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THE EOLE EXPERIMENT: EARLY RESULTS AND CURRENT OBJECTIVES

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EARLY RESULTS AND CURRENT OBJECTIVES

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December 1972

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THE EOLE EXPERIMENT:

EARLY RESULTS AND CURRENT OBJECTIVES

by

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ABSTRACT

The EOLE experiment with 480 constant level balloons released in the Southern Hemisphere is described. Each balloon floating freely at approximately the 200 mb level, is a precise tracer of the horizontal motion of air masses, the accuracy of which is limited only by the laminated structure of the stratospheric flow, within an RMS uncertainty of 1.5 m sec^{-1}. The balloons were found after 2 months to distribute at random over the whole hemisphere outside the Tropics, irrespective of their original launching site. Early results of Eulerian and Lagrangian averages of the EOLE wind data are given for describing the mean 200 mb zonal and meridional circulations. The effect of the small scale eddies of two-dimensional turbulence has been studied with respect to the relative eddy diffusion of pairs of balloons and the relative dispersion of triangular clusters. New estimates of the RMS divergence of the 200 mb flow are given, together with their scale dependence which was found to be a logarithmic law.

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THE EOLE EXPERIMENT:

EARLY RESULTS AND CURRENT OBJECTIVES

INTRODUCTION

As a prelude to the most extensive constant level balloon experiment attemped so far, the EOLE navigation and data collection satellite was launched by a Scout rocket from NASA's Wallops Island facility on August 16, 1971. The deployment of free floating constant volume balloons started shortly thereafter from three sites in the Republic of Argentina, and culminated in November 1971 with a maximum network of 280 balloons operating simultaneously. At that time, the 480-balloon supply allocated for the experiment was nearly exhausted and the population started to decrease as expected from estimates of the electronic package failure rate and balloon icing. As of this writing, 5 EOLE balloons are still floating around the Southern Hemisphere and tracked by the satellite; all of them have exceeded a one-year operational life. But of course, the most significant information expected from the program has already been acquired, processed, and made available to the Laboratorie de Météorologie Dynamique (principal investigator) and several investigators in the United States in NASA, NOAA, Colorado State University, the National Center for Atmospheric Research, the University of California at Los Angeles, and the University of Wisconsin, constituting the EOLE Data Interpretation Group.

In addition, the EOLE navigation and data collection satellite offered the opportunity for a preliminary test of current measurements by means of automatic instrumented drifting buoys, a program which might eventually evolve into a kind of marine EOLE experiment on an ocean-wide scale. With the cooperation of the Marine Sciences Directorate, Pacific Region, Environment Canada, 10 drifting buoys equipped with temperature sensors and a large sea-anchor or drogue, were built, launched in the North-Eastern Pacific and tracked by the satellite. This buoy experiment was only the first of a series of supplementary scientific and technical programs utilizing the extra-capacity of the EOLE satellite, some of which are still in operation as of this writing (such as tracking ships, a variety of drifting buoys, and icebergs). So, even though the EOLE satellite is still operating nominally at the present time and still in use for these supplementary experiments, the main experiment with constant level balloons is completed and it is appropriate to take stock of the scientific data and interpretation obtained so far.

THE CONCEPT OF HORIZONTAL SOUNDING

The EOLE program must be placed in perspective in a long series of ballooning experiments that began in the early fifties with the instrumented quasi-horizontal Transosonde flights over the United States and later from Japan across the Pacific Ocean (Anderson and Mastenbrook, 1956). The idea of a worldwide horizontal sounding system based on over-pressurized constant level balloons and satellite communications for navigation and data relay was proposed by Lally (1959) and Giles and Angell (1963). This project was not in fact implemented in the United States beyond developing the experimental Interrogation Recording and Location System (IRLS) for the NIMBUS 3 and 4 satellites (Cote, 1970) and tracking about thirty stratospheric balloons (Angell, 1972). The idea was taken up then by the French Centre National d'Etudes Spatiales (CNES) and implemented in cooperation with the United States (NASA). CNES developed and built the EOLE satellite as well as 500 constant level balloons and their sensors and communication packages. NASA provided a Scout rocket for launching the EOLE satellite into a quasi-circular orbit at a mean altitude of 800 km and an inclination angle of 50° to the equator. The EOLE experiment is by no means the final word on this technique of data collection and tracking Lagrangian tracers; another large program of this nature, the Tropical Wind, Energy Conversion, and Reference Level Experiment (TWERLE), is being prepared by a team of experimenters in the United States to fly on the Nimbus F satellite in 1974 (Masterson, 1970).

"Constant level" balloons are nothing but constant volume craft capable of floating stably at one nominal density level, corresponding in this case to the 200 mb pressure level of the standard atmosphere. It is not, of course, as easy to build a rigid "hull" for such a light craft as it is for a marine floater. The rigidity of constant volume is obtained by stressing an inextensible spherical polyethylene-terephthalate or Mylar[1] envelope with a moderate overpressure of the order of 10% of the outside atmospheric pressure. Even so, the stress on the envelope material is very large indeed because the balloon skin is very thin (50 μm); about 1/10 of the ultimate tensile strength of steel is reached in maximum stress areas. This explains why such a small overpressure (20 mb in our case) must be used, even though it does not give much reserve in the case of gas loss or accidental accretion of mass, e.g., accumulation of frost by inverse sublimation in saturated air at night or deposition of ice particles in dense cirrus clouds. For this reason, about half the balloon failures observed eventually can be attributed to loss of pressurization in the moist tropical atmosphere, particularly in three active convective regions: the Amazon basin, Central Africa, and a zone in the Tropical Pacific Ocean, between 150° and 180° West longitude. This meteorological failure mode, together with electronic package

[1]Dupont trademark.

failures, accounts for the observed decrease of the balloon population (Fig. 1). A very unfortunate event depicted in Fig. 1 was the accidental destruction of about 100 balloons on telecommand from the EOLE satellite on September 11, 1971, due to an operator mistake in keying the spacecraft operational schedule for one orbit. One will observe that the total active balloon population rose eventually to 280 in November 1971 and remained larger than 200 during a 50-day period in the Southern Hemisphere Spring (155 days with a population of 100 balloons or more). The mean operational lifetime of the constant level balloon (excluding from the statistics the September catastrophy) was finally established at 103 days. Also,

- 35 balloons lasted less than 10 days
- 178 balloons lasted more than 3 months
- 66 balloons lasted more than 6 months
- 14 ballons lasted more than 1 year.

THE EOLE DATA COLLECTION AND TRACKING SYSTEM

The EOLE satellite system has been designed to communicate with and locate a maximum of 512 addressable platforms, i.e., establish a two-way radio link successively with each individual platform, acquire and store the satellite-to-platform range r and range-rate $\dot{r}$ information together with precise timing data, and acquire and store meteorological data measured in situ by instruments on the platform and telemetered on the platform-to-satellite return link.

The spaceborne data collection equipment consists of a 464/402 MHz UHF interrogation/reception package with a helical antenna permanently oriented toward the Earth by passive gravity-gradient attitude stabilization. Upon successful interrogation of one platform, a two-way phase-coherent link is established between the platform transponder and the satellite, allowing a very precise measurement of the propagation delay (range r) and the Doppler shift (range rate $\dot{r}$). These measurements, together with accurate timing and excellent determination of the orbital parameters, provide simultaneously two geometrical loci of the platform position. Knowing in addition the altitude of the platform, one can then determine the geographical location of the platform with 1 to 2 km accuracy. The experience gained with the operation of the EOLE system using fixed platforms or beacons has definitely proven that we reach here the ultimate accuracy allowed by usual orbit determination methods currently applied to scientific and meteorological satellites. Future systems will require instead the more accurate methods used for geodetic and navigation satellites, or alternatively, use a global array of fixed platform to update the satellite trajectory on an orbit-to-orbit basis (Brachet, 1972).

