The Detection of Flow Asymmetries in the Tropical Cyclone Environment

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5 June 1990 and 26 September 1990

ABSTRACT

Data from a numerical simulation of a moving barotropic vortex on a sphere with 10-km resolution are used to assess the ability of a state-of-the-art objective analysis scheme to detect certain large-scale tropical cyclone asymmetries, the so-called "beta gyres" to which the cyclone motion appears to be attributed.

A series of analyses is conducted, first using the entire dataset and then taking subsets of it. Four subsets were considered in which data at a regular array of points were extracted, progressively increasing the separation between points. A fifth calculation was considered in which data were selected at points corresponding to the proposed upgraded upper-air network for a tropical cyclone motion experiment in the northwest Pacific region.

It is shown that for a moderate-sized tropical cyclone-scale vortex, a regular grid spacing on the order of 100–150 km is required to adequately define the gyres, at least when the ambient flow is weak. The upgraded upper-air network was found to be inadequate by itself for this purpose, suggesting that aircraft dropwindsonde data are a prerequisite for this task.

1. Introduction

Recent numerical simulations of vortex motion on a beta plane with zero basic flow (Chan and Williams 1987; Fiorino and Elsberry 1989; Smith et al. 1990) and with a spatially varying mean flow (Ulrich and Smith 1991) suggest that the advection of a tropical cyclone by some vertical average of the wind field across its center holds the key to understanding and predicting the motion of the storm. In the absence of a basic flow, the foregoing studies show that the flow asymmetry is dominated by a pair of counterrotating gyres with a mature scale on the order of 1000 km (the distance separating their centers). This is a scale that might be resolvable with existing observational networks, at least with some supplementary dropwindsonde soundings in the storm environment by reconnaissance aircraft. The gyres, which are produced largely by the advection of planetary vorticity (or, in the case of a basic flow, absolute vorticity) by the symmetric circulation of the vortex, have acquired the name beta gyres; a name that is adhered to in this study although a more accurate term might be "absolute vorticity gyres" As shown by Ulrich and Smith (1991), the gyres are not apparent when there is a basic flow unless the latter is subtracted from the total asymmetric flow itself. This has implications concerning the ability to extract the gyres from observational data, which are in any case sparse over the tropical ocean environment of cyclones.

The present study explores the observational requirements for detecting the beta gyres in nature. It was motivated by the proposed experiment on tropical cyclone motion in the northwest Pacific region, instigated by the United States Office of Naval Research (Elsberry 1990). One aim of the experiment was to document the gyre structure and its evolution in relation to cyclone motion. The question that immediately arises is: how adequate would the likely data network be for this purpose? However, a question of wider importance is: what resolution would be required to be able to resolve the symmetric vortex and to extract the flow asymmetries and, more specifically, to separate the basic flow and the beta gyres? Since the latter task presumes a partitioning in which the basic flow is known, the separation problem would appear to make sense only in a model simulation wherein the basic large-scale flow is externally imposed (Ulrich and Smith 1991). The gyres might be expected to be most detectable in atmospheric situations where the large-scale flow is relatively weak, analogous to the numerical cal-

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culation with zero basic flow. We shall focus attention on this situation.

The plan is to use the numerical model simulations of Smith et al. (1990), at least a small variation therefrom, to produce a suitable situation to analyze. Then the analysis scheme described by Lord and Franklin (1987) is applied to attempt to reconstruct the gyres for regular grids of varying resolution and for the land-based observational network likely to be available during the ONR experiment.

2. The simulated vortex

The vortex to be analyzed was created by solving the barotropic vorticity equation for the motion of an initially symmetric vortex in the absence of an environmental flow. The equation, valid on a spherical earth, is expressed in Mercator coordinates. The initial vortex is symmetric on the sphere and therefore appears slightly distorted by the coordinate transformation. The Mercator coordinates (x, y) are related to latitude and longitude coordinates (ϕ, λ) by the transformation

$$x = (a\cos\phi_0)\lambda, \tag{2.1a}$$

$$y = (a\cos\phi_0)\ln[(1+\sin\phi)/\cos\phi], \tag{2.1b}$$

where a is the radius of the earth and ϕ_0 is the latitude at which the transformation is true. By means of this transformation it is possible to provide model data at points that are readily acceptable by the analysis scheme.

