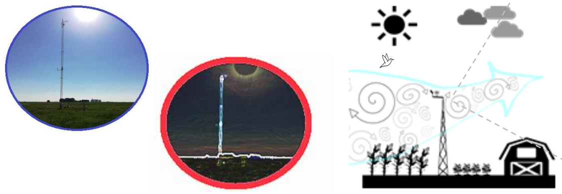
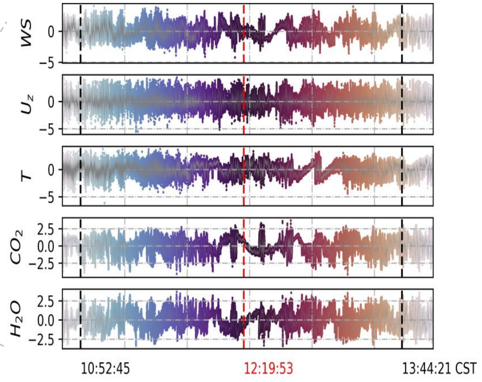
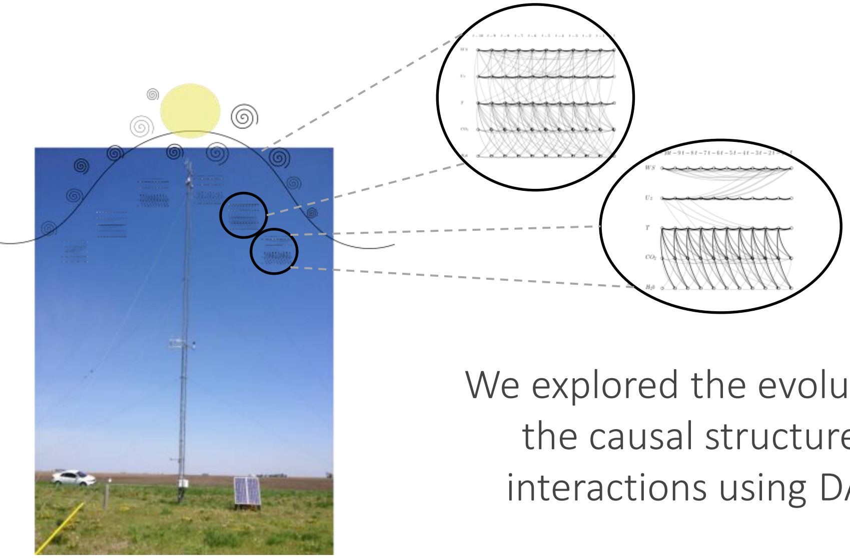
Are there distinct causal structures present within daytime turbulence in land-atmosphere exchange?

Causal interaction in high-frequency turbulence at the biosphere-atmosphere interface: Structural behavior.
Hernandez Rodriguez, L & Kumar, P, submitted to Chaos: An Interdisciplinary Journal of Nonlinear Science - IN REVIEW

We explored daytime turbulence during a clear sky day and during a solar eclipse using 10Hz data.



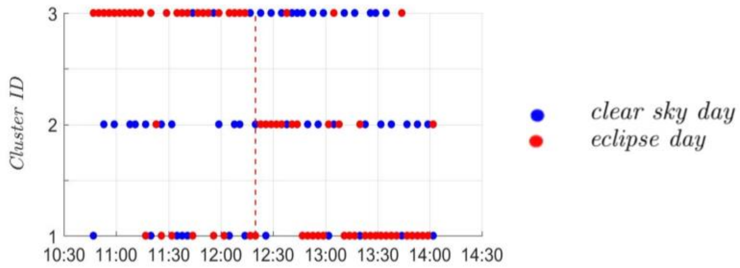




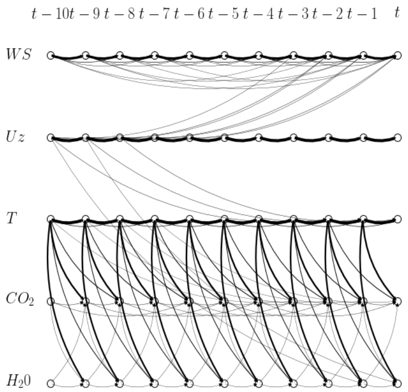
DAGs with concordant edges are more similar to each other.

We explored the evolution of the causal structure of interactions using DAGs.

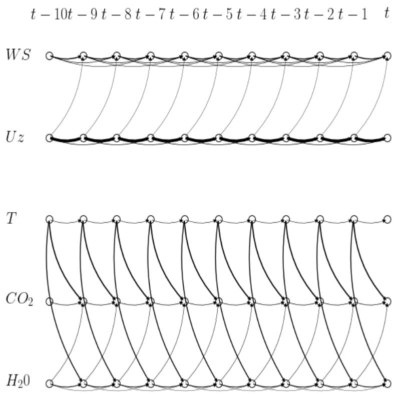
We identified three clusters of similar behavior in daytime turbulence.



