

The detection of hurricane asymmetries from aircraft reconnaissance flight data: Some simulation experiments

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SUMMARY

A series of observational system simulation experiments designed to investigate the data requirements for determining the flow asymmetry of a hurricane are described. Of particular interest is the azimuthal wave-number-one component of the asymmetry, which, together with the mean flow across the storm, is responsible for the storm motion. A principal finding is that the accuracy of retrieval of this component from wind data obtained from airborne omega dropwindsonde soundings depends on the orientation of aircraft flight patterns relative to that of the asymmetry. Since the orientation of the asymmetry is not known in advance, there will be an inherent uncertainty in the accuracy with which the asymmetry is determined. The simulation experiments enable one to estimate probable errors in the determination of the asymmetry and their implications for hurricane track errors.

The track errors are assessed by comparing the vortex track in a high-resolution control experiment with those that result from initial analyses based on simulated data sets of varying data density and quality. In some of the experiments, an increase in resolution along the flight tracks, or additional data in the storm environment, does not lead to an improvement in the forecast track, in contrast to increased data coverage on a regular grid. This at first sight surprising result is likely to be a consequence of the constant influence radius used in the objective analysis scheme, a factor which is currently being investigated.

The addition of random wind-measurement errors to the simulated data, comparable in magnitude to those in dropwindsonde measurements, does not lead to significantly inferior analyses or track forecasts based on them, suggesting that such errors are not the major cause of inaccuracy in diagnosing the vortex asymmetry. Moreover, the accuracy of the analysis is nearly independent of whether the data are taken at an instant of time, or over a typical nine-hour flight duration and then corrected to a storm-centred coordinate system.

KEYWORDS: Observing system simulation experiments Track forecasting Tropical cyclone

1. INTRODUCTION

Research over the last ten years into hurricane motion has indicated the importance of asymmetries in the vorticity and stream-function fields. These asymmetries are sometimes referred to as 'beta-gyres', because in one of their most elementary forms they are associated with the advection of planetary vorticity by the symmetric vortex circulation in the presence of the meridional gradient of planetary vorticity. However, there exists a range of other effects that can lead to vortex asymmetries (for recent reviews see Smith (1993) and Elsberry (1995)). As a result of their importance there have been studies of the data requirements necessary for resolving the asymmetries (Reeder *et al.* 1992; Weber and Smith 1995) as well as attempts to determine them from observational data (Franklin 1990; Franklin *et al.* 1996; Glatz and Smith 1996). A method for the objective analysis of aircraft observations is described by Bergman and Carlson (1975).

Numerical simulation experiments by Reeder *et al.* (1992) suggest that regularly spaced wind measurements with a horizontal resolution on the order of 100–150 km would be necessary to resolve the asymmetries of an average size hurricane adequately. As hurricanes develop and spend most of their lifetimes over the tropical oceans where observational data are sparse, the only data sets that have come close to meeting this requirement so far are those from synoptic flow experiments carried out over the Atlantic and Caribbean basins, and over the Gulf of Mexico, by the Hurricane Research Division (HRD) of the US National Oceanic and Atmospheric Administration (NOAA) Atlantic Oceanographic and Meteorological Laboratory. These experiments were based on multiple aircraft surveys of the storm environment using omega dropwindsondes (ODWs). Each flight pattern takes about 9 hours to complete, during which time a storm moving at a

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typical speed of 3 m s^{-1} will have moved a distance of about 100 km, comparable with the diameter of its core (i.e. the region inside the radius of maximum tangential wind speed). Data within a certain radius of the storm centre are sometimes specified relative to the moving storm for the analysis.

The impact of ODW data on the accuracy of hurricane track forecasts has been investigated by Burpee *et al.* (1984, 1996) and Franklin and DeMaria (1992). Franklin and DeMaria (1992) evaluated the benefits of ODW data on track forecasts in a sample of 14 synoptic flow experiments using a barotropic model, and showed that the additional data reduced the mean 24–36 h mean forecast-position errors of hurricanes by 12–16%. Using more-sophisticated forecast models, Burpee *et al.* (1996) showed that the use of ODW data leads to statistically significant reductions of 12–60 h mean forecast errors of 16–30%.

As far as we are aware the possible impact of ODW data on the structure of the flow asymmetries of hurricanes has not been investigated. While the data in individual hurricanes inevitably show asymmetries, it has proven difficult to explain these asymmetries in terms of our current understanding of vortex motion in simple theoretical models (see, for example, Franklin *et al.* 1996; Glatz and Smith 1996), making it hard to assess the relevance of the theories.

The difficulty arises in part because the model formulations invariably begin with a symmetric vortex in an environment whose structure is specified and has a spatial variation that is small compared with the vortex scale. Then, the flow asymmetries that develop in the model may be attributed to the interaction between the vortex and its environment. However, we cannot know *a priori* whether such an artificial scale-separation is valid in a particular hurricane. Also, because the partitioning between vortex and environment is not unique, we cannot determine whether the asymmetries we are seeking may be similarly attributed. Nevertheless, it is pertinent to ask whether the aircraft flight patterns currently in use would be adequate to determine the flow asymmetries that arise in the models.

It is reasonable to expect that the contribution of ODW data to improved hurricane track prediction is related to the improvement they bring in resolving the flow asymmetries of the storm. Therefore, it seems useful to develop a methodology for assessing flight strategies and to determine to what extent the calculated storm asymmetries are sensitive to particular flight patterns. This is the purpose of the present paper, where we describe a series of simulation experiments designed to address the questions raised above.

