Geoturb

Numerical modeling and theoretical challenges in atmosphere and ocean turbulence

October 2-4, 2013

Centre Blaise Pascal, ENS Lyon, France

CBP Centre Blaise Pascal FLMSN Université de Lyon CNRS ENS de Lyon

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PROGRAM

Wednesday

08:45-09:30	Joël SOMMERIA: *Bistability and equilibrium statistical mechanics in quasi-geostrophic flows*
09:30-10:15	Achim WIRTH: *Inertia-gravity waves generated by near balanced flow*
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14:00-14:45	*ANTOINE VENAILLE: Energy partition in freely evolving shallow water flows*
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Bistability and equilibrium statistical mechanics in quasi-geostrophic flows

Sommeria Joel [1], Mathur Manikandan [1]

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Equilibrium statistical mechanics predicts that 2D turbulence confined to a bounded domain self-organises into a mean flow as the inverse energy cascade piles up at the largest available scale. The choice between two symmetric states can result in a phase transition with symmetry breaking. In the presence of forcing and dissipation we expect the occurrence of random switching between the two states separated by long periods of persistence. Examples from laboratory experiments and numerical simulations will be given.

Bistability is observed in the atmosphere as a switch between a blocked state, during which a big anticyclone persists on a continent, and the more usual propagating planetary waves. Similarly the Kuroshio oceanic current near Japan switches between two configurations over a typically ten year time period. In these geophysical examples, Coriolis effects in the presence of large scale topography play an important role. Bistability has been previously reproduced in a annular tank by Tian et a. (1997) where an azimuthal jet interacts with a radial topography superimposed to a conical bottom aimed at reproducing the azimuthal propagation of planetary waves. Infrequent switches between these two sates have been observed. We have reproduced similar experiments leading also to bistability, but remarkably no switches are observed in spite of intense fluctuations. A third regime has been also identified with a more complex step-like features in phase ropagation.
Preliminary comparisons with a numerical model will be discussed. This problem is quite difficult because of the long time scale involved and the importance of boundary layer detachment from the lateral walls, which seems to be involved in the switching mechanism.

Inertia-Gravity Waves generated by near Balanced Flow

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Using a fine resolution numerical model ($4000^2 \times 2$ grid-points) of the two layer shallow-water equations of the mid-latitude β-plane dynamics, it is shown that there is no sudden breakdown of balance in the turbulent enstrophy-cascade but a faint and continuous emission of inertia gravity waves.
The wave energy accumulates in the equator-ward region of the domain due to the Coriolis parameter depending on latitude
and the dispersion relation of inertia gravity waves.

The quasi-geostrophic Eliassen-Palm flux tensor

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Geostrophic ocean eddies are often parameterised either via the Gent and McWilliams closure, or via a closure for the eddy potential vorticity fluxes (which are typically assumed to be down-gradient). The former has demonstrated utility in global ocean modelling, and is a popular choice in practice, but neglects the dynamical influence of horizontal Reynolds' stresses. The latter leads to the required generation of eddy enstrophy, but easily violates momentum conservation.
Here we describe, in a quasi-geostrophic context, the relationship between eddy momentum and buoyancy fluxes, and the eddy potential vorticity fluxes. The eddy-mean-flow interaction is more generally classified in terms of an eddy momentum stress tensor -- the Eliassen-Palm flux tensor -- whose divergence yields the eddy potential vorticity fluxes. Closures for this object can preserve the geometric structure of the interaction and conserve momentum naturally. The structure of the Eliassen-Palm flux tensor will be described, and links to eddy transport properties provided. The relationship to the more general primitive equation case will be outlined.

Eddy-modulated, near-inertial turbulence

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The horizontal velocity vector of linear, internal gravity waves rotates anticyclonically. Rotary spectra allow the decomposition of near-inertial currents into motions consistent and not consistent with internal waves. We explore the importance of the non-wave component, denoting this as «near-inertial turbulence». In both the Northern and Southern Hemisphere the internal waves dominated with near-inertial turbulence accounting for about 10% to 20% of the near--inertial variability. The monthly internal wave energy was found, unsurprisingly, to be uncorrelated with the monthly mean currents. In contrast, the monthly-mean super-inertial turbulence was significantly correlated with the monthly mean currents.