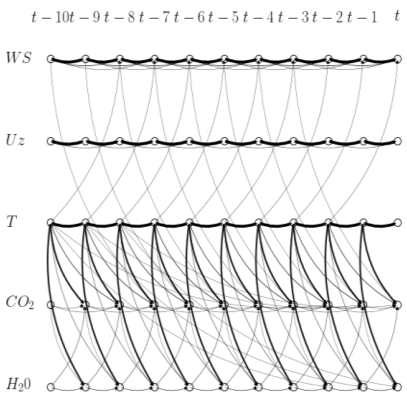
Cluster # 1



Cluster # 2



Cluster # 3

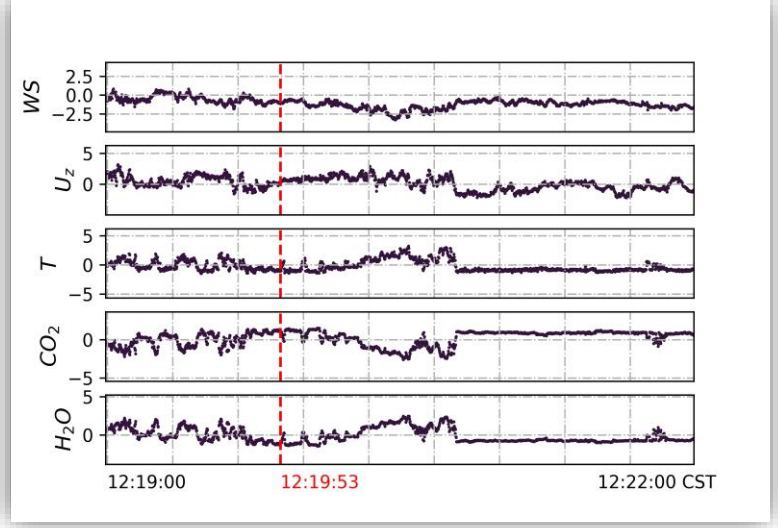


We found that thermodynamics has a larger impact on the scalar transport of H_2O and CO_2 than wind dynamics.

Leila Hernandez Rodriguez (now at Berkeley Lab, lchernandezrodriguez@lbl.gov) & Praveen Kumar (kumar1@illinois.edu)

In high-frequency observations (10Hz)
multiple variables capture a complex system of non-linear interactions

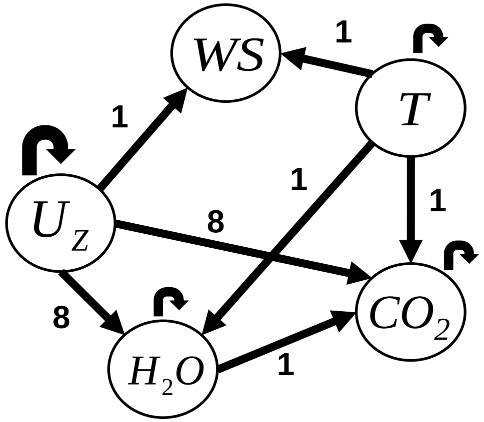
Time-series data



Process network representation

Structural causal model, SCM (Pearl,2000)

Ecohydrologic process networks (Ruddell & Kumar, 2009)



a variable

τ the influence between two nodes with lag τ

Links of information flow characterize joint variability in terms of process connectivity

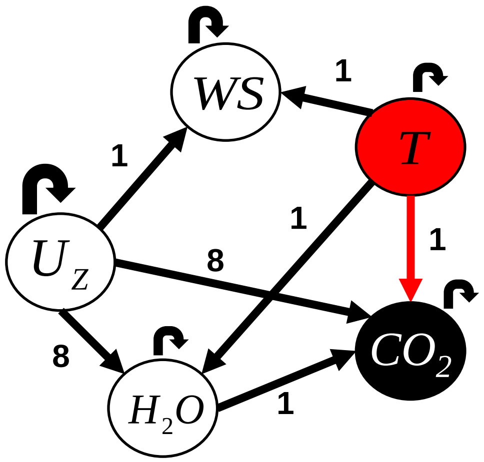
Patterns of fluctuations in the observations encode information about interactions.

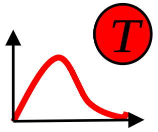
Leila Hernandez Rodriguez (now at Berkeley Lab, lchernandezrodriguez@lbl.gov) & Praveen Kumar (kumar1@illinois.edu)

Directed Acyclic Graphs (DAGs) can be used to represent the information transfer in time series, enabling a better understanding of system dynamics.

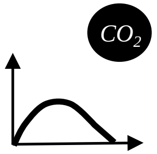
(Runge, J. et al. 2012, 2014, 2015).

From process networks…



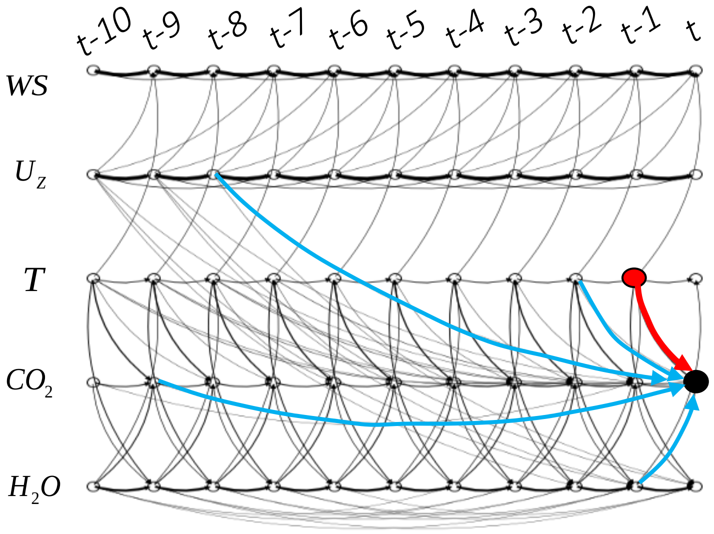


A perturbation can influence…



a **target** variable at a lagged time τ

to DAGs for time series



✓ A DAG does not contain cycles.

