19

Dynamics of Baroclinic Multiple Zonal Jets

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19.1 Introduction

19.1.1 Early studies

Soon after the foundations of geostrophic turbulence were laid down by Charney (1971a), attention of theoreticians turned to anisotropic effects due to the latitudinal dependence of the Coriolis parameter. Emergence of multiple alternating zonal jets from purely 2D (i.e., barotropic) small-scale turbulence on the β-plane was first studied by Rhines (1975), who argued that as time evolves the initial small-scale eddies merge and grow in size until they become large enough to be affected by the Rossby wave mechanism. At this stage the eddy energy is channeled into anisotropic jets rather than in isotropic large-scale eddies. This anisotropic energy transfer is explained by the presence of the purely meridional background potential vorticity (PV) gradient — the β-effect in the Rhines' model — that is a necessary aspect required for the jet formation. The other necessary aspect is nonlinearity of the governing dynamics, which is responsible for transfer of energy from the eddies into the jets. The main prediction of the Rhines' barotropic model is that the length scale of the jets scales as $L_R = \sqrt{U/\beta}$, where U is the velocity scale of the eddies (e.g., defined as rms of the eddy velocity). Rhines (1975) looked at decaying barotropic turbulence, but numerous later studies (discussed in other chapters of this book) considered forced barotropic turbulence in statistical equilibrium. Since baroclinic instability is not considered in these studies, the starting-point assumption is that the details of the baroclinic nonlinear interactions are not important, and these interactions can be represented by purely random small-scale forcing added to the barotropic model. This approach is based on the extreme assumption that the essential barotropic dynamics is completely decoupled from the baroclinic dynamics — this is a convenient framework, which helps to shed light on many important properties and mechanisms of the jet dynamics.

19.1.1.1 The Rhines scale

Relevance of the Rhines scaling to the jet width can be considered as a test of applicability of the barotropic dynamics. Almost all baroclinic-jet studies discussed in this chapter say something about validity of L_R, either positively or negatively. Let's discuss the main underlying issues. The starting point is that the Rhines scale correctly applies only to the barotropic decaying turbulence, because it is characterized by only one scale U. However, even in the forced barotropic models, strong multiple jets can provide their own velocity scales and significantly modify the mean PV gradient, which makes nonunique definition of a length scale based on velocity and PV gradient. In more general baroclinic situations, there are other physical scales, such as the Rossby deformation radii and background-flow velocity shear, therefore, one can construct a number of different length scales relevant for the widths of the jets (e.g., Okuno and Masuda (2003) and Smith (2004a) studied effect of finite Rossby deformation radius on jet scaling). In this situation, proper verification of the jet scaling should take into account all available choices and test the scale dependencies on, e.g., U or β, for broad range of parameters. The dependencies of the key scales on other parameters of the problem (e.g., domain size, initial and boundary conditions, dissipative and forcing parameters, stratification) must be also explored. However, the common practice is to note that in some regime the width of jets increases with some U and decreases with β, and, therefore, some kind of Rhines scaling seems to apply. Finally, the often observed similarity between equivalence of the Rhines scale L_R and the Rossby deformation radius is likely a result of linear theory (see section 4.7), because, with the eddy scale being initially of the order of the deformation radius, the linear theory bounds the eddy velocity by the velocity of the initial flow and this, at least initially, makes L_R and the deformation radius to be similar.

19.1.1.2 Criticism of barotropic inverse cascade

The popular conjecture of the barotropic inverse energy cascade operating in baroclinic turbulence and shaping up the jets (Salmon, 1980b) states that large-scale forcing provides energy input mostly into the baroclinic vertical mode, this energy is nonlinearly cascaded down towards smaller scales until at around baroclinic Rossby deformation radius it is transferred to barotropic-mode eddies, then, the barotropic inverse cascade transfers the energy contained in the barotropic mode towards larger scales (some energy is lost on the way due to various dissipative processes). This conjecture was criticized recently from several perspectives. First, it is not obvious that the cascade, that is, a series of consecutive transfers of energy between the neighboring scales, is needed to transfer the energy from the small scales up to the jets, because transfers of energy directly from the small scales to the jets are dynamically allowed and in fact are even preferred. Kaspi and Flierl (2007) demonstrated this point by considering a truncated baroclinic model without all the intermediate length scales; the model dynamics qualitatively reproduced the jets and the associated energy transfers

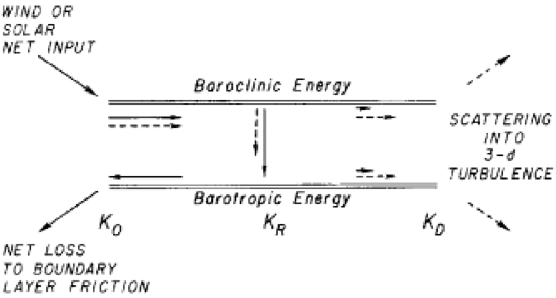

Figure 19.1 Adapted originally from Salmon (1980b); reproduction courtesy of Vallis (2006). Conceptual schematic of the energy (solid arrows) and potential enstrophy (dashed arrows) transfers in wavenumber space and between the vertical baroclinic and barotropic modes. The horizontal axis represents horizontal wavenumber, and the vertical discretization represents the barotropic and first baroclinic vertical modes.

from the small scales. Second, the baroclinic dynamics can be equally important in the energy transfer. This is demonstrated by Scott and Arbic (2007), who analyzed spectral energy transfers in another baroclinic model and showed that the upscale kinetic energy transfers are equally intensive for the barotropic and baroclinic modes. Thompson and Young (2007) also argued that the barotropic cascade does not happen, and, instead, the jets are maintained by both the barotropic and baroclinic modes. To summarize, existing evidence suggests that the baroclinic jet dynamics can not be described only by the barotropic interactons and the corresponding inverse cascade of energy, and baroclinic interactions have to be taken into account.

Search for extension of the barotropic model toward more physical, stratified model of geostrophic turbulence was started by Salmon (1980b), who hypothesized that stratified β-plane turbulence, even in the presence of large-scale baroclinic shear, must be controlled by the barotropic inverse cascade. In this conceptual framework, the main role of the large-scale baroclinic shear is to convert its energy into the kinetic energy of the small-scale barotropic eddies and, thus, to feed the upscale energy cascade toward the multiple jets (Fig. 19.1). The Salmon's conjecture strongly influenced later theoretical studies of stratified geostrophic turbulence and eddy-driven multiple jets.

To summarize, both important concepts that came out of the pioneering works of Rhines and Salmon — the Rhines scale and the barotropic inverse cascade — profoundly influenced all following studies.

19.1.2 Main topics

Since the early studies, a broad range of distinct topics and specific questions about the dynamics of *baroclinic* multiple jets was addressed in the works discussed in this chapter. These topics and questions can be sorted out into the following categories.

19.1.2.1 Phenomenology

What are the different multiple-jet flow regimes and the corresponding patterns of jets and ambient eddies? How do these regimes depend on the model physics (e.g., stratification, background PV gradient, forcing, degree of nonlinearity, etc.), as well as boundary and initial conditions? What are the spectral properties capturing the multiscale nature of the time-dependent part of the flow?

19.1.2.2 Linear control

To what extent and how the underlying linear dynamics controls properties of the eddies and jets? How relevant are the linear normal modes and linear stability arguments to the nonlinear dynamics?

19.1.2.3 Nonlinear interactions

How do the jets and ambient eddies interact with each other, especially in large-Reynolds-number (Re) flow regimes? What are the dynamical mechanisms that transfer the energy between different length and time scales and different dynamical modes? How relevant is the barotropic inverse energy cascade conjecture? How do the jets feed back on the eddies?

19.1.2.4 Jet latency, shape and strength

Let's refer to the jets as latent/manifest, if they are weak/strong relative to the ambient eddies. Why most of the oceanic jets and also the high-latitude jets on Jupiter are so latent, whereas the midlatitude jets on Jupiter are so manifest (e.g., as shown by Cassini data)? What are the physical and dynamical processes controlling the observed degree of latency? What are the dynamical mechanisms determining the jet widths, as well as the asymmetries between the eastward and westward jets? What are the bounding mechanisms limiting amplification of the jets and determining their amplitudes?

19.1.2.5 Isolated coherent vortices

In addition to the jets and ambient wave-like eddies, geostrophic turbulence is characterized by emergence of isolated and long-lived coherent vortices. How do these vortices interact with the multiple jets? How are they dynamically generated and steered by the background PV gradients? What are their structural and statistical properties and life cycles?

19.1.2.6 Background flows and topography

How do the background vertical and horizontal shear components, as well as flow direction and intensity control the jets and eddy properties? How do various oceanic bottom topography features block, steer, braid, stabilize and destabilize the jets, and how do they change the eddy patterns and eddy/jet nonlinear interactions? What are the effects of the lateral boundaries, which destroy zonal symmetry in the oceans?

19.1.2.7 Material transport

Studying anisotropic material transport properties of the system of jets, eddies, and isolated vortices is practically important subject. This problem is discussed in chapter 28 of this book, therefore, we skip it over but note that the dynamical mechanisms governing the material transport remain poorly understood.

