(Reprinted from Nature, Vol. 260, No. 5550, pp. 457–461, April 1, 1976)

Tornado forum

RECENTLY the proposal was made that motor traffic has contributed significantly to the sixfold increase in incidence of tornadoes in the USA in the past forty years.[1] The authors saw the vorticity introduced into the atmosphere by traffic driving on the right as favouring the generation of cyclonic tornadoes, and they were encouraged in this hypothesis by an increase in the proportion of cyclonic to anticyclonic tornadoes, and also by the low incidence of tornadoes reported on Saturdays, when traffic would be lower and more unidirectional (away from large cities).

The suggestion has provoked many responses and to publish them all would have occupied more space than we could allot. So we print below abridged versions of some of the communications received, followed by a reply from the authors.

[1] Isaacs, J. D., Stork, J. W., Goldstein, D. B., and Wick, G. L., *Nature*, **253**, 254–255 (1975).

A MOTOR vehicle or any other projectile in air produces vortices in its wake, but no net vorticity. If there are anticyclonic vortices along edges of the highway, as shown in Fig. 1 of Isaacs *et al.*, their vorticity must be balanced by cyclonic vorticity in the median strip.

The width of a highway is small compared to a cloud, and a significant updraft entraining the vortices produced by motor vehicles would realise no net contribution from that source. The main atmospheric phenomena produced by cars are turbulence, and gaseous and particulate combustion products along the highway, dissipating and diffusing downwind.

The low incidence of tornadoes on Saturdays perhaps reflects some unfortunate vagaries in reporting. Or, conceivably, changes in the atmospheric radiation budget and aerosol content induced by weekend factory closings and lowered air pollution produce changes in static stability and cloud particle development.

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WE believe that the mechanism for vorticity generation and accumulation in the atmosphere proposed by Isaacs *et al.* is based on misconceptions about the nature of vorticity. The atmosphere contains background vorticity arising from the rotation of the Earth and relative vorticity from weather disturbances and boundary effects, including moving vehicles. In fact the background vorticity can be ignored to high accuracy in the dynamics of flow around vehicles, since Coriolis effects are minute. The following argument depends, however, mainly on kinematical results, which are exact.

We begin by considering the generation of vorticity by a single moving vehicle. Absolute vorticity can be generated in a homogeneous fluid only at boundary surfaces moving relative to the fluid[1], and so is generated at the sides, top and bottom of the vehicle, at its wheels and at the ground in its neighbourhood. Once generated it is advected with the air stream into the vehicle's wake. The vortex filaments of the resulting relative vorticity vector field ω must either form closed loops or terminate at a boundary rotating relative to the Earth; and on this basis we can distinguish two constituents in the relative vorticity generated at a moving vehicle:

(1) When the vehicle moves in a straight line, closed vortex loops are shed continuously into its wake. These profoundly affect local levels of vorticity close behind the vehicle, but have no effect whatever either on the circulation round a contour enclosing the wake, or on the bulk integral

$$\int_V \omega \mathrm{d}V$$

over a volume V including the wake and the neighbourhood of the vehicle, because each vortex filament is closed. (None of these facts is changed by the presence within V of more vehicles whether driving on the right or on the left.)

(2) Vorticity having a net vertical component is generated when a vehicle turns, at a rate proportional to minus the rate of change of angular velocity of the vehicle about the vertical; see equation (1). There is an additional net horizontal component associated with the rotation of the wheels, which need not concern us further.

It is immediately clear that randomly varying vehicle movements can have no systematic gross effect over a large area as claimed by Isaacs *et al.* The vehicles could, however, produce localised concentrations of vorticity (changing sign over length scales of a few metres) the significance of which will depend very much on persistence and hence on interdiffusion rates. We shall discuss this question further elsewhere, but remark here that order-of-magnitude estimates based on plausible levels of turbulence suggest persistence times of minutes rather than hours, and vortices of dust devil rather than tornado scale.

If, as an opposite extreme, a large number of vehicles were to be driven simultaneously in fast clockwise circles, there would indeed temporarily be a cyclonic (that is, anticlockwise) contribution to the bulk vorticity integral. But this can be shown to be associated entirely with the air below vehicle rooftop level or, more precisely, below a plane surface s lying just above all the vehicles. When summed over the vast bulk of the atmosphere lying above s, the total component of vorticity normal to s caused by the vehicles is, and must remain, exactly zero (see equation (2) below). This is a consequence of the simple fact that each vehicle-generated vortex filament passing upward through s must go back down through s at another point, possibly terminating on a moving surface such as the underside of the same vehicle.

