Analyzing the Exceptional Arctic Stratospheric Polar Vortex in 2019/2020 using Lagrangian tools

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Weather and Climate Extremes and their Predictability
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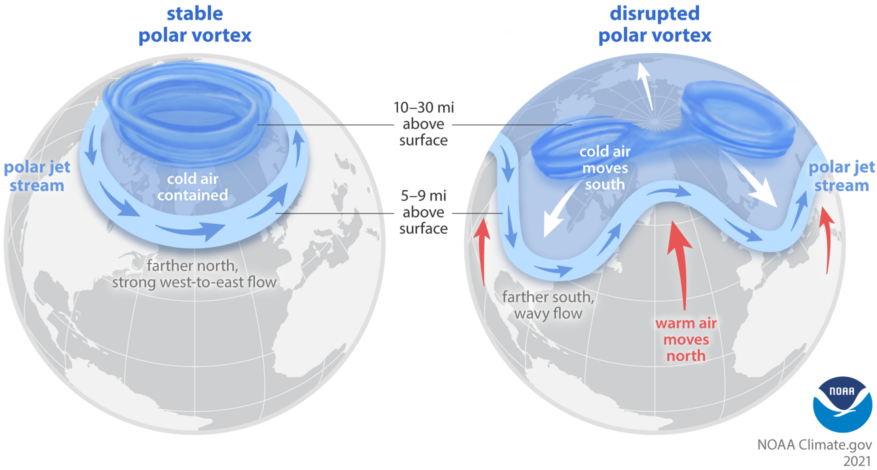
IMTech

MOTIVATION: Stratospheric Polar Vortex

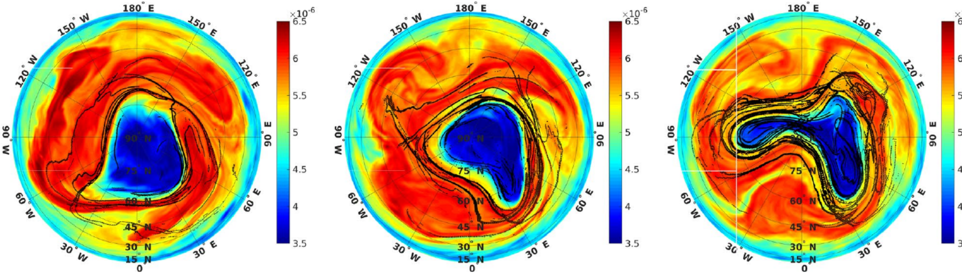


The Polar Vortex is a strong band of winds in the stratosphere, surroundings the North/South Pole 15 - 45km above the surface.

Stratospheric polar vortex disturbances profoundly influence **extreme weather events**

The 2019/2020 stratospheric polar vortex was the strongest, most persistent, and coldest on record in the Arctic.

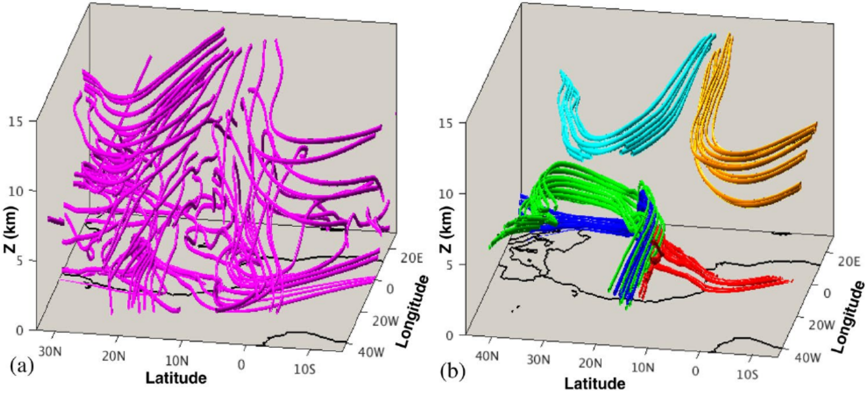
It was linked to weather extremes: including record heat, unusual patterns of precipitation, marine cold air outbreaks, windstorms...



What flow structures lead to the split?, How was the transfer of fluid parcels from one vortex to the other after the split?

