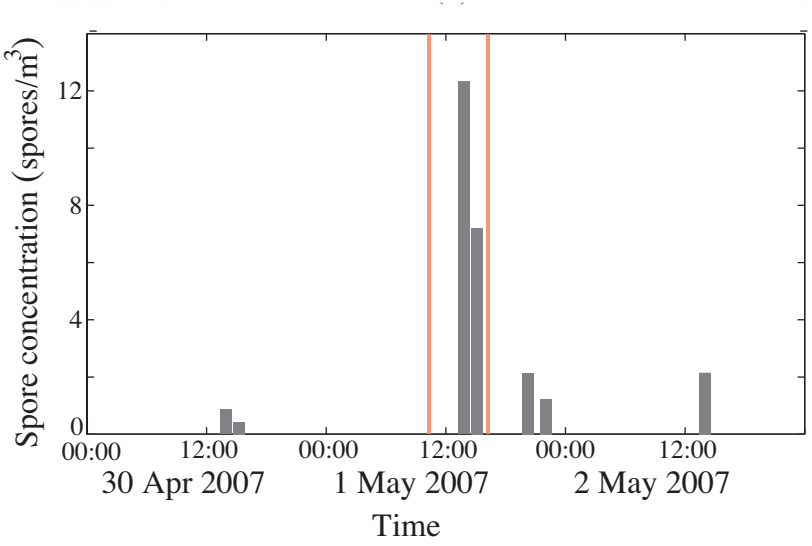


Volumes of differing spore composition partitioned by LCS

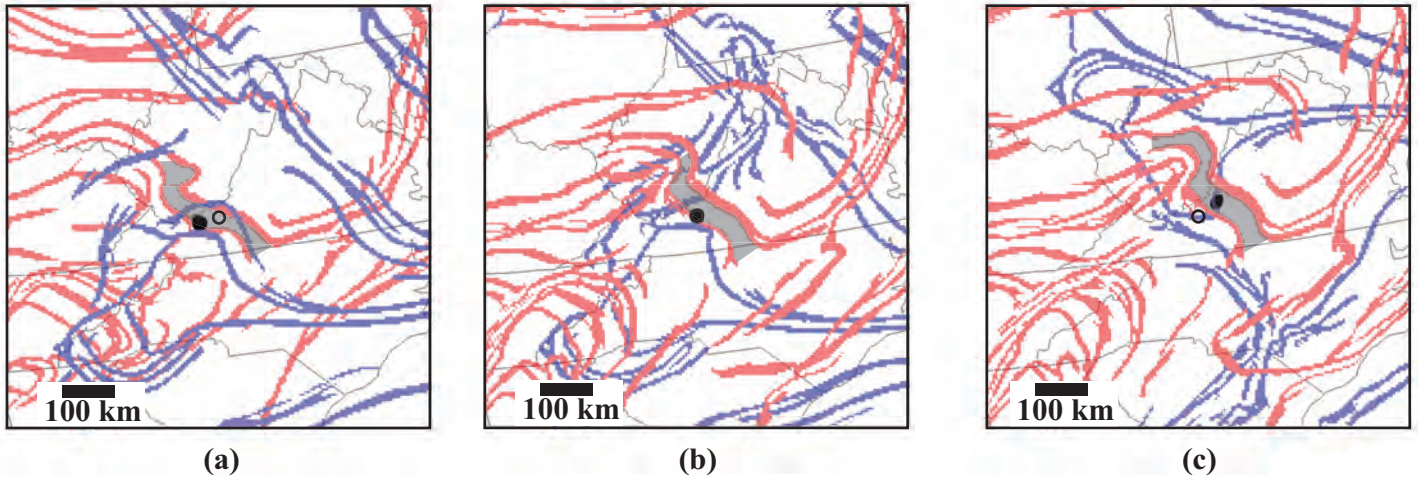


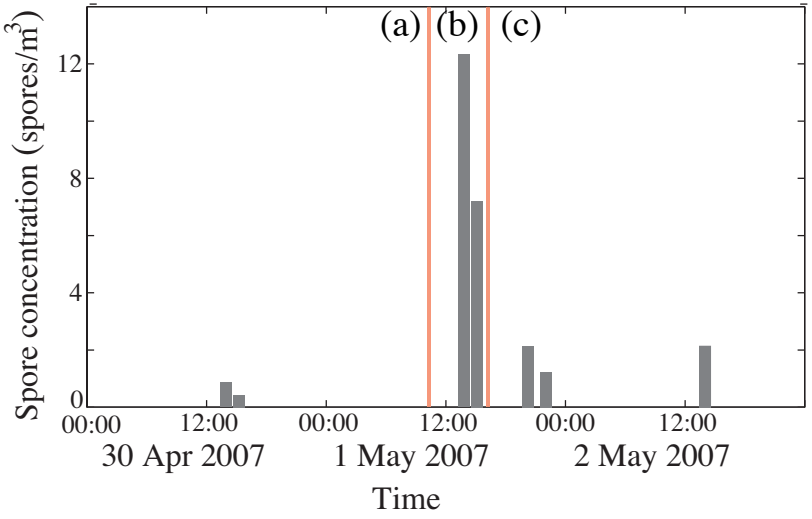
Our unmanned aerial vehicles (UAVs) are usually sampling one side or the other

Filament with high pathogen values ‘sandwiched’ by LCS

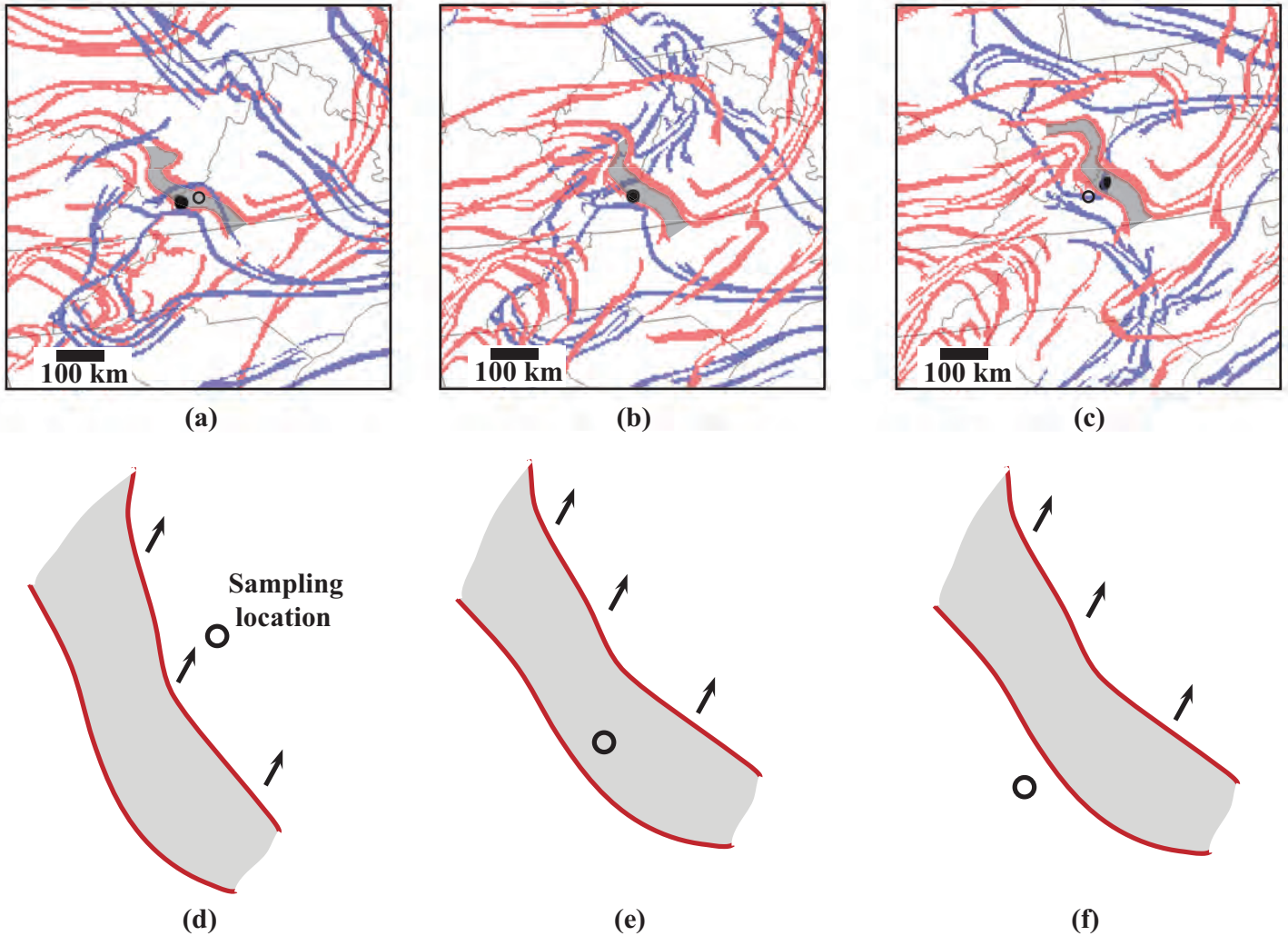


Filament with high pathogen values ‘sandwiched’ by LCS





Filament with high pathogen values ‘sandwiched’ by LCS



CHAOS 21, 033122 (2011)

