Shear Flows and Turbulence in Nature

Shear flows and turbulence have a major impact on the transport of quantities, from heat to material to pollutants. This article explores transport and its sensitivity to novel interactions between shear flow and turbulence.

Many geophysical systems have flows whose Reynolds number (or some other appropriate dimensionless scaling number) is sufficiently large that turbulence becomes an important feature of the fluid dynamics.[1] Such turbulent geophysical systems range from the magnetofluid in the Earth's interior, which creates the Earth's magnetic field, to fluids on its surface, such as oceans and the extended atmosphere.

In this article, we make a connection to the International Polar Year (IPY) by examining the turbulent transport of ozone into polar ozone holes. We also illustrate the study of turbulent transport with a hierarchical series of models (starting with the most complicated and getting simpler). These models help researchers investigate the transport dynamics at different levels of physical, mathematical, and computational complexity.

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Turbulent Transport

Turbulence is one of the major open research topics in classical physics. Although it's defined narrowly as the high-Reynolds-number behavior of flows in neutral fluids modeled by the Navier-Stokes equations or some variant thereof, it's also defined broadly as behavior in any system in which the nonlinear interactions between disparate scales dominate the dynamics.

In this article, we use the Navier-Stokes equation as our paradigm, but we work from a generalizable definition of turbulence as any system of incoherent fluctuations in which the nonlinear dynamics (couplings) dominate the linear dynamics to produce an exchange of fluctuation energy over many spatial scales. For this to hold true, the fluctuations must exist on many scales. These scales often encompass orders of magnitude, as illustrated in Figure 1—here, the turbulent structures are visible in the volcanic plume from the largest scales in the photo, down to the smallest resolvable scales.

The Navier-Stokes equation is

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\frac{\nabla p}{\rho} + \mathbf{F} + \mu \nabla^2 \mathbf{v},$$

where $\mathbf{v}$ is the velocity of a fluid parcel of mass density ρ, p is the pressure, μ is the kinematic viscosity, and $\mathbf{F}$ is an external force. The self-advection term $\mathbf{v} \cdot \nabla \mathbf{v}$ is the nonlinearity that couples disparate scales, and when it greatly exceeds the viscous term, turbulence generally occurs over a

International Polar Year

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This final article in the *CiSE* International Polar Year (IPY) series brings the application of some analytical and computational research originally developed for fusion plasmas to bear on geophysical systems such as the dynamics of the ozone hole. To check the latest status of the ozone hole over Antarctica, visit http://ozonewatch.gsfc.nasa.gov. The NOAA ozone Web site (www.ozonelayer.noaa.gov) displays data for both poles and has an extensive FAQ. Although the ozone hole over Antarctica doesn't yet seem to be decreasing, studies suggest that reducing the use of chlorofluorocarbons has led to an overall recovery of ozone in the upper stratosphere.

One of the objectives of the current IPY is to link researchers across different fields to address questions and issues lying beyond the scope of individual disciplines. Amazingly enough, numerous interdisciplinary activities are indeed emerging under the IPY banner as people from different disciplines work to synthesize their knowledge.

The Belgian government, for example, commissioned the International Polar Foundation (www.polarfoundation.org) to design and build a state-of-the-art ecofriendly research station for Antarctica, and in September, the Princess Elisabeth Antarctica was unveiled in Brussels as the first zero-emission research station. After several days of public viewing, the station was dismantled and is now being shipped to Antarctica, where it will be located between the Russian station Novolazarevskaya and the Japanese station Syowa. Visit www.antarcticstation.org for more information.

A better understanding of the health of indigenous populations in the Arctic is a new theme of the current IPY. Roughly 4 million people from numerous indigenous groups inhabit the Arctic, and the impact of a changing climate and environmental contaminants on their health is a growing concern. The Arctic Human Health Initiative (www.arctichealth.org/ahhi/) was formed to research current and developing human health issues in the north.

Some of the earlier articles in this series have dealt with ice, but as we view the record minimum Arctic sea-ice level in 2007 (http://arctic.atmos.uiuc.edu/cryosphere/), the extensive observations during this current IPY will be critical for understanding the processes that have led to these conditions. A movie of daily Arctic sea ice (warning: it's big) at http://arctic.atmos.uiuc.edu/cryosphere/sea.ice.movie.2007.mov provides a sobering view of the situation we might face in the future.

