Oceanic Vortex Pulsars

Pavel Berloff

Department of Mathematics, Imperial College London, UK

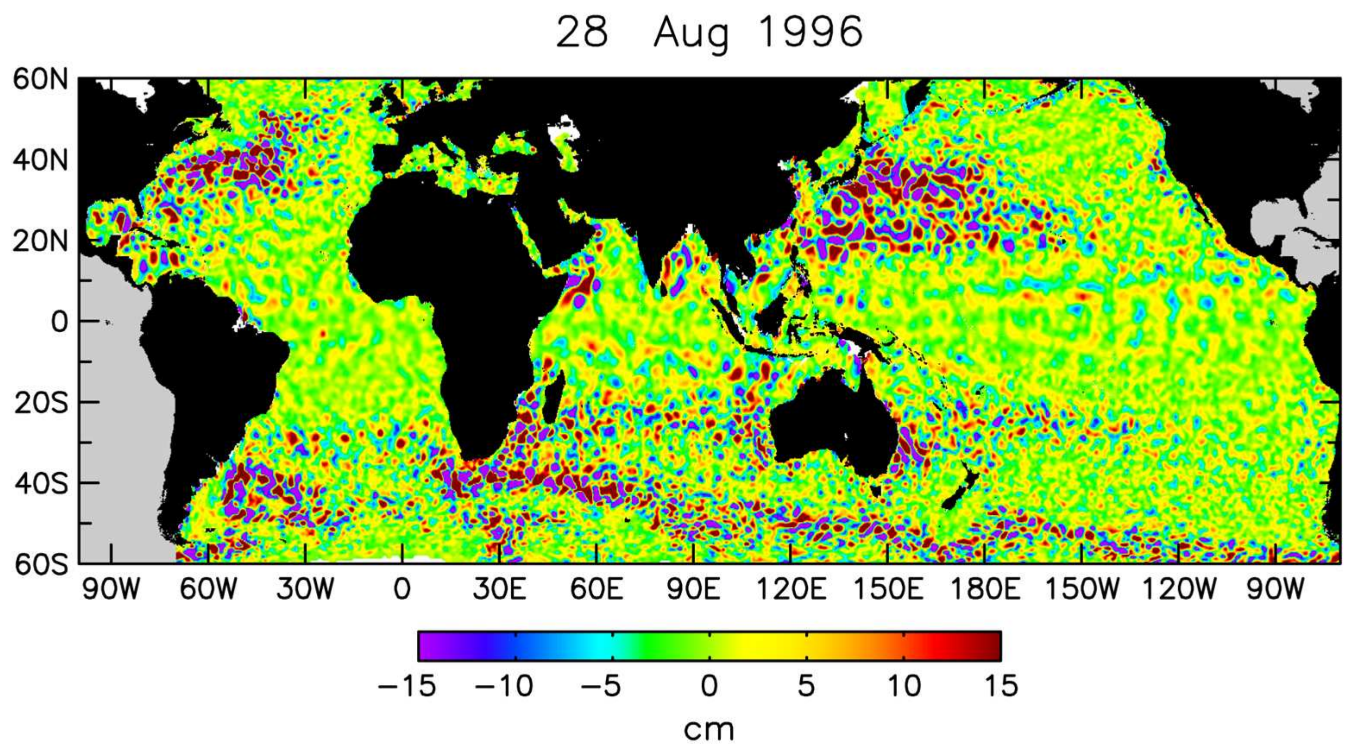
Georgi G. Sutyrin

University of Rhodes Island, Graduate School of Oceanography, USA

Results are published (Physica D – Nonlinear Processes).

Mesoscale Oceanic Eddies

Snapshot of the observed sea-surface height anomalies shows eddies all over the ocean

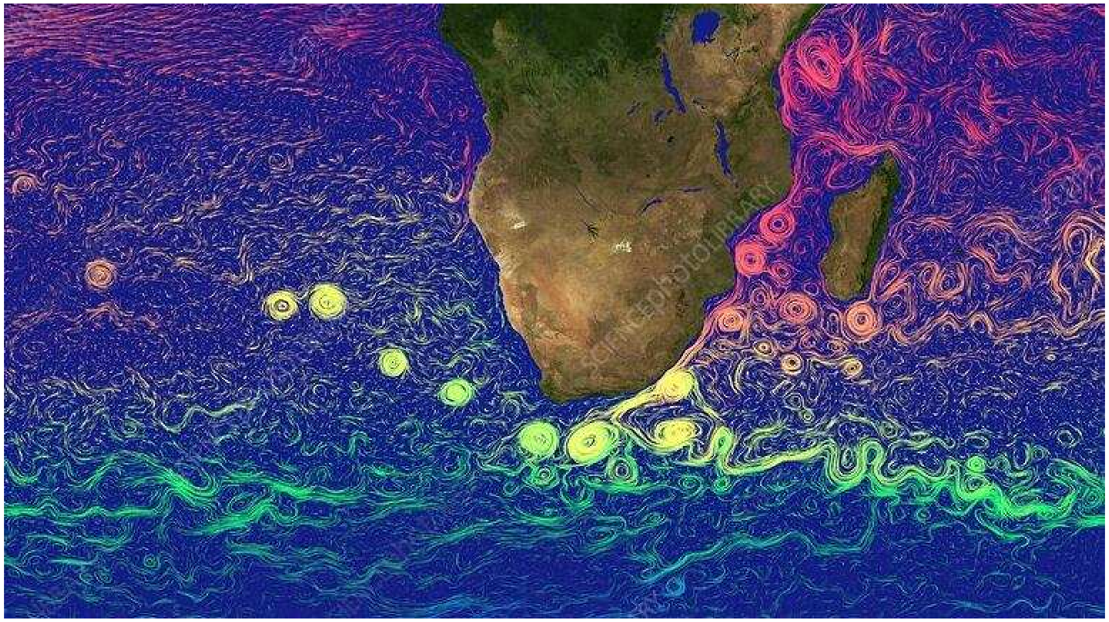


• Mesoscale eddies have important effects on the large-scale ocean circulation. Ocean circulation models must account for these effects either *directly* (i.e., by brute-force computing) or *indirectly* (i.e., by eddy parameterizations).