Our approach to answer these questions is based on following air parcels trajectories, examining barriers to the flow

[Curbelo, Chen, Mechoso (2021) Geophysical Research Letters]



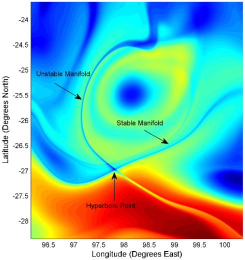
[Niang, Mancho, Garcia - Garrido, Mohino, Rodrigues-Fonseca, Curbelo (2020) Scientific Reports]

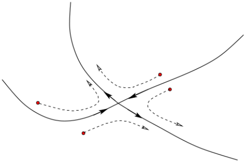
We would like to provide a guide that allows a precise selection of initial conditions which has enabled us to find new transport routes, as well as providing an integrated vision of transport.

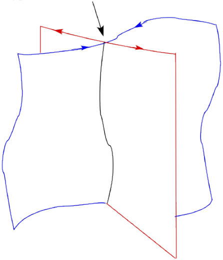
Lagrangian: sit on fluid particle, based on trajectories
Coherent: live-time long enough to significantly affect transport

By Haller and Yuan (2000), Lagrangian Coherent Structures (LCSs) are:

- Organizing centers for Lagrangian patterns,
- Material lines, hence transport barriers
- LCS exhibit locally the strongest attraction, repulsion or shearing in the flow





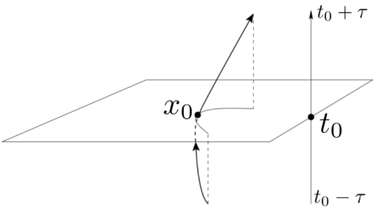


Lagrangian Coherent Structures control the stretching and folding of the fluid and help to identify regions in which parcels have a different dynamical fate.

Let $\mathbf{x}(t; x_0)$ a trajectory that starts at x_0 at time t_0 which is solutions of the time dependent systems

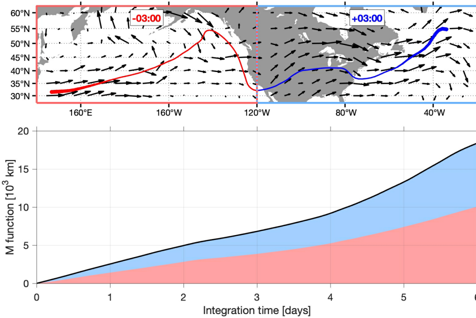
$$\frac{d\mathbf{x}}{dt} = \vec{u}(\mathbf{x}, t)$$

where $\vec{u}$ is the velocity vector field.



Lagrangian descriptors:

$$M(\mathbf{x}_0, t_0, \tau) = \int_{t_0-\tau}^{t_0+\tau} \|\vec{u}(\mathbf{x}(t; \mathbf{x}_0), t)\| \, dt$$



$\| \cdot \|$ is the Euclidean norm.
Poincaré's idea: Find geometrical structures that divide phase space into regions of trajectories with qualitatively distinct dynamical behaviors.

Image and video of Louis Rivoire (Harvard U.

METHODS: Lagrangian descriptors

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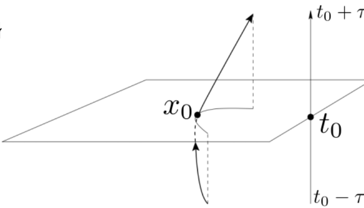
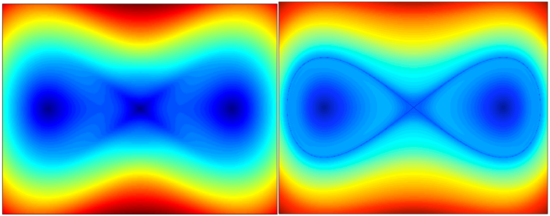


Lagrangian descriptors: $M(\mathbf{x}_0, t_0, \tau) = \int_{t_0-\tau}^{t_0+\tau} \|\vec{u}(\mathbf{x}(t; \mathbf{x}_0), t)\| \, dt$

$\tau = 2$ $\tau = 10$



For long enough τ converge towards "singular features" that highlight the stable and unstable manifolds of hyperbolic trajectory.