As we close this special theme track, we thank *CiSE*'s editor in chief, Norman Chonacky, its senior editor, Jennifer Stout, and all the staff on the publication for their support, help, and professionalism in making this series work. Last but not least, we thank the authors and anonymous reviewers who put together these outstanding articles and reviewed them so quickly.

range of spatial scales known as the *inertial range*. Typically, the damping in turbulent systems occurs at small scales, but in some systems, the drive and damping can occur at various scales and thus help set the turbulence's inertial range.

Turbulence is frequently described as a random process, and even though we can treat it as such for some purposes, it's important to remember that the Navier-Stokes equation is deterministic. The dynamics can be very high dimensional but essentially remain a form of chaos, meaning that the dynamics is deterministic but very sensitive to initial conditions, which fundamentally limits long-term prediction.

Although turbulence is a rich, beautiful, and complex phenomenon, it's the enhancement of transport by turbulence that is of greatest interest in many geophysical systems.[1] Think of classical diffusion as a random-walk process with the step size set by the distance between particle collisions (the mean free path). This distance tends to be very small (~10^{-6} m in air at sea level), so despite

Figure 1. The 1992 Mt. Spurr eruption. Note the turbulent structures, which are visible in the volcanic plume from the largest scales down to the smallest resolvable ones. (Source: //first name?// R. McGimsey, US Geological Survey, 18 August 1992; http://pubs.usgs.gov/dds/dds-39/album.html.)

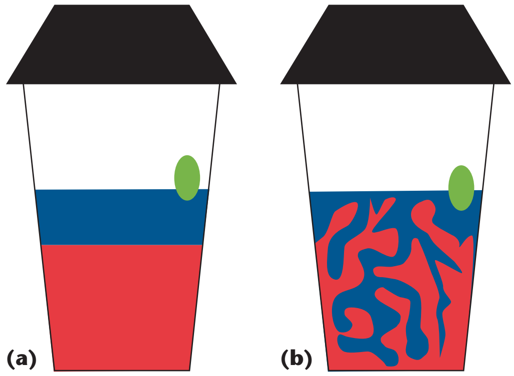

Figure 2. Turbulence in a martini. You can (a) wait hours for it to mix or (b) shake (or stir) it to mix it in seconds.

the high collision frequency, classical diffusion is relatively slow. This diffusion process on average moves material (or heat) from regions of higher concentration to lower concentration, thus slowly relaxing gradients in the diffusing quantity. Turbulence, however, can have average scale lengths much larger (centimeters, meters, or even tens of kilometers, depending on the system).

If we consider the process of turbulent transport as a random-walk process with the step size given by a typical turbulent eddy size, we can construct the effective turbulent diffusivity from step size and turbulent velocity (or eddy turnover time). In a turbulent system, this turbulent diffusion is usually many orders of magnitude larger than the classical diffusion and is called *anomalous diffusion*. Thus, the turbulent diffusion relaxes gradients much more rapidly. A classic example is mixing a drink:[2] if we carefully place a layer of gin on top of a layer of vermouth, the two will mix by classical diffusion over the course of many hours. (This assumes idealized liquids, so we aren't worried about density stratification and so forth.) If, instead of sitting quietly and watching the classical diffusion at work, we get impatient and shake (or perhaps stir) the drink, the turbulence will fully mix the components in seconds, as Figure 2 shows. The air in a large auditorium is another good example. If the air is still, the smell from a squirt of perfume at one end will take tens of hours to reach someone on the other end. However, if people move around in the room enough to cause a turbulent velocity field, some of the perfume (a detectable odor) will reach the other end in less than a few minutes.

In complex models (global climate models, for example), researchers often simulate turbulent transport with an effective diffusivity for scales below those resolved by the model. This practice is called *subgrid-scale modeling*, or parameterization. Because of the importance of subgrid scales in overall system dynamics, getting this parameterization right is crucial for matching the model to the real world. A principal goal in developing physical system models is the ability to do predictive modeling, so correctly capturing any subgrid-scale fluxes is key.