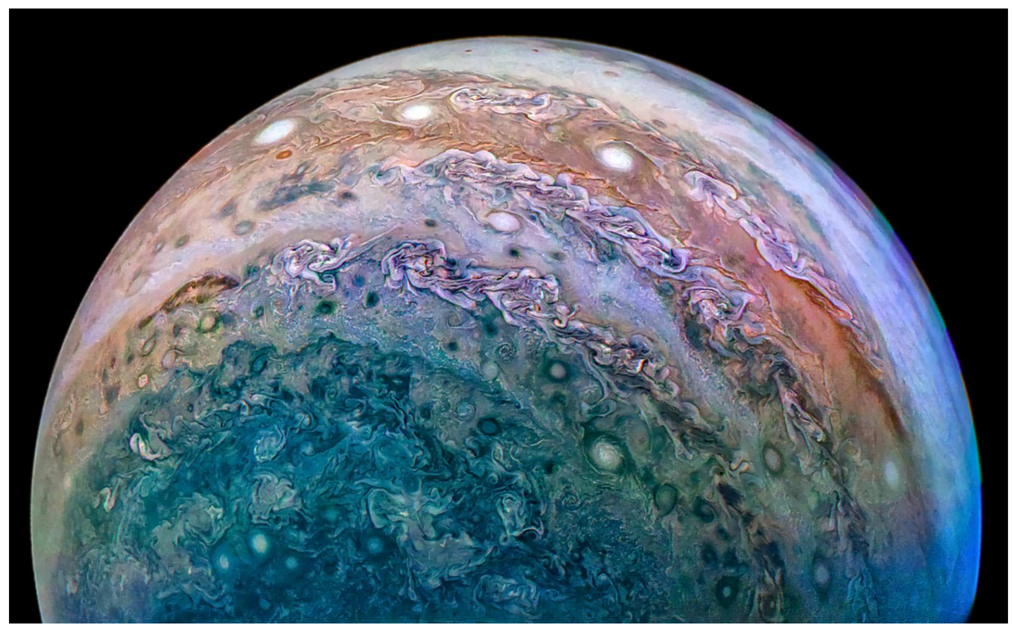
• Some of the mesoscale eddies are *isolated coherent vortices*, which intrigued and challenged theoreticians for a long time (e.g., McWilliams 1984).

• Isolated coherent vortices are *long-lived*, induce *long-range material transport* and *affect ambient circulation* (i.e., large-scale currents, turbulence and waves).

Isolated Coherent Vortices: Illustrations

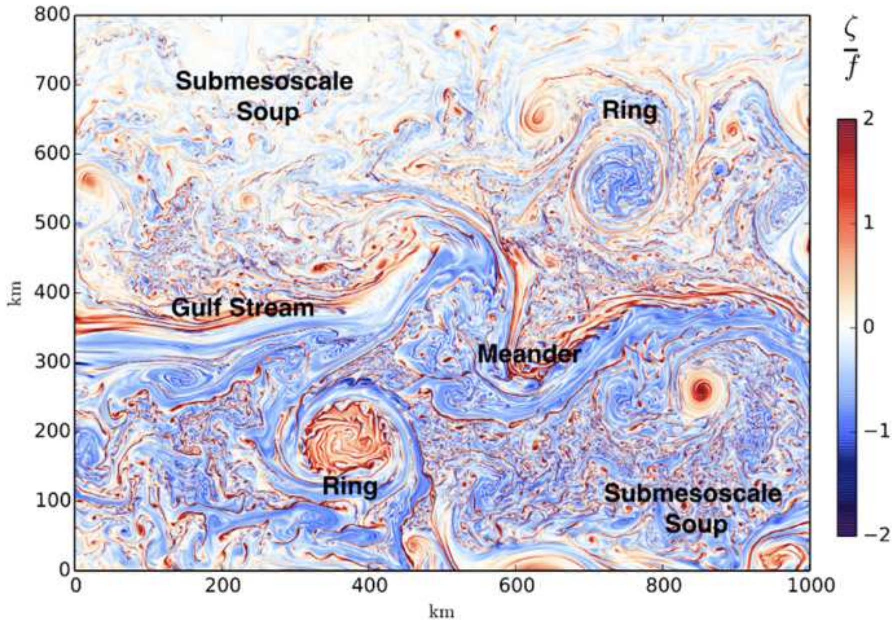


Retroflection of the Agulhas current sheds out powerful anticyclones propagating over years across the Atlantic.



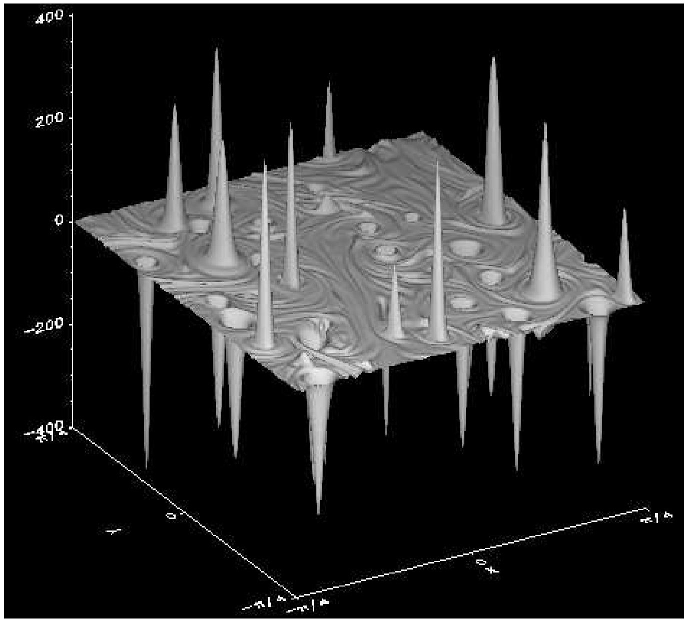
Intense and long-lived Jovian vortices tend to inhabit bands with westward zonal flows.

Isolated Coherent Vortices: Illustrations



High-resolution models uncover complex internal structure of the Gulf Stream rings, which are classical examples of coherent vortices, and also uncover complexity of the surrounding oceanic turbulence.

Idealized simulations of quasi-2D turbulence regimes show robust emergence of coherent vortices, but their characteristics depend on the dynamical details and history of evolution.



What Are Vortex Pulsars?

