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Kinematics of eddy–mean-flow interaction in an idealized atmospheric model

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Hello, my name is Sergey Kravtsov. I would like to introduce recent work, which is the first outcome of collaboration between Dr. Sergey Gulev's climate lab located within the Institute of Oceanology in Moscow, Russia and the University of Wisconsin-Milwaukee, where I currently work myself. In this work, we analyzed numerical experiments using an idealized model of turbulent zonal jets in the atmosphere and the ocean, with an eye to obtaining a self-consistent kinematic picture of interaction between somewhat faster and smaller-spatial-scale processes dominated by the so-called synoptic eddies and large-scale low-frequency processes identifiable in terms of the zonally elongated jet-like flow structures.

QG atmospheric model with topography (Kravtsov et al. 2005)

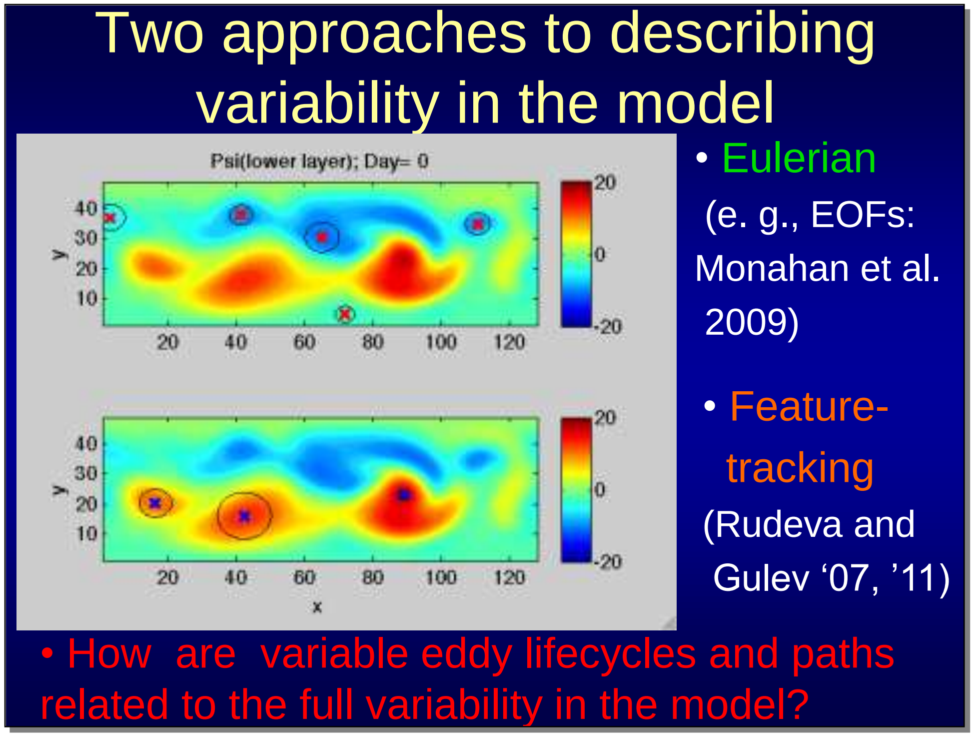
$$\frac{\partial \Pi_i}{\partial t} + J(\psi_i,\Pi_i) = Q_0(-1)^i F_i(x,y,\eta) - \delta_{i,1}\, k\nabla^2\psi_i$$

$$\Pi_i = \nabla^2\psi_i + (-1)^i f_0 \frac{\eta - \delta_{i,1} h_B(x,y)}{h_i} + \beta y;$$

$$\eta = (\psi_1 - \psi_2)/g'; \quad i = 1,\ 2$$

- Zonally-symmetric thermal forcing acting on η
- A metaphor for zonal flows in the ocean/atmosph.
- Study behavior in a range of Q_0, h_B and g'

