ON THE DEPENDENCE OF THE MOTION OF CYCLONES AND ANTICYCLONES ON THEIR SHAPE

by

Hilda T. Storari de Philander

Licenciada en Ciencias Meteorologicas

Universidad Nacional de Buenos Aires

(1965)

Submitted in partial fulfillment

of the requirement for the

degree of Master of

Science

at the

Massachusetts Institute of Technology
March 23, 1970

Signature of Author.....

Certified by .....

Accepted by .....

Chairman, Depart. Committee on Graduate Students

Lindgren

WITHDRAWN

MASS. INST. TECH.

JUN 4 1970

FROM

MIT LIBRARIES

On the dependence of the motion of cyclones and anticyclones on their shape

by

Hilda T. Storari de Philander

Submitted to the Department of Meteorology on March 1970, in partial fulfillment of the requirements for the degree of Master of Science.

Abstract

The dependence on the shape of the motion of cyclones and anticyclones next to the earth's surface is studied using four years of data. In addition, the characteristics of the distribution of the pressure systems according to their shape, longitudinal and latitudinal elongation, size and central pressure is studied. It is found that latitudinally elongated anticyclones have a larger meridional velocity component than the symmetrical or longitudinally elongated systems; and that longitudinally elongated cyclones have a larger zonal velocity component than the symmetrical or latitudinally elongated systems. Some interesting statistical properties of the distribution of cyclones and anticyclones according to the parameters mentioned above are described.

Thesis Supervisor: Victor P. Starr
Title: Professor of Meteorology

Table of contents

Introduction 10

Data 12

Part 1:

a) Analysis and Sample 15

b) Mean motions 19

c) Frequency distributions:

1) Central pressure 21

2) Size 26

3) Longitudinal elongation 32

4) Latitudinal elongation 36

5) Shape 43

Part 2:

a) Analysis and Sample 48

b) 1) i) Relationship between shape and size 50

ii) Relationship between shape and intensity 54

2) Dependence of the motions on the shape 57

3) i) Estimating the zonal wind component of the terrestrial wind field 108

ii) Estimating the flux of relative angular momentum 110

c) Relationship between intensity and motions, and size 115

Conclusion 121

References 123

Acknoledgements 124

List of tables

1. A Mean motion of the anticyclones belonging to each of the 5 shape groups for the total sample.

1. B Mean motion of the anticyclones belonging to each of the 5 shape groups for the 4 Winter seasons.

1. C Mean motion of the anticyclones belonging to each of the 5 shape groups for the 4 Spring seasons.

1. D Mean motion of the anticyclones belonging to each of the 5 shape groups for the 4 Summer seasons.

1. E Mean motion of the anticyclones belonging to each of the 5 shape groups for the 4 Fall seasons.

2. A Mean motion of the anticyclones belonging to each of the 3 shape groups for the total sample.

2. B Mean motion of the anticyclones belonging to each of the 3 shape groups for the 4 Winter seasons.

2. C Mean motion of the anticyclones belonging to each of the 3 shape groups for the 4 Spring seasons.

2. D Mean motion of the anticyclones belonging to each of the 3 shape groups for the 4 Summer seasons.

2. E Mean motion of the anticyclones belonging to each of the 3 shape groups for the 4 Fall seasons.

3 Correlation between shape and latitudinal displacement of the anticyclones for each season and for the 4 years average.

4 Correlation between shape and longitudinal displacement of the anticyclones for each season and for the 4 years average.

5. A Mean motion of the cyclones belonging to each of the 5 shape groups for the total sample.

5. B Mean motion of the cyclones belonging to each of the 5 shape groups for the 4 Winter seasons.

5. C Mean motion of the cyclones belonging to each of the 5 shape groups for the 4 Spring seasons.

5. D Mean motion of the cyclones belonging to each of the 5 shape groups for the 4 Summer seasons.

5. E Mean motion of the cyclones belonging to each of the 5 shape groups for the 4 Fall seasons.

6. A Mean motion of the cyclones belonging to each of the 3 shape groups for the total sample.

6. B Mean motion of the cyclones belonging to each of the 3 shape groups for the 4 Winter seasons.

6. C Mean motion of the cyclones belonging to each of the 3 shape groups for the 4 Spring seasons.

6. D Mean motion of the cyclones belonging to each of the 3 shape groups for the 4 Summer seasons.

6. E Mean motion of the cyclones belonging to each of the 3 shape groups for the 4 Fall seasons.

7 Correlation between shape and latitudinal displacement of the cyclones for each season and for the 4 years average.

8 Correlation between shape and longitudinal displacement of the cyclones for each season and for the 4 years average.

9. A Correlation coefficient and covariance between the meridional and latitudinal displacement of the anticyclones and between

the u and v components of the terrestrial wind field.

9. B Correlation coefficient and covariance between the meridional and latitudinal displacement of the cyclones and between the u and v components of the terrestrial wind field.

List of figures

1. A Frequency distribution of the central pressure of the anticyclones for the 4 Winter and Summer seasons for 2 latitude belts.

1. B Frequency distribution of the central pressure of the cyclones for the 4 Winter and Summer seasons for 2 latitude belts.

2. A Frequency distribution of the size of the anticyclones for the 4 Winter and Summer seasons for 2 latitude belts.

2. B Frequency distribution of the size of the cyclones for the 4 Winters and Summer seasons for 2 latitude belts.

3. A Frequency distribution of the longitudinal elongation of the anticyclones for the 4 Winter and Summer seasons for 2 latitude belts.

3. B Frequency distribution of the longitudinal elongation of the cyclones for the 4 Winter and Summer seasons for 2 latitude belts.

4. A Frequency distribution of the latitudinal elongation of the anticyclones for the 4 Winter and Summer seasons for 2 latitude belts.

4. B Frequency distribution of the latitudinal elongation of the cyclones for the 4 Winter and Summer seasons for 2 latitude belts.

5. A Frequency distribution of the shape of the anticyclones for the 4 Winter and Summer seasons for 2 latitude belts.

5. B Frequency distribution of the shape of the cyclones for the 4 Winter and Summer seasons for 2 latitude belts.

6. A The latitudinal distribution of the directly measured vertically averaged angular velocity for a period of 5 years, and 2 estimations made from the motions of the cyclones.

Introduction

It has been found (Macdonald 1966) that the motion of cyclonic and anticyclonic vortices next to the earth's surface depends on their size. The longitudinal motion of both kinds of systems is inversely proportional to their size; while except at low latitudes, the poleward motion of the cyclones is directly proportional to their size.

Ward (1966) has found the longitudinal motion of sunspots groups to be a function of their size and also of their relative longitudinal elongation. As in the case of the earth's systems, the biggest solar spots were found to have the smallest longitudinal component of motion. Regarding the longitudinal elongation, it was found that the more longitudinally elongated spots have a larger longitudinal motion component. Since size and longitudinal extent seem to have a positive correlation in the solar spots, this last effect on the motion cannot be due to a reflection of the size dependence.

The main purpose of this study was to try to find out if there is any relationship between the shape and the motion of cyclones and anticyclones in the earth's atmosphere. It was found

that there seems to be a positive correlation between the zonal motion of the cyclones and their longitudinal elongation, and between the equatorward motion of the anticyclones and their latitudinal elongation. These results mark an analogy to the behaviour of the tracers of the solar atmospheric motion. An explanation for the retardation of the motion of the bigger systems can be found for both atmospheres in the variation of the Coriolis parameter with latitude. But there has never been any attempt to include the assymetries in any theoretical studies, such as Kasahara (1957), in the examination of the displacement of vorticity concentrations in their surrouding fluid.

The results concerning the dependence of the motion on the shape of the system is presented in Part II; together with some results concerning the relationship between shape and other characteristic parameters of each system, such as intensity and size.

Part I presents the characteristics of the seasonal distribution with latitude of cyclones and anticyclones in respect to several parameters that were available, and studied, in their possible relationship with, or as part of, the shape of the systems. They are intensity and size, longitudinal and latitudinal elongation, and shape of the systems.

Macdonald (1969) also found an interesting property of the

smallest systems (especially cyclones) present in the atmosphere; they are the best tracers of both, the mean and the eddy components of the general circulation. From our analysis, it was not possible to find any differences in the way in which systems with different shapes contribute to an estimation of the instantaneous eddy flux of angular momentum. But it was found that longitudinally elongated small cyclones are probably the best tracers of the zonal wind component of the terrestrial wind field.

Data

The data used in this study were originally collected for Mr. Norman Macdonald for his study of the dependence of the motions of the cyclones and anticyclones on their size (Macdonald, 1967). They were taken from the daily maps of surface pressure distribution over the Northern Hemisphere collected by the USWB from January 1st 1959 to December 31st 1962. In the USWB maps, each system was identified and followed until its disappearance; the following parameter were collected from the daily 1200 maps for each system:

a) position of the center of the system in degrees of latitude and longitude

b) a measure of the size of the system as given by the

areas included within the last closed isobar.

c) the central pressure of the system

d) a measure of the longitudinal extent of the system, ie. the degrees of longitude covered by a line more or less parallel to the latitude joining the 2 extremes of the outermost closed isobar and passing through the center.

e) a measure of the longitudinal extent of the system as given by the length of the system measured on a line more or less parallel to the longitude, joining the 2 extremes of the outermost closed isobar and passing through the center.

The data were divided and handled in belts of 10° of latitude each from 10 to 70 degrees of latitude, while the region between 70 and 90 degrees of latitude was considered as one belt. The seasons were taken as follows; Winter: January through March; Spring: April through June; Summer: July through September; Autumn: October through December. Since there were 4 complete years of data, there were 12 months of data available for each season, hence, by "seasonal average" in the text, it must be understood to be the average of 4 seasons. Under "total" we list the averages for the whole sample.

In collecting the data from the original maps, one eighth of an inch was used as the unit of longitude in measuring the lati-

tudinal and longitudinal elongation of the system. Of course, such a length corresponds to different amounts of miles, for instance, on the earth's surface depending on the latitude, but since all the systems were taken in latitudinal belts, it can be assumed that, that distance is the same inside the limits of each band.

The same holds true for the size of the systems as given by the areas they cover. The unit of size used was 5×10^4 km^2.

Part I.

A) Analysis and Sample

This part presents the results obtained when a frequency distribution was made of all the data in order to get information about the range and characteristic of all the parameters studied, in particular the shape.

The proceeding used was roughly the following: the data were scanned to look for the extreme values of each parameter for all the systems present in each latitude belt. The difference between those two values was divided by 5 in the case of the longitudinal and latitudinal extent, and by 7 in the case of the other parameters, size, intensity and shape. That value was taken and added to the lowest extreme found, the interval between the lowest extreme and this value was taken as the lowest class of the parameter for that latitude belt. Successive addition to the upper extreme of the interval allowed to divide the whole range of the parameter into 5 or 7 classes. Then, the number of systems whose parameters had a value that fell into a certain class was counted. The cyclones and anticyclones were taken separately; and this was done for each season and for the full four years.

The mean value of each parameter for a given latitude

belt was also computed for all the seasons and it is also presented here. The mean motions of all the systems that entered in the statistics were computed and they are shown in part (a). Part (b) contains all the frequency distributions according to their intensity, size, longitudinal and latitudinal extent and shape.

Next, we present a tabulation of the main characteristics of the data as they were used to produce the frequency distributions.

The data entering in this part of the statistics were composed of all systems appearing on the original maps that have never moved more that 30 degrees of latitude in 24 hours and/or 90 degrees of longitude in the same length of time; and that was present in at least 2 consecutive maps. In addition, since the main object of this study was to try to find out if there was any dependence on the shape of the motions of all the systems, all those systems that appeared for more than 15 days in the original data were left out since they were probably mostly semi-permanent stagnant systems we are not concerned with. This process left out 240 systems; while, the limitation in the latitudinal and longitudinal motion filtered out some 36 systems.

The tables to be presented here give a general idea of the general distribution of highs and lows over the hemisphere through the seasons.

The number of systems that "seem" to have entered in this part of the statistics is higher than the total number of individual systems that were found in the maps. This is so because if during its lifetime, a system crossed from one latitude belt to another, it will have contributed to both belts statistics with the characteristic values of its parameters and motions as found in each belt during its presence there.

The following table shows the distribution for each season of the number of systems of high pressure present in each latitude belt.

BELT	10-20	20-30	30-40	40-50	50-60	60-70	70-90	Total
Season								
Winter	20	216	294	273	216	200	102	1321
Spring	10	160	291	303	256	175	136	1331
Summer	9	76	280	344	238	145	136	1228
Fall	9	168	354	341	206	185	114	1382
Total	48	620	1219	1266	916	705	488	5262

The number of anticyclones presented in the first latitude belt is obviously not enough to produce any statistically significant results. The maximum number of anticyclones were in or passed through at one time, the 40 to 50° latitude belt. There is a second mini-

mum in the polar belt.

The 20 to 30° of latitude belt presents the greastest variation in the number of systems between winter and summer compared with the other belts in all the seasons. The total number of systems that entered the statistics by each season were then; 1321 in winter, 1331 in spring, 1228 in summer and 1382 in the autumn; this gives a total of 5262 systems of high pressure.

The next table shows the number of low pressure systems present in each latitude belt during each season.

BELT	10-20	20-30	30-40	40-50	50-60	60-70	70-90	Total
Season								
Winter	93	192	460	574	529	333	211	2392
Spring	142	258	441	562	566	333	190	2535
Summer	173	316	359	487	524	376	213	2475
Fall	139	194	379	522	523	403	237	2339
Total	547	960	1639	2145	2142	1457	851	9736

The belts between 40 and 50, and 50 and 60 degrees of latitude presented almost equal number of systems during the 4 years, corresponding to the maximum. The equatorial belt presented the minimum. In this case, the total number of systems was: 2392 in winter, 2535 in spring, 2475 in summer and 2339 in autumn;

this makes a total of 9736 systems of low pressure entering the statistics. Since the number of individual systems followed in the original maps was about 8400; and the total number entering in the statistics was 14,998; follows that about half of all the systems crossed once during their lifetime from one belt to another.

B) Mean Motions

The average of the longitudinal and latitudinal motions of all the systems in a given latitude belt was computed. This was done to be able to compare these quantities with previous results from 5 years of data of which our four is a subsample.

Macdonald N. (1969) obtained for the 5 years the numbers in parenthesis in the following table: mean meridional, $\{\Delta\Theta\}$; and latitudinal, $\{\Delta\lambda\}$, motion of the cyclones and anticyclones for the total sample, in m/sec^{-1}, for each latitude belt.

Cyclones

Latitude belt	10-20	20-30	30-40	40-50	50-60	60-70	70-90
$\{\Delta\lambda\}$	-0.74	1.40	7.00	7.19	5.70	5.06	2.11
	(-0.73)	(0.63)	(6.06)	(7.61)	(5.45)	(5.03)	(2.39)
$\{\Delta\Theta\}$	1.81	1.16	2.58	2.97	1.68	0.90	-0.13
	(0.74)	(0.56)	(1.59)	(2.47)	(2.19)	(1.90)	1.32

Anticyclones

Latitude belt	10-20	20-30	30-40	40-50	50-60	60-70	70-90
$\{\Delta\lambda\}$	—	5.62	5.62	5.82	4.66	3.74	1.25
	—	(4.92)	(5.66)	(5.85)	(4.71)	(3.55)	(1.37)
$\{\Delta\theta\}$	—	1.16	-0.26	-1.94	-2.71	-2.32	-1.68
	—	(-0.78)	(-0.88)	(-1.53)	(-2.30)	(-1.85)	(-0.53)

With the rare exception of the mean latitudinal motion of the cyclones in the polar belt and of the anticyclones in the 20 to 30 degrees of latitude belt, the rest of the results essentially shows an agreement with Macdonald's results. The later disagreement is believed to be due to the fact that Macdonald's computations included also the long lived systems that are probably abundant at those latitudes.