Energy partition freely evolving shallow water flows

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Statistical mechanics approach for turbulent geophysical flows is a powerful theoretical tool to predict self-organization of these flows. Previous application of this theory have been restricted to quasi-geostrophic equations. Here we consider the more general shallow water equations that include gravity waves and allow for energy transfer toward small scales through waves. We show explicit computation of statistical equilibrium states for this model. These results are used to predict the amount of energy that should be transferred into waves or into a large scale geostrophic circulation for a given initial condition.

On the Kelvin-Helmholtz Instability with a Free Surface

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The well-posedness of the hydrostatic equations is linked to long wave stability criteria for parallel shear flows. In this talk, we revisit the Kelvin-Helmholtz instability with free surface at the top. This is a joint work with Michaël Renardy.

Direct and inverse cascades in rotating stably-stratified turbulence

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The concept of interscale energy cascade is well used in turbulence, but is often very superficially supported by rationale. What is the cause for the direction of this cascade, direct (towards smallest scales), inverse or other (e.g. transverse, by Horton et al. in homogeneous shear flows) ? I propose to discuss two important points, the number of invariants and the anisotropic structure. For instance, it is well known that conservation of both energy and enstrophy is a prerequisite for the inverse cascade in 2D unbounded turbulence, but such inverse cascade is not found in a strongly stratified fluid, in which both energy and potential vorticity (or toroidal mode) are (quasi) invariant: The strong and typical anisotropy of the toroidal cascade gives an explanation. In addition to a review of the problem in my team for rotating stratified turbulence, I will discuss new recent DNS results from Marino, Pouquet and Minnini on the occurrence of a remarkable inverse cascade when the Coriolis parameter f is close to the stratification frequency N. The case f = N merits particular attention, because strict 3D isotropy is permitted by dynamical equations, allowing a simplified analysis.

Limits of balance in rotating stratified flows

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A major unresolved question is: «under what conditions does a rotating, stably-stratified flow exhibit a forward energy cascade at small scales?» Put a different way, «what conditions lead to the breakdown of (geostrophic, hydrostatic or higher-order) balance?»
This question has been the subject of many papers, with no consensus. The key issue is: can an initially balanced flow spontaneously generate a significant amount of inertia?gravity waves? Moreover, do these waves ? via nonlinear interactions ? exhibit a forward energy cascade, possibly explaining the transition from a k ?3 intermediate to large-scale spectrum to a k ?5/3 small-scale spectrum claimed to exist in the Earth's atmosphere (Gage & Nastrom, 1985)?
A number of researchers claim that ageostrophic motions, developing from a loss of balance in an initially balanced flow, lead to a downscale energy flux ? a direct internal route for a flow to cascade to small scales, independent of boundary influences (Bartello 1985, Molemaker et al. 2005, Waite & Bartello 2006, Bartello 2010, Nadiga & Straub 2010, Nadiga 2013). These studies have considered the prototype non-hydrostatic Boussinesq equations, the simplest fluid dynamical model
containing both balanced vortical motions and unbalanced inertia?gravity waves, in a simple triply-periodic geometry (no boundaries). Other studies considering the same equations, however, have reached strongly contrasting conclusions (Dritschel & Viúdez 2003, 2007; Viúdez & Dritschel 2003, 2004, 2006; McKiver & Dritschel 2008). Instead of finding a direct energy cascade of ageostrophic motions to small scales, these studies demonstrated an extraordinarily weak generation of inertia?gravity waves and a near-complete dominance of balanced, vortical motions.
What could explain the differences? First, the latter studies better prepared the initial conditions to reduce the initial imbalance. Second, the latter studies used explicit potential vorticity conservation and a variable transformation to separate balanced and unbalanced motions at leading order (thermal-wind balance). This demonstrably reduces the false, numerical generation of inertia?gravity waves. Third, the latter studies used an anisotropic grid, with the vertical to horizontal grid box ratio scaling with the ratio f /N (Coriolis to buoyancy frequency), whereas the former studies used an isotropic grid.
This talk will discuss these and other differences, and propose a way forward to distinguish regimes of motion dominated by balance (as observed in the latter studies) from those exhibiting a strong degree of imbalance.