The strategy of this paper is similar to that adopted by Weber and Smith (1995) and is briefly as follows. First we carry out a numerical integration of the barotropic vorticity equation on a beta-plane in which there is either an imposed large-scale zonal shear flow, or simply no large-scale flow at all. At the initial time, a symmetric tropical-cyclone-scale vortex is inserted in the flow and the integration is carried out for a period of 144 h. As described earlier, the vortex circulation interacts with the imposed large-scale environment in its vicinity and asymmetries develop in the vorticity field. For example, if there is a gradient of absolute vorticity in the environment, lines of absolute vorticity will be advected by the vortex circulation and thereby distorted. This distortion is manifest as an asymmetry of the relative vorticity. Using a high-resolution grid for the integration, the evolution of the flow can be determined with precision, including the structure of the vortex asymmetries and the vortex track. We refer to this integration as the control calculation. At some given time, say after 72 h of integration, we extract wind data from the simulation at points located at intervals along two simulated aircraft flight tracks and at a few additional points corresponding with the location of land-based rawinsonde soundings that might be available in practice. In some of the calculations the time that would be required to obtain the aircraft soundings is allowed for. The wind data are taken as a simulated data set which is then subjected to a re-analysis and interpolated on to the original fine grid. The

re-analysis is used to determine the vortex asymmetries and also as an initial condition for a further 72 h integration. The vortex track so obtained is compared with the track in the control calculation.

The paper is organized as follows. In section 2 we detail the range of experiments that were carried out and in section 3 we describe the analysis method and show examples of analyses. In section 4 we investigate the impact of various analyses on the subsequent vortex tracks. A summary of our findings and their implications for hurricane prediction are presented in section 5.

2. SIMULATION EXPERIMENTS

The simulated data sets are obtained from an integration of the numerical model described by Ulrich and Smith (1991), starting with an initially symmetric hurricane-scale vortex in a zonal shear flow, or in an environment at rest. The model is barotropic and non-divergent and uses the vorticity/stream-function formulation to calculate the subsequent motion of the vortex in a zonal channel on a beta-plane. The channel is periodic in the zonal direction and has impermeable meridional boundaries. In the present calculations the domain size is 5000×5000 km and the grid size is 20 km.

(a) Control data sets

Calculations are carried out with no background flow and for a sinusoidal zonal flow of the form:

$$U(y) = U_0 \sin(\pi y/2L), \quad (1)$$

where y is the meridional coordinate, $2L$ ($= 5000$ km) is the domain size and U_0 is a constant. The wind fields obtained from these integrations after 72 h provide two high-resolution control data sets for the experiments to be described.

(b) Simulated observational data sets

Simulated observational data sets are obtained by interpolating the winds from the control-run fields to points corresponding with locations of typical rawinsonde measurements. These include ODW soundings in and around a hurricane from two instrumented aircraft as well as to a few land-based radiosonde soundings in the hurricane environment that might be available in real data situations. Examples of real data sets that have been obtained by the HRD are described by Franklin *et al.* (1996). Three sets of data locations are investigated here; these are summarized in Table 1. The first set of locations is that used in Hurricane Andrew (1992) and forms the basis of the experiments designated E1 in Table 1. The distribution of data points for E1–E3 is shown later in Fig. 3, together with some analysed asymmetries. Experiments E4 and E5 are designed to assess the effects of measurement errors on the calculation of the asymmetries.

For each set of experiments (E1–E5), sets of calculations are carried out for the case of zero background flow and for the zonal shear flow represented by Eq. (1) with $U_0 = 5 \text{ m s}^{-1}$. In these calculations no account is taken of the time that is required in practice to obtain the aircraft ODW data. In a second group of experiments this time is taken into account by relating the locations of the simulated soundings to a storm-centred coordinate system. However, the results of the latter differ little from those of the first group and are not discussed further. Apparently, the motion of the storm during the period required to collect the ODW data can be neglected.

It is conceivable that the accuracy of retrieval of the wave-number-one vorticity asymmetry depends upon the orientation of the flight track pattern to the asymmetry. Since in

TABLE 1. SUMMARY OF THE TEN SETS OF SIMULATION EXPERIMENTS (E1–E10) THAT WERE CARRIED OUT

Set	Simulation experiments
E1	Hurricane <i>Andrew</i> data distribution
E2	As E1, but with double the number of ODW locations
E3	Linear flight track segments, same data density as in E1
E4	As E1, but with Gaussian errors of 10% added to the wind data
E5	As E2, but with Gaussian errors of 10% added to the wind data
E6	As E1, but with extra points in the storm environment
E7	As E2, but with extra points in the storm environment
E8	Regular grid, 50 km resolution
E9	Regular grid, 100 km resolution
E10	Regular grid, 200 km resolution

Each set of experiments, detailed in column 2, contain 32 calculations, 16 for the case of no environmental flow and 16 for a zonal flow with $U_0 = 5 \text{ m s}^{-1}$ in Eq. (1).

practice the latter would not be known *a priori*, sixteen realizations are obtained for each simulated data set by successively rotating the data locations (in 22.5° steps) about the vortex centre. With these different samples of the wind field, a statistical analysis is carried out to obtain the average and standard deviation of the sample characteristics. Altogether more than 320 calculations are performed.

3. OBJECTIVE ANALYSES

Objective analyses of the simulated wind data are carried out using the successive-correction scheme developed by Pedder (1993) and are used to calculate the stream-function and vorticity fields. These, together with the wind fields, are stored on the same grid as in the numerical model for further analysis.

Following Smith *et al.* (1990), the vortex centre is defined as the position of the relative-vorticity maximum and is determined by using a quadratic fitting function. The flow at the centre is calculated in three different ways: directly from the wind fields at the known centre and at the analysed centre, and from the derivative of the stream-function field at the known centre. Around both centres, an azimuthal Fourier analysis of the stream-function and vorticity fields is carried out and the wave-number-one component of each asymmetry is compared with the corresponding field from the control run. In the figures the analysed centre is used because this is all that would be available in reality.