In the mean, cyclones between 20 and 70 degrees of latitude move eastward and northward. Between 10 and 20 degrees of latitude, they move northwards but westward; and between 70 degrees of latitude and the pole, they move eastward but southward. The anticyclones seem to move eastward but southward everywhere north of 30 degrees of latitude in the mean. South of that latitude, our results seem to indicate that the shorter lived systems may move also eastward but northward.

C1) Central Pressure

The following table shows the average central pressure (in mb) of the anticyclones corresponding to each season as a function of the latitude belt.

BELT	10-20	20-30	30-40	40-50	50-60	60-70	70-90
Season							
Winter	1015	1022	1028	1035	1034	1032	1033
Spring	1012	1019	1024	1024	1024	1024	1026
Summer	1012	1018	1022	1023	1021	1021	1022
Fall	1015	1021	1026	1032	1033	1031	1027

On the average, the anticyclones with the lowest central pressure are found at lower latitudes, while between 40 and 60 degrees of latitude the pressure is higher. Typically, the distribution of high pressure systems according to their intensity is skew at all latitudes during the autumn, spring and summer seasons, and slightly less so during the winter.

The following tables show the frequency distribution of the high pressure systems according to their central pressure, in mb for 3 latitude belts in winter and summer.

Winter

BELT							
20-30	1010.0	1014.7	1019.9	1024.8	1029.7	1034.6	1044.5
	1	8	37	81	59	23	7
40-50	1014.0	1020.3	1026.7	1033.0	1039.4	1045.7	1058.4
	1	14	54	105	55	32	12
60-70	1009.3	1016.3	1023.4	1030.4	1037.4	1044.4	1058.4
	1	7	21	54	70	40	7

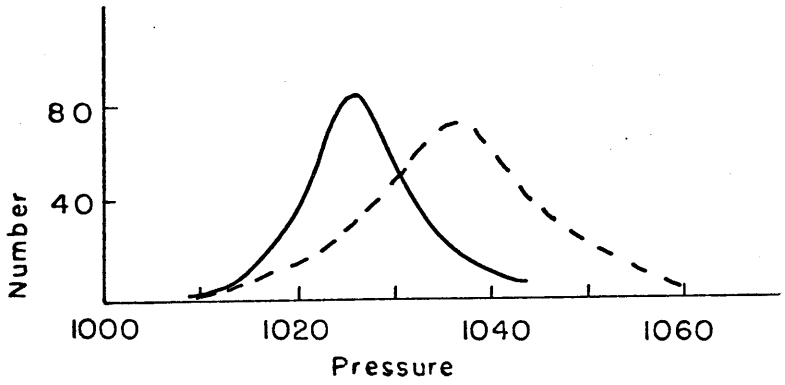
Summer

BELT							
20-30	1006.0	1010.0	1014.0	1018.0	1022.0	1026.0	1030.0
	1	2	11	24	17	13	8
40-50	1004.0	1008.0	1012.0	1016.0	1020.0	1024.0	1028.0
	7	14	27	43	61	83	109
60-70	1008.0	1011.9	1015.7	1019.6	1023.4	1027.3	1035.0
	2	3	12	35	41	38	14

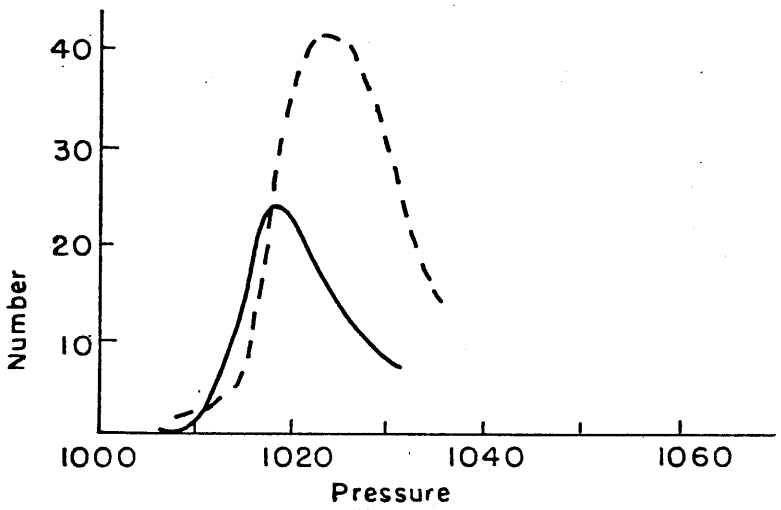
Figure 1-A also shows part of these distributions. The next table shows the average central pressure (in mb) of the low pressure systems corresponding to each latitude belt for each season.

BELT	10-20	20-30	30-40	40-50	50-60	60-70	70-90
Season							
Winter	1006	1008	1002	995	993	995	998
Spring	1003	1003	1005	1001	999	1001	1001
Summer	1003	1001	1004	1005	1000	999	997

Figure 1. A



Frequency distribution of the central pressure in mb of the anti-cyclones for the winter season for two latitude belts; —: 20 to 30; and — — —: 60 to 70 degrees of latitude.



Frequency distribution of the central pressure in mb of the anti-cyclones for the summer season for two latitude belts; —: 20 to 30; and — — —: 60 to 70 degrees of latitude

Fall	1005	1007	1004	999	993	994	998

On the average, cyclones with the lowest central pressure occur at high latitudes, with an absolute overall minimum in the intensity on the belt centered at 55° of latitude. This makes this belt the one with major contrast between the high and low pressure systems found on it. The belt centered at 15° of latitude on the other hand presents the least intense systems of both types. The following tables show the frequency distribution of the anticyclones according to their intensity in mb for 3 latitude belts in winter and summer.

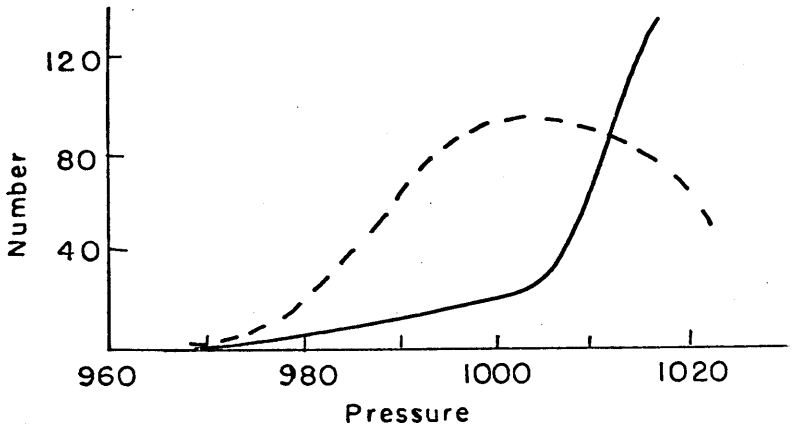
Winter

BELT							
20-30	973.7	979.8	985.8	991.8	967.9	1003.9	1016.0
	1	1	3	11	19	19	134
40-50	959	969.7	980.4	991.1	1001.9	1012.6	1034.0
	1	4	26	132	209	164	38
60-70	968	975.7	983.4	991.1	998.9	1016.6	1022.0
	2	8	30	68	91	79	55

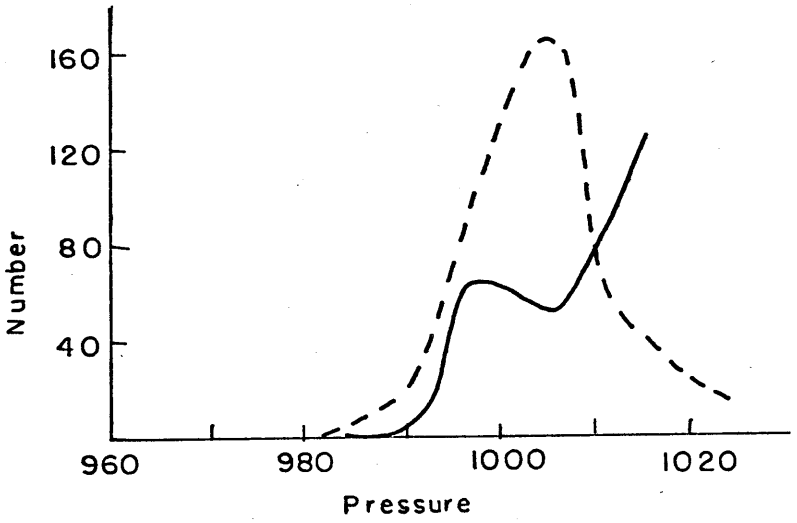
Summer

BELT							
20-30	984.0	988.4	992.8	997.1	1001.5	1005.9	1014.7
	1	0	12	65	60	52	126
40-50	984.0	989.4	994.9	1003.0	1005.7	1011.1	1022
	1	9	42	116	114	124	81
60-70	982.0	987.7	993.4	999.1	1004.2	1010.6	1022
	1	11	29	116	167	59	20

Figure 1. B



Frequency distribution of the central pressure in mb of the cyclones for the winter season for two latitude belts; —: 20 to 30; and — — —: 60 to 70 degrees of latitude.



Frequency distribution of the central pressure in mb of the cyclones for the summer season for two latitude belts; —: 20 to 30; and — — — —: 60 to 70 degrees of latitude.

Figure 1.B shows also part of these distributions. The distribution of the low pressure systems is more skewed than that of the anticyclones at all latitudes for all the seasons. For both types of systems there is an overall preference for finding less systems in the lower pressure side of the spectrum as expected, but of course this is less so for the cyclones.

C2) Size

The following table shows the average size of all the anticyclones found in a given latitudinal band for each of the seasons;

BELT	20-30	30-40	40-50	50-60	60-70	70-90
Season						
Winter	65.3	68.2	52.3	39.2	23.4	34.5
Spring	72.9	95.7	54.9	37.4	24.1	33.2
Summer	38.0	83.2	56.3	32.1	22.2	28.4
Fall	52.7	78.8	53.3	51.2	24.6	23.4

At low latitudes the systems have a preference for a bigger size in the spring. In the region between 20 and 40 degrees of latitude, the difference between the maximum and minimum sizes is rather big; this is not so anywhere else with the possible exception of the 50 to 60 degrees of latitude belt where in autumn the average jumps

to a slightly high value. Otherwise the rest of the belts seem to present a rather characteristic average-size for the systems present on them through the whole year. The apparent decreasing size of all the system poleward is a reflexion of the fact that all the areas where measured in the same units; toward the pole the systems do get smaller in size but they may still be covering the same percentage of the belt that was at lower latitudes.

The following table allows us to see the distribution of the anticyclones in winter and summer at three different latitudes according to their size.

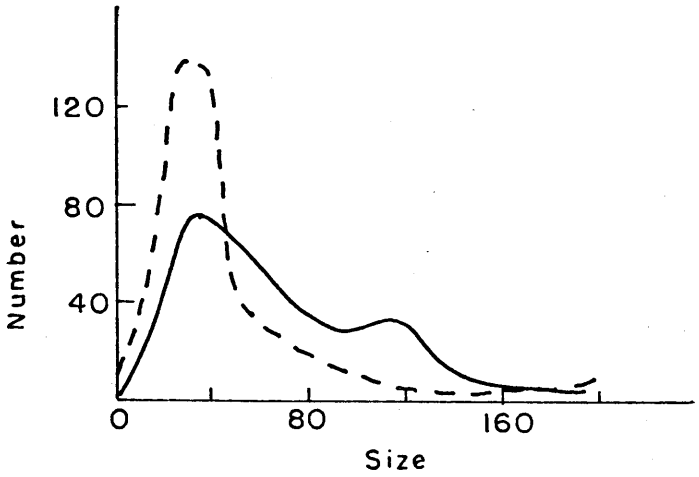
Winter

BELT							
20-30	4.0	31.7	59.4	87.1	114.9	142.6	198.0
	1	75	57	31	34	10	8
40-50	1.4	28.1	54.8	81.4	108.1	134.7	188.0
	2	125	70	34	23	12	7
60-70	2.0	28.4	54.8	81.2	107.6	134.0	186.8
	5	128	36	18	9	2	2

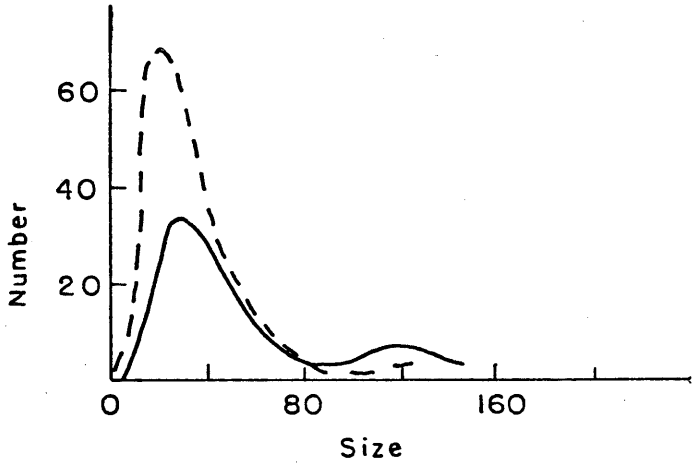
Summer

BELT							
20-30	3.5	25.1	46.8	68.4	90.1	111.7	155.0
	1	33	19	9	4	6	4
40-50	1.0	38.2	75.4	112.5	149.7	186.9	261.3
	1	224	76	24	10	4	4

Figure 2. A



Frequency distribution of the size of the anticyclones in the winter season for two latitude belts; —: 20 to 30, and — — —: 60 to 70 degrees of latitude. One unit equals 5×10^4 km^2.



Frequency distribution of the size of anticyclones in the summer season for two latitude belts; —: 20 to 30, and — — —: 60 to 70 degrees of latitude. One unit equals 5×10^4 km^2.

60-70	2.0 2	19.1 68	36.4 41	53.3 19	70.4 9	87.5 1	121.7 5

Figure 2.A shows also part of these distributions.

It can immediately be concluded that it is easy to find oversized systems with respect to the average at any given latitude. The assymetry of the distribution barely changes during the seasons and with latitude. The next table corresponds to the distribution for each season of the average sizes of all the cyclones in each latitude belt.

BELT	10-20	20-30	30-40	40-50	50-60	60-70	70-90
Season							
Winter	35.9	17.4	20.6	24.0	21.8	15.9	18.0
Spring	45.0	47.4	17.3	20.2	21.3	15.1	17.1
Summer	27.0	46.7	21.8	12.5	19.9	17.8	16.2
Fall	50.3	18.7	18.5	18.4	24.9	18.1	13.6

The maximum average size corresponds to the systems present in the 20 to 30 degrees of latitude belt during the spring and summer.

In the average, a cyclone covers an area of about half of that covered by an anticyclone. Since there are about twice as many cyclones as there are anticyclones, roughly the amount of negative vorticity present on the hemisphere equals that of posi-

tive vorticity next to the earth's surface. The next table shows the distribution of the cyclones in winter and summer in 3 latitude belts according to their size.

