Biserial correlation between vorticity field and precipitation: Rainfall diagnosis and prediction

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RESUMEN

Este trabajo concierne al examen de una metodología de la climatología sinóptica, la técnica de correlación biserial, que permite investigar, en este caso, la interrelación entre la circulación atmosférica y la precipitación. Se analiza el significado de los campos de correlación biserial obtenidos relacionando distintas variables representativas del flujo de escala sinóptica, particularmente campos de vorticidad, con la precipitación local, con el propósito de ahondar en metodologías que sean simples, eficientes y fáciles de interpretar para ligar la circulación de gran escala con la pequeña escala o local. Se propone una interpretación basada en las configuraciones de los campos de correlación biserial entre vorticidad en 500 hPa y precipitación, que tiene en cuenta los gradientes de vorticidad anómala con los efectos de cortante y curvatura involucrados, para elucidar posibles mecanismos que favorecen la ocurrencia de lluvia. Las anomalías en la curvatura de los sistemas sinópticos son en gran medida responsables de la precipitación. Se utiliza como ejemplo la precipitación diaria de Córdoba, Argentina, para ilustrar los resultados. Se puede identificar claramente la posición de los centros anómalos de vorticidad ciclónica y anticiclónica y de la corriente en chorro en asociación con la ocurrencia de precipitación. El análisis se hace extensivo para precipitaciones más copiosas.

PALABRAS CLAVE: Precipitación, vorticidad, correlación biserial.

ABSTRACT

This work concerns the examination of a methodology of synoptic climatology, the biserial correlation technique, which allows studying the relationship between atmospheric circulation and precipitation. The physical meaning of biserial correlation fields between variables representing synoptic-scale circulation, particularly vorticity fields, and local precipitation is explored. One purpose is to examine this approach used to link the large-scale circulation and the smaller-scale surface environment, which seems to be simple, efficient and easy to interpret. An analysis based on biserial correlation configurations between 500 hPa vorticity and precipitation takes into account anomalous vorticity gradients including curvature and shear effects to describe some mechanisms favoring the occurrence of rainfall. It is shown that anomalies in the curvature of synoptic systems are largely causing precipitation. Daily precipitation at Córdoba, Argentina is used as an example to illustrate the results. The position of the cyclonic and anticyclonic anomaly centers and the position of the jet streams in association with precipitation may be clearly identified. The analysis is made extensive to heavier rainfall.

KEY WORDS: Precipitation, vorticity, biserial correlation.

1. INTRODUCTION

The field of synoptic climatology studies the relationship between atmospheric circulation and meteorological phenomena at the surface in a given place or region. Most investigations in synoptic climatology utilize an empirical, deductive approach, in the sense that elements of statistics are used to link the circulation with a particular variable at surface (Yarnal, 1993). In general, the techniques employed in synoptic-climatological studies try to classify the atmospheric circulation in some way. This classification may lead to identify certain essential characteristics of the circulation in relation to the phenomenon at surface, which in this case is the occurrence of local precipitation, and to understand the mechanisms of some processes involved.

There exists a variety of techniques for the analysis of anomalies or for the study of the relationship between variables defining the circulation and the occurrence of local weather elements, which have been largely treated by Barry and Perry (1973). Research in synoptic climatology during the last two decades was reviewed by Yarnal (1993). Different methods of classification used in modern synoptic climatology may be cited, such as: the manual classification, where synoptic charts are put together subjectively in predetermined categories; the classification of maps based on cor-

relations initially proposed by Lund (1963) and then followed by Kirchhofer (1973); the techniques of representation of fields by means of orthogonal functions and harmonic analysis (Wadsworth, 1948; Friedman, 1955); the classifications based on eigenvectorial analysis introduced by Lorenz (1956), used either to classify synoptic types (Kalkstein *et al.,* 1987), synoptic maps (Richman, 1981; Compagnucci, 1988), or to regionalize (Ehrendorfer, 1987); the method of averaging fields corresponding to specific situations or composites; the technique of specification developed by Klein (1959) in a first work where he relates variables representing circulation with a concurrent variable at surface.

With respect to the technique of composite fields, or anomaly fields if they are subtracted from the mean field, it allows a quick understanding of data, on the one hand, and, on the other, it does not present any ambiguity in the classification. This procedure, which selects a number of fields satisfying an important criterion, for example occurrence or non-occurrence of precipitation, is easy to conceptualize and to apply; though it depends strictly on the criterion established. With the specification as a technique of synoptic climatology, it is possible to construct linear correlation fields between temporal series of the variable determining the circulation and the temporal series of the local variable at surface. The resulting correlation fields are analogous to anomaly fields, as is shown by Stidd (1954). One objective of this work is to delve into this kind of techniques of Synoptic Climatology that are simple, efficient and easy to interpret in physical-synoptic terms in front of others more sophisticated, but failing in revealing significant relationships (Klein and Walsh, 1983; Yarnal, 1993).

In the present work, the meteorological phenomenon at surface of interest is daily precipitation. To perform the synoptic-climatological analysis the biserial correlation technique will be used and discussed as applied to vorticity fields. The statistical parameter taking part is the biserial correlation coefficient (Pearson, 1909). This methodology that combines the technique of specification (with the variable at surface converted to a binary one) and the technique of composites (here, difference of composites or 'anomalies' between mean fields with precipitation and without precipitation are involved) is explained. On the other hand, biserial correlation fields take into account the climatological probability of precipitation so that patterns with different precipitation behavior may be compared. Moreover, an analysis of biserial correlation patterns between vorticity and precipitation through correlation field gradients coming from anomalies in the wind shear and the radio of curvature of synoptic systems is proposed. This analysis tends to interpret not only areas of maximum and minimum association between vorticity and precipitation, but also gradients appearing in these patterns and their possible causes in relation to the occurrence of precipitation. The results of this dynamic-climatological analysis are exemplified for the case of precipitation occurrence at Córdoba, Argentina.

