


Internal transport barriers in fluids and plasmas

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ABSTRACT

Turbulent flow in neutral fluids and fusion plasmas is known to have many commonalities, one example being the application of energy and enstrophy cascades. In this review, we discuss a cyclic process which may also be common to both fluids and plasmas: this includes exact coherent states (or magnetic islands), Reynolds stress-driven (zonal) flows and internal interface layers (or internal transport barriers). We connect this picture to the broader literature on layered “staircase” states in both magnetized plasmas and stratified/rotating fluids, where sharp interfaces separate well-mixed regions. We briefly review the current understanding of internal interface layers in fluids, summarize a minimal set of driving/damping relations for mean flows and transport suppression, and discuss open questions and possible research directions. The main objective is to create awareness of shared mechanisms to motivate further interdisciplinary research in this field, by both the fluid mechanics and plasma physics communities.

Abbreviations

See [Table 1](#).

1. Introduction

Thirty years ago, in 1995, two discoveries were published; one for (neutral) fluids, the other for (fusion) plasmas: In fluids, the existence of uniform momentum zones (UMZs) was presented [1] and in plasmas, internal transport barriers (ITBs) were observed [2,3]¹. These seemingly independent findings were not linked at the time, but evidence is mounting [4] that they may be manifestations of a common mechanism.

What has been compared in Ref. [4] is wall-bounded fluids in straight pipes and magnetically-bounded plasmas in tori. Although they appear very different, e.g. geometry (curvature) and boundary conditions (solid walls or magnetic fields), we have proposed a common cyclic process (CCP) consisting of these elements:

- Exact coherent states (ECS)/magnetic islands (MIs) \implies
 - Reynolds stress (RS)-driven (zonal) flows \implies
 - Internal interface layers (IILs)/internal transport barriers (ITBs)
- \implies

Here, the arrows indicate transitions to the next element. A schematic summary of this conjectured cycle is shown in [Fig. 1](#).

In this review we distinguish between the existence of the CCP ingredients (well established in both communities) and evidence for

Table 1

Alphabetical list of abbreviations used in this review.

Abbreviation	Meaning
CCP	Common cyclic process
DNS	Direct numerical simulation
ECS	Exact coherent state
GAM	Geodesic acoustic mode
IIL	Internal interface layer
ITB	Internal transport barrier
LBL	Laminar boundary layer
MI	Magnetic island
NSE	Navier–Stokes equations
PV	Potential vorticity
QG	Quasi-geostrophic
RPO	Relative periodic orbit
RS	Reynolds stress
SSP	Self-sustaining process
TB	Transport barrier
TBL	Turbulent boundary layer
TF	Thermal fissure
TNTI	Turbulent/non-turbulent interface
TW	Travelling wave
UCZ	Uniform concentration zone
UMZ	Uniform momentum zone
UTZ	Uniform thermal (temperature) zone
VF	Vortical fissure
ZF	Zonal flow

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¹ The UMZ paper was published in April 1995, the ITB papers in December 1995.

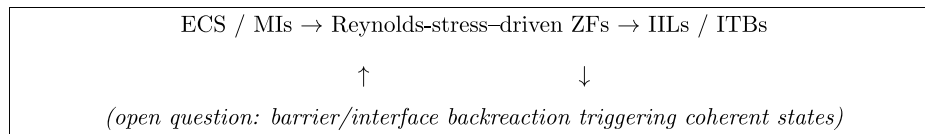


Fig. 1. Schematic of the conjectured common cyclic process (CCP). The first two links are supported by stress-driven mean-flow generation and transport-suppression diagnostics (Section 3), whereas closing the loop via IIL/ITB \rightarrow ECS/MI remains an open problem highlighted in Section 4 and Section 5.

causal directionality between them, which varies by system; the least constrained link remains the backreaction from barriers/interfaces to coherent states (IIL/ITB \Rightarrow ECS/MI).

This process is thought to be both self-regulating and self-sustaining; it is inspired by e.g. the self-sustaining process (SSP) [5] which consists of rolls, streaks and waves. While the title emphasizes IILs/ITBs, we use them as an entry point to a broader cyclic picture involving coherent states and zonal flows; this wider framing helps connect the fluid and plasma literatures within a single review narrative.