Winter

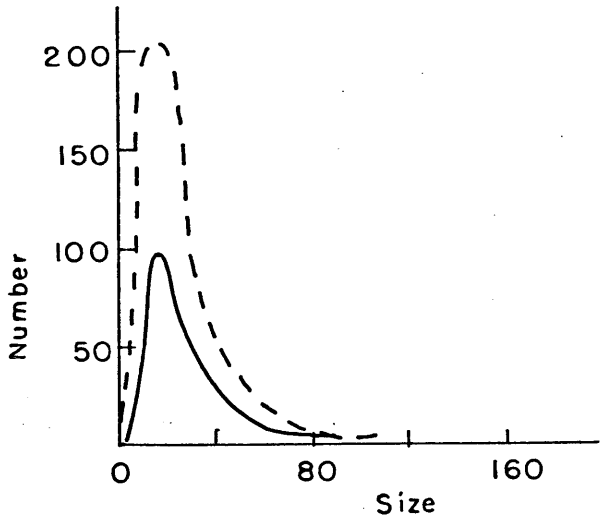
BELT							
20-30	1.5	14.8	28.0	41.3	54.5	67.8	94.3
	4	91	55	26	8	4	4
40-50	1.0	15.1	29.2	43.3	57.5	71.6	99.8
	10	292	152	73	26	15	6
60-70	1.0	18.0	35.0	52.0	69.0	86.0	120.0
	6	206	87	25	6	2	1

Summer

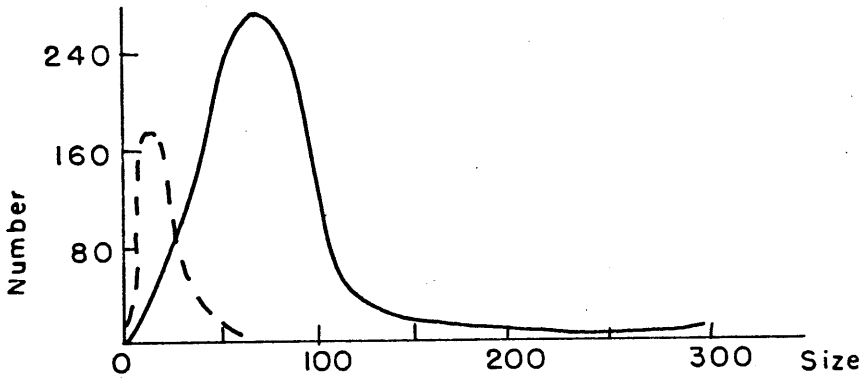
BELT							
20-30	1.0	60.1	119.3	178.4	237.6	296.7	415.0
	2	272	30	6	3	1	2
40-50	1.0	12.9	24.8	36.6	48.5	60.4	84.1
	12	281	121	52	13	4	4
60-70	1.0	9.6	18.1	26.7	35.2	43.8	60.9
	6	168	108	56	42	17	6

Figure 2-B also shows part of these distributions. The characteristics of their distribution is very much like that of the anticyclones.

Figure 2. B



Frequency distribution of the size of the cyclones in the winter season for two latitude belts; —: 20 to 30; and — — —: 60 to 70 degrees of latitude. One unit equals 5×10^4 km^2.



Frequency distribution of the size of the cyclones in the summer season for two latitude belts; —: 20 to 30, and — — —: 60 to 70 degrees of latitude. One unit equals 5×10^4 km^2.

C3) Longitudinal Elongation

This parameter gives a measure of how elongated the system is along the latitude circles. The following table gives the mean value of the parameter for all the cyclones in a given latitude belt for all the seasons. The meaning of the units was explained in Section (a).

BELT	10-20	20-30	30-40	40-50	50-60	60-70	70-90
Season							
Winter	1.4	1.0	1.1	1.1	1.1	0.9	1.0
Spring	1.8	1.8	1.0	1.1	1.1	0.9	1.0
Summer	1.3	1.8	1.2	0.9	1.1	1.0	0.9
Fall	1.8	1.0	1.0	1.0	1.2	1.0	0.9

Except for the low latitudes, in the mean, it would seem to be hard to find a cyclone very much more elongated than any other one; but this is not so. This fact is put in evidence by looking at the following table that gives the number of systems found in a given interval of the parameter for 3 latitude belts in 2 seasons.

Winter

BELT

20-30	0.3	0.7	1.2	1.6	2.1
	1	52	79	50	13
40-50	0.2	0.6	0.9	1.3	1.6
	1	84	180	142	100
60-70	0.2	0.7	1.2	1.7	2.2
	1	106	141	70	13

Summer

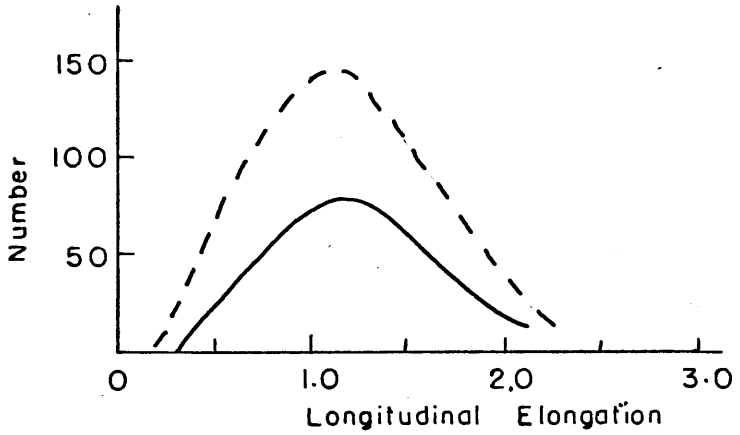
BELT

20-30	0.3	1.2	2.1	3.0	4.0
	1	168	94	31	10
40-50	0.2	0.6	0.9	1.3	1.7
	1	126	154	129	59
60-70	0.2	0.5	0.8	1.0	1.3
	1	56	101	99	70

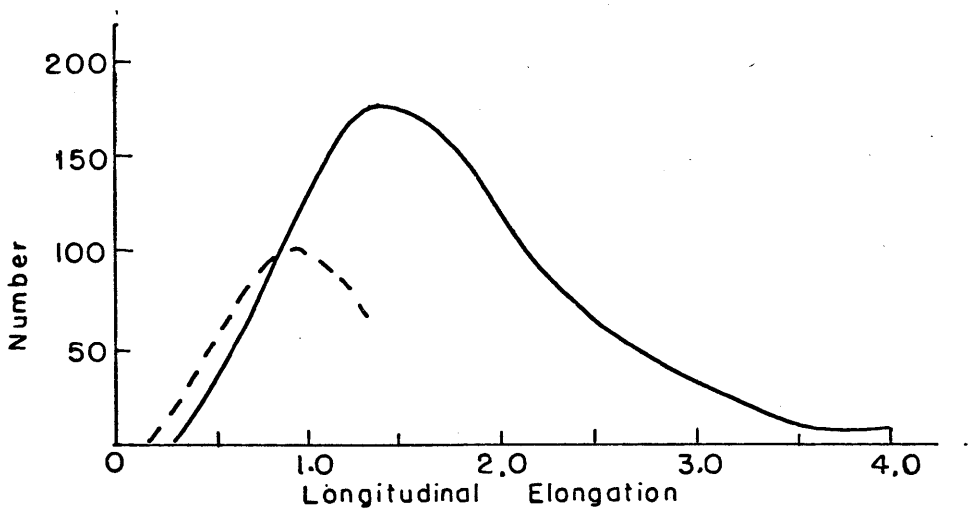
Figure 3.a Also shows part of these distributions

The average values for a given latitude belt comes from a rather wide range of values of the parameter. Only very little longitudinally elongated systems are rare. The next table gives the mean values of the longitudinal elongation for all the anticyclones found in a latitude belt for all the seasons.

Figure 3. A



Frequency distribution of the longitudinal elongation of the anti-cyclones in the winter season for two latitude belts; —: 20 to 30, — — —: 60 to 70 degrees of latitude. Units are explained in the text on page 13 .



Frequency distribution of the longitudinal elongation of the anti-cyclones in the summer season for two latitude belts; —: 20 to 30, — — —: 60 to 70 degrees of latitude. Units are explained in the text on page 13 .

BELT	10-20	20-30	30-40	40-50	50-60	60-70	70-90
Season							
Winter	2.6	2.6	2.3	1.8	1.6	1.2	1.4
Spring	1.9	2.7	2.8	1.9	1.6	1.3	1.5
Summer	1.4	1.8	2.6	2.0	1.5	1.2	1.4
Fall	2.5	2.3	2.5	1.9	1.8	1.3	1.2

The high pressure systems in the mean are rather more elongated in the west-east direction than the cyclones. Again, as with their size, and with the cyclones, the parameter seems to become smaller toward the pole.

Inspection of the following two tables that gives the frequency distribution for 2 seasons in 3 latitude belts brings the same conclusions for the cyclones:

Winter

BELT					
20-30	0.5	1.4	2.2	3.0	3.9
	1	61	66	40	34
40-50	0.3	0.8	1.4	1.9	2.5
	1	49	73	58	45
60-70	0.3	0.8	1.3	1.7	2.2
	1	52	56	43	23

Summer

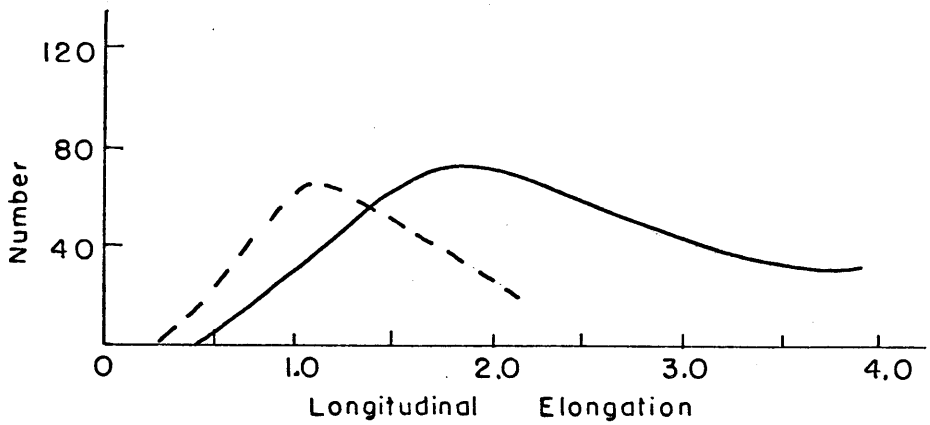
BELT					
20-30	0.7	1.2	1.6	2.1	2.6
	1	25	11	14	9
40-50	0.2	1.0	1.8	2.6	3.4
	1	102	127	62	34
60-70	0.3	0.8	1.2	1.7	2.1
	1	36	43	25	21

Figure 3.B shows part of these distributions

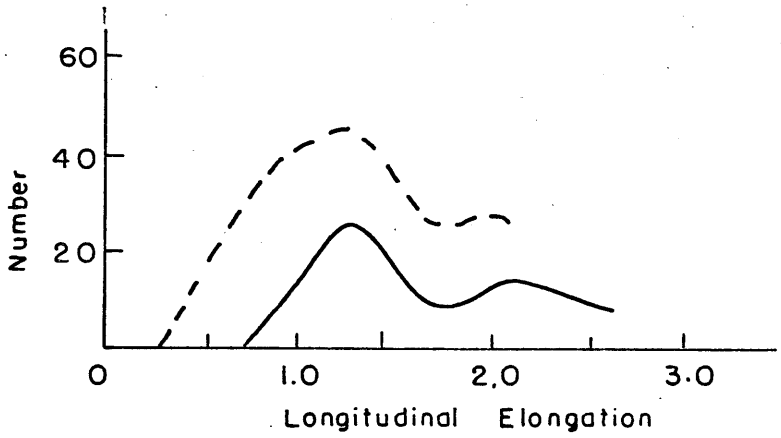
C4) Latitudinal Elongation

This parameter gives a measure of how elongated the system is along the meridian, that is, in the north-south direction. The mean values of this parameter found for the low pressure systems for each season for the different latitude belts is shown in the following table. The units are the same as those for the longitudinal elongation.

Figure 3. B



Frequency distribution of the longitudinal elongation of the cyclones in the winter season for two latitude belts; —: 20 to 30, and — — —: 60 to 70 degrees of latitude. Units are explained in the text on page 13 .



Frequency distribution of the longitudinal elongation of the cyclones in the summer season for two latitude belts; —: 20 to 30, — — —: 60 to 70 degrees of latitude. Units are explained in the text on page 13 .

BELT	10-20	20-30	30-40	40-50	50-60	60-70	70-90
Season							
Winter	1.5	1.1	1.1	1.2	1.1	0.9	0.9
Spring	1.6	1.5	1.0	1.1	1.1	1.0	1.0
Summer	1.3	1.4	1.0	0.9	1.1	1.0	0.9
Fall	1.7	1.1	1.1	1.0	1.2	1.0	0.9

The distribution is very much like that found for the longitudinal elongation of the systems except at low latitudes where the values are rather smaller. Inspection at the frequency distribution from which the mean values come, show that they come from a rather spread spectrum.

The next 2 tables gives the frequency distribution of the latitudinal elongation parameter for 2 seasons and 3 latitude belts.

Winter

BELT					
20-30	0.3	0.6	0.9	1.2	1.5
	1	25	46	46	40
40-50	0.2	0.6	1.1	1.5	1.9
	1	129	206	141	76
60-70	0.2	0.6	0.9	1.3	1.6
	1	67	99	92	40

Summer

BELT					
20-30	0.3	0.8	1.3	1.8	2.3
	1	89	116	67	27
40-50	0.2	0.5	0.8	1.1	1.3
	3	79	153	102	90
60-70	0.3	0.5	0.8	1.1	1.3
	5	64	87	104	78

The one difference with the distribution according to the longitudinal elongation is that the upper extreme values are smaller in the present case. The next 3 tables show that there is no important difference between the characteristics of the mean values and distributions of the anticyclones with that of the cyclones, except that the lower extent is more latitudinal than the latter. But this, plus the fact that the same is true for the longitudinal elongation is nothing more than another aspect of the fact that anticyclones are, on the average, larger than cyclones.

Average value of the latitudinal elongation for each latitude belt for the four seasons for the anticyclones.

BELT	10-20	20-30	30-40	40-50	50-60	60-70	70-90
Season							
Winter	1.4	1.6	1.8	1.6	1.5	1.1	1.6

Spring	2.4	1.6	2.1	1.7	1.5	1.3	1.5
Summer	1.5	1.3	1.8	1.7	1.4	1.2	1.4
Fall	1.6	1.5	1.9	1.6	1.6	1.2	1.3

Frequency distribution for 3 latitude belts and 2 seasons.

Winter

BELT

20-30	0.5	0.9	1.3	1.7	2.0
	2	24	42	58	42
40-50	0.3	1.0	1.6	2.3	2.9
	1	82	83	73	29
60-70	0.3	0.8	1.3	1.8	2.2
	2	51	69	38	20

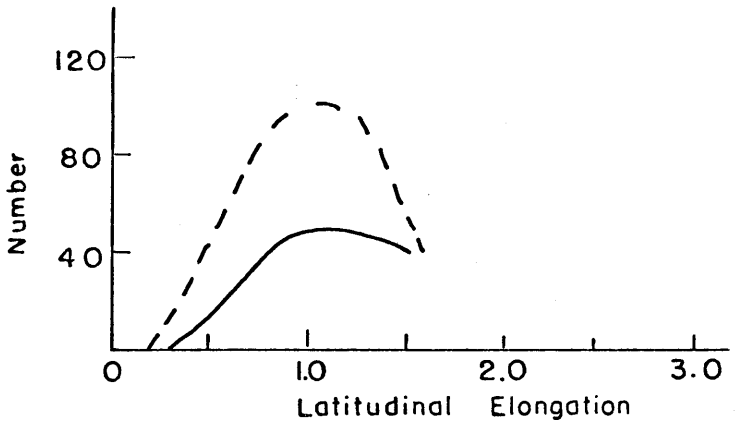
Summer

BELT

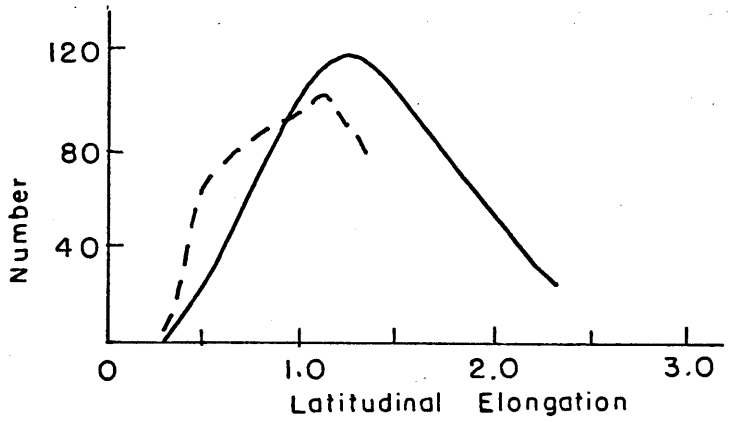
20-30	0.3	0.8	1.2	1.6	2.1
	1	12	23	17	17
40-50	0.3	0.7	1.2	1.6	2.1
	1	61	91	85	54
60-70	0.3	0.7	1.0	1.4	1.7
	1	25	26	31	30

Figures 4.A and 4.B show part of the frequency distributions corresponding to the anticyclones and to the cyclones.

