Models of the Great Red Spot

SIR—We note that the experiments of Sommeria *et al.*[1] and the numerical simulations of Marcus[2] are not acceptable models of Jupiter's Great Red Spot (GRS) because their approach does not meet the necessary conditions.

Necessary conditions for an adequate model of the GRS-like vortices include: (1) cyclonic–anticyclonic asymmetry — almost all large, long-lived vortices in the jovian and saturnian atmospheres are anticyclones (including the GRS vortex)[3,4]; (2) large radii, a, of the vortices (the characteristic length of the velocity gradient) relative to the barotropic Rossby–Obukhov radius, r_R (for a vertically homogeneous fluid) or the baroclinic Rossby radius, r_i (for an inhomogeneous fluid); for example, for the GRS, $a \approx$ 5,000 km (ref. 5), r_i = 1,000–1,500 km (refs 3,5), and $a >> r_i$. (Here $r_R = (gH)^{1/2}/2\,\Omega \sin \varphi$, where g is the acceleration due to gravity, H the thickness of an atmosphere, and φ is the latitude; $r_i \approx$ (⅕–¼) r_R in real atmosphere.)

Conditions (1) and (2) correspond to the 'intermediate geostrophic' (IG) regime of the Rossby vortex motion ($a > r_R$)[4]. Both of them were satisfied in our experiments[6–8] (see ref. 3 for review). In refs 1 and 2, a method of vortex production that allows generation only of cyclones and eliminates generation of anticyclones was used, not satisfying condition (1). In addition, the model fluid used has no free surface (it is contained between rigid lids), thus corresponding to a regime with $r_R \rightarrow \infty$ and, hence $a << r_R, r_i$ ('quasi-geostrophic' (QG) approximation, $a < r_R$), not satisfying condition (2).

We produced[3,6,8] a long-lived monopole IG Rossby anticyclonic soliton and so obtained a laboratory model of the jovian GRS driven by smooth counterstreaming fluid flows. We also showed that the long-lived Rossby soliton exists only when it has a sufficiently large amplitude and involves captured particles, that is, the Rossby soliton is a real vortex. Regarding cyclones, we showed that they were only generated by the counterstreaming cyclonic flows under the condition of extremely strong velocity shear, similar to conditions necessary for the existence of jovian cyclonic 'barges' (14° N).

The vortex Rossby soliton concept allows us to interpret satisfactorily the principal properties of the GRS: its anticyclonic polarity, its size, its rotation speed and its steady westward drift, its generation by counterstreaming flows (existing in jovian atmosphere) and its uniqueness along the whole perimeter of Jupiter. In agreement with this concept, there is a large, long-lived vortex in Jupiter's Northern Hemisphere (19° N) which corresponds to the GRS of the Southern Hemisphere (22° S): like the GRS, it is an anticyclone, it drifts westward with a speed of 2.5 m s^{-1} and has a size $a > r_i$. Because of its physical similarity to the GRS it is called the Little Red Spot[9].

An essential part of our results is represented incorrectly in ref. 1: we did observe the merging of vortex Rossby solitons under their mutual collisions. This phenomenon is in good agreement with the observed properties of the GRS and with the theory of the vortex (not 'purely wave') Rossby soliton; it also agrees with the computer work[4]. This phenomenon is in qualitative disagreement with the first ('purely wave') soliton theory of the GRS[10]; the latter uses the QG approximation ($a < r_i$) and does not agree with the GRS observations.

Our results are not affected by viscosity because, under the conditions of our experiments[6,7], the characteristic decay time of the IG Rossby anticyclone is about 20–25 s (ref. 11); hence, it is an order of magnitude greater than the vortex turnover time (≈2 s). The point is that, in the presence of a free surface, the viscous lifetime (τ_{visc}) of the IG Rossby vortex is much greater than the Ekman time (τ_E), because[11–13] $\tau_{visc} = \tau_E\,(1+F)$, where the Froude number, $F = a^2/r^2$, is much larger than unity for the IG regime. We predict that Neptune's Great Dark spot discovered recently[14] is an anticyclone.