We coined term *"vortex pulsars"* to attract attention to a *new class of long-lived vortices with the following "unusual" characteristics*:

- **Nonstationary**: both regularly pulsating and time-varying with broad-band temporal characteristics; controlled by waves and unstable modes;

- **Asymmetric**: not circular, with no mirror or angle symmetries, no vertical alignment;

- **NON-ISOLATED**: being an open system, actively interacting with environment, grazing on external energy and potential vorticity (PV);

- *Propagating*: both self-driven and steered by environment;

- *Long-lived*.

All real-world vortices are like this, but so far theoretical attention has been focused on oversimplified long-lived vortices — **time to change this paradigm**.

Crash Course on Geophysical Vortices

• *Simple elementary vortices.* Canonical vortex contains all its relative vorticity in a compact and rapidly rotating core, which is surrounded by decaying far-field velocity, obtained from the vorticity core via elliptic inversion (e.g., point vortices, vortex modon, Larichev-Reznik dipole).

• *Coherency.* The 2D Fourier spectrum of a vortex has non-random phases controlled by the nonlinearity; significant vertical alignment.

• *Shapes.* Not necessarily circular (e.g., elliptic deformations); baroclinic dipolar (hetonic) vertical structure; vertical tilt; transient features due to vortex-vortex interactions.

• *Propagation.* Vortices can self-propagate due to some dipolar moment present (e.g., Larichev-Reznik dipole) or due to the beta-effect.

• *Material Isolation.* Vortex cores may be significantly isolated from the ambient fluid, which is opposite to being involved in fluid exchange (e.g., Lagrangian coherent structures).

• *Long life.* The Great Red Spot on Jupiter is large anticyclone observed for 360 years; strong oceanic vortices may survive for years (especially in westward flows).

• *Vortex generation mechanisms.* Instabilities of large-scale currents; forward enstrophy cascade; local heating/cooling; outflow mechanism.

• *Vortex termination mechanisms.* Various instabilities, vorticity leakage, wave radiation, dissipative processes, shearing by large-scale flows, boundary effects.

• *Vortex-vortex interactions.* Vortex merger and splitting; resulting transient changes of vortex shapes and contents.

Ongoing Research Agenda on Coherent Vortices

• *Taxonomy and empirical detection?*
Need for more observations (especially in the deep ocean and of noisy properties, such as vorticity). Vortex definitions, detection, tracking, and asymmetries.

• *Generating mechanisms?*
Various ocean circulation instabilities (e.g., Gulf Stream and Agulhas rings; mid-ocean eddies); boundary effects; vortex splitting.

• *Maintaining mechanisms?*
Supply of energy and enstrophy from background flow; vortex merger; redistribution of angular momentum.

• *Damping mechanisms?*
Submesoscale turbulence; inertia-gravity wave radiation; boundary effects; ocean-atmosphere interactions.

• *Transport properties?*
Long-range advective transport of heat, vorticity, tracers; Lagrangian analyses; effect on clustering of buoyant tracers; biological effects.

• *Eddy parameterizations?*
Diffusive and nondiffusive effects; anisotropic and antidiffusive effects; search for local, nonlocal and data-driven closures.

On the level of intermediate-complexity dynamical models, the *goal of this study* is to find robust *long-lived vortices, not constrained by symmetries and stationarity*.

Quasigeostrophic (QG) Potential Vorticity (PV) Model

- Square doubly-periodic basin 1500×1500 km; flat bottom; β-plane; stacked isopycnal layers; highly nonlinear solutions; fine grid resolution (3 km); 25 km baroclinic Rossby radius.

- *Governing equations* describe QG PV dynamics:

$$\frac{\partial q_1}{\partial t} + J(\psi_1, q_1) = \nu \nabla^4 \psi_1 \,, \qquad \frac{\partial q_2}{\partial t} + J(\psi_2, q_2) = \nu \nabla^4 \psi_2 - \gamma \nabla^2 \psi_2$$

- *PV inversion* diagnostically connects PV q, PV anomaly ζ, and streamfunction ψ :

$$q_1 = \nabla^2 \psi_1 + S_1 (\psi_2 - \psi_1) + \beta y = \zeta_1 + \beta y \,, \qquad q_2 = \nabla^2 \psi_2 + S_2 (\psi_1 - \psi_2) + \beta y = \zeta_2 + \beta y \,.$$

- *Forcing* is provided by fixed, vertically sheared, zonal, *unstable* background flow:

