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Lagrangian Coherent Structures in the Thermosphere

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Illinois Institute of Technology

Supported by NSF and IIT Undergraduate Research Program Awards

Outline

- Motivation: material transport
- Objective: to find coherent structures in the thermosphere
- Background: Lagrangian coherent structures (LCSs)
- Methods:
  - Test I: Do LCSs exist?
  - Test II: Do they respond to geomagnetic activity?
  - Test III: Can they bound material transport in the thermosphere?
- Results
- Conclusion

Shuttle launch dumped water vapor in the thermosphere…

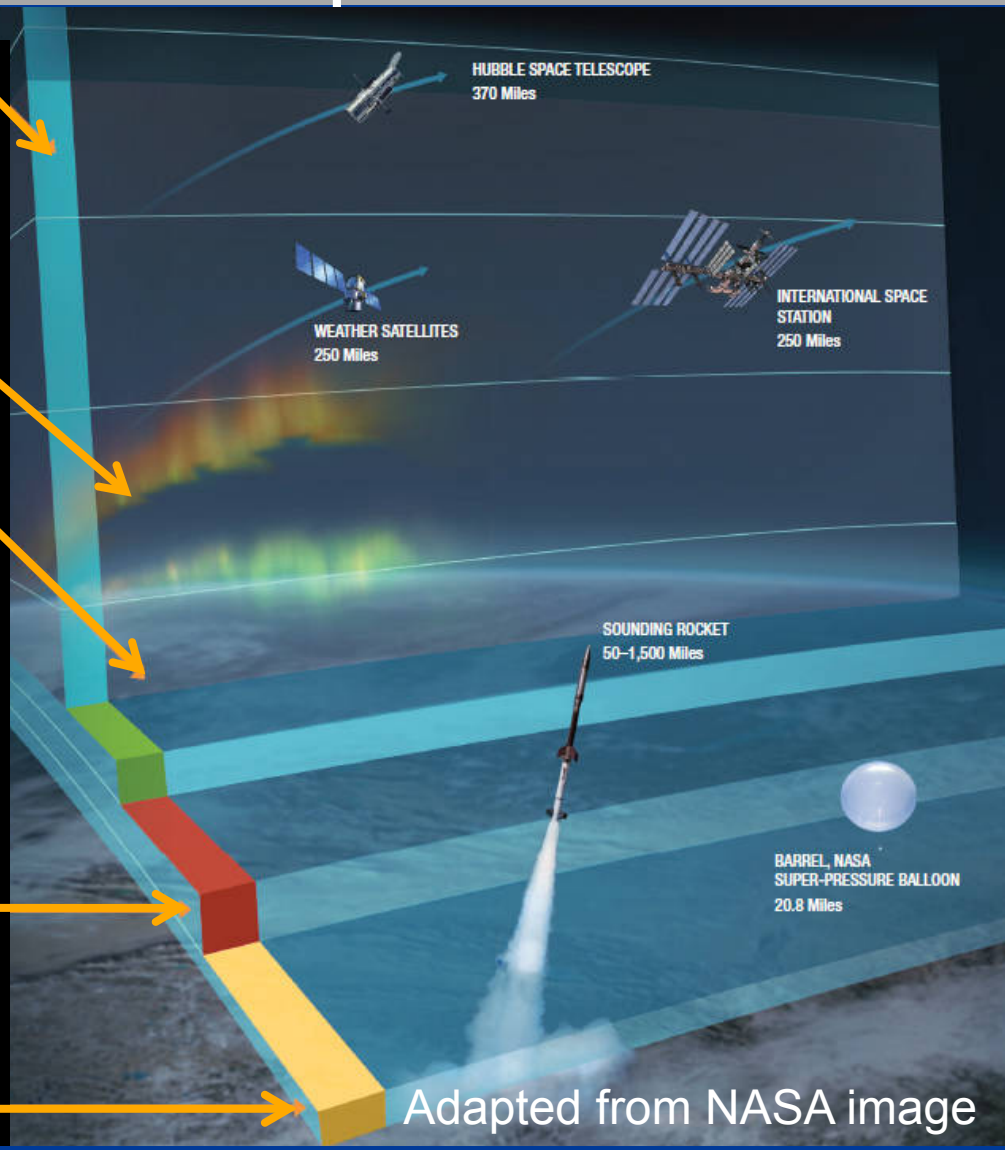
Thermosphere:
Neutrals
85 to 600 km

Ionosphere:
Plasma
85 to 600 km

Mesosphere:
50 to 85 km

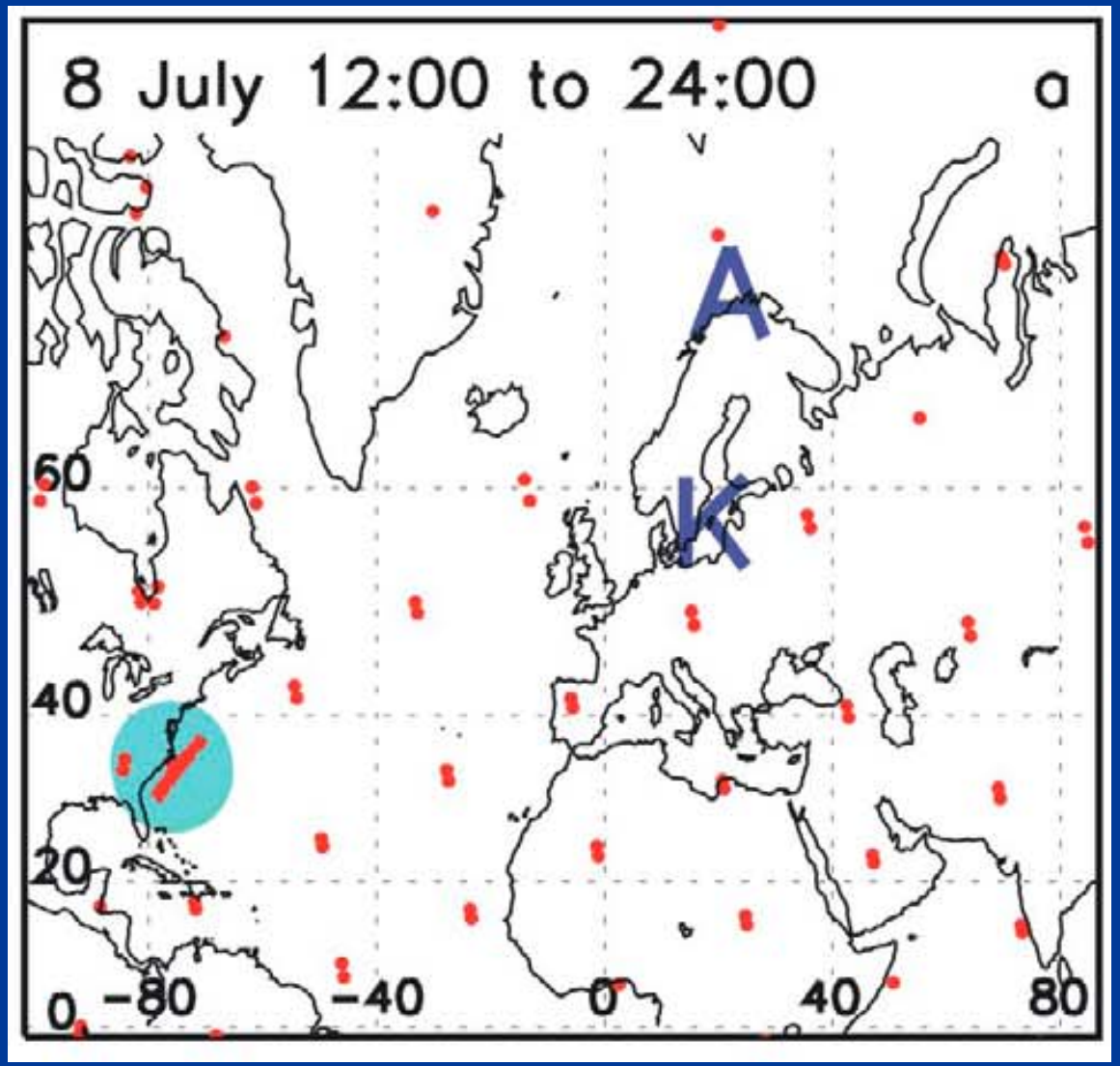
Stratosphere:
16 to 50 km

Troposphere:
0 to 16 km



Adapted from NASA image

…that was detected across the Atlantic and toward the Arctic*!



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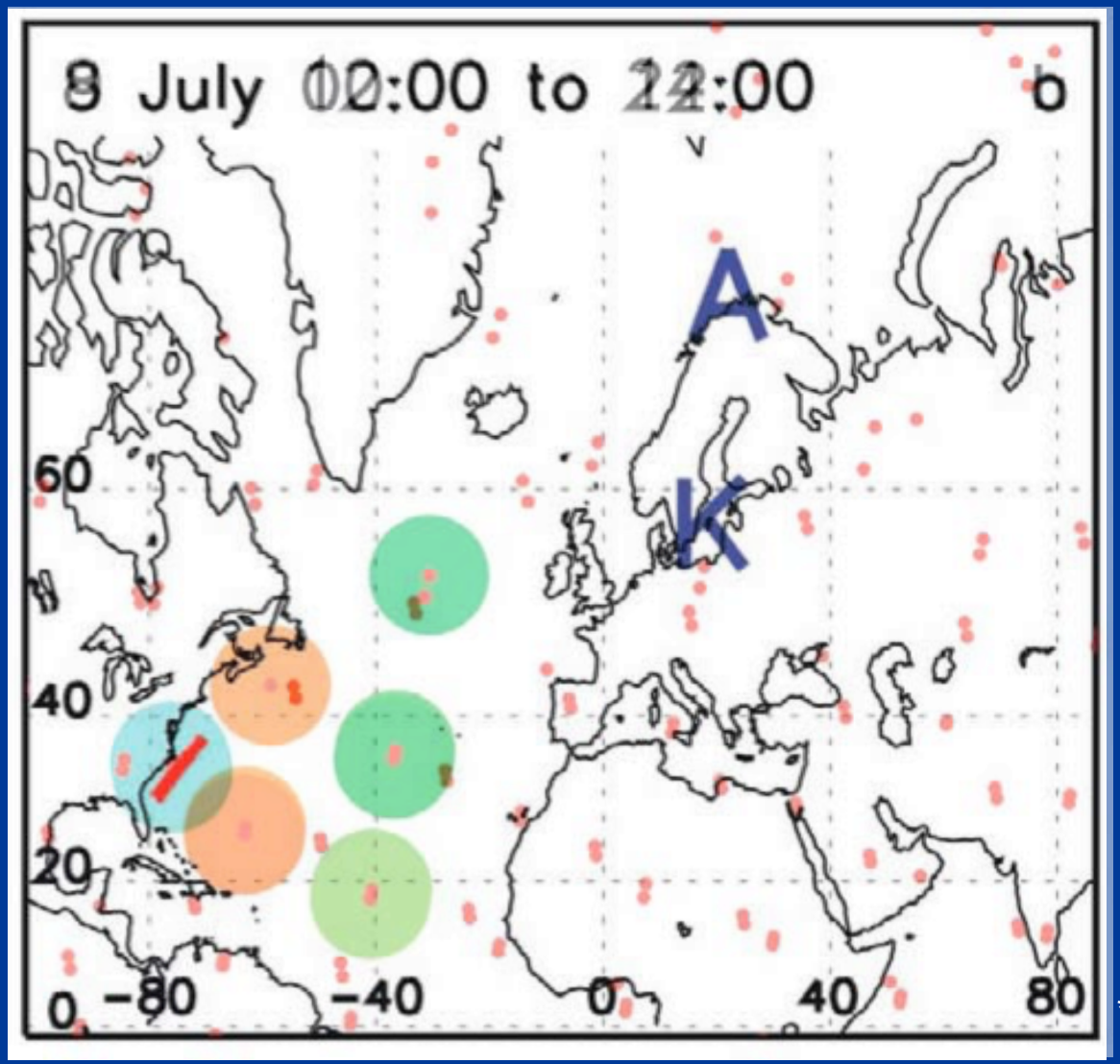