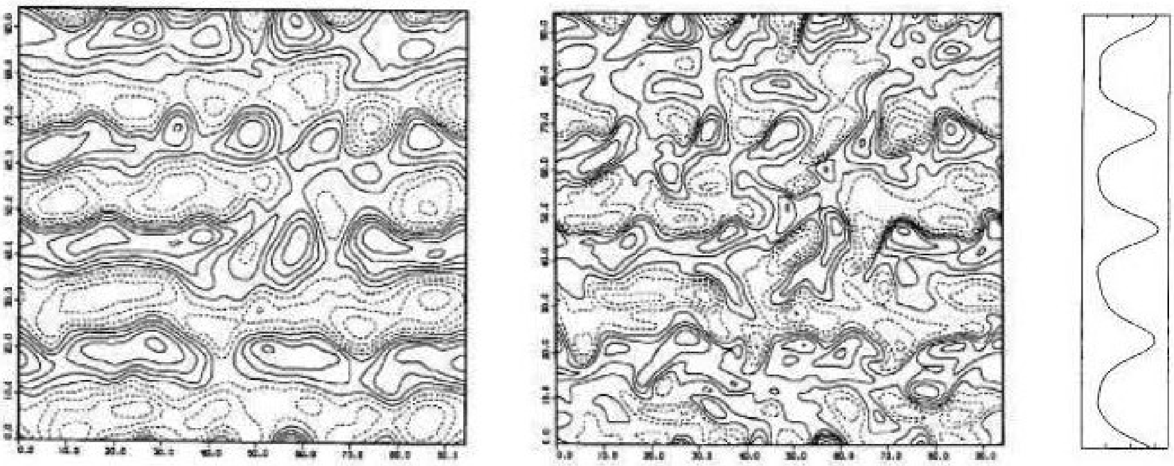

Figure 19.2 Adapted from Panetta (1993c). Left panel shows instantaneous barotropic velocity streamfunction; central panel shows the corresponding baroclinic velocity streamfunction (contour interval is $1/3$ of that in the left panel), and right panel shows the time-mean upper-layer zonal velocity profile. ©American Meteorological Society. Used with permission.

19.1.2.8 Applications of theories

In addition to addressing the fundamental physics mentioned above, research on multiple baroclinic jets has many applied aspects. First, there are practical needs to parameterize the important effects of the jets, together with ambient eddies and vortices, in non-eddy-resolving General Circulation Models (GCMs). Second, there is a need to understand what exactly we have to measure in geophysical fluids in order to test validity of relevant theories and accuracy of parameterizations, as well as their underlying assumptions.

19.2 The simplest baroclinic model

In this section we describe the simplest dynamical model for the baroclinic jets. Most of the studies discussed in this chapter, except for the GCMs in section 5.1, were carried out with either this model or a similar one. The simplest model considers two stacked isopycnal layers (the lighter-fluid layer is on the top), with the average depths H_1 and H_2, and communicating with each other through dynamic pressure anomalies. Extension of this model into any number of stacked isopycnal layers and even continuous stratification is straightforward. The governing equations are formulated in the quasigeostrophic (QG) framework (Pedlosky, 1987c) and consist of the adiabatic part, representing material conservation law for the PV Π and the diabatic part represented by the dissipative terms and external forcing, Φ,

$$\frac{\partial \Pi_1}{\partial t} + J(\psi_1, \Pi_1) = \nu \nabla^4 \psi_1 \qquad\qquad + \Phi_1(t,x,y), \quad \text{(19.1a)}$$

$$\frac{\partial \Pi_2}{\partial t} + J(\psi_2, \Pi_2) = \nu \nabla^4 \psi_2 - \gamma \nabla^2 \psi_2 + \Phi_2(t,x,y), \quad \text{(19.1b)}$$

where the upper- and lower-layer quantities are denoted by the subscripts 1 and 2, respectively; x is the zonal coordinate; y is the meridional coordinate; ψ is the velocity streamfunction; the nonlinear advection terms are written as the Jacobians $J(,)$; the bottom is controlled by friction parameter γ ; the eddy viscosity parameter is ν ; and β is the gradient of the Coriolis parameter $f = f_0 + \beta y$. The stratification parameters are $S_1 = f_0^2/(H_1 g')$ and $S_2 = (H_1/H_2)S_1$, where $g' = \rho'/\rho_0 g$ is the reduced gravity associated with the density jump ρ' between the isopycnal layers with the deep-layer density ρ_0. An important length scale of the problem describing eddies generated by baroclinic instability is the first baroclinic Rossby deformation radius,

$$Rd_1 = \sqrt{\frac{H_2}{S_1(H_1+H_2)}}. \qquad (19.2)$$

Relationship between q and ψ is given by the coupled elliptic problem:

$$\Pi_1 = \nabla^2 \psi_1 + S_1(\psi_2 - \psi_1) + \beta y, \qquad (19.3a)$$

$$\Pi_2 = \nabla^2 \psi_2 + S_2(\psi_1 - \psi_2) + \beta y, \qquad (19.3b)$$

where terms on the rhs are relative vorticity, density anomaly, and planetary vorticity anomaly, respectively. The equations (19.1a), (19.1b) and (19.3a), (19.3b) are solved with the mass and momentum conservation constraints (McWilliams, 1977), and with prescribed boundary and initial conditions. Discussion of the numerical algorithms is intentionally omitted here.

External forcing Φ must be physically justified. One of the key advantages of baroclinic models for studying multiple jets and ambient eddies is that they do not need a random forcing, that is otherwise required for mimicking effects of baroclinic instability and eddies generated by it. This allows to avoid serious problems associated justification of the random forcing. Baroclinic models explicitly represent baroclinic instability and, therefore, can generate mesoscale eddies in the dynamically consistent way. Forcing for these models can be provided by natural, external large-scale sources of PV that can generate baroclinically unstable large-scale flows (e.g., vorticity input by wind or buoyancy input by external temperature gradient). A useful simplification can be made by fixing some large-scale background flow (e.g., obtained from more complete model) and by rewriting the governing equations so, that they describe transient fluctuations and permanent anomalies of the background flow (e.g., as in Phillips, 1956; Haidvogel and Held, 1980a). In many studies considered further below, the external forcing is given in terms of the simplest "fixed" background flow, which is uniformly zonal and with spatially uniform vertical shear proportional to $U_1 - U_2$. Following the simplest choice, let's apply transformation

$$\psi_i \;\longrightarrow\; -U_i\, y + \psi_i\,, \tag{19.4}$$

and rewrite the governing equations as

$$\begin{aligned}\frac{\partial q_1}{\partial t} \;&+\; J(\psi_1, q_1) + (\beta + S_1 U_1 - S_2 U_2)\frac{\partial \psi_1}{\partial x}\\ &+\; U_1 \frac{\partial q_1}{\partial x} = \nu \nabla^4 \psi_1,\end{aligned} \tag{19.5}$$

$$\begin{aligned}\frac{\partial q_2}{\partial t} \;&+\; J(\psi_2, q_2) + (\beta - S_2 U_1 + S_2 U_2)\frac{\partial \psi_2}{\partial x}\\ &+\; U_2 \frac{\partial q_2}{\partial x} = \nu \nabla^4 \psi_2 - \gamma \nabla^2 \psi_2,\end{aligned} \tag{19.6}$$

where the layer-wise PV anomalies are defined as

$$q_1 = \nabla^2 \psi_1 + S_1\, (\psi_2 - \psi_1), \tag{19.7a}$$

$$q_2 = \nabla^2 \psi_2 + S_2\, (\psi_1 - \psi_2), \tag{19.7b}$$

and the external forcing is now represented by the terms containing U_1 and U_2. Then, the Reynolds number defined as

$$Re \;=\; \frac{(U_1 - U_2)\, Rd_1}{\nu}\,. \tag{19.8}$$

focuses on the eddies generated predominantly by baroclinic instability. Most of the multiple jet studies focus on flow regimes with moderately supercritical, background vertical shears, which ensure significant generation of eddies by the baroclinic instability. Since the eddy viscosity is meant to parameterize momentum transfers by unresolved small-scale motions, it is desirable to keep ν as small as possible [1], while simultaneously resolving the dynamical nonlinear interactions on the relevant small scales. This is the rational for computing solutions with progressively larger $Re,$ but it comes at the expense of progressively finer grid resolution.