In summary, neither mechanism (1) nor (2) can plausibly be connected with the generation of tornadoes, which takes place high above the ground and which involves air motions coherent over length scales of kilometres.

Isaacs *et al.* stated that cyclonic vorticity "is generated by the torque between the two opposing streams of traffic", and this led to their view that it is better to drive on the left than the right of the road. Unfortunately torque does not determine the generation of vorticity, either locally or globally. Although doubling the separation of two traffic streams may approximately double the torque (to say nothing of the far larger contribution from unidirectional traffic on widely-separated highways) it has absolutely no effect on the net generation of vorticity. The vorticity due to the traffic streams is, to an excellent approximation, the sum of the contributions produced at the surface of each vehicle, locally redistributed by advection and diffusion; and any effects on the bulk vorticity integral have nothing to do with the separation of traffic streams, nor with left as against right hand drive.

The basic mathematical fact underlying our discussion is the solenoidal property of ω: since ω is the curl of a velocity field, $\nabla.\omega$ is identically zero. It follows that

$$\int_V \omega_i \mathrm{d}V = \int_V \frac{\partial}{\partial x_j}\left(x_i \omega_j\right)\mathrm{d}V = \int_S x_i(\omega.\mathbf{n})\mathrm{d}S$$

where V is a suitable piece of the atmosphere, partially bounded by the surface S, comprising the ground and the surfaces of stationary and moving objects (vehicles, their wheels, aeroplanes) which are envisaged as the source of the contribution ω to the relative vorticity, itself supposed confined within V. From this identity it may readily be shown that

$$\int_V \omega \mathrm{d}V = -2\sum \Omega_r(t)V_r \qquad (1)$$

where $\Omega_r(t)$ is the angular velocity of the rth moving body, and V_r its volume. We here use the fact, fundamental to the vorticity generation mechanism, that the no slip condition[1] applies at all parts of the surface S.

Further, if all the moving objects lie below a plane surface s then, if ω_3 is the component of ω normal to s and v is the part of V above s,

$$\int_S \omega_3 \mathrm{d}S = -\int_V \nabla . \omega \mathrm{d}V = 0$$

Hence, by integration with respect to x_3,

$$\int_V \omega_3 \mathrm{d}V = 0 \qquad (2)$$

The results (1) and (2) are both exact, even for an atmosphere in which the motion is baroclinic, compressible, and turbulent.

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1 Batchelor, G. K., *An Introduction to Fluid Dynamics* 149, 277 (Cambridge University Press, 1967).

ISAACS *et al.* assert that the opposing streams of traffic on a road induce a net cyclonic vorticity in the atmosphere. Because vorticity diffuses exponentially slowly at large distances from a source, however, this is not so.

If the opposing traffic streams are modelled by infinite plates a distance D apart, then the resulting mean flow field at any finite time after the motion begins is of the form shown in Fig. 1. The detailed behaviour of the mean velocity profile near the plates is unimportant. Although the motion near the plates is turbulent in general, any far-field disturbance must propagate normal to the plates by the action of molecular diffusion, and so the mean velocity decays exponentially as $y \rightarrow \infty$. Thus, integrating the mean vorticity $\partial U/\partial y$ with respect to y, we find that the total vorticity per unit distance along the plates in the region $|y| > D/2$ is finite and equal to $2U_0$, whereas the total vorticity in $|y| < D/2$ is equal to $-2U_0$, where U_0 is the speed of each plate. Thus the cyclonic vorticity in the region between the plates is just balanced by the anticyclonic vorticity outside the plates. Alternatively, we see that the net circulation around a closed contour (as shown by the dotted line in Fig. 1) goes to zero as the y dimension of the contour increases. This is because the cyclonic torque induced by the plates is opposed by the inertia of the fluid at infinity, which is at rest.

