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Lagrangian and Eulerian lateral diffusivities in zonal jets

Stefan Riha [a,b,*], Carsten Eden [c]

[a] IFM-GEOMAR, Leibniz Institute of Marine Sciences (at Kiel University), Düsternbrooker Weg 20, 24105 Kiel, Germany
[b] Centro de Oceanografia, Faculdade de Ciências da Universidade de Lisboa, Campo Grande, 1749-016 Lisboa, Portugal
[c] KlimaCampus, Universität Hamburg, Bundesstr. 53, 20146 Hamburg, Germany

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ABSTRACT

Meridional diffusivities from Lagrangian particle dispersion and Eulerian diffusivities from a flux-gradient relationship are estimated in an idealized primitive equation channel model featuring eddy-driven zonal jets.

The Eulerian estimate shows an increase with depth and clear minima of meridional diffusivities within the zonal jets, indicating mixing barriers. The Lagrangian estimates agree with the Eulerian method on the vertical variation and also show indications of meridional mimima, although meridional variations are poorly resolved. We found early maxima in the particle spreading rates which should not be related to diffusivities since they are caused by the meandering zonal jets. The meanders also produce rotational eddy fluxes, which can obscure the Eulerian diffusivity estimates.

Zonal particle dispersion rates do not converge within the chosen lag interval, because of shear dispersion by the mean flow, i.e. it is not possible to estimate Lagrangian zonal diffusivities representative for regions of similar size of the zonal jet spacing. Removing the zonal mean flow, zonal and meridional dispersion rates converge and show much higher zonal than meridional diffusivities. Further, the pronounced vertical increase and indications of meridional minima in the Lagrangian meridional diffusivities disappear, pointing towards the importance of shear dispersion by the mean flow for the suppression of meridional mixing by zonal jets.

1. Introduction

Zonal jets might play an important role in the ocean circulation and their effects on tracer transport should be included in ocean climate models. Zonal jets are a characteristic feature of many observed flows in the ocean (Treguier et al., 2003; Maximenko et al., 2005) and atmosphere (Dritschel and McIntyre, 2008) and are believed to be both cause for, and effect of inhomogeneous transport in the sense that they partition the flow into regions of strong mixing separated by transport barriers.

Large-scale ocean (climate) models do not resolve mesoscale fluctuations and therefore cannot reproduce eddy-driven mean flow in general, and zonal jets in particular. In order to include these effects, proper parameterizations for the impact of zonal jets on turbulent mixing are needed. This study is a continuation of previous studies (Eden, 2009, in press) in which the zonal and meridional transport properties of an eddying channel model have been analyzed in an Eulerian framework and in which an eddy momentum flux parameterization for the zonally averaged flow was successfully tested, in the sense that it reproduced the zonal jets. In the present study, we extend the previous work by considering turbulent mixing in a Lagrangian framework, focussing on zonal and meridional mixing appropriate to passive tracers.

Lagrangian analysis is a useful complement to Eulerian analysis, since the former describes the purely advective stirring of a passive tracer in the flow field, without being influenced by additional processes acting on a passive tracer, like numerical diffusion or explicit relaxation. Such processes may have a large effect on Eulerian mixing estimates for passive tracers. Further, the Lagrangian analysis may provide a more direct linkage to observational estimates of mixing in the ocean where drifters and floats are often used for mixing estimates. The channel model used in this study provides an idealized framework to illuminate the relationship between Eulerian and Lagrangian analysis of turbulent mixing: it provides quasi-stationary velocity- and tracer fields featuring spatially inhomogeneous fluctuation statistics and minimal drift, and therefore yields reliable Eulerian and Lagrangian statistics with strong spatial dependence. Note that such statistics are often difficult to obtain from observations or realistic ocean model simulation.

In Section 2 we detail the numerical model and the methods which we use to estimate diffusivities from particle dispersion, while in Section 3 the possibility of a localization of the non-local Lagrangian particle statistics is explored. Section 4 discusses the results in terms of the meridional diffusivities inferred from the

* Corresponding author. Present address: Centro de Oceanografia, Faculdade de Ciências da Universidade de Lisboa, Portugal.
E-mail address: sriha@ifm-geomar.de (S. Riha).

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particle dispersion, while Section 5 focusses on the zonal dispersion. The last section summarizes and discusses the results of this study.

2. Methods

2.1. Lagrangian method

The Lagrangian method we employ in this study is based on the assumption that the evolution of the ensemble-mean field of a conservative passive tracer field is fully determined by Lagrangian single-particle statistics (Batchelor, 1949, 1952). Davis (1987) applied this theory to Lagrangian drifters in the ocean, and (Davis, 1991) outlined how diffusivities, appropriate to a flux-gradient parametrization of unresolved tracer transport, can be found in practice. We use the method to study synthetic drifters of channel models. Here, we shortly outline the computational method used to obtain diffusivity estimates, where we mainly follow the approach of Swenson and Niiler (1996).

Particle trajectories are obtained by integrating the velocity field of a primitive equation model configured to simulate flow in an idealized zonally periodic channel. The model is the same as the one used by Eden (2009) (specifically the experiment with Rossby radius of 96 km and Eady growth rate 4.8 d). The model equations are formulated in Cartesian coordinates and the domain is a square, zonally periodic channel of 4000 km width and 2000 m depth with flat bottom. Fig. 1 shows a snapshot of velocity and temperature (salinity is held constant) and some sample trajectories at 500 m. The horizontal and vertical resolution of the model are 16 km and 50 m, respectively. Boundary conditions are free slip and zero buoyancy fluxes at top, bottom and lateral boundaries. The zonal mean flow is established by relaxing the buoyancy at the northern and southern boundaries towards prescribed vertical profiles, resulting in a northward pointing (baroclinically unstable) horizontal temperature gradient throughout the domain.