Figure 4. A

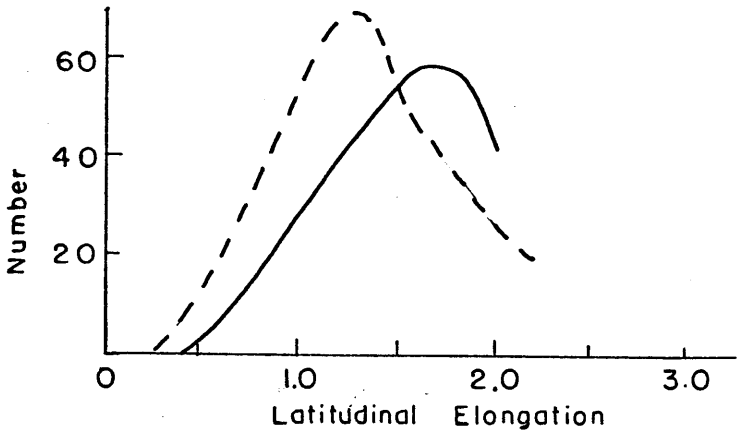


Frequency distribution of the latitudinal elongation of the anticyclones in the winter season for two latitude belts; —: 20 to 30, — — —: 60 to 70 degrees of latitude. Units are explained in the text on page 13 .

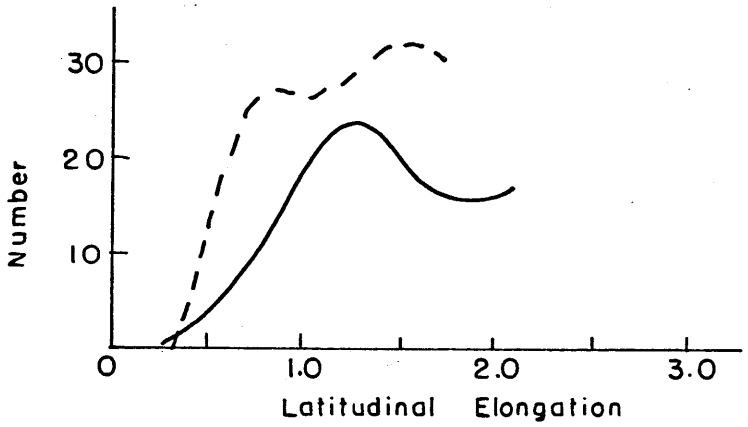


Frequency distribution of the latitudinal elongation of the anticyclones in the summer season for two latitude belts; —: 20 to 30; — — —: 60 to 70 degrees of latitude. Units are explained in the text on page 13 .

Figure 4. B



Frequency distribution of the latitudinal elongation of the cyclones in the winter season for two latitude belts; —: 20 to 30, — — —: 60 to 70 degrees of latitude. Units are explained in the text on page 13 .



Frequency distribution of the latitudinal elongation of the cyclones in the summer season for two latitude belts; —: 20 to 30; — — —: 60 to 70 degrees of latitude. Units are explained in the text on page 13 .

C5) Shape

This parameter was constructed by taking the ratio between the longitudinal and latitudinal elongation of each system. In that way, values of the shape much smaller than one (0.5 for instance) will indicate that the system is latitudinally elongated. Values of the shape close to one, (0.8 to 1.2 for instance) indicate that the system is roughly symmetric, while the shape is much bigger than one (2.8 for instance) the system is longitudinally elongated.

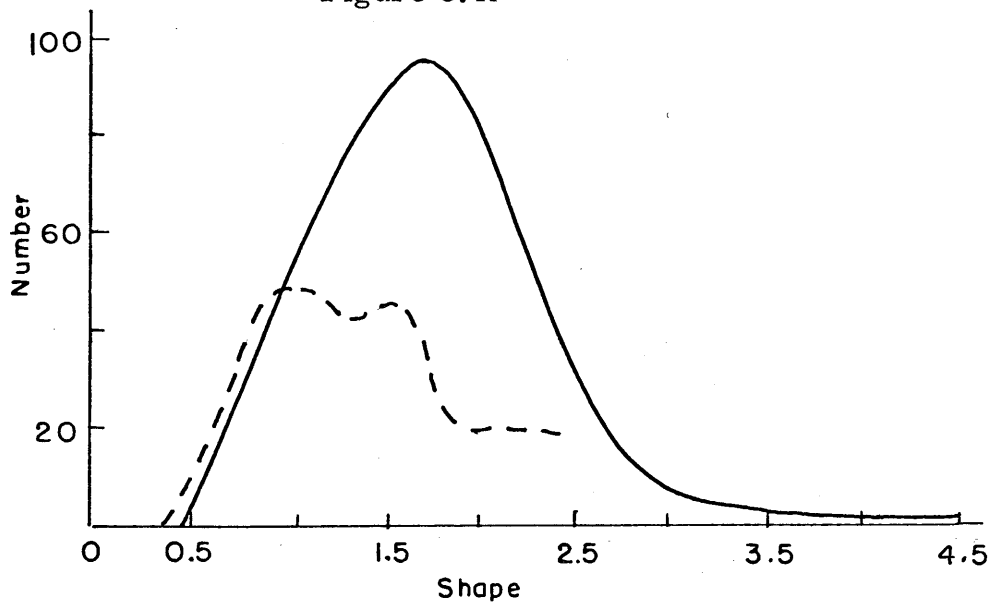
The mean value of this parameter for all the cyclones during the four seasons for each latitude belt is shown in the following table:

BELT	10-20	20-30	30-40	40-50	50-60	60-70	70-90
Season							
Winter	1.0	1.2	1.2	1.1	1.1	1.1	1.2
Spring	1.2	1.2	1.2	1.1	1.1	1.0	1.0
Summer	1.1	1.3	1.3	1.1	1.1	1.2	1.0
Fall	1.1	1.1	1.1	1.1	1.1	1.1	1.1

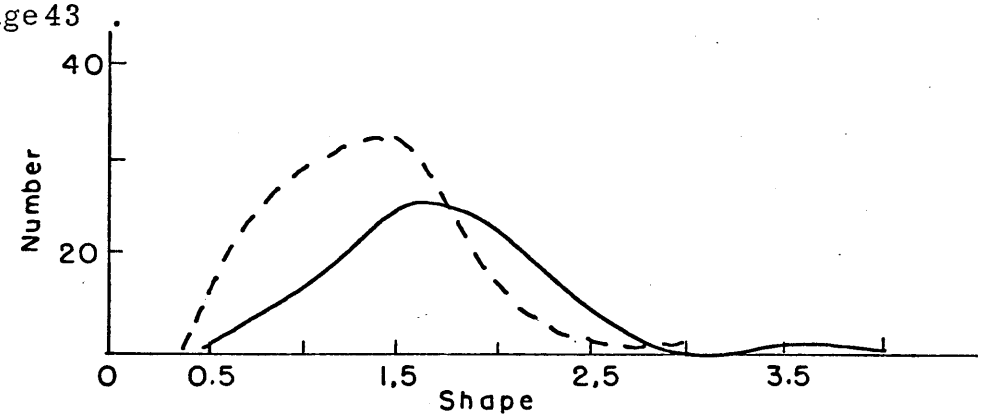
In the mean, the systems do not elongate latitudinally, and they elongate just slightly longitudinally at most latitudes.

Figure 5.A shows the frequency distribution of the shape of the cyclones as found for 2 typical latitude belts during 2 sea-

Figure 5. A



Frequency distribution of the shape of the anticyclones in the winter season for two latitude belts; —: 20 to 30, — — —: 60 to 70 degrees of latitude. The parameter is explained in the text on page 43 .



Frequency distribution of the shape of the anticyclones in the summer season for two latitude belts; —: 20 to 30, — — —: 60 to 70 degrees of latitude. The parameter is explained in the text on page 43 .

sons. They show that some cyclones do elongate latitudinally. It is easy to find systems that are very elongated longitudinally. Most of the systems are slightly elongated in that direction; of the rest, most of them are quite elongated in that direction; the rest are just slightly elongated latitudinally. There doesn't seem to be very important changes from one season to another.

The following table gives the mean shapes of all the anticyclones at a given latitude belt for the four seasons.

BELT	10-20	20-30	30-40	40-50	50-60	60-70	70-90
Season							
Winter	2.1	1.3	1.4	1.3	1.3	1.3	1.0
Spring	0.9	1.6	1.4	1.2	1.2	1.1	1.1
Summer	1.1	1.5	1.5	1.3	1.3	1.1	1.1
Fall	1.6	1.6	1.4	1.3	1.2	1.2	1.0

In the mean, the anticyclones are not latitudinally elongated either. They are more longitudinally elongated than the cyclones are, except in the polar belt.

Figure 5.B show the frequency distribution of the shapes of the anticyclones on 2 typical latitude belts for 2 seasons. The type of distribution of the high pressure systems is very much like that of the low pressure systems, except that the upper ex-

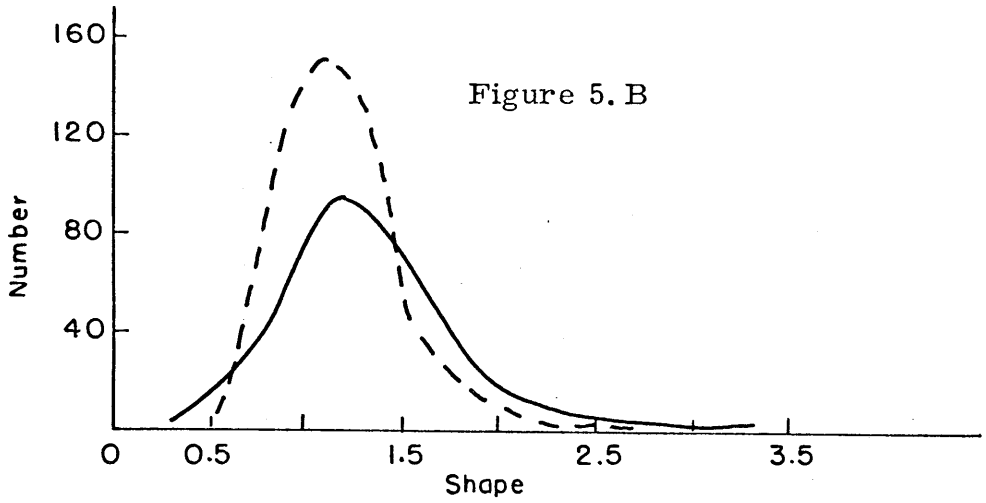
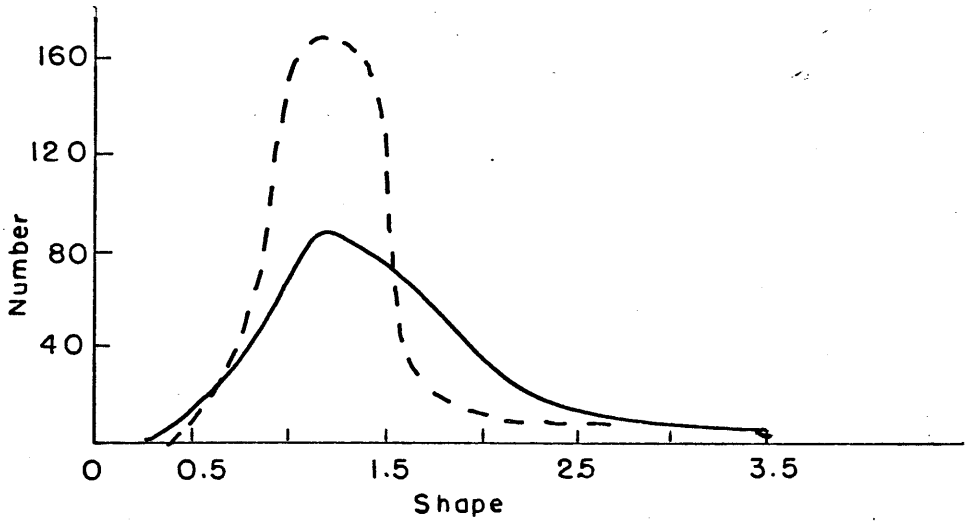


Figure 5. B

Frequency distribution of the shape of the cyclones in the winter season for two latitude belts; —: 20 to 30, — — —: 60 to 70 degrees of latitude. The parameter is explained in the text on page 43 .



Frequency distribution of the shape of the cyclones in the summer season for two latitude belts; —: 20 to 30; — — —: 60 to 70 degrees of latitude. The parameter is explained in the text on page 43 .

treme values are slightly bigger, and as mentioned before, the anticyclones are in the mean more longitudinally elongated.

Part II:

A) Analysis and Sample

The object of this part, is primarily to present the results obtained from the analysis of the dependence of the motion of the anticyclones and cyclones on their shape. There is also a description of the relationship between shape and the intensity and size of the systems. The relationship between parameters is calculated through the computation of day to day correlations and their levels of confidence. Section B) presents the correlations where shape enters as one of the parameters; in particular subsection B2) shows and discusses the mean motions of all the systems as a function of their shape.

As additional information, a brief section, C), showing the relationship between intensity and motion and size is also included. To compute the mean motions as a function of the shape of the systems, a rough, first division of the shape factor in the following 5 categories was made: up to 0.35, from 0.36 to 0.69, from 0.70 to 1.39, from 1.40 to 2.80, and over 2.80. This was done so for all the systems at all latitudes and for all the seasons. Section B3) also presents some inconclusive results concerning the behaviour of the systems as tracers as a function of their shape.

Next we describe the characteristics and amount of data that entered into this part of the computations. The correlations computed here are day to day, so that the number of data points that entered in them is larger than that described in Part I. The number of pairs of data points that entered in all the correlations where no division in shape was made were distributed as follows:

Anticyclones

Season	Winter	Spring	Summer	Fall	Total
BELT					
10-20	22	11	7	5	45
20-30	418	257	84	190	949
30-40	724	684	419	712	2539
40-50	632	505	649	665	2451
50-60	430	409	390	298	1527
60-70	397	244	182	301	1124
70-90	250	373	403	244	1270
Total	2873	2483	2134	2415	9905

There are not enough pairs of data points in the first latitude belt to produce significant results.

Cyclones

Season	Winter	Spring	Summer	Fall	Total
BELT					
10-20	224	249	285	307	1065
20-30	327	510	717	334	1888
30-40	881	759	567	530	2737
40-50	1200	1093	775	868	3936
50-60	1122	1118	1071	1067	4378
60-70	591	706	812	614	2723
70-90	523	424	444	484	1875
Total	4868	4359	4671	3304	16.642

The characteristics of the distribution of data points have remained very much like that of the distribution of systems entering in the statistics of Part I.

B1) i) Relationship between shape and size

There is a significant positive correlation between shape and size for all the systems. In particular, up to 50° of latitude for the anticyclones this is definitely so, and seems to be the case again in the belt near the pole. The situation is rather diffuse in between, but in any case if not significant, most of the correla-

tions are positive and significant. This coincides with the general ideas that bigger anticyclones tend to be more longitudinally elongated.

The following table show the correlations obtained as a function of latitude and of the seasons, and for the whole 4 years between shape and size for the high pressure systems. The asterisks denote those correlations which are significant at or below the 5% significance level.