However, this subgrid-scale parameterization—while clearly necessary for computational tractability—often leaves out smaller scales' real dynamics. Turbulence, for example, is a multiscale phenomenon, so leaving out existing scales can change the system's dynamics. As we model such systems, it's important to keep in mind what we're leaving out and what effect it can have on the modeled results. "Missing" physics can include a variety of items:

- The interaction between scales (both in a single field and between multiple fields) isn't a one-way street. Smaller scales affect larger scales, and larger scales affect smaller scales.
- The cut-off between 2D and 3D dynamics due to rotation or stratification isn't as clean as we pretend, so omitting the interaction between these different types of turbulence omits a physical process.
- By restricting system size, we omit some global dynamics that can fundamentally change system behavior.
- The representation of turbulence's sources and sinks and the scales at which they occur is crucial. Turbulence dynamics depend on the scales of drive and damping.
- Parameterizations (particularly subgrid-scale ones) omit the fast intermittent behavior observed in many natural systems. Small-scale stochastic forcing sometimes addresses this, but it's an open issue as to whether diffusive parameterization makes physical sense.

In addition to turbulence and turbulent transport, many geophysical systems have shear flows, which vary in a direction perpendicular to flow velocity. Figure 3 illustrates a sheared flow (purple arrows) in which velocity is in the x-direction and magnitude varies in the y-direction. Systems with both shear flow and turbulence include ocean currents and their offspring,[3] Mediterranean eddies,[4] many boundary layers and boundary-layer jets, ozone holes[5] (and atmospheric jets in general), high-altitude jets, the magnetopause, and many magnetospheric flows. Some of these flows can persist for months or even years, where-as others are much more transient, lasting seconds or minutes.

Sheared flows and turbulence can interact in various ways and have a significant impact on a system's transport properties:

- Small-scale turbulent diffusion across a larger-scale, quasi-static sheared flow can lead to enhanced transport, or *advective diffusion*. Turbulent diffusion transports material across a sheared flow from a lower- to higher-velocity region, thereby allowing for faster displacement of the material in the direction of the flow.
- Turbulence can produce sheared flows through momentum transport, an example of which is Reynolds-stress-driven shear flows. They're thought to be responsible for the sheared flows in systems as diverse as the solar convection zone, the atmosphere (for example, in quasi-biennial oscillation [QBO]), and laboratory plasmas.
- Unstable sheared flows can cause turbulence through instabilities such as the Kelvin-Helmholz (K-H) instability. Unstable shear flows have many possible causes, including stirring, large-scale drivers, geostrophic balance, gravity, and pressure driven through an opening, to name just a few. It's worth noting that some of these instabilities, such as the K-H instability, have different behaviors in different systems—for example, in a magnetized plasma the magnetic field and its configuration inhibit the onset of the K-H instability allowing a larger sheared flow to develop. This makes the effect discussed next easier to observe in plasmas.
- Sheared flows can reduce or suppress turbulence and turbulent transport.

Which of these four processes occurs in a given situation depends on flow stability properties, geometry, turbulence's driving sources, inhomogeneities, and the hierarchies of spatial and temporal scales within turbulence and shear flow.[6]

Sheared flows can reduce turbulent transport through at least four mechanisms. The order of these mechanisms is based on the probable ordering of thresholds for sheared-flow effects on transport, starting with an effect that requires the largest sheared flow down to one that requires the smallest.

In the first mechanism, sheared flows modify the turbulence's underlying linear drive, thereby reducing turbulence simply by reducing drive. This mechanism appears to be a subdominant mechanism in plasma experiments because turbulence is often observed in regions in which shear is predicted to totally quench turbulent motion, but it shouldn't be discounted if the linear drive is frequency-dependent and the shearing rate is large. (The shearing rate is the reciprocal of the time for parcels initially displaced across the shear to separate one correlation length along the flow.) This first mechanism isn't universal in the sense that it depends on the detailed spatial profiles of the quantities that govern instability.

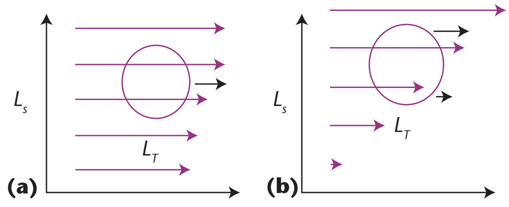

Figure 3. Sheared flow. An eddy in a sheared flow can have a shearing scale length (a) longer or (b) shorter than the turbulent scale.