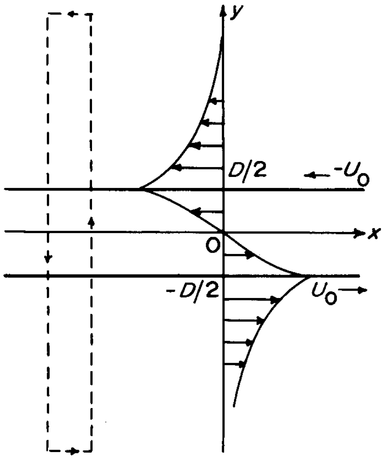

Fig. 1 Mean velocity $U(y)$ associated with the motion of two infinite plates ($y = D/2$ and $-D/2$) travelling at speed U_0 in opposite directions.

This result implies that although cyclonic vorticity is generated between the streams of traffic, there is no net generation of vorticity, because an equal amount of anticyclonic vorticity is also induced. It would seem therefore that, according to the hypothesis of Isaacs *et al.*, either both cyclonic and anticyclonic tornadoes ought to be equally probable, or no tornadoes ought to be generated, depending on whether the air is not, or is mixed horizontally in the process of tornado generation.

On the other hand, Isaacs *et al.* do give some strong circumstantial evidence for the connection between cyclonic tornadoes and traffic-induced vorticity. Their hypothesis can perhaps still be retained if the second ingredient involved in the generation of tornadoes, namely convection, is included. Any vorticity induced by traffic is initially confined to a layer a couple of metres deep near the ground. To produce a tornado, this vorticity must be preferentially advected vertically. Such motions are found in convection, which is an anisotropic process where horizontal mixing is suppressed[1]. Moreover, road pavement in general absorbs more solar radiation than does the surrounding terrain and so the road is expected to be a stronger source of convection than the surrounding terrain. (The cars themselves also act as a local heat source.) Convection therefore ought to occur preferentially from the road. Because the cyclonic vorticity (of mean strength $2U_0/D$) is concentrated over the road while the anticyclonic vorticity is diffused on each side of the road, it would appear that the convection leads to the preferential advection of cyclonic vorticity into the troposphere, as required by Isaacs *et al.* That is, cyclonic tornadoes can be produced because roads are sources of both cyclonic vorticity and convection.

This work was done in the Department of Mathematics, University of British Columbia, and was supported in part by the NRC.

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1 Manton, M. J., *Aust. J. Phys.*, 27, 495 (1974).

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A CALCULATION is indicated, though not shown, by Isaacs *et al.*, purporting to prove that motor vehicle traffic contributes significantly to the atmospheric vorticity over the USA and thereby leads to a more homogeneously cyclonic troposphere and consequently to changes in the broad scale spatial and temporal distribution and frequency of tornadoes. In the following I have attempted to repeat the calculation, with results substantially different from those of the authors.

A typical round trip is taken to be a straight line of length L, a straight line return and a U-turn at each end, with a separation between lanes of width d. If the average force exerted backwards by the wheels on the road is F, then the net anticyclonic angular momentum added to the earth, located at the centroid of the path, is $2FLd/V$, where V is the automobile speed, with nominally equal contributions coming from the straight legs and the U-turns. We assume the force F to be the air drag of the vehicle, given by

$$F = \rho a C_D V^2/2 \qquad (1)$$

where ρ is the air density, a is the cross-sectional area of the vehicle, and C_D is the drag coefficient, taken to be 0.5. Since the speed while making the U-turns is likely to be much less than that on the straight legs, we ignore those contributions, and the average torque produced by the vehicle is then

$$T = Fd = \rho a C_D V^2 d/2 \qquad (2)$$

Isaacs *et al.* assume that 2×10^6 automobiles are on the road in the USA at any time, and that the contributions to torque from autos and trucks are equal. Using these figures, and assuming a mean cross-sectional area of 3 m^2, $V = 20\ \mathrm{ms}^{-1}$, the lane spacing $d = 20$ m, and $\rho = 1.3\ \mathrm{kg\ m}^{-3}$, we obtain a net torque production of 3.2×10^{10} kg m^2 s^{-2}. In this calculation, the difference in direction between the torques produced in different parts of the USA is ignored, which amounts to assuming the cosine of angles smaller than $\sim 20°$ to be unity.