The research that lies ahead is to understand the process in more detail, both by approaching it from a fluid and a plasma perspective. Initially, it does appear that neither curvature or electromagnetic effects are needed. However, both characteristics – and likely others – may work to enhance or suppress the mechanism.

We assume that the reader is familiar with fusion plasma physics concepts such as magnetic field properties [6], $E \times B$ flow shear decorrelation [7] and zonal flows (ZFs) [8,9]. Recent work highlights that zonal jets and internal interfaces are ubiquitous in rotating and/or stratified fluids, where background potential vorticity (PV) gradients can be set by planetary rotation (the β effect, where f is the Coriolis parameter, y is the northward/meridional coordinate, and ∂_y denotes differentiation with respect to y , so $\beta \equiv \partial_y f$) and/or by topography (a topographic β effect). These systems can self-organize into PV staircases (PV ladders), i.e. mixed regions separated by sharp PV gradients collocated with jets, providing a natural analogue of $E \times B$ /pressure staircases and micro-barriers in plasmas [10–18].

Our review is organized as follows: A mini-review on IILs in fluids is contained in Section 2. In Section 3 we summarize a minimal theoretical framework for mean flow generation, PV/jet organization and transport suppression used as a lens for the subsequent discussion. Knowledge gaps are identified and discussed in Section 4. We make the case for possible research program areas in Section 5 and finally conclude in Section 6.

2. A mini-review on internal interface layers in fluids

We present a condensed version of material in Ref. [4]; additional references can be found in the cited paper. The phenomena are introduced in chronological order, spanning the years 1955–2021.

The scope is IILs, excluding laminar/turbulent boundary layers (LBL/TBL) associated with solid walls [19].

The first identification of an IIL in fluids, in 1955, is the turbulent/non-turbulent interface (TNTI) which is the interface between a TBL and a non-turbulent free-streaming flow [20]. The interfacial layer has a complex structure and acts as a bidirectional transport barrier (TB) between turbulent (rotational) and non-turbulent (irrotational) regions. A high-shear region (velocity jump) exists at the TNTI which is also associated with intense vorticity.

Forty years later, in 1995, UMZs were discovered, consisting of regions of almost constant streamwise momentum separated by thin viscous-inertial shear layers [1]. The layer was interpreted as a collection of vortices as opposed to the interpretation of the TNTI as being a continuous vortex sheet. In 2014, a large UMZ has been found in the core of channel flows, extending to 40%–45% of the channel [21]. This large UMZ has been named the “quiescent core”, since it is only weakly turbulent.

Uniform thermal (or temperature) zones, UTZ, were first introduced in 2019; they consist of relatively constant temperature regions separated by thermal interface layers [22].

Both UMZs and UTZs have IILs which are related to velocity (momentum) and temperature (heat), respectively. They have been modelled both individually and combined as uniform zones separated by vortical and thermal fissures (VFs/TFs). When both types coexist, the IILs have been found to be at similar but not identical locations.

The final type of IIL in fluids is uniform concentration zones (UCZs), first defined in 2021 [23]. The mechanism of uniform zone separation for concentration is not understood, but it has similarities with ramp-cliff structures seen in turbulent mixing [24], which may also be related to sawtooth crashes in fusion plasmas [25].

Thus, we conclude that IILs in fluids which separate uniform zones of momentum, heat and concentration have strong similarities with ITBs in plasmas.

3. Minimal theoretical framework for zonal flow–barrier feedback

To make the discussion self-contained, we summarize a minimal set of governing relations that (i) show how turbulence drives (zonal) mean flows and how these are damped, and (ii) connect mean-flow shear to the suppression of cross-field (or cross-stream) transport. We give compact expressions in two commonly used formulations (Reynolds-averaged momentum and potential vorticity form) and indicate their equivalence. Eqs. (1)–(5) are written in schematic, reduced form; their origin and the reductions applied are documented in Appendix.