2. METHODOLOGICAL ASPECTS AND APPLICATION

First, the biserial correlation coefficient is introduced as well as the statistical significance test used. It is argued that the main advantages of the biserial parameter are: it allows for dichotomous treatment of precipitation, and it quantifies the climatological probabilities of the event. Secondly, the relationship between biserial and linear correlation coefficient is presented. As correlation fields are analogous to composite-difference fields, then biserial fields, which are shown to be proportional to linear ones, also are. Finally, properties in correlation fields such as gradients are extensively examined in order to infer associations with precipitation and applied to biserial correlation patterns, mainly between vorticity and rainfall.

2.1 Biserial correlation

If precipitation is considered as a dichotomous variable (occurrence or non-occurrence of the event), then the correlation between precipitation and a numerical variable X may be described as follows (Panofsky and Brier, 1965):

$$r_{bis} = \frac{\overline{x_1} - \overline{x_0}}{S} \frac{p\,q}{z},\qquad(1)$$

where r_{bis} is the biserial correlation coefficient, $\overline{x_1}$ is the mean of $\times$ when the binary variable is 1 (occurrence), $\overline{x_0}$ is the mean of $\times$ when the binary variable is 0 (non-occurrence), p and q are the climatological probabilities of $\times$ when the binary variable is 1 and 0, respectively, z is the value of the Gaussian function at the point where the area under the curve divides into p and q, and S is the standard deviation of $\times$.

For a given difference between the means, $\overline{x_1} - \overline{x_0}$, and a given standard deviation S, the biserial correlation coefficient is maximum when the climatological probability p is 50%. Thus the biserial coefficient decreases when the cases belonging to one of the categories are few (they have low representation in the total sample).

The error of the biserial correlation coefficient is given by (Guilford and Fruchter, 1973):

$$error_{bis} = \frac{\sqrt{pq}\ z^{-1} - r_{bis}^2}{\sqrt{N}},\qquad(2)$$

where N is the total number of observations.

The statistical significance of the biserial correlation coefficient may be obtained applying the *t*-Student test, which compares the means of two samples in order to infer if they are statistically different (Panofsky and Brier, 1965). In this case, in the sample $i=1$ the event occurs, in the sample $i=0$, does not. If both samples are normally distributed, and assuming that the corresponding poblational variances are equal then the *t*-Student statistic for the difference between means corresponding to two independent samples is denoted by (Wilks, 1993):

$$t = \frac{\overline{x_1} - \overline{x_0}}{\sqrt{\dfrac{(N_1 - 1)S_1{}^2 + (N_0 - 1)S_0{}^2}{N_1 + N_0 - 2} \left(\dfrac{1}{N_1} + \dfrac{1}{N_0}\right)}}, \qquad (3)$$

where N_i and S_i are the size and standard deviation of x_i, respectively. This statistic is *t*-Student distributed with N_1+N_0-2 degrees of freedom.

2.2 Relationship between biserial and linear correlation

It is shown that linear correlation fields are proportional to biserial fields, then some derivations made from the former may be applied to the latter as explained later. The linear correlation coefficient between the variable x and the precipitation P, as a binary variable, is given by:

$$r = \frac{\overline{x_1} - \overline{x_0}}{S}\sqrt{p(1 - p)}, \qquad (4)$$

where p is, as above, the empirical or climatological probability of precipitation occurrence. Thus, the relationship between the biserial correlation coefficient and the linear one is:

$$r_{bis} = r\frac{\sqrt{pq}}{z}. \qquad (5)$$

This implies that for a given difference between means $\overline{x_1} - \overline{x_0}$ and a given standard deviation S, the biserial correlation coefficient is higher (in absolute value) than the linear correlation coefficient and its limit value is given by $\pm (p.q)^{1/2}/z$.

2.3 Analogy of correlation fields to difference or "anomaly" fields

As in Stidd (1954) it may be shown that the composite-difference field which comes from the subtraction of a variable x averaged for the cases under a certain condition (for example, occurrence of precipitation) from that averaged under the opposite condition is analogous to the correlation field between x and precipitation (provided that the standard deviation of the former be small in the study region). The same analogy is valid for the gradient of the correlation field isolines. Therefore, the correlation field (either the linear one or the biserial one as they are related as mentioned above) is equivalent to the difference field or anomaly field. Here, by anomaly it is meant the difference between two mean states of a variable conditioned by another one (for instance, rainfall or no-rainfall).

The relation among biserial-linear-composite-difference fields has been described. Inferences about gradients appearing in linear correlation fields which are discussed below may be applied to biserial fields, and associated with anomalous behavior of the variables examined: geopotential height, and, in particular, vorticity.

2.4 Relationship between geostrophic wind and precipitation through the correlation field gradient between height and precipitation

If the variable to be correlated with precipitation P is the geopotential height x at different gridpoints, the correlation field obtained not only indicates the zones where heights are highly related with the occurrence of this event (zones of maximum or minimum magnitudes of the coefficient) but also the gradient in this field has physical meaning, as will be seen below.