The two-layer quasi-geostrophic model we used is quite standard; it is arguably the minimal model to study interactions between eddies and zonal jets. The model is set up in a beta-plane channel, with periodic boundary condition in the zonal, east-to-west direction and no-slip conditions on the zonal, northern and southern boundaries of the channel. The bottom layer includes an idealized wavenumber-2 topography with the maximum height *h_B,* while the upper layer has a flat rigid lid. The model is thermally driven by the external forcing with the amplitude of *Q_0,* which heats up the southern part of the channel and cools down the northern part, thus resulting in the south–north gradient of the interface eta between the model layers and, — due to thermal-wind relation, — in the large-scale zonal current with vertical shear. Baroclinic instability of this current generates synoptic eddies, which interact with and further modify the original flow. The properties of these eddies strongly depend on the reduced gravity parameter *g′* related to the density stratification in the model. We study the behavior of the model in a range of the controlling parameters *Q_0, h_B* and *g′.*



There exist two complementary approaches to describing variability of the turbulent flows in the ocean and atmosphere. The first, Eulerian approach examines the evolution of the flow in a set of fixed spatial location. Shown here is a snapshot of the model's lower-layer streamfunction, with negative and positive values represented by the shades of blue and red, respectively. Note the region with strong gradient of the streamfunction, which separates the "red" and "blue" regions of the figure. This wavy jet is identifiable in the middle part of the basin and flows predominantly in the east-to-west (that is, left-to-right) direction along the axis of the channel.

In further evolution, however (see https://pantherfile.uwm.edu/kravtsov/www/downloads/QGtracktest0.avi), we will notice that at some times the existence of such a coherent predominantly zonal jet becomes far from obvious, and the flow is instead completely dominated by a smaller (zonal) scale eddy field. To recover the underlying large-scale structure of the flow in an Eulerian approach, one has to apply various filtering methods, such as low-pass filtering in time or zonal averaging in space. We will later on apply a slightly more advanced objective filtering technique based on the Principal Component Analysis (PCA), also known as the Empirical Orthogonal Function (EOF) analysis. This analysis will demonstrate that the dominant mode of flow variability in the model consists of persistent zonal-jet shifts to the north and south of its time-mean, climatological position.

An alternative, system-centered method of looking at the atmospheric general circulation is to recognize traveling synoptic eddies as natural building blocks of the atmospheric variability and perform their detection and tracking. An example of such tracking is visualized here by showing the paths and effective radii of cyclones (in the upper panel) and anticyclones (in the lower panel). The length of a typical eddy lifecycle, from birth to dissipation, is about 4 days, but it turns out that lower-frequency climate variability can be diagnosed through analyzing the slow changes in the eddy lifecycles and trajectories. **The central question we address in this study is that of a detailed empirical connection between these two — Eulerian and system centered — approaches to describing climate variability.**

Methodology-I

• Reconstruct synoptic eddy field by replacing eddy evolution *along tracks with a given lifetime* with *composite* evolution averaged over all such tracks. Discard eddy asymmetries:

$$\psi_{EDDY} = cI_0(\tau)\exp(-r/R_0(\tau))$$

T – time from birth, *r* – distance from current eddy center, I_0 – intensity, R_0 – radius, *c* – const

Note: all trajectories are from the full model!