However, the second mechanism—shear-induced decorrelation of turbulence—*is* universal, meaning it doesn't depend on the shear profile's details.[7] Here, an enhancement of the normal self-decorrelation (tearing apart) of eddies is caused by a distortion in the sheared flow. Figure 3 shows the threshold condition in shear strength; the high shear differentially advects fluid parcels across a correlation length in the flow direction in a fraction of the turbulent correlation time, thus increasing the decorrelation rate. In the presence of invariant external forcing, turbulent amplitudes must decrease to compensate for the larger decorrelation rate (this reduction requires $L_s < L_T$ with L_s representing the shear scale length and L_T the turbulent scale length). Figure 4 illustrates both the turbulent and the shear-enhanced decorrelation possible in a turbulent system with a flow.

A third mechanism is a shear-induced phase shift between the advected and the advecting fluctuations.[8] This mechanism is largely insensitive to shear profiles, with transport governed by the correlation between advecting and advected fields, making the phase difference between the two fluctuations extremely important. If the fluctuations are exactly out of phase, no transport occurs—if they're exactly in phase, transport is at its maximum. In some systems, this can be the dominant mechanism for reducing transport.

The last mechanism is a shear-induced decorrelation of transport events.[9] It only applies in systems in which the transport comes from bursty, correlated, avalanche-like transport events. In

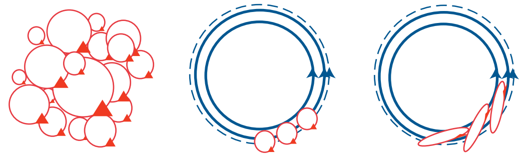

Figure 4. Decorrelation. Both (a) turbulent and (b) shear-enhanced decorrelation is possible in a turbulent system. In turbulent decorrelation, eddies interact with each other with no mean flow. In shear-enhanced decorrelation, initially circular eddies in a shear flow are stretched out and then decorrelated, which reduces both scale sizes in the direction of the shear and transport.

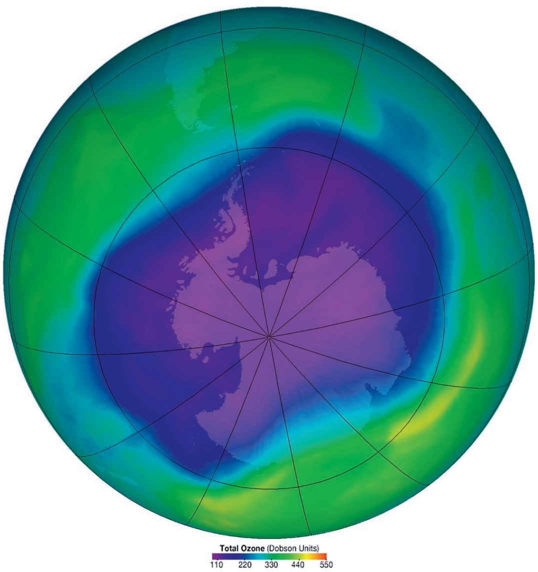

Figure 5. Large ozone hole. This snapshot of ozone concentration above the South Pole is from 24 September 2006. (Source: NASA Ozone Hole Watch; http://ozonewatch.gsfc.nasa.gov/.)

such a system, transport events can be decorrelated at a much smaller shearing rate than the turbulence itself.

Modeling the Ozone Hole

Because we want to examine shear flow/turbulence interactions in geophysical systems, we chose to look at the polar ozone hole's phenomenology as an example application.

Researchers have found that O_3 decreases inside the circumpolar vortex in late winter and early spring.[5] The depletion mechanism is a complicated multipart chemical and photochemical process. However, dynamical remixing with the ozone rich air outside the vortex is blocked by the circumpolar jet. The earth's rotation combined with cooling and subsidence lead to the winter circumpolar jet, which sets the stage for the hole. The chemical process starts in mid-winter with the depletion reaching its maximum in early spring. The depleted region refills (remixes) in late spring with the break down of the vortex due to large-scale wave breaking.

The ozone barrier (in the form of the jet), temperature, catalytic chemistry, and sunlight all combine to form the ozone hole (see Figure 5). Researchers have found that turbulence and turbulent transport are present, as is a source of ozone outside the hole (just outside the jet). The jet maximum forms a potential vorticity (PV) barrier that prevents large-scale instability in the form of wave breaking and large-scale mixing. However, this doesn't prevent small-scale turbulence from transporting ozone into the hole from sources outside of it. So why is there a sharp edge in the constituents, including the ozone? The answer lies in the interaction between turbulence and shear flows.

