Lagrangian analysis of atmospheric rivers

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ABSTRACT: Based on data retrieved from ERA-Interim, atmospheric rivers (AR) events over the North Atlantic Ocean that affect Iberian Peninsula were analyzed in terms of the Lagrangian transport. A two-dimensional approach was derived from water vapor flux to study the ARs spatiotemporal patterns occurring in the region. Using the Finite-Time Lyapunov Exponents (FTLE), Lagrangian Coherent Structures (LCS) were derived from the FTLE field. The LCS allow to identify separatrices of fluid regions with different advective properties. Our findings suggest that for strong filamentous AR, the transport of water vapor is advected from low latitudes, due to the presence of LCS heading the transport eastward.

KEY-WORDS: Atmospheric rivers; Lagrangian coherent structures; Lyapunov exponents.

1 INTRODUCTION

The transport of moisture from the tropics to mid-latitudes is not mild and uniform. More than 90% of poleward water vapor transport is accomplished by narrow and elongated (longer than 2000 km and narrower than 1000 km) structures within the mostly pre-cold frontal Warm Conveyor Belt (WCB), and the Low Level Jet (LLJ) of extratropical cyclones [1] commonly associated to the polar front. These structures, labeled as Tropospheric or Atmospheric Rivers (ARs), are defined as areas of Integrated Water Vapor (IWV) column over 2cm and winds stronger than 12.5 m/s, transporting water vapor in the lower troposphere, close to the 850 hPa level [2,3,4]. AR advection is the key to explain extreme precipitation and flood events, especially when they are forced to rise over the mountains. This connection has been analyzed over Western US Coast [3,5] and Europe [6,7], and a very high percentage of coincidence was found. For some AR events, a filament pattern develops in many parts of the world that lives enough time and strongly affects the overall mixing properties of a region where the AR takes place to be considered as a coherent structure.

The goal of this paper is to study the role that advection plays on the water vapor transport in the troposphere using Lagrangian measures such as the Finite Time Lyapunov Exponents (FTLE). The FTLE measures the maximum stretching rate over a fixed interval time of trajectories derived from neighboring fluid particles. Ridges of maximum separation rates in the FTLE are used to estimate the Lagrangian Coherent Structures (LCS) [8,9]. Lagrangian Coherent Structures (LCS) allow to identify regions with different transport properties and it is a tool to identify the invariant barriers in dynamical systems which head passive transport. The detection of coherent structures through Lagrangian measures was used to study complex dynamic of atmospheric, to characterize large scales phenomena, such as the Polar Vortex [10,11], the Subtropical Jet Stream [12], the transport in the troposphere by transient baroclinic eddies [13], or the transport of plankton bloom by the South Indian Ocean Countercurrent [14], among many others [15].

Specifically, our analysis is based on the study of spatiotemporal patterns formed during an AR event. Advection by unsteady wind fields in this kind of events shapes the water vapor transport structures, showing a widely variety of distributions. In particular for our region of interest, our data shows that AR events are dominated by eastward propagation, being some of them a strong jet from low latitudes. We show that for AR events with a filamentous shape, wind flow dominates the transport over other advection mechanisms and LCS along the AR event head the transport eastward [16].
2 DATA AND METHODS

We analyze the AR based on data retrieved from the European Center for Medium-Range Weather Forecast reanalysis, ERA-Interim, in terms of the Vertical integrals of Water Vapor and Eastward/Northward Water Vapor Flux at 0.7°×0.7° spatial resolution and six hours’ time resolution.

\[ Q = \frac{1}{g} \int_0^1 q \frac{\partial p}{\partial \eta} d\eta \]

\[ \Phi_x = \frac{1}{g} \int_0^1 uq \frac{\partial p}{\partial \eta} d\eta \]

\[ \Phi_y = \frac{1}{g} \int_0^1 vq \frac{\partial p}{\partial \eta} d\eta \]

with \( \eta \) a hybrid coordinate.