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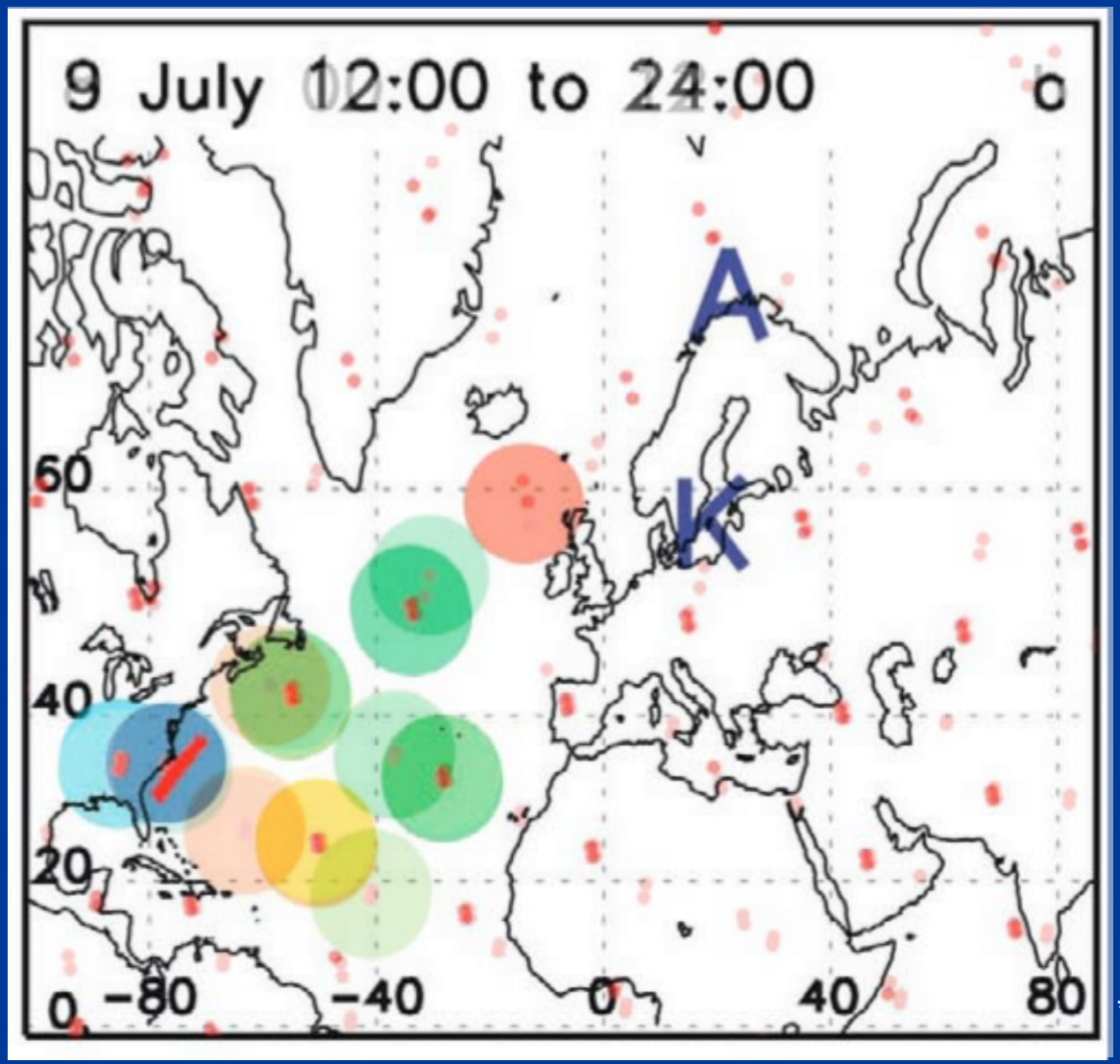

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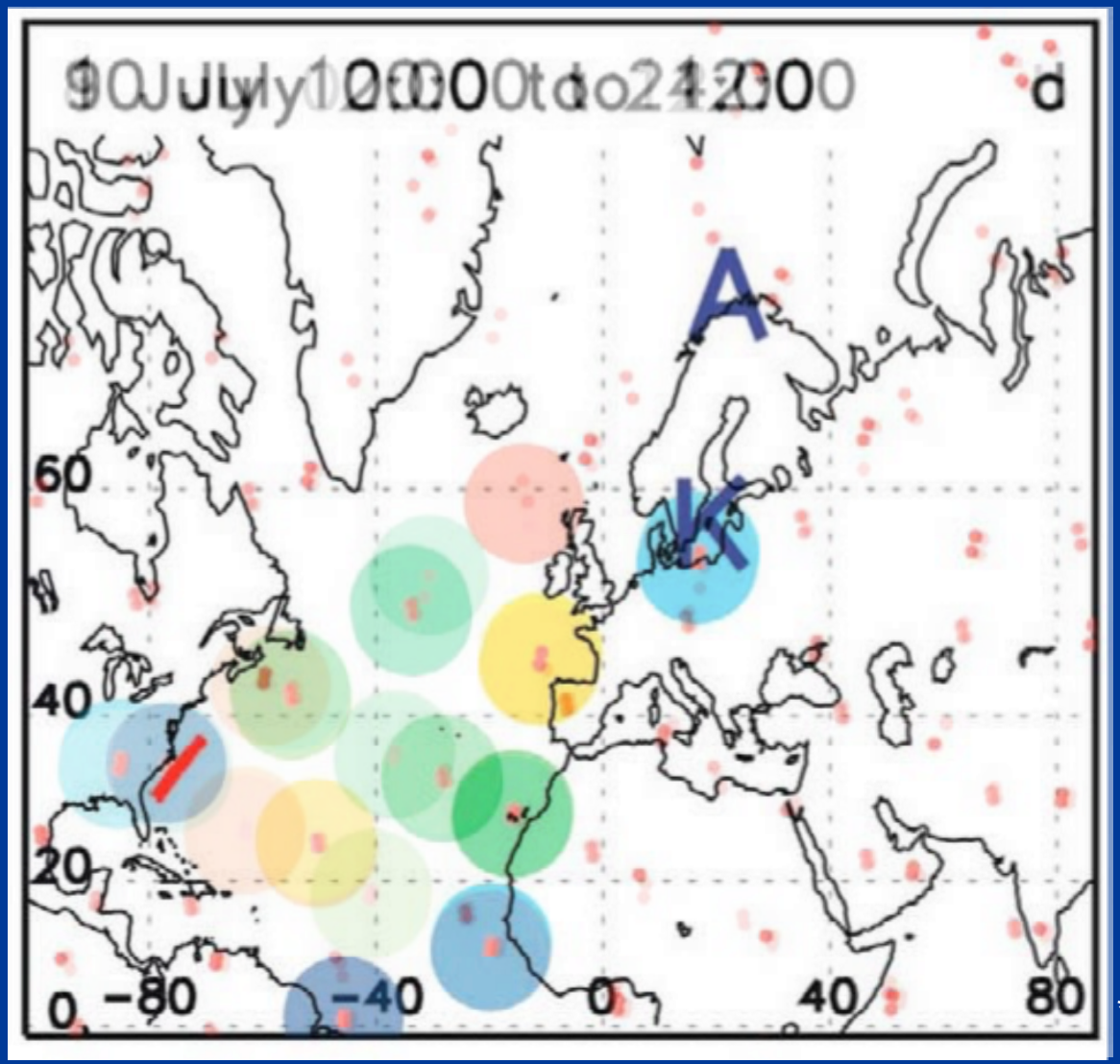

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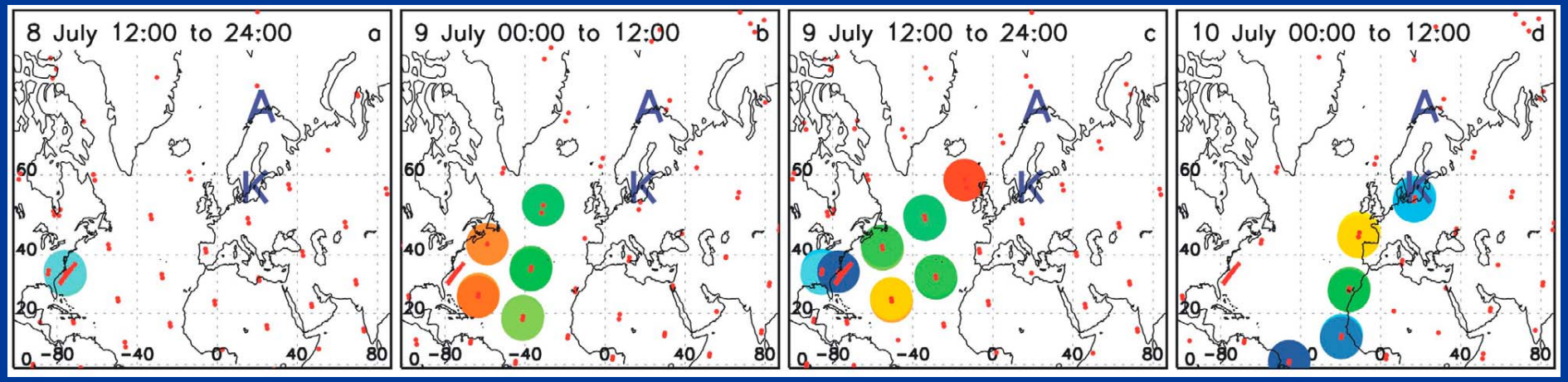
Transport



* Stevens et al., [2012]

Transport is governed by coherent structures : temporally and spatially persistent features that are not part of the mean flow.

Motivation

- Thermospheric coherent structures matter for:
  - Environmental impact
    - » Tracking emissions, contaminants, meteor ablation products.
  - Scientific understanding
    - » Generate stresses and vorticity.
    - » Play a role in energy cascade.

Questions: Are there coherent structures in the thermosphere?
Do they depend on geomagnetic activity?
Do they bound transport?

Eulerian vs Lagrangian frames

- Eulerian:
  - fixed grid for an observer, flow moves past
  - streamlines
  - useful for lab analysis of flows, but depends on the observer
- Lagrangian:
  - frame follows the fluid particle
  - Pathlines
  - Observer-independent, so useful for rotating frames

- Lagrangian coherent structures: defined by following particles

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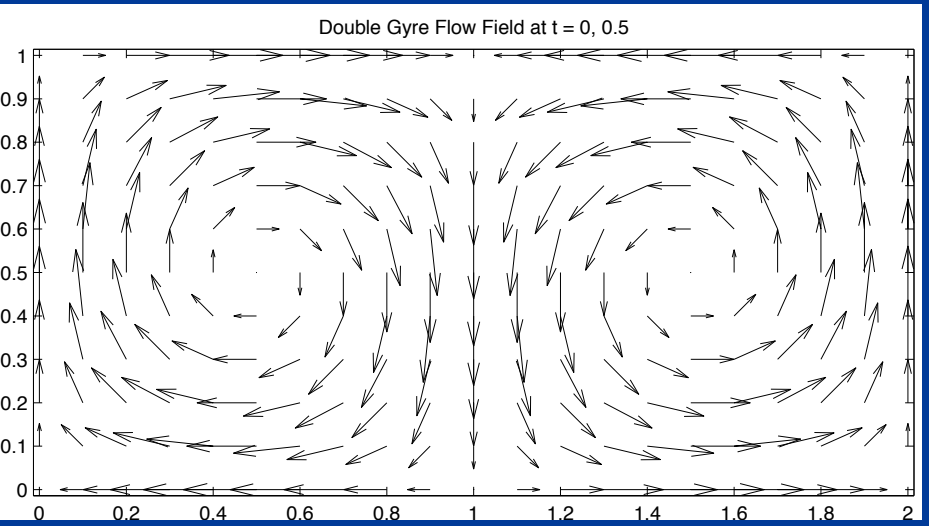
What is a Lagrangian coherent structure (LCS)?