✓ Edges thickness shows the coupling strength computed by information flow.

Notions of causal inference:

- The graphical way of causal representation (SCM) coupled with probabilistic estimation.
- Reflects propagation of fluctuations or variations among multiple lagged variables
- Causal dependence (assignment) is asymmetric:

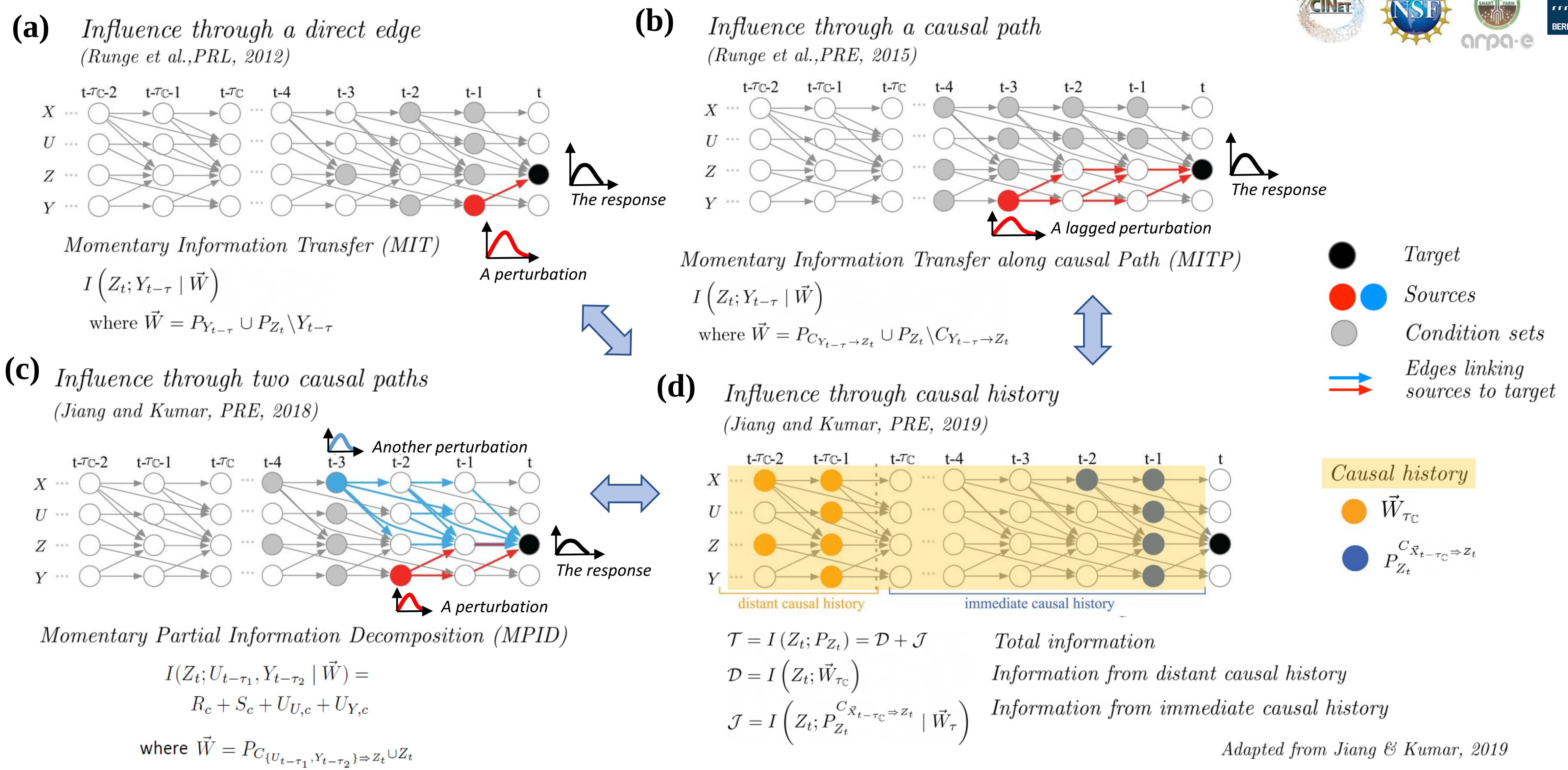
$T \rightarrow CO_2$ *is* not the same as $CO_2 \rightarrow T$

- Cause-effect influence occurs forward in time:

"The effect cannot precede the cause"

Leila Hernandez Rodriguez (now at Berkeley Lab, lchernandezrodriguez@lbl.gov) & Praveen Kumar (kumar1@illinois.edu)