The position of the analysed centre does not vary by more than 8 km from that in the control in all the cases investigated, and for the denser data sets it is within 2 km of the control. An accurate location of the vortex centre is important because any difference of the centre position leads to the appearance of a spurious wave-number-one mode which contaminates the analysis of this asymmetry near the vortex centre.

The accuracy of the objective analyses can be assessed by comparing the analysed wind speed and direction at the vortex centre, and the amplitude, direction and distance of the wave-number-one asymmetry with those from the control calculation.

In order to optimize the comparison, it is found necessary to choose the radius of influence, d , in the analysis scheme as a function of the data density. The value of d is taken to be the average of the distance between a data point and its closest neighbour, d^* , multiplied by an influence factor, γ . The value of γ is determined as follows. First,

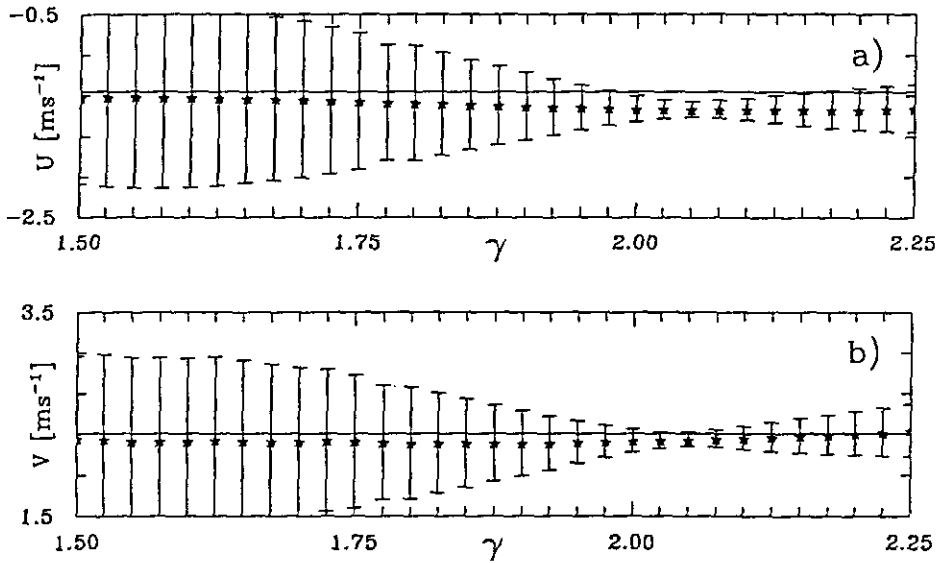


Figure 1. Mean values (denoted by stars) and standard deviations (represented by vertical lines) of (a) the u and (b) the v components of the flow at the vortex centre as functions of the radius of influence for the 16 analyses E2 (see Table 1) at 48 h when there is no environmental flow. The abscissa is the radius of influence (γ) multiplied by the average distance between two neighbouring data locations, in this case 109 km. The solid line represents the value from the control calculation.

a series of values for γ are chosen, ranging from 1.5 to 2.3 in steps of 0.05. For each of these values we calculate the wind velocity (u_0 , v_0) at both vortex centres, as well as the orientation, amplitude and size* of the stream-function and vorticity asymmetry. For each of these quantities, one obtains 16 realizations by rotating the data in angular steps of 22.5° . The mean and standard deviation of the values for the 16 realizations are calculated as a function of γ and are compared with the corresponding values for the control run. Figure 1 shows an example of such a calculation for one of the denser data sets (with data at 100 locations) obtained from the control flow at 48 h in the case of no environmental flow. The calculations in this figure are for u_0 and v_0 calculated at the analysed vortex centre. In this case the average values of the 16 realizations lie close to that in the control case, but the standard deviation has a minimum when $\gamma = 2.05$. For other values of γ there is a large difference between the analysed values of u_0 and v_0 and those in the control in some of the realizations. Thus, the optimum value of γ is chosen to be that for which the standard deviation is smallest. Similar values are obtained when the analysis is applied to the orientation, amplitude and size of the stream-function and vorticity asymmetry.

In reality, one would not know whether the value of γ is optimum, because one would have only one realization! This is where simulation experiments can serve as a guide. In the present calculations it is found that the optimum value of γ is such that the quantity $\gamma^2 d^*$ is approximately constant, equal to 450 km. Thus, knowledge of the distribution of data locations enables one to calculate an optimum radius of influence in the objective analysis scheme.

Figure 2 shows the comparison between the wave-number-one vorticity asymmetry for some of the data sets at 48 h in the case of no environmental flow with that from the

* The size is characterized by the distance separating the two extrema.