[Mancho, Wiggins, Curbelo and Mendoza (2013) Commun. Nonlinear Sci. Numer. Simul.

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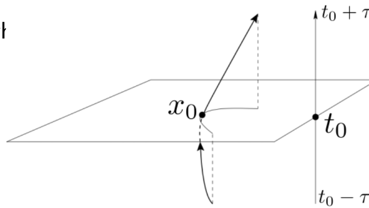

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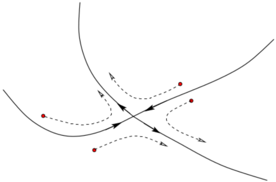
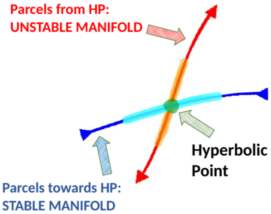
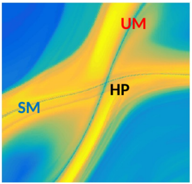
Hyperbolic Trajectories

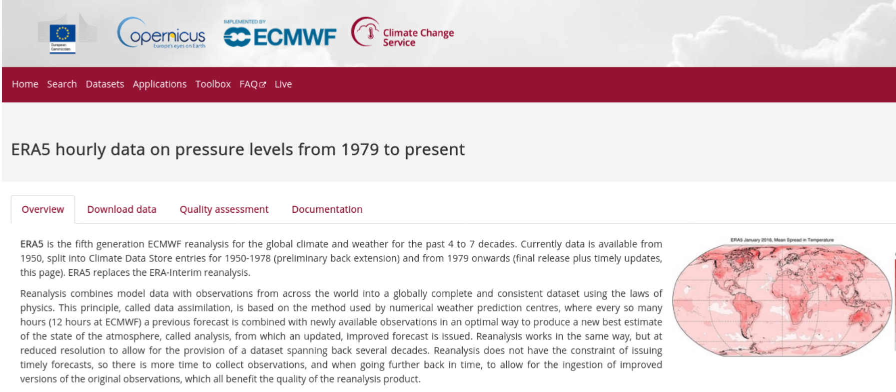




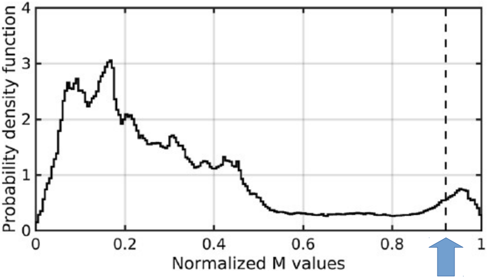


Reanalysis Data:

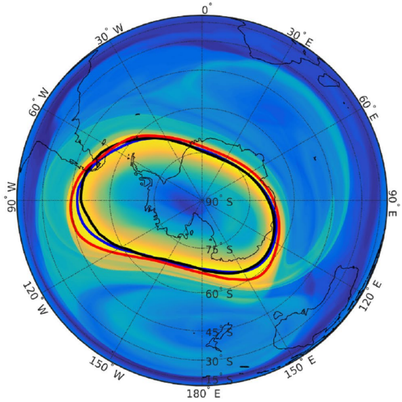
- ERA-5 data provided by ECMWF: zonal (u) and meridional (v) wind velocity, Temperature, Pressure, Ozone mass mixing ratio and Geopotential. Global grid 0.25x0.25 degree with 37 pressure levels. The temporal resolution of the data is 1 h, which is the highest available in the data set.



In our scenario, the boundary region of a vortex would be such that,
(i) it **divides** the core from its surroundings, and
(ii) it is free of hyperbolic trajectories and hence does **not produce filaments** during a certain time interval.