3.1. Mean (zonal) flow evolution: Reynolds stress drive and damping

For an incompressible fluid, decompose the velocity as $\mathbf{u} = \mathbf{U} + \mathbf{u}'$ where \mathbf{U} is a mean (or zonal) flow and primes denote fluctuations. Reynolds averaging the Navier–Stokes equations yields, schematically, [26]

$$\partial_t U = -\partial_y \langle u'v' \rangle - rU + \nu \partial_{yy} U + F_{\text{body}} \quad (1)$$

Here, ∂_t denotes the partial derivative in time. $U \equiv U(y, t)$ denotes the mean (zonal) velocity component, while u' and v' are the corresponding fluctuations in the mean flow and cross-stream directions. Angle brackets $\langle \cdot \rangle$ denote an average over time and/or homogeneous directions, and primes denote fluctuations about the mean. The quantity $\langle u'v' \rangle$ is the Reynolds stress, r is a linear drag coefficient (e.g. Ekman/wall friction), ν is the kinematic viscosity, ∂_{yy} denotes the second derivative in y , and F_{body} represents imposed body forcing or other mean forcing.

Rectification. The generation of a mean/zonal flow by turbulent fluctuations through nonzero correlations (e.g. $\langle u'v' \rangle$) is often termed *rectification*: nonlinear interactions among fluctuating modes produce a systematic mean tendency when averaged, converting part of the turbulent momentum transport into a coherent mean shear [27].

A closely related balance is used for zonal $E \times B$ flows in magnetized plasmas, [7,8]

$$\partial_r V_{E \times B} = -\partial_r \langle \tilde{v}_r \tilde{v}_\theta \rangle - \mu V_{E \times B} + \dots \quad (2)$$

Here, ∂_r denotes differentiation with respect to the radial-like coordinate r . $V_{E \times B}(r, t)$ is the zonal $E \times B$ flow, tildes denote fluctuations, and \tilde{v}_r and \tilde{v}_θ are the fluctuating radial and azimuthal/poloidal velocity

Table 2

A compact mapping between commonly used fluid and plasma variables in the ZF/TB literature. The mapping is schematic and intended to aid cross-disciplinary reading.

Concept	Fluids	Plasmas
Mean/zonal flow	$U(y, t)$ (zonal mean velocity)	$V_{E \times B}(r, t)$ (zonal $E \times B$ flow)
Drive term	$-\partial_y \langle u'v' \rangle$ (RS divergence)	$-\partial_r \langle \tilde{v}_r \tilde{v}_\theta \rangle$ (RS divergence)
Damping	rU (Ekman/wall), $\nu \partial_{yy} U$	$\mu V_{E \times B}$ (neoclassical/GAM)
Affected quantities	Momentum, heat and concentration	Particles and heat
Transport barrier	IIL (UMZ, UTZ, UCZ)	ITB, micro-barriers (steps)
PV/invariants	PV q (incl. topographic PV)	Generalized vorticity/PV-like invariants
Staircase state	PV staircase/terracing	$E \times B$ (pressure) staircase

components. The coefficient μ is an effective linear damping, e.g. neoclassical and/or geodesic acoustic mode (GAM) related, and \dots indicates additional terms (geometry/metric factors, viscosity, external sources) omitted here for compactness.

A compact cross-disciplinary mapping of variables used in the entire Section 3 is given in Table 2.

3.2. Equivalent potential vorticity form and the role of topography/stratification

In rotationally constrained fluids it is often advantageous to work in quasi-geostrophic (QG) variables [10,11]. The barotropic potential vorticity may be written as

$$q = \nabla^2 \psi + \beta y + q_{\text{topo}}, \quad q_{\text{topo}} \propto \frac{f_0}{H} \eta(x, y) \quad (3)$$

Here, q is the (barotropic) quasi-geostrophic potential vorticity, ψ is the geostrophic streamfunction, and ∇^2 is the horizontal Laplacian. f_0 is a reference Coriolis parameter, H is a representative fluid depth, and $\eta(x, y)$ is the topographic height variation; q_{topo} denotes the corresponding (topographic) PV contribution. The proportionality reflects that the exact prefactor and sign convention depend on the chosen QG scaling, vertical coordinate, and definition of η .