The range and range rate data processing was performed by the CNES Computing Center on a moderately delayed schedule consistent with a 24 to 48 hour restitution time. A rather severe data processing crisis was met in the early days of the experiment when it appeared that no amount of processing could eliminate reliably the ambiguity of two possible locations symmetrical with respect to the satellite sub-track, both being compatible with one record of r, $\dot{r}$ data along a single passage of the spacecraft. This meant that this ambiguity could only be resolved on the basis of meteorological likelihood and continuity of balloon trajectories. An appropriate velocity correlation filter was applied to successive balloon positions determined on successive orbits of the satellite to restore all proper locations but a few in a thousand.

On the whole, one can consider that the operation of the EOLE satellite and balloon system has proven to be remarkably successful from a technical standpoint, considering the sophistication of the electronic equipment and the rather extreme environment and engineering constraints placed on the balloon payloads, particularly. An extensive test program was conducted by CNES for assessing the effect of the impact of payload elements on airframes at the 600 mph cruising velocity of commercial jet aircraft at 200 mb altitudes. In order to satisfy the absolute requirement that such impact produce no damage beyond what is expected in normal aircraft operation, very restrictive design criteria of the balloon electronic package and sensors were established and adhered to, at the expense of developing some new components like a lightweight frangible nickel-cadmium battery, capable of operating over hundreds of charge-discharge cycles at -65C. A production of 4-meter-diameter spherical superpressure balloon envelopes was specially implemented for the experiment; and very careful packaging, pre-launch testing, and launching methods were established so that balloon failures recorded during ascent were less than 3% of the launches, while less than 2% of the balloons developed leaks in flight.

VERTICAL DISTRIBUTION OF THE EOLE BALLOONS

How constant is the flight altitude of "constant level balloons"? Carefully measured and weighted spherical superpressure balloons could be made to reach the same flight altitude with a very small margin indeed, of the order of ±20 m at 12,000 m, corresponding to a ±0.3% spread around the nominal pressure or density level (V. Lally, NCAR, private communication). This precision was certainly not achieved in a global project like EOLE for which a ±1% dispersion of the individual balloon mean flight level (density) was in fact observed. This is also the order of magnitude of the absolute accuracy of our ambient pressure barometer (±2 mb).

In addition to this initial altitude spread, "constant level" balloons undergo two kinds of vertical motions: a diurnal oscillation due to the residual elastic expansion of the envelope when the overpressure rises inside the sun-heated balloon (Fig. 2); and short period oscillations corresponding to the bobbing motion of the floater excited by gravity waves and/or clear air turbulence. As shown in Fig. 2, the diurnal oscillation reaches ±100 m for the EOLE balloons, while the short period bobbing is of the order of ±30 m (Morel, 1970).

Due to these various causes for vertical spreading, one must consider that individual wind measurements given by the EOLE system are samples taken at random in a 200 m thick layer of the atmosphere (or so) centered about the nominal flight level density $\rho = 0.328\,\mathrm{kg\ m^{-3}}$. Now, it is well known (Sawyer, 1961; Weinstein et al., 1966; Morel, 1970) that the atmospheric flow at lower stratospheric altitudes, has a layered structure associated with large vertical wind shears over vertical scales of the order of 100 meters. A rather extensive program undertaken by the Laboratoire de Météorologie Dynamique for measuring the wind shear or differential wind between a free floating balloon and a sensitive propeller anemometer hung 100 meters underneath, has yielded an RMS value of 1.5×10^{-2} sec^{-1} for the quasi steady wind shear. From this, one may conclude that the horizontal velocity of a representative air parcel cannot be measured by one discrete Lagrangian tracer with an accuracy better than 1.5 m sec^{-1} say. This is indeed the margin of uncertainty of EOLE wind data with respect to the mesoscale wind field, while the measurement error is only 0.5 m sec^{-1} (due to balloon location errors).

HORIZONTAL DISTRIBUTION OF THE EOLE BALLOONS

Some fear was expressed on several occasions prior to the experiment that large networks of constant level balloons would not be useful for a very long period on account of the balloons' eventually concentrating in large clusters at the pole or into the jet-stream (Mesinger and Mintz, 1970). EOLE did however confirm earlier experimental results (Morel, 1970) indicating that the latitudinal spreading due to eddy diffusion greatly exceeds the weak steady convergence of the mean flow, although a definite general tendency to drift into the South polar region was indeed observed during the austral summer.

The eddy diffusion rate of horizontal tracers was studied specifically by releasing the EOLE balloons by groups of four within a very short time (1 hour).

All such artificial clusters, spreading initially over 50 to 200 km, separated completely in one to three weeks (Fig. 3). The same behaviour was also observed with clusters which formed temporarily in the course of the experiment, thus enabling us to determine the variance of the relative (dispersion) velocity of a pair of tracers separated by a distance L (meters):

$$\overline{\left(\frac{dL}{dt}\right)^2} \simeq 4 \times 10^{-10}\ L^2\ (m^2\ sec^{-2}) \qquad (1)$$

meaning 2 m sec^{-1} RMS dispersion rate for tracers separated by 100 km and 20 m sec^{-1} RMS for a 1000 km separation. The law expressed in Eq. (1) for the scale dependence of eddy diffusion can be derived from a postulated k^{-3} dependence of eddy kinetic energy on the wavenumber k. Even more precisely, a detailed analysis of the Lagrangian tracer dispersion along the mean trajectory and normal to the trajectory, is consistent with the homogeneous isotropic two-dimensional turbulence model of the atmospheric circulation (Kraichnan, 1967; Charney, 1971) for scales up to 700 km. Larger scales of motion beyond 700 km do exhibit an increasing degree of anisotropy (Larchevèque, 1972).

Actually, this strong eddy diffusion process was such as to produce an essentially random distribution of tracers in the general westerly circulation of the Southern hemisphere, i.e., poleward of 15°-20° South. It is interesting to note that the same random latitudinal distribution obtained after a while for the three sub-populations of balloons released from any of the launching sites:

Mendoza	(33° South, 69° West)
Neuquen	(39° South, 68° West)
Lago Fagnano	(55.5° South, 67° West)

Fig. 4 shows for example successive stages of the latitudinal distribution of the constant level balloons released from the station of Mendoza; it is apparent that an ensemble of such tracers released from the same point loses completely the memory of its origin in about two months. This fact has considerable practical import on the deployment of a semi-permanent network of constant level balloon as envisioned for collecting wind and geopotential height observations during the First GARP Global Experiment: only two and at most three launching sites are sufficient to produce an even distribution of platforms within a few weeks, i.e., a time short with respect to the expected lifetime of such platforms.

In practice, the horizontal coverage of a random network of free floating balloons must be expressed in term of the probability that at least one measurement be made in one specified square latitude-longitude box for example, in each 24 hour period. This probability depends in turn, upon the box size, the density of platforms over the Earth, the velocity of the platforms and the frequency of the spacecraft passes within useful communication range. It must be emphasized that the EOLE satellite orbit had an inclination of 50° and was thus optimized to provide the maximum number of useful passes (up to 8 successive orbits) over balloons which were moving fastest, i.e., which could provide several non-redundant wind data during one 24 hour period. The resulting statistics are shown in Fig. 5 based on 200 balloons distributed in the Southern hemisphere poleward of 15° South. The cut-off of the observation probability at

75° South is the limit of the satellite communication range: from a 50° inclined orbit, the balloons straying over the South polar cap could not be reached. Several instances of a balloon remaining out of range near the South Pole for several weeks and reappearing again have been recorded.

DATA INTERPRETATION STRATEGY

During the one-year period September 1971 to September 1972, the EOLE satellite logged 168,000 balloon interrogations, all of which have been processed, controlled for quality and archived on digital files. Although this may appear a small enough data set, it can only be communicated to the scientific community in some synthetic or abstracted form of general significance, and yet not so abstracted that most of the information is lost. This remark is particularly cogent with respect to the large baroclinic disturbances of the general circulation which must essentially be studied in their day-to-day evolution.

We have therefore distinguished, somewhat arbitrarily three general classes of phenomena:

- the mean circulation including the zonal flow and standing planetary waves.
- the transient features associated with large baroclinic disturbances and energy transforming processes.
- the random (essentially) isotropic eddies of what may be considered the inertial sub-range of quasi two-dimensional "geostrophic" turbulence.