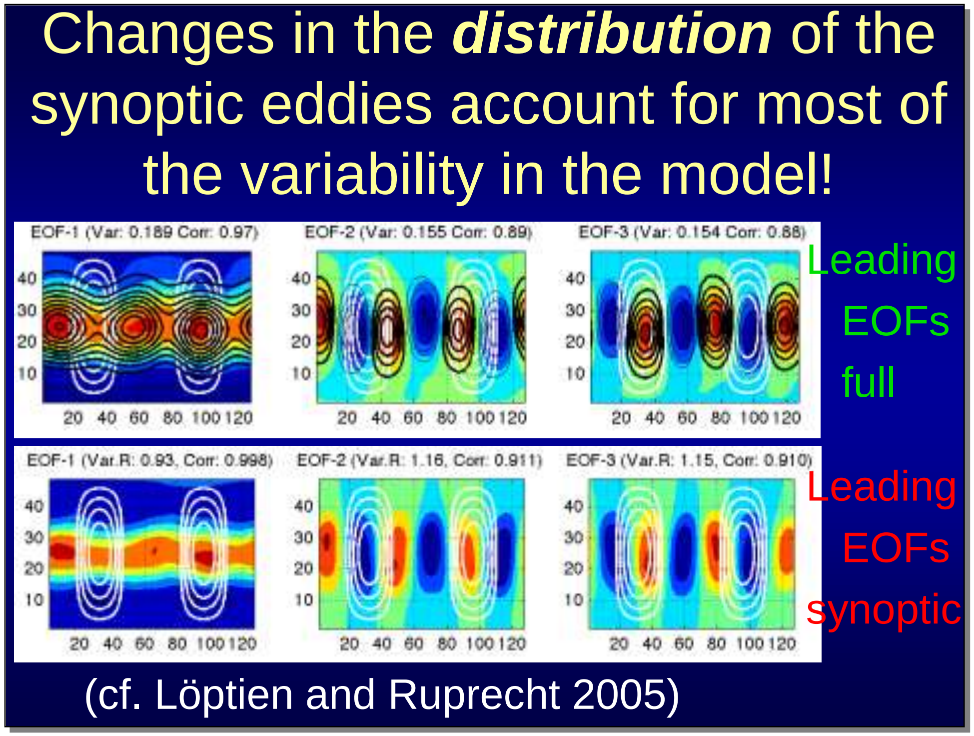
The centerpiece of our method was the construction of a synthetic streamfunction field, which consisted, at each time, of axisymmetric contributions from all the cyclones and anticyclones present at that time. These contributions were approximated as exponential functions decaying with the distance *r* from the eddy center and depending on eddy radius *R_0* and intensity *I_0* parameters obtained via eddy tracking in the lower-layer streamfunction field of each model simulation. It is important to note that the values of *R_0* and *I_0* used in creating the synthetic streamfunction were not the instantaneous values given by tracking, but the composite means over all eddy tracks with a given lifetime. For example, for a given 10-yr-long model simulation sampled once every 6 hours, we identified all cyclones with a lifetime of, say, 4 days, and computed the composite means of the cyclone radius and intensity for each of the 16 time values from the origin of the cyclone at 0 and decay of the cyclone at 4 days. We then repeated this procedure for cyclones with other lifetimes and then for all anticyclones. Hence, in the reconstructed "synoptic" streamfunction, we discarded eddy asymmetries and dispersion of eddy characteristics among the tracks with a given lifetime, but all the eddy trajectories in the synthetic field were identical with the eddy trajectories from the full model simulation.

Methodology-II

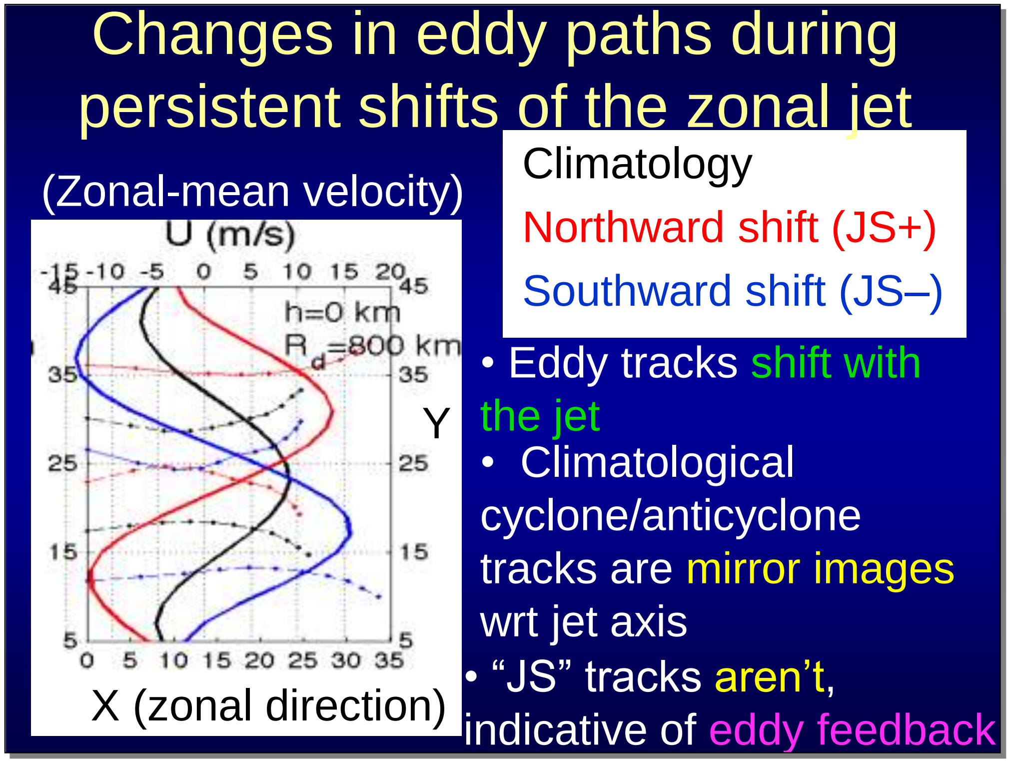
- Compare variability of the full vs. synoptic-eddy fields using EOF data compression