Zonal averaging of the QG PV equation yields the mean evolution in flux form

$$\partial_t \bar{q} = -\partial_y \langle v'q' \rangle - r_q \bar{q} + \dots \quad (4)$$

Here, the overbar $\overline{(\cdot)}$ denotes a zonal mean (or mean over the homogeneous direction, typically x), and primes denote deviations from that mean. Thus v' and q' are the fluctuating meridional velocity and PV, respectively, and $\langle v'q' \rangle$ is the meridional eddy PV flux. The coefficient r_q is a compact representation of linear damping in the mean PV budget (e.g. via drag), and \dots denotes additional forcing/diffusion terms not written explicitly.

Sharp PV gradients can persist where mixing is weak, producing PV staircases (PV ladders) with jets collocated at the interfaces [13,14].

Topography can play a central role in shaping the “average” (zonal-mean) flow in rotationally constrained systems because it modifies the background PV gradient via a topographic PV contribution (often phrased as a topographic β effect). Importantly, recent QG turbulence studies show that topographic PV gradients are not dynamically interchangeable with planetary β : depending on slope orientation and drag, topography can preferentially energize (or hinder) large-scale along-slope jets and alter modewise energy transfers [15]. Experimental work similarly finds that small-scale topography weakens jet strength and reorganizes inverse energy transfers into distinct regimes consistent with an effective β interpretation and blocked-flow behaviour at larger topographic influence [16].

3.3. Transport suppression and staircases

For a transported scalar a , zonal averaging gives [24]

$$\partial_t \bar{a} = -\partial_x \langle u'a' \rangle + S - \Lambda \bar{a}. \quad (5)$$

Here, the overbar $\overline{(\cdot)}$ denotes the same mean operator as in Eq. (4) (i.e. an average over the homogeneous/zonal direction(s), and where appropriate over a suitable time window), and primes denote deviations from that mean. ∂_x denotes differentiation with respect to the coordinate x normal to the interfaces (cross-field/cross-stream direction in the flux–gradient discussion). $\langle u'a' \rangle$ is the turbulent flux, the term S represents sources (or imposed gradients) and Λ is a linear relaxation/damping rate. Explicit molecular diffusion is omitted because the focus is on the effective turbulent transport across interfaces.

Internal interface layers/ITBs correspond to regions where the effective diffusivity is reduced while gradients sharpen. The feedback embodied in Eqs. (1)–(5) underlies staircase states in both magnetized plasmas and stratified/rotating fluids [12,17,18,28].

In both fluids and plasmas, we refer to an internal interface layer/transport barrier as a region where gradients sharpen while the turbulent flux (or effective diffusivity inferred from it) is locally reduced, consistent with Eq. (5).

Coordinate note. In Eqs. (1)–(5), the coordinate normal to the barrier/interface may be denoted by y (fluids), r (plasmas), or x (generic scalar flux form); all represent the cross-interface direction along which transport is reduced.

3.4. Sketch of the Reynolds stress to PV flux equivalence

A useful bridge between the Reynolds stress form and the PV flux form is obtained in the QG setting [10,11]. For a zonal mean flow $U(y)$, one may write $U = -\partial_y \bar{\psi}$. Differentiating this in y shows that the mean relative vorticity is $\bar{\zeta} = \nabla^2 \bar{\psi} = \partial_y U$ (for a purely zonal mean). In barotropic QG, the PV is $q = \zeta + \beta y + q_{\text{topo}}$, so the mean PV gradient contains $\partial_y U$. Eddy PV transport enters the mean PV budget through $-\partial_y \langle v'q' \rangle$ in Eq. (4). Using $q' = \zeta' + \dots$ and QG identities relating ζ' to velocity fluctuations, one can show that the divergence of eddy momentum flux (RS divergence) and the divergence of eddy PV flux are two equivalent ways of expressing mean flow rectification. This equivalence is widely used in geophysical turbulence closures and jet-staircase discussions [10,14].