In Mercator coordinates the barotropic vorticity equation takes the form

$$\frac{\partial\zeta}{\partial t} = m^2 J(\zeta, \psi) - \beta\frac{\partial\psi}{\partial x}, \tag{2.2}$$

where

$$\zeta = m^2\left[\frac{\partial}{\partial x}\left(\frac{v}{m}\right) - \frac{\partial}{\partial y}\left(\frac{u}{m}\right)\right] \tag{2.3}$$

is the vertical component of relative vorticity, ψ is the streamfunction defined by

$$u = m\frac{\partial\psi}{\partial y}, \quad v = m\frac{\partial\psi}{\partial x}, \tag{2.4}$$

u, v are the eastward and northward wind components on the spherical earth, $m(\phi) = \cos\phi_0/\cos\phi$ is the map factor of the coordinate transformation (2.1), $\beta = m^2(df/dy)$ is the variation of the Coriolis parameter f with latitude, and t denotes the time. Using (2.3) and (2.4), the streamfunction and vorticity are related by the equation

$$\nabla^2\psi = \zeta m^{-2}. \tag{2.5}$$

The tangential velocity profile of the initial vortex is identical with that used by Smith et al. (1990) and the calculations were carried out on a $18.58° \times 18.58°$ domain with a uniform grid spacing of 201 points in both coordinate directions. This is roughly equivalent to a resolution of 10 km. The model was integrated for a period of 24 h by the method described in Smith et al. (1990). At this time the vortex had developed an asymmetry consisting of a pair of large-scale counterrotating gyres due to advection of planetary vorticity by the vortex circulation. "Large scale" means that the separation of the gyre centers is several times the diameter of the vortex core, characterized by the radius of maximum tangential wind speed. In the model, the vortex motion is closely approximated by the streamflow across the symmetric vortex center associated with the vorticity asymmetry (e.g., Smith et al. 1990).

3. The analysis scheme

The analysis scheme uses the mechanical interpolation method described in the Appendix of Ooyama (1987). It employs a two-dimensional least squares fitting algorithm combined with a derivative constraint. The latter acts as a spatial low-pass filter on the analyzed field. The filter scale may be chosen to remove observational noise or fluctuations on scales too small to be resolved adequately by the data. The analyzed field is represented continuously throughout the domain as a bilinear combination of local basis functions centered at a two-dimensional array of nodal points. Further details may be found in Lord and Franklin (1987).

4. Results

Figure 1 shows the isopleths of relative vorticity ζ, streamfunction ψ, and the asymmetric part of the streamfunction ψ_{asym1}, based on an analysis of the model fields after 24 h of integration using all the model data points. Superimposed on each field is a map of the northwest Pacific region, the focus area for the ONR experiment, and shown in Fig. 1a is the enhanced upper-air station network as envisaged in the preliminary design of the experiment. In this case, the analysis used a 0.85-deg filter. The streamfunction asymmetry in Fig. 1c (ψ_{asym1}) was obtained by subtracting the initial symmetric streamfunction centered at the current position of the relative vorticity maximum from the total streamfunction. The relative vorticity maximum, which is not exactly collocated with the local streamfunction minimum, is defined to be the vortex center.[1] This characterization of the vortex asymmetry is based on a method of partitioning adopted by Kasahara and Platzman (1963; their method III). In this method, the "vortex" is *defined* as the initial symmetric vortex ap-

[1] In practice it may be impossible to distinguish between the location of the streamfunction minimum and that of the vorticity maximum. In the fine resolution model calculations, use of the streamfunction minimum as the vortex center leads to a pair of small-scale inner gyres.