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Towards a simple stochastic correction of kinetic energy spectra in fluids

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Both conservative and diffusive truncations of inviscid fluid models fail to capture the correct power law scaling of the kinetic energy spectrum at small scales. This scaling is important both for downscale transport of vorticity and energy, as for small upscale `backscatter' that influences variance. In this talk we discuss progress towards a simple correction using a stochastic thermostat approach from molecular dynamics. Thermostats are used in MD to perturb dynamics such that trajectories are ergodic in the canonical Gibbs measure (constant temperature). To apply these methods to discretized fluids, several challenges must be met: (i) we perturb only the smallest scales, hence controllability must be established; (ii) we are given expectations (kinetic energy spectrum) instead of invariant measure; (iii) we have to deal with forcing at low wave numbers; (iv) experience from heat conduction problems suggests that artifacts may occur. We report recent progress on these fronts.

Spontaneous low-frequency variability of the eddying ocean circulation: an OGCM study.

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Idealized studies have shown that the nonlinear ocean circulation may spontaneously generate 1-10 year variability under constant/seasonal atmospheric forcing; this chaotic phenomenon gets stronger with increasing Reynolds number and affects the horizontal circulation. Whether mesoscale turbulence directly feeds this low-frequency variability (e.g. Berloff et al 2007, Arbic et al. 2012) and/or favors random transitions between the oceanic system's multiple stable states (e.g. Hazeleger and Drijfhout 2000, Dijkstra and Ghil 2005) is still under debate.
Several primitive-equation global ocean simulations are being investigated to study the imprints of this intrinsic variability on observed climate-relevant quantities (sea-surface height/ temperature, meridional overturning circulation, etc). Intrinsic variance is negligeable in laminar IPCC-like (~2°) ocean models but becomes important when oceanic eddies are simulated ; in strong eddy-active regions, most low-frequency variance is produced intrinsically with secondary influence of the low-frequency atmospheric variability. Intrinsic variability features are depicted globally, and in more detail in the Gulf Stream area and in the ACC (patterns, spatio-temporal scales, variables concerned). These results suggest that eddying ocean models used in future climate predictions may yield a more chaotic variability, possibly impacting the overlying atmosphere; these results call for the investigation of nonlinear sources of intrinsic variability in "realistic" ocean simulations.

The Role of Jets in Mixing Across a Continental Shelf Break

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What controls mixing across a continental shelf break is considered using a high horizontal resolution quasigeostrophic model. The geometry is an idealized turbulent channel flow representing the circumpolar current and interacting with a sloping shelf topography. Results show that there are essentially three regimes controlling the mixing according to the width of the continental shelf break: (1) for very sharp shelves, mixing is continuous and no jet is observed on the shelf break, (2) for intermediate widths, a very strong and stable jet is observed on the shelf break, but becomes periodically unstable (leading to major mixing events), and (3) for wide shelves, a multiple jets regime is observed and mixing events are smaller but more frequent. An argument invoking baroclinic instability is used to explain these results. Experiments using a sinusoidal shelf break were also carried out. These show a behavior similar to that described above in the very long and very short shelf break wavelength limits. However, the jet formation can be totally suppressed when the wavelength of the shelf break corresponds to the typical size of an eddy.