An important dynamical property that quantifies effect of eddies on large-scale flow is the time-mean eddy forcing

$$F_i(x,y) = -\nabla\, \overline{\mathbf{u}_i'\, q_i'}, \tag{19.9}$$

which is the time-averaged eddy PV flux convergence typically calculated from the Reynolds decomposition of the flow, although other decompositions based on employing spatio-temporal filtering can be also applied. It is worth noting here, that full eddy forcing consists not only of the time-mean but also transient component, and the latter is not discussed in this chapter, because it is arguably much less important for the problem considered (e.g., in the context of baroclinic multiple jets, see Chemke and Kaspi, 2016a). In (19.9), $\mathbf{u}$ is the flow velocity, primes denote fluctuations around the time average, and overbar denotes time averaging over interval, which is long relative to the characteristic fast eddy times but short relative to the slow evolution time of the mean flow. According to (19.7a), (19.7b), eddy forcing can be decomposed into the stress components: convergence of the eddy relative-vorticity flux $F_i^{FS}(x,y)$ (or, equivalently, Reynolds stress) and convergence of the eddy heat flux $F_i^{FS}(x,y)$ (or, equivalently, form stress). Eddy forcing and its components can be also projected on the vertical barotropic and baroclinic modes, in order to characterize the modal interactions and vertical correlations. Since model (19.5)–(19.6) possesses zonal symmetry, the corresponding F_i and its stress components depend only on y. Analysis of spatial correlations between the stress components of F and the time-averaged flow solution can illuminate how eddy interactions maintain the jets.

19.3 Williams' and Panetta's milestones

The earliest multiple-jet simulations and study of the simplest baroclinic model (section 2) were carried out by Williams (1979) in application to the jovian atmosphere. Williams forced the eddies by the fixed and eastward [2], baroclinic background shear and considered two isopycnal layers of equal depth and horizontally double-periodic domain, and another influential paper that continued along these lines was by Panetta (1993c, hereafter, P93). In these solutions unstable shear generated mesoscale eddies and, eventually, a set of equilibrated multiple alternating jets with equally important barotropic and baroclinic components of the same sign (Fig. 19.2). Analysis of the flow solutions yielded discoveries and interesting observations, which profoundly influenced the field. First, Williams (1979) noticed the following: multiple jets are robust phenomenon occurring for a wide range of parameters; the statistically equilibrated flow regimes are reached after a long-time spin-up process; the jets always coexist with ambient transient eddies and have east-west asymmetry; and bottom drag weakens the jets and enhances their variability. These findings provided the basis for all future studies of the alternating baroclinic jets and were continued in P93.

First, P93 found that the spin-up transition from the perturbed state of rest is characterized by two stages: the initial exponential growth of the most unstable eddies and the following long period of the flow equilibration. Second, P93 noted that the equilibrated flow is characterized by the intrinsic low-frequency variability manifested by meridional migrations, mergers and meandering of the multiple jets (Fig. 19.3), as well as by intermittent bursts of eddy activity that switch from one side of a prograde eastward jet to the other. Third, P93 tested the baroclinic-adjustment conjecture of Stone (1978) within QG framework and showed that layer-wise PV gradients locally have opposite signs and relatively large magnitudes, thus, the multiple-jet flow does not have to adjust toward marginal stability. Fourth, P93 observed that the jets become more latent when the bottom friction coefficient γ increases. Fifth, P93 found

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[1] For example, in the ocean ν is estimated to be of the order of 1–10 $\mathrm{m}^2\ \mathrm{s}^{-1}$ (Muller, 1976), but QG models only begin to approach this range (Shevchenko and Berloff, 2015).

[2] Most of the later studies continued to focus on the eastward shear, although, westward shear is equally abundant in the oceans.

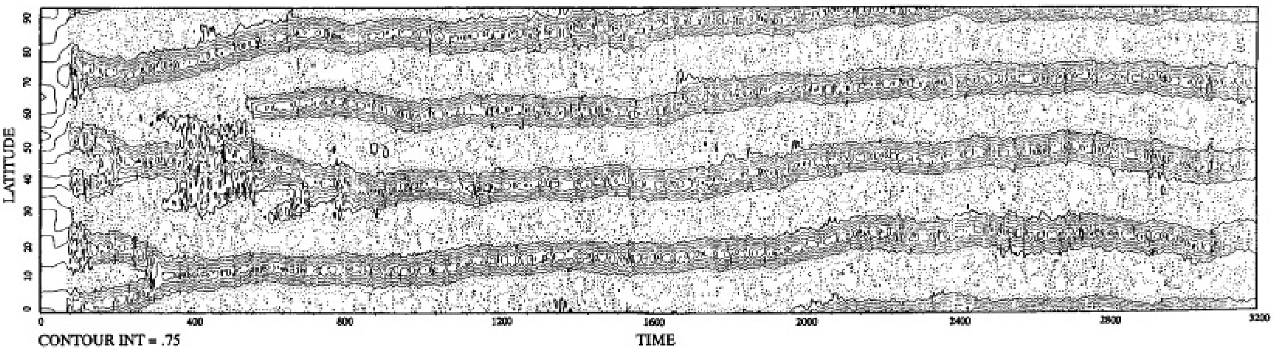

Figure 19.3 Adapted from Panetta (1993c). Large-scale low-frequency variability of the jets. Hovmuller diagram of zonally averaged upper-layer zonal flow as a function of time (in days) and latitude (in Rossby radii). ©American Meteorological Society. Used with permission.

that the eddy activities on the neighboring jets are largely uncorrelated from each other, thus, the eddies tend to be meridionally localized on their hosting jets. Sixth, P93 observed that the degree of PV homogenization between the eastward jets is weak relative to predictions by the randomly forced barotropic models, which are intentionally not discussed here. Seventh, P93 discovered that the jets are maintained by the Reynolds stress eddy forcing F_i^{RS} associated with upgradient momentum fluxes and resisted by the form stress eddy forcing F_i^{FS} associated with downgradient eddy buoyancy fluxes. Finally, P93 argued that the barotropic inverse energy cascade conjecture (Salmon (1980b); section 1.1) does not apply, because separation between the scales of eddy generation and maximum eddy energy is too small.

19.4 Dynamics in simple models

Below, we discuss in more detail the main research topics outlined in section 1.2 and addressed in idealized models and process studies since Williams (1979) and P93.

19.4.1 Inhomogeneity of background PV gradient

Most of the later baroclinic multiple jet studies have spatially homogeneous background PV gradients in each isopycnal layer, and this is convenient starting point, which allows to avoid extra length scales of the problem. In addition to meridional variation of the Coriolis parameter, there are several other sources of PV gradient inhomogeneity: (1) bottom topography and orography, (2) large-scale background circulation, and (3) spatially varying stratification. Simple-model studies, first, focused on (1), and later started to explore (2), whereas (3) was addressed only with GCMs. Existing studies show that PV gradient inhomogeneities have major effects on the multiple jets and ambient eddies. Treguier and Panetta (1994) considered meridionally inhomogeneous, zonal background flow and argued, that the larger is the flow inhomogeneity, the wider are the jets. Meridional boundary currents also make PV gradient inhomogeneous: linear stability analysis of nonzonal baroclinic currents shows, that they have radiating modes (Kamenkovich and Pedlosky, 1996a), which consist of multiple zonal jets in the interior of the basin, and this effect is more pronounced for the eastern boundary currents (Hristova et al., 2008a). Even if these radiating modes are weakly damped, they still can be excited by nonlinear interactions with the most unstable modes, which are trapped by the boundary current, as suggested by Wang et al. (2012b).

Details of random topography become increasingly important for multiple jets, as the length scale of the topographic features increases, and the dynamics becomes largely controlled by topography-trapped, stationary eddies (Treguier and Panetta, 1994; Thompson, 2010a). Such topography can braid the jets and control their widths, shapes and low-frequency variability, as well as the associated eddy-induced meridional transport (Thompson, 2010a). The low-frequency variability mechanism, which is similar to the one discovered by Hogg and Blundell (2006), is the following. At the outset of a typical cycle, flow with relatively strong multiple jets is strongly steered by topography, and at the same time available potential energy is large, eddy activity is weak, and the cross-jet transport is significantly suppressed. The non-zonality of the jet-like flow is the source of instability, which kicks in at small scales and grows to larger eddy scales, which are less controlled by the topography. These eddies substantially mix PV across the jet, and, therefore, the jet weakens. On the next stage the topographic steering is gradually restored, potential energy is built up, and the eddy activity weakens, then, the cycle is repeated.

Boland et al. (2012a) approached the problem from the other end and studied effect of a large-scale topographic slope with an arbitrary orientation. It was shown that the slope tilts the jets away from the strict zonality and aligns them perpendicular to the barotropic PV gradient (hence, the jets cross the layer-wise PV gradients). The PV conservation on fluid parcels results in the drift of the tilted jets across the domain. Chen et al. (2015a, 2016b) extended these results by studying baroclinic, nearly zonal and drifting jets in the presences of either meridional topographic ridge or wind-driven gyres. The former study showed that even in the far field these jets own their existence to the eddy forcing generated over the ridge, controlled by the ridge and acting via a nonlocal mechanism. The latter study revealed the jets more like driftting striations with eddy trains straddling them, propagating along them, and drifting together with them.