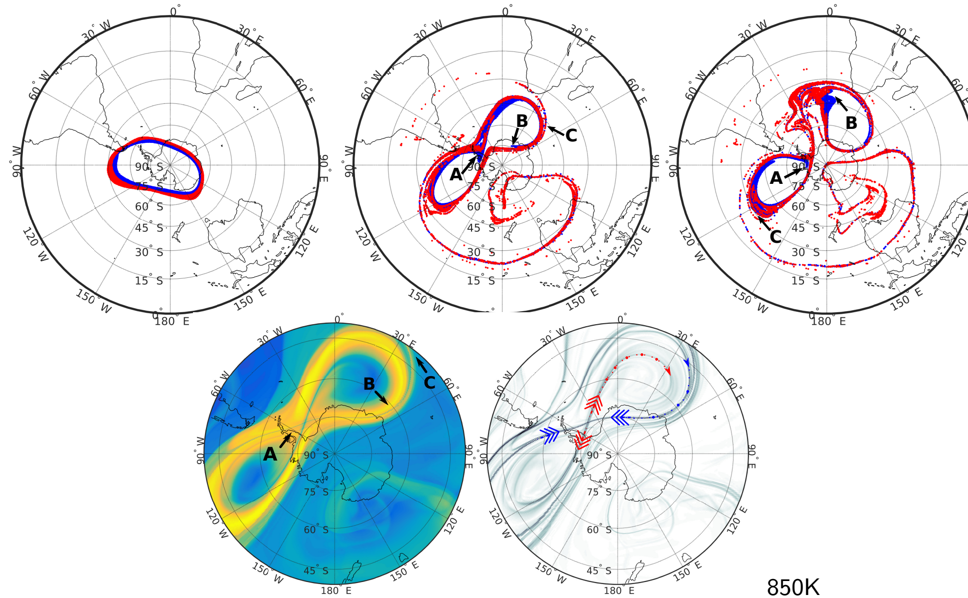
We choose this value of M as the outer and inner boundary of the SP



Blue line. Maximum of M for each longitude.
Red line: Outer contour of normalized M (92nd percentile).
Black line Maximum of the PV gradient (∇PV) for each longitude

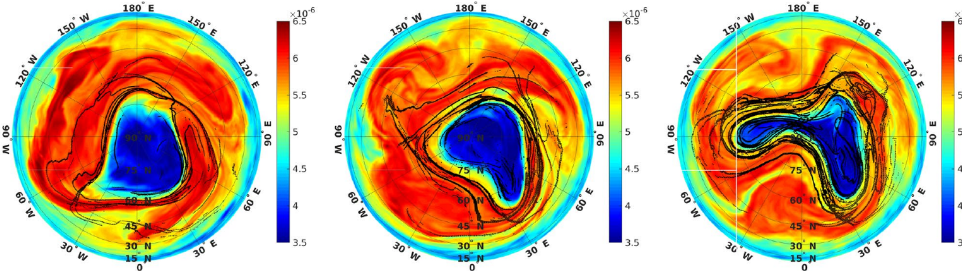
[Curbelo et al. (2019) Part I. Climate Dynamics]

(a) 9 September 2002 00:00 (b) 24 September 2002 09:00 (c) 26 September 2002 05:00



The Northern Hemisphere stratosphere during late winter and early spring of 2020 was punctuated by outstanding events both in dynamics and tracer evolution.

What flow structures lead to the split?, How was the transfer of fluid parcels from one vortex to the other after the split?



