

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

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Weather and Climate Extremes and their Predictability
CAFE Final Conference (28/09/2022)

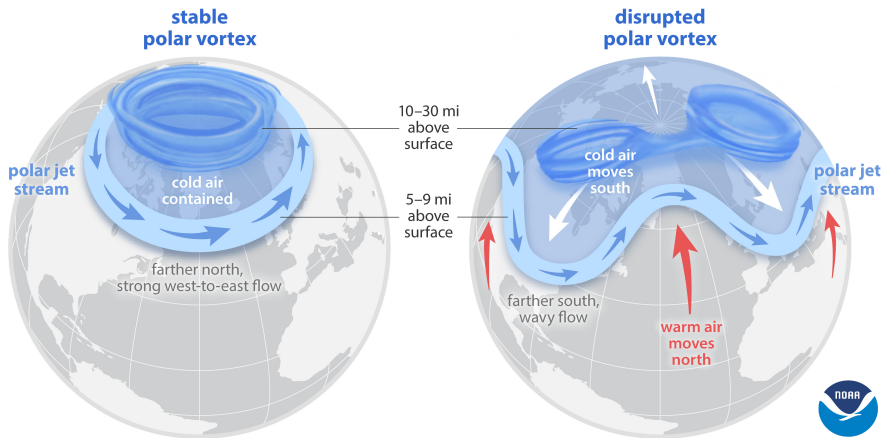
Joint work with: Gang Chen (UCLA), Carlos R. Mechoso (UCLA).



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DE CATALUNYA
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MOTIVATION: Stratospheric Polar Vortex



NOAA Climate.gov
2021

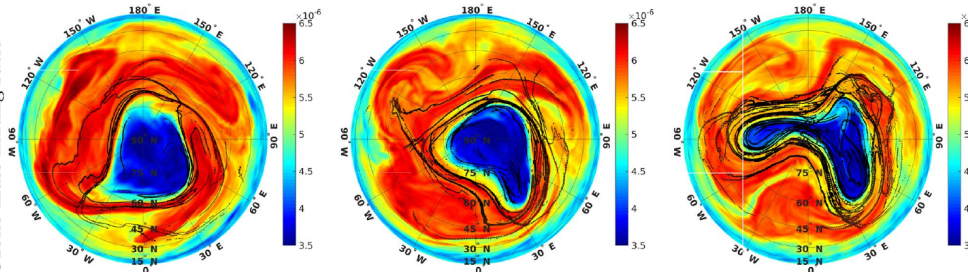
The Polar Vortex is a strong band of winds in the stratosphere, surrounding the North/South Pole 15 - 45km above the surface.

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

MOTIVATION: Northern Hemisphere Stratosphere winter/spring 2020

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

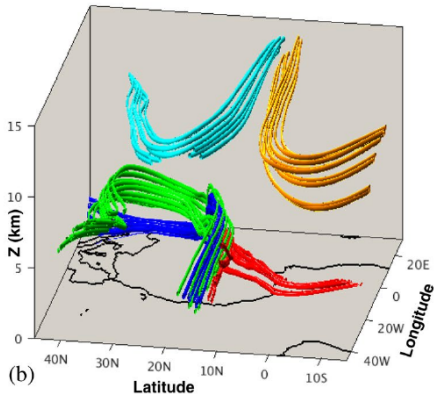
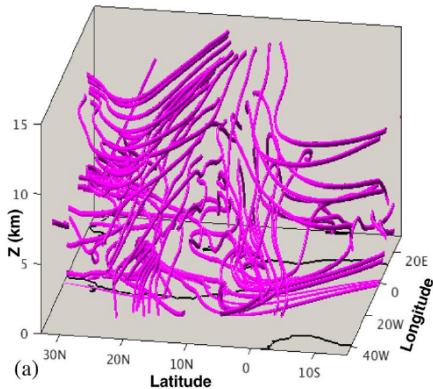
It was linked to weather extremes: including record heat, unusual patterns of precipitation, marine cold air outbreaks, windstorms...



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]

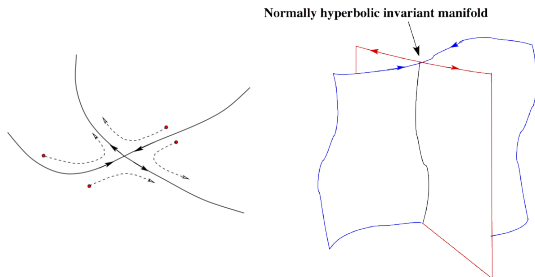
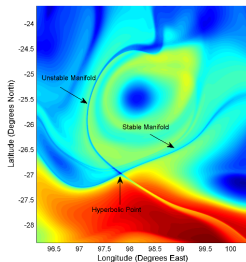
We would like to provide a guide that allows a precise selection of initial conditions which has enabled us to find new transport routes, as well as providing an integrated vision of transport.