- Study variations of the eddy tracks in the course of model’s low-frequency variability (LFV)

We then compared the original model-output and synthetic, eddy-reconstructed streamfunction fields using EOF data compression to see how well the tracking methodology describes the leading modes of variability in the model. We found (more details for this first important result in the next slide!) that the synthetic synoptic-field streamfunction obtained via eddy tracking not only reproduces well the fast propagating modes associated with eddies themselves (with typical time scales of a few days), but has essentially the same climatology and low-frequency variability (LFV) as those of the full streamfunction field. Motivated by this result, we went on to identify those eddy-track characteristics, whose slow changes corresponded to the modeled low-frequency variability and addressed causality between variations in eddy tracks and large-scale (that is, the zonal jet) flow.



In the next slide we show, with color shading, three leading EOFs of the lower-layer streamfunction in one of the model runs. The top row corresponds to the results using the full model generated streamfunction, while the bottom row shows the EOFs for the synthetic field obtained via eddy-tracking-based reconstruction. Without going into details, we note at once that the corresponding EOF patterns of the full and synthetic fields are nearly identical, while their time series, or principal components, are highly correlated (not shown here). The leading EOF has a nearly zonally symmetric anomaly pattern that describes, when added to the time-mean streamfunction (not shown here), the shifts of the zonal jet to the north and south of its climatological location, which is close to the axis of the channel. The time series associated with this variability is characterized by the prolonged periods of positive or negative phase, whose durations exceed the typical eddy lifetime of a few days. The next pair of EOFs describes one of the propagating modes associated with the synoptic eddies themselves, while the synoptic modes with higher wave numbers appear in the tails of the EOF spectrum and are not shown here. In summary, once again, the idealized round eddies with composite life cycles launched along actual eddy tracks derived from the full model describe the major fraction of the modeled flow's full variability, including its low-frequency component.



How exactly do the eddy characteristics change in the course of the model's low-frequency variability? To address this question, we've computed composites of various flow characteristics conditioned on the phase of the low-frequency jet-shifting mode time series, with the northward shifts denoted as "red" JS+ states, and southward shifts — as "blue" JS— states; climatological characteristics are shown in black color. The composite zonal-mean zonal wind profiles are shown as color coded heavy lines with values listed along the top horizontal axis of the plot. The composite eddy trajectories are drawn as dots with solid and dashed lines for cyclones and anticyclones, respectively. The cyclones' composite trajectories for a given state of the zonal-mean jet are always to the north of the anticyclones' trajectories.

Naturally, the composites of the zonal-mean zonal wind during the positive/ negative phases of the jet-shifting LFV are characterized by the northward/ southward shifts of the jet latitude relative to the jet’s climatological position, respectively, as well as by an intensification of the jet. The JS+ and JS– composites of the cyclone and anticyclone tracks reveal that: (i) the storm track shifts in latitude along with the jet; (ii) the lifetimes of shifted eddies exceed climatological eddy lifetime indicating enhanced persistence of the jet shifts, while other eddy-track characteristics such as mean radius or maximum intensity do not change much (not shown here) ; and (iii) while the all-track composites of cyclone and anticyclone trajectories are symmetric about the composite jet position, their JS+ and JS– composites are not. For example, in the JS+ state, the cyclone tracks to the north of the shifted jet are more zonally elongated, while the anticyclones southward of the shifted jet become stationary and curve to the south at the end of their lifecycle. The JS– tracks show the opposite tendencies. These are indications of a barotropic feedback between eddies and the jet, which enhances persistence of the shifted jet states.