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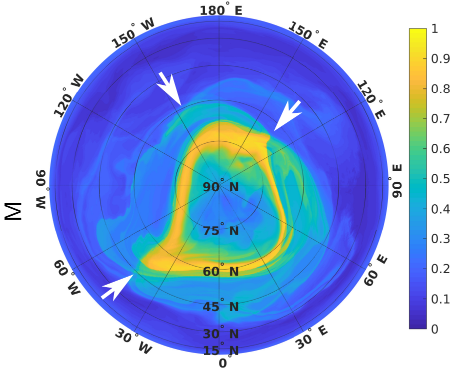
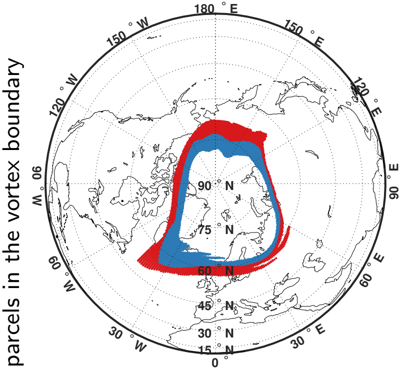
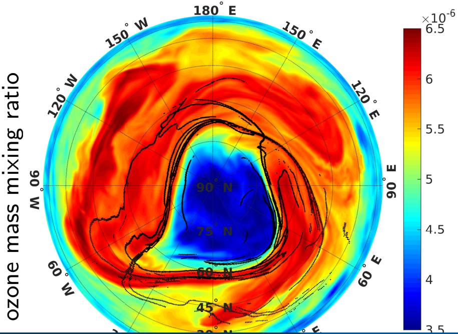
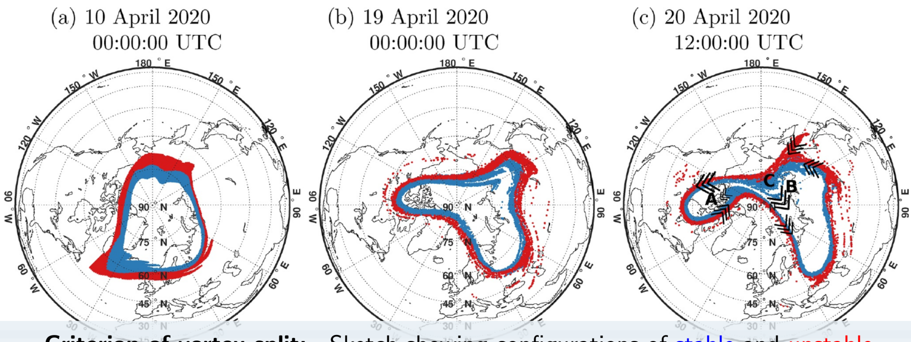






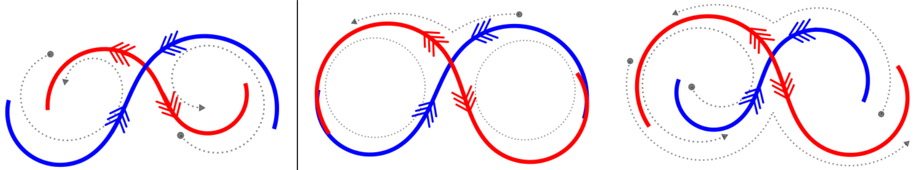
The Vortex Split in April 2020

10 April 2020 (530K)

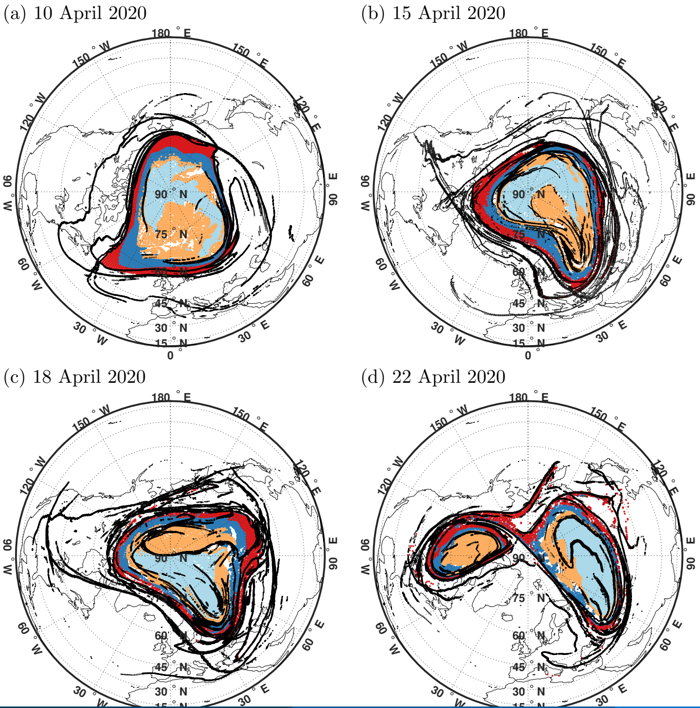


Criterion of vortex split: Sketch showing configurations of stable and unstable manifolds according to which one can expect at later times either vortex

splitting | or | no splitting



[Curbelo et al. (2019) Part II. Climate Dynamics]