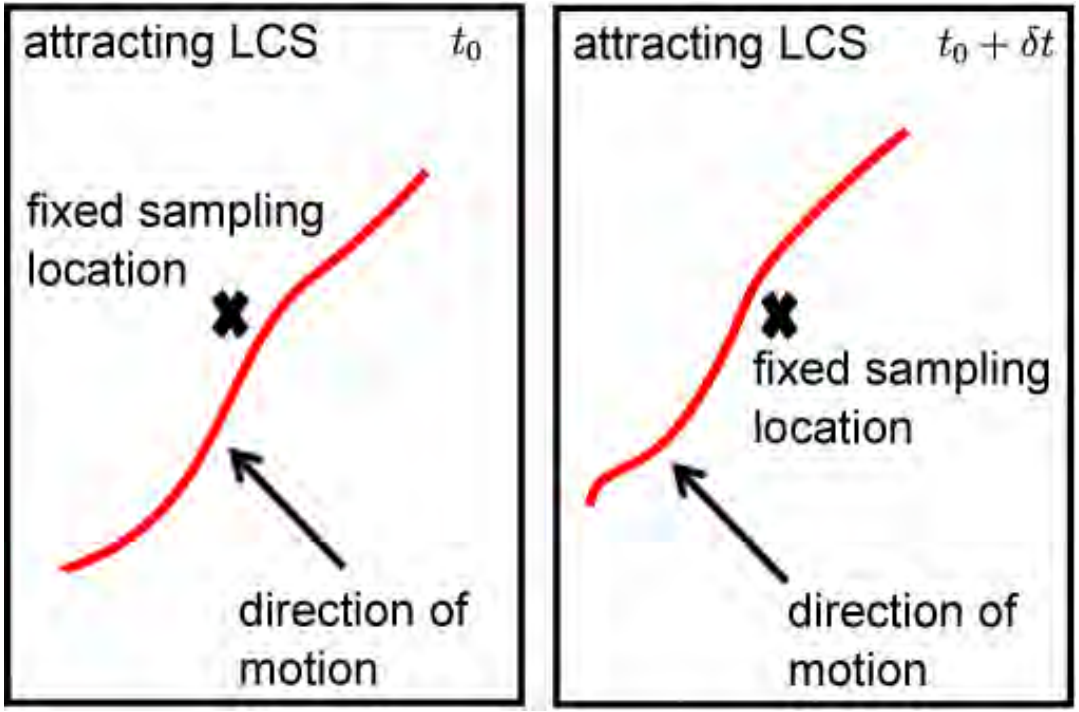
Lagrangian coherent structures are associated with fluctuations in airborne microbial populations

P. Tallapragada,[1] S. D. Ross,[2] and D. G. Schmale III[3]
[1]*Mechanical Engineering and Engineering Science, University of North Carolina at Charlotte, North Carolina 28223, USA*
[2]*Engineering Science and Mechanics, Virginia Tech, Blacksburg, Virginia 24061, USA*
[3]*Plant Pathology, Physiology, and Weed Science, Virginia Tech, Blacksburg, Virginia 24061-0390, USA*

- Punctuated change was associated with a LCS passage **>70% of the time**
- **Airborne biological agent concentrations can provide a proxy for measuring Lagrangian transport structure**

Sampling on either side of a LCS

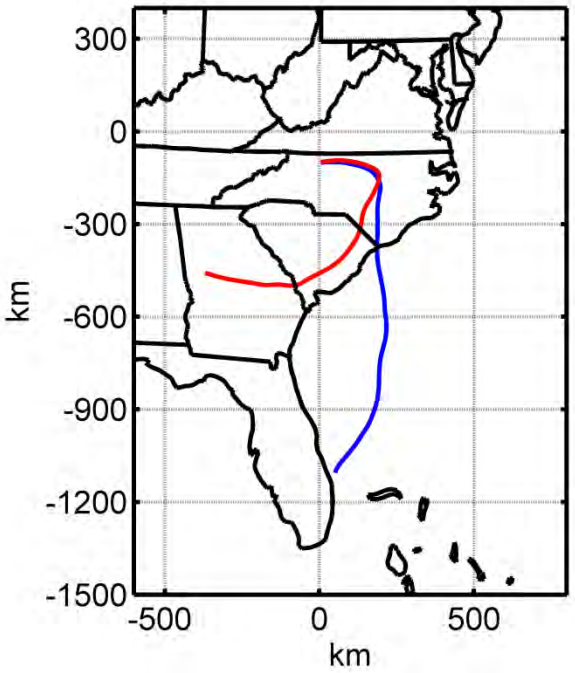
$$\delta \approx \lambda_{\max}^{1/2} \left[C_{t_0}^{t_0+T}(\underline{\mathbf{x}}_0) \right] \|\mathbf{v}(\underline{\mathbf{x}}_0, t_0)\| \delta t$$



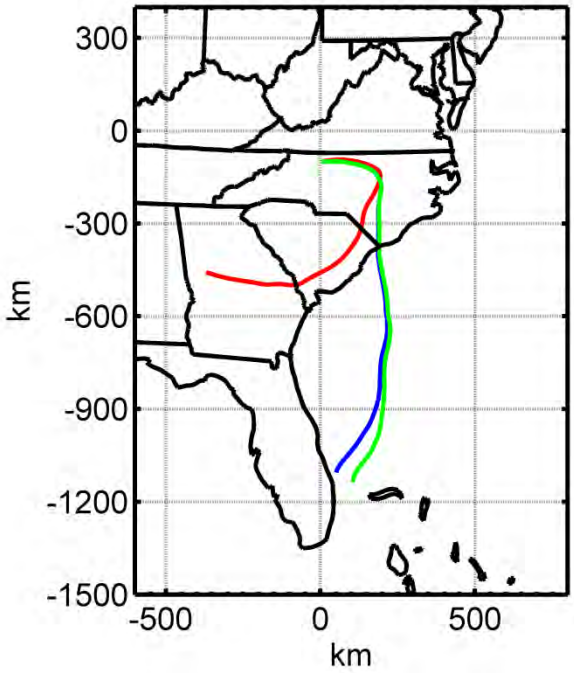
- **If seeking geographically diverse samples, sample on other side of a passing LCS**

Sampling on either side of a LCS

$$\delta \approx \lambda_{\max}^{1/2} \left[C_{t_0}^{t_0+T}(\underline{\mathbf{x}}_0) \right] \|\mathbf{v}(\underline{\mathbf{x}}_0, t_0)\| \delta t$$

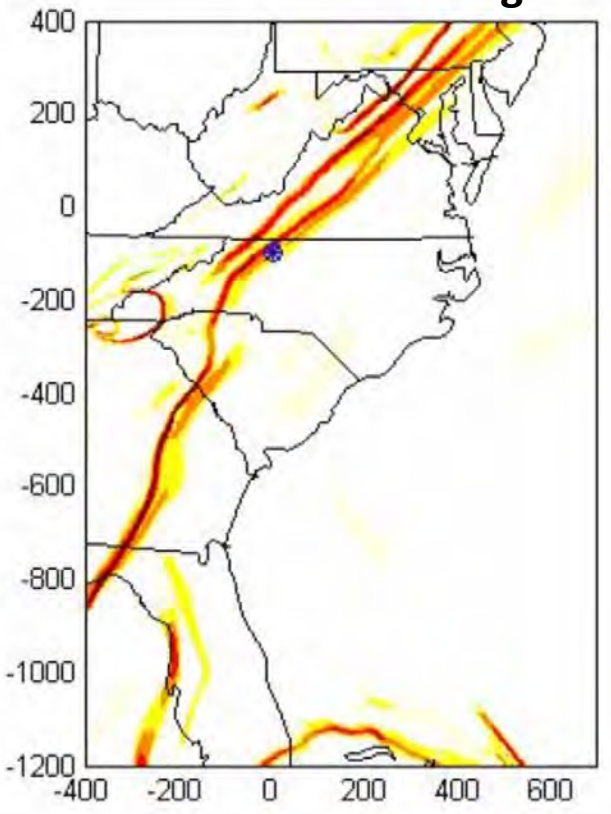


Red: sample time: 1315 UTC
Blue: sample time: 1415 UTC



Red: sample time: 1315 UTC
Blue: sample time: 1415 UTC
Green: sample time 1515 UTC