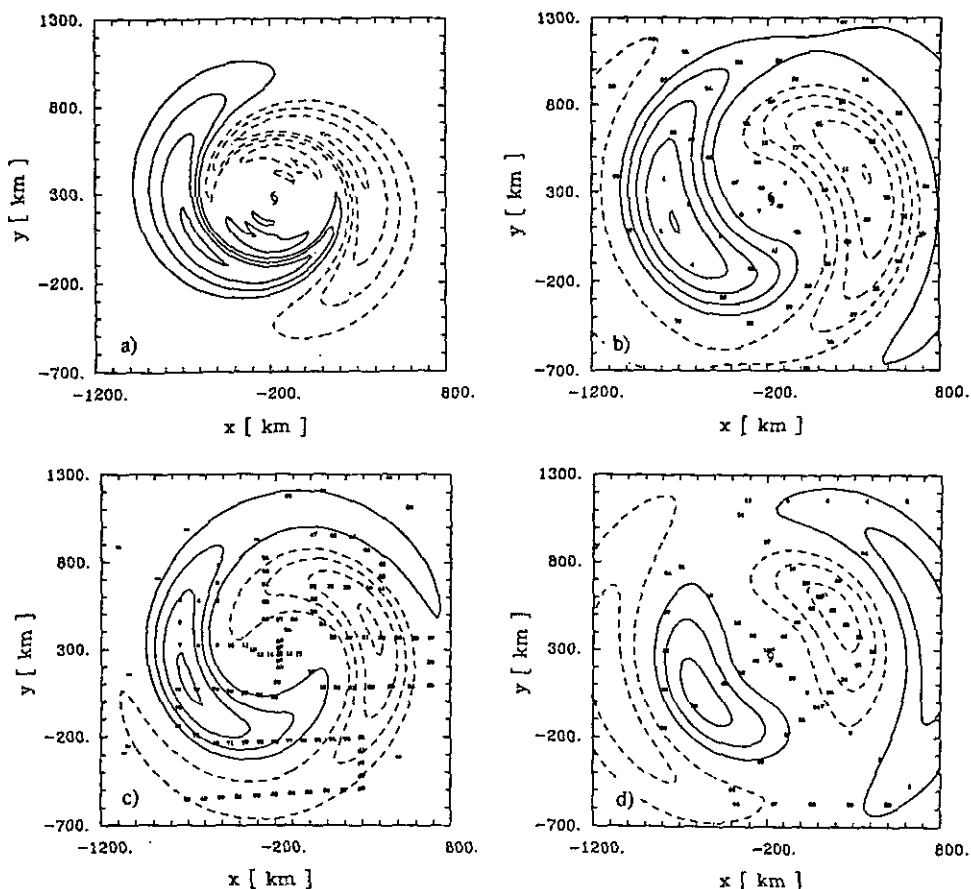


Figure 2. Example of the more superior analyses of the wave-number-one vorticity asymmetry after 48 h of integration in calculations (b) E1, (c) E2 and (d) E3 (see Table 1) with no environmental flow compared with (a) that in the control calculation. The small numbers denote the data locations. The contour interval is $5 \times 10^{-6} \text{ s}^{-1}$.

control flow. Shown are the results of cases with the least difference in amplitude, size and orientation of the asymmetries compared with the control field. In these cases there are data locations close to the extrema of the control field. Figure 3 shows the equivalent comparisons, but in the worst cases. It is clear that in these cases there are no data locations close to the extrema of the control field so that the true location and amplitude of the extrema are unresolved. It follows that an accurate determination of the wave-number-one asymmetry requires wind measurements near the maximum and minimum of the actual asymmetry, and the largest discrepancies between the analysed asymmetries and the control occur for data sets which do not include such measurements. Unfortunately, the location of the extrema of the actual asymmetry is not known *a priori* and without such knowledge it is difficult to find an optimum orientation for the aircraft flight patterns to best resolve the wave-number-one asymmetry. A higher density along the flight track increases the chance that data will be obtained in such locations, but with the limited range of the aircraft it may be difficult to achieve a data density to ensure that the asymmetries are adequately resolved. If the data locations are in few straight lines, as in Fig. 2(d), the chance of misrepresenting the vorticity and stream-function fields increases, even if the

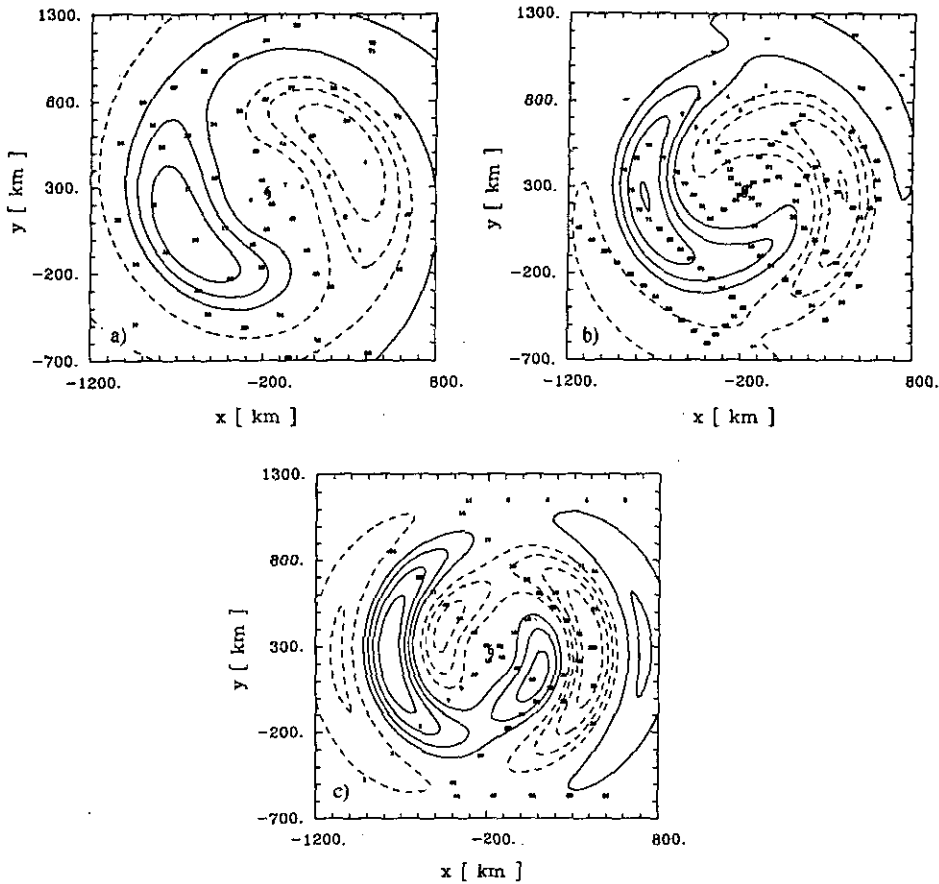


Figure 3. As in Fig. 2, but for the least superior analyses. The calculations for the data sets E1, E2 and E3 are shown in Figs. 3(a), (b) and (c), respectively; these should be compared with the corresponding field for the control calculation shown in Fig. 2(a).