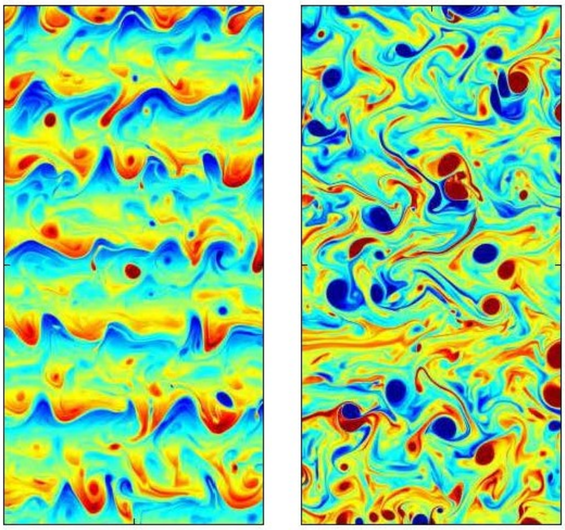

Figure 19.4 Adapted from Berloff et al. (2011a). Emergence of long-lived coherent vortices at large Reynolds numbers. Left panel: eastward background shear drives pronounced and strongly meandering set of jets, with the eastward jets acting as partial meridional transport barriers; isolated coherent vortices are relatively rare, weak and short-lived. Right panel: westward background shear drives very latent jets; isolated coherent vortices are abundant, strong and long-lived. Reproduced with the permission of Cambridge University Press.

19.4.2 Isolated coherent vortices

Numerous isolated coherent vortices (e.g., the Great Red Spot on Jupiter or numerous oceanic vortices) co-exist and interact with the multiple jets and wave-like eddies, therefore, they are an essential part of the story about multiple jets. However, neither vortex properties nor vortex interactions with the jets and eddies are properly understood, and general theory of β-plane nonlinear vortices living on unstable vertically and horizontally sheared flows has been never developed. Focusing on the Jupiter, Williams (1997) showed that coherent long-lived vortices are more easily generated by westward rather than eastward baroclinic shears; the vortices exhibit intrinsic oscillations and tend to have larger amplitudes at higher latitudes.

There are two main reason why effects of isolated coherent vortices on the jets are understudied in baroclinic models of the multiple jets. First, most of these models focus on eastward shears, which are less efficient for vortex generation. Second, the models operate at values of Re that are too small for spontaneous generation of vortices. Berloff et al. (2011a) reached much larger Re and discovered spontaneous generation of the vortices that co-exist with less coherent wave-like eddies. These vortices are more pronounced in the westward background shear (Fig. 19.4), in accord with Williams (1997). Most of the vortices are substantially "depth compensated", "shielded", and westward drifting. The vortices also drift meridionally, always down the PV gradient in each layer, in the opposite sense to predictions of the classical, single-layer theory of isolated vortices on the β-plane (McWilliams and Flierl, 1979).

19.4.3 Stochastic optimals

Another theory explains multiple jets as the "stochastic optimal" maintained by random eddy forcing (Farrell and Ioannou, 2008a, see also chapter 25 of this book). This study applies the stochastic structural stability theory to the quasi-linear model (DelSole and Farrell (1996a), in which interaction between the mean flow and eddies is greatly simplified: the dynamics is linearized around marginally stable pair of imposed zonal jets, whereas the eddy-eddy interactions are parameterized by a combination of stochastic excitation and effective dissipation; in addition, the baroclinic part of the solution is relaxed to the imposed jets. Although the model is formally baroclinic, it lacks nonlinearly equilibrated and dynamically consistent eddies generated by the baroclinic instability mechanism, and the eddy forcing is approximated by specific spatially homogeneous space-time correlated noise. Unlike this ansatz, dynamically consistent eddy forcing has significant and meridionally structured time-mean component, and the nonlinearly equilibrated jets are not marginally stable (e.g., P93 Berloff et al., 2009c,b). On the other hand, the stochastically excited eddies of Farrell and Ioannou are likely to be similar to the underlying linear normal modes (Berloff and Kamenkovich, 2013a,b) discussed in chapter 25.

19.4.4 Randomly forced jets

Randomly forced baroclinic model *without* fixed background flow explores the middle ground between artificially forced barotropic and naturally forced baroclinic models. Berloff (2005) considered a flow in an idealized closed basin, forced by random sources of PV. When the forcing is weak, a set of rectified multiple alternating jets is generated by the nonlinear interactions that involve interplay between the excited baroclinic basin modes and the secondary-instability modes feeding on them (see also study by LaCasce and Pedlosky, 2004, of the baroclinic basin modes). The jets tend to decay away from the western boundary and more so in the deep ocean. The temporally and zonally averaged zonal velocity does not exhibit asymmetry between the eastward and westward jets, as it is commonly found in the strong-jet regimes driven by unstable background shears.

The central result of this study is that the jets are controlled by the resonant basin modes obtained by linearization around the state of rest. The modes themselves can not maintain the jets, because they either lack meridional structure, or have inefficient nonlinear self-interactions, or are trapped near the western boundary. However, some of the modes have the secondary instabilities whose nonlinearly self-interactions produce eddy forcing maintaining the jets.

19.5 Nonlinear eddy forcing and jet formation

The time-mean eddy forcing that counteracts dissipation is required for the existence of stationary jets. How does this eddy forcing depend on the background flow and other parameters, and how do the jets feedback on it? All earlier studies (except

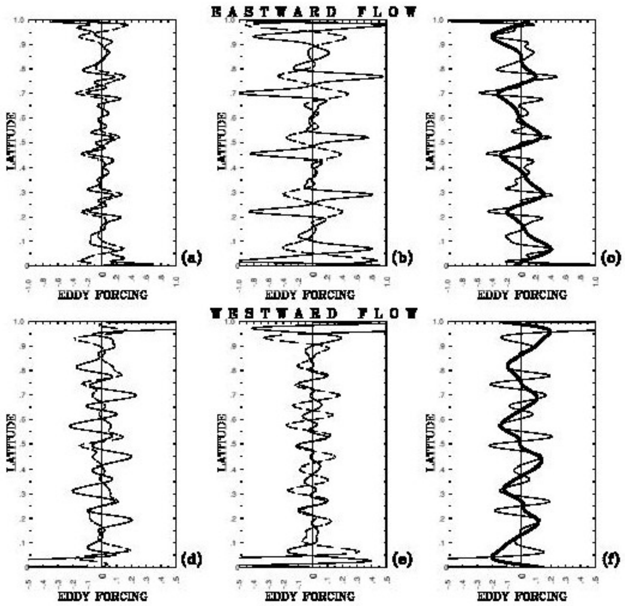

Figure 19.6 Adapted from Berloff et al. (2009c). Baroclinic time-mean eddy forcing and its components. Upper row: eastward background shear; lower row: westward background shear. [Left] barotropic-baroclinic (thin) and baroclinic-baroclinic (dashed curve) components; [middle] momentum (thin) and buoyancy (dashed curve) components; [right] full eddy forcing (thin) and time-mean baroclinic PV anomaly (thick curve). Eddy forcing and its components are shown with the same units, and PV profile is shown with arbitrary units. ©American Meteorological Society. Used with permission.

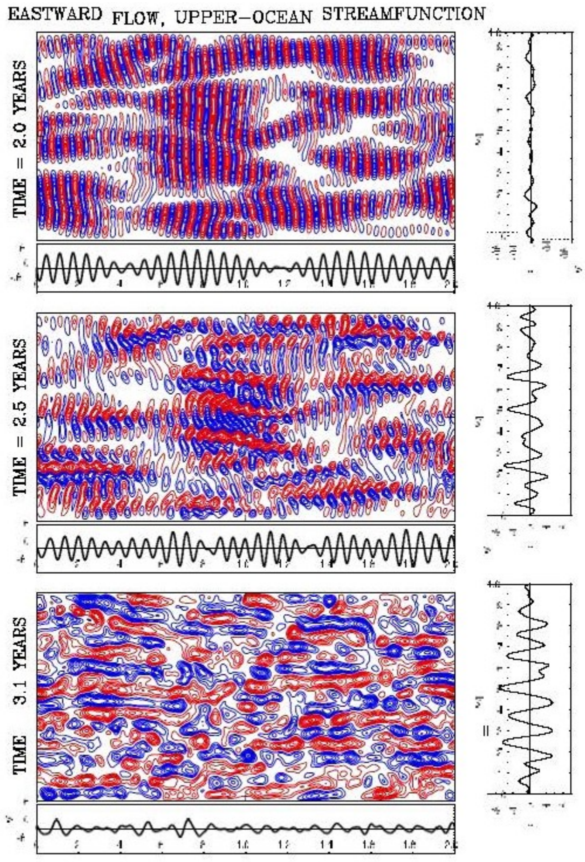

Figure 19.7 Adapted from Berloff et al. (2009b). Spin-up of the multiple jets. Color plots show instantaneous upper-layer velocity streamfunctions at different times. [Upper panel]: emergence of the

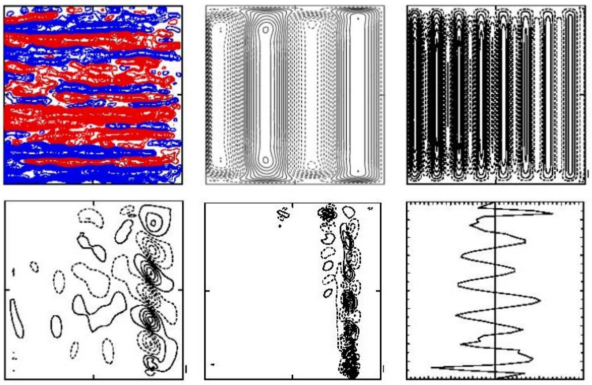

Figure 19.5 Adapted from Berloff (2005). Randomly forced multiple jets in a closed basin. Upper row: [left panel] time-mean jets, [middle panel] large-scale baroclinic basin mode, and [right panel] baroclinic basin mode with relatively short zonal scale (upper-ocean velocity streamfunction is shown in all panels). Lower row: [left panel] snapshot of the gravest parasitic instability mode (upper-ocean velocity streamfunction), [middle panel] the corresponding snapshot of the upper-ocean eddy forcing, and [right panel] zonal mean of the upper-ocean eddy forcing.