It may be shown that the gradient of the correlation field between a given variable and the precipitation is proportional to the correlation between the variable gradient and precipitation:

If the correlation coefficient between x and precipitation P is

$$r_{XP} = \frac{\displaystyle\sum_{i=1}^{i=N}(x_i - \overline{x}).(P_i - \overline{P})}{N S_X S_P} = \frac{\sum x P}{N S_X S_P}, \qquad (6)$$

then the horizontal gradient of this coefficient is

$$\nabla_h r_{XP} = \frac{1}{N S_P}\sum \nabla_h \frac{x P}{S_X} \qquad (7)$$

and, if the standard deviation of x is constant in the field, then

$$\nabla_h r_{XP} = \frac{1}{N S_X S_P}\sum \nabla_h x P =$$

$$= \frac{1}{N \, S_X \, S_P} \sum P \, \nabla_h x \cong \frac{1}{N \, S_X \, S_P} \sum P \frac{\Delta x}{\Delta n} \quad (8)$$

that is to say,

$$\nabla_h r_{XP} \cong \frac{S_{\nabla X}}{S_X} r_{\nabla X \, P}, \quad (9)$$

where S_x is the standard deviation of the function Λx, which is assumed approximately constant. Then, as indicated in Equation (9), the correlation between the gradient of $\times$ and precipitation P is proportional to the gradient of the correlation-field isolines between $\times$ and precipitation. Thus areas where the correlation field gradient is greater, the greater the correlation between the gradient of $\times$ and precipitation.

Since the geostrophic wind is proportional to the geopotential contour gradient (with the Coriolis parameter constant), then the correlation between geostrophic wind and precipitation is proportional to the correlation isopleth gradient between geopotential heights and precipitation (provided that the standard deviation of heights do not vary too much in the field). Moreover, as the correlation field is analogous to the anomaly field, then the greater the correlation field gradient, the greater the association between the anomalous geostrophic wind and precipitation. Thus the correlation field, and in particular the biserial one that will be described later, is proportional to the anomalous geostrophic wind (in intensity and direction) associated with the precipitation at one site. Correlation-field charts may be interpreted in the first approximation as though they were anomalous flow charts (Stidd, 1954). The configuration of the patterns may thus lead to a better understanding of the physical processes involved.

The biserial correlation field between the local precipitation at Córdoba (31°24'S, 64°11'W), Argentina, and 500-hPa geopotential heights corresponding to the southern region of South America is shown in Figure 1. We use 500-hPa daily geopotential height at 1200 UTC from European Centre for Medium Range Weather Forecasting (ECMWF) for January 1984 to December 1986. Daily precipitation data at Córdoba from the Servicio Meteorológico Nacional of Argentina for the same period are used. A precipitation event is defined as a rainfall in excess of 0.1 mm (≥ 0.1 mm). The climatological probability of precipitation at Córdoba during the austral warm semester is p = 0.35 (q = 0.65). Biserial correlation coefficients above 0.17 and 0.15 are statistically significant at the confidence levels of 99% and 95%, respectively, according to Section 2.1. The results presented here correspond to the southern summer (November-April).

Two areas of high biserial correlation with opposite signs are seen in Figure 1. The negative one with a certain NW-SE extension is centered at 35°S west of the Andes, suggesting that anomalously low geopotential heights in that region are associated with rainfall at Córdoba. The positive center is located over the north of Uruguay, showing that anomalously high geopotential heights occur east of the reference station in connection with rainfall. A positive area also appears about 55°S west of Tierra del Fuego. Thus the anomalies in atmospheric circulation of the middle troposphere associated with precipitation at Córdoba are highlighted by this configuration. Regions with anomalously stronger flow are also revealed, one in the center of Argentina with NNW component from the south of Brazil and north of Paraguay; the other with an anomalously strong eastern component about 45° west of the Andes.

2.5 Relative vorticity and precipitation

Perturbations on weather maps are associated with large values of vorticity. As is well known, mid-tropospheric variables such as 500-hPa relative vorticity may be considered a sensitive indicator of synoptic-scale vertical motion in the middle latitudes. For this reason, 500-hPa relative vorticity is investigated as a derived dynamic variable related to precipitation (let us remind that relative vorticity is directly related to geopotential height distribution via the geostrophic balance). As for synoptic-scale motions, the relative vorticity can be closely approximated by its geostrophic value (Holton, 1979).

Biserial correlation fields between geostrophic relative vorticity ζ and precipitation are regarded as analogous to anomaly charts of vorticity with respect to yes/no rainfall (by anomaly it is meant the difference $\overline{\zeta_{yes}} - \overline{\zeta_{no}}$). Through this methodology it is possible to identify regions with cyclonic and anticyclonic vorticity anomalies (centers with significantly negative and positive biserial correlation coefficients, respectively), which favor the production of precipitation at a given place. Besides, by a similar argument to that of the above section, gradients in biserial correlation fields are proportional to vorticity anomaly gradients. Anomalous vorticity gradients, even as regards direction and intensity, may stem from different effects, which we will try to individualize and analyze below.