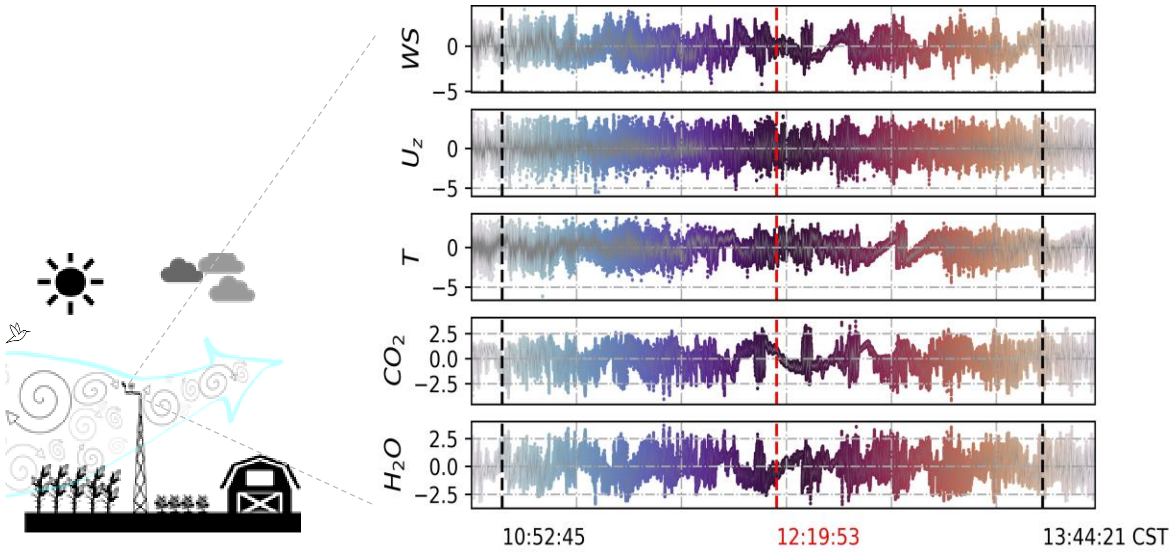
How does information flow in a multivariate system? *(Jiang & Kumar, 2019)*



Leila Hernandez Rodriguez (now at Berkeley Lab, lchernandezrodriguez@lbl.gov) & Praveen Kumar (kumar1@illinois.edu)

Are there different causal structures embedded in the daytime turbulence of the land-atmosphere exchange?

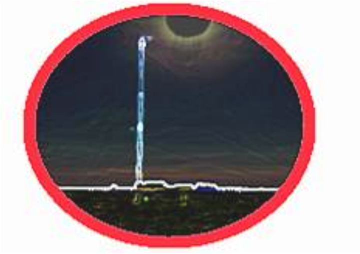
Causal interaction in high-frequency turbulence at the biosphere-atmosphere interface: Structural behavior.
Hernandez Rodriguez, L & Kumar, P, submitted to Chaos: An Interdisciplinary Journal of Nonlinear Science - IN REVIEW



Turbulence at the atmospheric boundary layer (ABL) is controlled by:

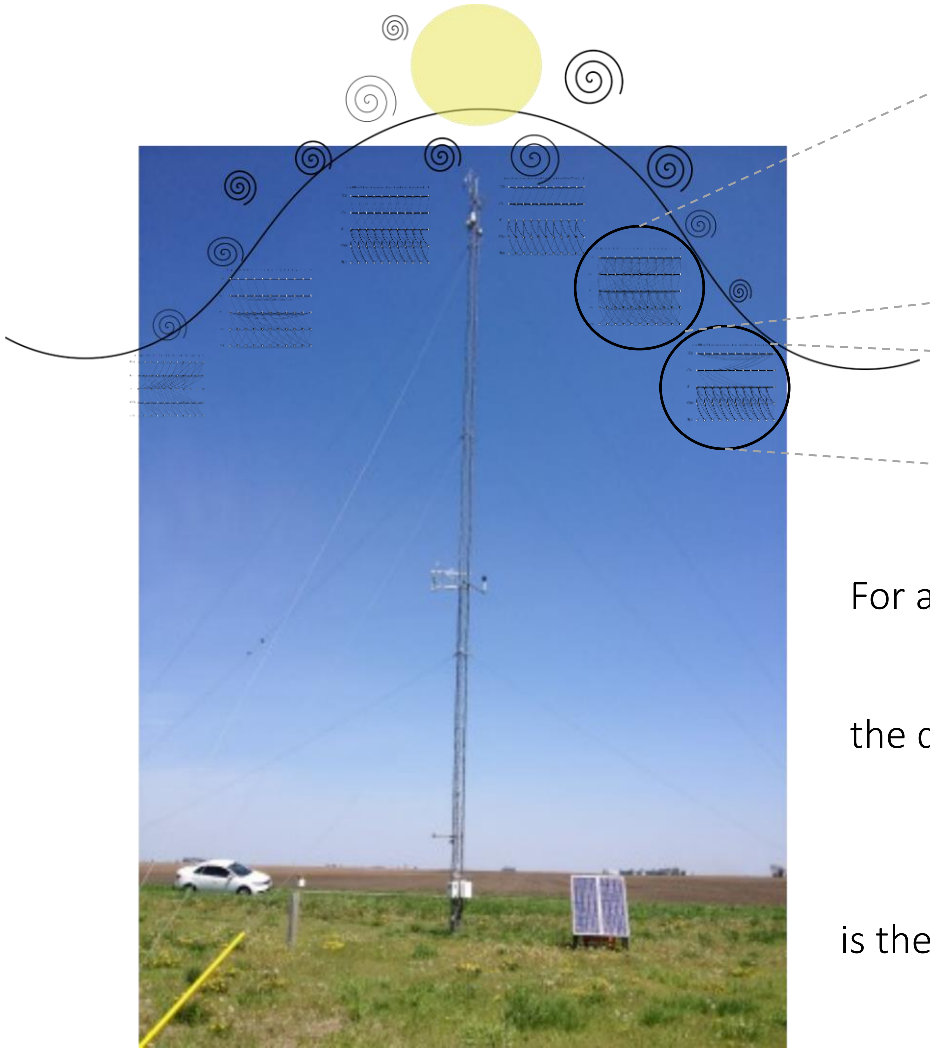
- Solar radiation: Diabatic heating increases turbulence. ET increases buoyancy of rising air.
- Surface friction: Rougher terrain, more turbulent flow.