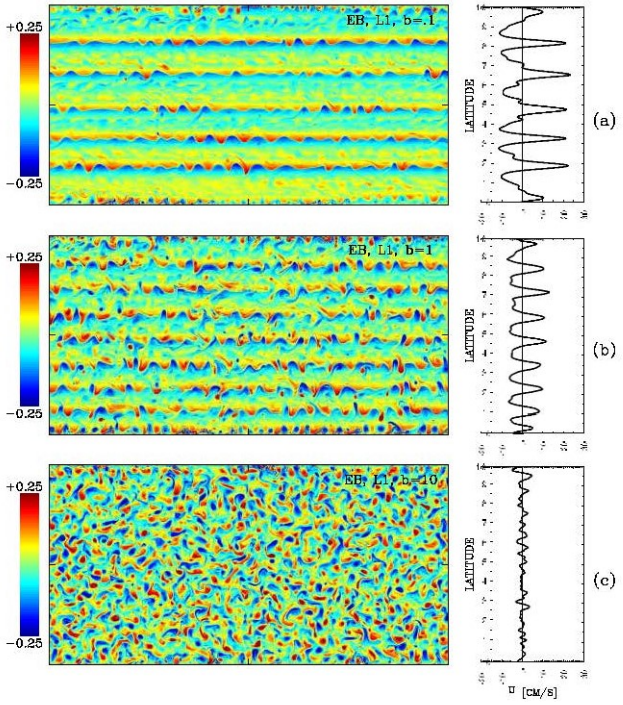

Figure 19.8 Adapted from Berloff et al. (2011a). Dependence of the large-Re flow regimes with multiple jets, eddies, and isolated coherent vortices on bottom friction. Solutions of the two-layer β-plane turbulence in the zonal channel are driven by a supercritical *eastward* baroclinic shear. Instantaneous upper-layer PV anomalies (color; normalized by the Coriolis parameter) are shown for (a) small, (b) medium, and (c) large value of the bottom friction coefficient; and the corresponding zonally averaged zonal velocity profiles are shown on the right panels. Reproduced with the permission of Cambridge University Press.

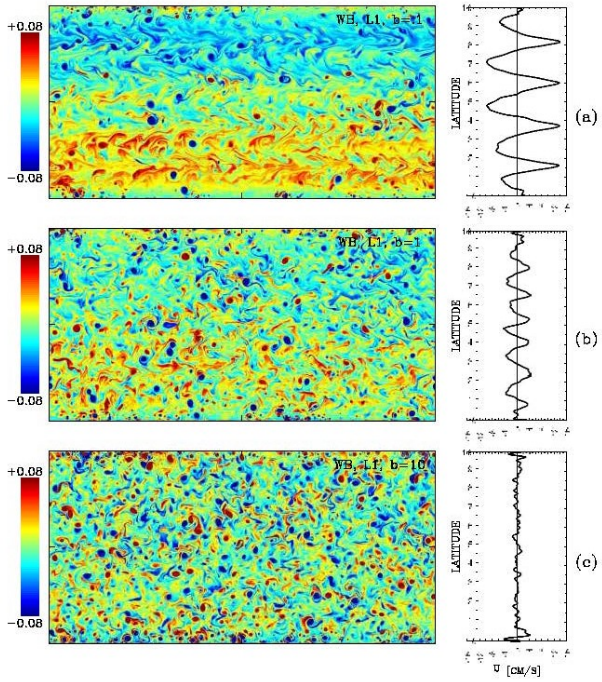

Figure 19.9 Adapted from Berloff et al. (2011a). The same as Fig. 19.8, but for a supercritical *westward* baroclinic shear. Note increasing latency of the alternating jets and the intensive generation of isolated coherent vortices. Reproduced with the permission of Cambridge University Press.

Williams, 1997) focused on the eastward background baroclinic shear, because it is more relevant for the jovian atmosphere. More recently, when alternating multiple jets were discovered in the ocean, it became clear that both westward and meridional background shears can also maintain the jets. Some of the oceanic jets stem from the eastern coasts, some others are steered by the bottom topography, but most of them occupy interior midlatitude ocean gyres and flow over relatively flat bottom. Large parts of the gyres are dominated by either eastward or westward baroclinic shear, and this justifies their analyses following below.

Multiple jets emerging in purely eastward and westward baroclinic shears were studied by Berloff et al. (2009c) in two- and three-layer models, and the underlying dynamics was illuminated with analysis of the eddy forcing components. In terms of the vertical mode interactions, it is shown that the barotropic-barotropic and baroclinic-baroclinic *time-mean* eddy forcings are equally important for maintaining the barotropic component of the jets. This result severely undermines relevance and utility of the barotropic models with purely random forcing. The barotropic component of the jets is maintained mostly by the barotropic and first baroclinic components of the eddy field, whereas, the baroclinic component of the jets is maintained by the first and second baroclinic components of the eddy field. Thus, interactions between barotropic and baroclinic modes play a key role in the dynamics. In the eastward baroclinic shear, the classical results (P93) are confirmed: the jets are maintained by the Reynolds stress eddy forcing, which is a "negative viscosity" phenomenon, but this process is largely balanced by the jet-resisting form stress forcing associated with the baroclinic instability of the jets, that is, by "positive diffusivity" (Fig. 19.6). In the westward baroclinic shear, the balance is completely opposite: the jets are maintained by "negative diffusivity", which is largely balanced by "positive viscosity" (Fig. 19.6).

The mechanism of the jet formation, starting from the perturbed state of rest and ending in the statistically equilibrated state, is illuminated by solving the following 3 linear stability problems, which are pertinent to the initial, intermediate and final stages of the flow spin-up and equilibration process. The first one is the primary instability of uniform background flow (classical Phillips problem) that predicts the fastest growing instability pattern in terms of the alternating meridional jets (a.k.a. "noodle modes;" Pedlosky, 1975a). The second one is the transverse instability of the flow which is a combination of the uniform background flow and the "noodle modes". This secondary instability sets the meridional scale of the emerging multiple jets to be about $15Rd_1$. It also efficiently projects on a few weakly damped, purely zonal linear normal modes, which grow in time and provide the template of the emerging multiple jets. Initially weak jets are east-west symmetric, in the sense that both prograde and retrograde jets have same shapes, but, as the jets become stronger, the east-west asymmetry develops, and the eastward jets become sharper and faster than the westward ones. The third linear stability problem studies progressive meridional localization of the eddies (starting from the primary-instability "noodle modes") on the emerging and growing zonal jets by considering a combination of the uniform background flow and finite-amplitude multiple jets as the background flow used for the linearization. This setup allows to analyze mutual feedbacks of the jets and eddies (see section 4.7) and also explains the bounding mechanism that limits growth of the jets: for excessively strong jets, the eddies straddling them become overlocalized meridionally, and the corresponding eddy forcing become inefficient in maintaining the jets.

19.6 Jet latency

Unlike the atmospheric jets, most of the oceanic ones are latent, that is, their amplitudes are weak relative to the ambient eddies, and the physical factors and mechanisms responsible for this difference are poorly understood. To characterize the jets, the isopycnal latency coefficient Λ can be defined so, that the larger it is, the more latent are the jets:

$$\Lambda = \left\langle \frac{\Sigma'}{\Sigma} \right\rangle^{1/2}, \tag{19.10a}$$

$$\Sigma = \frac{1}{A} \iint \langle q \rangle^2 dxdy, \tag{19.10b}$$

$$\Sigma' = \frac{1}{A} \iint \left[q - \langle q \rangle \right]^2 dxdy, \tag{19.10c}$$

where angular brackets denote time averaging; Σ is variance of the PV anomaly associated with the time-mean jets; Σ' is the variance of the ambient eddies; and averaging is done over the area A of the corresponding density level.