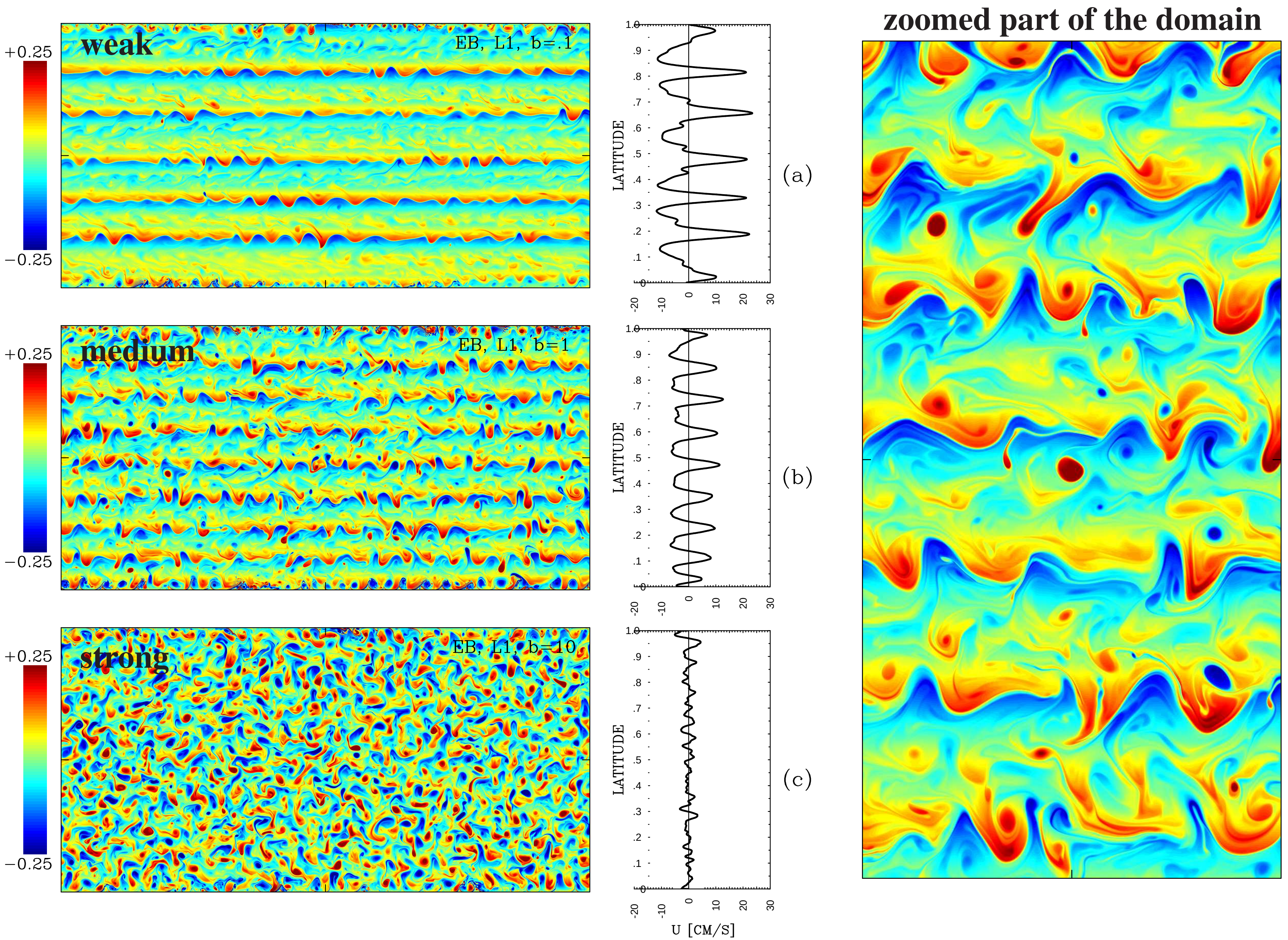
$$\psi_i \longrightarrow -U_i \, y + \psi_i \,,$$

then, the dynamics is:

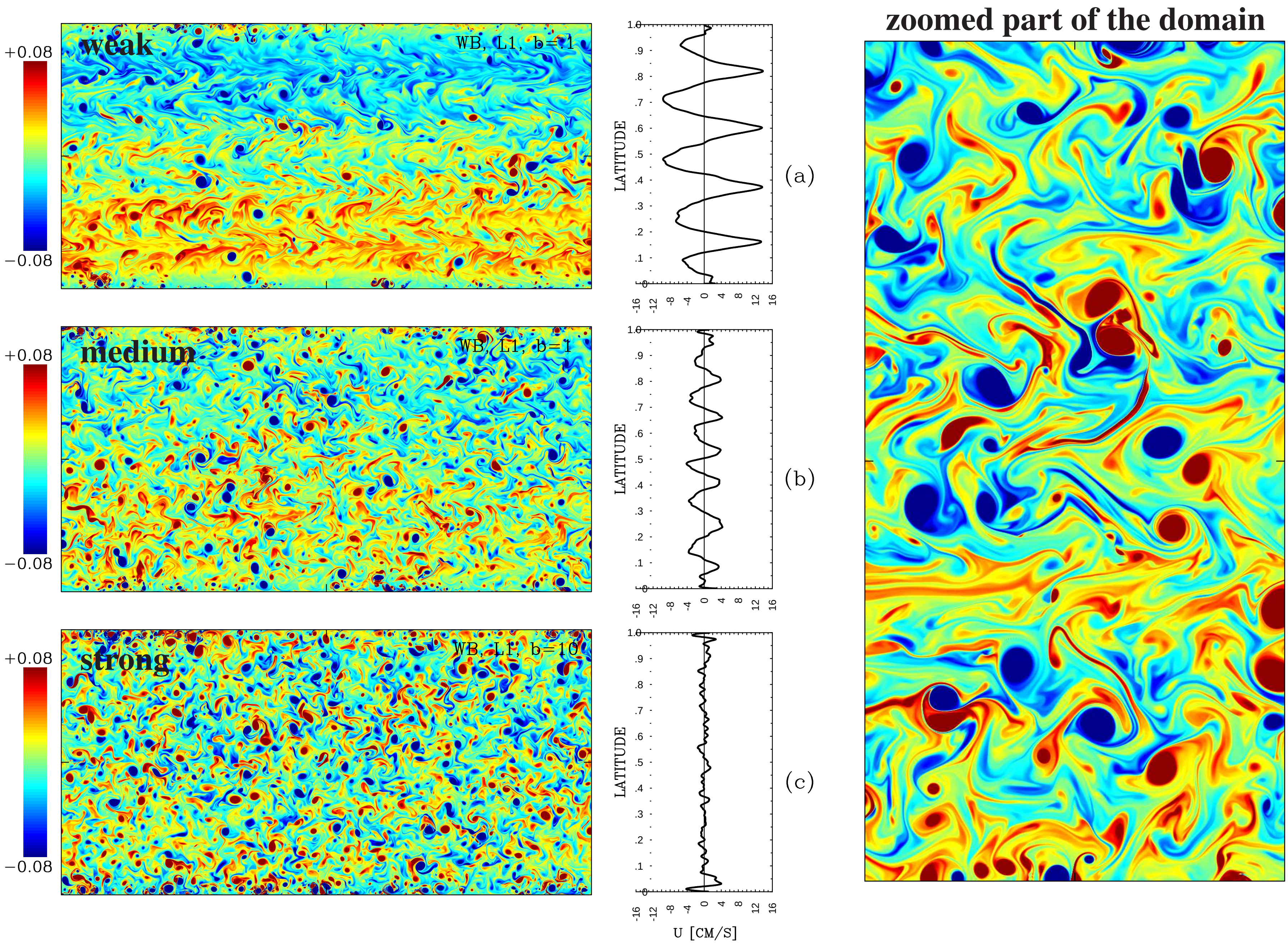
$$\begin{aligned}
\frac{\partial \zeta_1}{\partial t} + J(\psi_1, \zeta_1) + (\beta + S_1 U_1 - S_1 U_2) \frac{\partial \psi_1}{\partial x} + U_1 \frac{\partial \zeta_1}{\partial x} &= \nu \nabla^4 \psi_1 - \kappa \, \zeta_1 \,, \\
\frac{\partial \zeta_2}{\partial t} + J(\psi_2, \zeta_2) + (\beta - S_2 U_1 + S_2 U_2) \frac{\partial \psi_2}{\partial x} + U_2 \frac{\partial \zeta_2}{\partial x} &= \nu \nabla^4 \psi_2 - \gamma \nabla^2 \psi_2 - \kappa \, \zeta_2 \,.
\end{aligned}$$

- Red terms provide optional peripheral damping.