Definitions of zonal-jet and storm-track latitude time series

- Zonal jet position proxy — leading principal component of the zonal-mean zonal wind

- Storm-track latitude proxy:

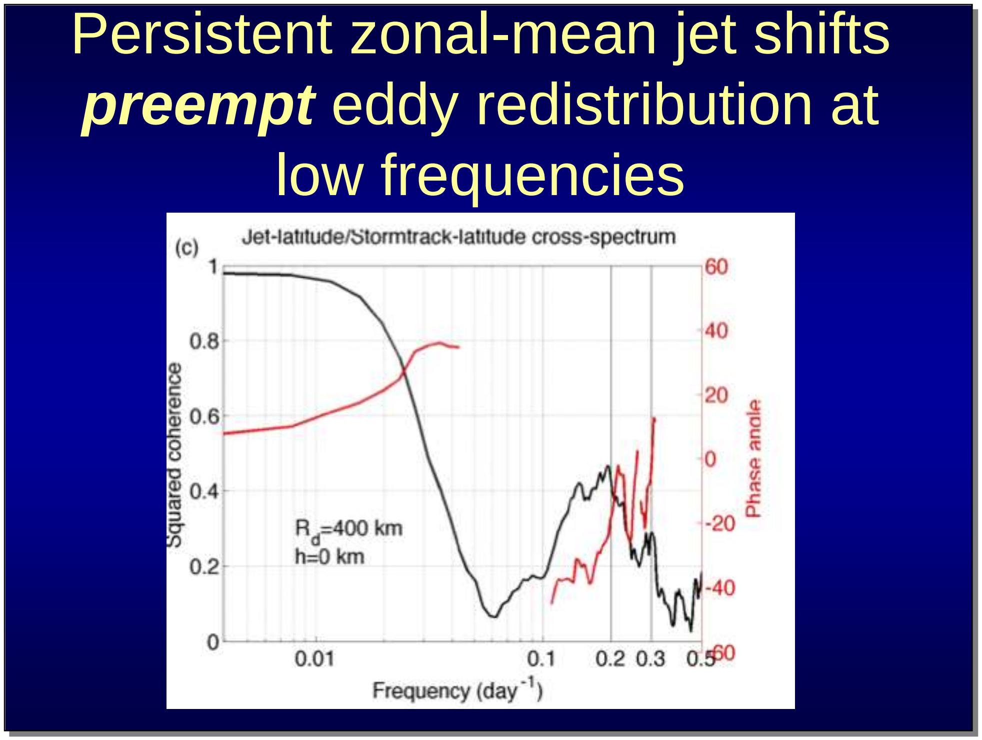
for each time, compute

(1) average latitude of all cyclones present, then

(2) average latitude of all anticyclones

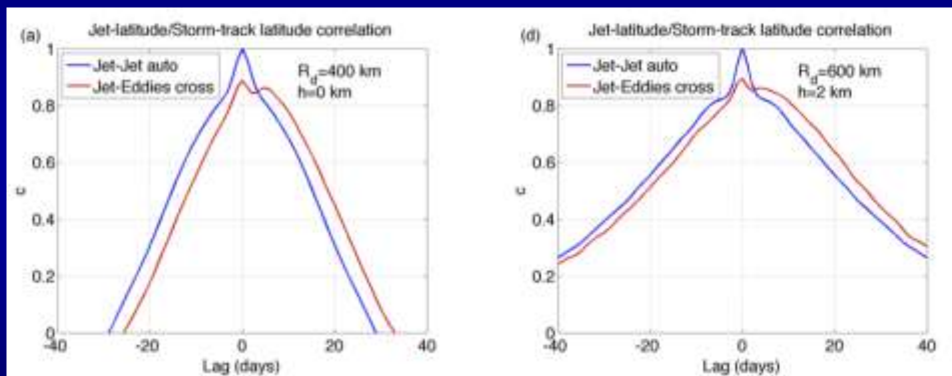
(3) take the average of (1) and (2)

Our results thus far showed that the low-frequency variability in the model has to do with that of the eddy trajectories. To study, statistically, details of interaction between the eddy tracks and zonal-mean jet shifts, we defined two time series. The first time series was simply the leading principal component of the zonal-mean zonal wind; it represented the jet-shifting variability in the model. The second time series was the proxy for the storm-track position. It was computed as the average among the latitudes of all cyclones/anticyclones present in the model domain at a given time.