A factor increasing latency of the oceanic jets is presence of meridional boundaries around ocean basins. Berloff et al. (2009c) demonstrated that when zonal channel is closed with the meridional walls, the latency of the jets sharply increases, but properties of the eddy forcing (section 4.5) remain qualitatively the same. The underlying mechanism is simple: meridional boundaries remove zonally uniform linear normal modes that provide the template for the emerging multiple jets (section 4.5), and, therefore, the eddy forcing can excite only transient, zonally elongated normal modes, which are more prone to viscous dissipation. The other factor increasing the latency in a closed basin is excitation of the weakly damped, large-scale transient basin modes by the eddy forcing (Berloff, 2005). These modes induce meridional oscillations of the jets and, therefore, smear out and weaken the time-mean jets. Bottom friction is another factor controlling the latency of the jets: the larger is the friction parameter, γ, the more latent are the jets (Berloff et al., 2011a, see also Figs. 19.8 and 19.9), in accordance with the empirical relation $\Lambda \sim \gamma^{0.4}$. Also, the jets maintained by the eastward, rather than westward, vertical background shear are substantially more resistant to the bottom friction, and, therefore, less latent. Finally, large Reynolds number Re (i.e., small eddy viscosity ν) is also significant factor affecting the latency, because not only it increases the latency by energizing the eddies more than the jets, but also it enhances the sensitivity of the latency to the increasing bottom friction (Berloff et al., 2011a). What are the mechanisms controlling the latency via bottom friction? Strong bottom friction, first, selectively damps the barotropic zonal modes, which provide the template for the jets; and, second, it decreases efficiency of the barotropic eddy forcing, which maintains the barotropic component of the jets. In the eastward background case, the second mechanism is partially compensated by the increasing efficiency of the baroclinic eddy forcing, thus, making the jets in this flow regime significantly more resistant to the bottom friction.

19.7 Linear-dynamics control

One of the fundamentals about the multiple jets and ambient eddies is understanding to what extent and how properties of the eddies are controlled by the underlying linear dynamics. In this context, significant “linear control” means that some linear dynamics can be used for predicting properties of the nonlinearly equilibrated eddies, as well as of the eddy/jet interactions and mutual feedbacks. The main snag about finding a useful linearization is that it should be made (a) around the mean flow including the jets, rather than around the state of rest, and (b) without the common assumption about spatial scale separation between the jets and eddies.

First attempts to understand the linear-dynamics control focused on *the most unstable* linear normal modes and argued, that there are qualitative similarities between the normal-mode eddy forcing and the actual eddy forcing induced by the nonlinear eddies (Lee, 1997, 2005; Berloff et al., 2009b; Yoo and Lee, 2010). Although encouraging, these studies have several shortcomings. First, they focused on the small-Re flow regimes, in which the linear control is always stronger; second, they consider flow regimes with manifest jets and explored relatively narrow ranges of parameters; third, they focused only on the most unstable normal modes, thus, missing the other modes, which can also be energized by flow instabilities and nonlinear interactions.

More recent attempt to understand the linear control was made by Berloff and Kamenkovich (2013a,b); hereafter BK13), who systematically analyzed a hierarchy of flows containing multiple jets by comparing properties of the nonlinear eddies, defined as the fluctuations around the time-mean flow (including the jets), and the linear normal modes of the time-mean flow. Each linear normal mode is characterized by the dispersion relation, spatial structure, correlation with the jets, and the eddy forcing (i.e., nonlinear self-interaction of the mode) and its components. All these characteristics were used to interpret the nonlinear solutions, which were analyzed both in physical and spectral domains for a broad range of parameters. In each flow regime zonal dispersion properties of the nonlinear eddies were described by the corresponding zonal wavenumber/temporal frequency (i.e., k–ω) spectrum. Different parts of the spectrum were filtered out, inverted back to the physical space and interpreted as specific types of the eddies. It was shown that most patterns of the k–ω-filtered eddies, as well as their eddy forcings, are similar to those of the underlying (i.e., with the same k and ω) linear normal modes. It was shown that most of the spectral power is concentrated not on the most unstable normal modes, but on stable, zonally elongated low-frequency normal modes. This is because the nonlinear interactions transfer the energy toward the largest zonal scales and lowest frequencies, until the energy is dissipated by the bottom friction; this is consistent with other energy transfer studies (e.g. Chemke and Kaspi, 2015a). The bulk of these interactions is nonlocal, in the sense that the mesoscale energy bypasses the intermediate length scales and goes directly into the largest zonal-jet scales available in the system.

The multiple jets feed back on the normal modes and alter their properties. In the presence of noticeable jets, most of the normal modes become localized meridionally and straddle either westward or eastward individual jets, and the population of normal modes splits into several distinct *mode types*. Some of the modes are more efficient in terms of nonlinear interactions with the jets (note, that self-interaction of a normal mode forms perfect triads with zonally uniform modes), and they constitute most of the nonlinear eddy forcing (section 4.5). The normal modes of the same type have specific structures of the eddy forcing, as well as its Reynolds and form stress components, and their projections on the vertical modes, and in most parts of the corresponding k–ω space they are similar to the eddy forcing extracted from the full nonlinear model.

Extension of the linear control idea to more complicated flow regimes, and, especially, to those that lack spatial symmetries, remains to be completed. Recently, Chen et al. (2016b) confirmed local linear control over nonstationary and nearly zonal multiple jets in the oceanic gyres, but further extension to the eddies straddling these jets requires more sophisticated approaches.

To summarize, it is found that control imposed by the linear dynamics over anisotropic baroclinic turbulence is signifi-

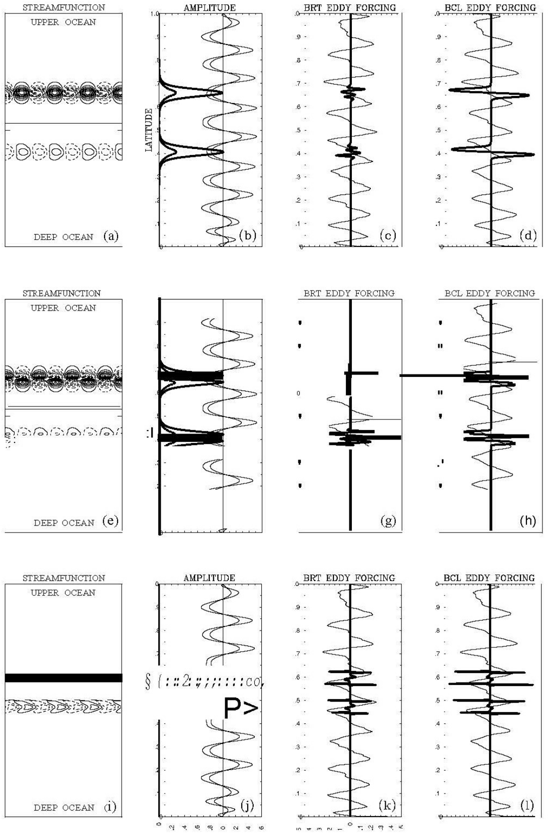

Figure 19.11 Adapted from Berloff et al. (2011a). Examples of some linear normal modes that are meridionally localized on the jets are shown along with the corresponding eddy forcing components. Upper, middle and low rows of panels illustrate properties of the type-1, type-2, and type-3 normal modes, respectively, that are localized on the jets from the middle of the channel. Left panels show velocity streamfunctions of the normalized normal modes (arbitrary units) in the upper and deep isopycnal layers, illustrated by the upper and lower fractions of the channel (divided by thin line corresponding to the middle of the central westward jet), respectively. Panels (b), (f) and (j) show amplitudes of the modes (thick curves; larger/smaller amplitudes correspond to the upper/deep layers), normalized by their maximum upper-ocean value. The corresponding time-mean velocity profiles are scaled by arbitrary value and shown to the right with thin curves positioned around unity. Panels (c), (g) and (k) show barotropic eddy forcings (thick curves) of the corresponding normal modes. Panels (d), (h) and (l) show the corresponding baroclinic eddy forcings (thick curves). Each eddy forcing curve is normalized by the maximum absolute value of the baroclinic eddy forcing, and the time-mean PV anomalies corresponding to the jets are shown with thin curves (arbitrary amplitudes). Reproduced with the permission of Cambridge University Press.

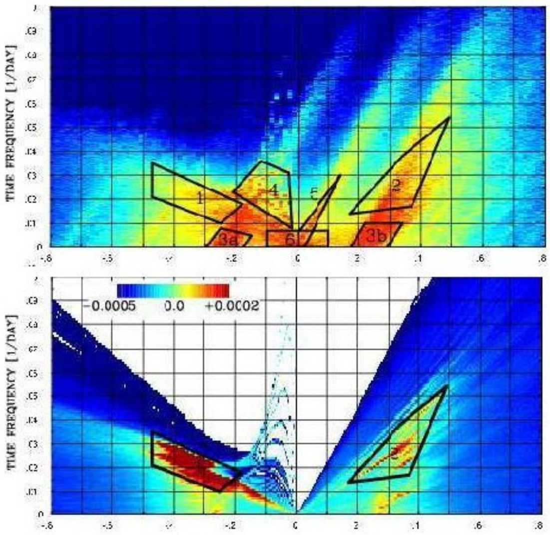

Figure 19.10 Adapted from Berloff and Kamenkovich (2013a,b). Nonlinear and linear k–ω spectra of the eddies. Upper panel: k–ω spectrum of a nonlinear flow solution with eastward background shear and manifest multiple jets. Lower panel: the corresponding ensemble-averaged linear spectrum (blue/red color indicates stable/unstable mode growth rates; white color shows that normal modes are absent). Horizontal axis indicates zonal wavenumbers, and negative values correspond to westward propagating phase. Outlined quadrangles indicate spectral regions used for spectral filtering. ©American Meteorological Society. Used with permission.

cant even at large Re, and this provides potential for improving predictions and closures for the eddies and eddy/jet nonlinear interactions.