4. Gap analysis

Here, we treat both existing research we have become aware of along with new research supporting elements of the conjectured CCP. We divide this into material originating from the fluid and plasma perspectives, where more material is devoted to fluids and less to plasmas.

We focus on the ingredients of the CCP, but also make statements on the causality of the ingredients when possible, see Table 3.

Using a flux-gradient terminology, where the radial flux is equal to the diffusion coefficient multiplied by the radial gradient, fluids and plasmas behave comparably without and with IILs/ITBs:

- Without IILs/ITBs: A large diffusion coefficient and a moderate radial gradient leading to a high radial flux
- With IILs/ITBs: A small diffusion coefficient and a steep radial gradient leading to a low radial flux

Table 3

An overview of transitions in the CCP for fluids and plasmas.

Fluids	Plasmas
ECS \implies ZFs	MIs \implies ZFs
ZFs \implies IILs	ZFs \implies ITBs
IILs \implies ECS	ITBs \implies MIs

4.1. Fluids

4.1.1. Exact coherent states

The first element (or ingredient) of the CCP is ECS, which are invariant solutions to the Navier–Stokes equations (NSE) [29]. They can be observed as either travelling waves (TWs) or relative periodic orbits (RPOs). These solutions to the NSE have mainly been identified for transitional flow, e.g. flow at the laminar/turbulent transition. They are difficult to identify for higher Reynolds numbers (Re) due to computational and theoretical limitations. However, they are currently a relatively mature part of fluids research.

4.1.2. Zonal flows

ZFs in fluids, the second element, have been introduced for geophysical flows through studies of geostrophic turbulence, which is fluid dynamics "near a state of geostrophic and hydrostatic balance" [30]. Here, a necessary component is system rotation — stratospheric geostrophic flow is mentioned as an example of flow shear decorrelation in Ref. [7].

An example of laboratory experiments with rotating fluids where a coupling to plasmas is explicitly made is Ref. [31]. ZFs are generated by mixing and homogenization of potential vorticity [30], where mixing is forced by pumping water in and out of holes in the bottom of a rotating tank.

ZFs have also been generated by Rayleigh–Bénard convection; here, vertical buoyancy due to a temperature difference can generate horizontal ZF leading to burstlike vertical heat transport [32]. Again, parallels to transport in plasmas are drawn; for example, ZFs in both fluids and plasmas are sheared normally to their directions of motion and reduce transport in this normal direction: Azimuthal/poloidal ZFs will reduce radial transport. Further, both fluid and plasma motion is roughly two-dimensional (2D) where ZFs have been found.

One case of ZFs in straight pipes has been reported for transitional flow [33,34]. Direct numerical simulations (DNSs) demonstrate that ZF is generated by RS which in turn suppresses small-scale turbulence leading to stochastic predator–prey dynamics [8,9]. Additional recent computational evidence supporting this picture is reported in [35,36]. The ZF is in the azimuthal direction, i.e. perpendicular to the streamwise flow and thereby 2D in nature. It is observed without external rotation and thermal forcing, which implies that these features are not necessary for ZF generation in fluids. However, it is proposed that ZF can be assisted by rotating the pipe, which would lead the transition to turbulence to take place at lower Re .

Another case where ZFs may exist for flow without rotation and thermal forcing is flow through curved pipes, where secondary vortices are generated perpendicular to the streamwise flow [37,38]. These secondary vortices may be generating ZFs, which would explain the delayed transition to turbulence for curved pipes compared to straight pipes [39]. Recent work further suggests that, in the presence of body forces such as curvature, the directed-percolation laminar–turbulent transition can become discontinuous via a tricritical point [40]. This is then similar to the “Dimitis shift” for plasmas where ZFs delay the onset of turbulence [41].

4.1.3. Internal interface layers

As we discussed in Section 2, there is a solid body of evidence for the existence of IILs.

4.1.4. Transitions

An example of the first transition, ECS \implies ZFs, is the generation of ZFs by travelling thermal waves [42]. The sequence of TWs leading to RS which in turn leads to ZFs thus appears plausible.