Back trajectories with attracting LCS

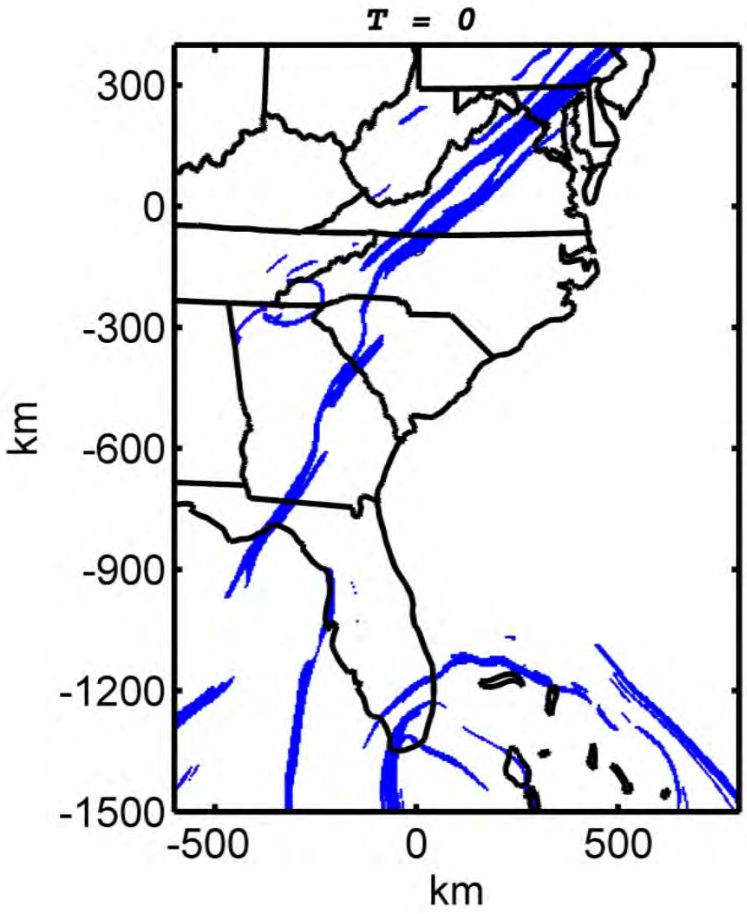


Movie is showing time backwards

Back-trajectories shown

Sampling on either side of a LCS

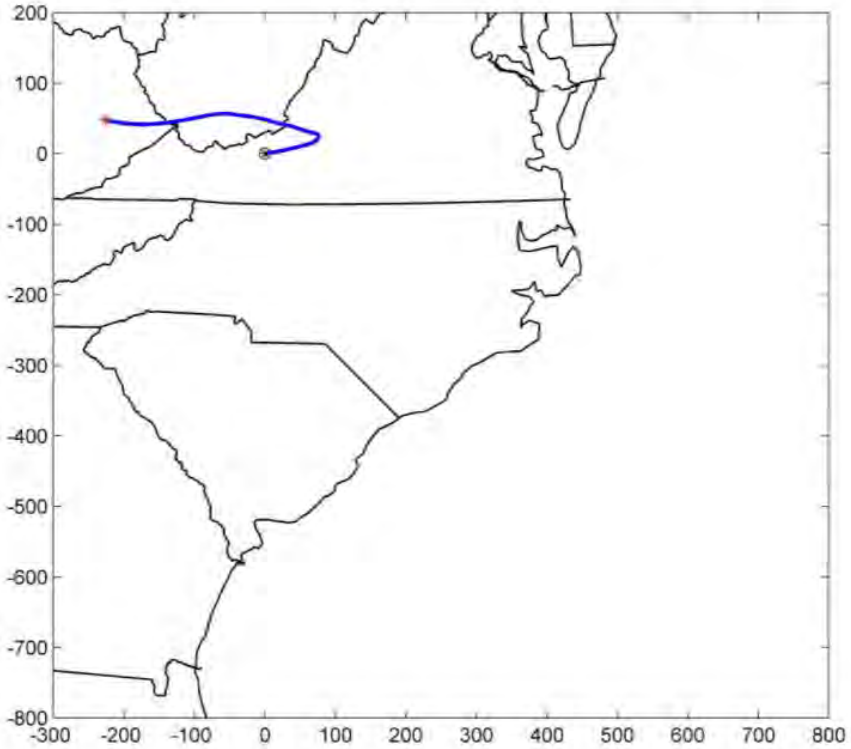
Probabilistic source regions (considering sub-grid scale turbulence)



Sampling times:
1) 9:15 am (left cloud),
2) 10:15 am (right cloud),
Sept 29, 2010

Sampling biological agents at a fixed location

Backward trajectory of particles, time delay = 1h



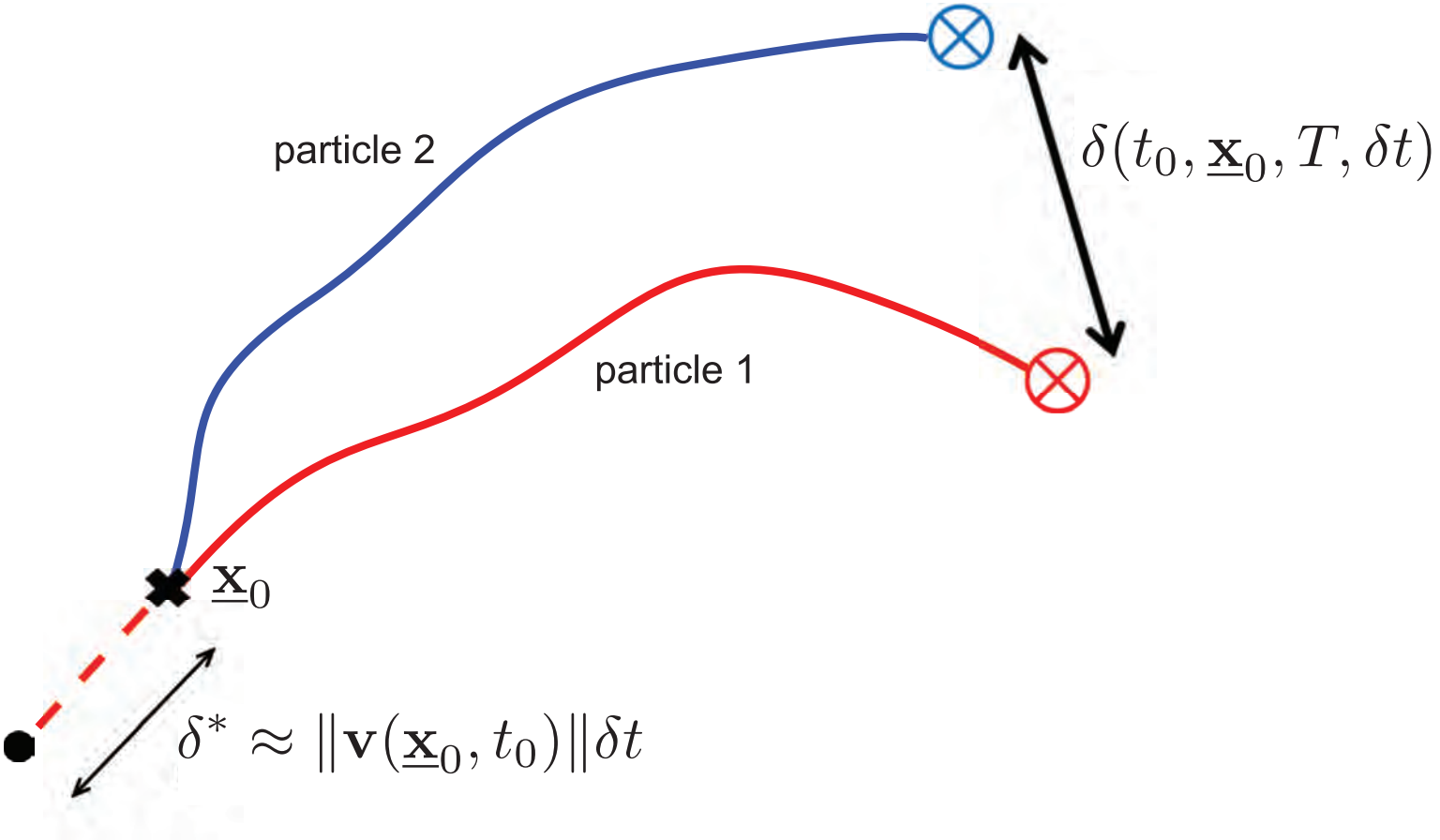
Sourceline of sampled points

made of initial points from sequentially sampled pathlines

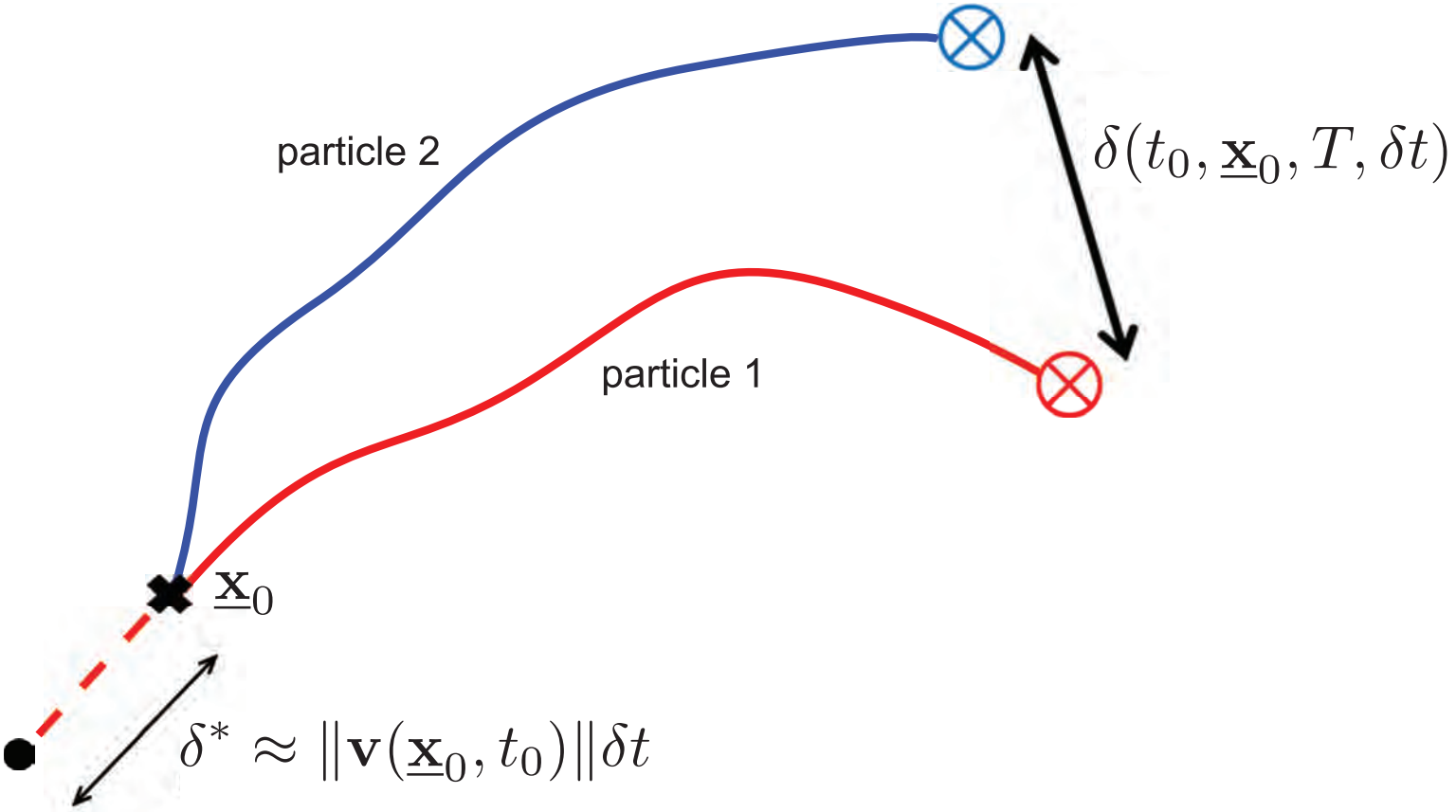
Strain along this curve related to FTLE

- Sampling point: Virginia Tech campus
- Sampling times: 8AM – 8AM, Sep 29 & 30, 2010
- Integration time: - 24 h.