Clearly, the first kind of scientific information is available in the various averages which could readily be computed from the raw EOLE data. We shall present a selection of these results below. At the other end of the spectrum, the small to intermediate scale eddies may, to a large extent, be described as a stationary, homogeneous and isotropic random-velocity field superimposed on the mean flow and may therefore be understood in terms of ready-made two-dimensional turbulence models (Kraichnan, 1967; Charney, 1971). This short scale part of the spectrum, corresponding to wavenumbers in excess of 30, say, is best studied from the random relative motion of two or more neighboring tracers. Analysis of pair dispersion and Lagrangian correlation statistics is underway and the first results on the dispersion of triangular clusters are available (see below, and also: Morel and Necco, 1972).

Finally, we come up with the conclusion that the most difficult and probably the most protracted part of the scientific interpretation of EOLE data will be that associated with the large scale transients. In order to proceed toward this goal, the EOLE data must be made more widely available in readily understandable formats. This is the reason why the Laboratorire de Météorologie Dynamique is now working on two kinds of visual displays: (a) an atlas of stream function maps (Fig. 6) inferred solely from EOLE data for the period October 1971 to February 1972, and (b) a moving picture of the animated EOLE balloon trajectories for the same period.

The stream function analysis routine which finally evolved from many half-successful attempts, is as follows. Firstly, the mean wind for one month is computed from the monthly averages of all balloon winds for each box of a stereographic grid over the Southern Hemisphere. Data gaps, particularly in the Tropics are filled by interpolating neighboring values or climatic means (at the Equator). This mean wind serves as the first guess field for the first day of analysis. An updated wind field is then computed from the first 12-hour set of EOLE data with three successive passes of Gandin's optimal interpolation scheme (Gandin, 1963) using progressively smaller correlation radii (2000, 1000 and 500 km): the resulting winds serve as the first guess for the next step. The second updated wind field is computed by the same method, only using the next 12 hours of data. Thus the second updated field incorporates all EOLE wind measurements collected in one 24-hour period and is used for computing the vorticity field and stream function for the day. This second updated wind field, properly smoothed to eliminate small scale features with little predictability, is also used for initiating the same analysis scheme on the next day. This sequence of operation is repeated for 15 days, when it is started afresh from a new estimate of the monthly mean field, etc.

The 12-hourly stream functions produced by this analysis scheme will also be used to extrapolate the balloon trajectories in the intervals between fixes by the EOLE satellite, i.e., 12 hours in the best cases and up to 20 hours for very high latitudes. A linear differential correction scheme will be applied along the extrapolated trajectory to make the estimated positions fit with the next series of actual fixes.

These two documents, a stream function atlas and an animated balloon movie, are expected to be available from the Laboratorie de Météorologie Dynamique in the second half of 1973.

EARLY RESULTS ON THE MEAN CIRCULATION

The Eulerian means of the zonal velocity computed from EOLE wind data were found to agree remarkably well with previous climatological studies, particularly the zonal wind latitudinal sections estimated by Van Loon et al. (1971) using geostrophic winds. The maximum monthly mean velocity is 30 m sec^{-1}, normally found at 40° South during the austral Spring and Summer. Naturally, the maximum instantaneous zonal velocity much exceeds the monthly mean value: velocities in excess of 80 m sec^{-1} have been recorded on many instances in local jets. It is interesting to note that similar estimates based on Lagrangian averaging yield rather different values of mean zonal velocity. Indeed, one would expect the Lagrangian mean of a stationary random velocity field to be somewhat smaller than the corresponding Eulerian mean since the Lagrangian tracers' characteristic of spending more time where the velocity is low introduces a negative bias. On the other hand, there may be a tendency for constant density tracers to be attracted into the fast moving jet and to skirt low velocity cellular circulations, with a corresponding bias toward faster zonal velocity. These two biases are certainly competing in the 200 mb circulation as the Lagrangian mean zonal velocity estimated from EOLE balloons is alternatively larger (low latitude) or smaller (mid-latitude) than the Eulerian mean. A detailed analysis of these baises has not yet been carried out however.

Many investigators have estimated the mean meridional circulation in the Southern Hemisphere from conventional meteorological data (Tucker, 1965; Obasi, 1963; Gilman, 1965) or from constant level balloon flights (Solot and Angell, 1969), but it is well known that such studies are very difficult on account of (a) possible geographical bias with respect to quasi-steady standing waves of the general circulation and (b) excessive variance of instantaneous meridional velocity values (15 m sec^{-1} RMS) with respect to the expected average (of the order of ± 0.1 m sec^{-1}). The EOLE experiment offered a unique opportunity to eliminate both difficulties. The EOLE horizontal soundings are naturally free from any geographical bias. Furthermore, by virtue of our being able to track the same tracer over an extended period, it is possible to get rid of the largest part of the meridional velocity variance associated with synoptic scale disturbances, by appropriate time-smoothing (Fig. 7). In Fig. 8 a Eulerian average of the time-filtered velocities associated with the smoothed balloon trajectories, provided the very first detailed time-latitude cross-section of the mean meridional circulation at 200 mb (Desbois, 1972). This cross-section covers only the mid-latitudes of the Southern Hemisphere as the steady Hadley circulation was strong enough to drive the balloons out of the tropical region and prevent their crossing over to the Northern Hemisphere.[2] The general poleward tendency in the austral summer was noticed by previous investigators (Solot and Angell, 1969) but the highly fluctuating character of the instantaneous mean velocity was not brought to light before. The effect of these short-term vacillations of the mean meridional flow on the angular momentum balance is being investigated now.

EARLY RESULTS ON QUASI-TWO-DIMENSIONAL EDDIES

We have already indicated that small to intermediate scale eddies of the general circulation could be amenable to an approximate theory in terms of quasi-two-dimensional, homogeneous and isotropic turbulence. How isotropic? An interesting finding, based on dispersion rate statistics for pairs of balloons separated by various distances, indicates a definite trend toward increasing anisotropy (in favor of the zonal direction) starting at the initial separation of 700 km (Fig. 9). Further analysis of refined balloon positions is underway to substantiate this result with more precise data.

Further, the analysis of 360,000 divergence estimates, inferred from the Lagrangian derivative dA/dt of the horizontal area of triangular balloon clusters, has been completed (Morel and Necco, 1972). The statistics of the variance of raw estimates, versus cluster scale are presented in Fig. 10. But it can be shown that a large contribution to these estimates results from eddy diffusion

[2]Out of 480 balloons released in the Southern Hemisphere for the EOLE experiment, only 2 were found to have wandered into the Northern Hemisphere 200 mb general circulation.

of the three tracers, rather than true divergence D of the flow. In fact, two eddy diffusion processes act to increase the variance of the Lagrangian derivative dA/dt: quasi two-dimensional turbulence with scale smaller than the cluster size and random velocity discrepancies due to the layered structure of the flow. Two-dimensional eddies produce a relative velocity variance $\overline{u'^2}$ proportional to the square of the cluster size (see Eq. 1), and it turns out that the corresponding contribution to divergence estimates is independent of scale. On the other hand, random velocity discrepancies between a discrete tracer and a representative air parcel displaced a few hundred meters in altitude, are constant (of the order of $\overline{u''^2} = (1.5\,\mathrm{m\ sec^{-1}})^2$ and therefore induce an L^{-2} dependence of the variance of divergence estimates which becomes very significant for triangular clusters smaller than 400 km say (Fig. 10):

$$\overline{\left(\frac{1}{A}\frac{dA}{dt}\right)^2} = \overline{D^2} + \frac{4\,\overline{u'^2}(L)}{L^2} + \frac{\sqrt{3}\,\overline{u''^2}}{L^2} \tag{2}$$

It has been possible to separate approximately the three terms appearing in Eq. (2) and to show that the variance of divergence estimates obtained from spatial domains of scale L is given by a logarithmic law:

$$\overline{D^2} \simeq 0.4 \times 10^{-10}\ \ln\left(\frac{L_1}{L}\right)\ \mathrm{sec^{-2}} \tag{3}$$

with $L_1 \simeq 7000\,\mathrm{km}$. This logarithmic law corresponds very precisely to the k^{-1} dependence of the square divergence spectral density (or the square vorticity spectral density) expected from Charney's theory of "geostrophic turbulence" (Charney, 1971). Eq. (3) inferred from EOLE data may therefore be a most sensitive experimental verification of the validity of the geostrophic approximation to intermediate scale features of the general circulation.