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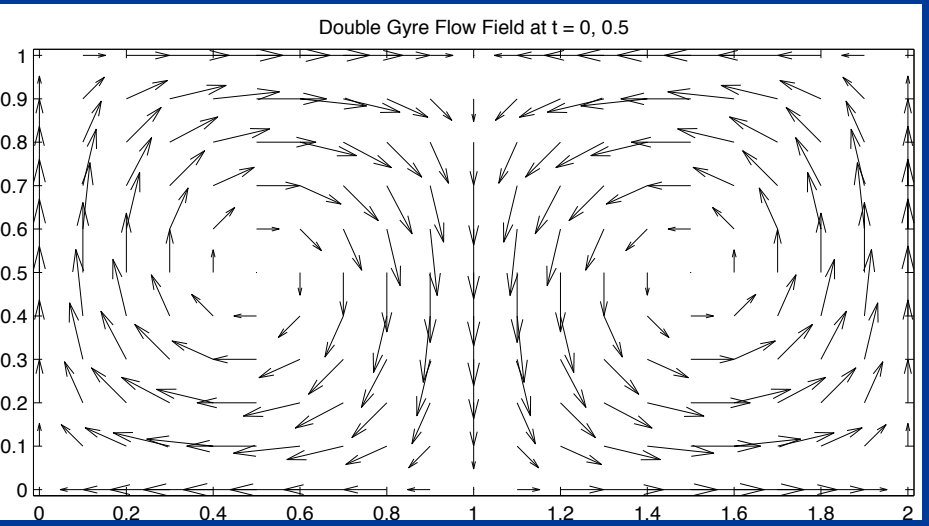
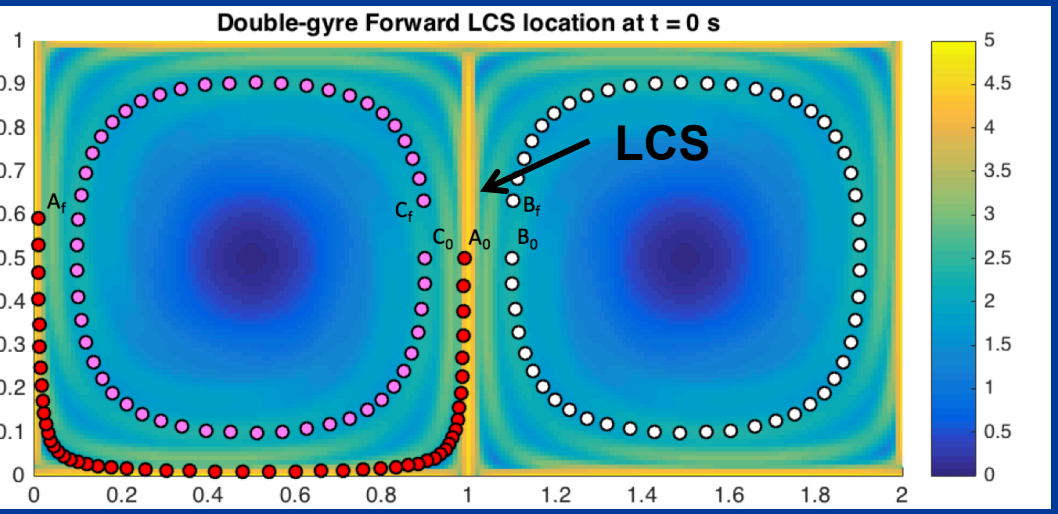
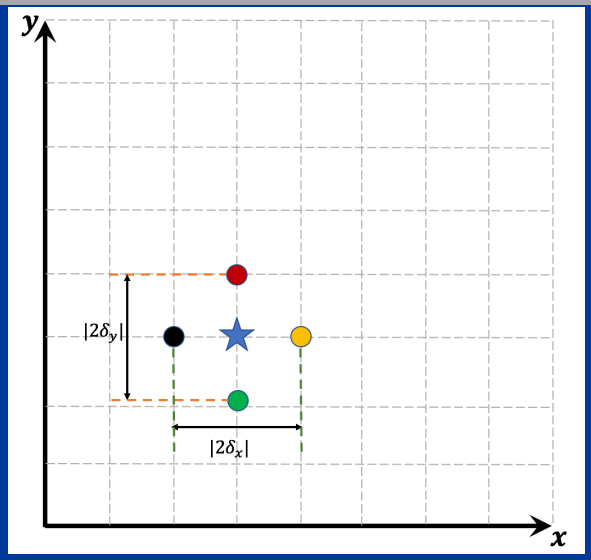




To find LCSs, compute the FTLE at each point



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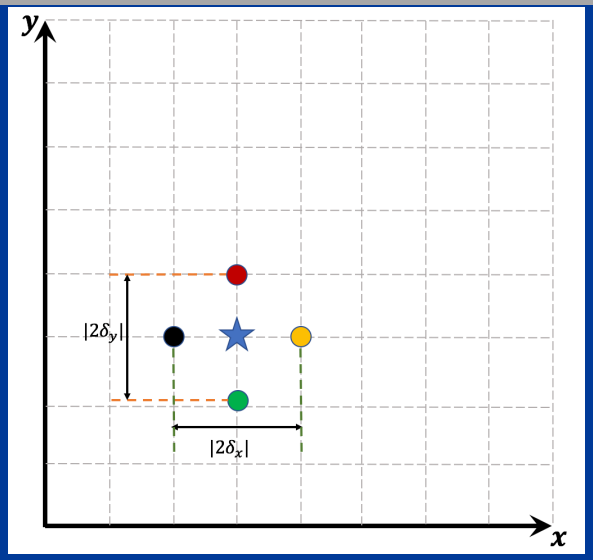

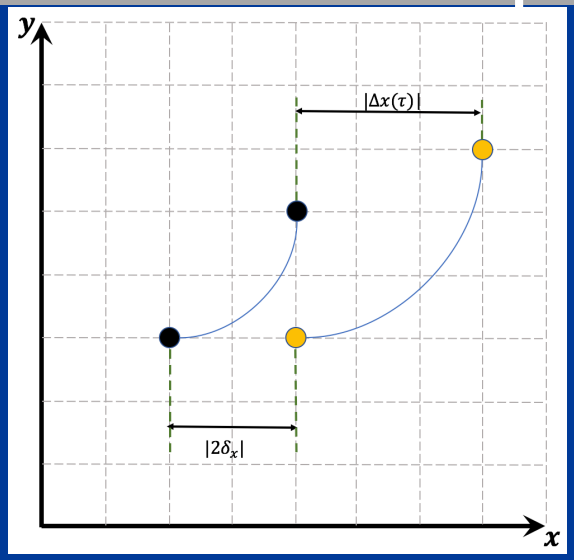

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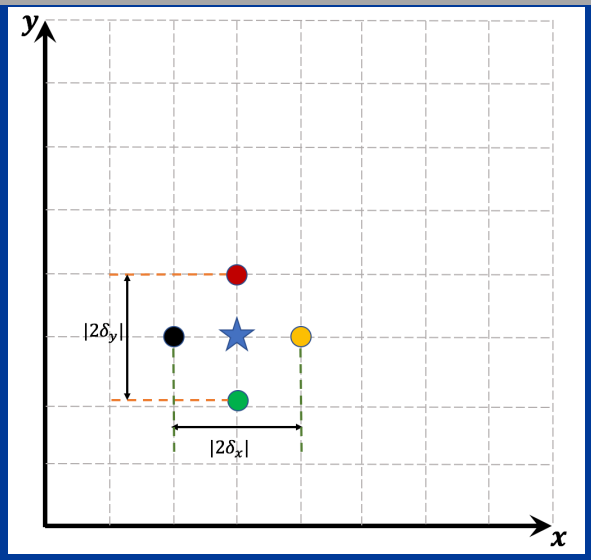

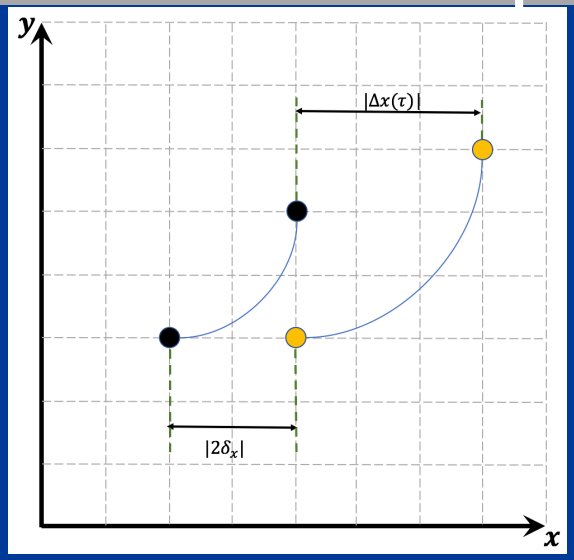

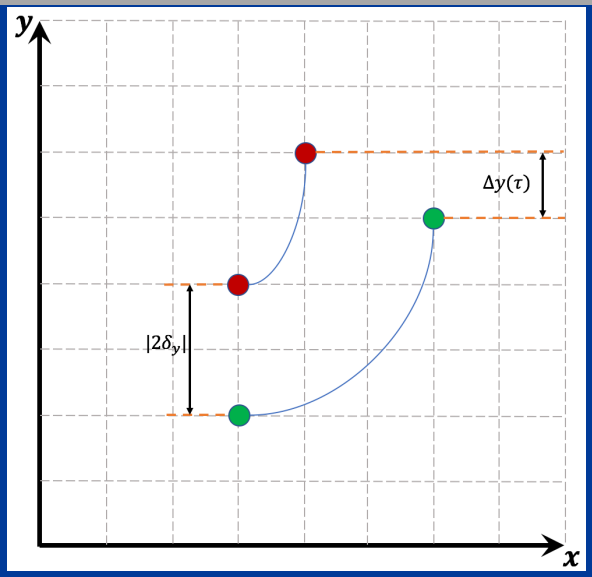

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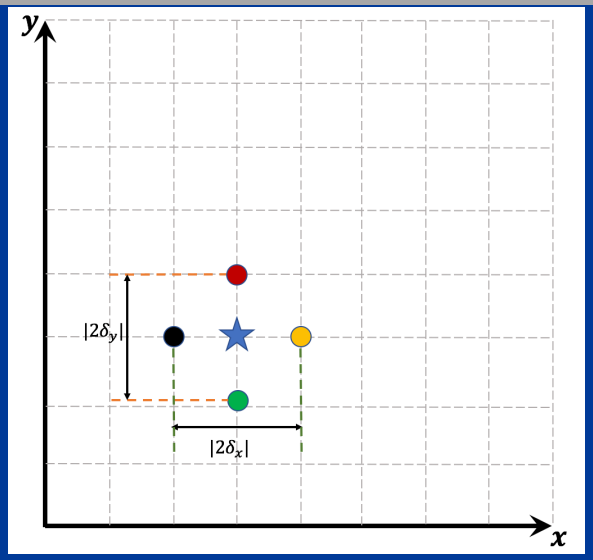

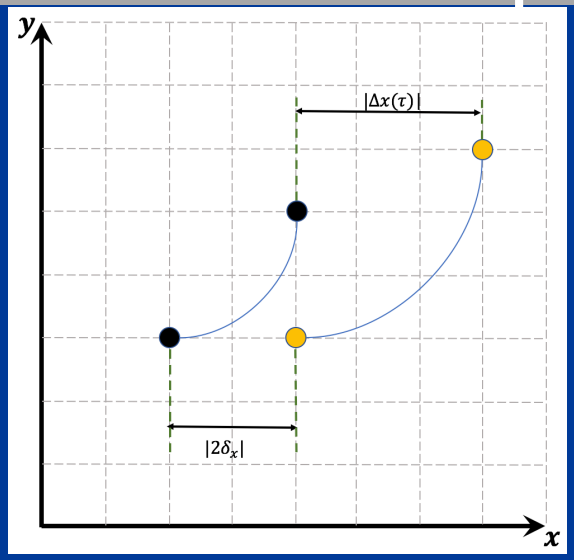

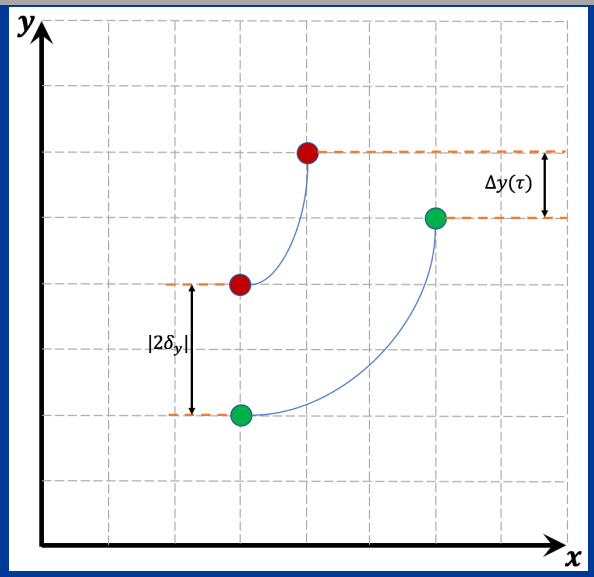

The Finite Time Lyapunov Exponent (FTLE) σ at each point is the maximum eigenvalue given by

$$\mathbf{J} = \begin{bmatrix} \frac{\Delta x(\tau)}{|2\delta_x|} & \frac{\Delta x(\tau)}{|2\delta_y|} \\ \frac{\Delta y(\tau)}{|2\delta_x|} & \frac{\Delta y(\tau)}{|2\delta_y|} \end{bmatrix}$$

$$\sigma(\mathbf{J}) = \frac{1}{|\tau|} \log\left(\sqrt{\lambda_{max}(\mathbf{J}^T\mathbf{J})}\right)$$