A general statistical mechanical approach for deriving parametrizations

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We consider the problem of deriving approximate autonomous dynamics for a number of variables of a dynamical system, which are weakly coupled to the remaining variables. Our findings have relevance for the construction of parametrizations of unresolved processes in many non-equilibrium systems, and most notably in geophysical fluid dynamics. We first propose a systematic way to construct a surrogate dynamics, such that the expectation value of any observable agrees, up to second order in the coupling strength, to its expectation evaluated on the full dynamics. By direct calculation, we find that, at first order, the coupling can be surrogated by adding a deterministic perturbation to the autonomous dynamics of the system of interest. At second order, there are two separate and very different contributions. One is a term taking into account the second order contributions of the fluctuations in the coupling, which can be parametrized as a stochastic forcing with given spectral properties. The other one is a memory term, coupling the system of interest to its previous history, through the correlations of the second system. If these correlations are known, this effect can be implemented as a perturbation with memory on the single system. Furthermore, we show that such surrogate dynamics agrees up to second order to an expansion of the Mori-Zwanzig projected dynamics. This implies that the parametrizations of unresolved processes suited for prediction and for the representation of long term statistical properties are closely related, if one takes into account, in addition to the widely adopted stochastic forcing, the often neglected memory effects. We emphasize that our results do not rely on assuming a time scale separation, and, if such a separation exists, can be used equally well to study the statistics of the slow as well as that of the fast variables. The results bear relevance also in the context of the applicability of the fluctuation-dissipation relation for geophysical fluid dynamical systems. [1,2].

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[2] J. Wouters and V. Lucarini, Multi-level Dynamical Systems: Connecting the Ruelle Response Theory and the Mori-Zwanzig Approach, J. Stat. Phys., doi: 10.1007/s10955-013-0726-8 (2013)

Computing rare events: adaptive multilevel splitting algorithms

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Adaptive multilevel splitting algorithms offer new and efficient ways to compute transitions between metastable states in various contexts. After showing simple examples, we describe recent theoretical results which give better insight on the statistical properties of these algorithms. We show in particular that in dimension higher than 1 and in the weak noise limit, the use of proper observables becomes critical.

Quadratic invariants for cluster of interacting wave triads.

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We consider clusters of interconnected resonant triads arising from the Hamiltonian three-wave equation. A cluster consists of N modes forming a total of M connected triads. We investigate the problem of constructing a linearly independent set of quadratic constants of motion. We show that this problem is equivalent to an underlying basic linear problem, consisting of finding the null space of a rectangular M × N matrix A with entries 1, -1 and 0. In particular, we prove that the number of independent quadratic invariants is equal to J ? N ? M? ? N ? M, where M? is the number of linearly independent rows in A. We formulate an algorithm for decomposing large clusters of complicated topology into smaller ones and show how various invariants are related to certain parts and linking types of a cluster, including the basic structures leading to M?

Large scale coherent flow structures in planetary turbulence arise from spectrally non-local interactions

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The commonly observed phenomenon of spontaneous jet formation in beta-plane turbulence is studied using Stochastic Structural Stability Theory (S3T),
which is an implementation of statistical mean state dynamics.
Jet formation is shown to result from a linear instability arising from a bifurcation in the system parameters and
leading directly to nonlinear finite amplitude jet equilibria.
Given that the S3T system does not contain the perturbation nonlinearity associated with the turbulent cascade, the close agreement in the dynamics and structure of jets arising in these S3T simulations and those arising in fully nonlinear turbulence simulations compels the conclusion that the turbulent cascade process is not required for jet formation in beta-plane turbulence.

Cumulant expansion closures for geophysical turbulence: From planetary scales to boundary layers

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Turbulence closures based on truncated cumulant expansions usually do not perform well in homogeneous turbulence problems, because the first moments are not of interest. However, geophysical turbulence problems are generally inhomogeneous, and first moments (e.g., mean temperatures, winds, and precipitation) are of primary interest. In addition, geophysical turbulence is often weak (with prominent waves and hence strong non-locality in space), rendering cumulant expansion closures that capture spatial correlations promising. Here I give an overview of cumulant expansion closures at second order (CE2), applied to geophysical turbulence from the scales of planetary circulations to boundary layers. Gross features of planetary circulations can be captured in CE2 closures, but there are also notable failures, in particular in representing turbulent momentum fluxes, for which critical layer dynamics not captured at CE2 are crucial. For boundary layers and clouds, cumulant expansion closures represent a fundamentally new approach of approaching the closure problem, one that now, with sufficient computational power, may lead to much better subgrid-scale closures than those currently employed in climate models.