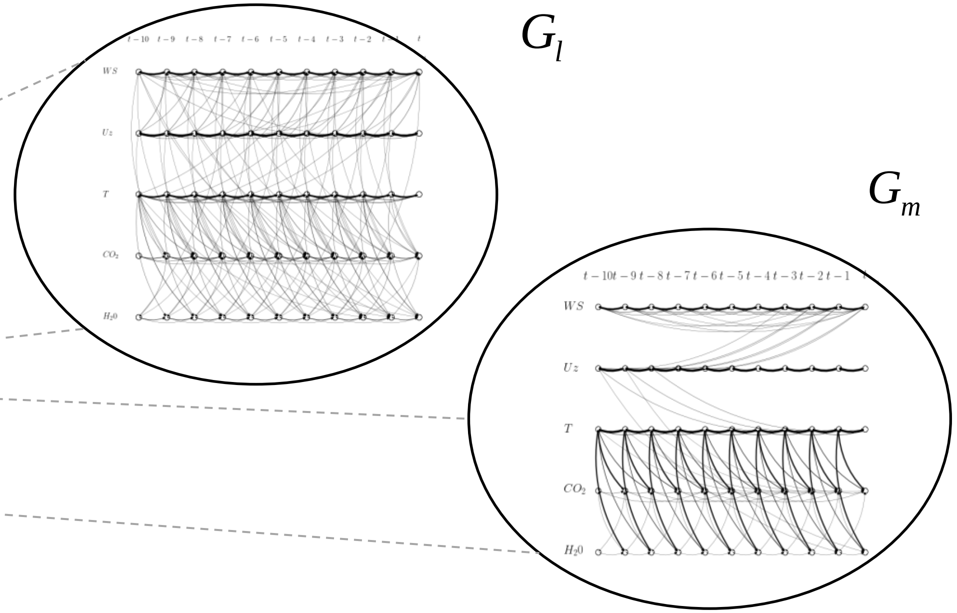
We explore the evolution of the causal structures of interactions in turbulence during a clear sky day and during a solar eclipse.



Leila Hernandez Rodriguez (now at Berkeley Lab, lchernandezrodriguez@lbl.gov) & Praveen Kumar (kumar1@illinois.edu)

We used a cascade of DAGs to explore the evolution on the causal structure of the system connectivity





○ *Vertices (or nodes)*

→ *Edges (or links)*

DAGs with concordant edges are similar to each other.

For a pair of DAGs

$$G_l = (V, E_l) \text{ and } G_m = (V, E_m)$$

the distance between them is denoted by

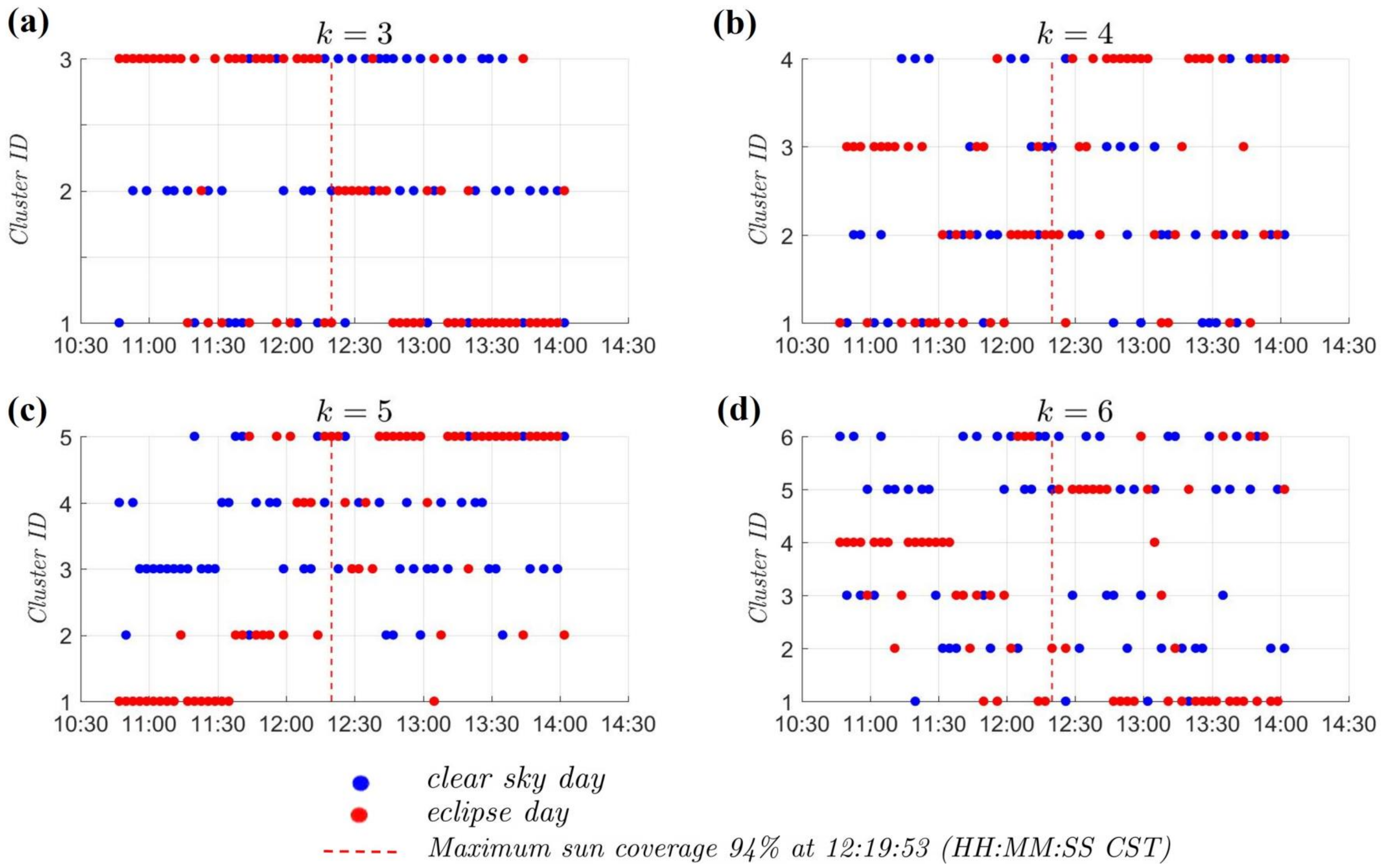
$$K^{(p,q)}(G_l, G_m) = \sum_{\substack{(i,j)\in V\times V \\ i<j}} K_{i,j}^{(p,q)}(G_l, G_m)$$ *(Malmi et al, 2015)*