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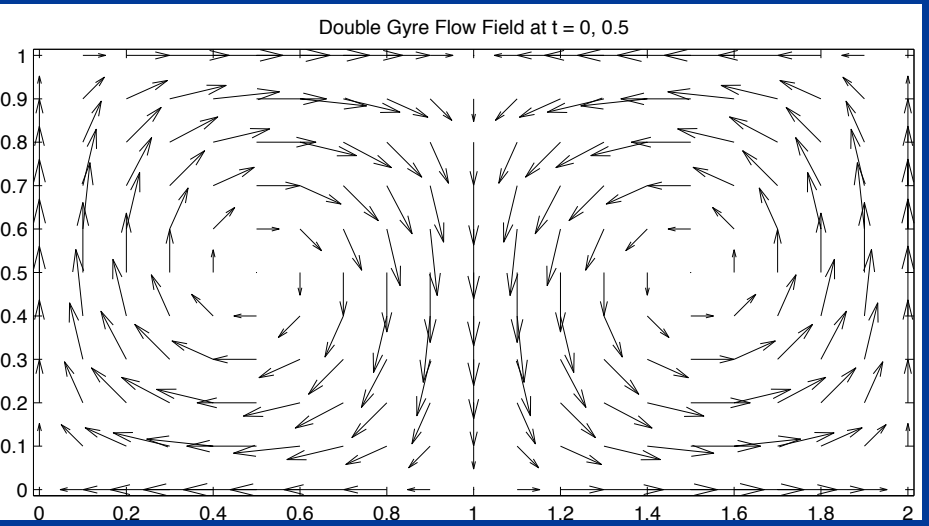
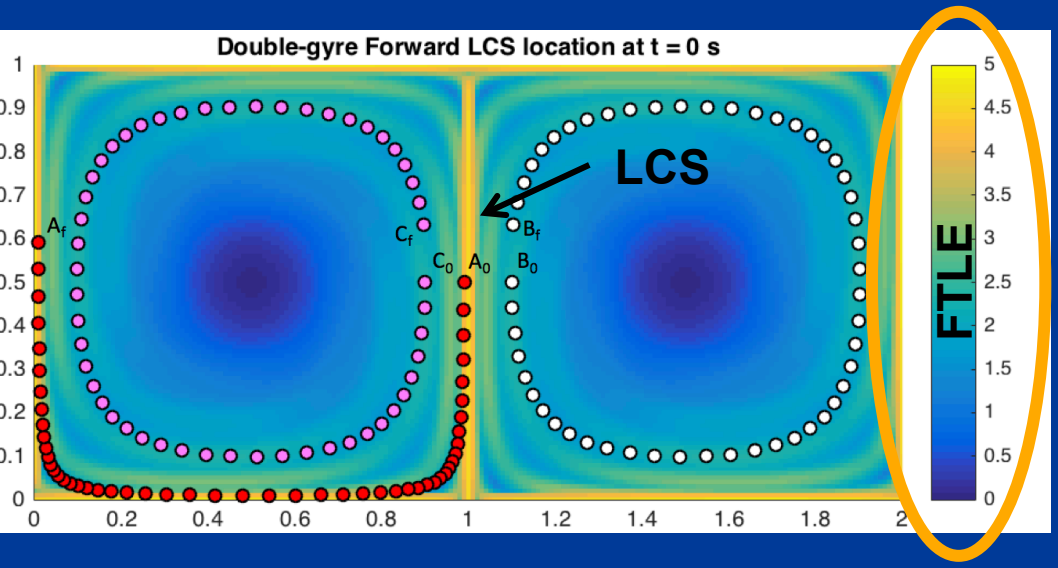
What is a Lagrangian coherent structure (LCS)?



The color map is the FTLE value and the ridge of maxima denotes the LCS.



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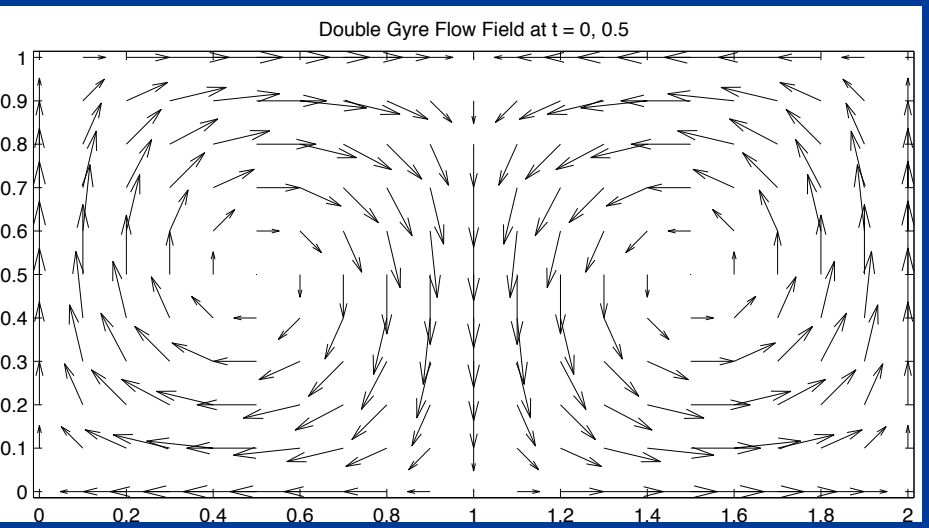
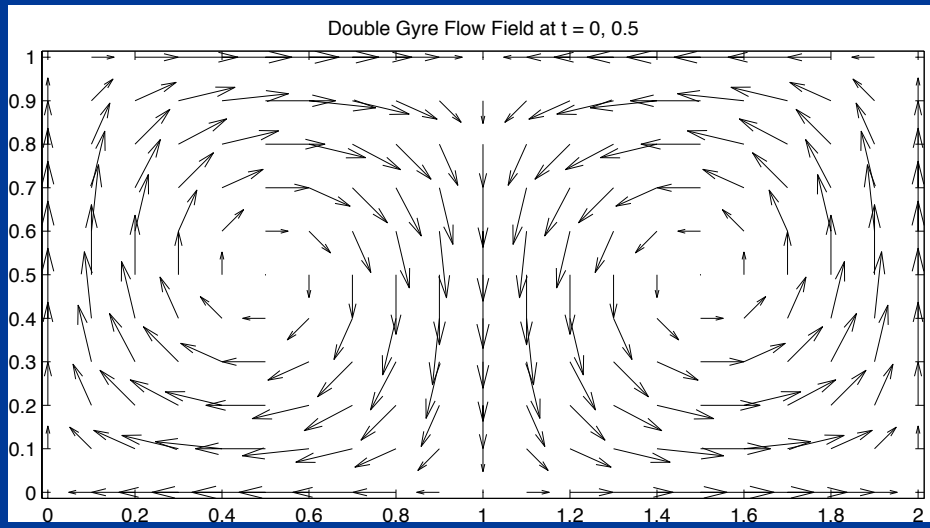
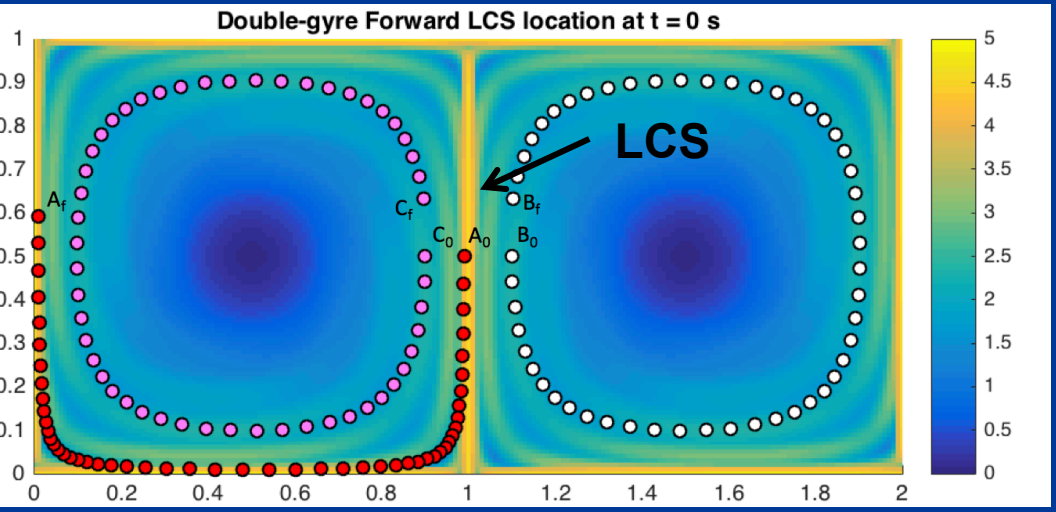
LCS for a time-varying nonlinear flow







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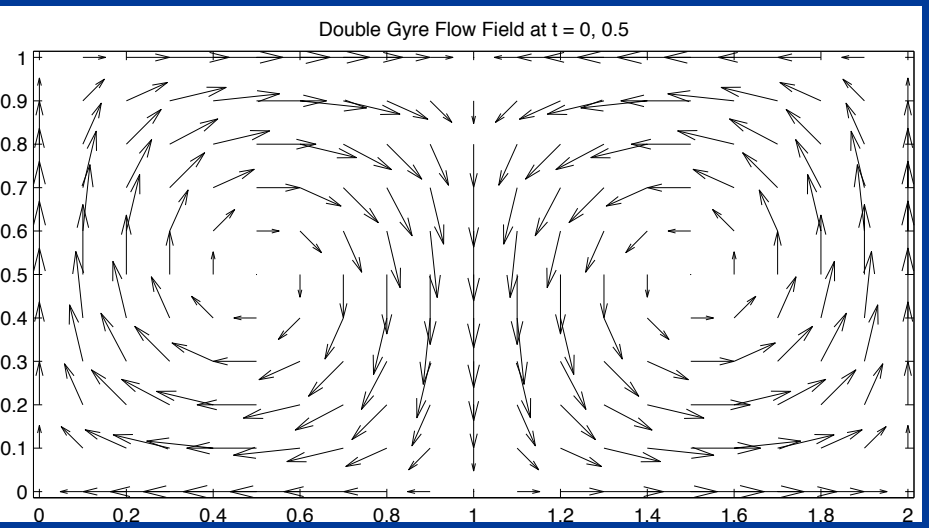

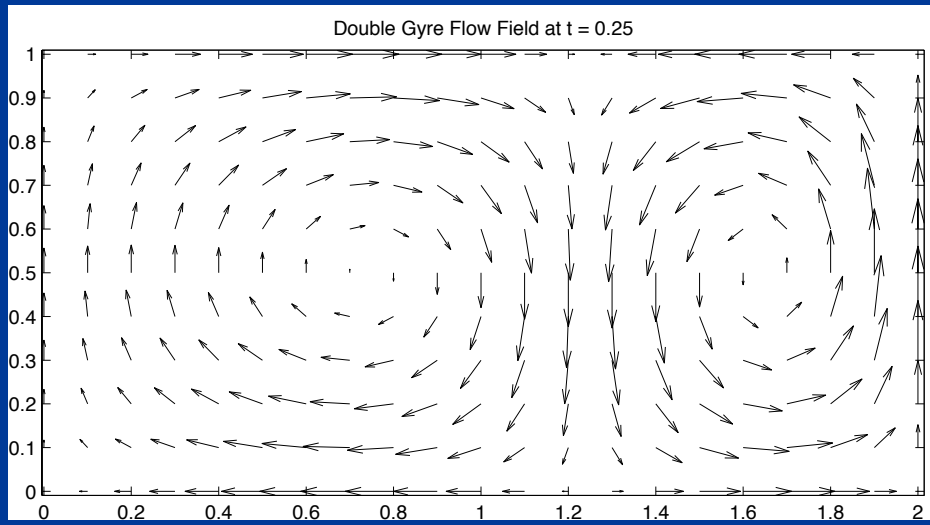

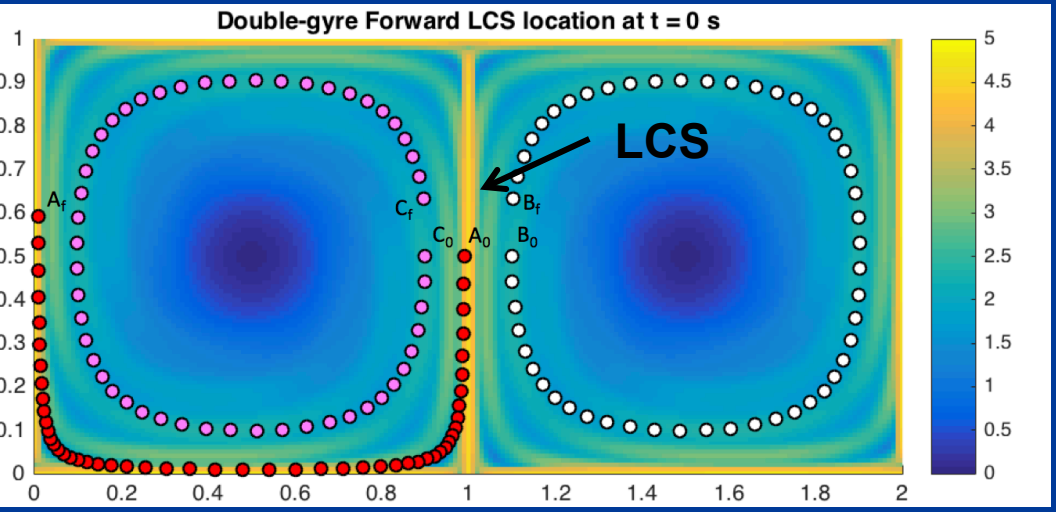

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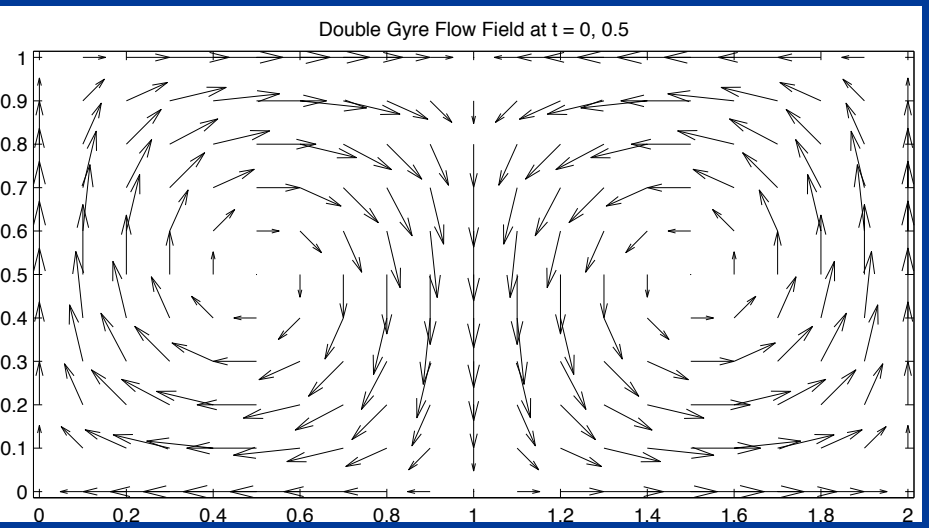