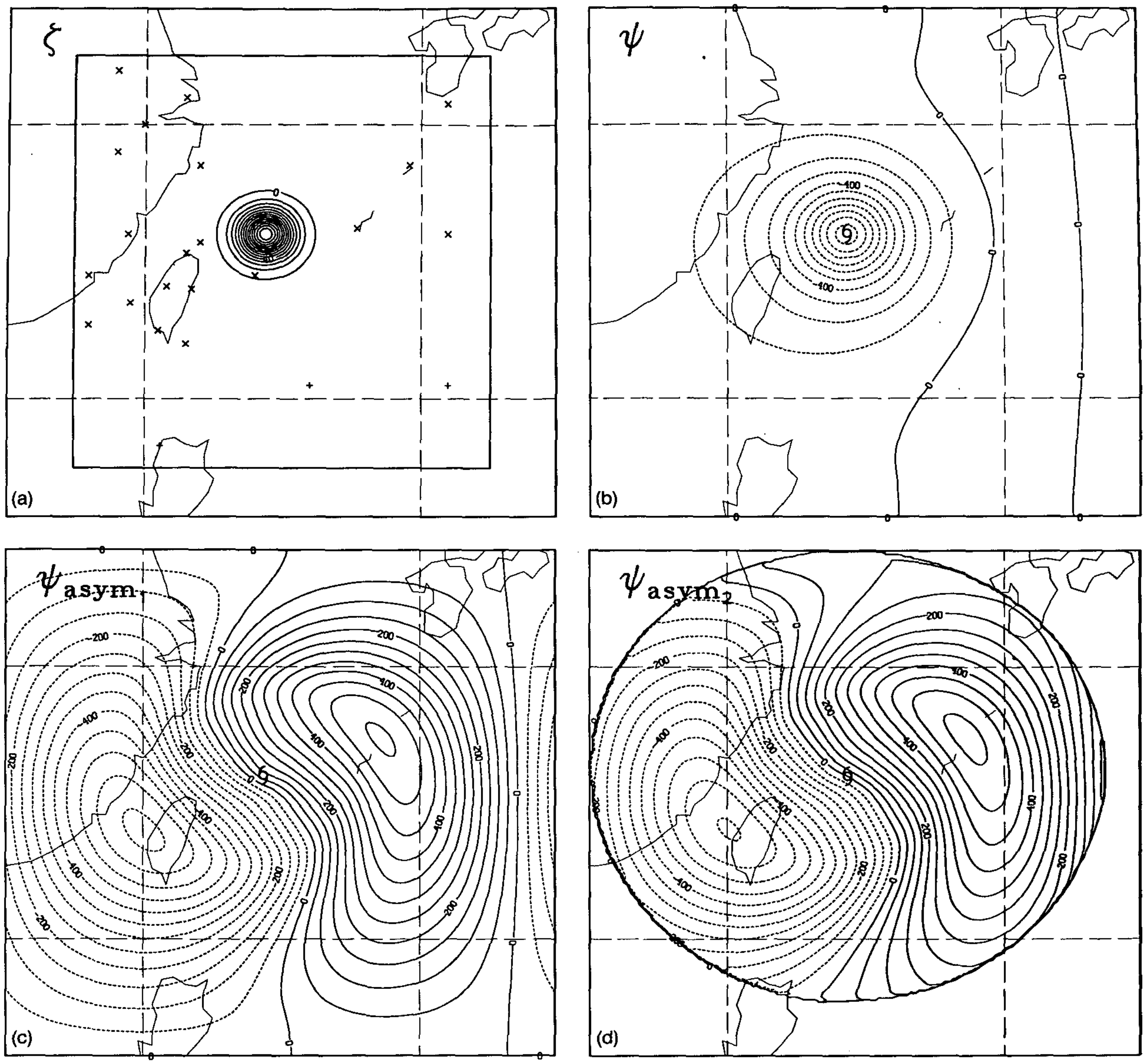

FIG. 1. Isopleths of (a) relative vorticity ζ; (b) streamfunction ψ; (c) asymmetric streamfunction ψ_{asym1}, based on the Kasahara–Platzman partitioning method; (d) asymmetric streamfunction ψ_{asym2}, based on the removal of the azimuthally averaged streamfunction about the vortex center. The analysis uses all the model grid points together with a 0.85-deg filter. Contour intervals are in (a) $1 \times 10^{-4}\ \mathrm{s}^{-1}$, (b) $1 \times 10^{6}\ \mathrm{m}^2\ \mathrm{s}^{-1}$, (c) $5 \times 10^{4}\ \mathrm{m}^2\ \mathrm{s}^{-1}$, and (d) $5 \times 10^{4}\ \mathrm{m}^2\ \mathrm{s}^{-1}$. Small dashed lines indicate negative values. Superimposed on (a) is the enhanced upper-air network envisaged in the preliminary design of the ONR field experiment. The inner, solid square indicates the analysis area, the x's denote existing upper-air stations and the +'s denote additional stations. Large dashed lines indicate the latitude circles 20° and 30°N and meridians 120° and 130°E.