CONCLUSION

The EOLE experiment, completed five years after the pioneer flights of the GHOST program, has provided for the first time a completely homogeneous set of very accurate, in-situ measurements of one meteorological parameter, i.e., the horizontal wind at one nominal density level (approximately 200 mb) on a planetary scale. The implementation of this experiment has been made possible by a truly international effort, not only of the national Agencies CNES and NASA, which cooperated in the successful launching of the EOLE satellite, but also of the many scientists who offered guidance in designing the atmospheric aspect of this project and helping carry out the development of the constant volume balloons.

Now, this unique data set stands ready for further scientific analysis and reflection. Our aim in writing this review paper has been to try and show that the EOLE data are not just a bounty for constant level balloon enthusiasts but, hopefully, a powerful tool for developing a more refined understanding of the general circulation kinematics. We wish to emphasize again our feeling that more international cooperation is needed now after the completion of the experiment to achieve this goal.

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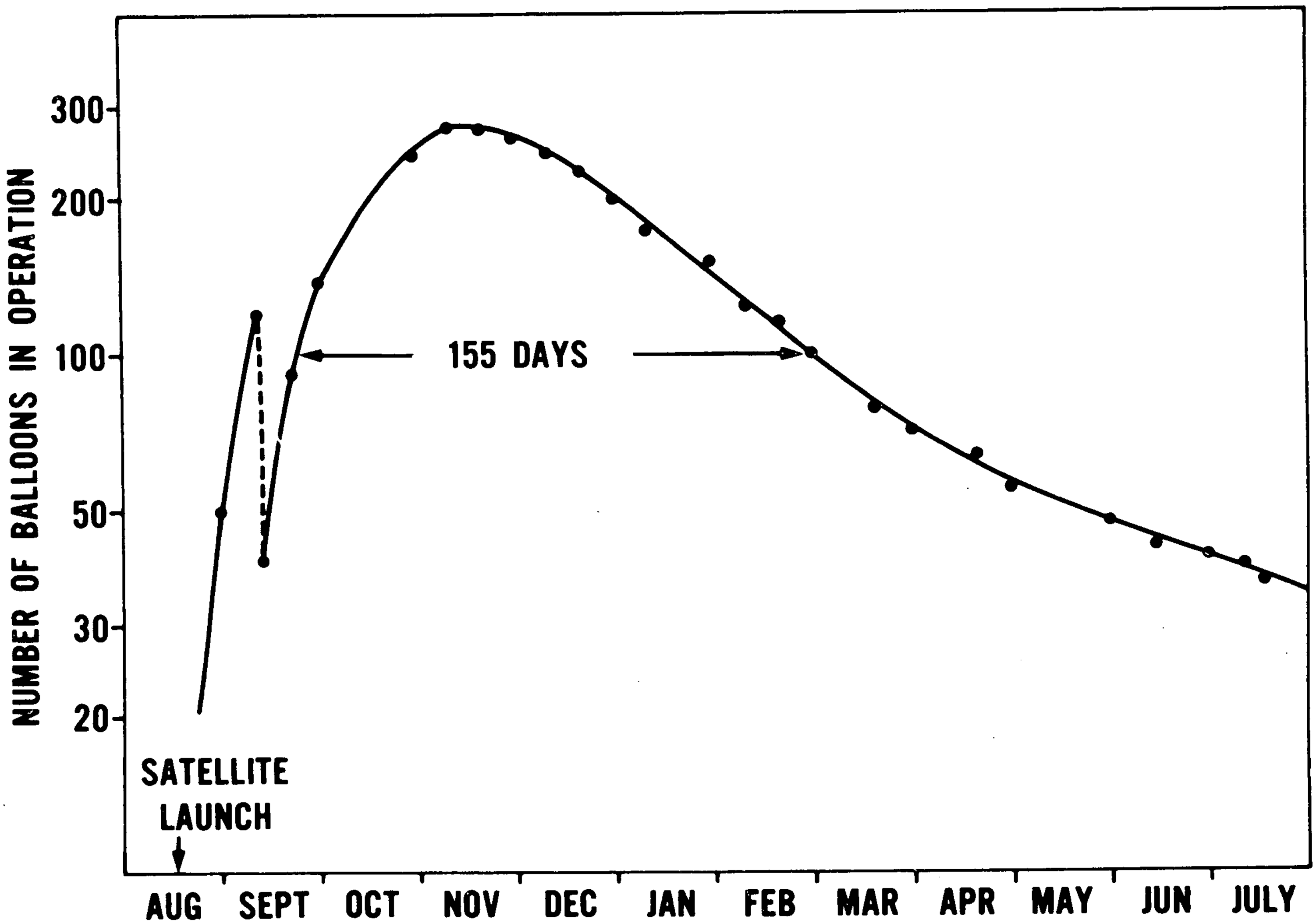

Figure 1. Record of the number of balloons operating simultaneously during the EOLE experiment (August 1971-July 1972).