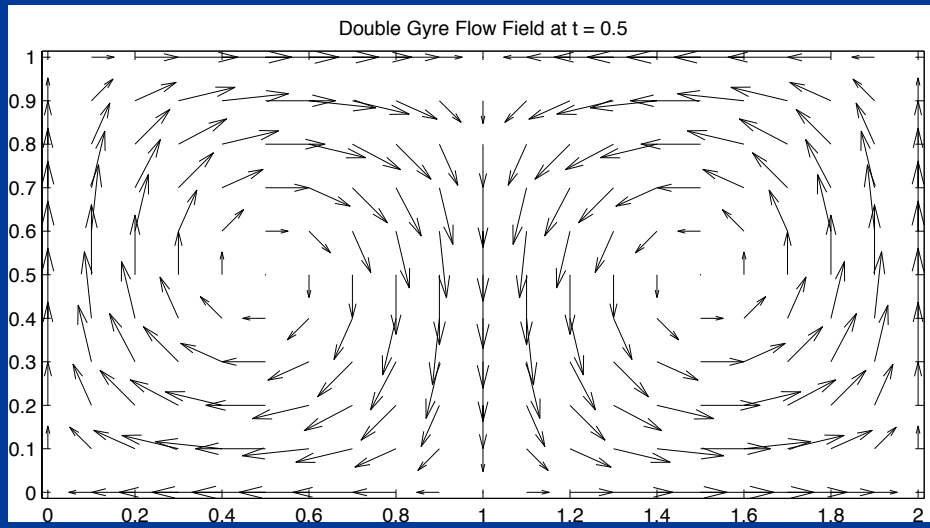

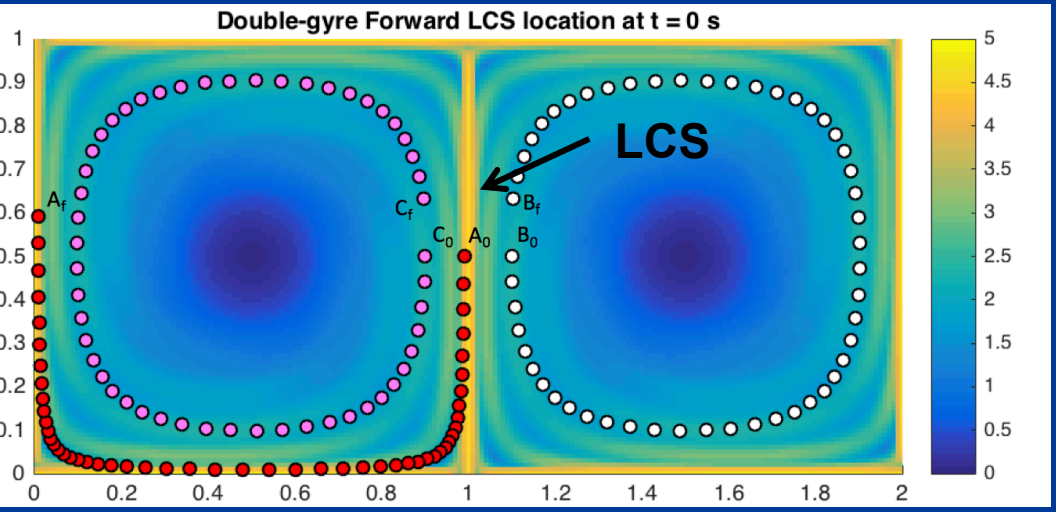

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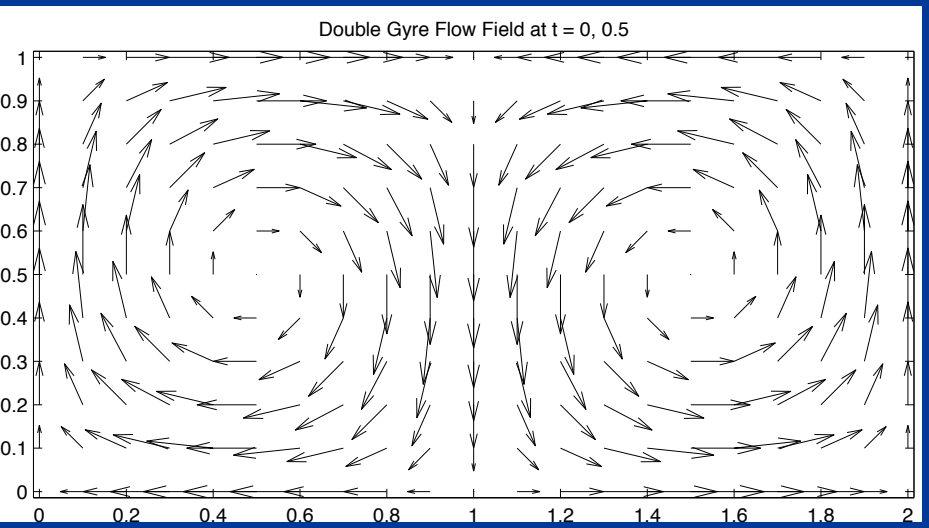

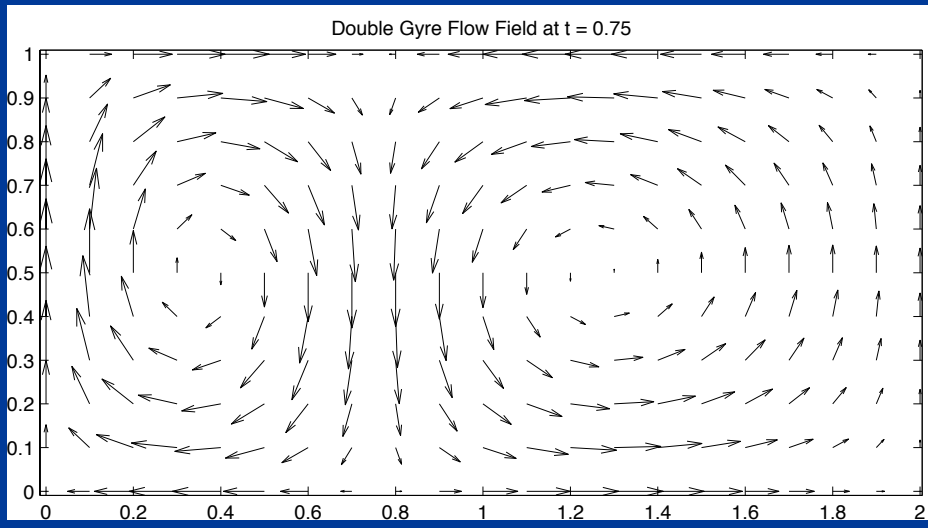

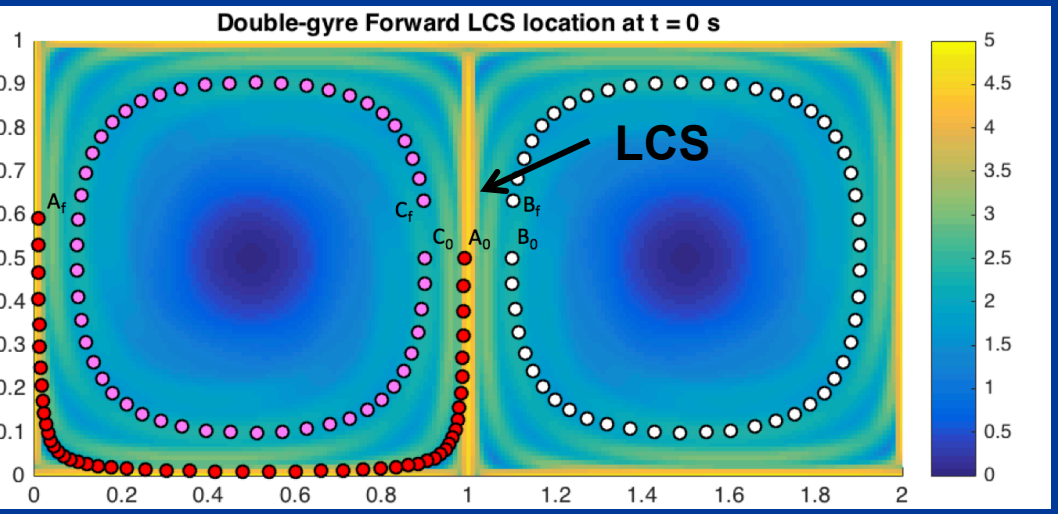

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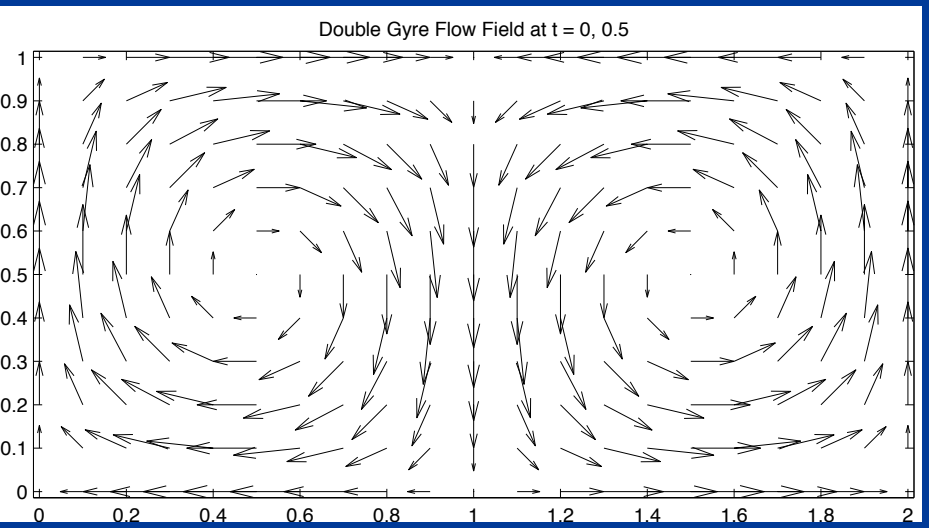