Kinetic theory of jet dynamics in planetary turbulence

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Geophysical turbulent flows are characterized by their self-organisation into large scale coherent structures, in particular parallel jets. We will present a theory in order to describe the effective statistics and dynamics of these jets. We prove that this closure is exact in the limit of a time scale separation between the forcing and the inertial dynamics. The equation obtained describes the attractors for the dynamics (alternating zonal jets), and the relaxation towards those attractors. At first order, these attractors are the same as the ones obtained from a second order closure, already studied (SSST, CE2). It also goes beyond, indeed it describes the stationnary distribution of the jets (fluctuations and large deviations), and predicts the corrections to the quasi-linear approximation. We will also discuss possible generalisations to non-zonal coherent structures.

Upper-ocean turbulence at meso and submesoscales

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Until the last 10 years, it was thought that the ocean dynamics at mesoscales (horizontal scales of 50-500 km) was driven by interior potential vorticity anomalies. This led to the development of the geostrophic turbulence theory as initiated by Charney (1971). We are now able to revisit these questions with more realistic primitive-equation simulations at very high resolution.
In this talk, I will review our current understanding on this topic and the new dynamical picture that emerges. Surface oceanic layers are characterized by strongly energetic submesoscales (1-30km in width). These structures are important for explaining the properties of turbulent baroclinic flows near the surface. Their dynamics is strongly tight to the surface density anomalies. On the contrary, the ocean interior is governed by the dynamics of the interior potential vorticity anomalies. This has some important consequences for turbulent energy fluxes, ageostrophic processes and for vertical fluxes of tracers.

Random Transitions In Stochastic Turbulent Flows

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Many turbulent systems exhibit random switches between qualitatively different attractors. The transition between two different attractors is often an extremely rare event that cannot be computed through direct numerical simulations due to complexity limitations. In this talk, we develop a path integral approach to studying bistability in the quasi-geostrophic equations, which enable us to compute the most probable transition trajectories or instantons between two coexisting attractors. By representing the transition probability between two given attractors as a path integral, we can determine the most probable transition by the minimization of an appropriate action functional.

Parametric Subharmonic Instability and mixing of Stratified Fluids

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Internal waves are believed to be of primary importance as they affect ocean mixing and energy transport. Several processes can lead to the breaking of internal waves and they usually involve non linear interactions between waves. In this work, we study experimentally the Parametric Subharmonic Instability, which provides an efficient mechanism to transfer energy from large to smaller scales. It consists in the destabilization of a primary wave and the spontaneous emission of two secondary waves, of lower frequencies and different wave vectors.We observe that the instability displays a different behavior if the primary wave is a monochromatic vertical mode-1or a plane wave. Moreover, using a time-frequency analysis, we are able to observe the time evolution of the secondary frequencies. Using a Hilbert transform method we measure the different wave vectors and compare with theoretical predictions. Then, using various techniques to characterize the amount of mixing taking place, we try to establish the role played by this instability in the mixing processes of stratified fluids.

Dissipation of geostrophic eddies and generation of mixing in the Southern Ocean

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High-resolution simulations with rough bottom topography are used to investigate energy pathways and dissipation mechanisms in the Southern Ocean. Simulations explicitly resolve processes of energy transfer from balanced to unbalanced motions such as submesoscale instabilities in the upper ocean and internal waves generation at rough topography in the deep ocean. Results show that flow-topography interactions effectively catalyze dissipation of balanced flows by direct generation of internal waves and other small-scale motions, accounting for about two-thirds of the total energy dissipation. The rest of the energy dissipation takes place mostly in the upper ocean and is attributed to submesoscale processes. Energy dissipation by the bottom boundary layer, parameterized here with quadratic bottom drag, is small compared to the dissipation by resolved motions. The implications of these results for ocean mixing and the global overturning circulation will be discussed.