Model solutions for *eastward background flow* and for weak, medium and strong values of the bottom friction (snapshots of the upper-layer PV anomalies).



Model solutions for *westward background flow* and for weak, medium and strong values of the bottom friction (snapshots of the upper-layer PV anomalies).



Vortex Pulsar Solutions and Analyses

[1] Start model integrations from different initial conditions, in order to obtain *multiple solutions* belonging to different basins of attractions. Check out numerical convergence.

[2] Integrate the model from some initial condition until its solution reaches some *statistical equilibrium*.

[3] Change slightly *parameters* U_1, ν, γ (and κ if needed) and compute new solution.

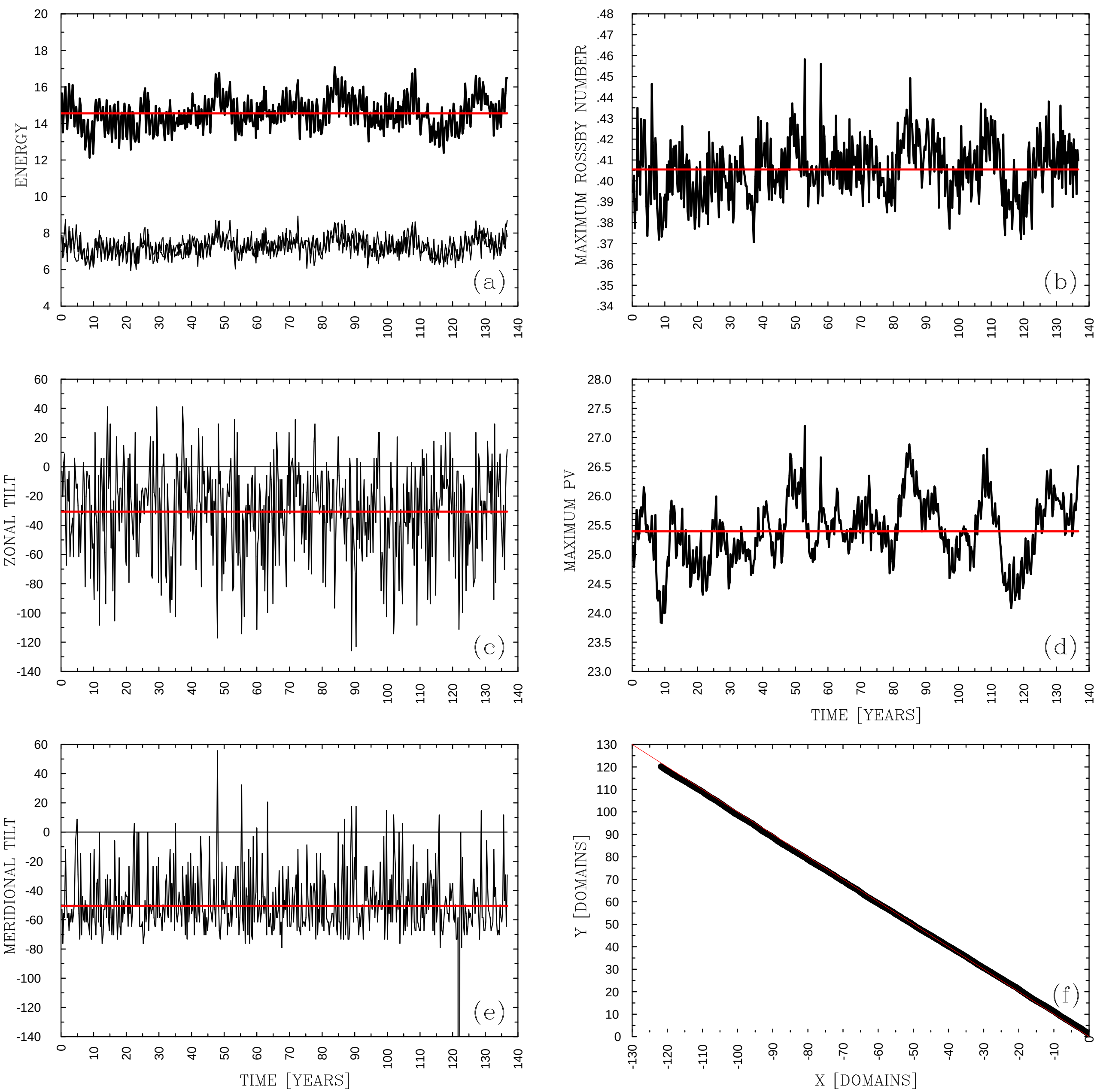
[4] Analyse *vortex propagation*, which is quasi-steady and north-westward (for upper-ocean cyclones), and obtain trajectory and drift velocity (speed and angle).

[5] Analyse *vortex characteristics* in the coordinate system co-moving with mean velocity of the vortex center: extract various time series, time-mean and fluctuation fields, vertical tilt, dynamical balances and energetics.

[6] Interpret the obtained results and draw conclusions.