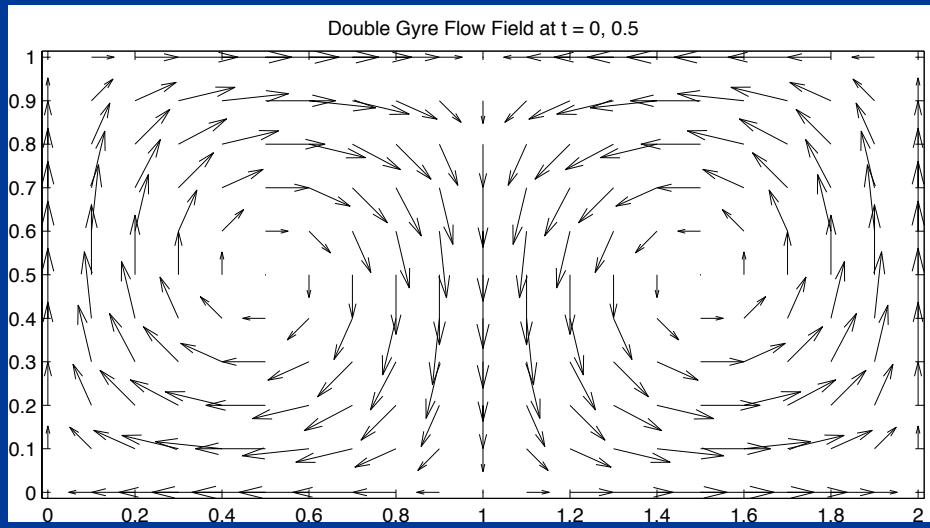

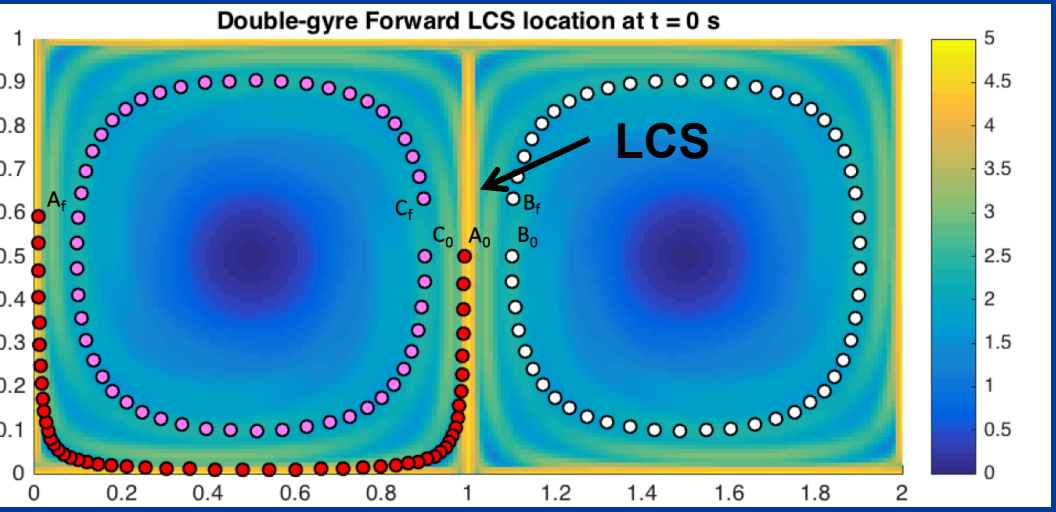

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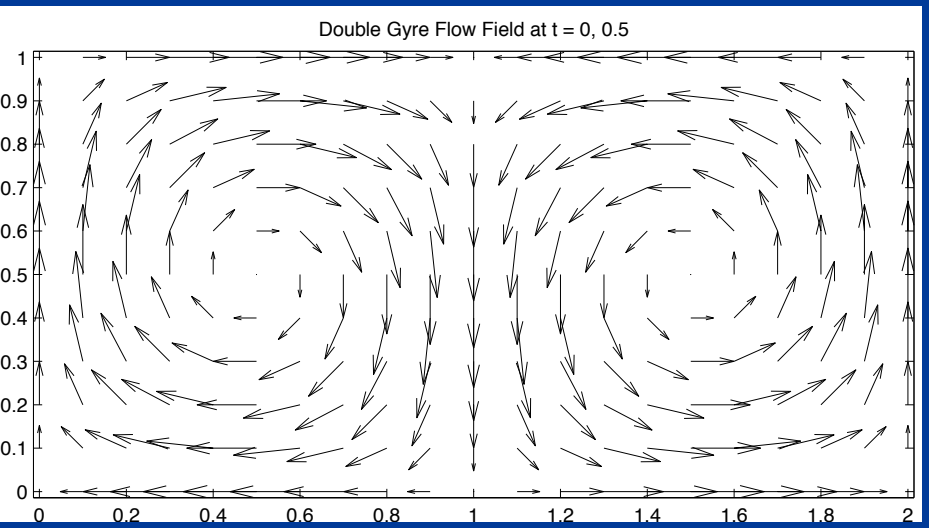
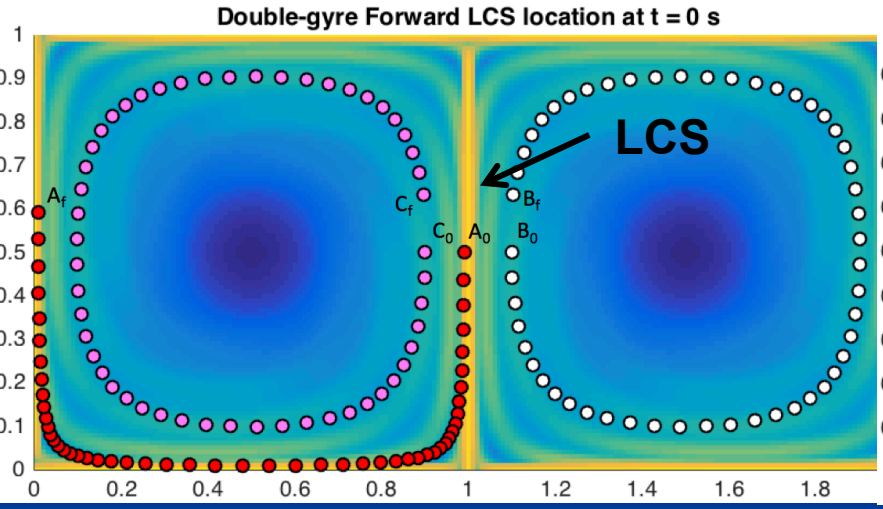
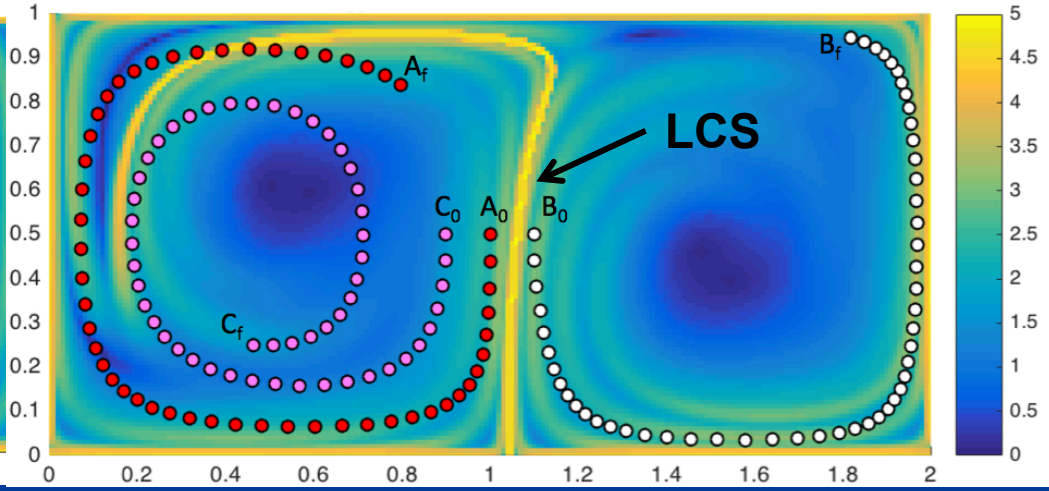


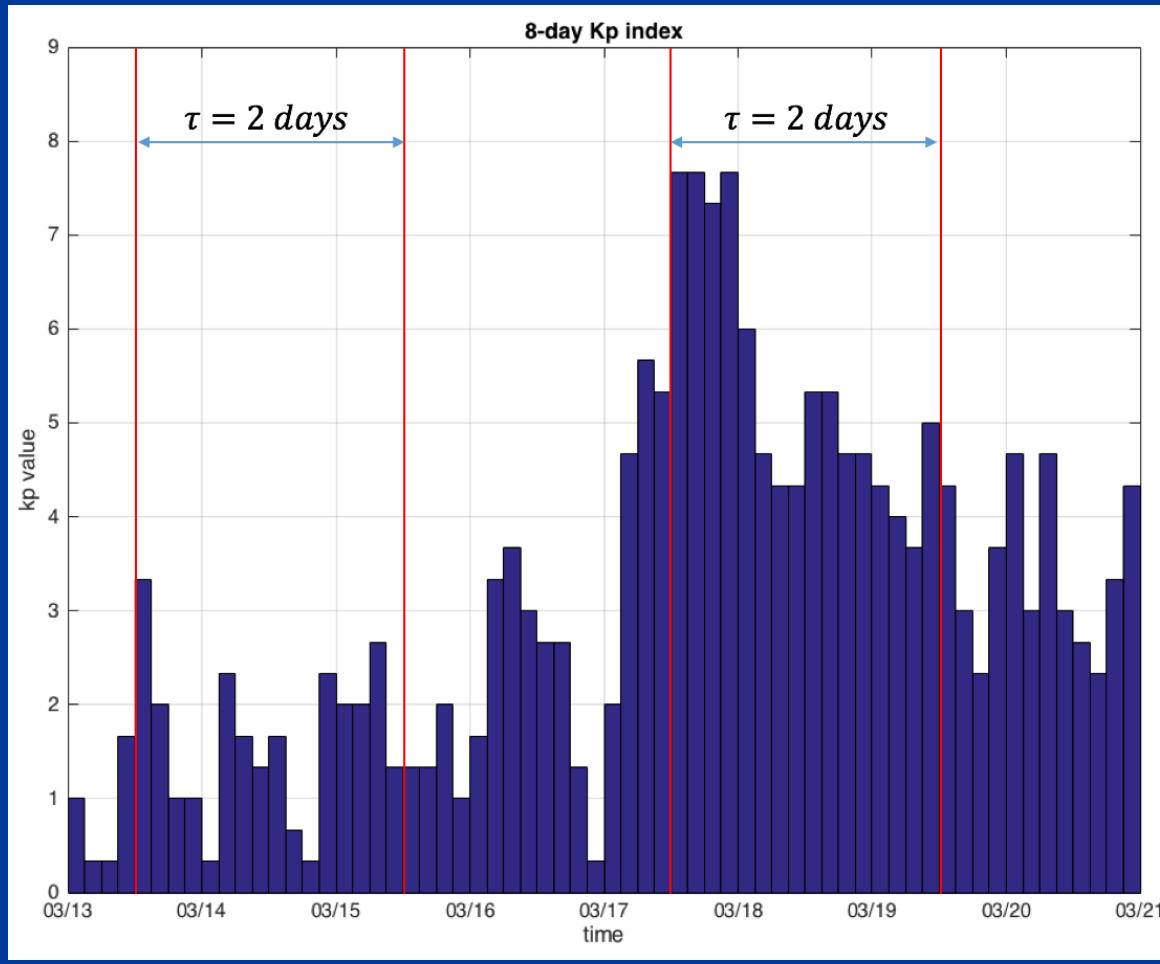
LCS: a manifold (i.e., a ridge or surface) of maximal separation or convergence.





Method

- Horizontal Wind Model 2014 for flow fields
  - 150 km, 250 km, 350 km.
- Geomagnetically quiet time vs. active time.
- Advect particles, compute FTLE, plot LCSs.