2.5.1 Analysis of vorticity "anomaly" gradients

The biserial correlation chart between 500-hPa relative vorticity and southern summer precipitation at Córdoba is shown in Figure 2. As in the case before, occurrence is considered if daily precipitation at Córdoba is ≥ 0.1 mm, and non-occurrence, otherwise. The remaining of this study
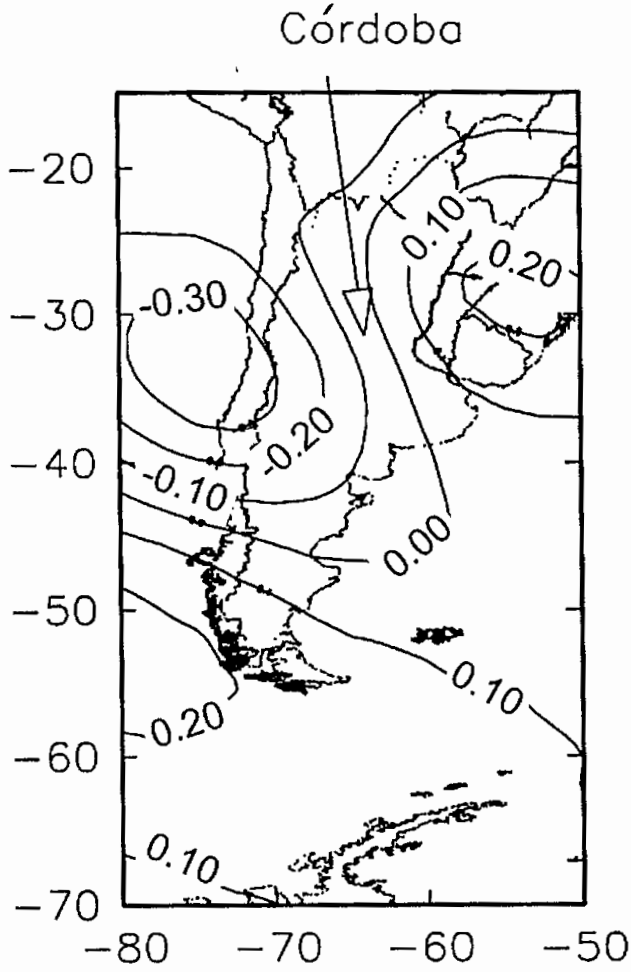
Córdoba

Fig. 1. Biserial correlation field between 500 hPa geopotential heights and the daily precipitation ≥0.1 mm at Córdoba (see text), during the austral summer (November to April).

concerns the interpretation of the gradients observed in the patterns obtained.

Relative vorticity was calculated by the Laplacian of geopotential heights, under the geostrophic hypothesis,

$$\zeta_g = (g/f_0)\ \nabla^2 z \qquad (10)$$

where ζ_g is the relative geostrophic vorticity; z is the geopotential height; g is gravity acceleration; and f_0 is the Coriolis parameter at 42°S, 65°W representing the local region of interest.

An anomaly in the vorticity defined in natural coordinates by

$$\zeta = V/R - \partial V/\partial\eta \qquad (11)$$

may be caused by a change of the wind velocity V, of the radius of curvature R, or of the wind shear $\partial V/\partial\eta$. In differential terms, this is

$$d\zeta = \frac{1}{R}dV - \frac{V}{R^2}dR - d\left(\frac{\partial V}{\partial\eta}\right) \qquad (12)$$

and in finite differences,

$$\Delta\zeta = \frac{1}{R}\Delta V - \frac{V}{R^2}\Delta R - \Delta\left(\frac{\partial V}{\partial\eta}\right) = \zeta'. \qquad (13)$$

Here ζ' is the anomaly in the vorticity. Thus

$$\zeta' = \frac{1}{R}V' - \frac{V}{R^2}R' - \left(\frac{\partial V}{\partial\eta}\right)', \qquad (14)$$

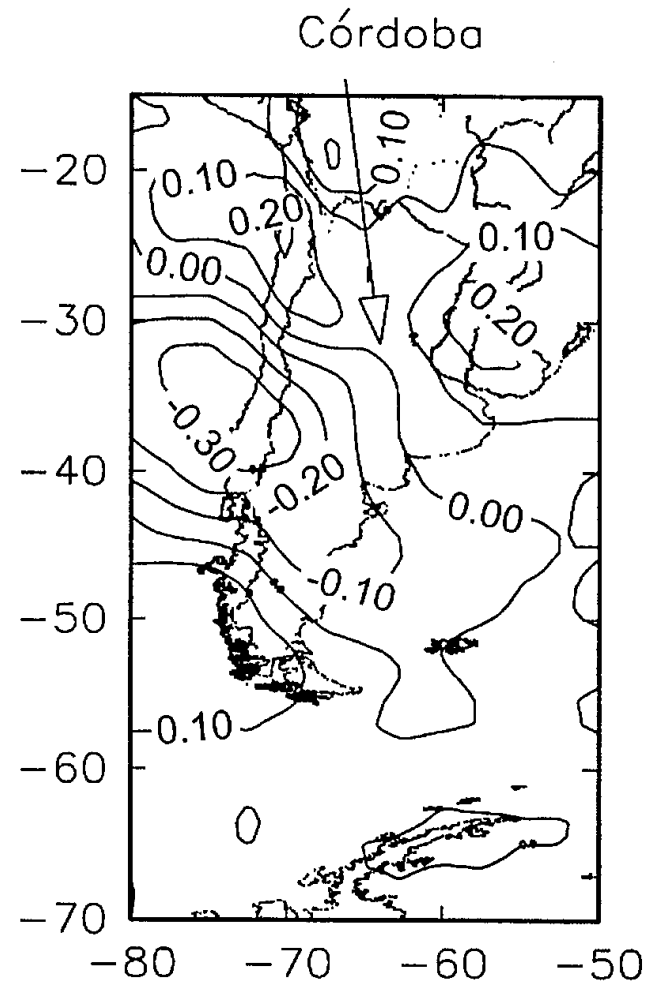where the primes indicate anomalies or variations.

Córdoba

Fig. 2. Biserial correlation field between 500 hPa relative vorticity and the daily precipitation ≥0.1 mm at Córdoba, during the austral summer.