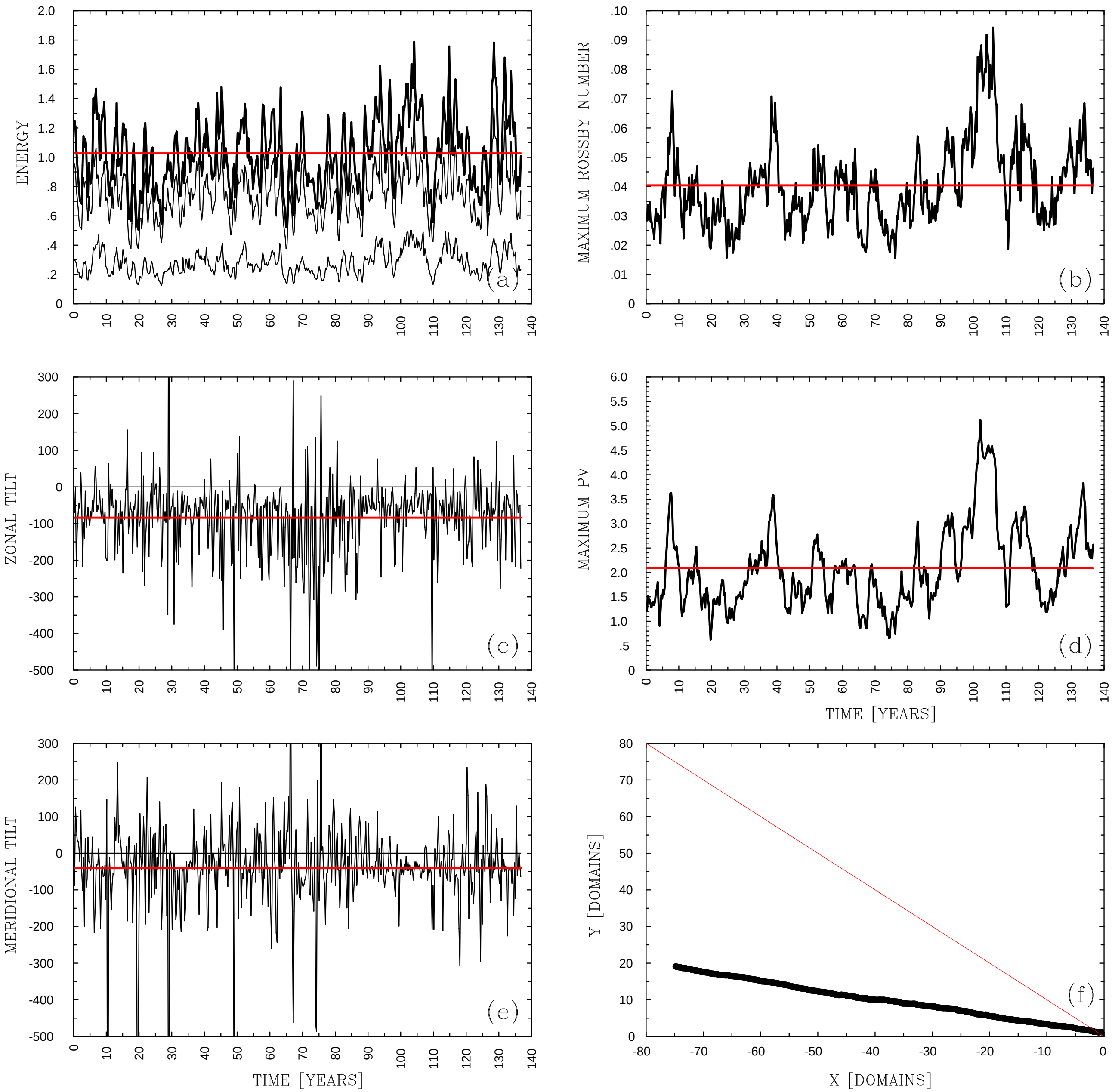
Typical time series have the following characteristics...

Time series: "strong" solution



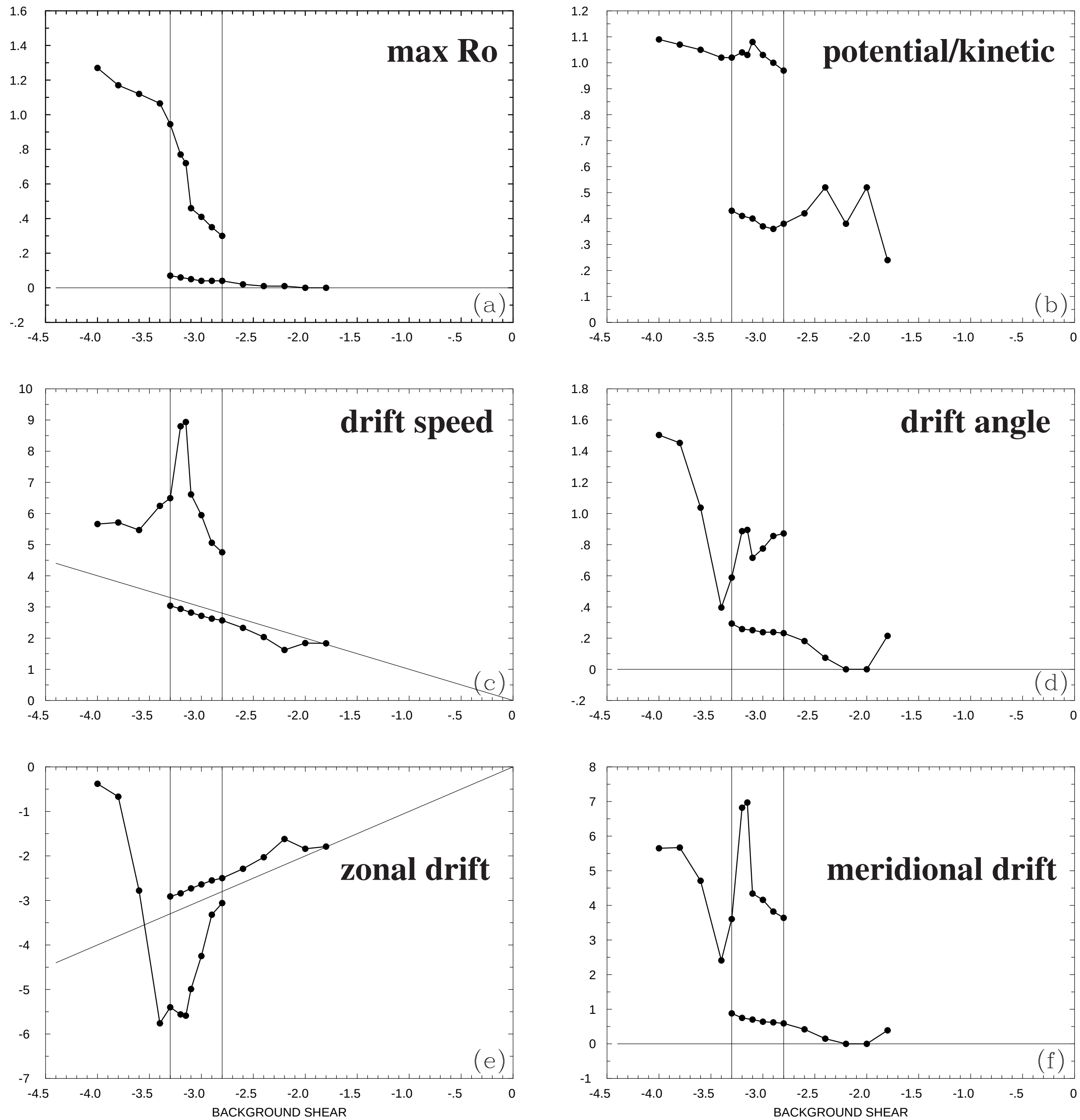
- Relatively small fluctuations
- Relatively large Rossby number
- Relatively small tilt in vertical, consistent with dipolar propagation
- Relatively small PV oscillations in the core
- Nearly straight and fast north-westward drift at a steep angle.