propriately relocated, and the residual flow is defined as the environment. It was used recently in diagnostic studies of vortex motion by Smith et al. (1990) and Ulrich and Smith (1991) and is a key step in the development of an analytic theory of vortex motion (Smith and Ulrich 1990). An alternative method of defining the asymmetry is to remove at each time an azimuthal average of the total streamfunction about the vortex center from the total streamfunction itself. This is denoted by ψ_{asym2} and this field is shown in Fig. 1d for the analysis time (24 h). As shown below, this method has advantages when used in conjunction with the objective analysis scheme.[2] The four fields shown in Fig. 1 are very close to the model output fields prior to analysis and for economy of space, the latter are not shown. Thus, the former can be regarded as the control analysis.

[2] This is not to say that the Kasahara–Platzman method of partitioning would not be suitable for use over a subsequent time period using the azimuthal average at 24 h to define the vortex.

TABLE 1. Details of the ten individual analyses discussed in text. The table indicates the resolution of the data (km), the wavelength of the low-pass filter (degrees), the type of partitioning used to calculate the asymmetric streamfunction, and the figure in which the calculation is displayed. Shown, also, are the speed (m s^{-1}) and direction (degrees) of the asymmetric flow across the vortex center in each case.

Figure	Resolution (km)	Filter (deg)	Speed (m s^{-1})	Direction (deg)	Partitioning
1c	10	0.85	2.0	301.4	Kasahara–Platzman
1d	10	0.85	2.0	302.8	Azimuthal average
2c	10	3.5	0.9	296.9	Kasahara–Platzman
2d	10	3.5	1.8	319.0	Azimuthal average
3a	50	3.5	1.3	324.2	Azimuthal average
3b	100	3.5	1.3	325.0	Azimuthal average
3c	150	3.5	1.0	345.4	Azimuthal average
3d	200	3.5	1.5	250.2	Azimuthal average
4c	RAOB stations	3.5	3.0	83.4	Azimuthal average
4d	RAOB stations	6.0	2.6	99.6	Azimuthal average

Comparing Figs. 1c and 1d shows that, for the control case, the two methods of partitioning yield a very similar asymmetric gyre structure. This is reflected in the data in Table 1 which details the speed and direction[3] of the asymmetric flow across the vortex center in the various calculations. It is noted that the speed is identical in both Figs. 1c and 1d while the direction differs by only 1.4 deg.

Figure 2a shows the total relative vorticity distribution obtained by applying the analysis scheme with a 3.5-deg filter to the entire model-generated data (i.e., using the data at all grid points). As expected, the inherent smoothing degrades the vorticity field (compare Figs. 1a and 2a) and likewise the circulation as characterized by the streamfunction field. For this reason, direct application of the Kasahara–Platzman method of partitioning to the analyzed data (i.e., using the initial analytically prescribed vortex) leaves a large residual symmetric component in the environmental vorticity and streamfunction fields. The effect is to suppress the asymmetric component as illustrated in Fig. 2c, which should be compared with Fig. 1c. To recover the full asymmetry one must remove a symmetric vortex that has been similarly degraded by the analysis scheme, or, alternatively, a symmetric vortex constructed by taking an azimuthal average of the field in question about the vortex center. This study used the latter method, and Fig. 2d shows the streamfunction asymmetry that was determined from the analyzed data. Comparing this with Fig. 1d, the control calculation, it is seen that in spite of the filter, the analysis has reproduced the asymmetric gyre structure with considerable accuracy, including, in particular, the strength of the asymmetric flow across the vortex center, this being only 0.2 m s^{-1} less than in the control case (see Table 1). However, the direction differs by 16 deg.

Since such a high data concentration is typically unavailable around tropical cyclones, a natural question that emerges is: to what extent does the capability of the analysis scheme to reproduce the beta gyres deteriorate as the data density is reduced? To investigate this a series of calculations was conducted for regular data networks with decreasing resolution. Finally, an analysis was performed in which data were sampled at points corresponding approximately with those of the enhanced radiosonde network for the proposed ONR experiment.