Lagrangian Coherent Structure (LCS)

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



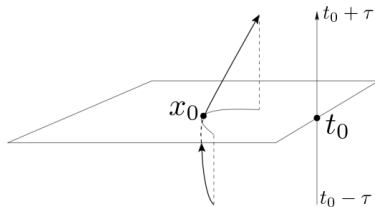
Lagrangian Coherent Structures control the stretching and folding of the fluid and help to identify regions in which parcels have a different dynamical fate.

METHODS: Lagrangian descriptors

Let $\mathbf{x}(t; \mathbf{x}_0)$ a trajectory that starts at \mathbf{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.

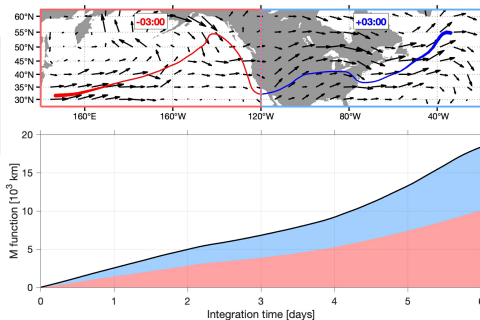


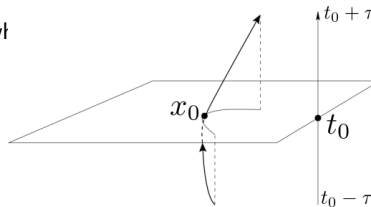
Image and video of Louis Rivoire (Harvard U.)

METHODS: Lagrangian descriptors

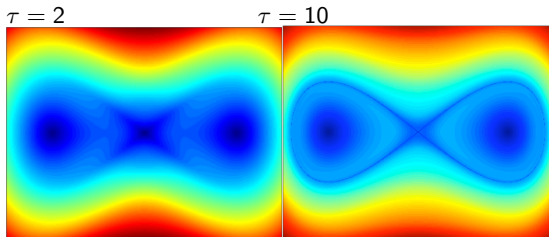
Let $\mathbf{x}(t; \mathbf{x}_0)$ a trajectory that starts at \mathbf{x}_0 at time t_0 w/ solutions of the time dependent systems

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

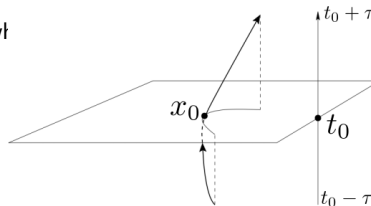
[Mancho, Wiggins, Curbelo and Mendoza (2013) Commun. Nonlinear Sci. Numer. Simul.

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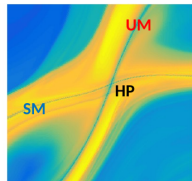
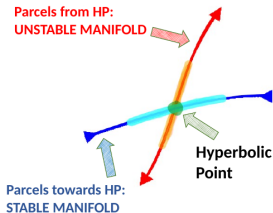
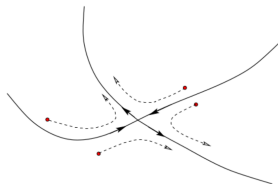
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Hyperbolic Trajectories



Reanalysis Data:

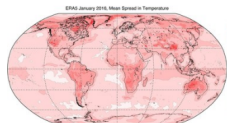
- ERA-5 data provided by ECMWF: zonal (u) and meridional (v) wind velocity, Temperature, Pressure, Ozone mass mixing ratio and Geopotential. Global grid 0.25x0.25 degree with 37 pressure levels. The temporal resolution of the data is 1 h, which is the highest available in the data set.



The screenshot shows the top section of the ERA5 data website. At the top, there are logos for the European Union, Copernicus (Earth's eyes on Earth), ECMWF (implemented by), and the Climate Change Service. Below the logos is a dark red navigation bar with links for Home, Search, Datasets, Applications, Toolbox, FAQ, and Live. The main heading reads "ERA5 hourly data on pressure levels from 1979 to present". Below the heading is a navigation menu with tabs for Overview, Download data, Quality assessment, and Documentation. The "Overview" tab is currently selected.