Time series: “weak” solution



Characteristics of the other vortex solution are shown for comparison...

Distinct Branches of Strong and Weak Pulsars

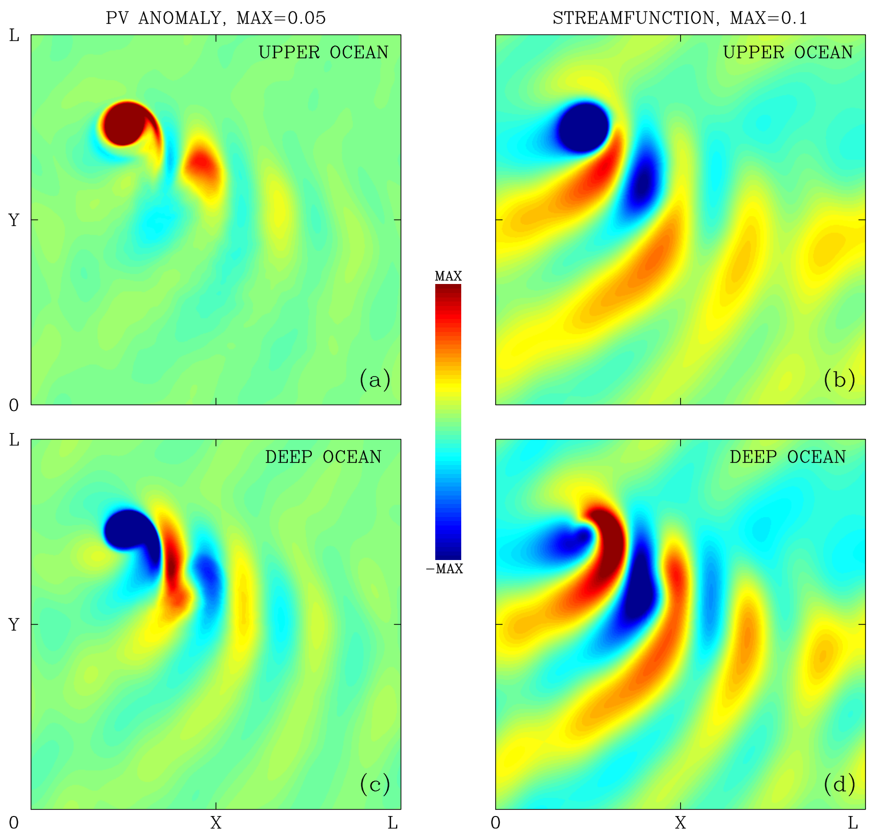


- *Strong pulsars* are:
  [1] very intense,
  [2] thermally capacious,
  [3] fast drifting,
  [4] with steep angle,
  [5] moderately tilted,
  [6] depth compensated.

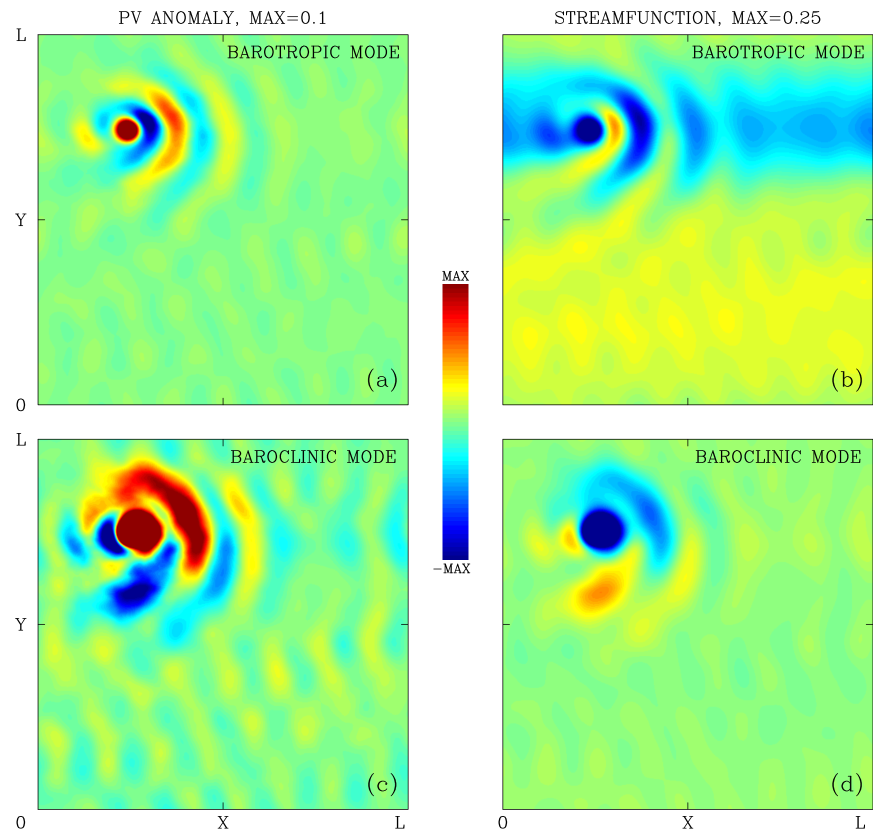
- *Weak pulsars* are:
  [1] moderately intense,
  [2] slow drifting,
  [3] with small angle,
  [4] very tilted,
  [5] very nonstationary.