Sequential release (or capture) from a fixed location

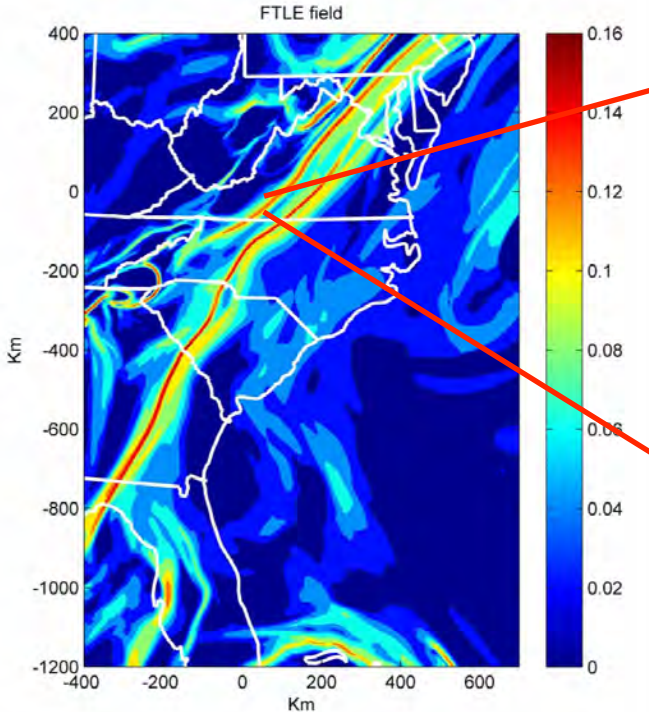


Sequential release (or capture) from a fixed location

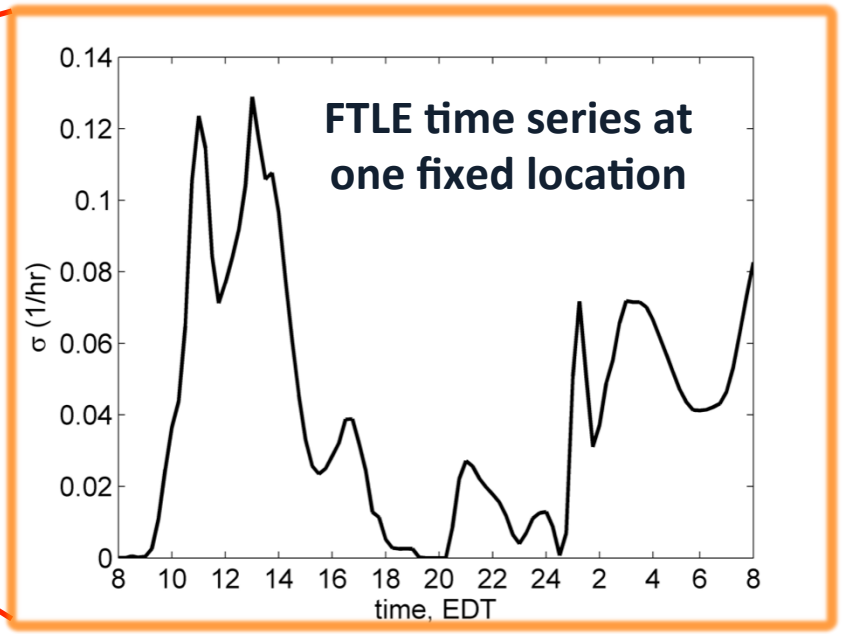


$$\sigma_{t_0}^{T}\left(\underline{\mathbf{x}}, t_0\right) \approx \lim_{|T| \gg \delta t} \lim_{\delta t \to 0} \frac{1}{|T|} ln \frac{\delta\left(t_0, \underline{\mathbf{x}}_0, T, \delta t\right)}{\left\|\underline{\mathbf{v}}\left(\underline{\mathbf{x}}, t_0\right) \delta t\right\|}$$

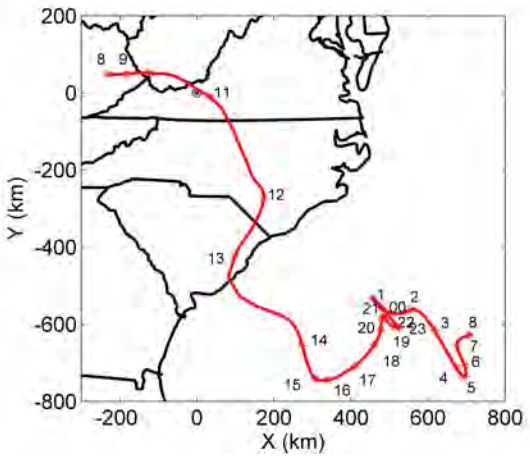
Sequential release (or capture) from a fixed location



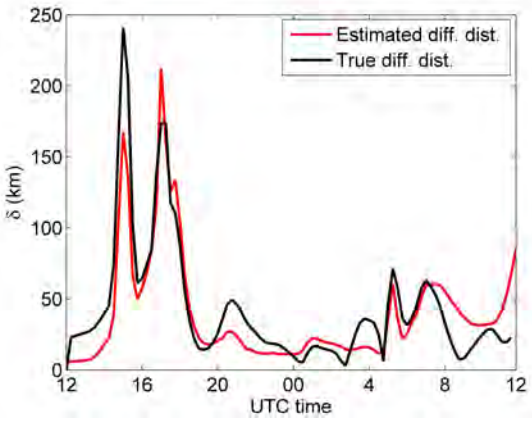
FTLE for T = -24 hr



Sourceline of sampled points

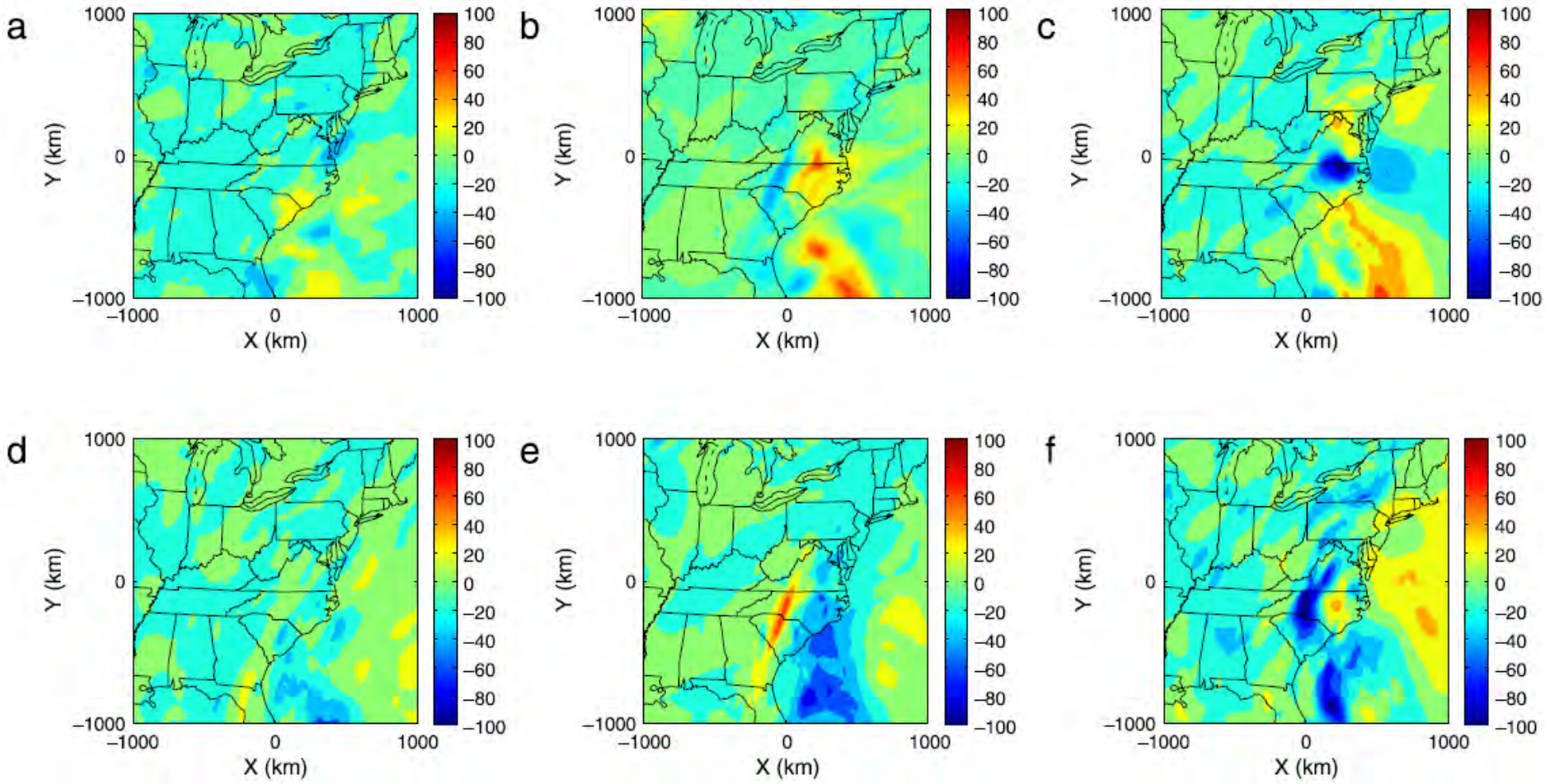


Distance between adjacent points along sourceline



Forecasting atmospheric LCS

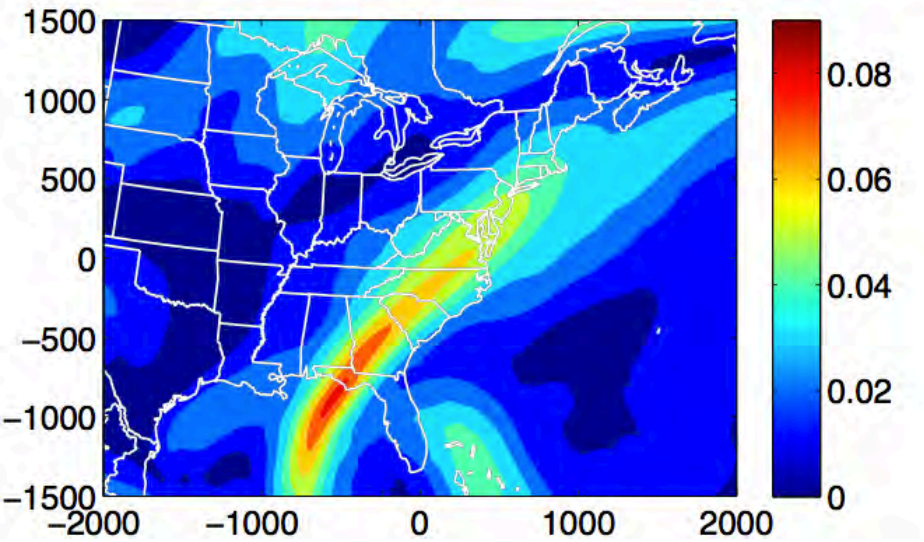
Wind field errors are not small or localized in time