As mentioned before, biserial correlation fields are vorticity anomaly fields, i. e. ζ' fields, and the question is what $\nabla\zeta'$ means with respect to precipitation.

The differential of ζ' is

$$d\zeta' = \frac{1}{R}dV' - \frac{V'}{R^2}dR - \frac{R'}{R^2}dV +$$

$$+ V\frac{R'}{R^3}dR - \frac{V}{R^2}dR' - d\left(\frac{\partial V}{\partial \eta}\right)' \quad (15)$$

and in terms of gradients in the n̂ direction (n̂ escalar product $\nabla\zeta'$)

$$\hat{n}.\nabla\zeta' = lim_{\Delta n\to 0}\frac{\Delta\zeta'}{\Delta n} = \frac{1}{R}\frac{\Delta V'}{\Delta n} - \frac{V'}{R^2}\frac{\Delta R}{\Delta n} -$$

$$-\frac{R'}{R^2}\frac{\Delta V}{\Delta n} + V\frac{R'}{R^3}\frac{\Delta R}{\Delta n} - \frac{V}{R^2}\frac{\Delta R'}{\Delta n} - \frac{\Delta\left(\frac{\partial V}{\partial \eta}\right)'}{\Delta n} \quad . \quad (16)$$

The terms in the right-hand side containing non-primed gradients are negligible.

The terms $R^{-1}\Delta V'/\Delta n$, $-VR^{-2}\Delta R'/\Delta n$ and $-\Delta(\partial V/\partial n)'/\Delta n$ are of order ~10^{-11} or ~10^{-12} s-1m-1, while the others are at least two orders of magnitude less. It may be shown that the curvature radius gradient $\Delta R/\Delta n$ and the wind gradient $\Delta V/\Delta n$ are smaller than those produced by the anomalies, $\Delta R'/\Delta n$ and $\Delta V'/\Delta n$, respectively (Ruiz and Vargas, 1993). Therefore, vorticity anomaly gradients would be mainly caused by wind anomaly gradients, curvature radius anomaly gradients, and shear anomaly gradients:

$$\nabla\zeta'.\hat{n} = lim_{\Delta n\to 0}\frac{\Delta\zeta'}{\Delta n} \cong$$

$$\cong \frac{1}{R}\frac{\Delta V'}{\Delta n} - \frac{V}{R^2}\frac{\Delta R'}{\Delta n} - \frac{\Delta\left(\frac{\partial V}{\partial \eta}\right)'}{\Delta n} \quad (17)$$

Each term in the right-hand side of Equation (17) will be analyzed in order to examine possible causes of anomalous vorticity gradient, $\tilde{N}\zeta'$:

(a) $R^{-1}\Delta V'/\Delta n$. This term is due to anomalous wind shear. Take a trough (R<0) at the 500-hPa level in the Southern Hemisphere, which deepens in association with precipitation in a determined place. The anomalous wind field to the north of the low center, though in its surroundings, is shown in Figure 3. The directions of the terms involved are also displayed (direction of n̂ to the north). Here, the direction of the anomalous vorticity gradient matches the direction of n̂ north of the strongest anomalous wind inside the region affected by the low, and it is opposite to the south. In general, in a trough this gradient is towards the low starting from the zone of stronger anomalous wind, and towards the high in the outer zone. The opposite happens with ridges or anticyclones.

Thus the gradient in the biserial correlation field of Figure 2, between the negative center about 37°S 73°W and the positive center about 31°S 58°W, does not change direction. Hence the term $R^{-1}\Delta V'/\Delta n$ does not explain it completely.

(b) $-VR^{-2}\Delta R'/\Delta n$. This term appears when the curvature of the synoptic systems (1/R) becomes greater in one zone than in another, as compared with the situation without precipitation. This means that there exists a gradient of anomalous curvature. If a low is deeper when rainfall conditions are present, there will be a zone of positive anomalies of the radius of curvature. The sense and radial direction of $\nabla\zeta'$ is displayed in Figure 4, where R_{-2}, R_{-1} and R_0 are the anomalies of the radius of curvature at different distances ($R_{-2} < R_{-1} < R_0$). In this case, the direction of the gradient of anomalous vorticity is towards the exterior of the low.

A similar argument may be made for a region of high pressure. Here the direction of the gradient of anomalous vorticity is always towards the high.

In conclusion, $\nabla\zeta'$ goes always from the zones with cyclonic anomalous curvature to the zones with anticyclonic anomalous curvature. It increases with wind velocity and decreases with radius of curvature. Therefore, the gradient in the biserial correlation field of Figure 2 is essentially due to the spatial variation of anomalous curvatures of synoptic systems, and to a lesser extent to the vari-
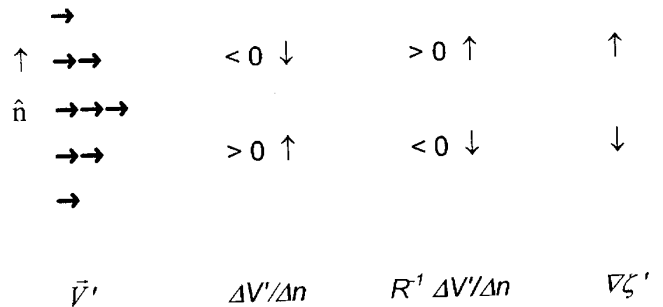

Fig. 3. Schematic diagram showing the anomalous wind field (by anomaly it is meant the difference between two mean states: yes/no rainfall) to the north of a low in the Southern Hemisphere and the direction of the term R⁻¹ ΔV'/Δn in the equation of $\nabla\zeta'$.