Season	Winter	Spring	Summer	Fall	Total
BELT					
20-30	0.37*	0.36*	0.07	0.55*	0.40*
30-40	0.32*	0.25*	0.17*	0.23*	0.25*
40-50	0.13*	0.02	0.04*	0.11*	0.08*
50-60	0.03	0.10*	0.02	0.08*	0.04
60-70	-0.07	0.02	0.04	0.09	0.01
70-90	0.26*	0.19*	0.16*	0.10	0.18*

As it can be seen from the table there are more significant correlations than one would expect to find by chance. Up to 50 degrees of latitude, even when not too high, the correlations seem to indicate a relationship between size and shape: being positive it implies that bigger anticyclones are more longitudinally elongated

than the smaller ones. North of 70° of latitude this is also true. In the belt between 50 and 70° of latitude, the results are not conclusive: the correlation coefficients are very low.

Ward (1966) found the same kind of relationship that we have found here in overall bases: the most longitudinally elongated sun spots, the streamers, are also the biggest of all the sunspots. But his results are better defined; but then he had 10 years of sunspots data.

The following table shows the values of the correlation coefficients as found for the cyclones for each latitude belt and season and for the 4 years. Five percent of confidence level is indicated by an asterisk.

Season	Winter	Spring	Summer	Fall	Total
BELT					
10-20	0.24*	0.20*	0.25*	0.38*	0.28*
20-30	-0.02	0.29*	0.27*	0.09	0.22*
30-40	-0.05	0.09*	0.27*	-0.09	0.10*
40-50	-0.08*	-0.04	0.00	-0.03	-0.05
50-60	-0.04	0.01	-0.01	-0.01	-0.01
60-70	-0.02	-0.06	-0.02	0.05	-0.01
70-90	0.09	0.07	0.03	0.04	0.07

In the case of the cyclones, a relationship between shape and size seems to be well defined only at low latitudes, with the exception of the winter season in the 20 to 30° of latitude belt. There are not as many significant correlations in this case as there was in the case of the anticyclones. Between 40 and 70° of latitude, practically all correlations are negative but the individual correlations are not significant.

Macdonald (1967) found a definite relationship between the size and motion of the cyclones and anticyclones; the smaller systems move more rapidly toward the east than the bigger ones. Since in particular, the anticyclones seem to have a positive correlation between size and shape, a reflection of the motion-size relationship would appear making the systems with a lower shape number move faster toward the east. But this effect, if at all present, is overcompensated by the shape - motion relationship as we shall later see. Nothing can be said for the cyclones north of 40° of latitude except that small negative correlations are plentiful. South of that latitude, the situation is the same as for the anticyclones.

B1) ii) Relationship between shape and intensity

In this case, again the results concerning the anticyclones are slightly more significant than those referring to the cyclones. On the average, the high pressure systems seem to have a positive correlation between shape and central pressure. Since a higher shape number means a more longitudinally elongated system, this would indicate that those systems are more intense than latitudinally elongated systems. Since for the cyclones, a more intense system means a lower central pressure, the same type of conclusion would be b rought up by mostly negative correlations. But the results for the cyclones are not conclusive.

The following 2 tables show the values of the correlation coefficient as computed for anticyclones and cyclones as a function of latitude for the four seasons and the four years. An asterisk denotes that correlation is significant at or below the 5% significance level.

Anticyclones

Season BELT	Winter	Spring	Summer	Fall	Total
20-30	0.13*	0.32*	0.28*	0.16	0.23*
30-40	0.10*	0.19*	0.30*	0.14*	0.14*
40-50	0.24*	-0.17*	0.04	0.17*	0.10*
50-60	0.02	-0.01	0.04	0.06	0.01

60-70	-0.07	-0.02	0.03	0.14*	0.08*
70-90	0.17*	0.15*	0.14*	0.21*	0.13*

Cyclones

Season	Winter	Spring	Summer	Fall	Total
BELT					
10-20	-0.24*	-0.06	0.05	0.01	-0.07
20-30	0.04	-0.20*	-0.10*	-0.02	-0.11*
30-40	0.03	-0,03	-0.00	0.13*	0.03
40-50	-0.01	0.01	0.04	0.09*	0.04
50-60	0.04	-0.02	-0.02	-0.02	-0.01
60-70	0.02	0.04	0.10*	-0.06	0.03
70-90	-0.01	-0.11	-0.09*	-0.04*	-0.07

For the anticyclones the table shows that there are more significant results than what one would expect by chance. Up to 40° of latitude the correlations are high enough to establish some dependence of the shape with the intensity of the systems or viceversa. This is again true in the polar region, but it cannot be said to be so in middle latitudes. As it will be seen, just as it is always thought, there is a very strong correlation between size and intensity of the systems; positive in the case of the anticyclones, negative for the cyclones. Since there is a slight positive corre-

lation between the size and shape of the anticyclones, the apparent effect of the intensity on the shape could just be a reflection of the relationship between size and intensity. The effect could be less noticeable in the cyclones, since the relationship between their shape and size is very undefined.

B2) Relationship between shape and motions

Tables 1 (A to E) show the mean meridional ($\Delta\Theta$) and latitudinal ($\Delta\lambda$) components of the displacement of the anticyclones computed for the entire period and for each 3 months season from the four years of data. The systems are divided into the 5 shape categories as described in section A). Tables 3 (A to E) show the same means computed for the cyclones over the four year sample.

Because of the small number of systems that fell into the 2 extreme categories of the original shape division (up to 0.35 and larger than 2.80), the systems were divided again into only 3 shape categories. They were: up to 0.70, 0.70 to 1.40, and larger than 1.40. They roughly include the latitudinally elongated systems, the almost symmetrical systems and the longitudinally elongated systems respectively. The mean meridional and latitudinal motions of each of these groups were computed. The results are shown in tables 2 (A to E) and 4 (A to E). The characteristics of the motions remain essentially the same in both cases, but are somewhat more ordered in the later case. They are to be described next.

Anticyclones

Table 1.A shows that over the 4 years average the equa-

torwards component of the displacement of the anticyclones decreases in magnitude, as the shape number increases, at all latitudes north of 20 degrees, but it is least pronounced between 50 and 60 degrees of latitude. The same is generally true for all seasons although the effect is least noticeable in the higher middle latitudes. In 13 instances out of the 16 possible, the mean meridional motion decreases as the shape parameter increases as shown in Table 1.A. The probability of obtaining 13 or more decreases out of 16 cases by chance is 0.02. A similar calculation of the probability of observing as many instances of ($\Delta\theta$) decreasing as the shape parameter increases over the seasons is below the 5% confidence level in all of them except the Autumn. The probability of observing the distribution by chance is denoted in each table by P.

Table 1.A

Mean motion of the anticyclones belonging to each of the 5 shape groups for the total sample for each latitude belt, in meters per second. N denotes the number of systems that entered in the average. An asterisk indicates that there were less than 20 systems. A positive value of $\{\Delta\theta\}$ indicates poleward motion; a positive value of $\{\Delta\lambda\}$ indicates eastward motion.

P = 0.02.

Shape:	Up to 0.35	0.35 to 0.70	0.70 to 1.40	1.40 to 2.80	Larger than 2.80
$20\text{-}30^{\circ}$					
$\{\Delta\theta\}$	*	-2.02	-0.81	-0.71	-1.26
$\{\Delta\lambda\}$	*	2.29	4.83	6.13	11.61
N	*	28	372	495	53
$30\text{-}40^{\circ}$					
$\{\Delta\theta\}$	*	-1.84	-2.97	-0.76	-0.63
$\{\Delta\lambda\}$	*	5.44	6.91	6.25	4.90
N	*	77	1195	1071	68
$40\text{-}50^{\circ}$					
$\{\Delta\theta\}$	*	-3.42	-1.96	-0.99	-0.81
$\{\Delta\lambda\}$	*	5.83	6.33	6.72	4.28
N	*	313	1287	805	38
$50\text{-}60^{\circ}$					
$\{\Delta\theta\}$	*	-2.54	-2.62	-1.55	-0.58
$\{\Delta\lambda\}$	*	4.78	5.22	5.08	6.07
N	*	295	746	455	20
$60\text{-}70^{\circ}$					
$\{\Delta\theta\}$	*	-2.70	-2.12	-1.07	*
$\{\Delta\lambda\}$	*	3.55	3.48	4.24	*
N	*	225	545	329	*

Table 1.A continued

$70\text{-}90^{o}$					
$\{\Delta\theta\}$	0.65	-0.94	-0.24	-0.08	*
$\{\Delta\lambda\}$	0.46	0.88	1.48	2.04	*
N	28	382	535	309	*

Table 1.B

Mean motion of the anticyclones belonging to each of the 5 shape groups for the 4 winter seasons for each latitude belt, in meters per second. N denotes the number of systems that entered in the average. An asterisk indicates that there were less than 20 systems. A positive value of $\{\Delta\theta\}$ indicates poleward motion; a positive value of $\{\Delta\lambda\}$ indicates eastward motion.

P = 0.02

Shape:	Up to 0.35	0.35 to 0.70	0.70 to 1.40	1.40 to 2.80	Larger than 2.80
20-30°					
$\{\Delta\theta\}$	*	*	-0.54	-0.52	-1.16
$\{\Delta\lambda\}$	*	*	5.74	7.66	8.51
N	*	*	153	227	30
30-40°					
$\{\Delta\theta\}$	*	-2.40	-1.48	-0.36	*
$\{\Delta\lambda\}$	*	6.86	8.17	6.87	*
N	*	77	349	282	*
40-50°					
$\{\Delta\theta\}$	*	-4.94	-1.68	-0.83	*
$\{\Delta\lambda\}$	*	5.06	5.47	5.14	*
N	*	85	298	226	*

Table 1.B continued

50-60°					
$\{\Delta\theta\}$	*	-2.40	-3.37	-1.88	*
$\{\Delta\lambda\}$	*	4.17	5.32	4.22	*
N	*	84	186	148	*
60-70°					
$\{\Delta\theta\}$	*	-2.54	-1.72	-0.86	*
$\{\Delta\lambda\}$	*	3.14	3.43	3.67	*
N	*	65	178	140	*
70-90°					
$\{\Delta\theta\}$	*	-2.26	-0.44	-0.04	*
$\{\Delta\lambda\}$	*	0.81	1.09	1.63	*
N	*	80	105	57	*

Table 1. C

Mean motion of the anticyclones belonging to each of the 5 shape groups for the 4 spring seasons for each latitude belt, in meters per second. N denotes the number of systems that entered in the average. An asterisk indicates that there were less than 20 systems. A positive value of $\{\Delta\theta\}$ indicates poleward motion, a positive value of $\{\Delta\lambda\}$ indicates eastward motion. P = 0.02

Shape:	Up to 0.35	0.35 to 0.70	0.70 to 1.40	1.40 to 2.80	Larger than 2.80
20-30°					
$\{\Delta\theta\}$	*	*	-0.99	-0.34	*
$\{\Delta\lambda\}$	*	*	3.93	4.89	*
N	*	*	104	132	*
30-40°					
$\{\Delta\theta\}$	*	-1.21	-1.10	-0.76	-0.75
$\{\Delta\lambda\}$	*	3.77	6.23	6.17	3.10
N	*	48	312	297	26
40-50°					
$\{\Delta\theta\}$	*	-2.50	-2.15	-1.03	*
$\{\Delta\lambda\}$	*	6.72	6.59	7.58	*
N	*	67	279	153	*

Table 1.C continued

50-60°					
$\{\Delta\theta\}$	*	-2.41	-2.72	-1.04	*
$\{\Delta\lambda\}$	*	5.05	4.75	4.13	*
N	*	72	210	123	*
60-70°					
$\{\Delta\theta\}$	*	-2.33	-3.07	-1.29	*
$\{\Delta\lambda\}$	*	3.73	4.28	5.25	*
N	*	64	133	46	*
70-90°					
$\{\Delta\theta\}$	*	-0.64	-0.23	0.18	*
$\{\Delta\lambda\}$	*	0.76	1.57	2.24	*
N	*	109	155	99	*

Table 1. D

Mean motion of the anticyclones belonging to each of the 5 shape groups for the 4 summer seasons for each latitude belt, in meter per second. N denotes the number of systems that entered in the average. An asterisk indicates that there were less than 20 systems. A positive value of $\{\Delta\theta\}$ indicates poleward motion; a positive value of $\{\Delta\lambda\}$ indicates eastward motion. P = 0.02.

Shape:	Up to 0.35	0.35 to 0.70	0.70 to 1.40	1.40 to 2.80	Larger than 2.80
20-30°					
$\{\Delta\theta\}$	*	*	-0.71	-0.34	*
$\{\Delta\lambda\}$	*	*	0.00	4.88	*
N	*	*	40	34	*
30-40°					
$\{\Delta\theta\}$	*	-0.59	-0.58	-0.64	*
$\{\Delta\lambda\}$	*	0.33	4.63	3.74	*
N	*	26	185	200	*
40-50°					
$\{\Delta\theta\}$	*	-3.56	-1.70	-0.76	*
$\{\Delta\lambda\}$	*	5.92	5.93	8.19	*
N	*	68	355	219	*

Table 1.D continued

50-60°					
$\{\Delta\theta\}$	*	-2.10	-1.72	-1.43	*
$\{\Delta\lambda\}$	*	4.63	5.16	0.54	*
N	*	81	192	108	*
60-70°					
$\{\Delta\theta\}$	*	-3.95	-2.18	-1.21	*
$\{\Delta\lambda\}$	*	3.21	3.20	5.60	*
N	*	53	74	51	*
70-90°					
$\{\Delta\theta\}$	*	-0.28	-0.33	-0.57	*
$\{\Delta\lambda\}$	*	1.25	1.75	2.65	*
N	*	116	164	110	*

Table 1.E

Mean motion of the anticyclones belonging to each of the 5 shape groups for the 4 autumn seasons for each latitude belt, in meters per second. N denotes the number of systems that entered in the average. An asterisk indicates that there were less than 20 systems. A positive value of $\{\Delta\theta\}$ indicates poleward motion; a positive value of $\{\Delta\lambda\}$ indicates eastward motion. P=0.11

Shape:	Up to 0.35	0.35 to 0.70	0.70 to 1.40	1.40 to 2.80	Larger than 2.80
20-30°					
$\{\Delta\theta\}$	*	*	-1.15	-1.38	*
$\{\Delta\lambda\}$	*	*	6.83	5.97	*
N	*	*	75	102	*
30-40°					
$\{\Delta\theta\}$	*	-2.27	-1.08	-1.21	*
$\{\Delta\lambda\}$	*	7.57	7.47	7.46	*
N	*	49	349	292	*
40-50°					
$\{\Delta\theta\}$	*	-2.58	-2.28	-1.09	*
$\{\Delta\lambda\}$	*	5.83	7.31	6.22	*
N	*	93	355	207	*

Table 1. E continued

50-60°					
$\{\Delta\theta\}$	*	-3.51	-2.71	-1.90	*
$\{\Delta\lambda\}$	*	5.55	5.80	4.29	*
N	*	58	158	76	*
60-70°					
$\{\Delta\theta\}$	*	-1.95	-1.74	-1.19	*
$\{\Delta\lambda\}$	*	4.35	3.00	3.86	*
N	*	43	160	92	*
70-90°					
$\{\Delta\theta\}$	*	-0.97	0.04	-0.45	*
$\{\Delta\lambda\}$	*	0.60	1.11	0.56	*
N	*	77	111	43	*

The probability that these decreases associated with an increase in the latitudinal component of the shape parameter would occur by chance is higher when the shapes are placed in 3 shape categories as it can be seen in Tables 2A-2E.