The next transition, ZFs \implies IILs has also been observed in thermal systems as mentioned in our discussion of ZFs [32].

The final transition, IILs \implies ECS, is the backreaction of IILs on ECS. This transition is the one associated with most uncertainty: We have not been able to identify this process in the literature and it represents a gap (or weakness) in the CCP.

4.2. Plasmas

4.2.1. Elements

All elements of the CCP, i.e. MIs, ZFs and ITBs have been firmly established over several decades, so their existence is not in dispute.

4.2.2. Transitions

The first transition, MIs \implies ZFs has been identified and studied for a longer period, see e.g. [43,44]; zonal fields, the magnetic counterpart to ZFs, also interact with the MIs [45].

The second transition, ZFs \implies ITBs, is discussed in Ref. [8] and it is shown that ZFs are an essential element in the formation of ITBs. Note that in addition to RS, ZFs can also be generated by drift waves.

The third transition, ITBs \implies MIs can be studied by e.g. external magnetic field configuration scans where MIs are manipulated to modify the ITBs [46]. This is strictly speaking an inverse transition, MIs \implies ITBs; however, the forward transition has also been demonstrated by scanning internal heat deposition instead of the external magnetic field configuration [47].

5. Roadmap topics

For the reader searching for books which combine fluids and plasmas more comprehensively, we recommend Refs. [48,49]. On the connection between fluids and astrophysical plasmas, Ref. [50] is a very useful resource.

Interdisciplinary efforts in fluid-plasma research remain highly relevant, as e.g. demonstrated by the joint special topic on fluid and plasma turbulence in Phys. Fluids and Phys. Plasmas [51]. To cite from this Editorial, possible common ground includes "the role in many fluid systems of nonlinearly self-organized structures and the role in many plasma systems of collective modes of the linearized dynamical equations". Our work fits very nicely into this overlapping region of fluids and plasmas.

Below we collect various open points which can be addressed to improve our understanding of phenomena common to fluids and plasmas.

5.1. Missing fluid transition

We have not been able to identify research on the fluid transition IILs \implies ECS in the literature. This may be due to lack of knowledge, because the research has not been done or because the transition does not exist.

We propose research in this direction to find an answer to the question of the existence of this transition. In the framework language of Section 3, the transition IILs \implies ECS would require a demonstrable route by which interface formation (i) modifies the stress divergence $-\partial_y \langle u'v' \rangle$ and/or effective damping in Eq. (1), thereby reorganizing the mean flow, and (ii) feeds back on coherent structures that seed Reynolds-stress production and mean flow rectification. Identifying such a feedback loop is currently the key missing closure on the fluid side of the CCP.

5.2. Is the common cyclic process applicable to fluids?

This question remains relevant; it could also be the case that the CCP is not applicable to both fluids and plasmas. This would imply that complete universality does not exist, i.e. that the process does not consist of exactly the same ingredients for fluids and plasmas.

An interesting point to consider is e.g. whether ZFs are needed for the fluid process? Figs. 21 and 22 in Ref. [52] show that TWs lead to momentum transport barriers as seen by the streamwise velocity gradients. Is this a direct transition from an ECS to an ILL? From the plasma point of view, note the similarity to Figure 1 in Ref. [3], where a comparable structure of the ion toroidal rotation frequency is found.

5.3. Decoupling of transport channels in fluids?

Decoupling of transport channels has been observed in plasmas. It has often been associated with (quasi-)coherent modes, which are thought to lead to increased radial particle transport in contrast to reduced radial energy transport. However, we have not found similar observations in the fluids literature.

Can ECS in fluids play a similar role, e.g. to allow momentum transport while still enabling an energy transport barrier?

We have seen the coexistence of multiple transport barriers in fluids as well as plasmas; the question is whether ECS or a different coherent mode could degrade the UMZ without impacting the UTZ?

5.4. Toroidal geometries with fluids

An interesting development has been taking place in the field of toroidal geometries with fluids over the last fifteen years, both simulations [53,54] and experiments [55,56]. This facilitates a direct comparison between fluids and plasmas in toroidal geometries.