Baja

R_{-2} ↑   < 0 ↓   > 0 ↑   ↑

R_{-1}

$\hat{n}$ R_0

R_{-1}

R_{-2} ↓   > 0 ↑   < 0 ↓   ↓

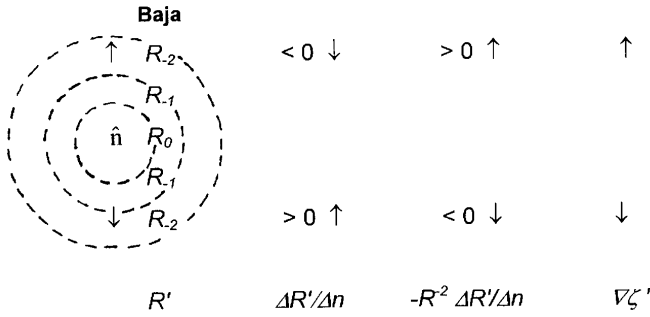R' $\Delta R'/\Delta n$ $-R^{-2}\,\Delta R'/\Delta n$ $\nabla\zeta'$

Fig. 4. Schematic diagram showing the anomalous curvature radii (by anomaly it is meant the difference between two mean states: yes/no rainfall) in the surroundings of a low which is deepening in the Southern Hemisphere and the direction of the term $-R^{-2}\,\Delta R'/\Delta n$ in the equation of $\nabla\zeta'$.

ation of intensity of anomalous wind. The latter (term (a)) is opposed to the gradient observed in certain regions. Thus, anomalies in the curvature of synoptic systems are largely causing the gradient of ζ', and in consequence, the precipitation.

(c) $-\Delta(\partial V/\partial n)'/\Delta n$. This term represents the spatial variation of the anomalous shear. It may become important when an area has a stronger anomalous wind. Suppose a region with western winds and anomalies as in Figure 5.

North of the maximum wind there is an anticyclonic anomalous shear; to the south, it is cyclonic. This generates a gradient of anomalous shear towards the north (either in presence or absence of curvature). If we take into account term (a), both contributions have the same sign north of the maximum, and the opposite sign to the south. If we add term (b) with direction from the low to the high, $\nabla\zeta'$ will become stronger north of this jet stream. This may explain the tight gradient in the biserial correlation field in some delimited zones, for example between 30°S and 34°S over the Andes

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↑   →→   < 0   > 0 ↑   ↑

$\hat{n}$ →→→

→→   > 0   > 0 ↑   ↑

→

$\bar{V}'$ $(\partial V/\partial\eta)'$ $-\Delta(\partial V/\partial\eta)'/\Delta n$ $\nabla\zeta'$
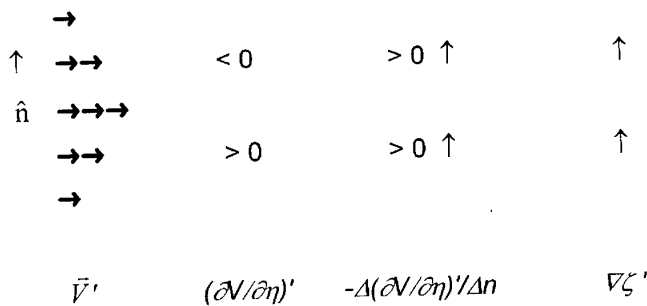
Fig. 5. Schematic diagram showing the spatial variation of the shear in a field of anomalous western winds (by anomaly it is meant the difference between two mean states: yes/no rainfall) and the direction of the term $-\Delta(\partial V/\partial\eta)'/\Delta n$ in the equation of $\nabla\zeta'$.

(Figure 2), which links strong western anomalous wind with precipitation occurrence at Córdoba during the southern summer.

Thus, when analyzing biserial correlation fields between relative vorticity and precipitation, it is interesting to examine not only positive and negative centers (position and intensity) of significant coefficients, but also gradients in the correlation field (direction and intensity) in order to relate them with possible physical features that are forcing the pattern observed. Figure 6 shows a summary of the effects of the gradient of anomalous vorticity ($\nabla\zeta'$) associated with the occurrence of local precipitation. Note that this schematic graphic displays a synoptic situation of the Southern Hemisphere. The term corresponding to the gradient of anomalous curvature $\nabla\zeta'_b$ is clearly directed from the low to the high. The term corresponding to the gradient of anomalous wind shear $\nabla\zeta'_a$ has opposite directions depending on the sign of the curvature radius and the position of the stronger wind. In the case of the low, $\nabla\zeta'_a$ reinforces the vorticity anomaly gradient from the stronger wind towards the high, and weakens $\nabla\zeta'$ in the other direction. Stronger gradients in the correlation field may be found in some areas due to these two effects. In the case of a high, $\nabla\zeta'_a$ weakens the vorticity anomaly gradient in the neighborhood of the high. The effect of the gradient of anomalous shear $\nabla\zeta'_c$ appears when there is an anomalous wind shear independently of curvature. Its direction is from the low to the high. Therefore, $\nabla\zeta'_c$ increases the gradient in the correlation field markedly, and it is a signal of existence and preferential location of anomalously strong winds or jet streams in connection with precipitation at the reference station.

2.5.2 Vorticity patterns for heavy precipitation

To study moderate to heavy precipitation events, daily local rainfall above some determined values, say ≥10 mm, ≥ 20 mm and ≥40 mm, is analyzed. The biserial correlation coefficient discriminating occurrence and non-occurrence groups is now evaluated considering the event occurs if precipitation is above 10 mm. Biserial vorticity patterns with precipitation above 20 mm and 40 mm are also obtained.