After a four year long spinup phase of the integration, 10,000 particles are distributed randomly within the domain and then integrated for about 4 years (6 years for experiment NOMEAN, which is described below) using the instantaneous velocity field of the model. Particle positions are stored in intervals of 12 h. Every four-year trajectory is cut into overlapping pieces (so called pseudo-trajectories) of 200 d (Fig. 2). The overlap is 100 d. Treating these pseudo-trajectories as individual trajectories, we obtain about 120,000 individual 200-d trajectories. The trajectory of each float can be written as $\mathbf{X}(t,\mathbf{X}_0)$, where t is a time-lag coordinate ranging from day -100 to day 100, and $\mathbf{X}_0$ is the position of the trajectory at $t = 0$. The meridional plane is partitioned into 20×10 bins, 20 in y-direction and 10 in z-direction, corresponding to grid boxes of an equally spaced grid (Fig. 2(b)). The turbulent velocity statistics and particle statistics are expected to be constant in zonal direction; the bin size therefore extends over the whole domain in zonal direction. Each pseudo-trajectory is mapped to the bin which encloses its position $\mathbf{X}_0$ at $t = 0$, marked with a red dot in the schematic Fig. 2a. In this way, every bin is associated with a set of pseudo-trajectories, and the Lagrangian statistics computed from this set can be mapped to the corresponding bin (see Fig. 2). After a pseudo-float $\mathbf{X}(t,\mathbf{X}_0)$ has been mapped to a grid box, we redefine the pseudo-trajectory as $\mathbf{X}(t) := \mathbf{X}(t,\mathbf{X}_0) - \mathbf{X}_0$. All pseudo-trajectories in a bin then satisfy $\mathbf{X}(0) = 0$, and it is convenient to imagine an individual coordinate system for each bin, with the origin located at the grid box center, and to assume that all pseudo-trajectories associated with the bin have been released at the grid box center. Note that we assume that all statistics are homogeneous in the individual bin. The time-axis in this coordinate frame ranges from $t = -100$ d to $t = 100$ d. Where necessary, we distinguish the timeseries $\mathbf{X}(t)$ from the original one, $\mathbf{X}(t,\mathbf{X}_0)$, by referring to the former as *normalized* particle trajectory. In a sense, this procedure can be thought of constructing an ensemble of single-particle point-release experiments from trajectories that where actually collected by random-encounter sampling in a finite volume (bin): we construct one set of pseudo-trajectories for each bin (using all pseudo-particles mapped to the bin during the multi-year experiment), and analyze this set imagining that each individual element was released exactly at the bin center, with the time-label of release being $t = 0$. This is similar to the approach of Swenson and Niiler (1996).

We use two different single-particle dispersion rate estimates ($D1$ and $D2$) that have also been used in previous studies and are extensively described in Taylor (1922) and Davis (1991). A brief introduction to Taylor's discussion about the analogy between turbulent dispersion and diffusion can be found in the appendix. The lateral (isopycnal) diffusivity is expressed as a 2×2 flux-gradient tensor K_{ij}, where $i,j = 1,2$, and may depend on position (bin). Note

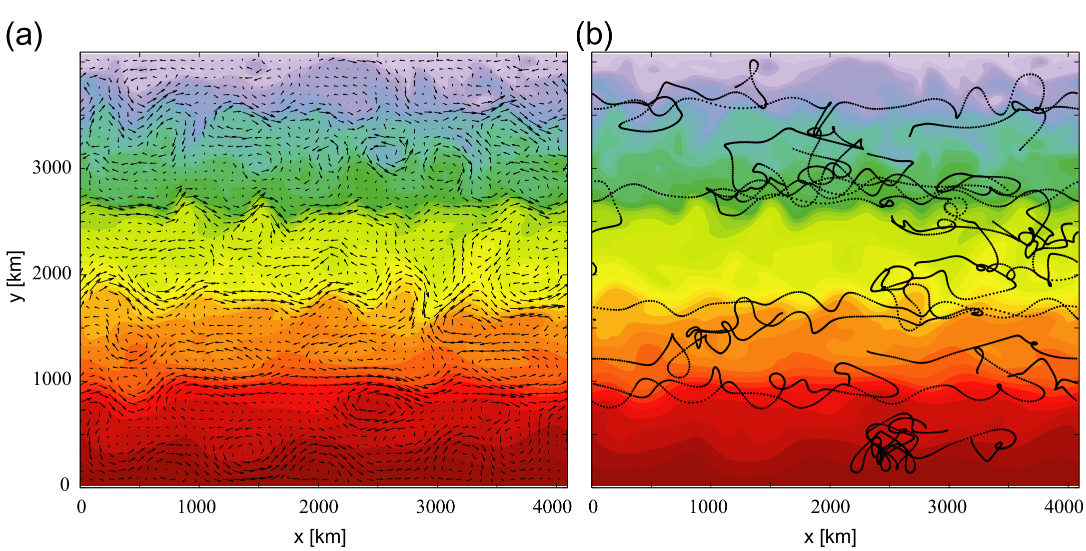

Fig. 1. (a) Snapshot of velocity (arrows) and temperature at $z = -500$ m after the spinup phase of the integration. Zonal and meridional axis are in km, the north–south temperature gradient is about 20 K and the maximal velocities are about 1 m/s. (b) The same snapshot of temperature and eight arbitrarily chosen trajectories during 400 d each at the same depth level.