The research has been focused on the transition of laminar to turbulent flow and how that depends both on Re and the curvature, i.e. the ratio of the torus minor and major radii or the inverse aspect ratio to use the plasma terminology.

TWs have been observed at the transition along with cross-stream flow structures, such as azimuthal flow close to the wall. Thus, two elements of the CCP have been observed, but clear evidence of UMZ does not exist yet. It would be interesting to pursue this, perhaps by re-analysing existing measurements and simulations as a first step.

5.5. Linear plasma devices?

We have initiated a literature review on the CCP in linear plasma devices; in terms of ingredients, there is evidence of ZFs [57] and edge transport barriers (ETBs) [58] but not ITBs.

We have not found evidence for MIs in linear devices and no clear transitions. This may also be because we are not aware of the relevant research papers.

5.6. New experimental devices

In addition to theoretical work and model-building, it is obvious to consider the design and construction of new flexible experiments to study fluids and plasmas. This is supported by statements in e.g. Refs. [7,8] which are collected in Ref. [4].

Ideally, a device would have a flexible geometry (straight/toroidal) and include shaping options for the cross-section. It should have the capability of containing both a fluid and a plasma in the same geometry.

5.7. Framework-based closure tests and diagnostics

The minimal relations in Section 3 suggest three concrete, cross-disciplinary “closure tests” that would either strengthen or falsify parts of the CCP. First, a *stress-budget closure test* for ZF formation requires measuring the Reynolds stress divergence (or its plasma analogue) and checking whether it balances damping at ZF onset [Eqs. (1) and (2)]. Second, a *flux-suppression (barrier) test* requires co-locating barrier interfaces with reductions in the turbulent scalar flux $\langle u' a' \rangle$ and/or the effective diffusivity inferred from Eq. (5), and correlating this with mean shear inferred from Eq. (1) or Eq. (2). Third, for rotating/stratified subsets of the CCP, a *PV-staircase test* requires checking whether jets/interfaces coincide with suppressed eddy PV flux $\langle v' q' \rangle$ and sharp mean PV gradients in Eqs. (3)–(4), and whether these PV diagnostics align with scalar-barrier diagnostics from Eq. (5).

5.8. Topography-aware staircase diagnostics and closure tests

Topographic control of mean flows enters through q_{topo} in Eq. (3) and the mean PV flux balance Eq. (4). As a concrete realization of the PV-staircase closure test above, a natural programme is to combine (i) topography-aware tests of jet formation and energy partition with (ii) quantitative staircase diagnostics for micro-barriers, expressed in the scalar balance Eq. (5). In practice, this means measuring step size, interface thickness and barrier permeability (effective diffusivity) and comparing these metrics across fluids and plasmas using the mapping in Table 2. Such diagnostics also provide direct closure tests of the flux-gradient paradigm and of the RS/PV flux rectification pathways discussed in Section 3.

6. Conclusions

Fluids and plasmas have large areas of common ground; one manifestation is internal interface layers in fluids and internal transport barriers in plasmas. In this review we attempt to build a case for a common cyclic process which includes coherent structures and zonal flow in addition to interface layers or transport barriers.

We focus on material for fluids, since this is a plasma physics journal where readers have a stronger background in plasmas. Our mini-review on internal interface layers in fluids shows that they are very similar to internal transport barriers in plasmas. The proposed framework connects turbulence-driven mean flows, PV staircases/topography and transport suppression across the fluid and plasma domains.

For the common cyclic process, we detail both the individual elements and their transitions to identify known results and possible knowledge gaps.

Finally, a research program – or roadmap – contains areas which merit further investigation. This is not something which can be carried out by individual persons or even solitary research groups. Therefore this review is a call to action for the combined fluid and plasma communities to get involved: The potential gains for both fields make a common path the obvious way forward.

Ethics approval and consent to participate

Ethics, Consent to Participate, and Consent to Publish declarations: not applicable.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author used ChatGPT-5.2 in order to search for literature and edit contents. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

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This review is dedicated to everyone who shares my joy of fluids and plasmas: Let us continue to build barriers where they are useful and tear them down where they are harmful.