Variables given by Equations (1) and (2) were used to determine the Eastward and Northward Average Drift Velocities,

\[ < \dot{x} > = \frac{\Phi_x}{Q} \]

\[ < \dot{y} > = \frac{\Phi_y}{Q} \]

with these new variables, the 2D flow velocity field is,

\[ \mathbf{V_l} = (< \dot{x}(\theta, \varphi, t) >, < \dot{y}(\theta, \varphi, t) >) \]

To obtain particle trajectories, we advect an uniform rectangular grid of tracers 1/5º from an initial position \( r_i(t_0) \) using the velocity fields given by Equation (4) to a final position \( r(t + \tau) \) with an integration time of \( \tau = 120 \) hours, typical time scale for the formation and propagation of the AR. Finally, after each finite time advection, \( \tau, r(t_0 + \tau) = \Omega_\tau^{t_0}(r(t_0)) \) we compute the Finite Time Lyapunov Exponents (FTLE) using:

\[ \sigma(r, t, \tau) = \frac{1}{|\tau|} \log \sqrt{\mu_{\max}(C(x_\tau))} \]

where \( \mu_{\max} \) is the maximum eigenvalue of the right Cauchy-Green deformation tensor \( C = F^{\top}F \), where \( F \) is defined by \( F(r_i) = \nabla \Omega_\tau^{t_0}(r_i(t_0)) \).

The FTLE field at a given location measures the maximum stretching rate over the interval \( \tau = t_0 \) of trajectories starting near the point \( \mathbf{r} \) at time \( t_0 \) Ridges of the FTLE field are used to estimate finite time invariant manifolds in the flow that separate dynamically different regions. Repelling (attracting) Lagrangian Coherent Structures for \( \tau > 0, (\tau < 0) \) are time-dependent generalizations of the stable (unstable) manifolds of the system. These structures govern the stretching and folding mechanism that control flow mixing.

3 RESULTS

Atmospheric Rivers have been observed as filamentous jet structures on the integrated water vapor column \( Q \), Equation (1). Figure 1(a) shows an example of an AR jet transporting water vapor over the North Atlantic Ocean towards the Iberian Peninsula. As a result of this jet, intense precipitation rates were recorded at the North-West of the Iberian Peninsula. The ridge larger values of \( Q \) connecting the tropics with the North Atlantic Ocean shape a continuous AR structure. The backward FTLE field is shown in Figure 1(b). Note that the filament joining the Iberian Peninsula to the Gulf of Mexico shows a clear relationship to the Atmospheric River depicted previously. From a Lagrangian point of view, AR can be considered as an attracting LCS or unstable manifold of the flow dynamical system.
Figure 1: Atmospheric River event on May 19, 2000 in terms of the integrated water vapor column $Q$ (a), and the corresponding backward FTLE field (b).

Figure 2: Lagrangian Coherent Structures (blue dots) and integrated water vapor column $Q$ for the same Atmospheric River than in Figure 1.

Lagrangian Coherent Structures calculated from the backward FTLE fields are compared to the $Q$ field, Equation (1), in Figure 2 for the AR shown previously. LCS and $Q$ ridges show a filamentous structure, and have one or two narrow jets growing from low latitudes transporting water vapor to medium latitudes. This kind of ARs develop in winter season.

We hypothesized, that for AR with a narrow, well defined, shape, the main water vapor transport from the low latitudes is the passive advection due to wind advection, but for AR with a scattered shape (mainly during summer season), large areas with high concentrations of water vapor have been observed which have not a correspondence with advected passive tracers. In these regions, our approach is not valid, and the water vapor does not come only from low latitudes, but the source of water vapor maybe comes from a continuous evaporation mechanism, vertical transport between different pressure layers, or other physical transports that our approach cannot describe. In terms of the Lagrangian transport, LCS identified as attracting manifolds of the flow develop and follow the AR only if the wind is the main mechanism that advects water vapor from low latitudes into the northern ones.

4 CONCLUSIONS

The propagation of Atmospheric Rivers over the Iberian Peninsula has been studied in terms of Lagrangian tools. Based on an integrated water vapor flow obtained from the ERA-Interim database, AR events have been clearly identified with LCS. Two different events have been analyzed. On the one hand, for narrow filamentous ARs, with a fast and persistent eastward transport, an attracting LCS that acts as a boundary develops and heads the transport with the same shape than the river. This kind of AR is dominated by a strong wind advection which transports water vapor from low latitudes and typically develops in winter. On the other hand, for unstructured rivers, mostly occurring during the summer season, no jet-type LCS seems to develop. This kind of events is not only defined in terms of wind...
transport, and the separation between passive advection and other transport mechanisms, is not solved by our approach.

Finally, we conclude that this connection between LCS and an AR in terms of Lagrangian transport, should be take into account for future studies and help to characterize this kind of events. An extensive analysis with more AR events could help to set up a definition of AR in terms of Lagrangian analysis. Our results presented here maybe of importance for other regions where AR activity exists.

REFERENCES