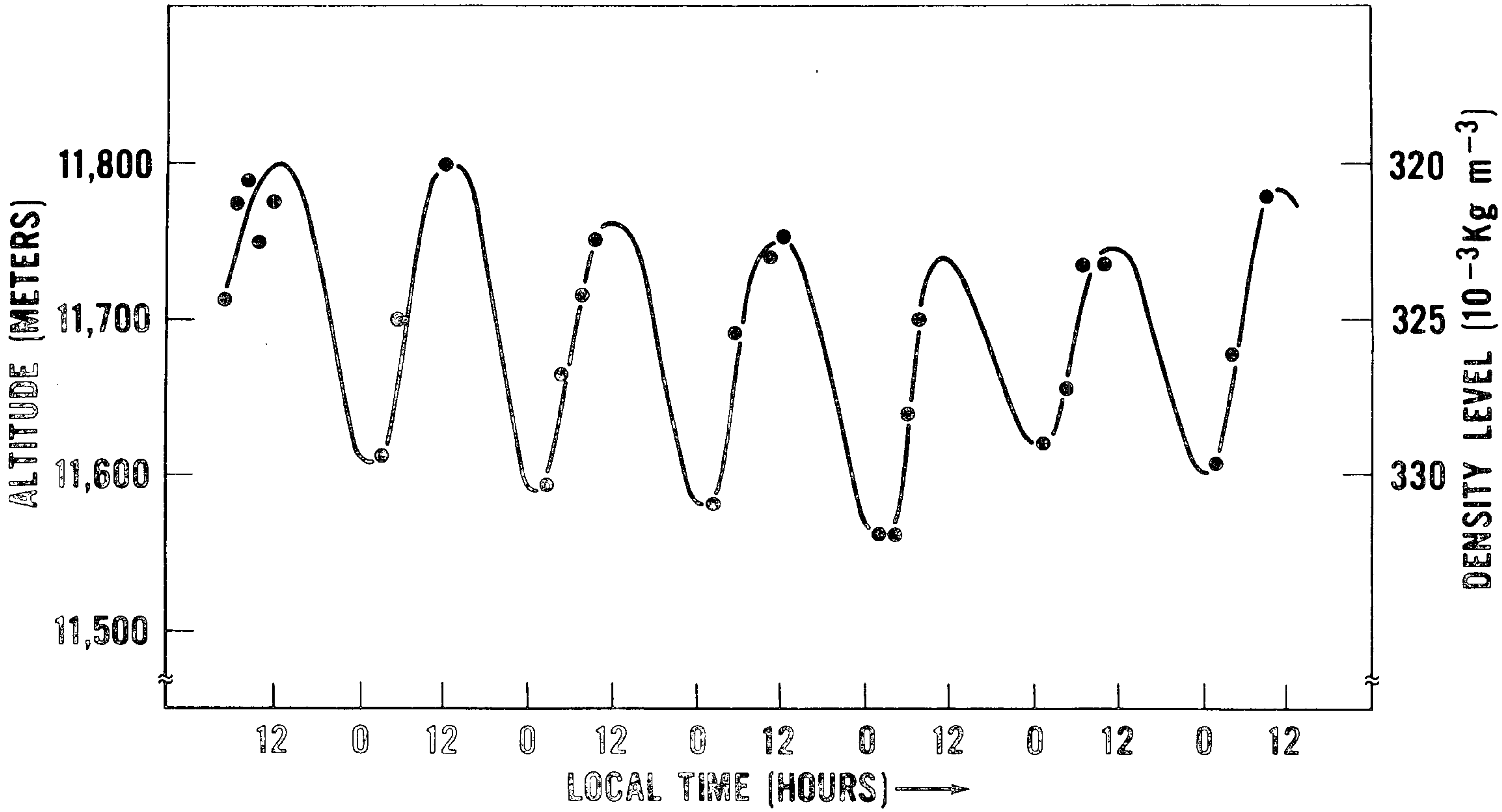

Figure 2. Diurnal altitude excursion of one EOLE balloon associated with residual expansion of the envelope due to solar heating and increased helium overpressure.

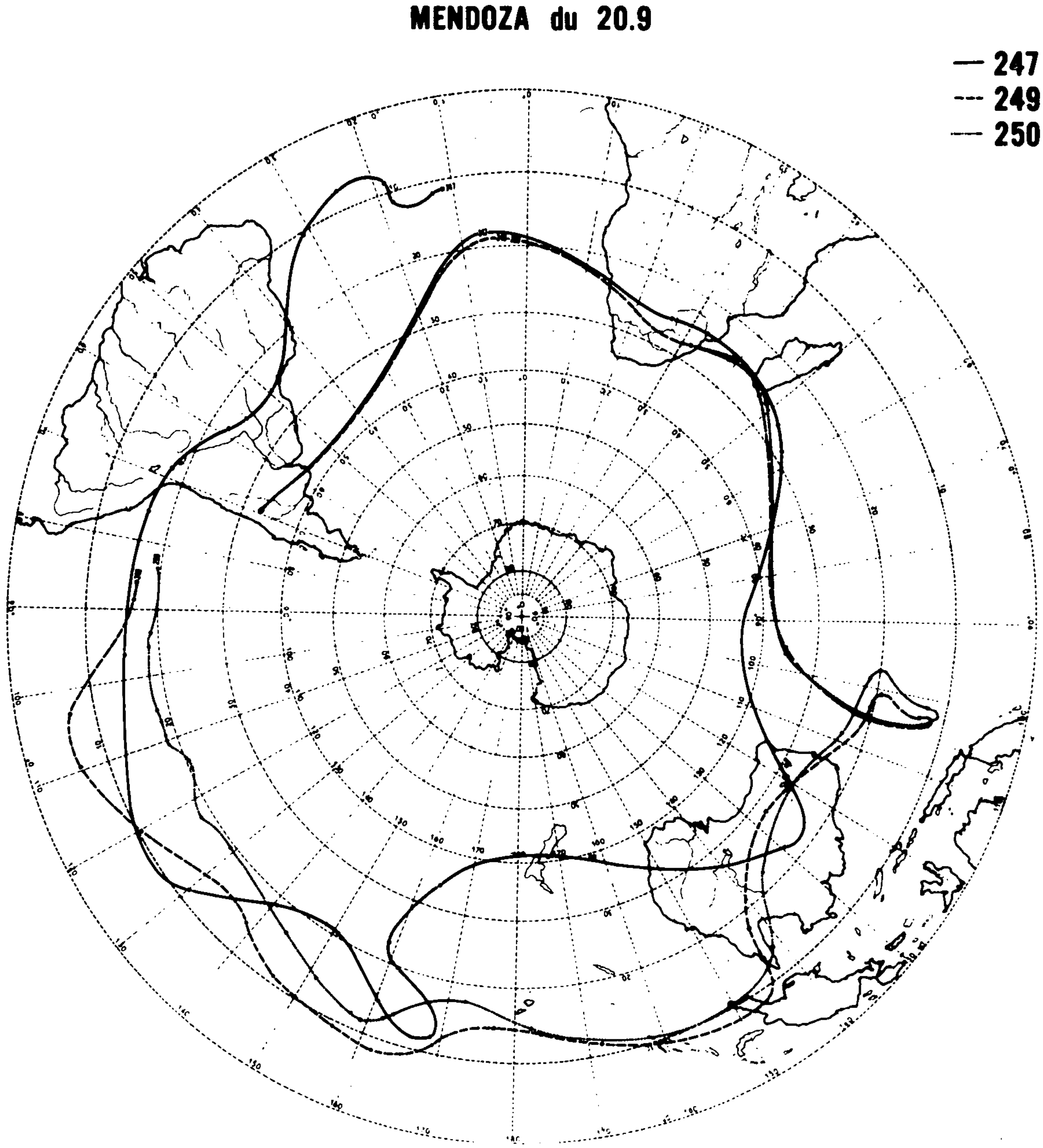

Figure 3. Initial trajectories of three identical constant level balloons numbered 247, 249, and 250, released almost simultaneously from the Mendoza, Argentina launching site on September 20, 1971. The eventual separation of such clusters normally takes place after one full revolution around the Earth if the balloons do not stray into the Tropics.