A Beta Plane Model

To investigate the interaction between an atmospheric jet and turbulence, we use a barotropic beta plane turbulence model for fluid dynamics on a rotating sphere,

$$\frac{\partial \nabla^2 \phi}{\partial t} + \nabla \phi \times \hat{z} \cdot \nabla \nabla^2 \phi + \beta \frac{\partial \phi}{\partial x} - \mu \nabla^4 \phi = S,$$

where ϕ is the geostrophic stream function, β is the local meridional derivative of the Earth's rotation velocity, and μ is the kinematic viscosity. Due to the atmosphere's rotation and stratification, for appropriate scales, a 2D approximation for stratospheric dynamics is generally valid and captures much of the system's dynamics. We can evolve the system with or without a jet (for comparison), and for both driven and decaying turbulence. The jet flow is in the zonal direction with a cosine variation in the meridional direction. This variation has the advantage of computational simplicity in a pseudo-spectral code, and it also allows a clear spatial separation between the maximum in shear and the maximum in the curvature so that we can distinguish the effects of each on fluctuations and transport.

Figure 6 shows the vorticity field for decaying beta plane turbulence with and without a jet, each after integration for a time of $t = 2.2$ (in normalized time units). Without a jet, eddy distribution is isotropic; with a jet, eddies in regions that have weak shear resemble those without a jet, and those in regions with strong shear are reduced in amplitude, elongated in the zonal direction, and reduced in size in the meridional direction.

To quantify this observation, we used tracers such as those shown in Figure 7 to construct meaningful measures of the transport.[10] We can track average transport behavior by introducing an ensemble of tracer particles, with each ensemble member advected passively by the flow. We calculate effective zonal (K_{xx}) and meridional (K_{yy}) diffusivities from the separation of pairs of tracer particles and diffusivities from the mean squared difference between displacements of particle pairs in zonal and meridional directions $<(x_i - x_j)^2>$ and $<(y_i - y_j)^2>$. The indices i and j refer to different tracer particles. The instantaneous slope of $<(x_i - x_j)^2>$ and $<(y_i - y_j)^2>$ versus time determines the diffusion coefficients.

Figure 8 shows the result of this analysis. As the jet amplitude is increased, the global cross-flow diffusivity K_{yy} decreases up to the point at which the jet becomes K-H unstable. This decrease—and the reduction of fluctuation intensity in the regions of strong shear evident in Figure 6—indicates that some combination of the second and third turbulence-reduction mechanisms we described earlier are at work. At the point of K-H instability, the unstable jet drives the turbulence to higher amplitude, relaxing the flow gradient. Both the higher intensity of turbulence and the reduced gradient increase the effective diffusivity. Figure 8b shows these diffusivities as a function of the turbulent amplitude (for a fixed jet amplitude). As the turbulence's amplitude increases, the advective (parallel) diffusivity decreases until it's of the same magnitude as the cross-flow diffusivity. At this point, turbulence dominates the shear flow, and the diffusivity is effectively isotropic. For smaller turbulence amplitude, the shear decorrelation mechanism we described earlier makes the diffusion anisotropic. Local diffusivities calculated from localized tracer ensembles show that diffusion is at a minimum in the regions of maximum shearing rate, not the regions of maximum flow.

This result suggests a mechanism for the sharp gradients observed at the edge of sheared flows (such as the circumpolar jet), despite background turbulence—namely, shear suppression of the turbulence and turbulent transport. This smaller-scale effect, combined with the large-scale dynamical suppression of the large-scale wave breaking by the PV barrier, can keep the hole isolated from the ozone-rich surrounding air.

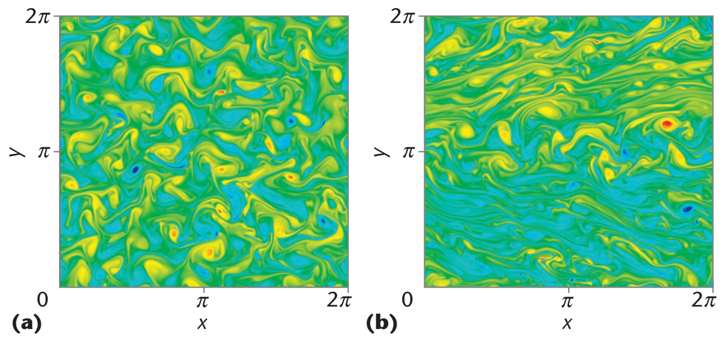

Figure 6. Vorticity field for beta plane turbulence. By comparing a snapshot of the turbulence with (a) no jet and (b) with a strong jet, we see a reduction in the cross flow scale lengths and amplitude of the turbulence in the case with the jet.