The asymmetric streamfunction fields for the regular data network experiments are shown in Fig. 3 using a 3.5-deg filter as in Fig. 2d. Figure 3a shows a calculation in which every fifth point from every fifth row of model generated data was sampled. This gives a network resolution on the order of 50 km. Comparing this field with those in Fig. 1d and 2d, it is noted that the broad-scale features of the asymmetric gyre structure are well captured, but even at this relatively fine resolution there are significant differences in detail. In particular, the angle of the streamflow across the vortex center is more northward by 21 deg. Also, the scale of the gyres is reduced, but their strength is underestimated leading to a weaker flow across the vortex center (65% of that in the control case).

Figures 3b–d show the asymmetric streamfunction patterns calculated for regular data network resolutions of approximately 100, 150, and 200 km, respectively. The calculation with 100-km resolution was not appreciably different from that with 50 km and the differences in the speed and direction of flow across the vortex center are minor, although they differ markedly from the control case (see Table 1). However, a significant deterioration in the analyzed gyre structure is evident with 150-km resolution (Fig. 3c) and the calculation with 200-km resolution was unacceptable—the gyres bearing little resemblance to those in the control calculation and the implied flow across the vortex center being in the wrong quadrant!

Figures 4a–c show the total vorticity, total streamfunction, and asymmetric streamfunction using data at points corresponding with the enhanced radiosonde network. Now the analysis is very poor and, like the

[3] These were derived by taking a weighted average of the velocity at the vorticity maximum and the four neighboring grid points.