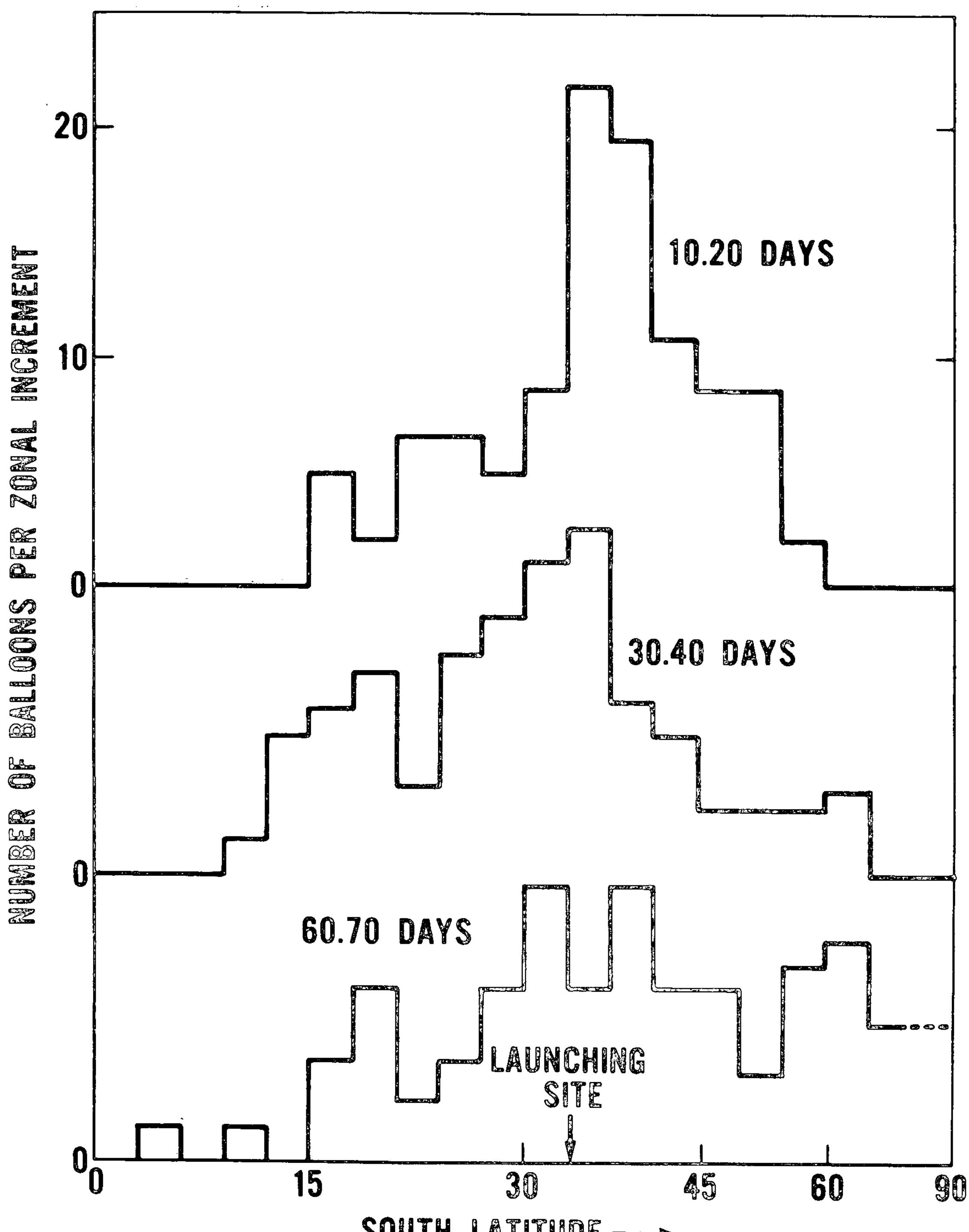

Figure 4. Latitudinal distribution of balloons released from one launching site (Mendoza). Note that the memory of their common origin is essentially lost after 60 days of flight.

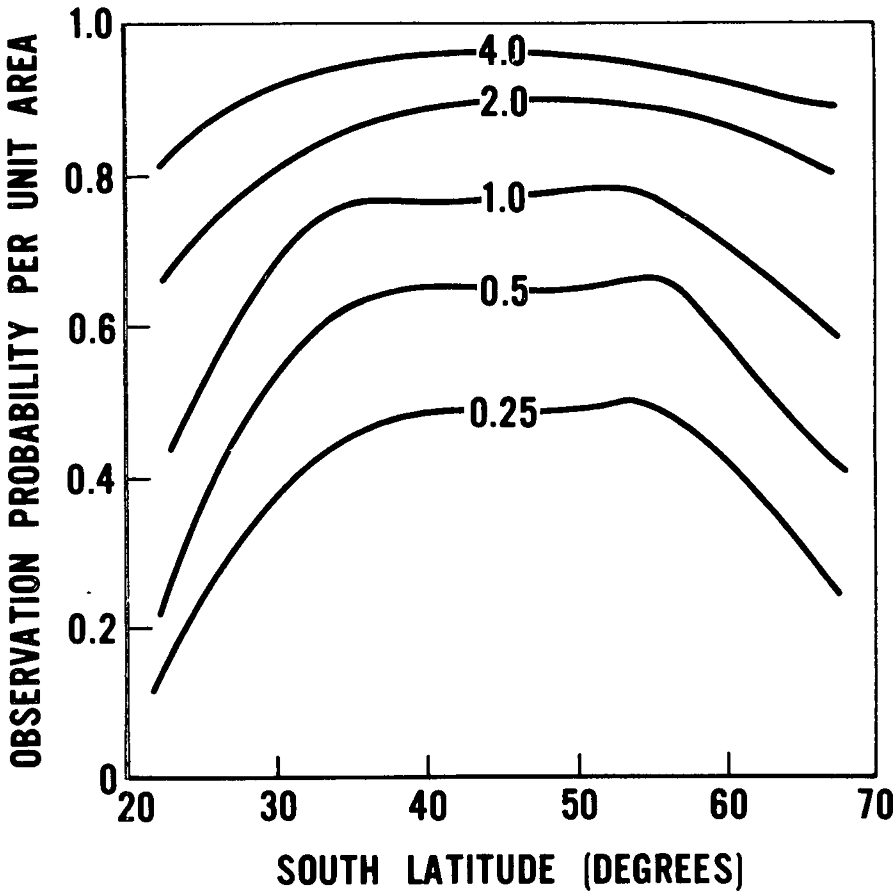

Figure 5. Probability of obtaining at least one non-redundant EOLE balloon observation per 24 hours in a square $\Delta\phi$, $\Delta\lambda$ - box, at various latitudes. The probabilities are given for various densities of platforms expressed by the average number per box ranging from 1/4 to 4.

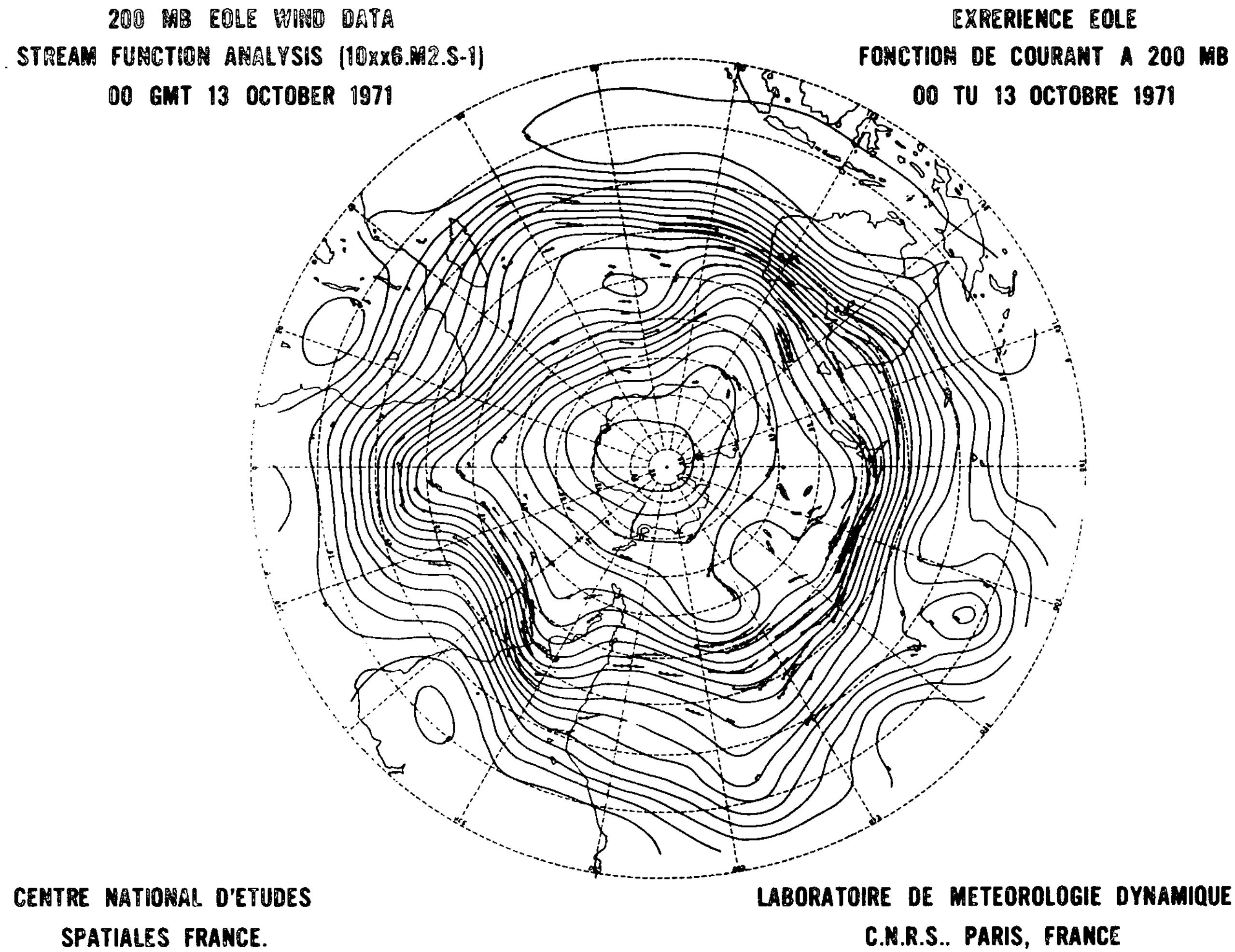

Figure 6. Typical daily stream function map inferred from EOLE winds. The contour interval shown is 15 x 10^6 m^2sec^{-1}. The original data are plotted as actual displacements of the tracers in the interval between two successive passages of the spacecraft.