The angular momentum, M, of a rotating body is the second radial moment of its vorticity

$$M = \int \zeta r^2 \mathrm{d}m$$

where ζ is the vertical component of vorticity and dm is the mass differential. Over the USA during most seasons, the mean vorticity of the atmosphere is close to the vertical component of the Earth's vorticity, $f \simeq 10^{-4}$ s^{-1}. Thus the angular momentum of the atmosphere of the USA is roughly

$$M = (p_0/g)Af\bar{r}^2/2,$$

where p_0 is the mean surface pressure, g is the acceleration of gravity, A is the area of the USA, and r is the mean radius, corresponding to the moment of inertia of the USA, which we estimate to be 2,000 km. Taking p_0/g to be 10^4 kg m^{-2} and $A = 8\times10^{12}$ m^2, we obtain $M = 1.6\times10^{25}$ kg m^2 s^{-1}. Thus it would seem that the motor vehicle torque would have to continue for 10^{14} s, about 3 Myr, to show a noticeable effect. The natural turnover time of angular momentum in the atmosphere is of order days or weeks, however, so that the effects suggested by Isaacs *et al.* seem very unlikely.

About the largest effect that could conceivably be produced in the way the authors envisage would occur if all the vehicles in the USA drove in the same direction along highways close to the USA coastlines and borders. In this case the effect would be increased by a factor of 10^5, but would still be too small to be noticeable.

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THERE is a Saturday anomaly in the reporting procedures that affects the final numbers in the paper of Isaacs *et al.* The major source of information about tornadoes in the USA since 1953–54 has been press clippings from out-state newspapers. This drastic change in data-gathering techniques can best be seen in the figure on p. 35 of ref. 1. The average annual totals jumped from $\sim$ 280 yr^{-1} to 640 yr^{-1} beginning in 1954. In Missouri the use of press clipping information coincided with a change in the average annual total reports from 13 yr^{-1} to 33 yr^{-1}. One might conclude, therefore, that in Missouri almost two-thirds of the total reports are strongly dependent on press clipping information. For the entire USA it would seem that more than half of the total number of reports depend to some extent on press clippings.

In general, these additional tornado reports generated by press clipping information tend to be the smaller, short lived mini-tornadoes in largely rural areas. The small amount of property damage and infrequent personal injuries does not make them newsworthy items for the large metropolitan dailies. These storm reports are frequently covered only by local weeklies and the smaller out-state 'daily' papers. It is in these 'dailies' that the anomaly on Saturdays has its origins.

A substantial percentage of out-state daily papers do not publish on Sundays, and a surprising number do not publish on both Saturday and Sunday. In Missouri, for example, 45 of the 61 daily papers do not publish on Sunday and 24 of 61 do not publish on both Saturday and Sunday. Thus, the events of Saturday are frequently old news by the time these dailies go to press on Monday. The minor tornado activity that occurs on Saturday is not nearly as intensively covered as a similar occurrence on any other day of the week. This discontinuity in the basic source of information for tornado reports could easily account for a decrease in Saturday totals of $\sim$ 10–15%. When up to two-thirds of the basic information sources for more than half of the usual total reports cut back to 25–50% efficiency for Saturday events, we end up with an anomaly.

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1 Court, A., *Tornado Incidence Maps, ESSA Tech. Memo. ERLTM—NSSL*, **49** (1970).

THE evidence given by Isaacs *et al.* for their discovery is that, first, "the annual centre of tornado intensity weighted by area . . . has increasingly occupied the eastern portion of the continent", and second that of those few tornadoes for which rotation sense was reported, during the past 12 yr (1962–1973) 8.1% were anticyclonic compared with only 36.4% in the preceding 12 yr; and third, especially, that only 1,868 of 15,234 tornadoes during 22 yr occurred on Saturdays.

Tornadoes are reported by people according to damage done, and as the US population expanded westwards so did tornado reports. Since 1925, the apparent centre of tornado incidence has moved generally south-westwards into eastern Kansas (by 1925), to central Kansas (by 1951), and to central Oklahoma (by 1963). Oklahoma, now the region of greatest incidence, was shown as tornado deficient on earlier maps because it was the last Plains state to be settled[1].

Rotation sense is given for too few tornadoes to be of significance; the big surprise is that any anticyclonic tornadoes whatever are reported. "Motor vehicles are the only man-made source of non-random vorticity we know", the authors say. Perhaps they have never seen two railway trains pass at full speed, or noted the action of exhaust fans and rooftop ventilators.