ERA5 is the fifth generation ECMWF reanalysis for the global climate and weather for the past 4 to 7 decades. Currently data is available from 1950, split into Climate Data Store entries for 1950-1978 (preliminary back extension) and from 1979 onwards (final release plus timely updates, this page). ERA5 replaces the ERA-Interim reanalysis.

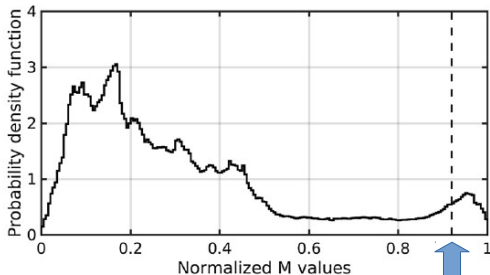
Reanalysis combines model data with observations from across the world into a globally complete and consistent dataset using the laws of physics. This principle, called data assimilation, is based on the method used by numerical weather prediction centres, where every so many hours (12 hours at ECMWF) a previous forecast is combined with newly available observations in an optimal way to produce a new best estimate of the state of the atmosphere, called analysis, from which an updated, improved forecast is issued. Reanalysis works in the same way, but at reduced resolution to allow for the provision of a dataset spanning back several decades. Reanalysis does not have the constraint of issuing timely forecasts, so there is more time to collect observations, and when going further back in time, to allow for the ingestion of improved versions of the original observations, which all benefit the quality of the reanalysis product.



1. Definition of kinematic Stratospheric Polar Vortex (SPV)

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.



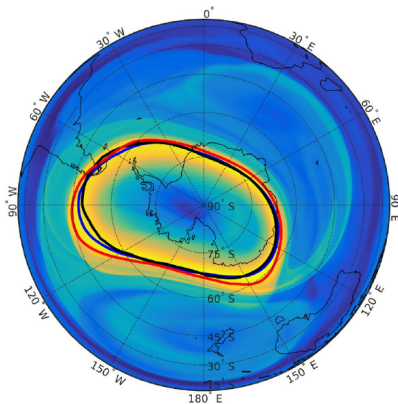
We choose this value of M as the outer and inner boundary of the SF

Blue line. Maximum of M for each longitude.

Red line: Outer contour of normalized M (92nd percentile).

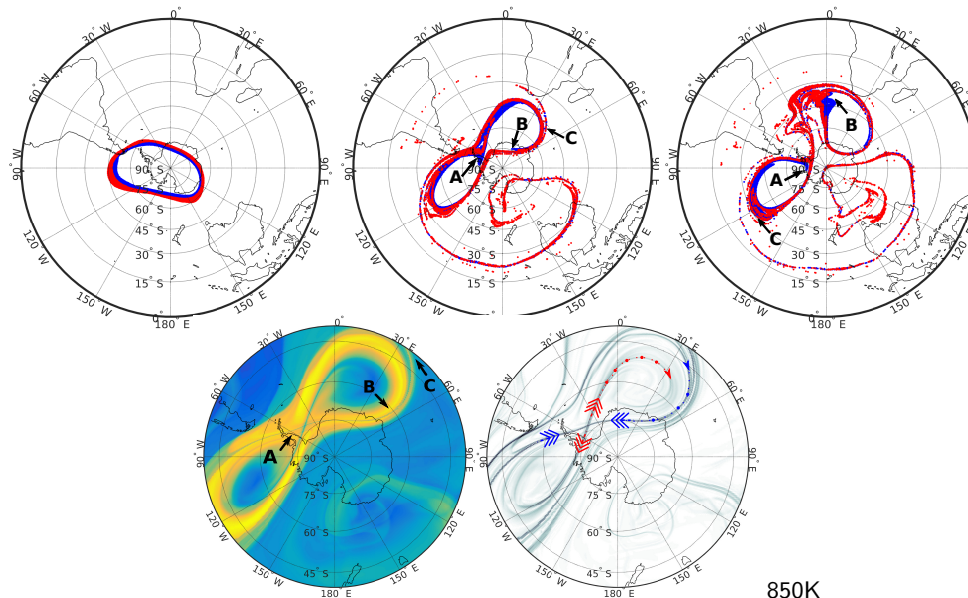
Black line Maximum of the PV gradient (∇PV) for each longitude