is the sum of penalties associated to the vertices i and j, with respect to the parameters

p and q , where $0 \leq p , q \leq 1$

Leila Hernandez Rodriguez (now at Berkeley Lab, lchernandezrodriguez@lbl.gov) & Praveen Kumar (kumar1@illinois.edu)

Time-ordered distribution of clustered DAGs for different numbers of clusters

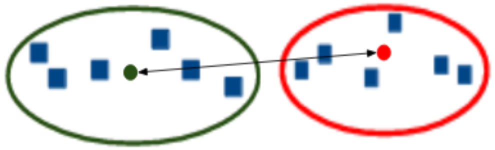


Leila Hernandez Rodriguez (now at Berkeley Lab, lchernandezrodriguez@lbl.gov) & Praveen Kumar (kumar1@illinois.edu)

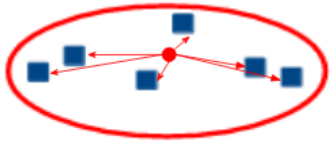
We developed the Dunn Index for DAGs: Determining an unbiased number of clusters k *(based on Dunn, 1974)*

- Ratio of the minimum of inter-cluster distances and maximum of intracluster distances.
- The more the value of the Dunn index, the better the clusters.

$$\text{Dunn Index} = \frac{\text{min(Inter cluster distance)}}{\text{max(Intra cluster distance)}}$$



Inter cluster distance



Intra cluster distance

For two clusters centroids

C_i and C_j

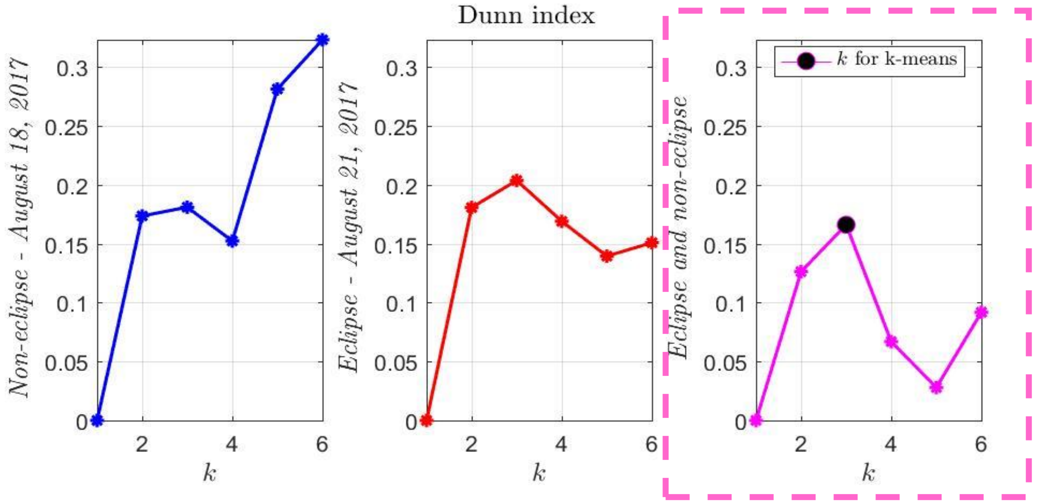
$$DI_m = \frac{\min\limits_{1 \leqslant i < j \leqslant m} \delta(C_i, C_j)}{\max\limits_{1 \leqslant k \leqslant m} \Delta_k}$$