However, we must say that independent of the above, the experiments of Sommeria *et al.*[1] seem to be very impressive from a hydrodynamical point of view.

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MARCUS AND SOMMERIA *ET AL.* REPLY—The theory and experiments of Antipov *et al.*[6–8] are in the intermediate geostrophic regime, and ours[1,2] are in the quasi-geostrophic. Both IG and QG are special cases of single-layer shallow-water theory but the approximations are mutually exclusive, and the dynamics of long-lived vortices are different for the two regimes. Thus the issue is whether the GRS is QG or IG — we argue it is QG based on Voyager observations.

The distinction between IG and QG depends on the size of the baroclinic (inner) Rossby radius r_i. For scales of motion larger than r_i, the IG rather than the QG approximation is appropriate. Estimations of r_i near the GRS range from 500 to 5,000 km; hence, because the GRS is 12,000 km by 26,000 km, several authors[4] conclude the GRS must be IG. Voyager data, however, show that the GRS velocity is mostly in a thin, large diameter, annular region. The correct length scale to compare with r_i is the half-width of this annulus, approximately 2,000 km, which is the characteristic scale l over which the velocity varies. A careful comparison of Voyager data with numerical solutions of full shallow-water equations yields[15,16] 2,000 km $\leqslant r_i \leqslant$ 3,000 km; hence, the QG approximation for the GRS is justified. The numerical solutions also show that the potential vorticity q can be approximated to within 15% by the QG expression $q = Q[(f+\omega)^{-1}\nabla.(f^{-1}\nabla gh) - gh(fr_i)^{-2}]$, where ω and Q are the vorticity and potential vorticity of the zonal velocity, h the height of the upper surface of the vortex not including the zonal component, f the Coriolis parameter and g the effective gravity. Our simulations show that QG vortex dynamics are *insensitive* to the value of r_i. Therefore, experiments with a rigid lid ($r_i = \infty$) simulate GRS dynamics.

We showed[1,2] that a large QG vortex can form from the turbulent merging of smaller vortices. The resultant large vortex (which is not a soliton) has approximately uniform q (which forces $l \approx r_i$) and a quiet interior with v and vorticity increasing exponentially until they peak in an annular strip of thickness $2r_i$ at the vortex's edge. This is a very good description of the GRS. By contrast, an IG Rossby soliton is gaussian with vorticity and angular velocity peaked at its centre[4].

Antipov *et al.* emphasize that the GRS is anticyclonic, as in IG theory, whereas QG vortices are cyclonic or anticyclonic. Their use of IG theory to explain the GRS's anticyclonicity is not compelling because another explanation is then needed for the majority of jovian vortices: most of the > 100 vortices observed by Voyager have $l \leqslant R \leqslant$ 1,300 km, where R is the vortex radius. Even if r_i were as small as 1,300 km, these vortices would be QG — yet 90% are anticyclonic[17]. Thus, physics beyond the shallow-water approximations is needed to explain the anticyclonicity.

Antipov *et al.* argue that westward drifts of the GRS (−3.5 m s^{-1}) and Little Red Spot (−2.5 m s^{-1}) support IG-soliton theory because QG vortices remain stationary with respect to the local zonal flow, whereas IG solitons drift westward at the Rossby drift velocity: −4.6/(1,000 km)^2 m s^{-1} at the latitude of the GRS. Drift speeds of jovian vortices are measured with respect to System III coordinates, but there are uncertainties of at least ±5 m s^{-1} in determining the velocity of the deep zonal flow with respect to System III. Thus, the vortex drift speeds are all zero within the observational uncertainty. Williams and Wilson[18] appeal to the uncertain zonal velocity to salvage their IG soliton model of the White Oval BC, which drifts eastward at 4 m s^{-1}. Note