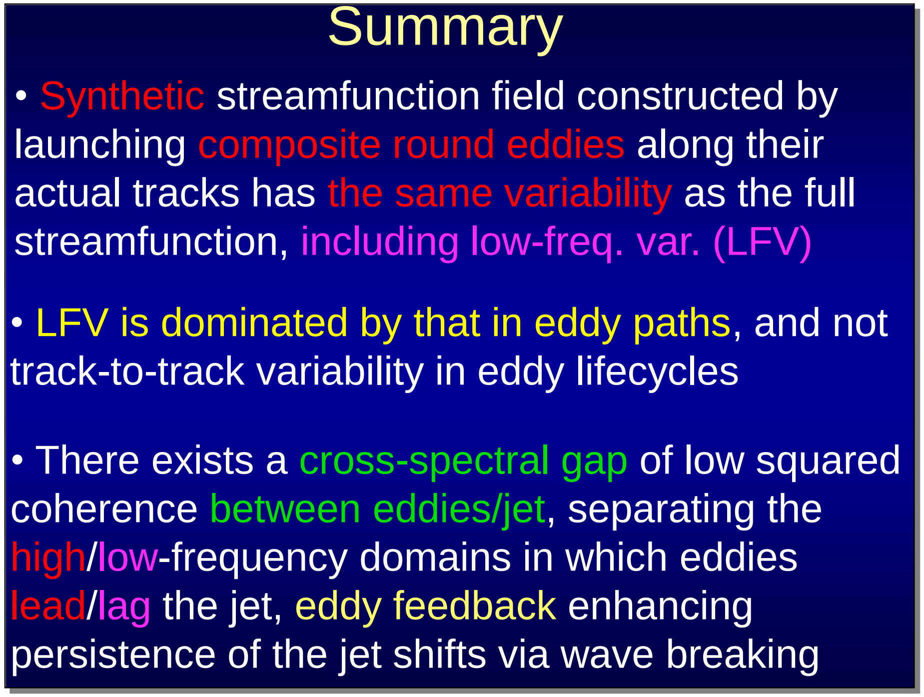


The next slide shows some cross-spectral characteristics of these two time series. In particular, black line and numbers listed on the left vertical axis denote the squared coherence, while the red line and numbers listed on the right vertical axis refer to the phase angle between these time series, with positive lags corresponding to eddies leading the jet; both characteristics are functions of frequency, as shown on the horizontal axis. The most striking property of this graph is that the zonal-mean jet leads the eddies at low frequencies on the left end of the spectrum, where the eddies and the jet are also very well correlated. This lead–lag relationship between the eddies and the jet is opposite of that at high frequencies, where the changes in the latitude of eddies lead the zonal-mean jet shifts, and the squared coherence values are moderate. At the intermediate frequency range, the coherence between the eddies and the jet is low, and the phase angle between the two time series is not well defined.

Zonal-jet position can predict stormtrack latitude at a later time



These results can be restated in terms of the eddies/jet predictability by computing the cross-correlation function between the zonal-wind and storm-track time series. It shows that the storm-track latitude can be better predicted in the medium-to-long time range using the zonal-mean jet latitude information, than the jet latitude using the storm-track latitude as a predictor.



The central result of this study is that the synthetic synoptic eddy field constructed by launching the composite-mean round cyclones and anticyclones along their actual simulated tracks in the model has the same time mean and very similar leading modes of variability compared to the full streamfunction field. Thus, the distribution of synoptic eddies carries a lot of information not only about the propagating high-frequency modes, but also about the LFV, which is dominated by that in the eddy paths.

However, kinematic dominance of eddy field is only a part of the complete story. Our second important result is the finding of a “cross-spectral” gap of low squared coherence between eddies and the jet separating the high/low frequency domains in which the eddies lead/lag the jet. This result demonstrates that the LFV dominated by the zonal-mean jet shifts is dynamically more involved than simply reflecting an artifact of averaging over random low-frequency changes in the distribution of the synoptic systems.

Select references

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I would like to conclude my presentation by putting up a few important references that are relevant to various parts of this talk and provide further information about the topics considered here.