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ISAACS*, STORK AND WICK* REPLY—Opposing streams of traffic in the USA exert anticyclonic torques on the solid Earth and, from action and reaction, compensating cyclonic torques on the atmosphere. These torques tend to slow down the Earth's rotation and to increase the cyclonic rotation of the local atmosphere in conservation of angular momentum.

We agree with Kessler[1], Morton *et al.*[2] and Manton[3] that there is zero net vorticity in the total atmosphere caused by traffic. Our original discussion was based on vorticity rather than angular momentum. We were in error in not recognising that a discussion of the process from a consideration of vorticity is much less direct than from a consideration of angular momentum. Angular momentum is a more fundamental quantity in the formation of strongly rotating storms.

There can be little doubt that US automotive traffic introduces cyclonic angular momentum into the local atmosphere, which can participate in the formation of tornadoes. To illustrate how this occurs, consider this example: if you set fluid in a bowl into circulation by periodically immersing your hands and moving them past one another in straight lines always in the same relative direction but in any orientation and location, the fluid will gain angular momentum. Yet for this same fluid the no-slip condition at the boundaries requires zero net vorticity. The boundary vorticity does not preclude the formation of a vortex when the fluid is allowed to flow through an orifice in the bottom of the bowl. The important points are that angular momentum can be introduced by linear motions in this way, and that it can participate in a vortex while the net vorticity remains zero.

The apparent paradox of automobile-generated angular momentum with zero vorticity is probably resolved through several mechanisms in the atmosphere. As in the example of the bowl, the boundary vorticity in the atmosphere may propagate and act outside the area of

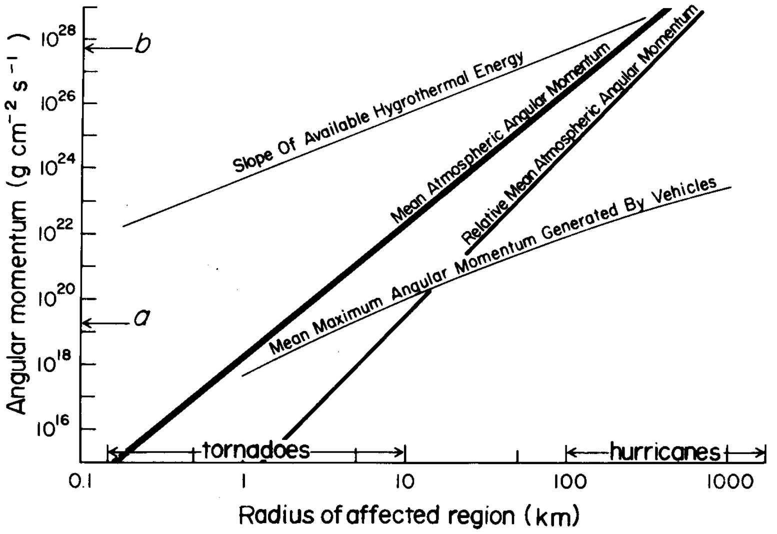

Fig. 1 Atmospheric angular momentum as a function of the affected area and anthropogenic input. The mean atmospheric angular momentum contained in a mass of air is that due to its planetary rotation around its central axis and is involved in radial convergence. It scales as the fourth power of the radius of the affected area. The mean relative atmospheric angular momentum is that involved in linear convergence over the dimensions on the abscissa, and scales as the fifth power of the radius. (Both are at ~45° latitude.) The angular momentum generated by the vehicles is based on the area, the residence time of air over the region (10^5–10^6 s) and the maximum density of traffic within such an area. The dimensions involved in the convection of a tornado or hurricane are indicated on the abscissa. The points labelled *a* and *b* indicate the angular momentum of a single giant tornado and of a hurricane, respectively. For a similar atmosphere and similar equilibrium altitude, the hygrothermal energy available to convective storms scales as the square of the radius of the affected region. (The line is drawn with an arbitrary ordinate intercept.)

convergence, as we originally proposed. The resolution may not be unrelated to our recent observation alongside a highway bearing heavy traffic that anticyclonic filaments of small-scale rotation are embedded in large-scale cyclonic rotation.

