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The statistical nature of turbulent barotropic ocean jets

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ABSTRACT

Jets are an important element of the global ocean circulation. Since these jets are turbulent, it is important that they are characterized using a statistical framework. A high resolution barotropic channel ocean model is used to study jet statistics over a wide range of forcing and dissipation parameters. The first four moments of the potential vorticity distribution on contours of time-averaged streamfunction are considered: mean, standard deviation, skewness and kurtosis. A self-similar response to forcing is found in the mean and standard deviation for eastward barotropic jets which exhibit strong mixing barriers; this self-similarity is related to the global potential enstrophy of the flow. The skewness and kurtosis give a behaviour which is characteristic of mixing barriers, revealing a bi/trimodal statistical distribution of potential vorticity with homogenized potential vorticity on each side of the barrier. The mixing barrier can be described by a simple statistical model. This behaviour is shown to be lost in westward jets due to an asymmetry in the formation of zonal mixing barriers. Moreover, when the statistical analysis is performed on eastward jets in a streamfunction following frame of reference, the distribution becomes monomodal. In this way we can distinguish between the statistics due to wave-like meandering of the jet and the statistics due to the more diffusive eddies. The statistical signature of mixing barriers can be seen in more realistic representations of the Southern Ocean and is shown to be an useful diagnostic tool for identifying strong jets on isopycnal surfaces. The statistical consequences of the presence, and absence, of mixing barriers are likely to be valuable for the development of stochastic representations of eddies and their dynamics in ocean models.

1. Introduction

Ocean jets such as the Gulf Stream, Kuroshio Extension, as well as the jets embedded within the Antarctic Circumpolar Current, represent some of the most turbulent regions of the ocean (e.g., Stammer and Wunsch, 1999). Such jets have an important influence on the large scale circulation of the ocean and atmosphere. For example, Scaife et al. (2011) highlight that model representation of winter atmospheric blocking is greatly improved when the horizontal resolution of the North Atlantic ocean is increased, thereby improving the representation of the Gulf Stream. From a hydrographic survey, Bower et al. (1985) determined that water masses are mixed across the Gulf Stream at depth, but that the Gulf Stream acts as a barrier towards the surface where the jet is strongest, inhibiting exchange of tracers between the subtropical and subpolar gyre. More recent studies (Ferrari and Nikurashin, 2010; Klocker et al., 2012) show the suppression of mixing, and consequently the transport of heat and salt, across jets within the Antarctic Circumpolar Current. This suppression of mixing can be attributed to the tendency of strong jets to form mixing barriers, regions of high potential vorticity gradient which eddies have difficulty penetrating.

The tendency for strong jets to form mixing barriers is, in fact, a consequence of the turbulence which sharpens the jets and maintain strong potential vorticity gradients by providing up-gradient fluxes of momentum (Starr, 1968). Evidence for this jet sharpening behaviour has a long history in baroclinic (e.g. Fultz et al., 1959) and barotropic (e.g. Sommeria et al., 1989) jets which is comprehensively reviewed in Dritschel and McIntyre (2008). The highly anisotropic picture we have formed from these studies is that of a potential vorticity step corresponding to the jet itself, sharpened by the eddies, with regions of near homogenized potential vorticity to either side of the jet within which the eddies act diffusively.

The dynamical description of ocean jets is complemented by attempts to derive statistical models of turbulent geophysical flow (Esler, 2008). This is motivated in part due to the stochastic nature of turbulent flows which necessarily require more than a purely deterministic description. Moreover, with increasing interest in the application of stochastic parameterization to ocean modelling (e.g.,

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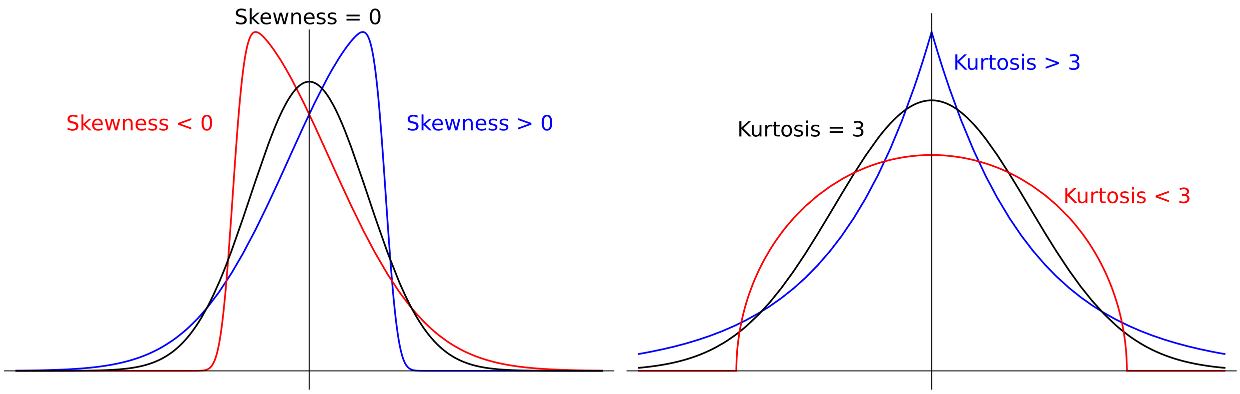