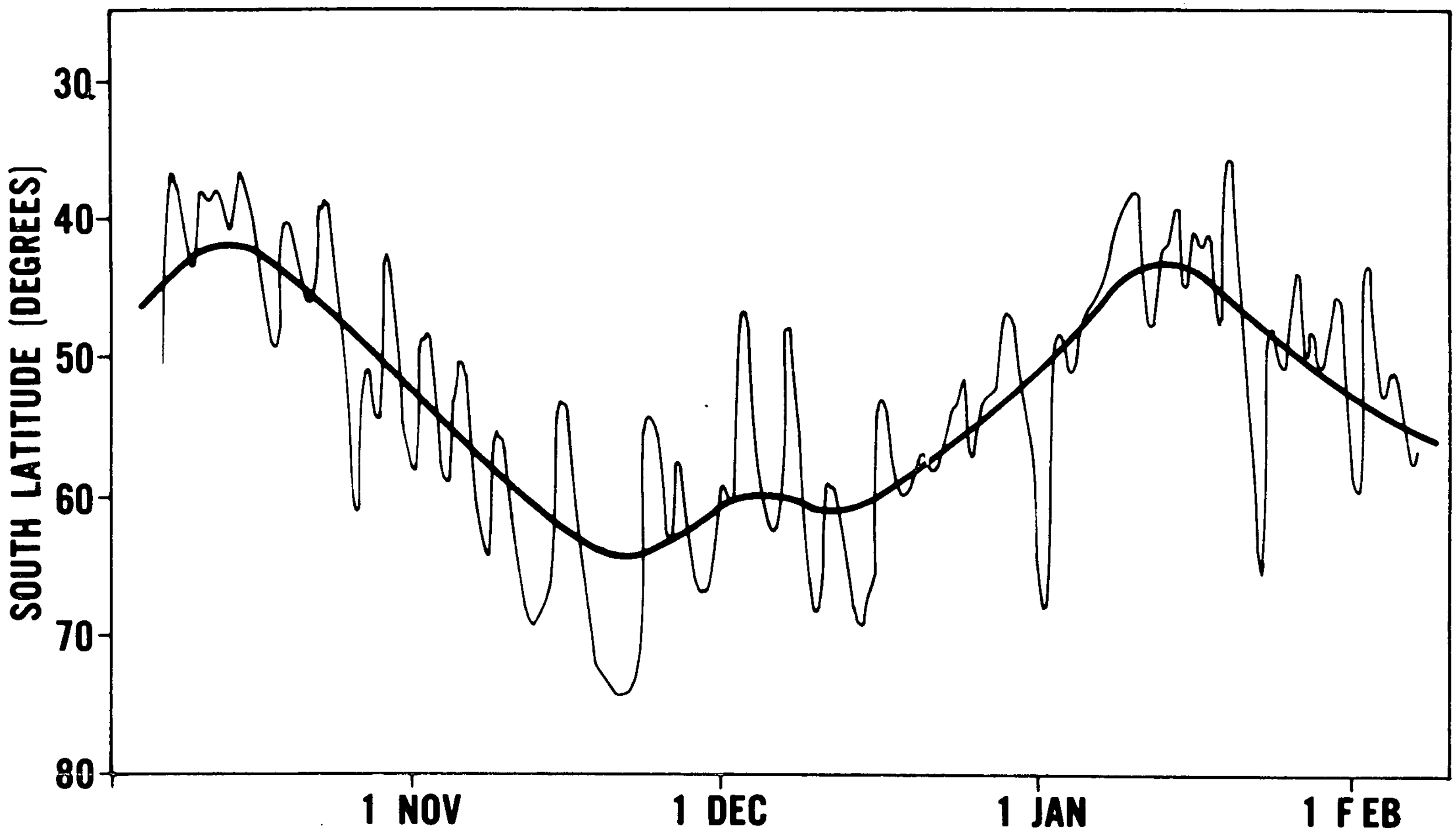

Figure 7. Typical latitude excursions of one EOLE balloon (thin line) and smoothed trajectory obtained by a running time average (full line).

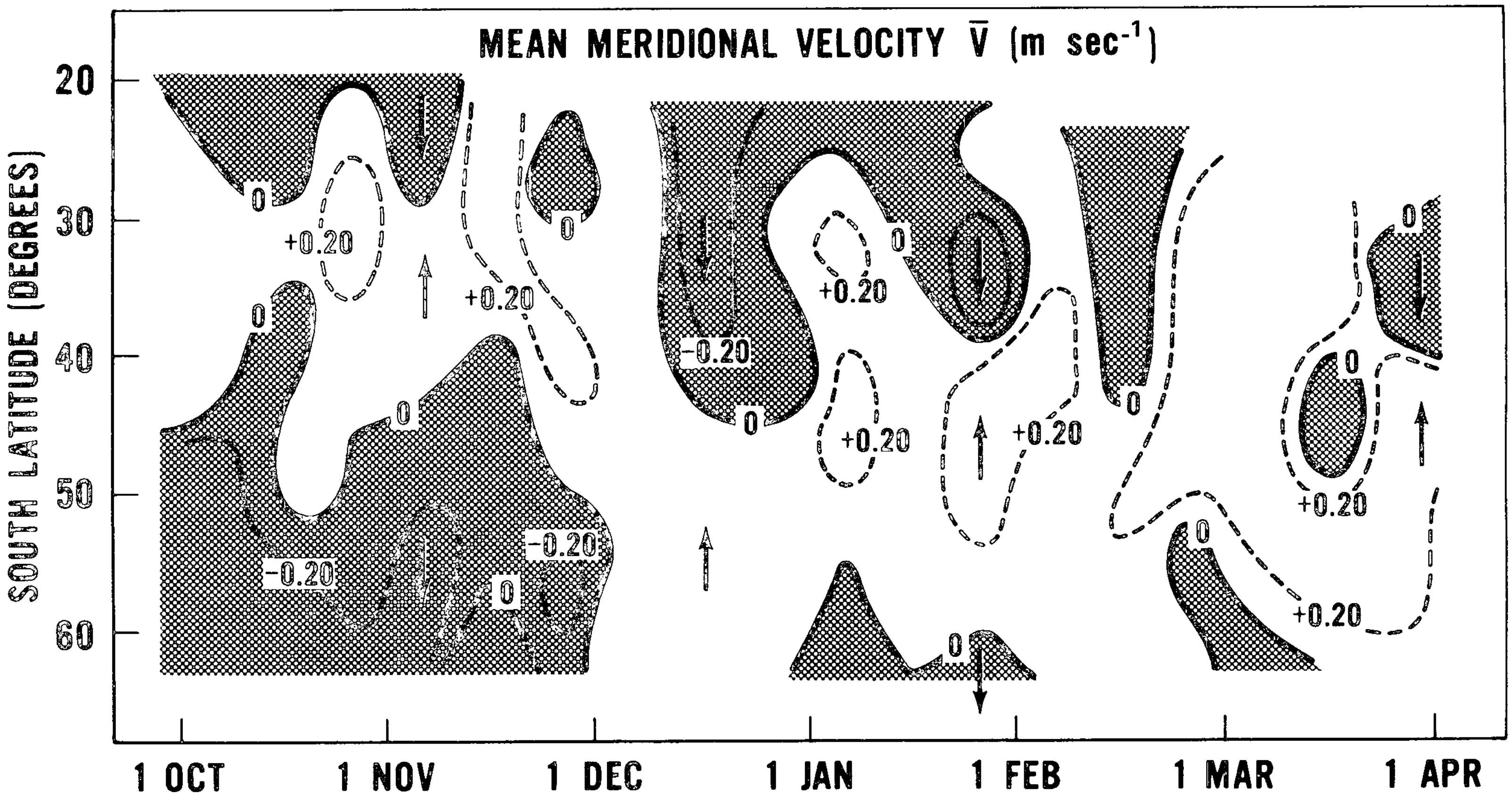

Figure 8. Latitude-time cross section of the instantaneous mean meridional velocity at 200 mb, derived from smoothed EOLE balloon trajectories (see Figure 7 above).