- Pulsars are *open systems* that feed on background energy and shed off excess PV.

Time-Mean Strong Pulsar (layer-wise)



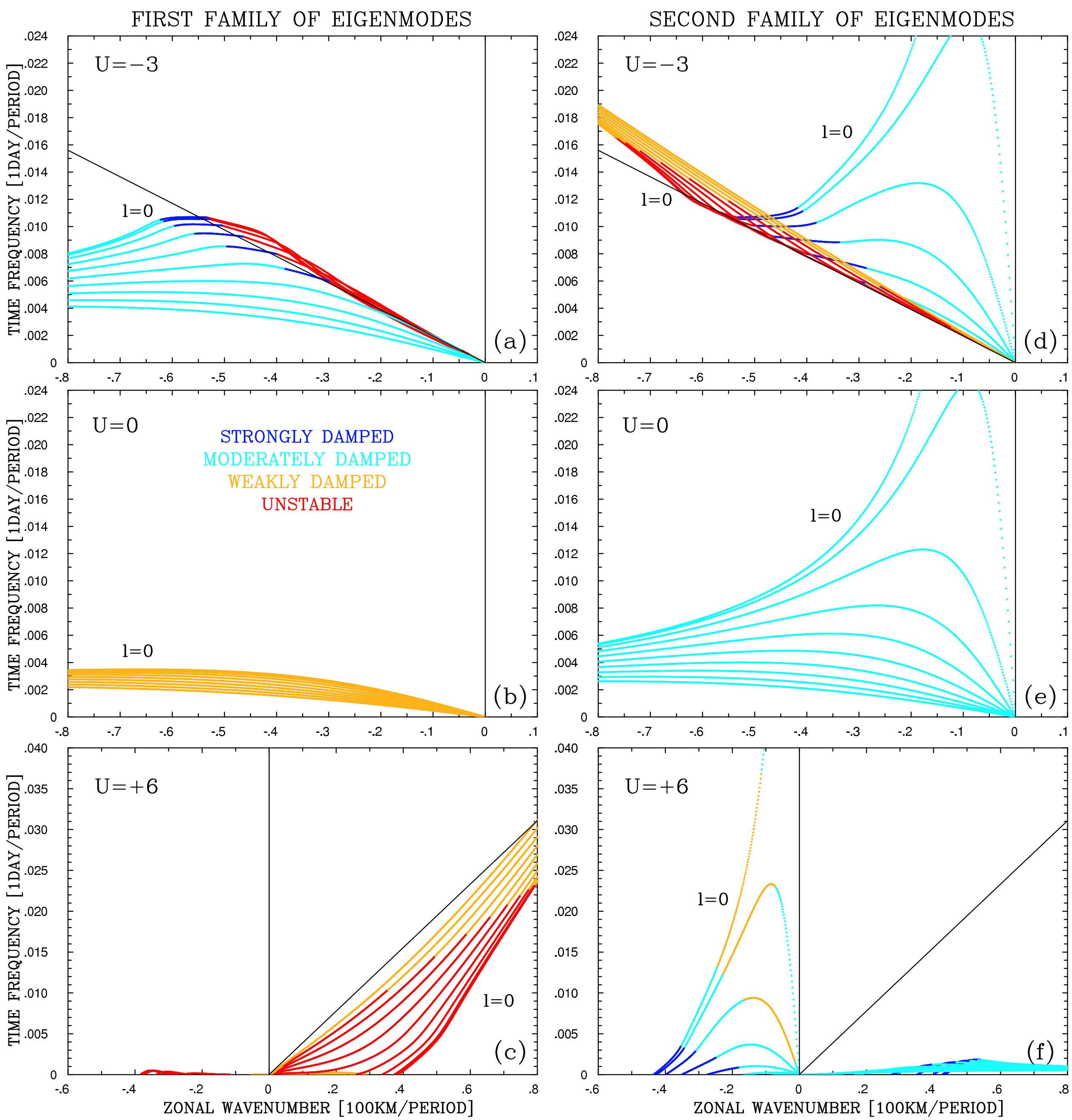
Time-Mean Weak Pulsar (mode-wise)



- Pulsars are *asymmetric* — this is needed to extract available (potential) energy.
- Pulsars are *nonstationary* — this is needed to shed off excess PV.
- Strong pulsar consists of *strongly nonlinear circular core* and *weak wavy wake*.
- Weak pulsar can be viewed as a *weakly nonlinear Rossby waves packet*.

$$J(\overline{\psi_1}, \overline{q_1}) \quad - c_x \frac{\partial \overline{q_1}}{\partial x} - c_y \frac{\partial \overline{q_1}}{\partial y} \quad + \overline{J(\psi_1', q_1')} \quad + \frac{\partial \overline{\psi_1}}{\partial x}[\beta + S_1 U_1] + U_1 \frac{\partial \overline{q_1}}{\partial x} = \nu \nabla^4 \overline{\psi_1}$$

Two-Layer Homogeneous Normal Modes



Color: growth rates

- Background flow couples barotropic and baroclinic components of the normal modes.
- Large effect of even weak $\sim 1\, cm/s$ background flows.
- Nearly non-dispersive tongue of normal modes.

Summary of Results

We considered an idealized QG model with background, spatially homogeneous and vertically sheared westward flows, and found statistically equilibrated, coherent vortex pulsars.

• *Two distinct families of pulsars* were found.

• Pulsars are fundamentally *non-isolated coherent vortices*, because they extract energy from the background circulation and expel excess PV (due to material down-gradient propagation) back into the environment.

• Pulsars can be interpreted in terms of forward both energy and enstrophy cascades.

• Pulsars are persistent, robust and can be perpetual.

• Pulsars steadily drift, due to their dipolar moments, along nearly straight trajectories.

• Pulsars are fundamentally asymmetric and nonstationary.

• Pulsars can be viewed as specific baroclinic dipoles.

Future Research Avenues

- Interpretation of observational data from the perspective of propagating pulsars.
- Pulsars on inhomogeneous background flows (and involved mutual feedbacks).
- Lagrangian analysis of the PV ventilation process in pulsars.
- Interpretation of pulsars in terms of the Rossby waves (i.e., linear normal modes) packets.
- Vortex-vortex interactions within pulsar vortex gases.
- Obtaining pulsars with the full hydrostatic Boussinesq approximation.