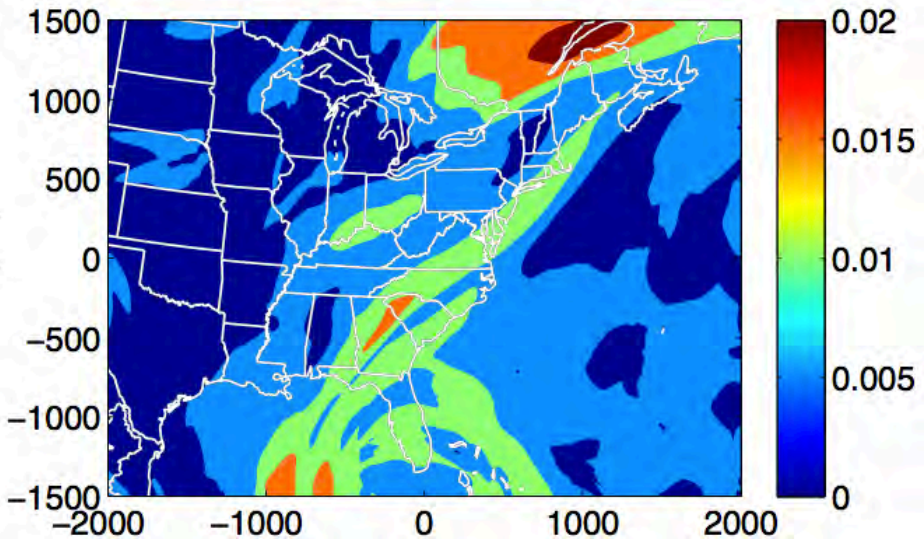
BozorgMagham, Ross, Schmale [2013] *Physica D*

Forecasting atmospheric LCS

Using an ensemble forecasting approach
- Global scale (low res.) model
- ensemble of 15 members



Ensemble average

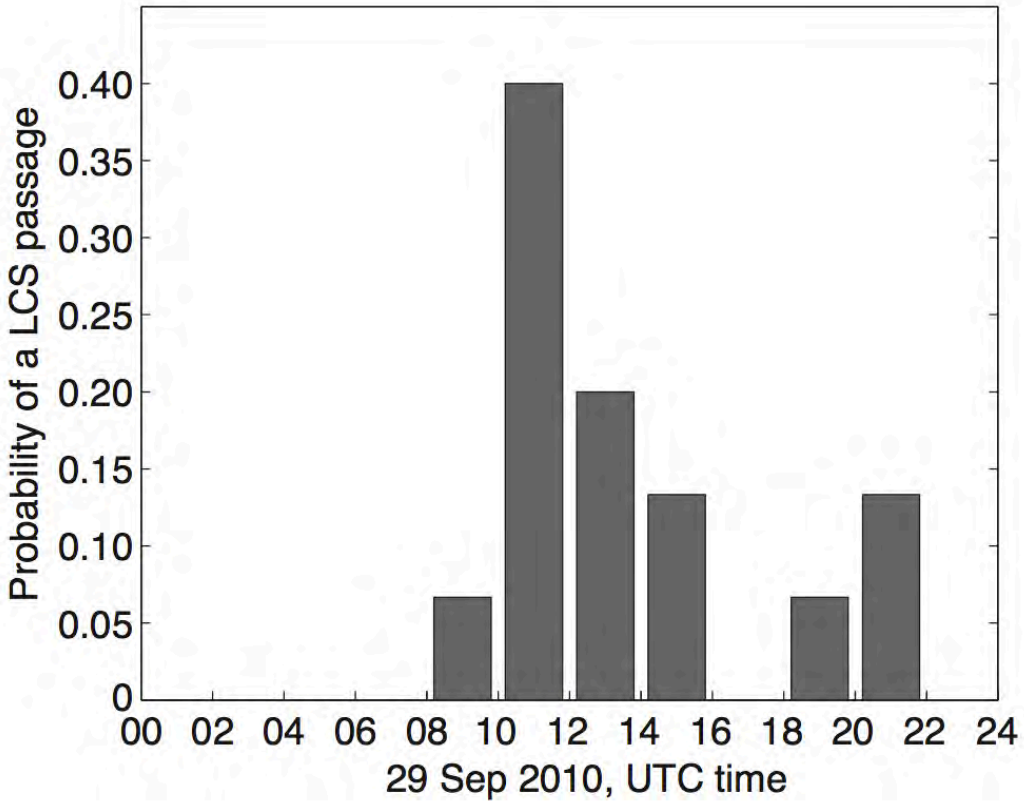


Standard deviation

BozorgMagham, Ross [2013]