Fig. 1. *Left*: examples of positively skewed (*red*) and negatively skewed (*blue*) distributions compared with a normal distribution (*black*). *Right*: examples of leptokurtic (*red*), kurtosis greater than three, and platykurtic (*blue*), kurtosis less than three, distributions compared with a normal distribution with a kurtosis of three (*black*). All distributions shown have a mean of 0 and a standard deviation of 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Berloff, 2005; Porta Mana and Zanna, 2014; Grooms et al., 2015; Zanna et al., 2017) it is important to understand the underlying statistics of geophysical flows and the fundamental organizing principles behind them. Many statistical mechanics theories of turbulent flow are derived in the absence in of forcing and dissipation: the so-called Robert–Sommeria–Miller equilibrium statistical mechanics (Bretherton and Haidvogel, 1976; Salmon et al., 1976; Robert, 1990; Miller, 1990; Robert, 1991; Robert and Sommeria, 1991). Equilibrium statistical mechanics theories of geostrophic turbulence predict a functional dependence of the mean potential vorticity on the mean streamfunction (e.g., Bouchet and Venaille, 2012). However, the ocean lies in a forced-dissipative regime for which a non-equilibrium statistical mechanics theory is required.

The goal of this study is to understand the statistics of forced-dissipative ocean jets and how these are influenced by the dynamics of a mixing barrier. We explore the sensitivity of the jet statistics to forcing and dissipation and show that self-similarity exists across a wide range of parameters, describing the characteristic statistical signature of a mixing barrier.

To address this goal, we examine the mean state of the flow and its variability in the presence of forcing and dissipation using mean, standard deviation and higher order moments such as skewness and kurtosis. We will also compare and contrast these statistics to the predictions of equilibrium statistical mechanics. The energy and enstrophy conserving theory considered in this study is that presented in Jung et al. (2006). Jung et al. (2006) differs from other tests of equilibrium statistical mechanics (e.g. Qi and Marston, 2014; Dritschel et al., 2015) in that it derives a spatially coarse-grained version of the theory in order to test the theory in a barotropic rotating annulus laboratory experiment. When only energy and potential enstrophy are conserved, the relationship between mean potential vorticity and the mean streamfunction is linear while the standard deviation is constant with respect to streamfunction according to equilibrium statistical mechanics. These predictions are derived in Jung et al. (2006) and are consistent with other interpretations of the theory (e.g. Salmon et al., 1976). Understanding these relationships in a forced-dissipative system, however, remains an open problem which we will discuss during the course of this study.

In addition to understanding how the mean and standard deviation relations change in the presence of forcing and dissipation, it is important to consider higher order moments of the flow, such as skewness and kurtosis, which exist only when the potential vorticity distribution is non-Gaussian. As illustrated schematically in Fig. 1, different values of skewness and kurtosis of the probability distribution characterize asymmetry and intermittency (extreme events) in turbulent flow. These moments have been shown to be important in describing the statistics of passive tracers (e.g., Bourlioux and Majda, 2002). The character and nature of skewness and kurtosis in turbulent geophysical flows have been considered by Thompson and Demirov (2006) and Hughes et al. (2010). In particular, Hughes et al. (2010) establish a mechanistic link between skewness and kurtosis and the large scale dynamics of jets, allowing these authors to use these moments to identify mixing barriers. In a highly non-linear dynamical system such as the ocean, we might expect extreme events in active tracers such as potential vorticity to have an impact on the mean large-scale circulation and to be sensitive to forcing and dissipation. In this manuscript, we study the potential vorticity statistics of a barotropic jet in a reentrant channel, varying the strength of forcing, the linear drag coefficient, and the direction of forcing. These experiments are used to pursue the following aims:

- To understand the dependence of the statistics of a turbulent flow on forcing and dissipation in the presence and absence of a mixing barrier.
- To establish a statistical picture of mixing barriers with a simple statistical model which will inform the stochastic parameterization of eddy-mean flow interaction.
- To distinguish between the statistics of eddies and the statistics of waves.

The results are restricted here to barotropic flows, an understanding of which is a prerequisite for understanding more complex flows with baroclinicity.

The structure of the paper is as follows. In Section 2, the model and experiments are presented. In Section 3, the dynamics of the west/eastward jet asymmetry is discussed. In Section 4, the mean and standard deviation of potential vorticity are calculated as a function of time-averaged streamfunction in order to contrast with the equilibria of the ideal dynamics, and a self-similar response to forcing and dissipation is discussed. In Section 5, the higher order moments of skewness and kurtosis are similarly considered. A clear link is made between the presence of a meandering mixing barrier and a characteristic skewness/kurtosis behaviour. In Section 6, the importance of the meandering mixing barrier in determining the statistics of the flow is further considered, and the statistics calculated on instantaneous contours of streamfunction in order to follow the large scale meanderings of the mixing barrier in a quasi-Lagrangian sense. In Section 7, a further discussion of: joint potential vorticity and streamfunction statistics; the importance of mixed distributions; implications for stochastic parameterization; and application to Southern Ocean jets using an observation constrained primitive equation model. Finally, Section 8 contains some concluding remarks.