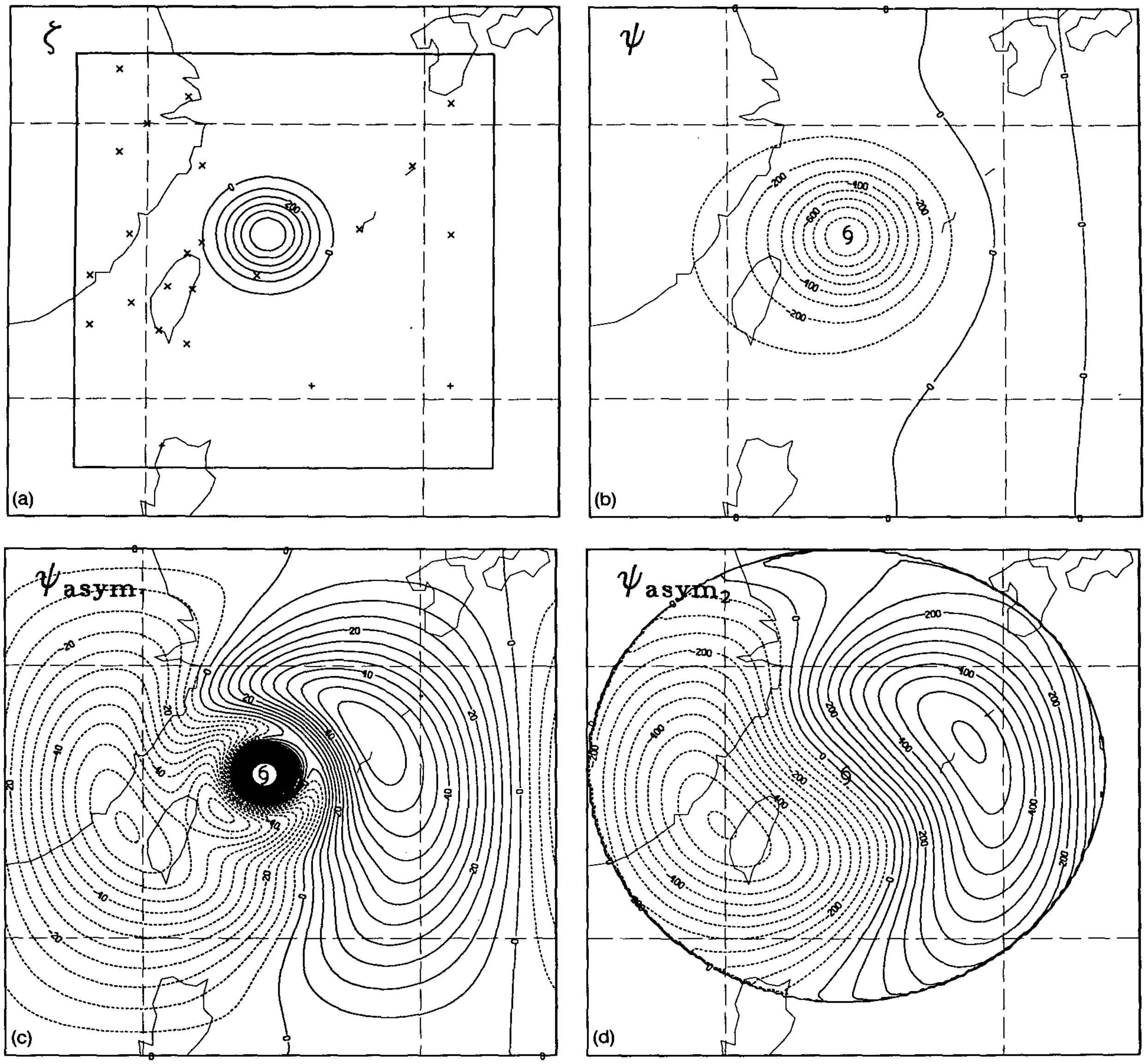

FIG. 2. As in Fig. 1, except the analyses use a 3.5-deg filter. Note that the additional smoothing reduces the vortex strength (the vorticity maximum is less than half its value in Fig. 1) and this impacts adversely on the Kasahara–Platzman method of partitioning to characterize the asymmetry. However, ψ_{asym2} in (d) compares well with that in Fig. 1d.

200-km resolution regular network calculation, the asymmetry is not at all realistic, although the pattern does show a pair of large-scale gyres! Moreover, the amplitude of the asymmetry has strengthened appreciably. This is because the vortex, which is symmetric to a first approximation, is poorly represented, thereby introducing a high degree of asymmetry into the analysis. Calculations for the vortex in different positions relative to the data network were even poorer since, in the present case, the vortex was at least relatively central within the network. The analysis is not improved by increasing the filter size as can be seen by comparing Figs. 4c and 4d. The latter shows the asymmetric streamfunction calculated using a 6-deg filter. It is striking, however, that with the resolution afforded by the station network alone, the analyzed asymmetric flow field and, in particular, the gyre structure thereof, are quite sensitive to the filter size used. These results caution against interpretations of inferred gyre structure based on irregularly spaced observations with a relatively coarse resolution and a high degree of smoothing.

5. Conclusions

A series of analyses of simulated vortex data has been performed in order to investigate the data network required to adequately resolve the "beta gyres" associated with moving tropical cyclone-scale vortices.