19.8 Dynamics in GCMs

General circulation models (GCMs) are formulated in terms of the (hydrostatic or nonhydrostatic) primitive equations and, therefore, they have two main advantages over the quasi-geostrophic models. First, GCMs contain more physics, such as diabatic processes, two-way interactions between motions and mean stratification, compressibility of the atmospheres, non-geostrophic momentum balances and explicit vertical motions, and, second, comprehensive GCM simulations can be directly compared with available observations. Below, we describe the main findings about the baroclinic multiple jets from planetary atmospheric and oceanic GCMs.

19.8.1 Atmospheric models

Most of the atmospheric studies deal with Jupiter's weather layer, which is characterized by three distinct regions: (i) the nearly vortex-free equatorial region with broad super-rotating eastward current; (ii) the middle latitudes populated by manifest jets, eddies and coherent vortices; and (iii) the high latitudes populated by latent jets and eddies. Our focus here is on the middle and high latitudes. Below the weather layer, the atmospheric circulation is widely assumed to be organized in terms of cylinders aligned with the axis of rotation (Fig. 4.30 in chapter **??**). The motions along these cylinders are largely uncertain, with two extreme views being adopted: one in which the jets and eddies are concentrated in the thin weather layer, and

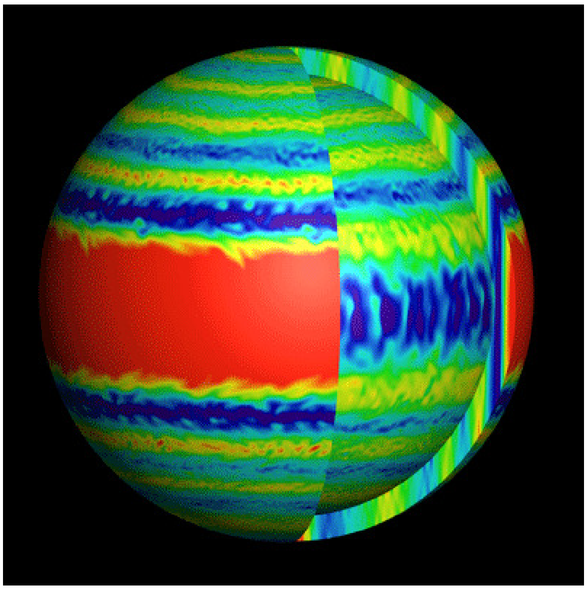

Figure 19.12 Adapted from Heimpel et al. (2005). Snapshot of the azimuthal velocity field from the simulation of the Jupiter atmosphere circulation. Reprinted by permission from Macmillan Publishers Ltd.

layer that leads to baroclinic instability and eddy generation, and (b) convective heating from the deep interior (in case the GCM focuses on the shallow weather layer and does not solve for the deep interior) that is viewed in terms of localized and intermittent forcing events. In GCMs the former type of forcing can be explicitly simulated (Kaspi et al., 2009), represented by adding restoring terms to the momentum equation (Showman et al. (2006)), represented by large-scale heating gradient (Williams, 2003; O'Gorman and Schneider, 2007) or intrinsic heating (Liu and Schneider, 2010). However, even the nature of the forcing does not necessarily determine the vertical structure of the jets. In particular, the surface-confined forcing can lead to the formation of deep jets due to the effect of ageostrophic meridional overturning cells (Showman et al., 2006; O'Gorman and Schneider, 2007; Lian and Showman, 2008). This connection indicates importance of explicit baroclinic processes even for the barotorpic jets. O'Gorman and Schneider (2007) further argued that in this regard the terrestrial oceans are different, since their deep interior is largely adiabatic and geostrophic motions at all depths are required to balance the ageostrophic overturning. However, the diabatic effects in the deep ocean can also be significant (section 5.2), and the similarity between Jupiter and terrestrial oceans can be greater than anticipated. Alternatively, it was argued that even surface-intensified jets and eddies can be due to the deep forcing (e.g. Kaspi et al., 2009).

Unlike in quasigeostrophic models, in primitive-equation models baroclinic eddies can feed back on the vertical stratification and alter its static stability. It was argued that the baroclinic jet dynamics is capable of increasing the static stability (O'Gorman and Schneider, 2007), which, in turn, leads to the shallower jets and overall limits vertical penetration of motions (Showman et al., 2006). It was also argued that the fluid compressibility has similar effect and leads to the surface intensification of the jets (Kaspi et al., 2009). GCMs allow for deeper studies of how the stratification influences horizontal structure and robustness of the jets. Along these lines Sayanagi et al. (2008) demonstrated that long Rossby deformation radius Rd_1 leads to manifest multiple jets, whereas short Rd_1 in combination with long Rhines scale leads to vortex-dominated flow regime — this may explain the observed latitudinal variations of the jovian jet latency. Williams (2003) explored the importance of stratification by contrasting two static density profiles, which result in either stationary jets or jets migrating toward the equator. Furthemore, Williams (2003) argued that the baroclinic eddy forcing is crucial for maintaining the multiple jets, and the eastward jets are maintained by converging eddy fluxes of momentum, like in the earlier quasigeostrophic predictions (section 4). Observations and energy balance arguments also indicate that the key eddy forcing is baroclinic (Liu and Schneider, 2010).

To test the idea that moist convection can also drive the multiple jets, Lian and Showman (2008) included an active hydrological cycle and found that the latent heating generates baroclinic eddies that lead to an upscale energy transfer and multiple jets. The resulting jet patterns, including the directions of either subrotating or superrotating equatorial jets, were consistent with all the four gas giant planets.

Recently, Kaspi et al. (2009) developed a non-hydrostatic and compressible model of Jupiter in the anelastic approximation, which is more appropriate for the large density variations of the jovian atmosphere, than the traditional Boussinesq approximation, and argued that the included new physics leads to the surface-intensified structure of the jets. As a result, the dynamical balances become altered: traditionally ignored parts of the Coriolis term become important; the modified thermal-wind relation implies that the velocity shear in the direction parallel to the rotation axis depends on the vertical stratification term. The baroclinic vorticity production is, thus, altered by compressibility, and as a result, convective eddy structures drive eddy angular momentum fluxes across the Taylor columns and transfer the momentum to the exterior of the planet.

On the basis of GCM simulations, Chemke and Kaspi (2015a,b) studied the properties of multiple jets as a function of latitude and argued that baroclinic multiple jets have widths controlled by the Rhines scale based on vertically integrated eddy kinetic energy, rather than by local baroclinic deformation radius. They also showed that the jets drift poleward due to the poleward bias in baroclinicity parameter (i.e., the local Eady growth rate), which causes poleward bias in eddy momentum flux convergence. To what extent all these properties are controlled by the underlying linear dynamics (section 4.7) remains to be understood.

19.8.2 Oceanic models

Spatial resolution remains the main limiting factor of the ocean general circulation models (OGCMs), although, they are now capable of resolving substantial part of mesoscale motions. Vertically coherent, multiple zonal jets have been obtained in several high-resolution OGCM simulations (Masumoto et al., 2004; Nakano and Hasumi, 2005a; Richards et al., 2006a; Kamenkovich et al., 2009d; Melnichenko et al., 2010a). These jets are latent, upper-ocean intensified, and with equally strong

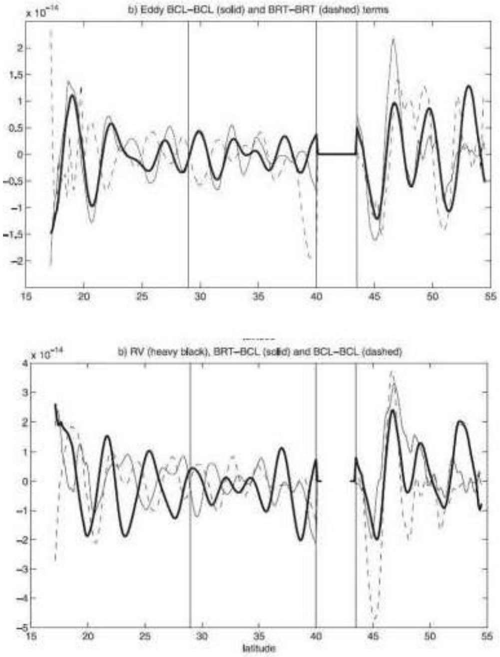

Figure 19.14 Adapted from Kamenkovich et al. (2009d). Roles of eddies in supporting barotropic and baroclinic jets (see the text). Upper panel: Zonal-mean BRT-BRT (dashed) and BCL-BCL (thin solid) eddy forcings for the barotropic jets. The zonal-mean barotropic relative vorticity, scaled to be comparable in magnitude to the advective terms, is shown by the heavy solid line. Lower panel: Zonal-mean BRT-BCL (solid) and BCL-BCL (dashed) eddy forcings for the baroclinic jets. The zonal-mean baroclinic relative vorticity, scaled to be comparable in magnitude to the advective terms, is shown by the heavy solid line. ©American Meteorological Society. Used with permission.