intra-cluster-distance

$$\Delta_k = \sigma_k^2 = \frac{\sum k^2(\bar{D}, D_k)}{n_k}$$

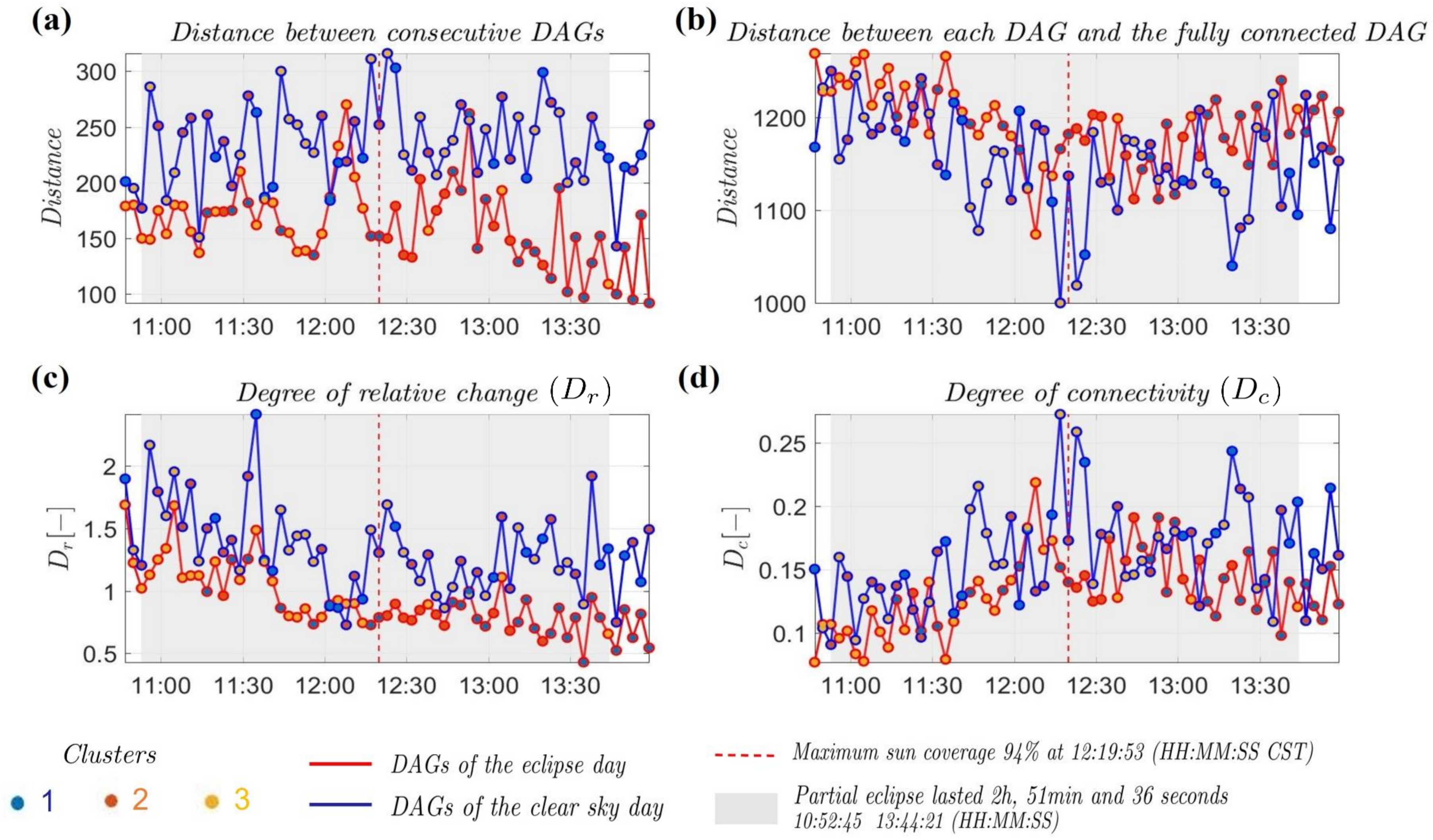
$D_k =$ distance between cluster's centroid and each DAG

$n_k =$ number of elements in cluster k



Leila Hernandez Rodriguez (now at Berkeley Lab, lchernandezrodriguez@lbl.gov) & Praveen Kumar (kumar1@illinois.edu)

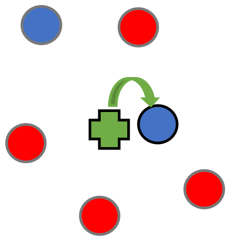
Three well differentiate clusters of similar behavior appeared, creating patterns of consecutive DAGs



Leila Hernandez Rodriguez (now at Berkeley Lab, lchernandezrodriguez@lbl.gov) & Praveen Kumar (kumar1@illinois.edu)

We selected the closest DAG to the centroid of the cluster as representative of its interdependencies

$$K^{(p,q)}(G_l, G_m)$$



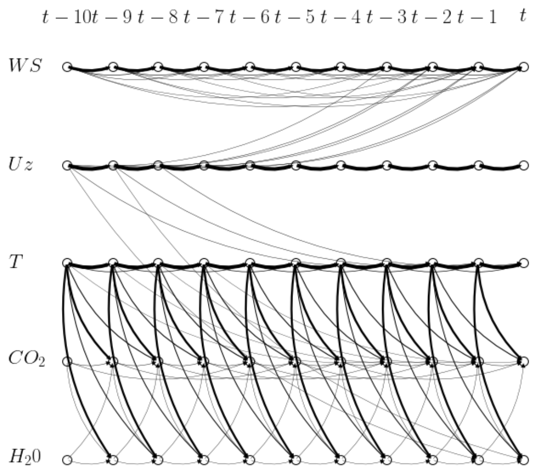
In a cluster, the centroid is the closest real DAG to the synthetic centroid.