The corresponding climatological (empirical) probabilities of daily local precipitation at Córdoba above the limit values mentioned before for the southern warm semester are as follows (for instance, rainfall is above 20 mm during 7.5 per cent of days in summer):

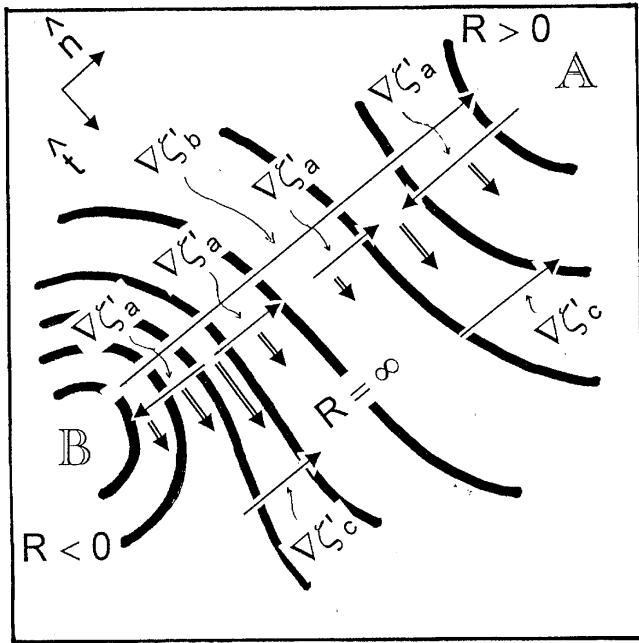| Precipitation	Climatological probability
≥ 0.1 mm	35%
≥ 10 mm	13%
≥ 20 mm	7.5%
≥ 40 mm	2%

Fig. 6. Schematic graphic showing the different effects producing $\nabla\zeta'$ (gradient of anomalous vorticity). Double arrows indicate anomalous winds. Simple arrows indicate the direction of the gradients of anomalous vorticity involved: $\nabla\zeta'_a$ (by anomalous wind shear), $\nabla\zeta'_b$ (by anomalous curvature), $\nabla\zeta'_c$ (by gradient of anomalous shear). R: radius of curvature.

Fig. 7. Biserial correlation field between 500 hPa relative vorticity and the daily precipitation ≥10 mm at Córdoba, during the austral summer.

Figure 7 shows the biserial correlation field between 500-hPa relative vorticity and occurrence of precipitation above 10 mm. The pattern is rather similar to that in Figure 2; however, the anomalous cyclonic center upstream of Córdoba shifts northwards and is entirely located over the Pacific ocean west the Andes. The significant anticyclonic center over the east of the continent is nearer to the reference station; thus, anticyclonic circulation is affecting Córdoba when moderate rainfall occurs while in Figure 2 (≥ 0.1 mm) the zero-correlation line crosses the station. The gradient in the correlation field $\nabla\zeta'$ between the two centers in Figure 7 is not strong. It is mainly due to the anomalous system curvature $\nabla\zeta'_b$. It is stronger around 35°S due to the anomalous shear $\nabla\zeta'_a$ with an anomalous wind component in the north-south direction. This effect is even more noticeable in the biserial vorticity pattern for precipitation above 20 mm (not shown). The strongest gradient is found about 30°S in SW-NE direction due to the gradient of anomalous shear, $\nabla\zeta'_c$ indicating the preferential latitude and direction of anomalous westerly wind that favors heavier precipitation at Córdoba.

For high precipitations above 40 mm these features are brought out (Figure 8). It may be seen that the wavetrain structure of midtropospheric cyclonic and anticyclonic vortices reaches lower latitudes, and the circulation index is re-
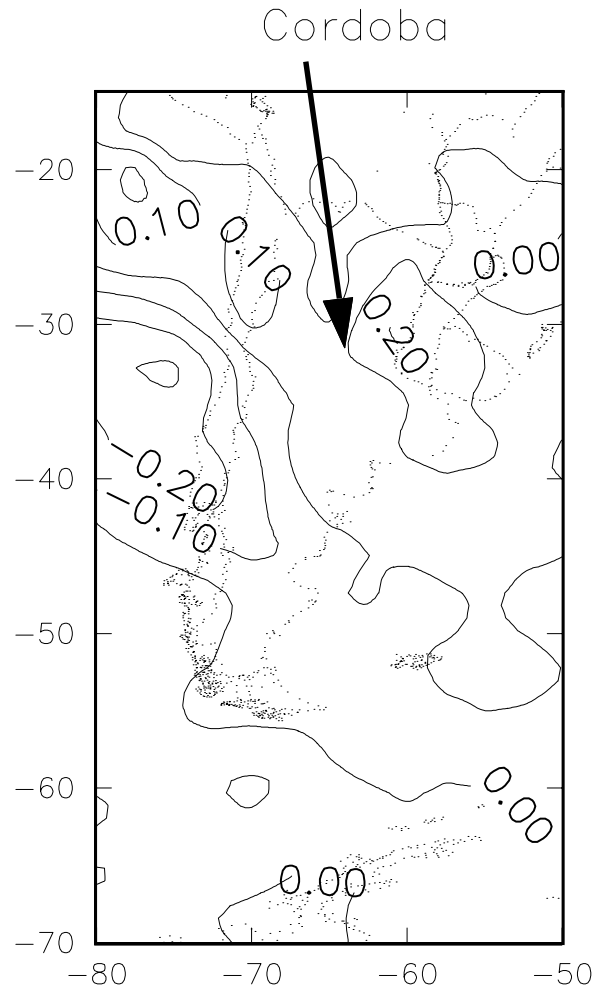
versed to some extent. Note some blocking action in the South Atlantic as shown by anomalous anticyclonic circulation.