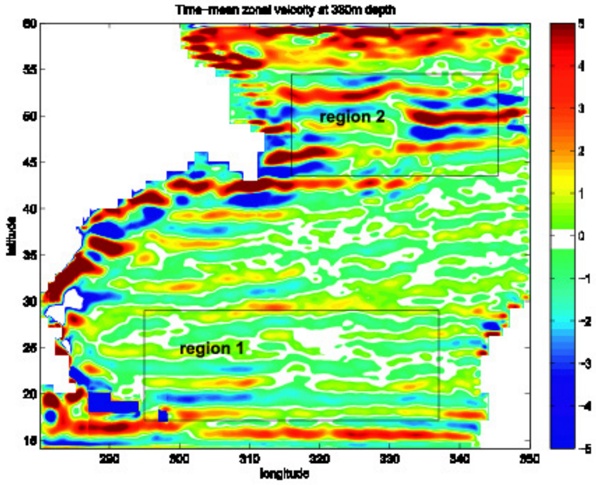

Figure 19.13 Adapted from Kamenkovich et al. (2009d). Multiple alternating jets simulated by a comprehensive, eddy-resolving GCM of the North Atlantic. Shown is zonal velocity at 500 m depth and averaged over 9 years. Outlined rectangles indicate dynamically distinct regions 1 and 2 characterized by the eastward and westward large-scale baroclinic shears, respectively. ©American Meteorological Society. Used with permission.

barotropic and baroclinic components (Fig. 19.13). In agreement with quasigeostrophic results, the barotropic and baroclinic dynamics are strongly coupled. Kamenkovich et al. (2009d) analyzed this coupling by examining the time-mean balances for the buoyancy, relative and potential vorticity, in an OGCM of the North Atlantic. The time-mean balance for the relative vorticity can be written as

$$\overline{\mathbf{u}' \cdot \nabla q'} = -\overline{\mathbf{u}} \cdot \nabla \overline{q} - \beta \overline{b} \overline{f u'} + f\,\overline{\frac{\partial w}{\partial z}} + \overline{\Phi} + \overline{F} + \overline{D}\,, \quad (19.11)$$

where $\mathbf{u}$ is the three-dimensional velocity (u, v, w), overbar stands for the time averaging ("mean part") and primes denote flow perturbations. The (small) term $\overline{\Phi}$ stands for the combined effect of nonlinear stretching and vertical component of the baroclinic vector, and $\overline{D}$ is the time-mean dissipation. The above equation is the balance between the eddy forcing on the left-hand side and the mean advection (first and second terms) and stretching (third term) on the right-hand side. Note that the first three mean terms are zero in simple zonal-channel flows discussed in section 4, but they are large in comprehensive OGCM simulations.

Spatial correlations between the terms in (19.11) and the time-mean jet anomalies quantify roles of the eddy forcing in the jet dynamics: a positive correlation implies that the term maintains the jets. Kamenkovich et al. (2009d) demonstrated that the eddy forcing supports the jets and gained further insight by projecting flow onto barotropic and baroclinic components:

$$\begin{aligned} \mathbf{u}' \cdot \nabla q' \quad &= \quad \langle \mathbf{u}'^* \cdot \nabla q'^* \rangle + \overline{\mathbf{u}'^* \cdot \langle \nabla q' \rangle} + \overline{\langle \mathbf{u}' \rangle \cdot \nabla q'^*} \\ &+ \quad \langle \mathbf{u}' \rangle \cdot \langle \nabla q' \rangle + \left(\overline{\mathbf{u}'^* \cdot \nabla q'^*} \right)^*, \end{aligned} \quad (19.12)$$

where the angle brackets stand for the vertical averaging, and asterix stands for the deviation from the vertical average. The first rhs term is the vertically averaged baroclinic-baroclinic (BCL-BCL) interaction that represents the action of baroclinic eddies on the barotropic mode; it acts to sustain the barotropic jets (Fig. 19.14a). As in zonally symmetric quasigeostrophic flows (section 4), this result outlines the fundamental challenges in representing the barotropic component of the jets with purely random forcing representing baroclinic eddy effects. The second and third terms (BRT-BCL) provide jet-resisting effect (spatial correlation with the jets is -0.4) of the barotropic-baroclinic eddy interactions. Significance of the eddy forcing and mean-advection terms in the dynamical balance was also reported by Melnichenko et al. (2010a), but the vertical-mode decomposition and the spatial correlations were not explored. Kamenkovich et al. (2009d) also carried out analysis of the eddy forcing role for the banded jet-like structures in the density and PV fields. The main conclusion for the density balance is that, in most of the subtropical gyre, the eddy-induced density advection acts to sustain the isopycnal height anomalies, which support vertical shear in the jets. This finding is in disagreement with the common assumption that eddies tend to flatten isopycnals, and in agreement with the quasigeostrophic "negative diffusivity" eddy effects discussed in section 4.

In the ocean gyres, the multiple zonal jets cross the mean PV contours and the resulting divergence of the mean PV advection is largely compensated by the eddy PV advection (Melnichenko et al. (2010a)), therefore, one can argue that the jets are driven across the mean PV contours by the eddy forcing. Divergence of the eddy heat fluxes (i.e., form stress) plays an important role in the dynamical balance. The PV balance is complex, and there are diabatic terms due to the vertical mixing that tend to compensate the form stress (Kamenkovich et al. (2009d)). The diabatic effects are expected to be strong in the deep ocean around rough topography, and this effect is somewhat analogous to the deep-interior diabatic processes in jovian atmosphere.

To summarize, analysis of the OGCM-simulated jets reveals the key roles of the eddy forcing and interactions between baroclinic and barotropic eddies, in overall agreement with the quasigeostrophic predictions. Effects of the mean advection are also found important, but the quasigeostrophic models have not yet addressed them.

19.9 Future research avenues

Although research on the dynamics of baroclinic multiple jets noticeably accelerated over the last decade, the scope of the open questions only broadened. Some important future research avenues are summarized and discussed below.

19.9.1 New physical effects

Progress is needed in understanding the recently discovered physical phenomena pertinent to the multiple jets. First, the robust linear-dynamics control of the eddies was demonstrated in idealized large-Re flow regimes (BK13a,b), but the physical limits of this control remain unexplored and unmarked. Second, neither equatorward drift of the jets (Williams (2003) nor low-frequency variability, migrations and tilts of the jets (e.g., Thompson (2010a) are properly understood. Third, effects of the lateral boundaries—relevant only for the oceanic jets—are large but poorly understood. Fourth, at the largest Re considered, in addition to the eddies and jets, populations of isolated, coherent and long-living vortices are generated by the ambient flow. Neither statistical description nor dynamical understanding of these vortices is minimally satisfactory. Moreover, theory is absent for dynamically consistent, long-living, isolated coherent vortices in the vertical and horizontal velocity shears, on the β-plane.

19.9.2 Extended hierarchy of models

Progress is needed in completing the hierarchy of baroclinic models for systematic studies of the physical processes affecting the jets, because it is highly plausible that different jets in nature are maintained by different dynamical mechanisms. Despite significant progress, the model hierarchy is still poorly developed in the following directions. First, progressively more realistic background flows generating the eddies and, ultimately, the jets should be explored. Second, the hierarchy of models remains poorly explored in strongly nonlinear regimes characterized by larger Re and broader range of dynamically active scales. Achieving larger Re requires not only more efficient numerical algorithms, but also finer computational grids that steeply rise the computational costs. For example, even in the simple quasigeostrophic framework, the grid resolution required for capturing PV dynamics is ~ 1 km, and it will take another decade to reach this level for routine simulations. Third, the hierarchy of models used for process studies must be further extended to account for non-quasigeostrophic effects, such as spatially varying stratification, geostrophically unbalanced dynamics, and steep bottom topography (for the oceanic jets). In this context, there is a striking gap: the multiple jets problem has never been addressed in idealized primitive-equation models at large Reynolds numbers, which is a natural conceptual link between the intensively studied quasigeostrophic dynamics and poorly understood dynamics of GCMs. The most physically complete models in the explored hierarchy are to be the comprehensive primitive-equation models that have all the important physical processes (e.g., realistic stratification, steep topography and ageostrophic motions). The corresponding solutions are, however, computationally most demanding because of both complexity of the equations and long equilibration times of the deep atmospheres and oceans.

19.9.3 Wave turbulence theory

Evidence suggesting that the underlying dynamics can be understood in terms of the nonlinearly interacting "waves", which are the linear normal modes of the mean flow, appeals to study in details the corresponding triad interactions and energy transfers. Wave turbulence description of these interactions may be feasible and useful (Nazarenko, 2011b) but remains completely unexplored in the context of baroclinic jets discussed in this chapter.