Seeking Lagrangian Coherent Structures in Ionospheric-Thermospheric Flows

Ningchao Wang, Seebany Datta-Barua, Dino Okic
Illinois Institute of Technology, Chicago, IL

Objective:
- Find the coherent structures in the test flow fields (i.e. regular pendulum, double-gyre).
- Find the coherent structures in the flow in the ionosphere and thermosphere for the first time.

Introduction:
- Ionosphere-Thermosphere (IT) system
  - The ionosphere and thermosphere are coupled together from 100km above the Earth’s surface.
  - The ionosphere is a plasma formed by solar Ultraviolet (UV) radiation.
  - The thermosphere is dominated by neutral wind processes.
  - The ionosphere-thermosphere (IT) system interacts through energy exchange and transport by collisions, diffusion and advection.

- Lagrangian Coherent Structure (LCS)
  - The LCS is a boundary defining regions of minimum separation in the flow.
  - The LCS is found by following individual particles/ fluid elements in a flow (i.e. viewing the fluid in a Lagrangian frame).
  - The LCS shape is determined by measuring the deformation from initial conditions of the flow trajectories with time.

Finite Time Lyapunov Exponent (FTLE)
The FTLE is a scalar field defined by the maximum eigenvalue $\lambda_{\infty}$ of the Cencik-Green deformation, or strain, tensor $(\nabla H)$

**Results for test flow fields:**
- Regular pendulum [7]:
  
  Velocity components:
  \[
  \begin{align*}
  u &= y, \\
  v &= -\sin(x)
  \end{align*}
  \]
  
  The flow field is the phase portrait of the pendulum.
  
  - The flow field is not changing with time, because the velocity is time invariant.
  - The LCS is not changing with time.
  - Where the divergence is not strong, the LCS does not have a sharp boundary.

- Double-gyre [8]:
  
  Potential flow equation:
  \[
  \psi(x, y) = \sin(x) \cdot \sin(y),
  \]
  
  Where:
  \[
  \begin{align*}
  f(x, y) &= 2\cdot x, \\
  g(x, y) &= 2\cdot y
  \end{align*}
  \]
  
  Velocity components:
  \[
  \begin{align*}
  u &= 2\sin(x) \cdot \sin(y), \\
  v &= \cos(x) \cdot \cos(y)
  \end{align*}
  \]
  
  - This is time-varying system.
  - The flow field is changing with time, shown in fig. 4(a), 4(b), and 4(c).
  - The LCS is changing with time, shown in fig. 4(b), 4(d), and 6(f).
  - There is a strong separation, so the LCS has a sharp boundary.

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References:
(3) Barua, Dino Okic (2015). Future work: Fig. 3 LCS locations and flow fields for neutral wind over North America at 400km above.
(4) Barua, Dino Okic (2015). The LCSs are different at different altitudes, likely because of the altitude dependence of thermospheric dynamics.
(5) Barua, Dino Okic (2015). For the time variant flow fields, the LCSs are changing with time (i.e. double-gyre).

Conclusions:
- For the test flow fields:
  - Found and illustrated the LCS in two sample flow fields.
  - For the time variant flow fields, the LCSs are changing with time (i.e. double-gyre).
  - For the time invariant flow field, the LCS is not changing with time (i.e. regular pendulum).
- For the neutral wind flow fields:
  - For the first time, found and illustrated the LCS in the neutral wind flow fields over the US mainland and North America.
  - There appear to be two LCSs over western North America.
  - The LCSs are different at different altitudes, likely because of the altitude dependence of thermospheric dynamics.
  - The LCS boundary is not sharp in cases where the separation is not strong.

Future work:
- Explore the LCS of the neutral wind flow field in IT system globally.
- Lengthen the integration time to check the variation of the LCS with time.
- Compare the LCS in different seasons in a year or different years in a solar cycle.
- Explore the LCS of the ionospheric drift velocities.