number of data points is the same as in Fig. 2(c). In particular, the number of cases that resolve the asymmetries poorly grows, because the probability increases of the extrema being unsampled. Thus, the worst analysis in the 16 realizations in a particular case is obtained from the data sets which have the data points in a line (Fig. 3(c)), although in some cases the analysed asymmetry is acceptable.

For all the environmental flows studied, the inner fields (within 500 km of the vortex centre) are best resolved by the densest data sets. For the data sets which have nearly 100 data points within 500 km of the vortex centre (e.g. E2), the standard deviation of the difference between the analysed strength and orientation of the wave-number-one asymmetry and the corresponding control values is approximately 5%. With data density commonly achieved by the HRD (around 50 ODWs) the standard deviation increases to 18%, and grows steadily as the data density is reduced further. The accuracy of the analysis is nearly independent of whether the data are taken at an instant of time, or over a 9-hour interval and then corrected to a storm-centred coordinate system. Therefore we have not shown results for the latter experiments.

The accuracy of retrieval of the wave-number-one asymmetry has implications for the accuracy of determining the flow across the vortex centre. For an accurate determination

TABLE 2. MEAN AND STANDARD DEVIATION OF THE WIND COMPONENTS (m s^{-1}) AT THE VORTEX CENTRE (U_c , V_c) IN THE FIVE SETS OF SIMULATION EXPERIMENTS (E1–E5; SEE TABLE 1) COMPARED WITH THE COMPONENTS IN THE CONTROL CALCULATION

Data distribution	Zonal flow speed U_0			
	$U_0 = 0 \text{ m s}^{-1}$		$U_0 = 5 \text{ m s}^{-1}$	
	U_c	V_c	U_c	V_c
Control	-1.26	2.31	-0.83	2.65
E1	-1.28 ± 0.65	2.48 ± 0.69	-0.77 ± 0.70	2.96 ± 0.68
E2	-1.43 ± 0.08	2.25 ± 0.07	-0.93 ± 0.05	2.67 ± 0.07
E3	-1.30 ± 0.16	2.41 ± 0.18	-0.89 ± 0.28	2.91 ± 0.26
E4	-1.36 ± 0.32	2.15 ± 0.33	-1.00 ± 0.34	2.64 ± 0.31
E5	-1.33 ± 0.69	2.38 ± 0.78	-0.96 ± 0.77	2.94 ± 0.87

of the wind speed and direction of the flow across the centre, it is desirable to have data points near the centre, but the winds need not be measured exactly at the vortex centre. A comparison of the mean and standard deviation of the wind components at the vortex centre in the five sets of simulation experiments (E1–E5) with those in the control calculation is shown in Table 2.

For these quantities alone, no clear picture emerges that one data set is superior to the other. For example, when $U_0 = 0$, the value of U_c in experiment E1 is closer to the control than in the case where the resolution is doubled (experiment E2), but the situation is reversed for the value of V_c . However, increased resolution reduces the standard deviation between realizations. The calculation with random wind errors added to the data (experiments E4 and E5) does not give significantly inferior retrievals for U_c and V_c , although the standard deviation is higher than the equivalent cases (E1 and E2, respectively) without errors. A likely explanation for the findings is that the flow across the vortex centre is determined predominantly by the asymmetric structure in the region where the data coverage is adequate. However, as can be seen especially in Fig. 3, the outer part of the asymmetric field is not always well recovered. Similar remarks apply in the experiments which include a zonal basic flow (4th and 5th columns in Table 2).

The re-initialization of the asymmetry for an accurate prognosis of the vortex track discussed in section 4 requires a sufficiently accurate analysis of both the mean tangential circulation of the vortex and the wave-number-one vorticity asymmetry. The radial structure of the tangential circulation will have implications for how closely the latter evolves with time compared with that in the control calculation.

Figure 4 shows the comparison between the azimuthally-averaged tangential wind speed in the two sets of 16 calculations E1 and E2 with that of the control calculation when there is no basic flow. The results are broadly as one might expect. The improved resolution in E2 enables the symmetric circulation to be determined with greater accuracy. In these calculations the peak wind speed is about 32 m s^{-1} and is attained at a radius of 200 km compared with values 38 m s^{-1} and 150 km, respectively, in the control calculation. In E1, where there are fewer data points, the symmetric wind profile is broader and less peaked with a maximum wind speed of about 21 m s^{-1} at a radius of more than 250 km. Note, however, that the standard deviation of the 16 calculations in both cases is practically negligible. The analysed anticyclonic circulation, between 600 and 900 km in E1 and beyond 780 km in E2, will have a significant influence on the subsequent evolution