Forecasting atmospheric LCS

Forecasting an LCS passage time

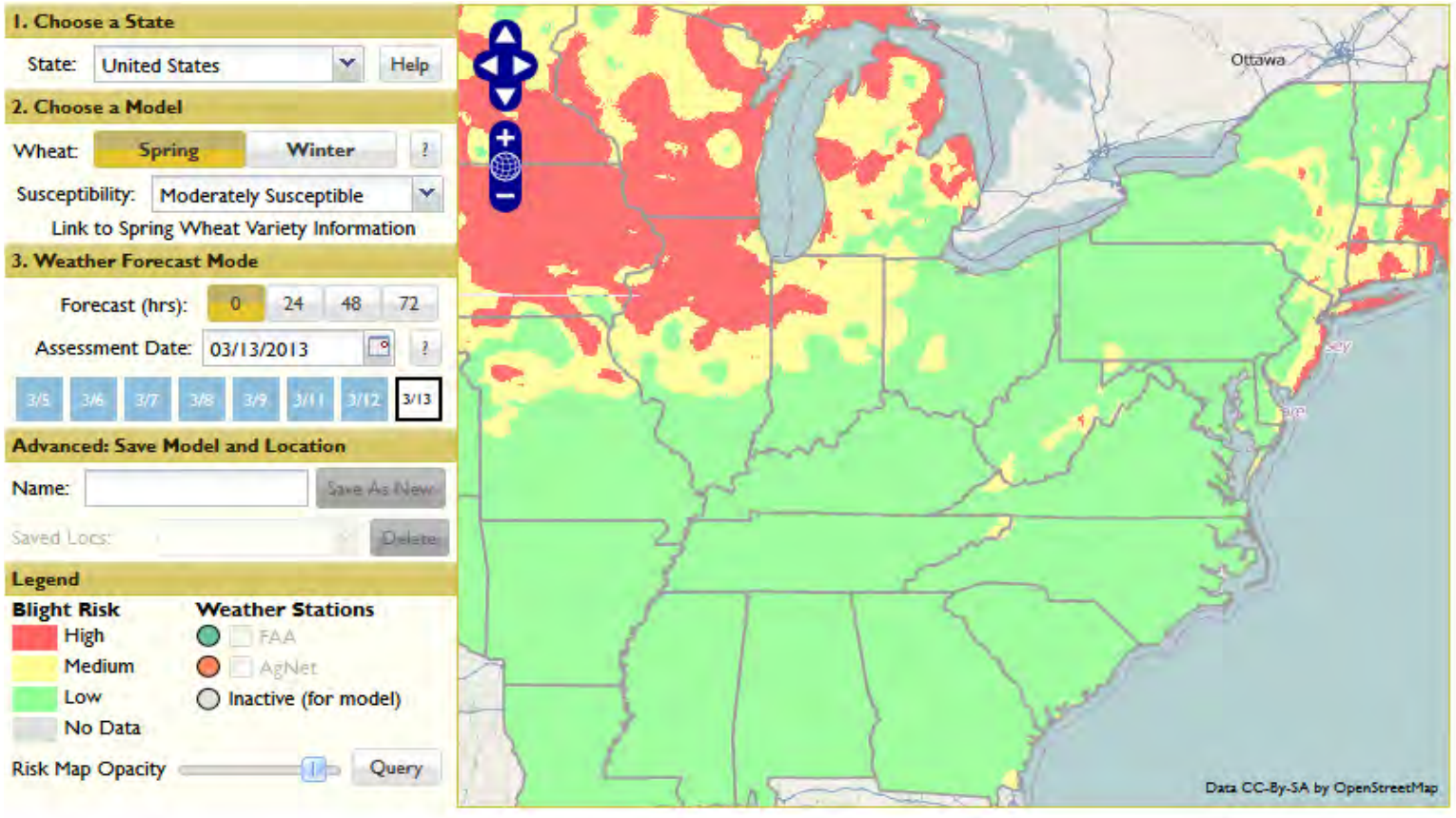


Can correctly forecast within 2 hours 60% of the time

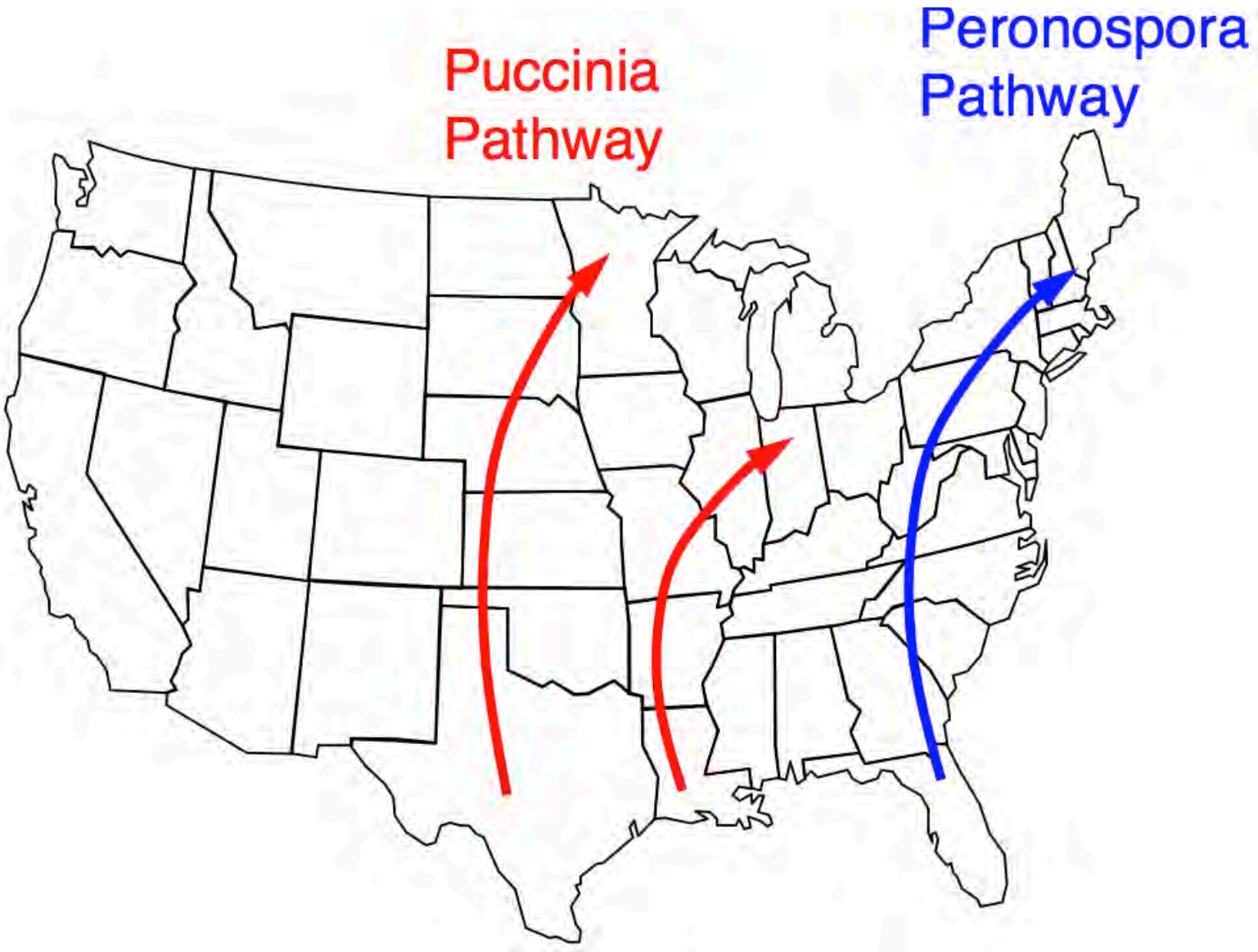
BozorgMagham, Ross [2013]

Practical application: early warning systems

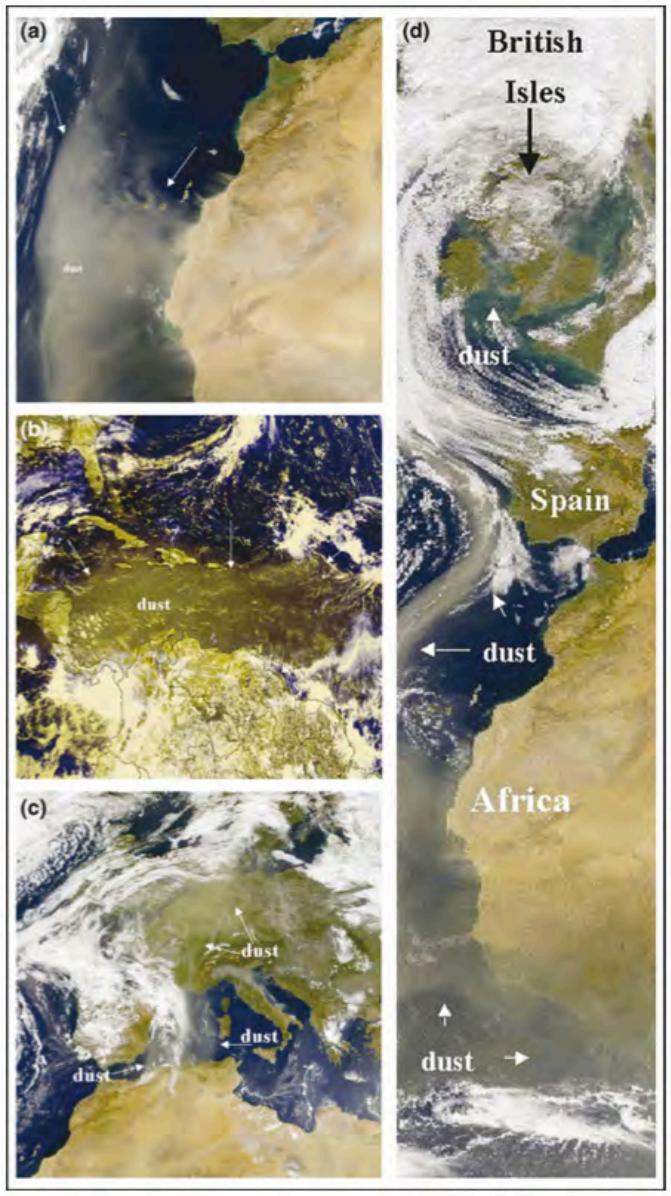
LCS or other transport analysis methods could help inform farmers regarding possible zones of disease spread

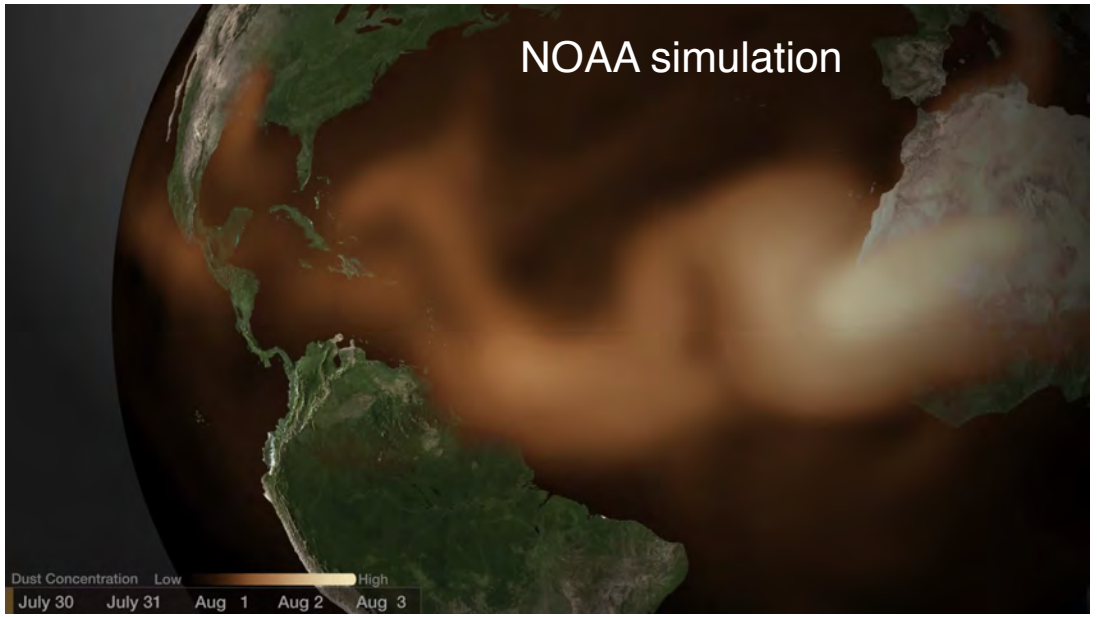


Likely dispersal pathways or persistent barriers

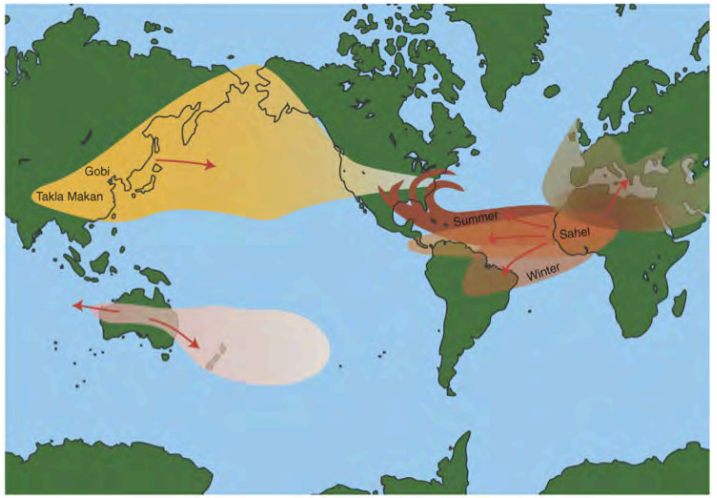


Aerobiology and the global transport of desert dust





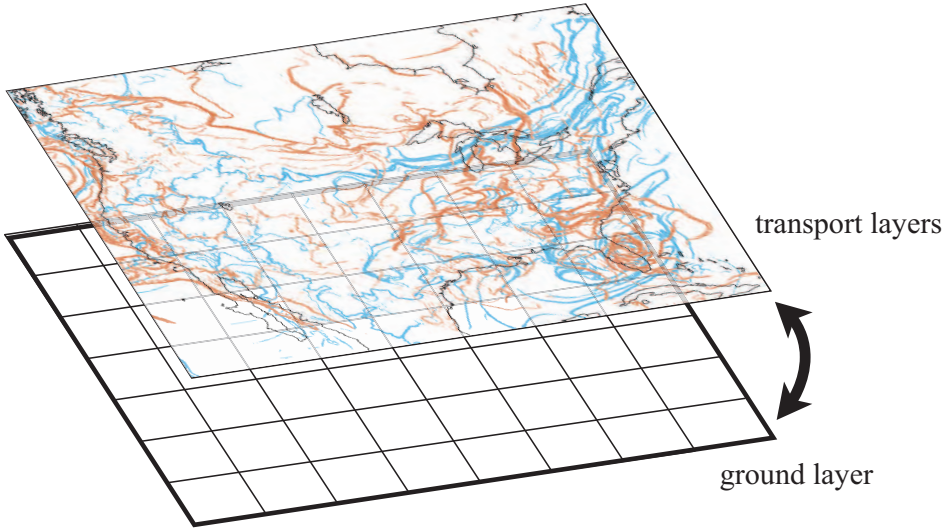
Lagrangian 'bridges' connecting distant ecosystems