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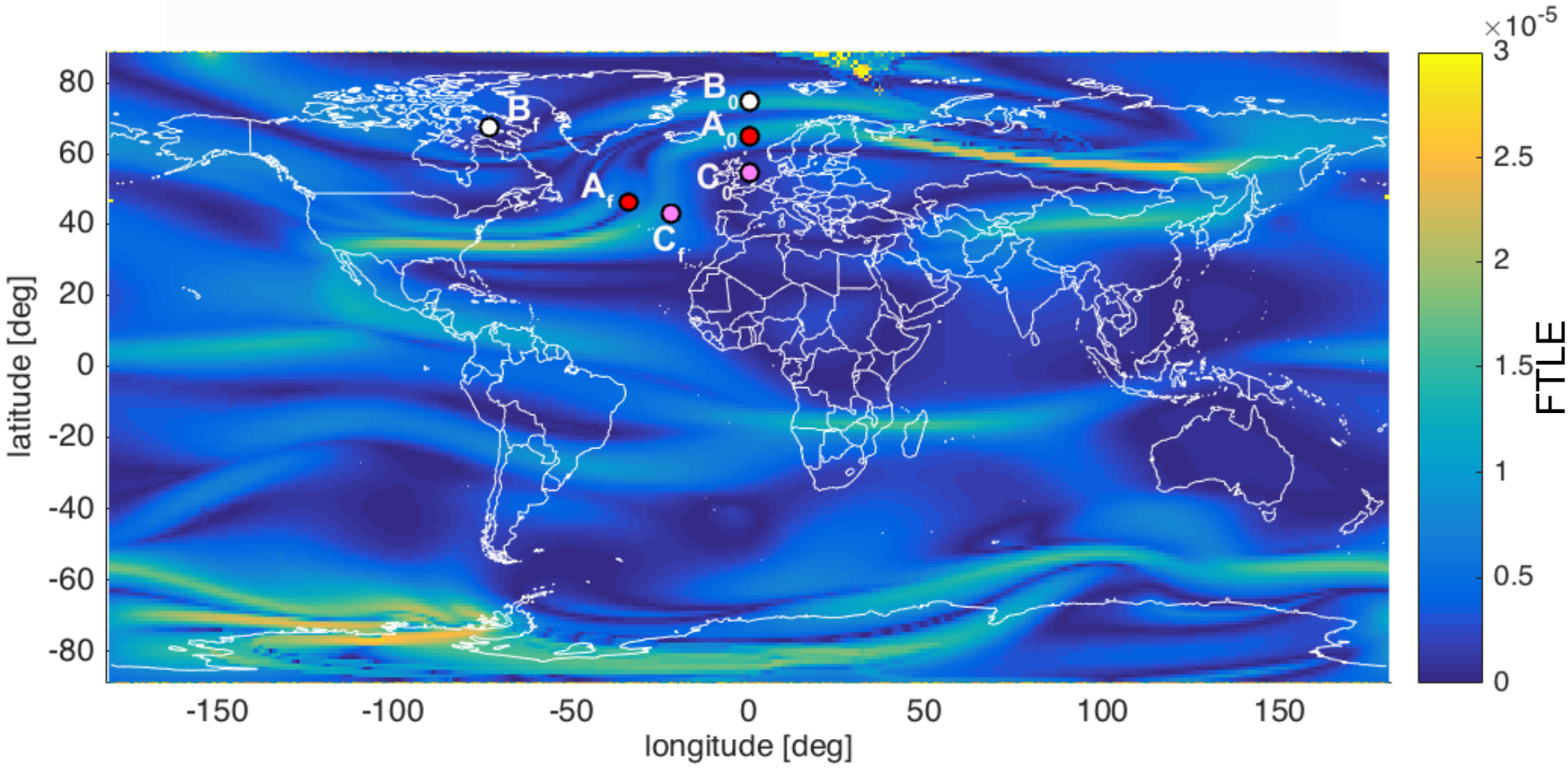
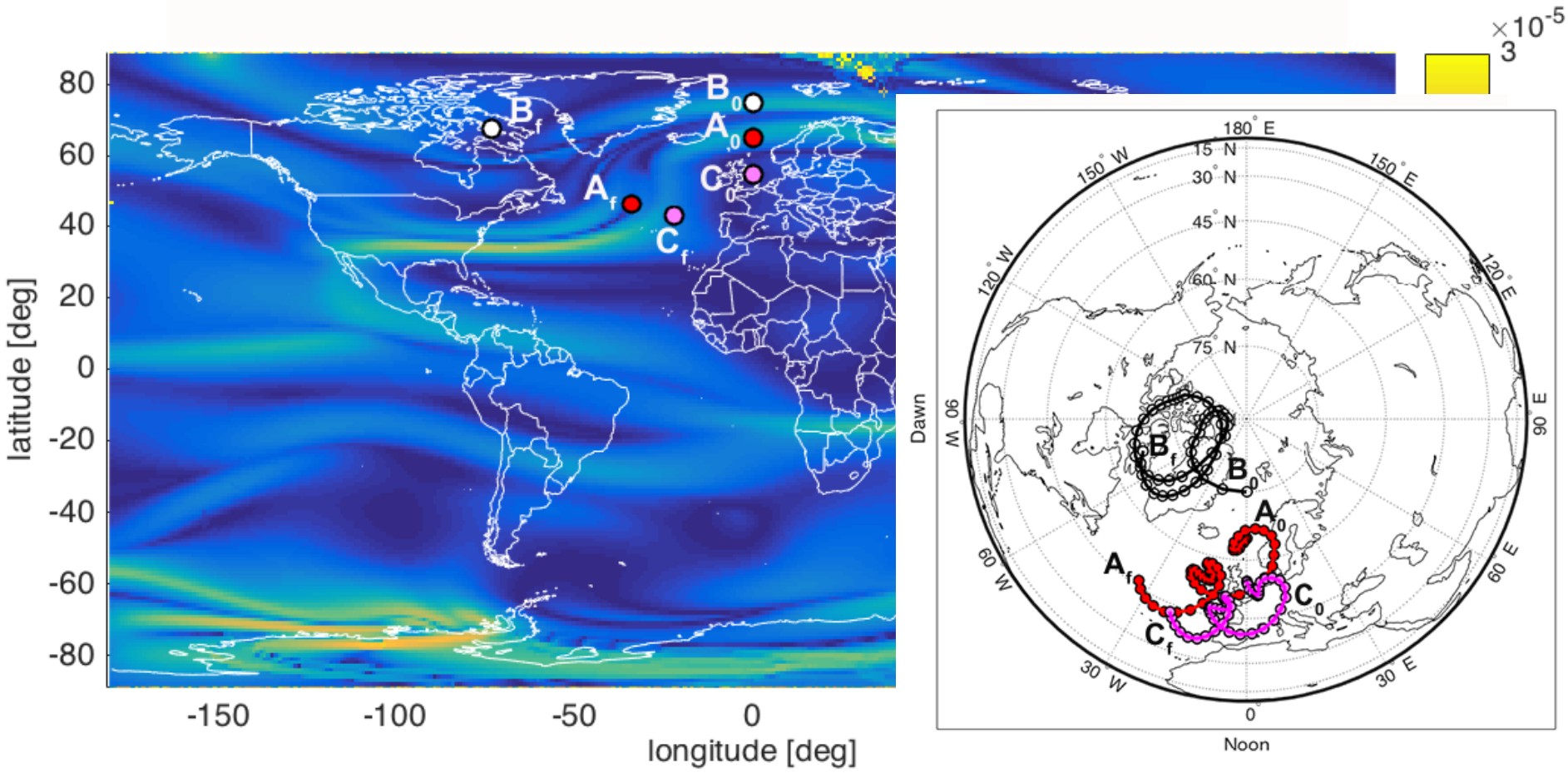
LCS at 150 km altitude



Wang et al., 2017

LCS at 150 km altitude



Wang et al., 2017

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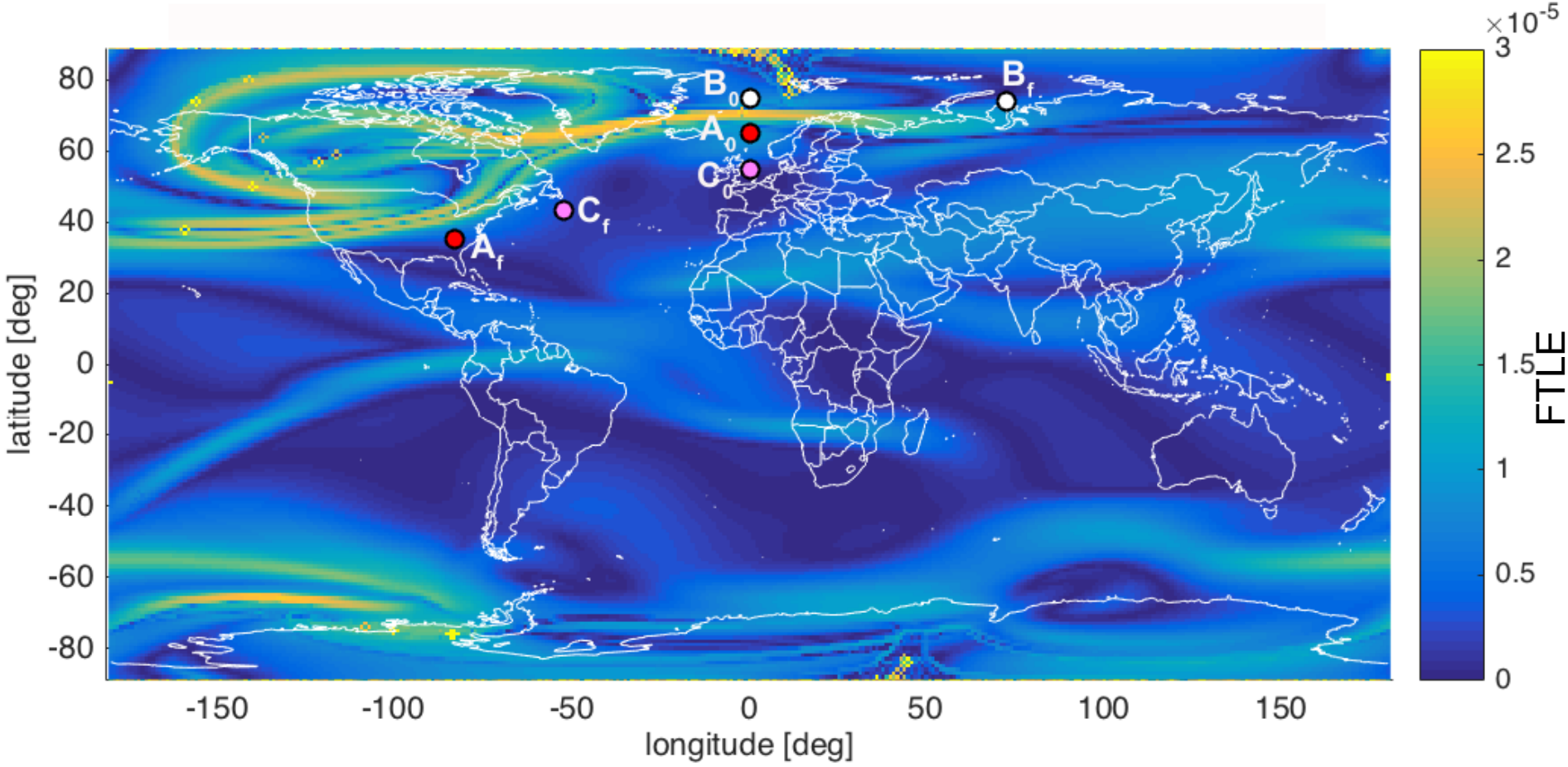
LCS at 250 km altitude