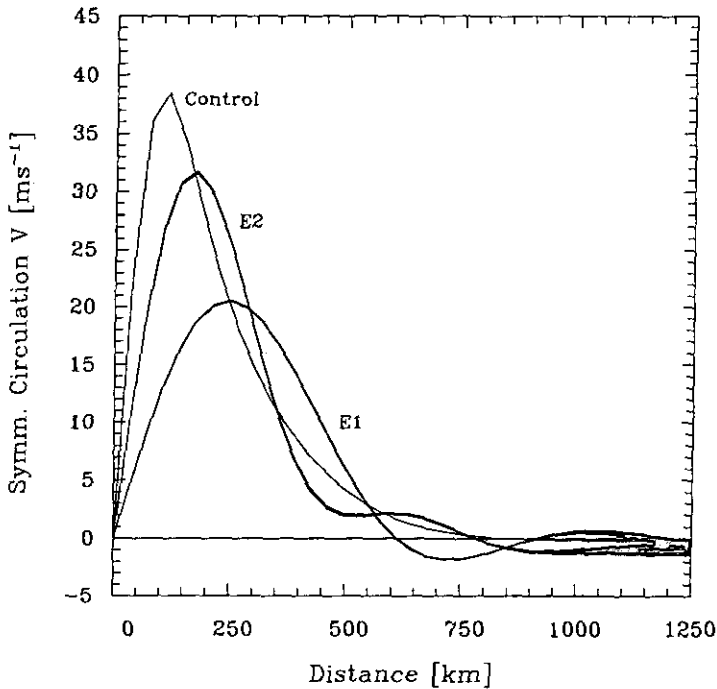


Figure 4. Radial profiles of mean tangential velocity after 48 h of integration in the 16 calculations in E1 and 16 in E2 with no environmental flow (see Table 1) compared with that in the control calculation. Note that the standard deviation in the two sets of calculations is so small at radii less than 900 km that the curves essentially lie on top of each other.

of the wave-number-one asymmetry compared with that in the control, and presumably contributes to the track errors discussed later.

4. TRACK FORECASTS USING THE ANALYSES

The analysed stream-function and vorticity fields at 48 h are used to re-initialize the numerical model, and the model is integrated for a further 72 h. The calculated vortex tracks are compared with the tracks from the control calculation to assess the impact of varying amounts of simulated data on determining the future track.

Figure 5 shows the comparison between the tracks of the 16 realizations in experiments E1–E3 and E5, for the cases with no environmental flow, with that in the control experiment. The mean position errors after 24, 48 and 72 h in these and other cases are summarized in Table 3. This table contains also the mean position errors of tropical-cyclone forecasts in all basins by the UK Meteorological Office in 1996, which are broadly typical of operational forecast performance, although somewhat better than average (UK Meteorological Office, *Monthly summary of tropical cyclone activity and forecasts*, January 1997). In addition it shows the mean forecast error after 24 h and 48 h using post-processed ODW data and a barotropic forecast model in the cases investigated by Franklin and DeMaria (1992: see their Table 2). Note that the mean errors in most of the experiments here are considerably less than those currently achieved in practice, even those based on barotropic forecasts using actual ODW data.