Table 2. A

Mean motion of all the anticyclones belonging to each of the three shape groups for the total sample for each latitude belt, in meters per second. N denotes the number of systems that entered in the average. A positive value of $\{\Delta\theta\}$ indicates poleward motion; a positive value of $\{\Delta\lambda\}$ indicates eastward motion. P=0.03

Shape:	Up to 0.70	0.70 to 1.40	Larger than 1.40
$20\text{-}30^{o}$			
$\{\Delta\theta\}$	-2.21	-0.81	-0.76
$\{\Delta\lambda\}$	2.22	4.84	6.06
N	29	371	549
$30\text{-}40^{o}$			
$\{\Delta\theta\}$	-1.77	-1.13	-0.76
$\{\Delta\lambda\}$	5.54	6.91	6.16
N	203	1191	1145

Table 2.A continued

40-50°			
$\{\Delta\theta\}$	-3.33	-1.98	-0.98
$\{\Delta\lambda\}$	5.73	6.37	6.72
N	314	1288	849
50-60°			
$\{\Delta\theta\}$	-2.53	-2.62	-1.48
$\{\Delta\lambda\}$	4.81	5.19	5.14
N	304	741	482
60-70°			
$\{\Delta\theta\}$	-2.66	-2.12	-1.04
$\{\Delta\lambda\}$	3.60	3.52	4.28
N	231	541	352
70-90°			
$\{\Delta\theta\}$	-0.77	-0.31	-0.17
$\{\Delta\lambda\}$	0.80	1.52	2.07
N	404	539	327

Table 2.B

Mean motion of the anticyclones belonging to each of the 3 shape groups for the 4 winter seasons for each latitude belt, in meter per second. N denotes the number of systems that entered in the average. An asterisk indicates that there were less than 20 systems. A positive value of $\{\Delta\theta\}$ indicates poleward motion, a positive value of $\{\Delta\lambda\}$ indicates eastward motion. P = 0.49.

Shape:	Up to 0.70	0.70 to 1.40	Larger than 1.40
20-30°			
$\{\Delta\theta\}$	*	-0.54	-0.59
$\{\Delta\lambda\}$	*	5.74	7.76
N	*	153	257
30-40°			
$\{\Delta\theta\}$	-2.44	-1.49	-0.33
$\{\Delta\lambda\}$	6.79	8.15	0.82
N	78	348	298
40-50°			
$\{\Delta\theta\}$	-5.00	-1.72	-2.60
$\{\Delta\lambda\}$	5.06	5.47	5.29
N	88	296	248

Table 2. B continued

50-60°			
$\{\Delta\theta\}$	-2.38	-3.33	-1.81
$\{\Delta\lambda\}$	4.31	5.34	5.90
N	89	184	157
60-70°			
$\{\Delta\theta\}$	-2.25	-1.83	-0.84
$\{\Delta\lambda\}$	3.20	3.39	3.92
N	68	175	154
70-90°			
$\{\Delta\theta\}$	-1.99	-0.49	0.00
$\{\Delta\lambda\}$	0.53	1.45	1.58
N	85	107	58

Table 2. C

Mean motion of the anticyclones belonging to each of the 3 shape groups for the 4 spring seasons for each latitude belt, in meters per second. N denotes the number of systems that entered in the average. An asterisk indicates that there were less than 20 systems. A positive value of $\{\Delta\theta\}$ indicates poleward motion, a positive value of $\{\Delta\lambda\}$ indicates eastward motion. P = 0.15.

Shape:	Up to 0.70	0.70 to 1.40	Larger than 1.40
20-30°			
$\{\Delta\theta\}$	*	-0.99	-0.37
$\{\Delta\lambda\}$	*	3.95	4.52
N	*	103	147
30-40°			
$\{\Delta\theta\}$	-1.29	-1.07	-0.78
$\{\Delta\lambda\}$	3.78	.23	5.91
N	49	310	325
40-50°			
$\{\Delta\theta\}$	-2.48	-2.16	-1.04
$\{\Delta\lambda\}$	6.69	6.61	7.63
N	68	277	160

Table 2.C continued

50-60°			
$\{\Delta\theta\}$	-2.53	-2.71	-1.05
$\{\Delta\lambda\}$	4.96	4.75	4.14
N	74	210	125
60-70°			
$\{\Delta\theta\}$	-2.17	-3.11	-1.21
$\{\Delta\lambda\}$	3.67	4.27	5.25
N	65	132	47
70-90°			
$\{\Delta\theta\}$	-0.40	-0.28	0.26
$\{\Delta\lambda\}$	0.78	1.63	2.13
N	114	155	104

Table 2. D

Mean motion of the anticyclones belonging to each of the 3 shape groups for the 4 summer seasons for each latitude belt, in meters per second. N denotes the number of systems that entered in the average. An asterisk indicates that there were less than 20 systems. A positive value of $\{\Delta\theta\}$ indicates poleward motion, a positive value of $\{\Delta\lambda\}$ indicates eastward motion. P = 0.49.

Shape:	Up to 0.70	0.70 to 1.40	Larger than 1.40
20-30°			
$\{\Delta\theta\}$	*	-0.71	-1.62
$\{\Delta\lambda\}$	*	0.00	1.33
N	*	40	35
30-40°			
$\{\Delta\theta\}$	-0.59	-0.59	-0.58
$\{\Delta\lambda\}$	0.33	4.65	3.63
N	26	184	209
40-50°			
$\{\Delta\theta\}$	-3.41	-1.75	-0.71
$\{\Delta\lambda\}$	5.71	5.96	8.24
N	65	359	225

Table 2. D continued

50-60°			
$\{\Delta\theta\}$	-2.10	-1.79	-1.26
$\{\Delta\lambda\}$	4.63	5.11	5.77
N	81	188	121
60-70°			
$\{\Delta\theta\}$	-3.88	-2.06	-0.95
$\{\Delta\lambda\}$	3.26	3.32	5.81
N	53	75	54
70-90°			
$\{\Delta\theta\}$	-0.23	-0.35	-0.55
$\{\Delta\lambda\}$	1.13	1.73	2.80
N	121	164	118

Table 2. E

Mean motion of the anticyclones belonging to each of the 3 shape groups for the autumn season for each latitude belt, in meters per second. N denotes the number of systems that entered in the average. An asterisk indicates that there were less than 20 systems. A positive value of $\{\delta\theta\}$ indicates poleward motion, a positive value of $\{\delta\lambda\}$ indicates eastward motion.

P = 0.29

Shape:	Up to 0.70	0.70 to 1.40	Larger than 1.40
20-30°			
$\{\delta\theta\}$	*	-1.14	-1.43
$\{\delta\lambda\}$	*	6.83	5.64
N	*	75	110
30-40°			
$\{\delta\theta\}$	-1.83	-1.08	-1.25
$\{\delta\lambda\}$	8.03	7.46	7.48
N	50	349	313
40-50°			
$\{\delta\theta\}$	-2.34	-2.31	-1.03
$\{\delta\lambda\}$	5.70	7.33	6.74
N	93	356	216

Table 2. E continued

50-60°			
$\{\Delta\theta\}$	-3.34	-2.69	-1.84
$\{\Delta\lambda\}$	5.60	5.71	4.19
N	60	159	79
60-70°			
$\{\Delta\theta\}$	-2.57	-1.66	-1.32
$\{\Delta\lambda\}$	4.50	3.14	3.51
N	45	159	97
70-90°			
$\{\Delta\theta\}$	-0.82	-0.13	-0.33
$\{\Delta\lambda\}$	0.62	1.12	0.68
N	84	113	47

Table 3 shows the correlations between shape and latitudinal displacement of the anticyclones for each season and for the four years average, for each latitude belt. An asterisk indicates those correlations which are significant at or below the 5% confidence level. In addition, those correlations whose sign coincide with the sense of the dependence on the shape found from the mean motions, are underlined once. Of the rest, those whose sign coincides with the general tendency of the motion have been underlined twice. That is, those are the cases in which the correlation is positive and the mean meridional motions show that the systems with the lowest shape number move slower across the paralells than those with the highest shape number; or the correlation is negative and the mean motions show that the systems with the lowest shape number move faster than those with the highest shape number. In the rest of the cases, (not underlined) the sign of the correlation and that expected from the mean motion does not agree.

Table 3

Season Belt	Winter	Spring	Summer	Autumn	Total
20-30	0.01	-0.01	-0.05	-0.07	-0.01
30-40	0.11*	0.03	0.02	0.02	0.05*
40-50	0.14*	0.10*	0.19*	0.07	0.12*
50-60	0.08	0.12*	0.10	0.06	0.09*
60-70	0.07	0.05	0.15	0.07	0.09*
70-90	0.12	0.01	-0.04	0.03	0.02

Because of the overall preponderance of positive correlations, even when just part of them are significant; and the agreement of the correlations with the tendency of the overall mean motions, when not in total agreement with each of them, seems to be enough indication that the more the systems depart from a longitudinal elongation, the faster they move on the average, across the paralells toward the equator.

Next we describe the characteristics of the zonal motions of the anticyclones. In the 4 year average, the eastward component of the velocity of the anticyclones between 20 and 30; 40 and 50; and 70 and 90 degrees of latitude, increases in mag-

nitude with the shape number. This is less noticeable elsewhere. The same is true for the individual seasons, except for the autumn, which shows the least noticeable increase in middle latitudes. If the same test that was used in the meridional component of the velocity is applied to this case, it is found that these results are not significant. The probability that we would get such apparent dependence by chance is rather high. P = 0.10.

Table 4 shows the correlations between shape and longitudinal displacement of the anticyclones for each season and for the four years, for each latitude belt. Again an asterisk indicates those correlations that are significant at or below the 5 percent significance level. The meaning of the underlines remains the same as that in the preceding case.

Table 4

Season Belt	Winter	Spring	Summer	Autumn	Total
20-30	0.11*	-0.04	0.02	-0.07	0.06
30-40	-0.04	-0.02	0.04	0.02	-0.01
40-50	0.00	0.08	0.13	-0.03	0.03
50-60	0.11*	-0.06	0.02	-0.09	0.01
60-70	0.09*	0.04	0.23	-0.05	0.06
70-90	0.10	0.11	0.15*	0.05	0.12*

We notice that there is agreement between correlations and mean motions in the case of positive correlations (faster eastwards moving anticyclones are more longitudinally elongated), as well as in the case of negative correlations. Except perhaps for the summer season in which mean motions and correlations support each other's results, and the correlations are all of one sign, it is not possible to conclude any possible dependence between shape and zonal motions in the anticyclones: there are too few positive or negative correlations supported by the corresponding mean motions. But then, in the summer season most of the correlations that would indicate a larger eastward com-

ponent of the velocity with shape number are not significant. At least if there is a relationship, it is not nearly as significant as the case for the latitudinal displacement.

Cyclones

If we look at the mean meridional motions of the cyclones, we find from Tables 5. A that in the 4 year average there is only a systematic behavior of the systems motions with respect to their shape in the 10 to 20 and in the 60 to 70 degrees of latitude belt. In the rest of the table, some of the more latitudinally elongated systems seem to have a larger meridional component on the average than those longitudinally elongated, but at times more symmetrical systems seem to move even faster.
During the 4 seasons, as it can be seen from Tables 5B- 5E, there are about as many cases in which more latitudinally elongated systems have a larger meridional velocity component of the velocity as cases in which more longitudinally elongated systems do.

Table 5.A

Mean motion of all the cyclones belonging to each of the 5 shape groups for the total sample, for each of the latitude belts in meters per second. N denotes the number of systems that entered in the average. An asterisk indicates that there were less than 20 systems. A positive value of {00} indicates poleward motion, a positive value of {01} indicates eastward motion.

P = 0.02

Shape:	Up to 0.35	0.35 to 0.70	0.70 to 1.40	1.40 to 2.80	Larger than 2.80
10-20°					
{00}	*	0.63	0.79	0.90	*
{01}	*	0.27	-0.92	-0.26	*
N	*	120	774	164	*
20-30°					
{00}	*	0.37	0.76	0.10	1.88
{01}	*	1.02	0.77	1.26	-1.71
N	*	268	1160	418	24
30-40°					
{00}	*	1.43	1.88	1.55	0.88
{01}	*	4.81	6.96	8.03	5.66
N	*	329	1698	641	50

40-50°					
$\{\Delta\theta\}$	*	2.32	2.77	2.03	-0.19
$\{\Delta\lambda\}$	*	7.02	7.48	8.25	9.55
N	*	437	2824	646	20
50-60°					
$\{\Delta\theta\}$	*	2.08	2.55	1.25	*
$\{\Delta\lambda\}$	*	5.23	5.71	6.44	*
N	*	500	3207	651	*
60-70°					
$\{\Delta\theta\}$	*	2.36	1.95	1.23	*
$\{\Delta\lambda\}$	*	4.67	5.10	6.31	*
N	*	376	1804	513	*
70-90°					
$\{\Delta\theta\}$	*	1.43	1.43	1.52	*
$\{\Delta\lambda\}$	*	1.90	2.29	2.81	*
N	*	241	1280	342	*

Table 5.B

Mean motion of all the cyclones belonging to each of the 5 shape groups for the 4 winter seasons for each latitude belt in meters per second. N denotes the number of systems that entered in the average. An asterisk indicates that there were less than 20 systems. A positive value of $\{\Delta\theta\}$ indicates poleward motion; a positive value of $\{\Delta\lambda\}$ indicates eastward motion.

P = 0.001

Shape:	Up to 0.35	0.35 to 0.70	0.70 to 1.40	1.40 to 2.80	Larger than 2.80
10-20°					
$\{\Delta\theta\}$	*	0.62	0.00	-0.27	*
$\{\Delta\lambda\}$	*	0.24	0.86	1.41	*
N	*	64	130	29	*
20-30°					
$\{\Delta\theta\}$	*	0.21	-0.41	0.40	*
$\{\Delta\lambda\}$	*	2.09	2.41	3.32	*
N	*	78	168	74	*
30-40°					
$\{\Delta\theta\}$	*	1.10	1.86	1.81	*
$\{\Delta\lambda\}$	*	7.20	9.42	9.75	*
N	*	86	573	217	*

Table 5.B continued

40-50°					
$\{\Delta\theta\}$	*	2.13	3.06	4.75	*
$\{\Delta\lambda\}$	*	8.52	7.91	8.36	*
N	*	116	896	183	*
50-60°					
$\{\Delta\theta\}$	*	3.28	2.95	1.51	*
$\{\Delta\lambda\}$	*	5.21	5.45	5.79	*
N	*	146	798	171	*
60-70°					
$\{\Delta\theta\}$	*	4.12	2.50	1.15	*
$\{\Delta\lambda\}$	*	3.29	4.62	6.80	*
N	*	79	387	121	*
70-90°					
$\{\Delta\theta\}$	*	1.91	1.21	1.51	*
$\{\Delta\lambda\}$	*	2.11	2.55	3.23	*
N	*	46	361	112	*

Table 5.C

Mean motion of all the cyclones belonging to each of the 5 shape groups for the 4 spring seasons for each latitude belt in meters per second. N denotes the number of systems that entered in the average. An asterisk indicates that there were less than 20 systems. A positive value of $\{\Delta\theta\}$ indicates poleward motion; a positive value of $\{\Delta\lambda\}$ indicates eastward motion.

P = 0.05

Shape:	Up to 0.35	0.35 to 0.70	0.70 to 1.40	1.40 to 2.80	Larger than 2.80
10-20°					
$\{\Delta\theta\}$	*	*	0.97	0.98	*
$\{\Delta\lambda\}$	*	*	-0.15	-0.17	*
N	*	*	172	58	*
20-30°					
$\{\Delta\theta\}$	*	0.23	0.43	0.76	*
$\{\Delta\lambda\}$	*	0.74	1.33	2.21	*
N	*	76	320	105	*
30-40°					
$\{\Delta\theta\}$	*	1.56	1.61	1.66	*
$\{\Delta\lambda\}$	*	3.72	6.07	7.83	*
N	*	109	457	171	*

Table 5.C continued

40-50°					
$\{\Delta\theta\}$	*	1.97	2.46	2.13	*
$\{\Delta\lambda\}$	*	5.93	6.81	7.99	*
N	*	133	776	177	*
50-60°					
$\{\Delta\theta\}$	*	1.88	2.23	1.28	*
$\{\Delta\lambda\}$	*	4.99	5.42	6.73	*
N	*	117	846	150	*
60-70°					
$\{\Delta\theta\}$	*	2.93	2.31	0.62	*
$\{\Delta\lambda\}$	*	4.60	5.78	5.76	*
N	*	104	459	130	*
70-90°					
$\{\Delta\theta\}$	*	1.38	1.72	1.56	*
$\{\Delta\lambda\}$	*	2.36	1.49	2.05	*
N	*	57	301	66	*

Table 5. D

Mean motion of all the cyclones belonging to each of the five shape groups for the 4 summer seasons for each latitude belt in meters per second. N denotes the number of systems that entered in the average. An asterisk indicates that there were less than 20 systems. A positive value of $\{\Delta\theta\}$ indicates poleward motion; a positive value of $\{\Delta\lambda\}$ indicates eastward motion.