Notwithstanding, it is noted that for high precipitaton cases, such as above ≥40 mm, the statistical significance of biserial correlation coefficients is modified. The proportions of events within the occurrence and non-occurrence groups change in a great extent (for instance, the climatological probability of occurrence of precipitation above 40 mm is 2%). Then, statistically significant biserial coefficients to the 95% and 99% level are now those in absolute value higher than 0.25 and 0.32, respectively, according to Section 2. 1.

3. CONCLUSIONS

The analysis of biserial correlation patterns obtained by correlating geopotential heights or vorticity fields and precipitation in a reference location is presented and applied to
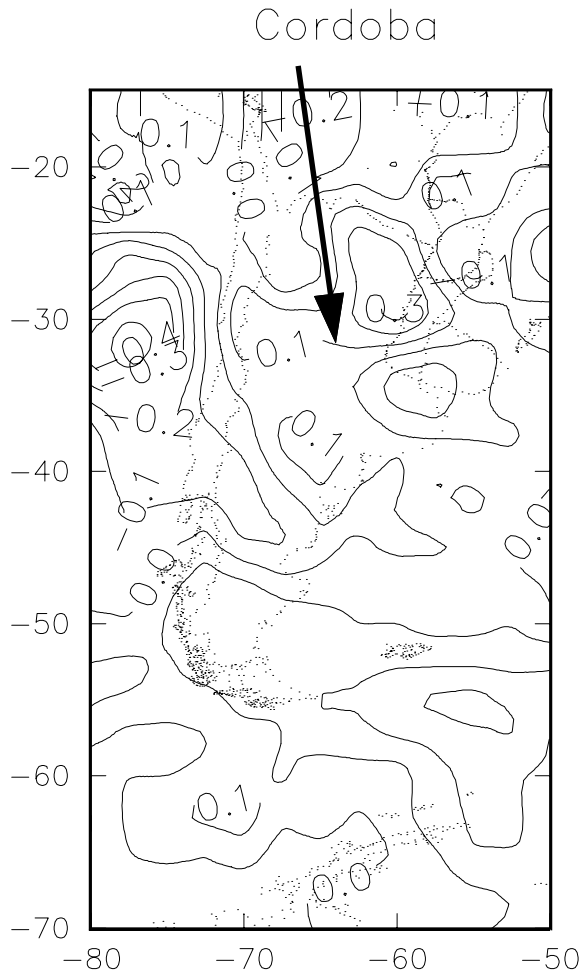
Cordoba

Fig. 8. Biserial correlation field between 500 hPa relative vorticity and the daily precipitation ≥40 mm at Córdoba, during the austral summer.

Córdoba, Argentina. This approach allows us to determine mid-tropospheric circulations leading to precipitation and suggests a way of rainfall prediction.

Regarding to biserial correlation configurations between geopotential height and precipitation at Córdoba, anomalously low heights at 33°S west of the Andes and anomalously high heights over the north of Uruguay are associated with rainfall. Regions with anomalously stronger flow are also revealed, one in the center of Argentina with NNW component from the south of Brazil and north of Paraguay; the other with an anomalously strong eastern component about 45° west of the Andes.

Anomalies in atmospheric circulation of the middle troposphere in conexion with precipitation at Córdoba are highlighted by biserial vorticity patterns. Cyclonic vorticity anomalies may be clearly identified about 38°S, 75°W. Anti-

cyclonic vorticity anomalies are found north of the negative (cyclonic) center at 25°S and over the Argentine Litoral (30°S, 62°W). Note the different vorticity anomaly gradients (gradients in the biserial correlation field) produced by this configuration. The gradient of the anomalous curvature of synoptic systems is the main factor responsible for the gradient of anomalous vorticity in the correlation fields, and hence, for local precipitation. The gradient of anomalous wind velocities, particularly near the significant centers (either the positive or the negative ones), is opposite in sign to that observed, thus its influence on precipitation would be less. However, the spatial variation of the anomalous shear would be especially important for the intensification of the gradient in the field, which relates stronger winds in defined zones with the occurrence of precipitation. This is the case for the tight gradient in the biserial correlation field between 30°S and 34°S over the Andes, which links strong western anomalous wind or jet streams with precipitation occurrence at Córdoba during the southern summer.

The biserial correlation coefficient is an useful statistical tool for the analysis of samples where the proportions of observations of an event vary, since these coefficients may be compared as they take into account the frequencies involved. So, less frequent events as heavy precipitation may be examined and compared. For heavy precipitation events the strongest gradient is found about 30°S in SW-NE direction due to the gradient of anomalous shear, indicating the preferential latitude and direction of anomalous westerly wind that favors heavier precipitation at Córdoba. The wavetrain structure of midtropospheric cyclonic and anticyclonic vortices reaches lower latitudes, and the circulation index is reversed to some extent. Some blocking action is detected in the South Atlantic.

On the other hand, biserial correlation-field charts provide a systematic and reliable technique for pattern classification of height and dynamical variables having place in precipitation and non-precipitation synoptic situations for use in diagnosis / forecast or synoptic climatology studies.

This study is being made extensive to other localities and regions of Argentina to document how synoptic-scale systems, such as cyclones and anticyclones associated with frontal zones, examined through mid-troposphere vorticity contribute to precipitation.

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