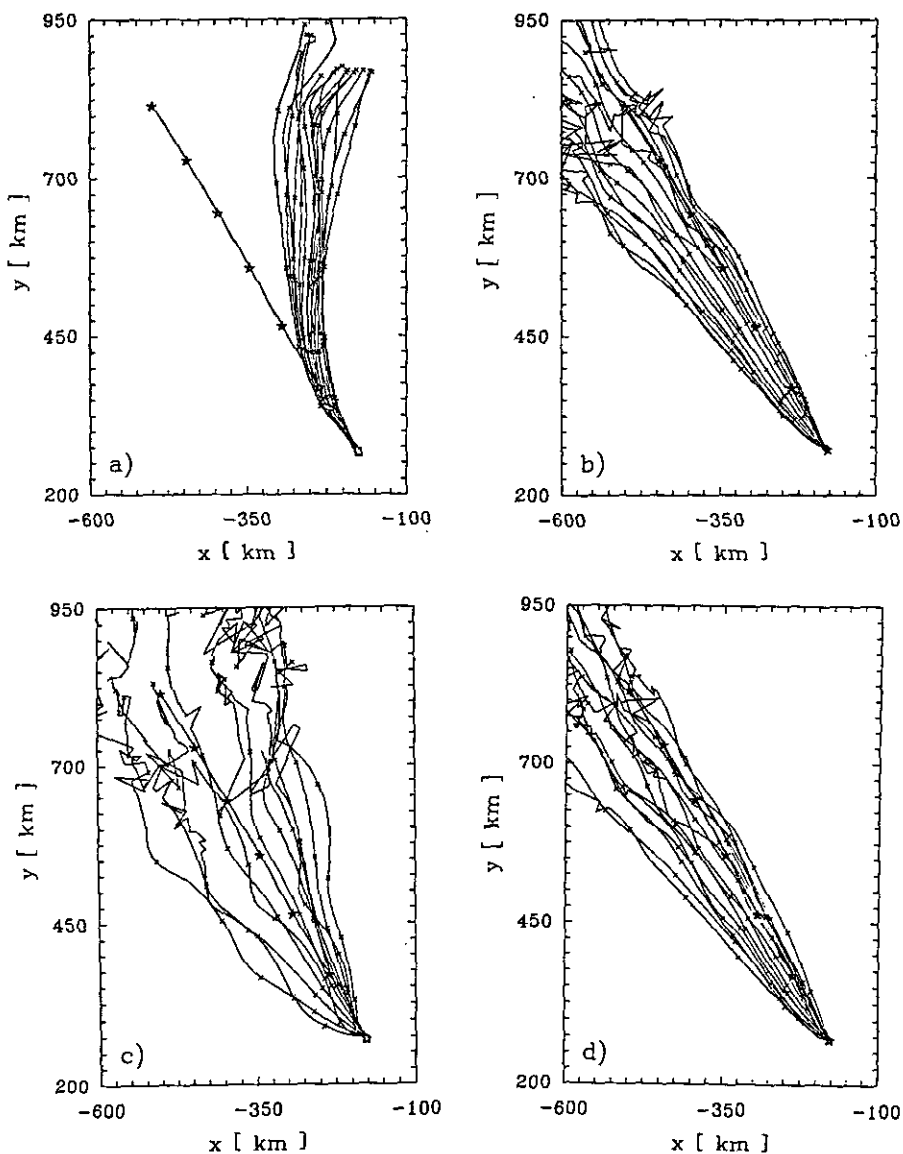


Figure 5. Vortex tracks after 72 h of integration with no environmental flow in the 16 calculations in (a) E1, (b) E2, (c) E3 and (d) E5 (see Table 1) in comparison with the track in the control run (thicker line). The crosses (stars on the thicker line) denote the centre position at 12 h intervals.

With the data distribution achieved in Hurricane *Andrew*, the vortices in all the 16 realizations begin to move in the direction of that in the control, but they all develop a northward bias as time proceeds. Mean position errors increase from 55 km at 24 h to 301 km at 72 h. With double the amount of data along the simulated flight tracks (Fig. 5(b)), these errors are reduced to 28 km at 24 h and 178 km at 72 h; in this case the tracks generally cluster around the control. For the linear flight tracks (Fig. 5(c)), the spread in the tracks is larger than in either of the foregoing calculations (standard deviation 132 km at 48 h compared with 27 km for E1 and 56 km for E2).

TABLE 3. MEAN TRACK ERRORS (KM) AND THEIR STANDARD DEVIATIONS (IN BRACKETS) AT 24, 48 AND 72 H IN SELECTED SETS OF SIMULATION EXPERIMENTS (SEE TABLE 1)

Experiment set	Time		
	24 h	48 h	72 h
E1 $U_0 = 0 \text{ m s}^{-1}$	55 (15)	152 (27)	301 (38)
E2 $U_0 = 0 \text{ m s}^{-1}$	28 (32)	67 (56)	178 (76)
E3 $U_0 = 0 \text{ m s}^{-1}$	59 (80)	87 (132)	128 (166)
E4 $U_0 = 0 \text{ m s}^{-1}$	52 (22)	139 (49)	259 (70)
E5 $U_0 = 0 \text{ m s}^{-1}$	33 (33)	54 (52)	158 (71)
E1 $U_0 = 5 \text{ m s}^{-1}$	51 (9)	48 (31)	120 (58)
E2 $U_0 = 5 \text{ m s}^{-1}$	86 (36)	218 (70)	401 (110)
With outer data			
E6 $U_0 = 0 \text{ m s}^{-1}$	80 (20)	188 (41)	347 (75)
E7 $U_0 = 0 \text{ m s}^{-1}$	69 (23)	175 (48)	315 (82)
E6 $U_0 = 5 \text{ m s}^{-1}$	167 (142)	319 (222)	413 (292)
E7 $U_0 = 5 \text{ m s}^{-1}$	82 (21)	119 (61)	203 (102)
Regular grid			
$U_0 = 0 \text{ m s}^{-1}$			
E8 50 km	18 (1)	27 (3)	43 (5)
E9 100 km	25 (2)	90 (5)	176 (7)
E10 200 km	43 (11)	140 (19)	272 (18)
UKMO 1996	172	274	400
Real ODW data	173	449	

For comparison, mean tracks errors from the UK Meteorological Office Prediction Scheme for all world basins during 1996 are shown in the penultimate row and those using real omega dropwindsonde (ODW) data in conjunction with a barotropic forecast model in the last row.

When wind errors are included as in experiments E4 and E5 (see also Fig. 5(d)), the mean track errors are only marginally reduced compared with the corresponding calculations (E1 and E2) without errors, but the standard deviation is somewhat larger in E4 than in E1. Evidently, the presence of measurement errors in the winds of the size studied here are not a significant factor in determining the accuracy of the vortex tracks. The mean track errors in experiments E3 are smaller than in E1 after 24 h, but the standard deviation is considerably larger as is evident in Fig. 5.

The tracks in the presence of a 5 m s^{-1} zonal flow are shown in Fig. 6. Surprisingly, after 24 h, the mean track error in the E1 calculation is much smaller than in the absence of a basic flow; indeed the mean error is only 120 km after 72 h, compared with 301 km when there is no mean flow. This result is hard to explain and might be fortuitous! Even more surprisingly, the errors are considerably less than in the case where the number of data points along the aircraft tracks is doubled (E2); then the 72 h mean error is 401 km. In addition, the tracks in this case more resemble those in the case of zero basic flow! It seemed to us that one possible explanation for this could be the fact that the distribution of data points is insufficient to resolve the basic flow adequately. To assess this supposition we repeated the four calculations E1 and E2 with and without a basic flow with the inclusion of 20 additional data points outside the region previously sampled, but lying within a distance of 2500 km from the vortex. The results of these experiments *vis-à-vis* the track errors are