Wang et al., 2017

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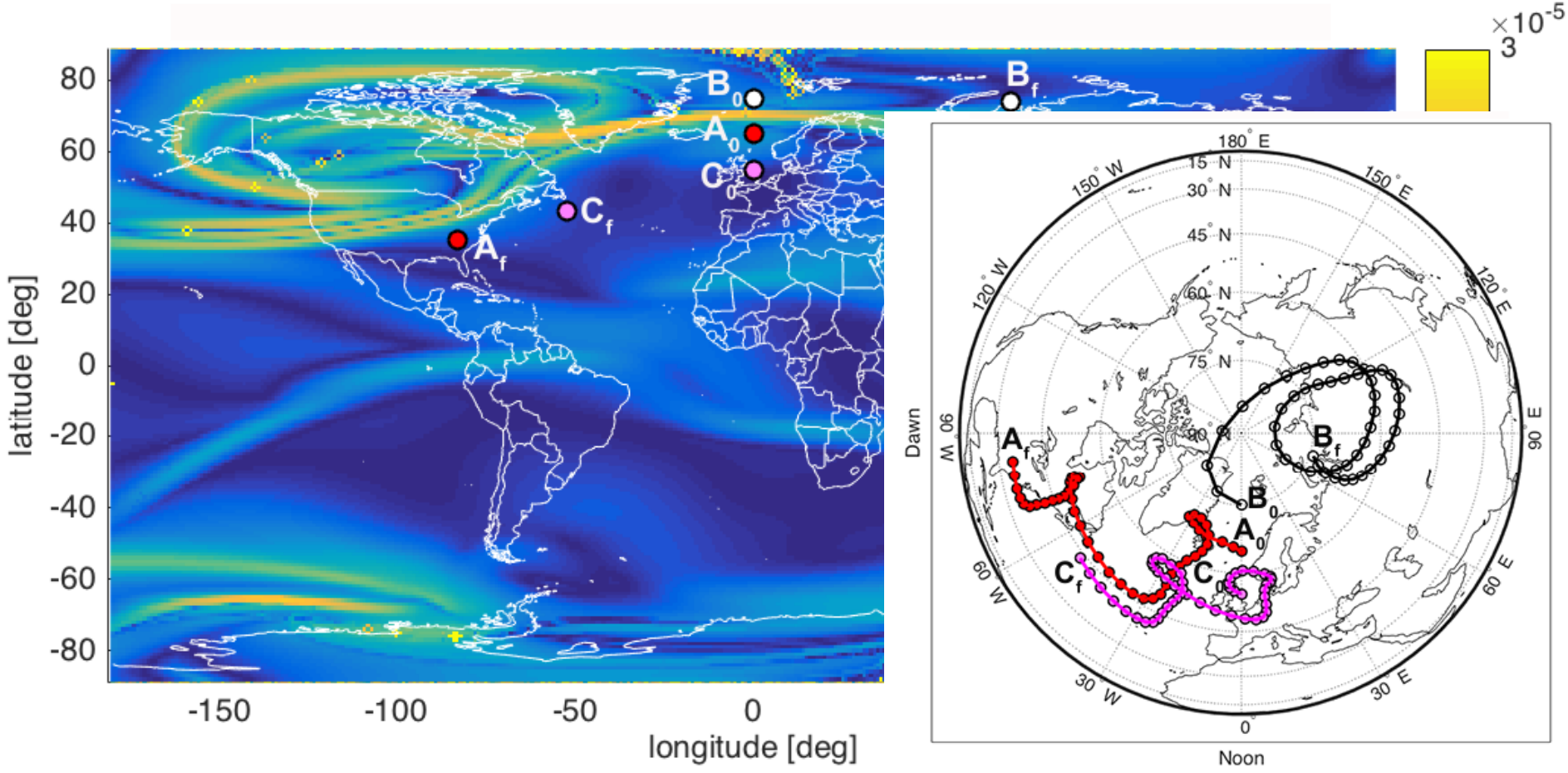
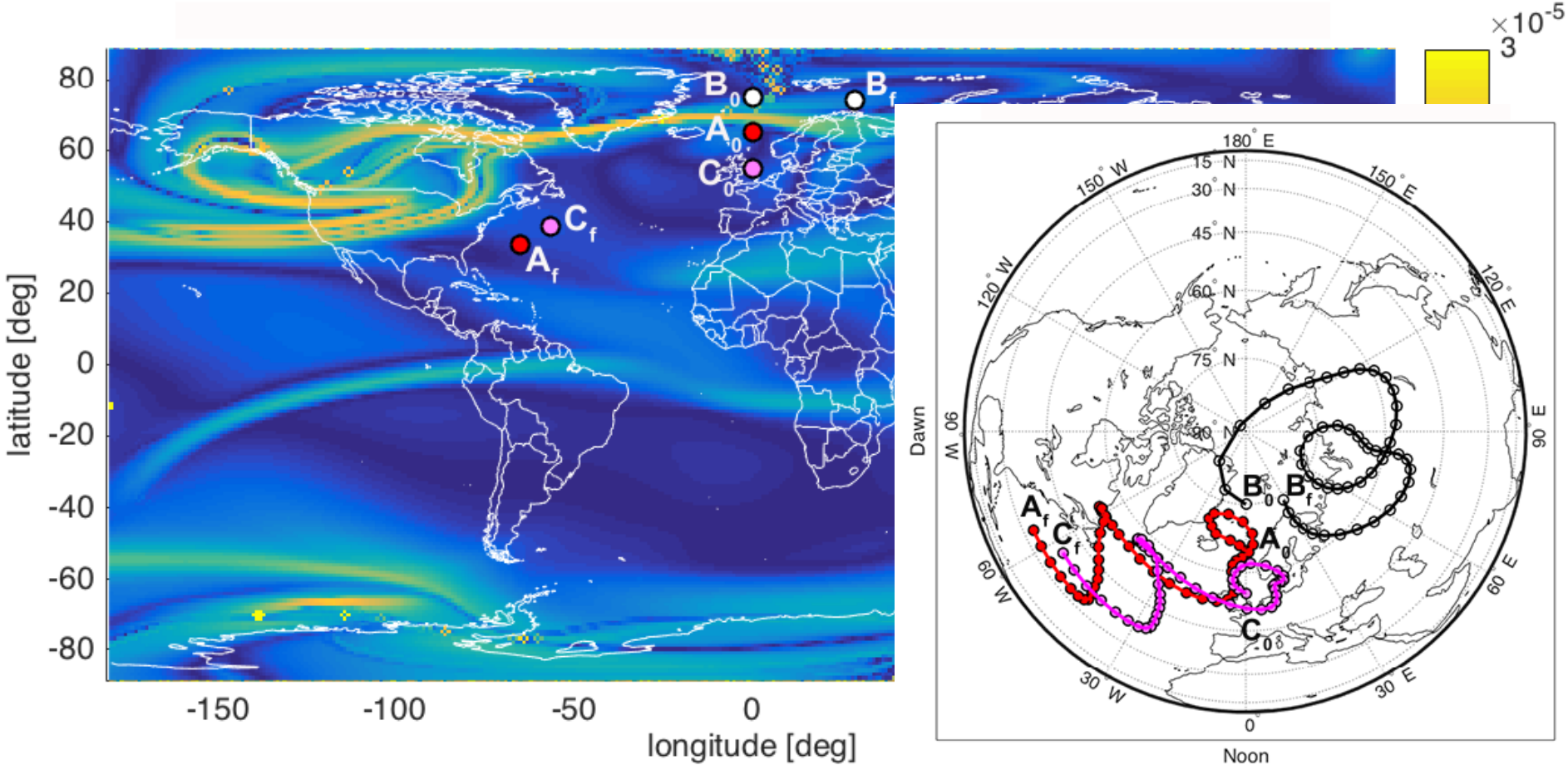


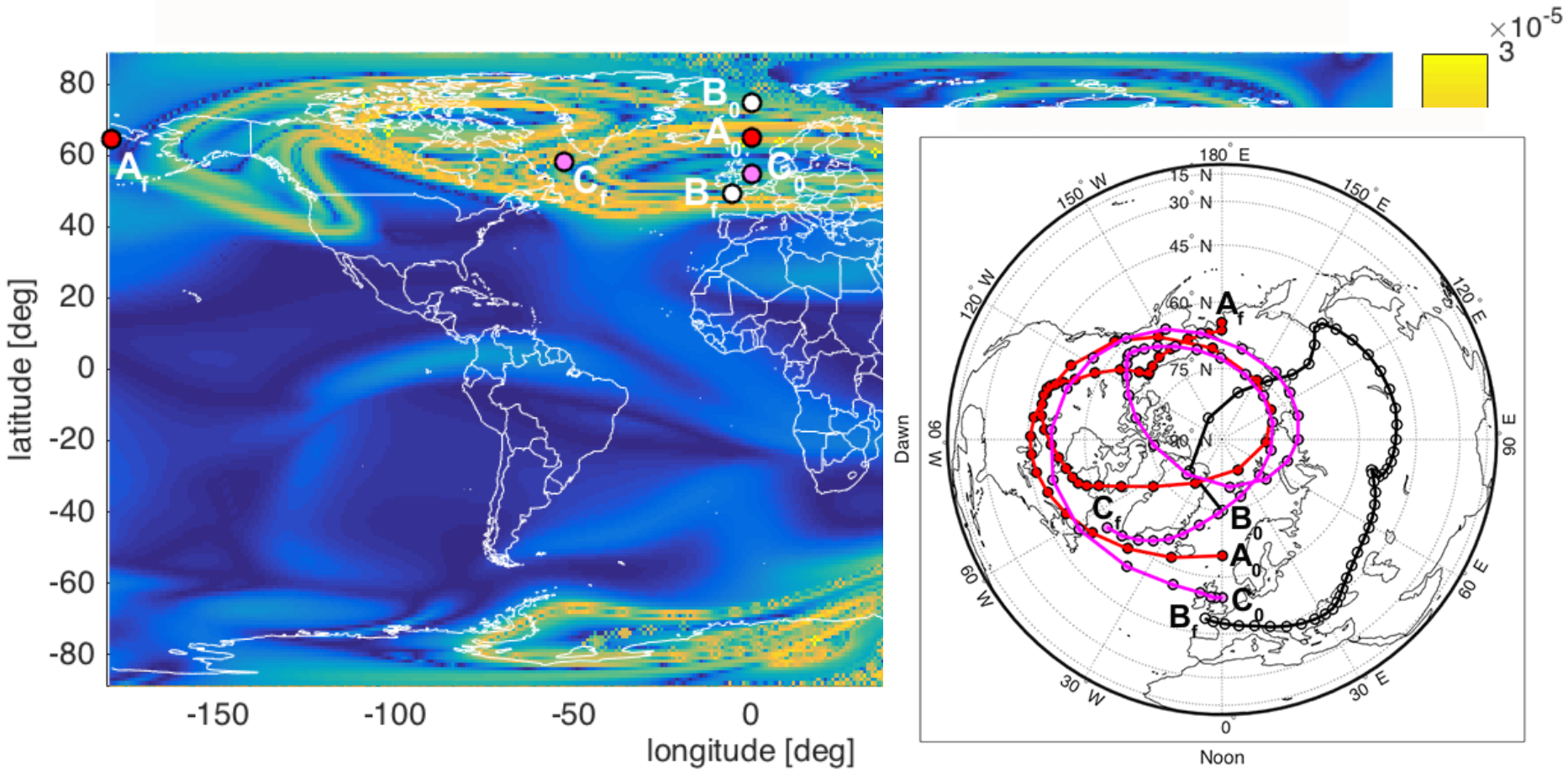
Wang et al., 2017

LCS at 350 km altitude



Wang et al., 2017

LCS at 250 km during a storm



Wang et al., 2017

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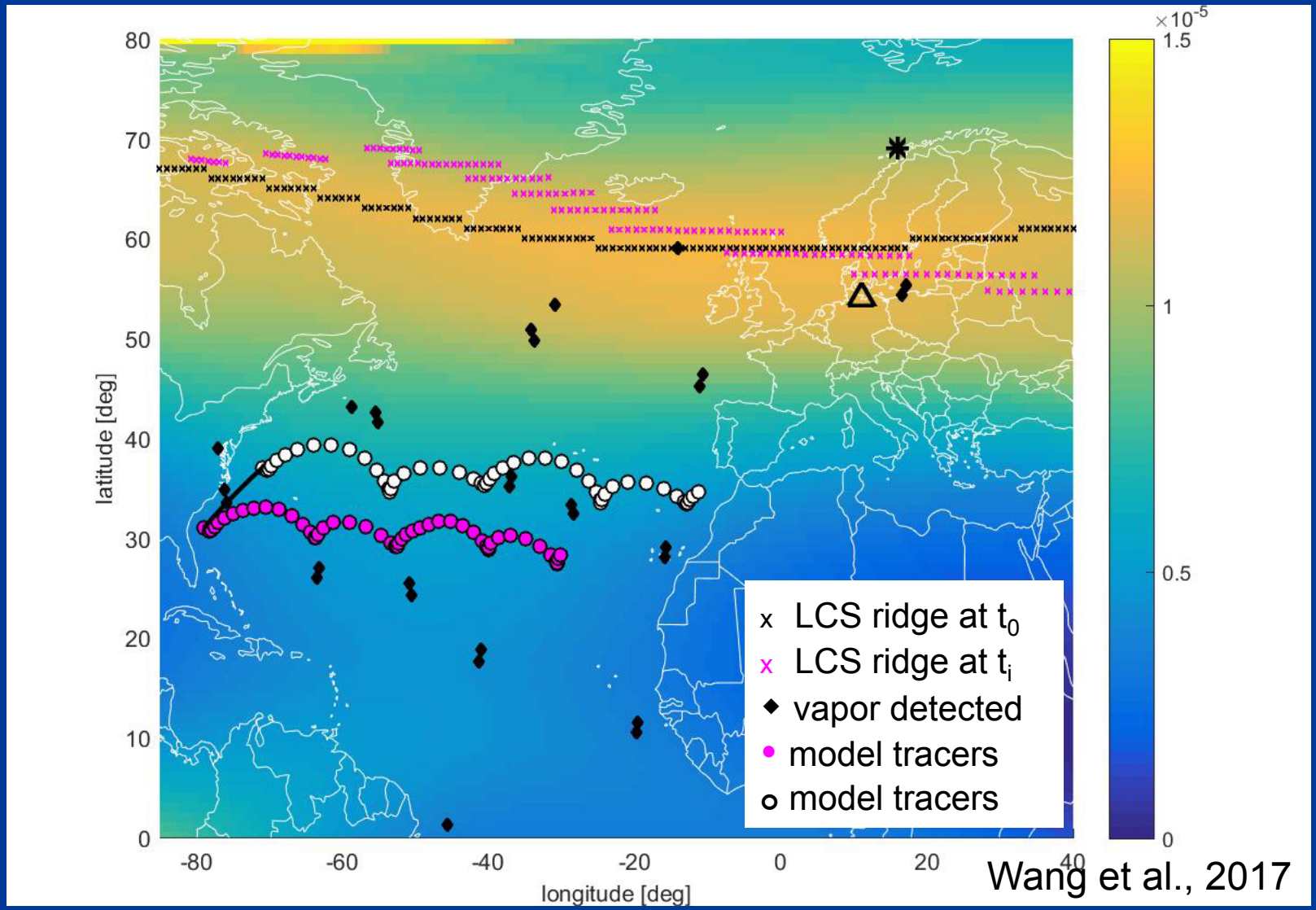
The LCS barrier for the shuttle water vapor plume



Wang et al., 2017

Conclusion

- LCSs are found in global two-dimensional model horizontal flows of the thermosphere.
- LCSs are more prominent at higher altitudes and latitudes and respond to geomagnetic activity.
- A thermospheric LCS is found to be the poleward barrier of space shuttle water vapor plume transport [Wang et al., 2017]
- Next: ionospheric LCSs (CEDAR poster Wednesday by Wang et al., MDIT-09)

References

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Wang, N., U. Ramirez, F. Flores, and S. Datta-Barua (2017), Lagrangian coherent structures in the thermosphere: Predictive transport barriers, Geophys. Res. Lett., 44, doi: 10.1002/2017GL072568.

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- Armour College of Engineering Program for Undergraduate Research Education (PURE) award. Shawn Shadden for providing the publicly available FlowVC code.

- Douglas Drob for providing the Horizontal Wind Model (HWM14) software and valuable comments on the context of the work.