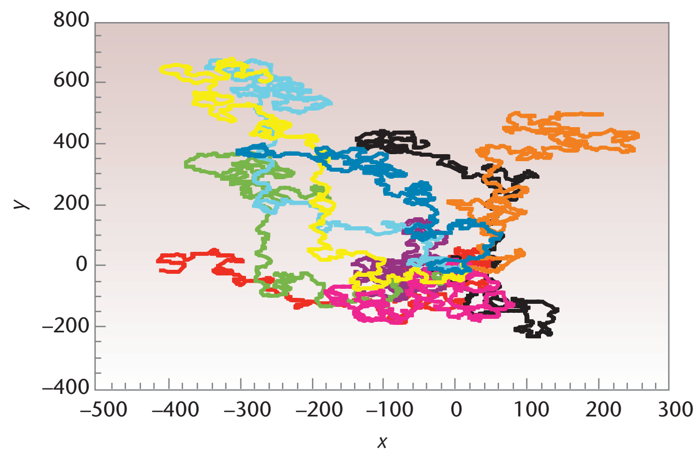

Figure 7. Tracers. The trajectories of nine tracer particles shows anomalous diffusion-like paths as well as the multiple scale sizes characteristic of a turbulent system.

Simple Models of Interaction

As we discussed in the beginning of this article, turbulence can also create sheared flows, and as we've seen, these sheared flows can then react back on the turbulence itself. The conditions required for this are inhomogeneous and anisotropic turbulence, which can lead to a nonzero Reynolds stress that can in turn produce shear flows.[11] If the sheared flow is stable, it can then increase the turbulence's decorrelation, thereby reducing the turbulent amplitude. A strong two-way coupling exists between the turbulent fluctuations and averaged flows. Many turbulence models show this behavior, but it's often useful to extract the minimal physics needed for the process of interest and then construct a model with just that physics. We can then investigate the process's sensitivity to the physics and the parameters involved.

In this case, we construct a simple set of cou-

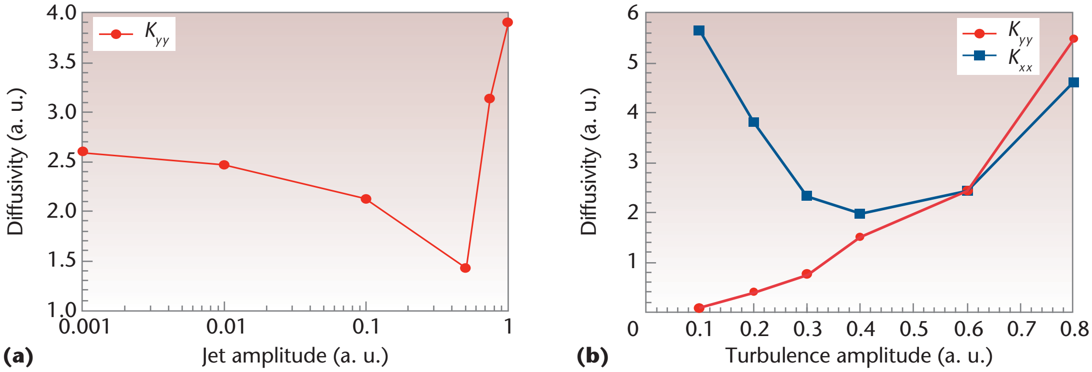

Figure 8. Analysis results. (a) Cross-jet diffusion is a function of jet strength, with diffusion decreasing until the jet becomes K-H unstable. (b) Cross and parallel diffusion with a constant (stable) jet is a function of turbulence amplitude. Parallel "advective" diffusion dominates until turbulent shearing exceeds jet shearing.

pled ordinary differential equations to model the coupling of the flow with the turbulence and thus gain insight into the system's behavior.[12] The coupled system is governed by

$$\frac{d\mathbf{E}}{dt} = \gamma_0 \mathbf{E} - \alpha_1 \mathbf{E}^2 - \alpha_2 U^2 \mathbf{E},$$

$$\frac{dU}{dt} = -\mu U + \alpha_3 U\mathbf{E} + \tau,$$

where $\mathbf{E}$ is the normalized average turbulent fluctuation amplitude; U is the averaged flow shear; γ is the linear drive term; the α terms are the nonlinear saturation, shear suppression, and Reynolds stress flow generation terms; μ is the flow-damping term; and τ represents an external torque. The system allows two stable steady-state solutions (and one unstable solution).