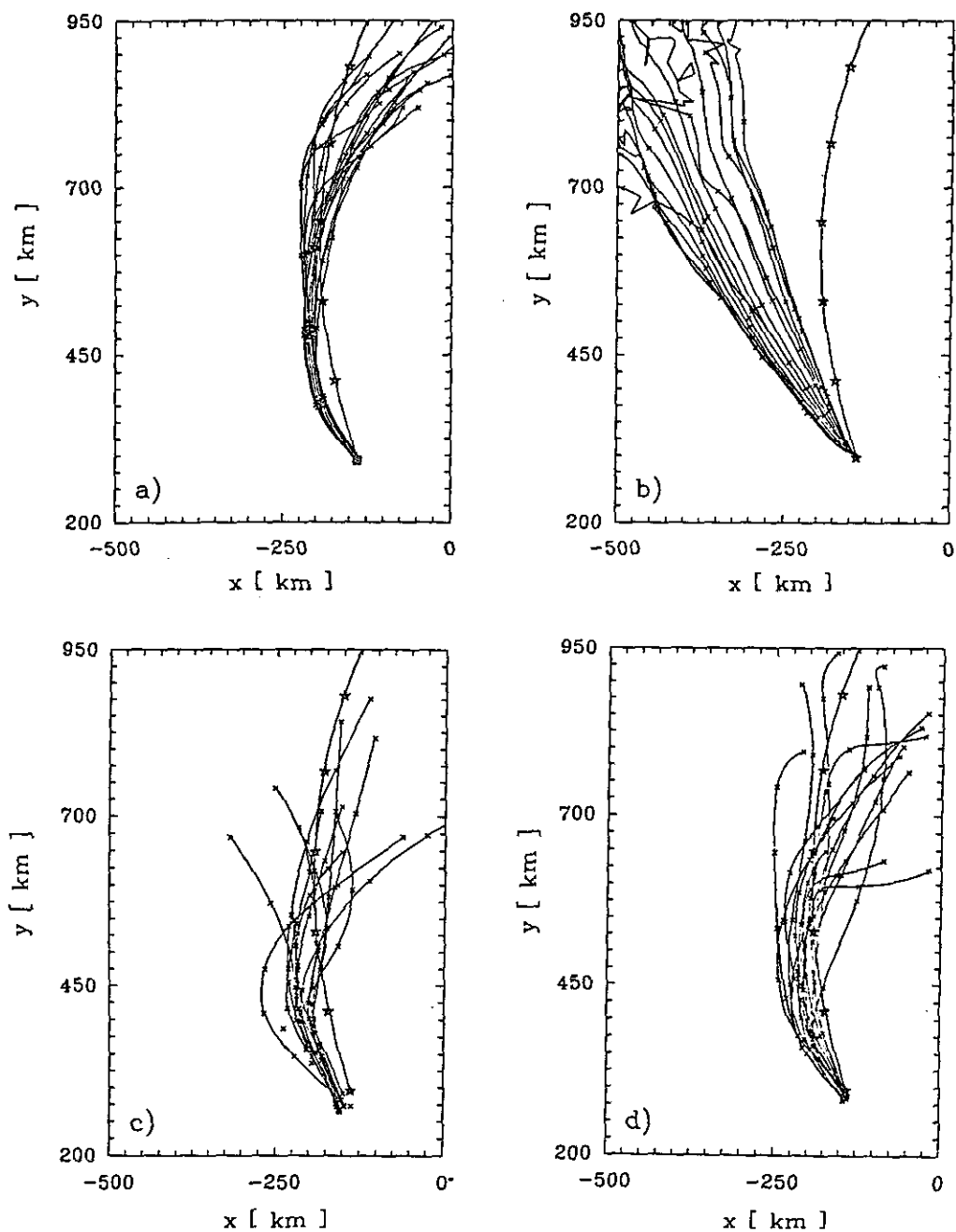


Figure 6. As Fig. 5, but with a zonal flow flow in the 16 calculations and for (a) E1, (b) E2, (c) E6 and (d) E7.

summarized in Table 3. While the track errors in the case E2 are noticeably improved, the mean errors in all the other calculations deteriorate markedly. This shows that our supposition was false and it led us to sample the control data on a regular grid, similar to the calculations carried out by Reeder *et al.* (1991) and Weber and Smith (1995). In this case, the mean errors listed in Table 3 show no surprises; they diminish monotonically as the data resolution improves, consistent with the findings of Reeder *et al.* and Weber and Smith.

The foregoing results expose a weakness of using a fixed influence radius over the entire analysis domain for data sampled on an irregular grid. Similar conclusions have been arrived at by Pedder (personal communication) in connection with the analysis of fronts. However, the development of a more sophisticated analysis procedure to overcome this problem will require time and an investigation of the problem will hopefully be reported in due course.

5. CONCLUSIONS AND OUTLOOK

We have developed a methodology for a systematic evaluation of the data requirements for an accurate analysis of the flow asymmetry of a hurricane using predominantly airborne omega-dropwindsonde soundings. We have shown that the accuracy of retrieval of the wave-number-one component of the asymmetry depends on the orientation of aircraft flight patterns relative to that of the asymmetry. The fact that this orientation would not be known in reality implies that there will be an inherent error in any particular analysis and this will flow on to affect forecast track errors using the analysis as the initial condition for a numerical forecast. The methodology allows one to estimate probable errors in the determination of the asymmetries and the corresponding track errors.

We have found that the accuracy of the analysis is nearly independent of whether the data are taken at an instant of time, or over a nine-hour interval typically required to obtain such data, and then corrected to a storm-centred coordinate system.

While the calculations are based on a barotropic model and a particular analysis scheme, the methodology could be extended using more sophisticated forecast models and other analysis schemes.

A finding that is at first sight surprising is that increasing the data density along the aircraft flight tracks, or the acquisition of additional data in the storm environment, does not necessarily lead to an improvement in the track prediction, in contrast to increased data resolution on a regular grid. This appears to be a consequence of the use of a constant influence radius in the objective analysis scheme when the data are sampled on an irregular grid and requires further study. Investigations of this aspect are in progress and the results should be reported in due course. It is found, however, that increasing the data density along the aircraft flight tracks can significantly improve the determination of the azimuthally-averaged tangential wind profile.

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