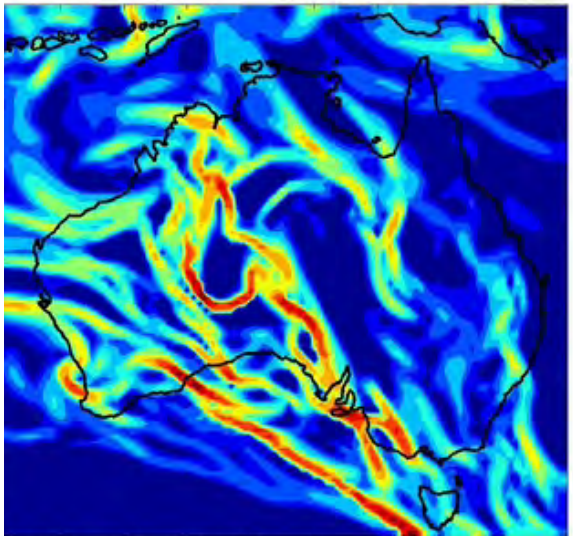


Kellogg, Griffin [2006]

Final thoughts: coherence/transport in aerobiology

- Could provide insight to spatiotemporal data and models
- Future:
  - 3D
  - Can LCS inform better management practices (e.g., fungicide spraying?)
  - Map of global connectivity
  - Effect of climate change

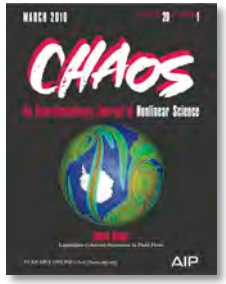




The End

Sponsors: NSF DEB-0919088
NSF CMMI-1100263

Thank You



Main Papers:

- BozorgMagham, Ross, Schmale [2013] Real-time prediction of atmospheric Lagrangian coherent structures based on forecast data: An application and error analysis. *Physica D* 258, 47-60.
- Lin, BozorgMagham, Ross, Schmale [2013] Small fluctuations in the recovery of fusaria across consecutive sampling intervals with unmanned aircraft 100 m above ground level. *Aerobiologia* 29(1), 45-54.
- BozorgMagham, Ross [2013] Atmospheric Lagrangian coherent structures considering unresolved turbulence and forecast uncertainty, *submitted*.
- Prussin, Marr, Schmale, Ross [2013] Experimental validation of a long-distance transport model for plant pathogens: Application to Fusarium graminearum.

- Tallapragada, Ross, Schmale [2011] Lagrangian coherent structures are associated with fluctuations in airborne microbial populations. *Chaos* 21, 033122.
- Lekien & Ross [2010] The computation of finite-time Lyapunov exponents on unstructured meshes and for non-Euclidean manifolds. *Chaos* 20, 017505.

Extra Slides

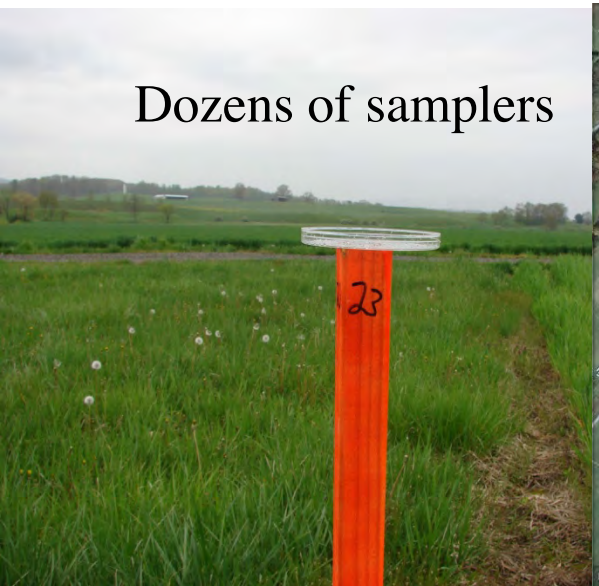
Field experiments: tracking movement of plant pathogen from a controlled source

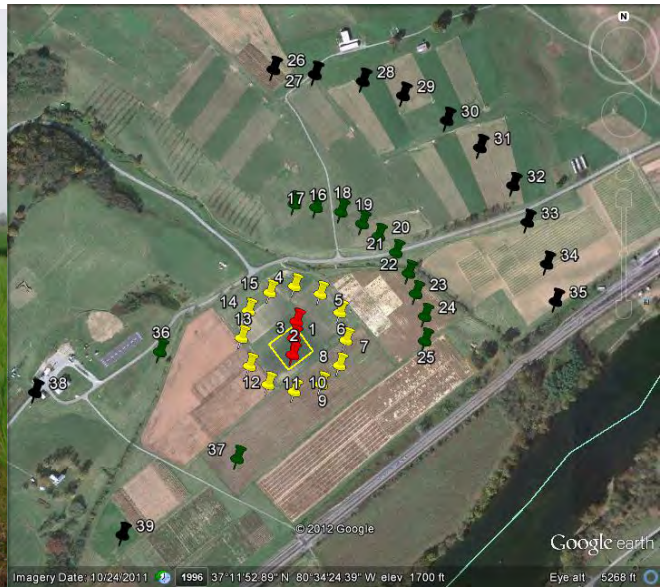
5 acres of winter wheat

Inoculum preparation

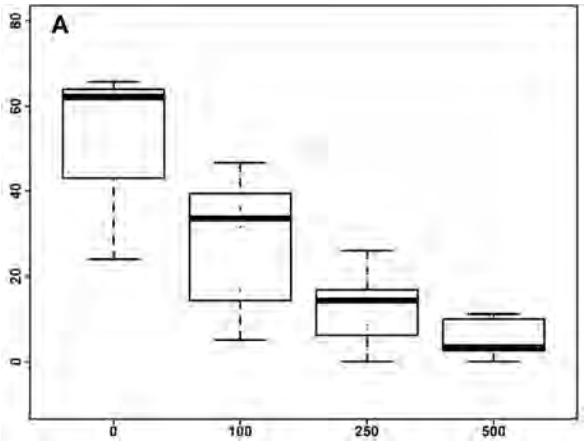
Field inoculation

Dozens of samplers





Pathogen deposited decreases with distance



Food supply concerns, bioterrorism

Wheat scientists seek to slow crop fungus in Africa, Asia

Recommend Be the first of your friends to recommend this.

Thu Aug 30, 2012 10:00pm EDT

*** Stem rust, originating in Uganda, spreads to Yemen, Iran**

* Fears that it could sweep eastwards in Asia

By Alister Doyle

OSLO, Aug 31 (Reuters) - Wheat experts are stepping up monitoring of a crop disease first found in Africa in 1999 to minimise the spread of a deadly fungus that is also a threat in Asia, experts said on Friday.

A "Rust-Tracker", using data supplied by farmers and scientists, could now monitor the fungus in 27 developing nations across 42 million hectares (103 million acres) of wheat - an area the size of Iraq or California.

"It's the most serious wheat disease," Ronnie Coffman, vice-chair of the Borlaug Global Rust Initiative (BGRI), told Reuters ahead of a meeting of wheat experts in Beijing from Sept. 1-4.

"If it gets started...it's like a biological firestorm," he said. Experts will review progress in combating the disease, with fungicides and 20 new resistant varieties developed in recent years.

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Annu. Rev. Phytopathol. 2003. 41:155–76
doi: 10.1146/annurev.phyto.41.121902.102839

First published online as a Review in Advance on April 16, 2003

THE THREAT OF PLANT PATHOGENS AS WEAPONS AGAINST U.S. CROPS

L.V. Madden[1] and M. Wheelis[2]
[1]*Department of Plant Pathology, Ohio State University, Wooster, Ohio 44691; email: madden.1@osu.edu*
[2]*Section of Microbiology, University of California, Davis, California 95616; email: mlwheelis@ucdavis.edu*