Abstracts of Poster Presentations

Anisotropic, supersonic turbulence in the context of astrophysics

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Turbulence is a major structuring agent in astrophysics. A prominent example where (supersonic) turbulence is believed to play a decisive role is star formation. From observations we know that the initial mass function, the number of stars of a given mass that form per time, is a power law of the mass of the star. The slope of the power law is likely co-determined by the turbulence characteristics. The turbulence in star forming regions must be driven, energy must be injected permanently. Whether this injection occurs at large or small scales, at the scale of the entire star forming region or on the scale of individual, forming stars, is debated. Another example with far reaching consequences is (subsonic) turbulence as a mixing agent for chemical elements in stellar atmospheres. The mixing of the elements, in turn, co-decides on the mass loss and evolution of the star.

Here we present results from an idealized study. The study is inspired by the first of the above two examples. It aims at exploring the characteristics of supersonic turbulence that is driven on very large scales. We employ 3D numerical simulation and study within the frame of Euler equations head on colliding isothermal flows. We analyze the turbulence in the flow collision zone and contrast our findings with results from 3D periodic box simulation where turbulence is forced isotropically. We show that the large scale driving leaves its imprint on various characteristics of the turbulence, which is strongly anisotropic and inhomogeneous. We argue that, in fact, it is very hard if not impossible under isothermal conditions to reach isotropy while remaining supersonic.

Most interesting with regard to the above mentioned star formation - turbulence connection is our finding that the density probability function of our turbulence deviates strongly from a log-normal distribution. By contrast, isothermal turbulence that is driven isotropically has a (nearly) log-normal distribution - which enters many of todays star formation theories. We question this wide spread view of things and discuss implications of our findings in this context.

A second, widely studied turbulence characteristic in the context of star formation are structure functions and derived quantities. Structure functions are a crucial measure as they can be extracted from observational data of star forming regions. Based on these observations, and in combination with theoretical and numerical results, conclusions are drawn on the driving of the turbulence (solenoidal or compressible, large scale or small scale) as well as on the co-dimension of the most dissipative structures. Again, the theoretical and numerical side is so far strongly dominated by results for isotropic turbulence. Here, a wealth of results exist, for example theoretical results on the link between structure functions and co-dimensions of the most dissipative structures (see Dubrulle (1994) and She and Leveque (1994) for the subsonic case; Boldyrev (2002) for the supersonic case).Again, we re-visit these results in the light of our own findings, in the light of inhomogeneous and anisotropic turbulence. We point out, in particular, the potentially prominent role of line of sight effects when interpreting observational data from star forming regions. More generally, we caution that the use of isotropic, isothermal, supersonic turbulence may be a too simplistic model when it comes to interpret the physics contained in observational data of molecular clouds and star forming regions.

A theory for the emergence of large scale structures in planetary turbulence

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Planetary turbulent flows are observed to self-organize into large scale structures such as zonal jets and coherent vortices. One of the simplest models that retains the relevant dynamics is a barotropic flow in a beta-plane channel with turbulence sustained by random stirring. Non-linear integrations of this model show that as the energy input rate of the forcing is increased, the homogeneity of the flow is first broken by the emergence of non-zonal, coherent, westward propagating structures and at larger energy input rates by the emergence of zonal jets. We study the emergence of coherent structures using a non-equilibrium statistical theory, Stochastic Structural Stability Theory (S3T). S3T directly models a second order approximation to the statistical mean turbulent state and allows identification of statistical turbulent equilibria and study of their stability. When these equilibria become S3T unstable the statistical state of the turbulence bifurcates to a new state. In this work we present the bifurcation properties of the homogeneous turbulent state in barotropic beta-plane turbulence and obtain analytic expressions for the emergence of zonal and non-zonal large scale coherent flows. Numerical simulations of the non-linear equations are found to reproduce the characteristics (scale, amplitude and phase speed) of the structures predicted by S3T.

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