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



2. Criterion for vortex splitting. The SPV in September 2002

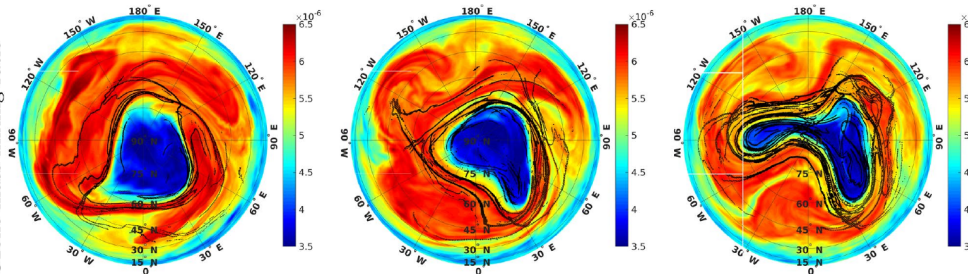
(a) 9 September 2002 00:00 (b) 24 September 2002 09:00 (c) 26 September 2002 05:00



850K

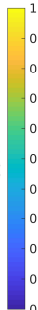
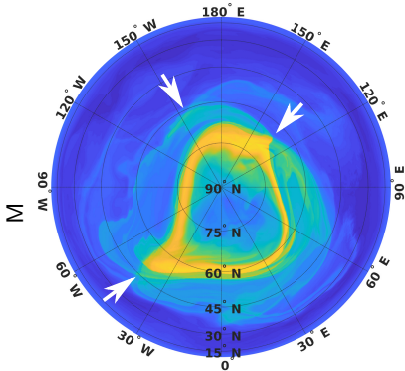
The Northern Hemisphere stratosphere during late winter and early spring of 2020 was punctuated by outstanding events both in dynamics and tracer evolution.

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

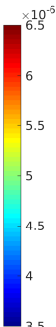
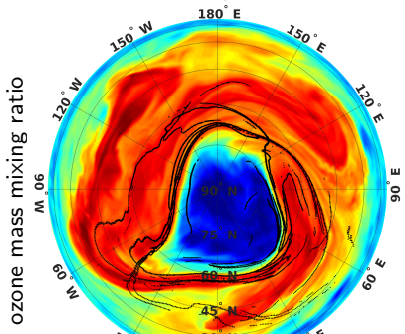
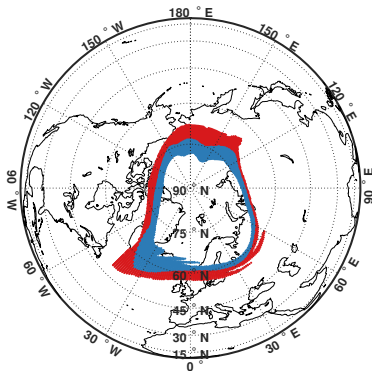


Our approach to answer these questions is based on following air parcels trajectories, examining barriers to the flow

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



parcels in the vortex boundary

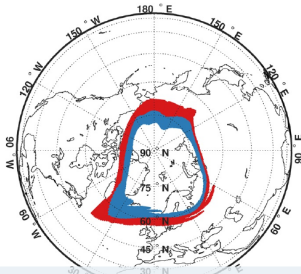


The Vortex Split in April 2020

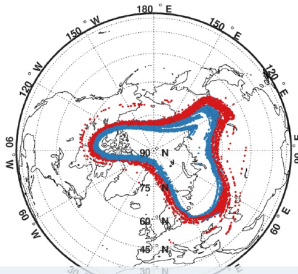
10 April 2020 (530K)

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

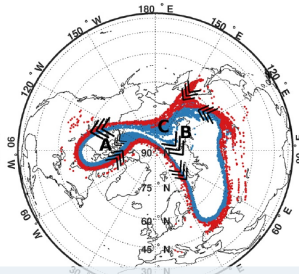
(a) 10 April 2020
00:00:00 UTC



(b) 19 April 2020
00:00:00 UTC

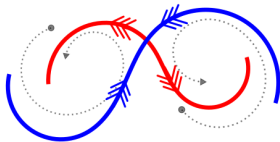


(c) 20 April 2020
12:00:00 UTC



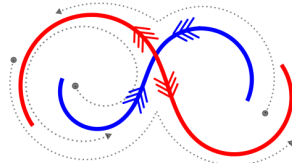
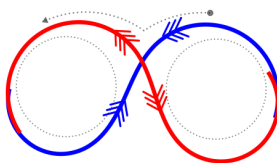
Criterion of vortex split: Sketch showing configurations of **stable** and **unstable** manifolds according to which one can expect at later times either vortex