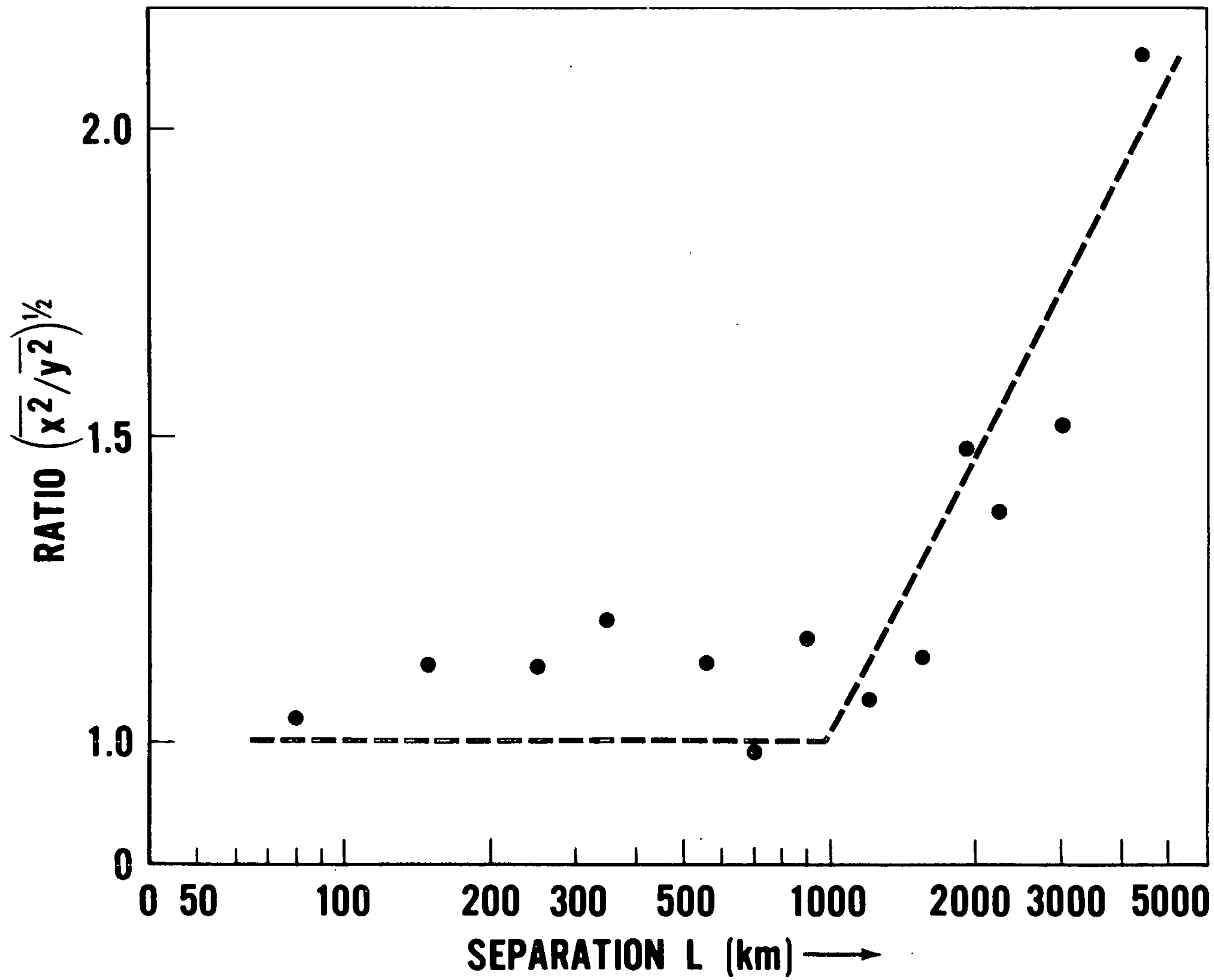

Figure 9. The anisotropy of the eddy-diffusion process becomes noticeable when the separation of the Lagrangian tracers exceeds 700-1000 km.

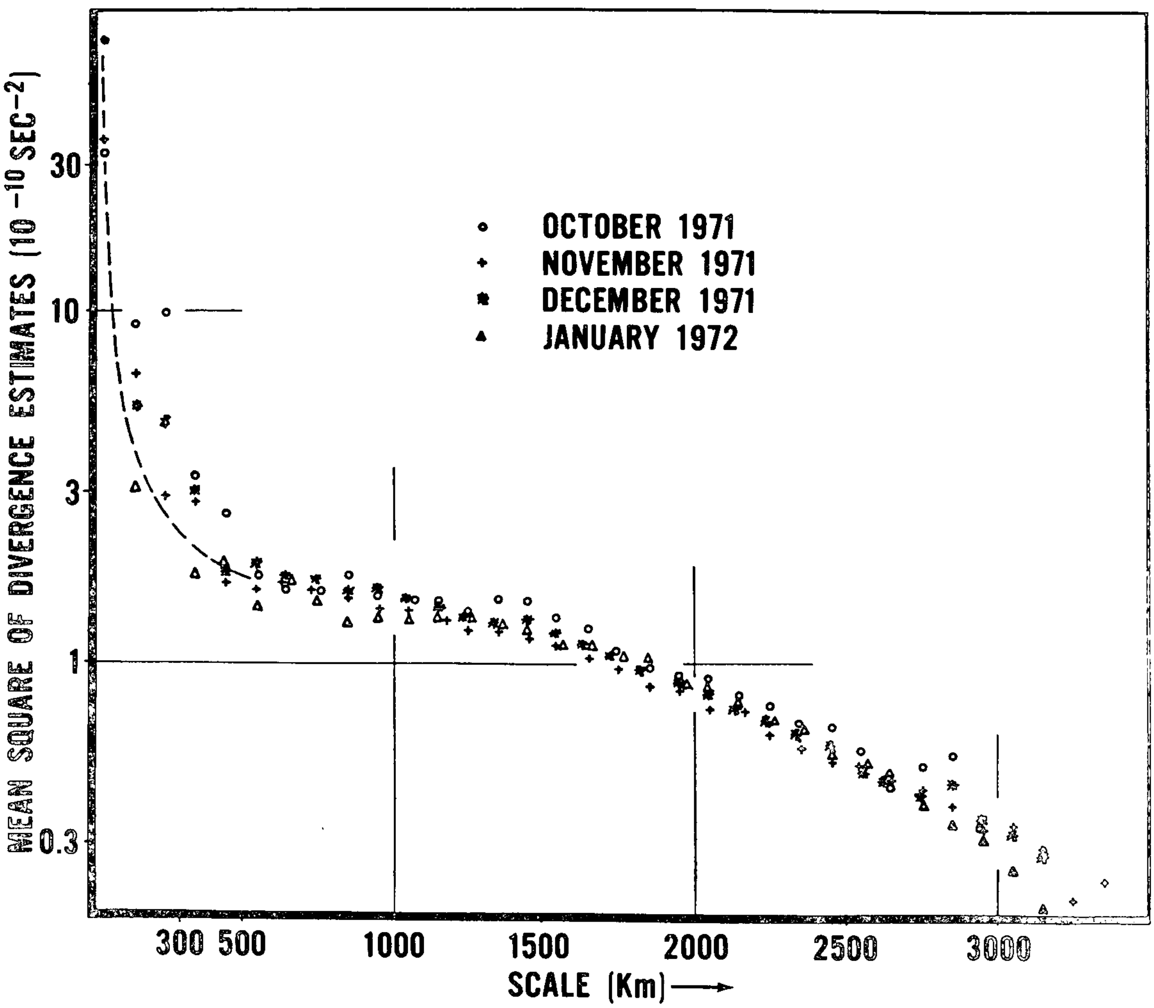

Figure 10. Scale dependence of raw estimates of the mean square divergence at 200 mb, inferred from the Lagrangian derivative of the area of triangular clusters.