We found that variables of different natures show different behavior:

- Dynamic character of the atmosphere: Horizontal and vertical wind components, WS and U_z
- Thermodynamics: Temperature, T.
- Scalar transport at the biosphere-atmosphere interface: CO_2 and H_2O

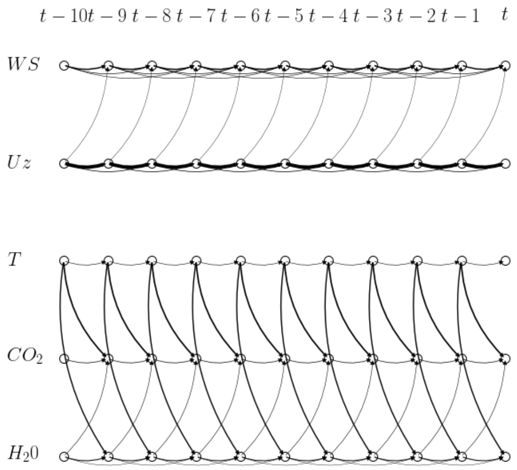
Cluster # 1

2017/08/21 13:25-13:28



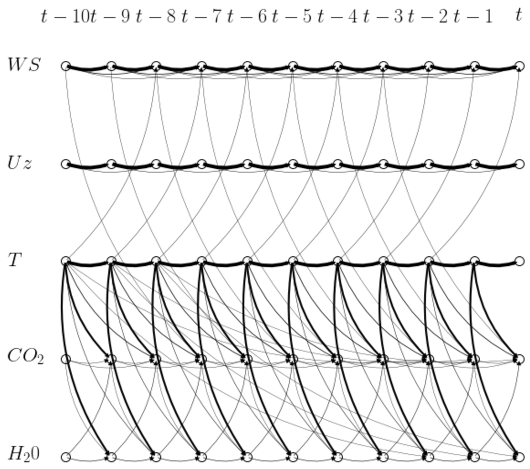
Cluster # 2

2017/08/18 10:49-10:52



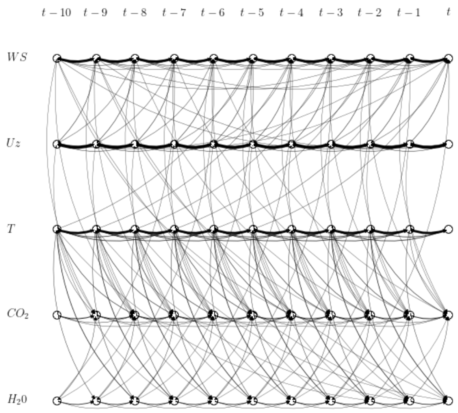
Cluster # 3

2017/08/21 13:40 – 13:43

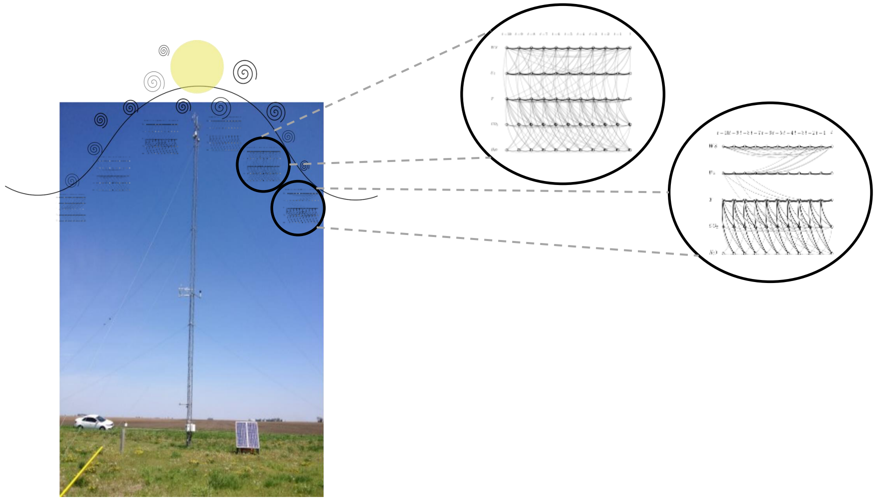


Leila Hernandez Rodriguez (now at Berkeley Lab, lchernandezrodriguez@lbl.gov) & Praveen Kumar (kumar1@illinois.edu)

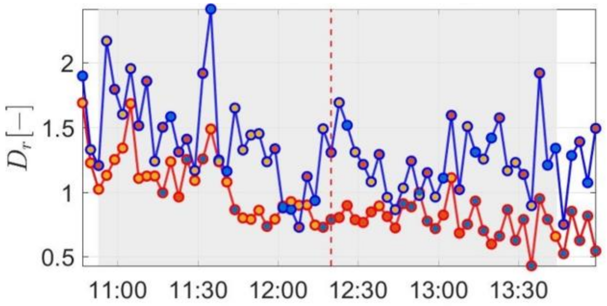
We learned that the evolving system creates patterns of similar behavior



Causal dependencies propagate fluctuations that produce patterns of similar behavior at high frequency.



We developed a framework to explore the evolution of the causal structure.



We identified three clusters of similar turbulence behavior and observed that thermodynamics primarily influenced the buoyant movement of scalars during daytime.

Leila Hernandez Rodriguez (now at Berkeley Lab, lchernandezrodriguez@lbl.gov) & Praveen Kumar (kumar1@illinois.edu)