splitting



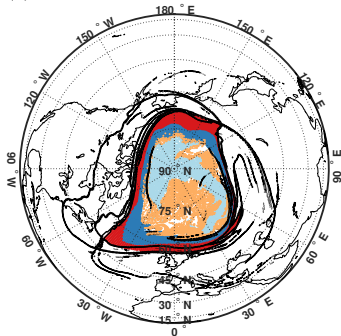
or

no splitting

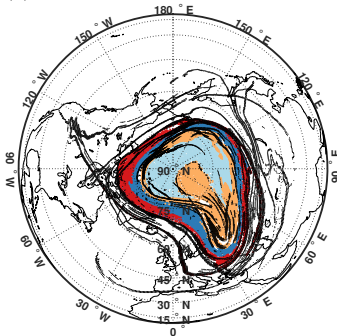


[Curbelo et al. (2019) Part II. Climate Dynamics]

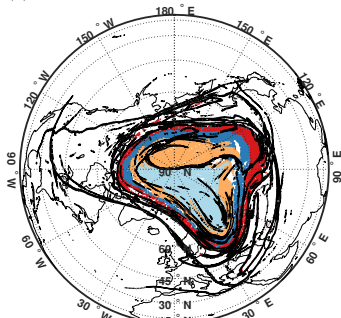
(a) 10 April 2020



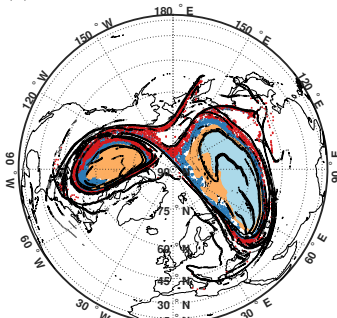
(b) 15 April 2020



(c) 18 April 2020



(d) 22 April 2020



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%

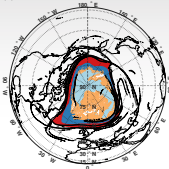
O_3 values in the lower 2% for the level

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

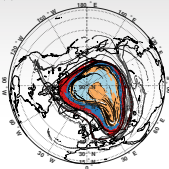
Geophysical Research Letters®

28 August 2021 · Volume 48 · Issue 16

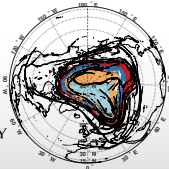
(a) 10 April 2020



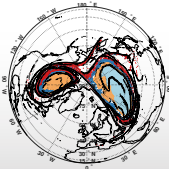
(b) 15 April 2020



(c) 18 April 2020



(d) 22 April 2020



WILEY

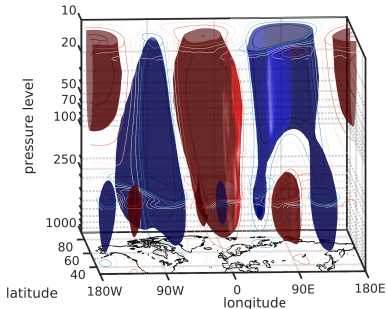
Vortex edge
 Parcels **inside** or **outside** the contour defined by the maximum value of M at each longitude

Inside the vortex
 ($O_3 < 10\%$)
 O_3 values both above the lower 2% O_3 values in the lower 2% for the level

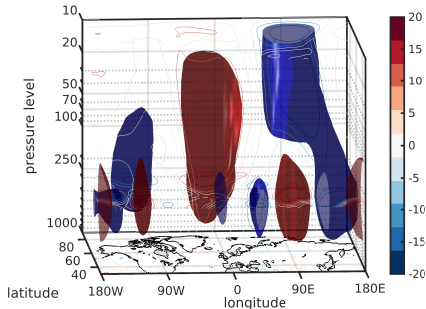
At the split, ozone poor air remains in the main vortex.

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

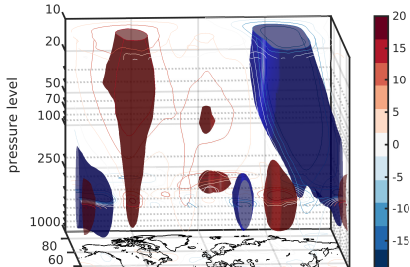
22 April 2020



27 April 2020

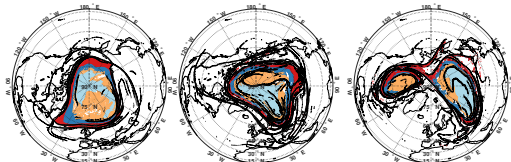


30 April 2020



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

Summary and conclusions



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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