Appendix. Equation provenance and schematic reductions

This appendix documents the provenance of the five governing relations introduced in Section 3 [Eqs. (1)–(5)] and clarifies how each expression has been *schematically reduced* for compactness and cross-disciplinary readability. In all cases, the relations are standard balances in their respective literatures; here we retain only the dominant terms needed for the qualitative arguments and diagnostic tests described in the main text.

Eq. (1): mean flow evolution in fluids (Reynolds stress form)

Primary source: Pope, *Turbulent Flows* (2000), Chapter 4 (“Mean-flow equations”), which derives the Reynolds-averaged momentum equation and the Reynolds stress divergence term [26].

Reductions applied: Eq. (1) is not reproduced verbatim; it is a reduced 1D balance for a zonal mean velocity component $U(y, t)$ intended to highlight the rectification term $-\partial_y \langle u'v' \rangle$. Relative to the general Reynolds-averaged momentum equation, we (i) restrict to a single mean component with one inhomogeneous direction y , (ii) omit explicit mean advection and mean pressure-gradient terms (which can be absorbed into forcing in reduced models), (iii) include a linear drag term $-rU$ as a compact representation of Ekman/wall drag, and (iv) group remaining body forces and/or imposed forcing into F_{body} .

Eq. (2): zonal $E \times B$ flow evolution in plasmas (Reynolds stress drive and damping)

Primary sources: Diamond et al. (2005) review of zonal flows [8] and Terry (2000) review of shear-suppression physics [7].

Reductions applied: Eq. (2) is a minimal “skeleton” form consistent with standard zonal flow balances in the above reviews. It retains (i) Reynolds stress drive via the radial divergence of the azimuthal momentum flux $-\partial_r \langle \bar{v}_r \bar{v}_\theta \rangle$ and (ii) a linear damping term $-\mu V_{E \times B}$ (standing in for neoclassical/GAM and related damping channels). Additional terms appearing in more complete formulations (e.g. geometry/metric factors, viscosity, polarization/finite Larmor radius effects, external momentum sources) are suppressed into “...” for compactness.

Eq. (3): quasi-geostrophic potential vorticity with topography

Primary sources: Vallis (2006) and Pedlosky (1987) for the definition of PV in QG models and for the way bottom topography enters as a PV contribution (often discussed via a “topographic β ” effect) [10,11].

Reductions applied: Eq. (3) is written in a standard barotropic QG form. The topographic contribution is expressed using a proportionality, $q_{\text{topo}} \propto (f_0/H)\eta(x, y)$, because the exact prefactor and sign convention depend on the chosen QG scaling, vertical coordinate, and definition of η .

Eq. (4): zonal-mean PV evolution in flux form

Primary sources: Standard QG PV conservation/budget equations in Vallis (2006) and Pedlosky (1987), including zonal averaging and eddy PV flux divergences [10,11].

Reductions applied: Eq. (4) is a compact zonal-mean PV budget emphasizing the eddy PV flux divergence $-\partial_y \langle u'q' \rangle$. A linear damping term $-r_q \bar{q}$ is included as a shorthand for frictional/drag effects commonly present in QG models. Other terms (forcing, diffusion/hyperdiffusion, higher-order physics) are suppressed into “...”.

Eq. (5): mean transported-scalar balance (flux–source–sink)

Primary sources: the mean scalar equation in Pope (2000), Chapter 4, [26] and the passive-scalar review by Warhaft (2000) [24].

Reductions applied: Eq. (5) is a reduced 1D mean scalar budget written to make the flux–gradient viewpoint in Section 4 explicit. Relative to the general advection–diffusion equation for a scalar, the full divergence $-\nabla \cdot \langle u'a' \rangle$ is written as a single derivative $-\partial_x \langle u'a' \rangle$, sources/sinks are represented by a generic source S and a linear relaxation term $-\Lambda \bar{a}$, and explicit molecular diffusion is omitted because the focus is on effective turbulent transport suppression across interfaces.

Data availability

No data was used for the research described in the article.

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