P = 0.05

Shape:	Up to 0.35	0.35 to 0.70	0.70 to 1.40	1.40 to 2.80	Larger than 2.80
10-20°					
$\{\Delta\theta\}$	*	*	1.12	2.11	*
$\{\Delta\lambda\}$	*	*	-2.52	-2.52	*
N	*	*	239	31	*
20-30°					
$\{\Delta\theta\}$	*	-0.19	1.34	-0.33	*
$\{\Delta\lambda\}$	*	-0.14	-0.70	-0.27	*
N	*	66	432	196	*
30-40°					
$\{\Delta\theta\}$	*	0.41	1.77	0.64	1.07
$\{\Delta\lambda\}$	*	1.81	3.15	4.74	15.71
N	*	66	308	162	23

Table 5. D continued

40-50°					
$\{\Delta\theta\}$	*	2.40	2.19	1.35	*
$\{\Delta\lambda\}$	*	5.62	6.42	7.33	*
N	*	96	506	164	*
50-60°					
$\{\Delta\theta\}$	*	1.17	2.19	0.73	*
$\{\Delta\lambda\}$	*	4.99	5.50	5.98	*
N	*	141	764	160	*
60-70°					
$\{\Delta\theta\}$	*	0.89	1.34	1.12	*
$\{\Delta\lambda\}$	*	5.09	4.63	6.06	*
N	*	112	522	169	*
70-90°					
$\{\Delta\theta\}$	*	1.57	1.51	2.10	*
$\{\Delta\lambda\}$	*	1.64	2.10	2.83	*
N	*	77	302	65	*

Table 5. E

Mean motion of all the cyclones belonging to each of the five shape groups for the 4 autumn seasons for each latitude belt in meters per second. N denotes the number of systems that entered in the average. An asterisk indicates that there were less than 20 systems. A positive value of $\{\Delta\theta\}$ indicates poleward motion; a positive value of $\{\Delta\lambda\}$ indicates eastward motion. P = 0.03

Shape:	Up to 0.35	0.35 to 0.70	0.70 to 1.40	1.40 to 2.80	Larger than 2.80
10-20°					
$\{\Delta\theta\}$	*	1.06	0.76	0.72	*
$\{\Delta\lambda\}$	*	-0.14	-0.83	0.09	*
N	*	28	233	46	*
20-30°					
$\{\Delta\theta\}$	*	1.66	0.97	0.00	*
$\{\Delta\lambda\}$	*	1.29	1.53	2.36	*
N	*	48	240	43	*
30-40°					
$\{\Delta\theta\}$	*	2.67	2.33	2.36	*
$\{\Delta\lambda\}$	*	6.46	7.44	10.15	*
N	*	68	360	91	*

Table 5. E continued

40-50°					
$\{\Delta\theta\}$	*	2.98	3.19	3.26	*
$\{\Delta\lambda\}$	*	8.15	8.54	9.70	*
N	*	92	646	122	*
50-60°					
$\{\Delta\theta\}$	*	1.81	2.82	1.46	*
$\{\Delta\lambda\}$	*	5.93	6.49	7.30	*
N	*	96	799	170	*
60-70°					
$\{\Delta\theta\}$	*	1.96	1.78	2.36	*
$\{\Delta\lambda\}$	*	5.53	5.40	6.91	*
N	*	81	436	93	*
70-90°					
$\{\Delta\theta\}$	*	0.93	1.37	2.10	*
$\{\Delta\lambda\}$	*	1.64	2.92	2.83	*
N	*	61	322	99	*

Table 6. A

Mean motion of the cyclones belonging to each of the 3 shape groups for the total sample for each latitude belt in meters per second. N denotes the number of systems that entered in the average. An asterisk indicates that there were less than 20 systems. A positive value of $\{\Delta\theta\}$ indicates poleward motion; a positive value of $\{\Delta\lambda\}$ indicates eastward motion. P = 0.006

Shape:	Up to 0.70	0.70 to 1.40	Larger than 1.40
10-20°			
$\{\Delta\theta\}$	0.55	0.78	1.03
$\{\Delta\lambda\}$	0.30	-0.93	-0.19
N	120	772	173
20-30°			
$\{\Delta\theta\}$	0.36	0.75	0.26
$\{\Delta\lambda\}$	0.98	0.74	1.15
N	280	1160	448
30-40°			
$\{\Delta\theta\}$	1.40	1.85	1.52
$\{\Delta\lambda\}$	4.54	6.95	7.88
N	337	1707	693

Table 6.A continued

40-50°			
$\{\Delta\theta\}$	2.31	2.76	1.97
$\{\Delta\lambda\}$	6.92	7.46	8.33
N	439	2819	678
50-60°			
$\{\Delta\theta\}$	2.01	2.57	1.25
$\{\Delta\lambda\}$	5.27	5.69	6.54
N	499	3196	683
60-70°			
$\{\Delta\theta\}$	2.47	1.94	1.17
$\{\Delta\lambda\}$	4.66	5.09	6.79
N	382	1804	537
70-90°			
$\{\Delta\theta\}$	1.36	1.44	1.54
$\{\Delta\lambda\}$	1.93	2.28	2.80
N	236	1286	353

Table 6.B

Mean motion of the cyclones belonging to each of the 3 shape group for the 4 winter seasons for each latitude belt in meters per second. N denotes the number of systems that entered in the average. An asterisk indicates that there were less than 20 systems. A positive value of $\{\Delta\theta\}$ indicates poleward motion; a positive value of $\{\Delta\lambda\}$ indicates eastward motion. P = 0.001

Shape:	Up to 0.70	0.70 to 1.40	Larger than 1.40
10-20°			
$\{\Delta\theta\}$	0.54	-0.01	-0.22
$\{\Delta\lambda\}$	0.25	0.87	1.36
N	65	129	30
20-30°			
$\{\Delta\theta\}$	0.21	-0.42	0.66
$\{\Delta\lambda\}$	2.13	2.28	3.38
N	80	168	79
30-40°			
$\{\Delta\theta\}$	1.14	1.83	1.72
$\{\Delta\lambda\}$	7.03	9.42	9.64
N	84	575	183

Table 6.B continued

40-50°			
$\{\Delta\theta\}$	2.06	3.06	1.59
$\{\Delta\lambda\}$	8.31	7.87	8.52
N	117	891	192
50-60°			
$\{\Delta\theta\}$	3.25	2.94	1.45
$\{\Delta\lambda\}$	5.22	5.39	6.07
N	148	794	180
60-70°			
$\{\Delta\theta\}$	4.31	2.52	1.04
$\{\Delta\lambda\}$	3.23	4.59	6.77
N	80	387	124
70-90°			
$\{\Delta\theta\}$	1.66	1.23	1.65
$\{\Delta\lambda\}$	2.16	2.54	3.13
N	44	363	116

Table 6.C

Mean motion of the cyclones belonging to each of the 3 shape groups for the 4 spring seasons for each latitude belt in meters per second. N denotes the number of systems that entered in the average. An asterisk indicates that there were less than 20 systems. A positive value of $\{\Delta\theta\}$ indicates poleward motion; a positive value of $\{\Delta\lambda\}$ indicates eastward motion.

P = 0.001

Shape:	Up to 0.70	0.70 to 1.40	Larger than 1.40
10-20°			
$\{\Delta\theta\}$	*	0.96	0.94
$\{\Delta\lambda\}$	*	-0.15	-0.06
N	*	172	60
20-30°			
$\{\Delta\theta\}$	0.36	0.37	0.85
$\{\Delta\lambda\}$	0.51	1.33	2.15
N	80	321	109
30-40°			
$\{\Delta\theta\}$	1.47	1.59	1.70
$\{\Delta\lambda\}$	3.48	6.04	7.83
N	117	459	183

Table 6.C continued

40-50°			
$\{\Delta\theta\}$	2.01	2.46	2.12
$\{\Delta\lambda\}$	5.81	6.81	8.04
N	136	776	181
50-60°			
$\{\Delta\theta\}$	1.61	2.25	1.23
$\{\Delta\lambda\}$	5.07	5.40	6.81
N	113	762	157
60-70°			
$\{\Delta\theta\}$	3.03	2.29	0.53
$\{\Delta\lambda\}$	4.71	5.72	5.78
N	108	458	140
70-90°			
$\{\Delta\theta\}$	1.38	1.72	1.49
$\{\Delta\lambda\}$	2.36	1.51	1.93
N	57	300	67

Table 6.D

Mean motion of the cyclones belonging to each of the 3 shape groups for the 4 summer seasons for each latitude belt in meters per second. N denotes the number of systems that entered in the average. An asterisk indicates that there were less than 20 systems. A positive value of $\{\Delta\theta\}$ indicates poleward motion; a positive value of $\{\Delta\lambda\}$ indicates eastward motion.

P = 0.01

Shape:	Up to 0.70	0.70 to 1.40	Larger than 1.40
10-20°			
$\{\Delta\theta\}$	*	1.13	2.49
$\{\Delta\lambda\}$	*	-2.52	-2.16
N	*	240	35
20-30°			
$\{\Delta\theta\}$	-0.27	1.35	-0.17
$\{\Delta\lambda\}$	-0.01	-0.70	0.50
N	70	431	216
30-40°			
$\{\Delta\theta\}$	0.09	1.79	0.69
$\{\Delta\lambda\}$	1.56	3.17	4.25
N	70	311	186

Table 6.D continued

40-50°			
$\{\Delta\theta\}$	2.52	2.16	1.40
$\{\Delta\lambda\}$	5.55	6.42	7.44
N	96	505	174
50-60°			
$\{\Delta\theta\}$	1.16	2.19	0.72
$\{\Delta\lambda\}$	5.03	5.49	5.93
N	142	762	167
60-70°			
$\{\Delta\theta\}$	0.87	1.34	1.17
$\{\Delta\lambda\}$	5.08	4.64	5.92
N	112	521	179
70-90°			
$\{\Delta\theta\}$	1.49	1.53	2.07
$\{\Delta\lambda\}$	1.79	2.06	2.87
N	75	303	66

Table 6. E

Mean motion of all the cyclones belonging to each of the 3 shape groups for the autumn season for each latitude belt in meters per second. N denotes the number of systems that entered in the average. An asterisk indicates that there were less than 20 systems. A positive value of $\{\Delta\theta\}$ indicates poleward motion; a positive value of $\{\Delta\lambda\}$ indicates eastward motion

P = 0.001

Shape:	Up to 0.70	0.70 to 1.40	Larger than 1.40
10-20°			
$\{\Delta\theta\}$	1.05	0.73	0.82
$\{\Delta\lambda\}$	-0.14	-0.84	0.12
N	28	231	48
20-30°			
$\{\Delta\theta\}$	1.52	0.96	0.09
$\{\Delta\lambda\}$	1.29	1.46	2.71
N	50	240	44
30-40°			
$\{\Delta\theta\}$	2.96	2.28	2.26
$\{\Delta\lambda\}$	6.39	7.44	10.76
N	66	362	102

Table 6. E continued

40-50°			
$\{\Delta\theta\}$	2.88	3.18	3.09
$\{\Delta\lambda\}$	8.24	8.51	9.61
N	90	647	131
50-60°			
$\{\Delta\theta\}$	1.80	2.80	1.54
$\{\Delta\lambda\}$	5.99	6.48	7.34
N	96	792	179
60-70°			
$\{\Delta\theta\}$	2.13	1.79	2.25
$\{\Delta\lambda\}$	5.39	5.40	6.96
N	82	438	94
70-90°			
$\{\Delta\theta\}$	0.94	1.32	1.13
$\{\Delta\lambda\}$	1.54	2.91	2.95
N	60	320	104

Table 7 shows the correlations between the meridional component of the velocity of the cyclones and their shapes. The asterisks and underlines have the same meaning as in the previous cases.

Table 7

Season Belt	Winter	Spring	Summer	Autumn	Total
10-20	-0.02	0.01	0.15*	0.01	0.05
20-30	0.10	0.02	-0.06	-0.09	0.01
30-40	-0.01	0.02	-0.04	0.00	-0.01
40-50	-0.06*	-0.03	-0.07*	-0.02	-0.05*
50-60	-0.10*	-0.07*	-0.06*	-0.04	-0.07*
60-70	-0.11*	-0.14*	-0.03	0.01	-0.07*
70-90	0.03	0.01	-0.01	-0.03	0.00

As it can be seen from the table, there is a great variety of combinations. It is true that most of the significant correlations are supported by the corresponding mean motions, but there are many correlations whose signs and that of the displacement do not agree, and for that reason one is led to the conclusion that there is no relationship between the mean meridional motions of cyclones and their shape.

As for as the zonal average motions of the cyclones are concerned, there is pronounced and directly proportional relationship between those displacements and the shapes of the systems. In the 4 years average, all the cyclones north of 30 degrees of latitude have an average eastward component of their displacement that increases as the shape number increases. These results turn out to be significant as the 5% confidence level when the probabilities are computed as they were in the case of the anticyclones. The probability that the number of observed increases in ($\Delta\lambda$) as the shape increases were due to chance, is given by P in each set of data (Tables 5A - 5E, and 6A - 6E). The results obtained for the winter season are the most significant. On almost all latitudes, the average zonal motion increases substantially as the shape categories increases. The results are very noticeable also in the other 3 seasons with confidence levels ranging between 1 and 5% except in the spring season.

Table 8 shows the correlations between the zonal component of the velocity and the shape of the cyclones for all the seasons and the four years average for each latitude belt. Again the underlines and asterisks have the same meaning as in the 3 previous cases.

Table 8

Season Belt	Winter	Spring	Summer	Autumn	Total
10-20	0.09	-0.02	0.05	0.05	0.02
20-30	-0.02	0.07	-0.03	0.05	-0.02
30-40	0.04	0.18*	0.07*	0.24*	0.09*
40-50	0.01	0.13*	0.12*	0.08	0.07*
50-60	0.06	0.06	0.05	0.02	0.05*
60-70	0.18*	0.06	0.09	0.08	0.10*
70-90	0.03	0.02	0.04	0.07	0.05*

Due to the quite good agreement between the signs of the correlations, mostly positives indicating one particular dependence, and those tendencies given by the mean motions, specially north of 30 degrees of latitude, it seems reasonable to conclude that the more the systems depart from a latitudinal elongation the faster they move on the average, across the meridians toward the east.

Hence, we may conclude that the anticyclones have a larger average meridional motion the more they are latitudinally elongated, while the cyclones move faster toward the east, the more they are longitudinally elongated.

