9.5 CROSS-JET TRANSPORT IN QUASI-GEOSTROPHIC SIMULATIONS

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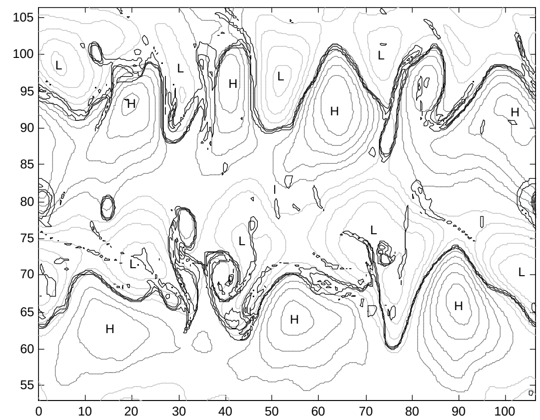
We are interested in the nature of transport across jets whose structure is dynamically determined, rather than specified a priori. We therefore use models in which little information is explicitly provided concerning large-scale flow structure. Then Lagrangian data may be used both directly, to shed light on cross-jet transport, and indirectly, to probe flow structure.

We have used both barotropic and baroclinic quasi-geostrophic beta-plane models. Each kind of model has been used in studies of the jet formation process. The barotropic model we have used, which imposes little direct control of large scale structure, assumes a small scale stirring mechanism. The baroclinic model assumes a spatially uniform temperature gradient. In each case the large scale eddy field which results from turbulent energy transfers from smaller scales is arranged in zonally oriented street-like arrays: model parameters can be adjusted to minimize meridional movement of these arrays to facilitate focus on cross-jet transport.

In the context of extra-tropical tropospheric or upper ocean jets, results from the baroclinic models appear to us more interesting. They show that meridional transport consists of two stages, each with a distintive scale: rapid sweeping by the large-scale eddy field to bounding regions of high PV gradients (formed by these eddies); and subsequent movement across the bounding regions. The eddy street model allows predictions about the first stage which are supported by the Lagrangiian data. The second stage is mediated by Rossby wave-breaking. Lagrangian data on transport in this stage provides an indirect measure of wave-breaking frequency.

The figure at right shows the upper layer eddy streamfunction field from a two-layer QG simulation. The corresponding PV field has sharp gradients in the westerly jet cores; two PV contours (in bold) showing the location of these cores are added to the figure. Note the "break"



evident in the more southern PV filament. This break, part of an event that gave rise to a series of cyclones (also visible as thick contours), is the primary avenue for cross-jet transport.

The baroclinic simulations show for meridional transport a distinctive sub-diffusive regime intermediate between the initial ballistic and ultimate diffusive regimes in the familiar Taylor analysis. It is interesting to note that other physical situations involving transport through an array of vortices show similar two-stage aspects and an intermediate subdiffusive regime, albeit with completely different bounding zone physics (eg. Cardoso et alia, 1988). (By contrast, the zonal transport is super-diffusive.)

Results on cross-jet transport using a barotropic model are qualitatively different, due to the much more quiet large-scale eddy field with weak meridional motions. The results suggest some limitation to the utility of such models once one looks beyond zonal averages.

SOME BAROCLINIC MODEL RESULTS

The baroclinic model is the doubly-periodic two-layer beta-plane model used by Panetta (1993) and Held and Larichev (1995). Particle trajectories are calculated using a 4th-order Runga-Kutta scheme combined with a 16-point Lagrangian interpolation (Haidvogel 1985, Hua

1994). Tracers are released at selected locations in statistically equilibrated flows.

For a set of 1024 tracers released in the upper layer along a latitude line equidistant between two westerly jets (a zone of easterlies), evolution of the meridional tracer distribution is shown in the upper figure at right using 11 curves bounding the centiles of the distribution. Release latitude is labeled "0". South of the lowest curve there are no tracers, south of the next line 10% are found, etc. North of the top curve there are no tracers. The horizontal straight lines indicate time-mean positions of the nearest westerly jets (centers of the high PV-gradient zones).

The middle figure shows the rms. meridional displacement of the ensemble as a function of time: both scales are logarithmic and displacement is scaled by the square root of time. There is a period of ballistic motion, followed by one of spreading at a power of time less than one half (sub-diffusive), followed by transition to the period of diffusive spreading. The vertical line in the middle panel indicates the time at which the upper figure's time axis ends. The end of the sub-diffusive regime comes when 30- 40% of tracers have crossed the neighboring westerlies.

The bottom figure (no root-time scaling) shows results from experiments with different assumed ratios of planetary to baroclinic PV gradient, scaled by large-eddy turnover time and length scale: predictions based on the eddy-street view do well in of the ballistic regime. For the sub-diffusive regime, the scaling exponent increases, and regime duration decreases, as the wave-breaking activity becomes more vigorous.

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