At any rate, our calculations of the torque and resulting angular momentum agree with those of Lilly[4], but are more conservative by a factor of about eight. We do not consider, as he did, that the torque on the atmosphere be applied to the entire air mass over the USA as though the atmosphere were a solid body. Rather this torque must exert its influence locally, and in areas consonant with those involved in the convective processes of a tornadic storm. Furthermore, if variations in local vehicle concentrations of two orders of magnitude are taken into account, our calculations show that vehicle-produced torque, over reasonable periods of time, can produce angular momentum of the same order or greater than the natural background (see Fig. 1). The angular momentum introduced annually by vehicles is sufficient to account for that present in ~ 10^5 giant tornadoes. (A total of ~ 600 including all sizes are actually reported per year.)

Court's point[5] that the centre of tornado occurrence has moved westward makes it even more impressive that the centre of tornado intensity, which is what we reported, has increasingly occupied the eastern sections of the USA. The obvious inference here is that the more intense tornadoes have been increasingly found in the east in support of our original thesis.

We agree that too few observations of the rotational sense of tornadoes have been reported to make these data highly significant. A χ^2 test based on these data shows, however, a statistically significant shift from anticyclonic to cyclonic tornadoes over the 24-yr period, and thus these data support our hypothesis. The fact that anticyclonic tornadoes exist at all is important in showing that local effects other than planetary rotation can be significant for the formation of tornadoes. One of these local effects could be vehicle-generated cyclonic angular momentum.

Darkow[6] raises an interesting point in attributing the weekly periodicity of the tornado data to periodicity in newspaper reporting. The possibility of reporting peculiarities being the cause has also concerned us. Before our initial publication, one of us contacted the Administrator of the National Oceanic and Atmospheric Administration, who was certain that weekend reporting was adequate or even intensified because of increased exposure to more people at weekends. In addition, since the data on the tornado tape we acquired from the National Severe Storms Forecast Center (NSSFC) are listed by source, we were able to separate out those that were identified as press clipping data (33%). The remaining data showed an even stronger weekly periodicity than reported for the total. These remaining data are considered to be the most reliable data by NSSFC.

As a further check we had plotted tornado injuries, damage, tornado days, path area and sums of *f*-scale numbers by day of week. We thought that tornadoes of sufficient significance to require the reporting of these parameters would not be subject to such reporting vagaries as might affect the reporting of lesser tornadoes. In every case Saturday was low, thus increasing our confidence in the validity of the findings.

Weekend changes in the production of factory wastes could conceivably influence the static stability and cloud-particle development as suggested by Kessler[1]. It is difficult, however, to see why this phenomenon would have its effect only on Saturday and not on Sunday. Presumably a factory that is closed on Saturday will remain so on most of Sunday. As a further check, we have obtained a tape of thunderstorm data from NSSFC and analysed it for weekly periodicity. We found none. Thus it seems that the periodicity in tornado occurrence is not dependent on convective storm periodicity but more probably on the periodicity of input of that unique and essential ingredient of tornadoes–angular momentum.

Referring again to Fig. 1, the planetary angular momentum scales by the fourth or fifth power of the radius of the area involved in convection, depending on the type of convergence, while energy scales only as the second power of the radius. Thus a strong argument can be made that, if energy limits the population of strongly rotating convective storms of the magnitude of hurricanes (which seems to be the case), storms of the magnitude of tornadoes are comparatively deficient in planetary angular momentum, as related to energy by at least three orders of magnitude. The fact that most thunderstorms do not involve tornadoes seems to support this statement. This argues that angular momentum, rather than energy, limits the population of tornadoes, and that any input of cyclonic angular momentum increases their incidence, as we have proposed.

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1 Kessler, E., *Nature*, **260**, 457 (1976).
2 Morton, B. R., Smith, R. K., and McIntyre, M. E., *Nature*, **260**, 457–458 (1976).
3 Manton, M. J., *Nature*, **260**, 458 (1976).
4 Lilly, D. K., *Nature*, **260**, 458–459 (1976).
5 Court, A., *Nature*, **260**, 459 (1976).
6 Darkow, G. L., *Nature*, **260**, 459 (1976).

Printed in Great Britain by Henry Ling Ltd., at the Dorset Press, Dorchester, Dorset