For a relatively accurate depiction of the beta-gyre

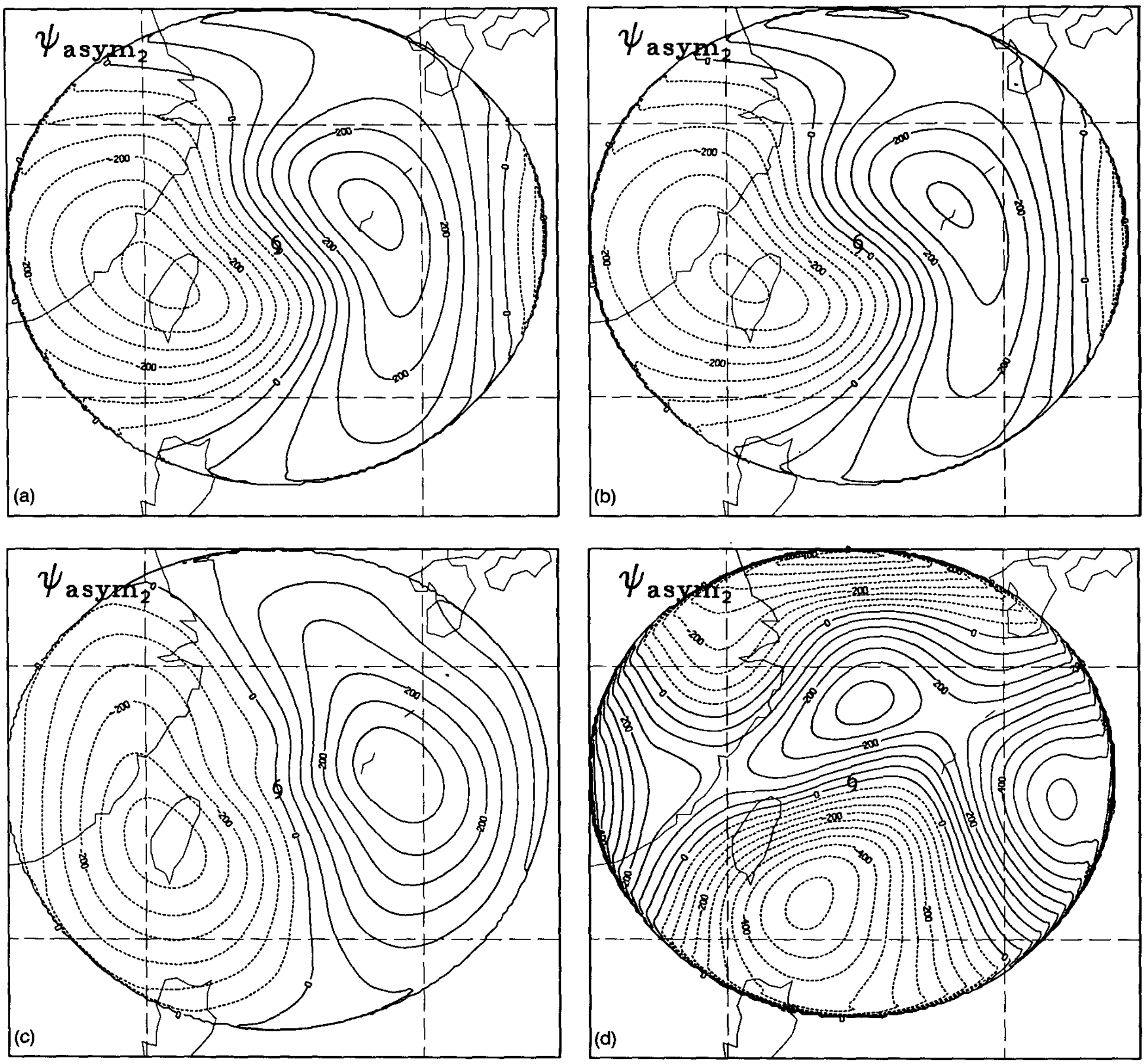

FIG. 3. Asymmetric streamfunction ψ_{asym2} in four regular network calculations as the station separation Δ is increased. (a) Δ = 50 km; (b) Δ = 100 km; (c) Δ = 150 km; and (d) Δ = 200 km. The contour interval is the same as for ψ_{asym2} in Figs. 1 and 2. The analysis use a 3.5-deg filter as in Fig. 2.

structure, a regular data network with a resolution on the order of 100 km is required. Such a network would be feasible in practice only with aircraft reconnaissance including regular dropwindsondes. Without aircraft reconnaissance, typical land/ship-based data networks including the enhanced network for the ONR experiment are inadequate to resolve the gyres satisfactorily, as well as the associated streamflow across the cyclone center, even in the most favorable circumstance when the cyclone is in the center of the network and the ambient flow is weak. Analysis of the gyres can be expected to be even more difficult in the presence of a significant basic steering current.

This paper has assessed the ability of an analysis, based only on observations, to reconstruct the beta gyres from both adequately sampled and undersampled networks. Typically, in an operational numerical weather prediction environment, an analysis is constructed from both the observations and a background field, which is usually produced by an assimilating model. In data-sparse regions, it follows that the analyses are as much (or more) a product of the assimilating model than they are of the observations. Since a model may contain the gyres (Fig. 1), their presence in the analysis does not necessarily imply that they exist in nature or that the model is replicating nature's gyres. Separating the contributions of the model and the observations remains a challenge for future studies.