Vortex edge

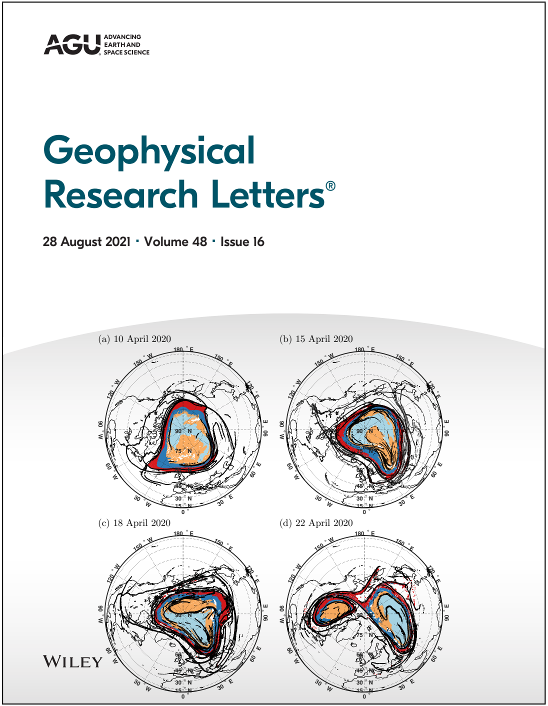
Parcels inside or outside the contour defined by the maximum value of M at each longitude

Inside the vortex (O_3 <10%)

O_3 values both above the lower 2%

O_3 values in the lower 2% for the level

At the split, ozone poor air remains in the main vortex.



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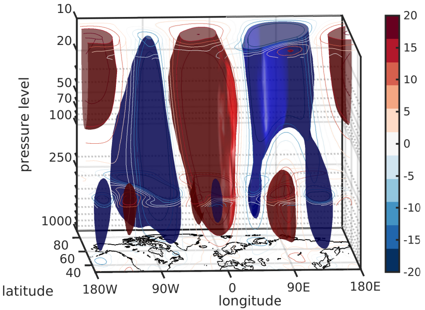
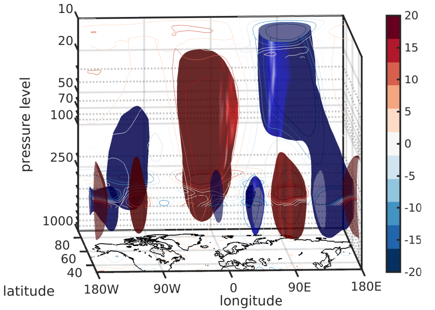
Transfer of Fluid Parcels Between the Vortices **after** the Split

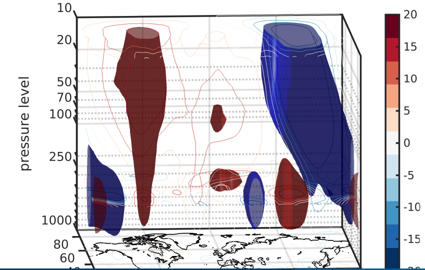
22 April 2020



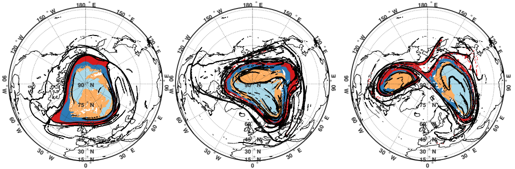
27 April 2020



30 April 2020



Isosurfaces of deviations of quasi-geostrophic stream function from the zonal mean. (Surfaces at $-15 \cdot 10^6 m^2/s$ and $-15 \cdot 10^6 m^2/s$)



Reference: Curbelo, Chen and Mechoso. Geophysical Research Letters (2021), 48, e2021GL093874.

We have explored aspects of the evolution of and transport in the lower to middle stratosphere in the period preceding the spring-time vortex breakup:

- Trajectories of fluid parcels during vortex rupture were shown and structures with a special configuration of flow barriers were identified in the vortex split
- The air in the offspring vortex originated well inside the main vortex, but the air with lowest ozone values remained confined within the main vortex (persisted into mid-May)

Implications: how ozone-depleted air may be transported as the vortex is eroding in spring.

THANKS

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