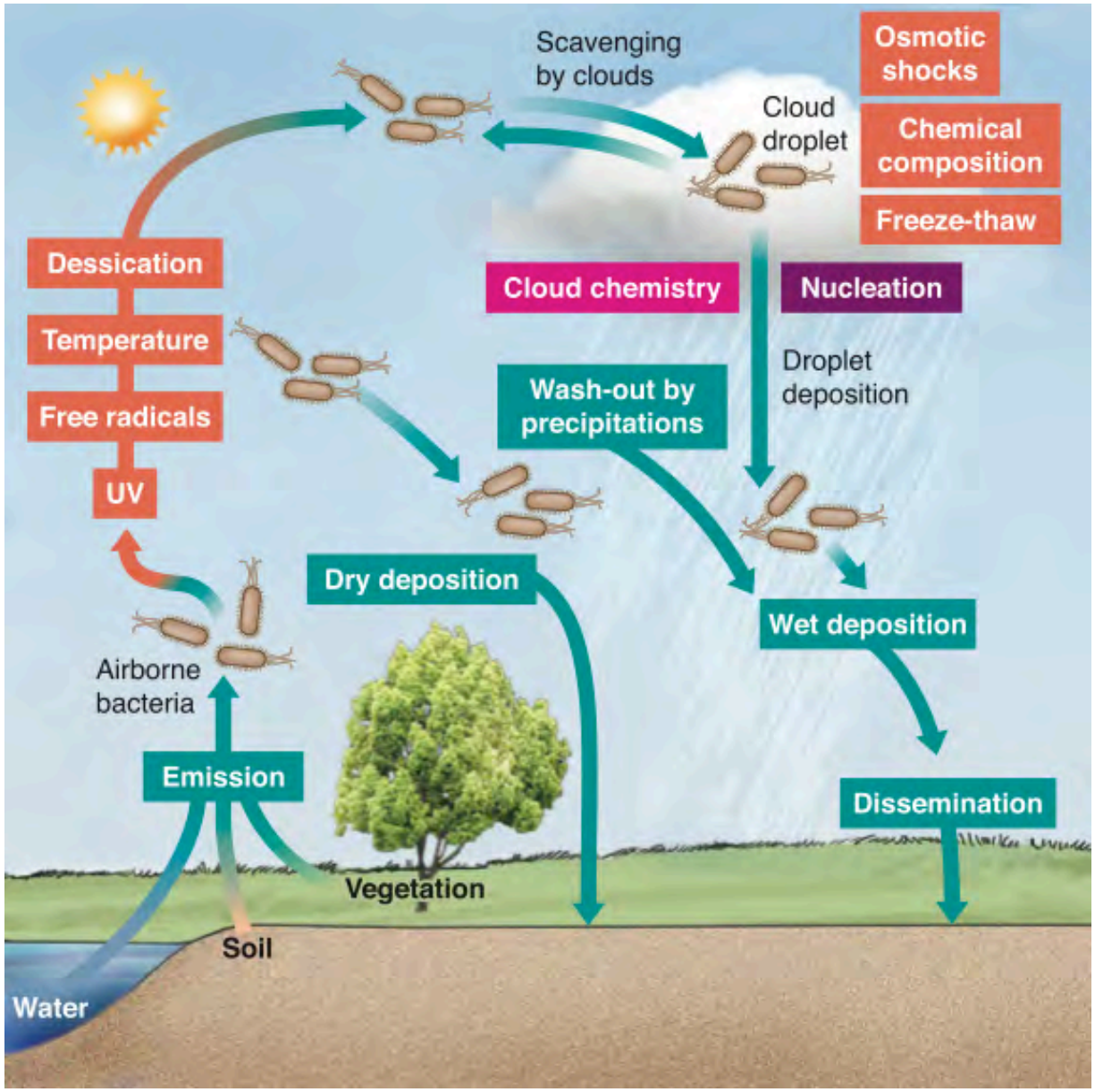
Key Words agricultural vulnerability, biological weapons, bioterrorism, crop biosecurity, plant disease invasion, plant disease persistence and spread, risk analysis

■ **Abstract** The U.S. National Research Council (NRC) concluded in 2002 that U.S. agriculture is vulnerable to attack and that the country has inadequate plans for dealing with agricultural bioterrorism. This article addresses the vulnerability of U.S. crops to attack from biological weapons by reviewing the costs and impact of plant diseases on crops, pointing out the difficulty in preventing deliberate introduction of pathogens and discovering new disease outbreaks quickly, and discussing why a plant pathogen might be chosen as a biological weapon. To put the threat into context, a brief historical review of anti-crop biological weapons programs is given. The argument is made that the country can become much better prepared to counter bioterrorism by developing a list of likely anti-crop threat agents, or categories of agents, that is based on a formal risk analysis; making structural changes to the plant protection system, such as expanding diagnostic laboratories, networking the laboratories in a national system, and educating first responders; and by increasing our understanding of the molecular biology and epidemiology of threat agents, which could lead to improved disease control, faster and more sensitive diagnostic methods, and predictions of disease invasion, persistence, and spread following pathogen introduction.

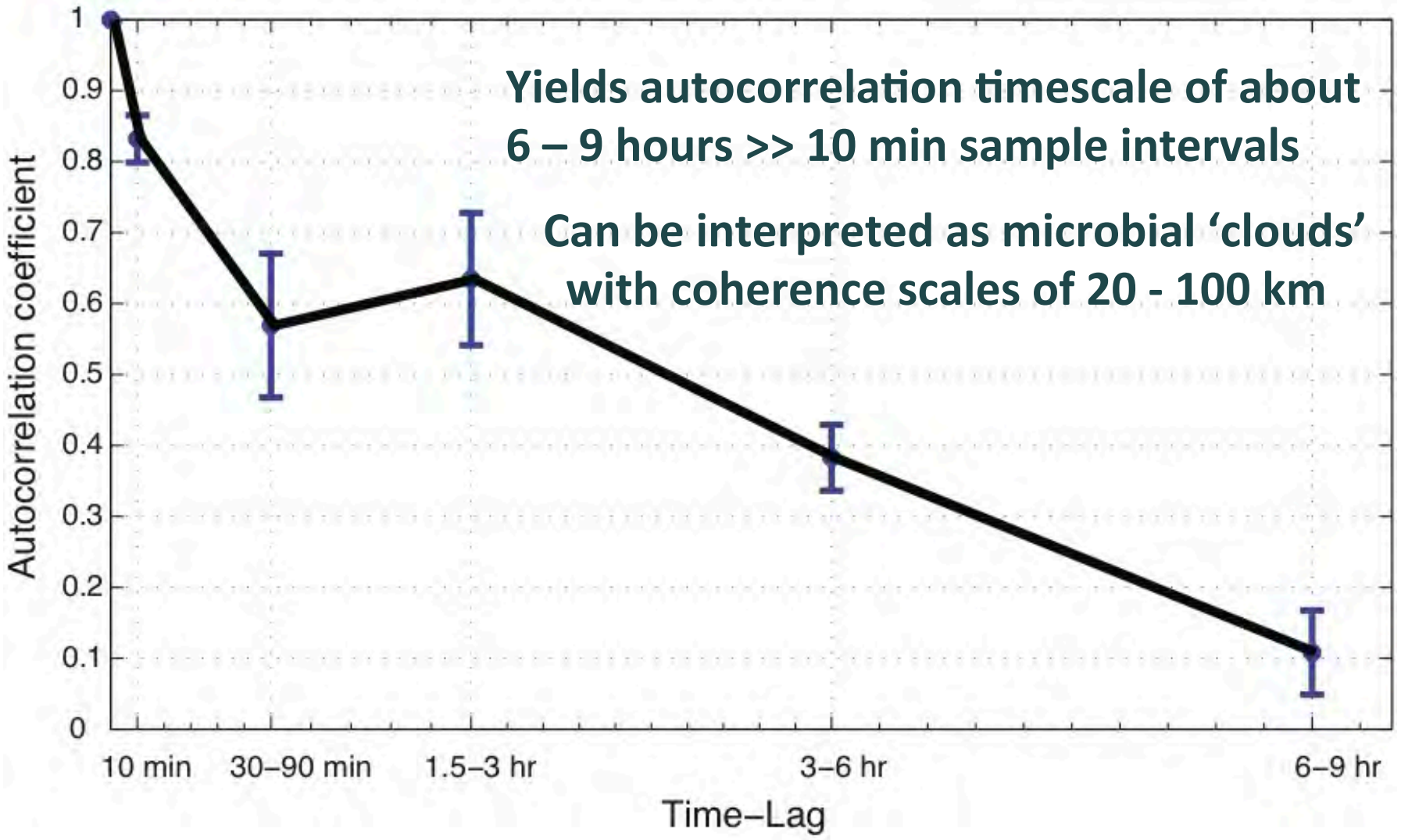
INTRODUCTION

Using [biological weapons] to attack livestock, crops, or ecosystems offers

Microbes ride in clouds, catalyze rain



Auto-correlation vs. time-lag

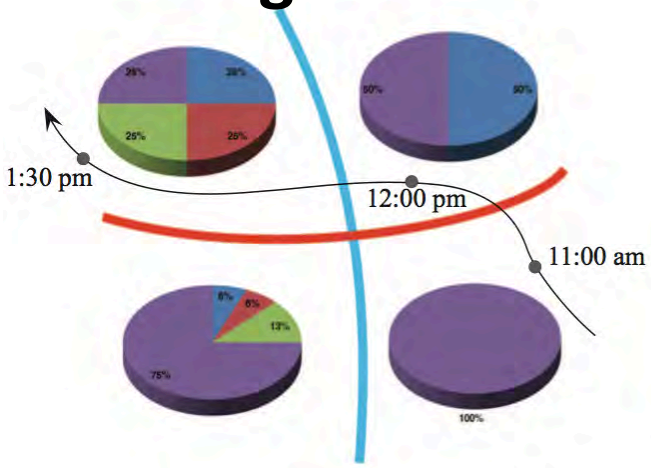


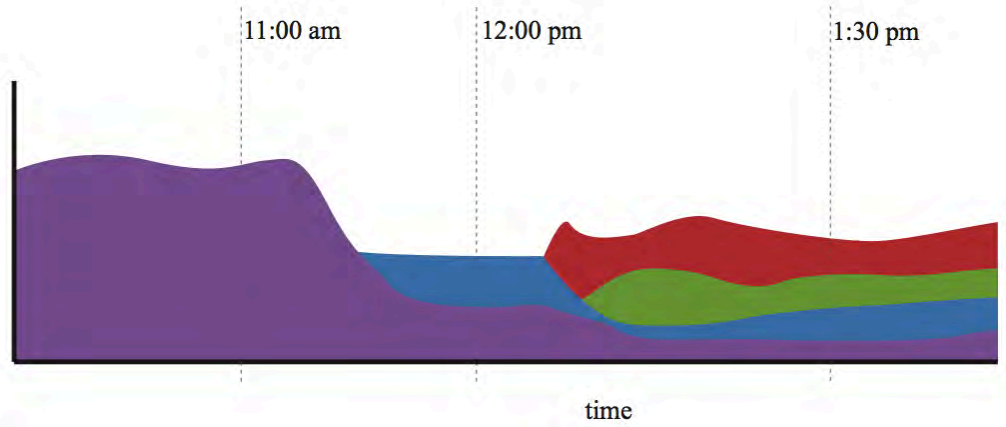
Yields autocorrelation timescale of about 6 – 9 hours >> 10 min sample intervals

Can be interpreted as microbial 'clouds' with coherence scales of 20 - 100 km

Future and ongoing work

- **Airborne collections may encode recent atmospheric mixing events**





- **Consider geodesic theory to find KAM-like boundaries which can transport microbes**