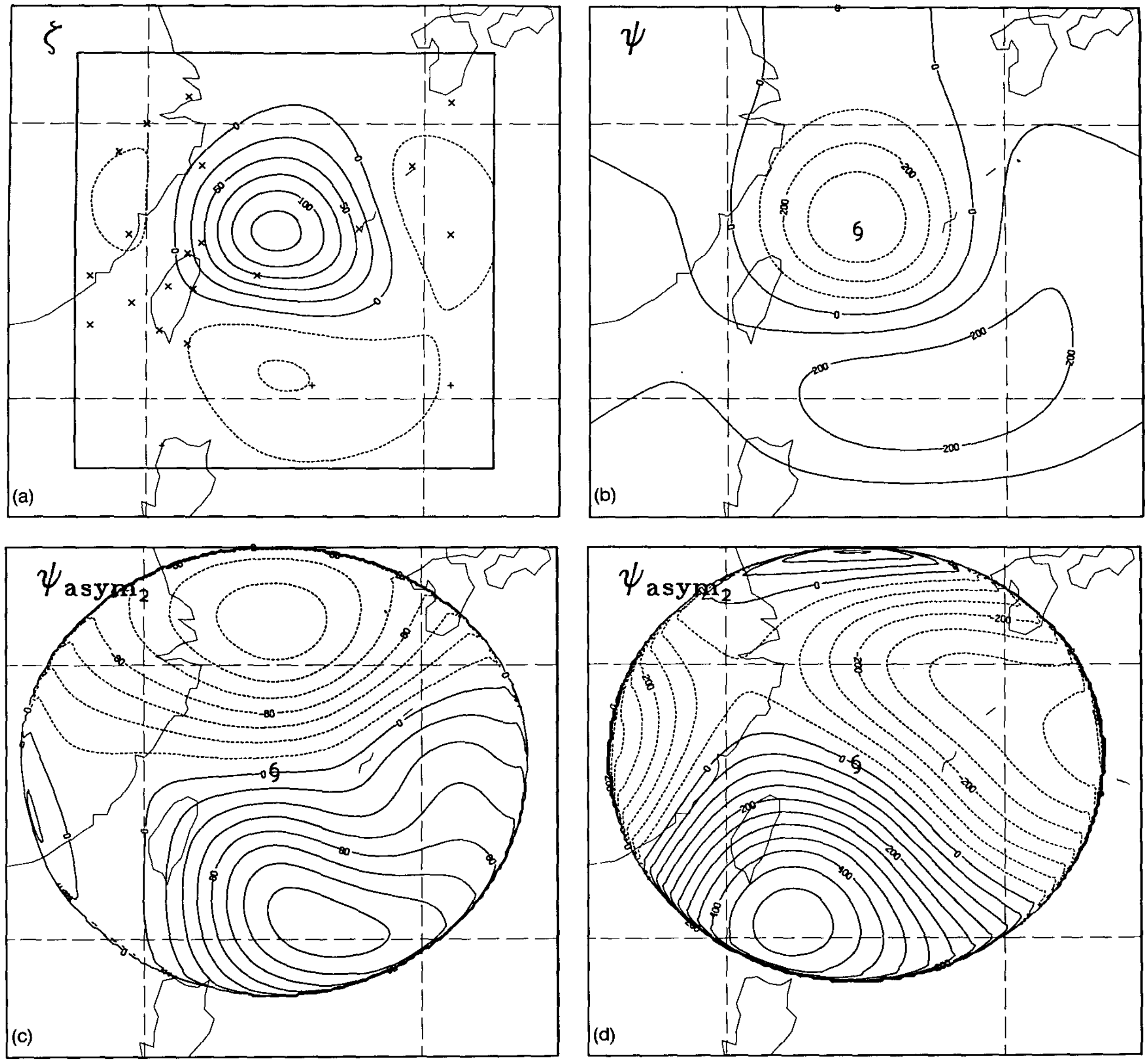

FIG. 4. Isopleths of (a) relative vorticity ζ; (b) streamfunction ψ; and (c) and (d) asymmetric streamfunction ψ_{asym2}, based on the proposed ONR field experiment network. In (a), (b), and (c) a 3.5 deg filter is used and in (d) a 6.0-deg filter. Although the analyses of ψ_{asym2} show gyres, these bear little resemblance to the true gyres in Fig. 1d. Note that the contour intervals in (a) and (c) differ from those used in previous figures; the contour interval in (a) is 2.5×10^{-5} s^{-1}, and in (c) is 2×10^{6} m^2 s^{-1}.

Acknowledgments. The first two authors acknowledge partial support for this project through Grants N 00014-87-J-1250 and N 00014-90-J-1487 from the United States Office of Naval Research.

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NOTES AND CORRESPONDENCE