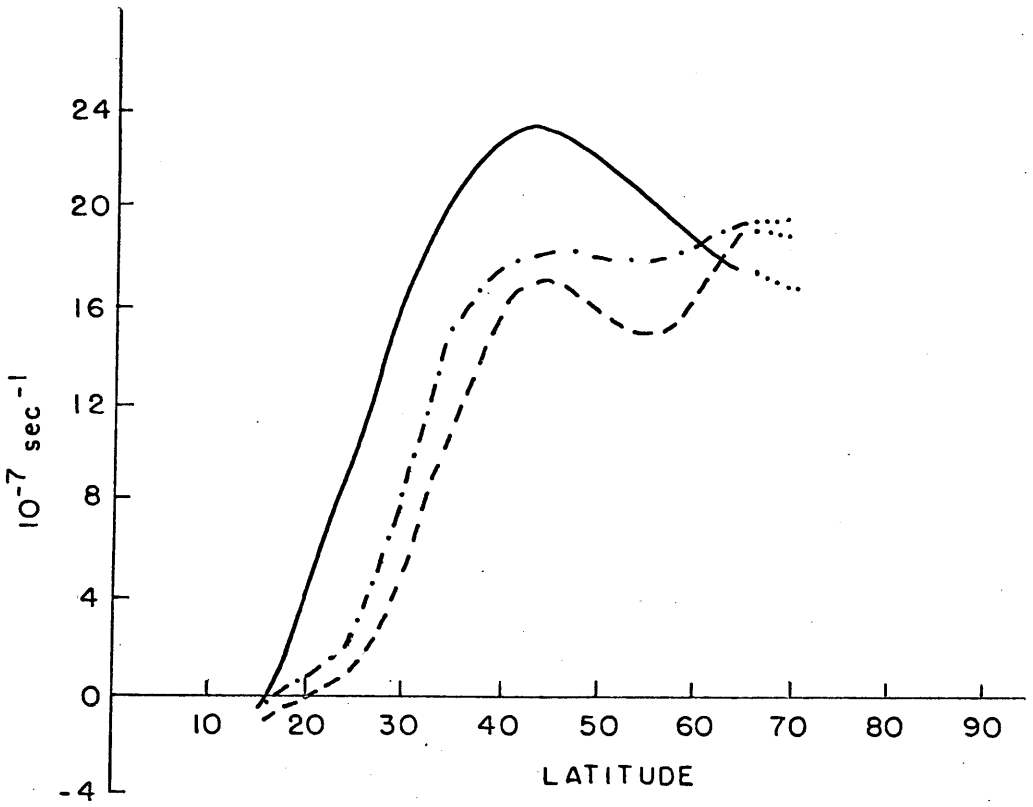
If these differences on the velocity of the systems depending on their shape number were just a reflexion of the size influence in the motion, we should expect a priori, a definite negative correlation between the size and the shape of the systems, but we have seen that this is not so. The other possibility would be that the differences are due to a reflexion of the size dependence through the intensity parameter; but if this were so, it would act on the opposite direction on the anticyclones since intensity and shape are positively correlated in them, and so is intensity and size. For the cyclones such a dependence would not be possible since intensity and shape are practically not correlated in any definite form as we have seen. Hence, we must conclude that the shape factor by itself determines differences in the way in which the systems behave.

B3) i) Estimating the zonal component of the terrestrial wind field

In his paper that described the results of attempts to estimate the zonal wind component of the terrestrial wind field and the meridional flux of relative angular momentum from easily identifiable features, Macdonald (1969), found that the zonal displacement of the small cyclones more closely approximates the directly measured vertically averaged zonal wind field of the earth's atmosphere than any other feature tested. This estimation is specially good at middle latitudes. In all the cases, yearly and seasonal averages, the cyclones move with an angular (or linear) velocity that is somewhat smaller than that of the measured winds. A comparison of the meridional profile of the angular velocity of the longitudinally elongated cyclones, found in our four years of data, with the average velocity obtained by the displacement of small systems found over a period of 5 years* seems to indicate that the former are even better tracers of the mean zonal wind field as shown is Figure 6.A. The shape of the estimated meridional profiles remains very much alike. The values computed from the longitudinally elongated cyclones

*4 years overlap

Figure 6. A



The latitudinal distribution of the directly measured vertically averaged angular velocity $\{u\}/R\cos\varphi$ for a period of 5 years: —; compared to the angular velocity estimates made from, 1) the average of the daily displacement of small cyclones: — — —, for the same period of time (after Macdonald, 1969); and 2) from the average of the daily displacement of the longitudinally elongated cyclones for 4 years of that period: —·—·—

are systematically higher than those provided by the small cyclones. However, no conclusions can be definite due to the fact that one of the estimations lacks the data of one of the year's actual measurements. We expect that if the more longitudinally elongated small cyclones are taken and their average zonal velocity is computed as a function of latitude, they will turn out to be the best tracers. A study of that effect is underway.

ii) Estimating the eddy flux of angular momentum

As described by Starr (1968), the instantaneous eddy flux of angular momentum accros a latitude φ , at one level, per unit of mass, can be measured by the quantity $[u' v']2\pi R^2 \cos^2\varphi$, where the primes denote deaperture from the mean [ ]; and R is the mean radius of the earth.

Macdonald (1969) found that a reasonable estimation of that transport can be obtained from easily identifiable features in the terrestrial atmosphere from calculating the quantity $[\Delta\lambda' \Delta\theta']2\pi R^2 \cos^2\varphi$ where $[\Delta\lambda' \Delta\theta']$ denotes the covariance of the longitudinal and latitudinal displacement of cyclones and/or anticyclones. It was found that the best estimates were made when small cyclones were used only. We computed the covariances of the longitudinal and latitudinal displacements of cyclones and anticyclones for the

Table 9.A

The correlation coefficient (r) and the covariance (cov.) between the meridional and latitudinal displacement of the anticyclones as a function of the 5 shape groups for each latitude belt for the four years of data; as compared with the correlation coefficient and the covariance of the u and v components of the terrestrial wind field for five years of data which contain our four, after Macdonald (1969). An asterisk indicates those correlations that are significant at or below the 5 % significance level.

BELT	10-20	20-30	30-40	40-50	50-60	60-70	70-90
Directly measured winds							
	0.045	0.053*	0.062*	0.034*	-0.006	-0.017*	-0.009
	5.12	11.26	12.69	6.72	-1.74	-5.42	-3.61
Shape parameter: up to 0.35							
	——	——	0.87	-0.07	-0.41	-0.21	0.06
	——	——	12.59	-1.64	-13.46	-8.54	2.01

Shape parameter: from 0.35 to 0.70

—	0.16	-0.01	0.03	-0.11*	-0.01	-0.15*
—	3.68	-0.32	0.99	-4.09	-0.54	-9.74

Shape parameter: from 0.70 to 1.40

—	0.02	0.06*	0.04*	-0.06*	0.10*	0.06*
	0.49	2.09	1.54	-2.55	5.54	5.93

Shape parameter from 1.40 to 2.80

—	0.11*	0.06*	0.06*	0.09*	0.11*	0.09*
—	2.47	1.83	2.26	7.22	7.19	8.88

Shape parameter: larger than 2.80

—	0.14	-0.00	0.13	-0.10	0.19	0.59*
—	2.48	-0.00	3.45	-4.06	9.24	36.57

Table 9.B

The correlation coefficient (r) and the covariance (cov.) between the meridional and latitudinal displacement of the cyclones as a function of the 5 shape groups for each latitude belt for the four years of data; as compared with the correlation coefficient and the covariance of the u and v components of the terrestrial wind field for five years of data which contain our four, after Macdonald (1969). An asterisk indicates those correlations which are significant at or below the 5 % significance level.

BELT	10-20	20-30	30-40	40-50	50-60	60-70	70-90
Directly measured winds							
	0.045	0.053*	0.062*	0.034*	-0.006	-0.017*	-0.009
	5.12	11.26	12.69	6.72	-1.74	-5.42	-3.61
Shape parameter: up to 0.35							
	—	-0.74*	0.13	0.13	—	-0.03*	—
	—	-6.19	1.22	1.94	—	-1.49	—

Shape parameter: from 0.35 to 0.70

0.17*	-0.02	0.13	0.00	-0.07*	-0.11*	-0.03
2.38	-0.25	4.18	0.00	-3.07	-6.70	-2.53

Shape parameter: from 0.70 to 1.40

-0.07*	0.09*	0.16*	0.07*	-0.04*	0.00	0.00
-0.92	1.66	5.02	2.59	-1.66	0.00	0.00

Shape parameter: from 1.40 to 2.80

0.08	0.06	0.31*	0.18*	0.07*	0.06	0.13*
1.31	1.30	10.45	6.54	3.02	3.19	10.82

Shape parameter: larger than 2.80

-0.60	-0.31*	0.33*	0.22	0.77*	-0.37	0.27
-15.05	-5.56	10.71	5.27	24.50	-12.05	40.52

five shape categories described earlier, and, as it can be seen from examination of Tables 9.A and 9.B, found no indication of any shape in particular giving a better estimate of the relative angular momentum transport by the eddy process.

C) Relationship between central pressure and size, and motion

The relationship between size and central pressure of the systems is in the sense that anticyclones with the highest central pressure are those of very large size; while the opposite is true with the cyclones. Macdonald (1967) found the same situation in his first study using 2 years of data.

All the correlation coefficients between size and central pressure as a function of latitude and of the seasons found in the following table, are significant at or below the 5 per cent significance level.

Anticyclones

Season	Winter	Spring	Summer	Fall	Total
Belt					
20-30	0.16	0.36	0.07	0.26	0.26
30-40	0.25	0.45	0.40	0.38	0.36
40-50	0.31	0.50	0.47	0.27	0.31
50-60	0.38	0.38	0.39	0.35	0.36
60-70	0.38	0.31	0.38	0.44	0.34
70-90	0.46	0.51	0.39	0.41	0.39

Cyclones

Season	Winter	Spring	Summer	Fall	Total
Belt					
10-20	-0.38	-0.09	-0.24	-0.09	-0.14
20-30	-0.36	-0.36	-0.23	-0.54	-0.33
30-40	-0.41	-0.44	-0.34	-0.54	-0.39
40-50	-0.45	-0.48	-0.47	-0.44	-0.47
50-60	-0.43	-0.51	-0.55	-0.47	-0.47
60-70	-0.30	-0.52	-0.49	-0.39	-0.40
70-90	-0.41	-0.53	-0.47	-0.40	-0.43

As for the relationship between central pressure and the motion of the systems is concerned, the following 4 tables show the correlation coefficients between central pressure and meridional and zonal displacements of the cyclones and anticyclones, for each season, year average and for each latitude belt. An asterisk indicates those correlations which are significant at or below the 5 % significance level.

Anticyclones

Correlation between latitudinal displacement and central pressure

Season	Winter	Spring	Summer	Fall	Total
Belt					
20-30	0.06	-0.01	0.13	-0.02	0.04
30-40	-0.04	0.05	-0.01	-0.08*	-0.03
40-50	-0.02	0.05	0.02	0.00	-0.00
50-60	-0.05	-0.04	-0.10*	-0.08	-0.08*
60-70	-0.06	-0.18*	-0.10	0.04	-0.02
70-90	-0.03	-0.06	-0.04	-0.01	-0.04

Correlation between longitudinal displacement and central pressure

Season	Winter	Spring	Summer	Fall	Total
Belt					
20-30	-0.14*	-0.06	0.05	-0.12	-0.02
30-40	-0.15	-0.04	-0.04	-0.06	-0.01
40-50	-0.21*	-0.09*	-0.05	-0.21*	-0.16*
50-60	-0.22*	-0.10*	-0.04	-0.23*	-0.11*
60-70	-0.04	-0.11	-0.09	-0.13*	-0.10*
70-90	0.12	-0.10*	-0.05	0.07	-0.01

Cyclones

Correlation between longitudinal displacement and central pressure

Season	Winter	Spring	Summer	Fall	Total
Belt					
10-20	0.02	0.08	0.11	0.22*	0.16*
20-30	-0.19*	-0.00	0.15*	-0.09	0.08*
30-40	-0.19*	-0.05*	0.02	-0.09*	-0.13*
40-50	0.07*	-0.04	-0.05	0.01	-0.02
50-60	0.20*	0.07*	-0.02	0.17*	0.11*
60-70	-0.02	-0.10*	-0.15*	-0.10*	-0.09*
70-90	-0.08*	-0.04	-0.14*	-0.12*	-0.11*

Correlation between latitudinal displacement and central pressure

Season	Winter	Spring	Summer	Fall	Total
Belt					
10-20	-0.01	0.02	-0.11	-0.19*	-0.11*
20-30	-0.02	-0.00	-0.11*	-0.27*	-0.10*
30-40	-0.22*	-0.03	-0.14*	-0.15*	-0.16*
40-50	-0.27*	-0.11*	-0.20*	-0.21*	-0.21*
50-60	-0.20*	-0.14*	-0.15*	-0.21*	-0.19*
60-70	-0.01	0.07	0.09*	-0.02	0.03
70-90	-0.06	-0.08	-0.06	-0.08*	-0.06*

The first table does not show enough significant negative correlation to suggest any special dependence between the meridional displacement of the anticyclones and their central pressure even when most of the correlations are negative.

The second table seems to indicate a significant negative correlation between the zonal motions and the central pressure of the anticyclones. Many correlations in the winter, spring, and autumn and year average are high and significant. In the summer, the sign is maintained even when the results are not significant at or below the 5% significance level. This is not surprising

since other studies have shown that the larger systems move slowly and a positive correlation exists between the size and central pressure of the anticyclones.

The last table shows that a definite relationship exists between the meridional motions and central pressure of cyclones. Most correlations are significant in the summer, autumn and year average, and they are rather high; and still keep the same sign as the other two seasons.

The third table shows again many significant correlations, but this time there are too many significant correlations of each sign to allow for any conclusion. This result is surprising since earlier studies have shown that the displacements of cyclones was negatively correlated with their size. Since a high negative correlation has also been found between size and central pressure, one would expect a priori, that the cyclones with the lowest central pressure would move most slowly across the meridian.

Hence, we may conclude that there seems to be a relationship between the central pressure and the eastwards motion of the anticyclones: stronger systems move slower in that direction; as well as between the central pressure and the zonal motion of the cyclones; stronger systems move more slower in that direction.

Conclusion

The results presented in Part I were obtained form the frequency distribution of several characteristics of the cyclones and anticyclones that were found over a period of four years on the sea level maps of the Northern Hemisphere.

Regarding the central pressure of the systems, it was found that the distribution of the anticyclones according to this parameter is much less skewed than that of the cyclones at all latitudes for all the seasons. The anticyclones with the highest central pressure were found between 40 and 60 degrees of latitude, while the cyclones with the lowest central pressure were found between 40 and 50 degrees of latitude.

As for as the size of the systems is concerned, it was found that except at low latitudes, there seems to be a characteristic average size for the systems present at each latitude belt for the anticyclones as well as for the cyclones.

It was found that on the average, only at low latitudes do the cyclones elongate longitudinally while the anticyclones do so much more at all latitudes.

It is surprising to find that the same is true on the average applied to the latitudinal elongation of the systems.

Regarding the shape of the systems, it was found that in the mean, they are longitudinally elongated, specially the anticyclones at low middle latitudes.

In Part 2 it was shown that the motion of those synoptical scale vortices next to the earth's surface depends on their shape. It was found that the zonal component of the velocity of the cyclones is directly proportional to their longitudinal elongation. At the same time, the more latitudinally elongated anticyclones have a larger meridional component of displacement. This effect was shown not to be a reflexion of the size dependence of their motions, as found by Macdonald (1967), and to be independent of the central pressure of the systems.

These results are partially analogous to Ward's findings that the zonal proper motion of sunspots is largest for the "streamers" that are elongated in the west-east direction.

It is also apparent that the shape of vortices should be considered as important in any theoretical studies of their motion through the use of hydrodynamical models.

Acknowledgments

Funds for this research were provided by U. S. Air Force Contract Number F 19628-67-C-0229.

I am indebted to Mr. Norman Macdonald who suggested the topic investigated here, and whose constant enthusiasm and interest in the results made the writing of this thesis an enjoyable experience.

Professor Victor P. Starr has been very kind and concerned in overseeing this thesis to its completion.

I am obliged to Miss Cora Gordon who with infinite patience typed the manuscript; and to Miss Isabelle Kole who drafted the figures.

References

Kasahara, Akira: 1957; Journal of Meteorology, 14, 386-402

Macdonald, Norman: 1966; Tellus 18, p 13

_____: 1968; Tellus 20, p. 300

_____: 1969; Planet. Space Sci., Vol. 17, 1149

Starr, V.P.: 1968; Physics of Negative Viscosity Phenomena p. 256, McGraw-Hill, New York

Ward, F.W.: 1966; Pure and Applied Geophysics, Vol 63.