Figure 9a shows the solution for large damping relative to the drive, in which the flow is zero and all the energy goes into the turbulence; Figure 9b shows the solution for large drive relative to damping. Here, the system transitions to a state in which some of the energy is taken from the turbulence and drives the sheared flow. The system can access this transition either through a reduction of the damping or an increase in the drive. This type of model helps researchers understand the interaction between sheared flow and turbulence and has yielded insight into transport barriers in plasmas (regions of reduced transport and hence increased gradients). Such insights might also be applicable to geophysical flows such as the QBO.

Finally, we can use an even simpler model to investigate the interaction between the sheared flows and correlated transport events that are thought to be important in confined plasmas as well as thermally driven fluid turbulence. To understand the complex gradient-driven dynamics of correlated-event-dominated turbulent (anomalous) transport, researchers have used a simple cellular automata self-organized-criticality model based on the dynamics of avalanches in sandpiles.[13] The cellular automata rules governing the system are simple: if the local gradient is greater than a critical gradient, the sandpile becomes locally unstable, and a given number of grains fall to the next site down. This uncomplicated model displays remarkably rich dynamics that have many characteristics in common with the observed transport dynamics in marginal temperature-driven turbulence and in magnetically confined plasmas.

Transport events (such as avalanches) span all sizes up to the system size in an unsheared system, leading to very efficient transport. However, large transport events break apart in the sheared region, reducing effective transport. This sheared decorrelation reduces diffusivity and fundamentally changes the scaling of the dynamics. For a visualization of the effect sheared flows have on avalanche sizes and hence transport, see http://ffden-2.phys.uaf.edu/avalanche.html. The insights gained from this model has yielded new understanding of transport in plasmas and has led to an appreciation of the physics needed in more complete models to capture the dynamics in experiments.

The real impact of turbulence and shear-flow processes on transport is an open question. If subgrid scales are subject to a suppression of trans-

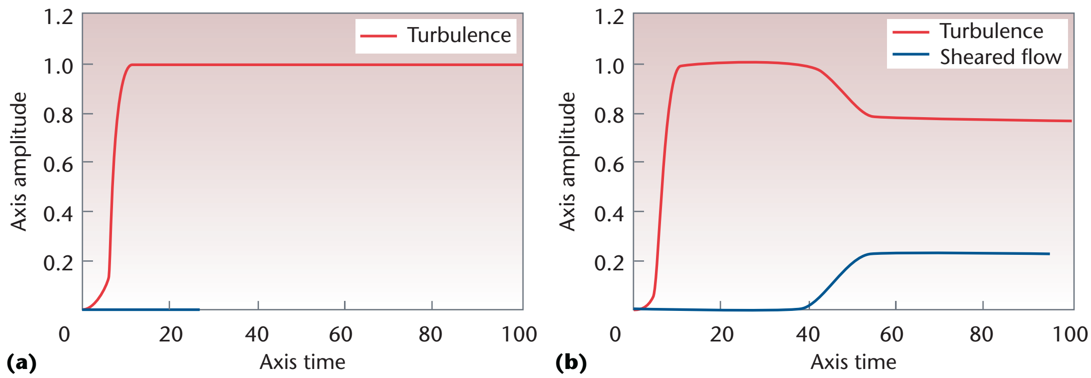

Figure 9. Solutions (red is turbulence and blue is sheared flow). For (a) large damping relative to drive, we get strong turbulence but no shear flow steady state. For (b) large drive relative to damping, we get a steady state with suppressed turbulence and a shear flow.

port by shear flow, then subgrid-scale parameterization becomes quite different from what it would be otherwise. How to best incorporate such effects in subgrid-scale parameterization is therefore another open issue. Our analysis of these interactions illustrates how we can fruitfully analyze and understand complex dynamics through a hierarchical approach to modeling. We represented each process with a successively simpler model, yet the effect of shear flow was consistent both qualitatively and quantitatively. The simplicity of some of these models lets researchers and students interact at many levels. With a hierarchical approach, we can isolate, understand, and model essential physics, first in a simple setting with transparent effects and then in increasingly more realistic settings.

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