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# WORLD-WIDE CLOUD COVER DISTRIBUTION FOR USE IN COMPUTER SIMULATIONS

Prepared under Contract No. NAS 8-21040 by
Paul E. Sherr, Arnold H. Glasen, James C. Barnes
and James H. Willand

ALLIED RESEARCH ASSOCIATES, INC.



For

NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama

June 14, 1968

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# WORLD-WIDE CLOUD COVER DISTRIBUTION FOR USE IN COMPUTER SIMULATIONS

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Virginia Road
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For

Aero-Astrodynamics Laboratory



NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER

# PREFACE

This cloud cover study is the only known work designed especially for earth oriented space missions. Being a first effort, the conditioned statistics are particularly weak in some cases; however, judicious use of the study should produce reasonable results.

It must be emphasized that these data should not be used for purposes other than those for which they were designed. In particular. the statistics should not be used for detailed cloud climatologies for specific locations.

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We also wish to express our thanks to Mr. C. William Rogers for his analysis in the selection of prototype stations for each region, and to Mr. James Pike for his assistance in the preparation of this report.

## ABSTRACT

Probability distributions for world-wide cloud cover have been prepared for use in the simulation of earth-oriented observations from space. Five cloud groups, including one for clear and one for overcast skies, are presented for 29 cloud climatological regions, for eight times of day and for each month of the year. In addition, conditional distributions were prepared to represent the temporal and spatial conditionality of the cloud cover 24 hours later or 200 nm away. These data are contained on 1740 punched cards. An additional 140 cards define the mar regions in latitude/longitude coordinates.

Marked changes in the cloud cover distributions corresponding to changes in the sampled area size are demonstrated. Techniques are presented to allow the ground observations (representing approximately a 30 nm circular area) to be transferred into distributions representing enlarged sample areas. Mathematical procedures are also presented to scale the conditional distributions to other times and distances.

Engineering and simulation applications of the cloud data bank are discussed, and two examples are given. One example demonstrates a Monte Carlo approach for establishing the sighting probability of a given set of landmarks. The other example uses an analytical approach to determine probable cumulative area coverages for a photographic mission using N orbital passes.

Printouts of the data, discussions of the data collection effort, and suggested subroutines for using the data are presented in the appendices.

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# 1. INTRODUCTION

Cloud cover is a significant operational element in all earth-oriented space experiments. The experimental success for many space missions is almost wholly dependent on the amount of obscuring cloudiness and on the operational procedures adopted to cope with it. Future earth-oriented experiments, especially those concerned with multiband synoptic photography, multichannel radiometry, infrared spectroscopy, and laser systems are all known to be extremely sensitive to the earth's cloud cover. In addition, proposed passive microwave systems are probably affected by certain cloud covers and certainly by rainfall intensities greater than a few millimeters per hour.

To perform proper mission analysis and simulation during the planning of future missions, and to determine the probable success of already planned earth-oriented space missions, statistical data on world-wide cloud distributions are required. These cloud statistics must be in a form that permits their easy use in a computer subroutine in mission analysis or simulation computer programs.

## 1.1 Objectives

The basic objective of the study reported in this document was the creation of a master file of tabulated cloud statistics and cloud distributions on a world-wide basis. A requirement was that these statistics be tabulated and made available either on IBM punched cards or magnetic tape such that statistical analyses of cloud amounts could easily be performed for monthly, seasonal, and annual reference periods for selected stations on the earth.

In addition, conditional statistics have been generated to take adequate account of the time and space dependence of the cloud regime at one point on that of another point which is nearby in either space or time. The tabulated statistics must include provisions for taking account of the diurnal variation in cloud cover throughout the day and night.

Several secondary objectives are also apparent. For example, a comparative analysis is desirable to determine the relationship between cloud cover as it might be viewed from a satellite versus that observed from the ground, so that the probability that the earth's surface can be observed from a satellite can be inferred from ground-observed data. An engineering interpretation of the tabulated cloud statistics and cloud distributions in terms of requirements for an earth satellite sensor operation should be performed as a demonstration of the use and validity of the tabulated statistics.

Several guidelines were provided in the contractual statement. These included the following:

1. A minimum number of stations should be selected for the purpose of characterizing the monthly, seasonal, and annual distributions of cloud types for selected regions which typify the diverse cloud types and frequencies.
2. The statistical data will be drawn from existing records, where possible, and extrapolated, interpolated and evaluated for appropriate areas over the earth.
3. Day-night and monthly reference periods may be feasible.

In addition to these stated guidelines, it became obvious early in the performance of the work that much could be gained from trips to NASA centers and to various NASA contractors to determine requirements for cloud cover data in current mission planning and simulation endeavors. This task has been included as a requirement and objective of the contract.

## 1.2 Specific Tasks

Certain specific tasks were involved in meeting the objectives. Five major tasks were defined. These included: (1) the definition of homogeneous cloud climatic regions; (2) the survey and collection of appropriate conventional and satellite cloud statistics; (3) the definition of mission simulation requirements; (4) the data tabulation; and (5) the assessment of engineering applications with a validation or test of the tabulated statistical data.

In the first task, earlier work on cloud climatology was reviewed to assess whether large-scale homogenous cloud regions could be defined such that the statistics from a single station within the region would adequately represent the entire region. This task led to the selection of 29 regions to represent the world-wide cloud climatology.

The second task was to survey and collect data to validate and establish that the regions did indeed represent homogenous cloud climatological regions. It was also necessary to determine whether representative data of sufficient record length could be obtained for all the chosen climatic regions. Where such conventional cloud climatological data did not exist, procedures for suitably synthesizing the data had to be established. In addition, it was determined that the cloud climates of certain Southern Hemisphere regions were replicated by a seasonal reversal of Northern Hemisphere stations, and that such Northern Hemisphere stations had a more reliable data base than any of the stations within the given Southern Hemisphere regions. In particular, many Southern Hemisphere stations had periods of record shorter than five years and many had only daylight observations.

During the mission simulation requirements definition study, effort was concentrated on visiting contractors and NASA centers directly involved in the simulation of manned and unmanned earth-oriented experiments from space. As a result of these visits, the simulation requirements for cloud cover data were established and a cloud model was defined. Data formats were defined and certain procedures for data manipulation were also developed. These data manipulation techniques principally involve the requirement for varied sampling area size associated with different sensors and different orbital heights. It was determined that cloud cover distributions are very dependent on viewed area size and thus some provision had to be made to allow the proper cloud cover probability distribution to be derived depending upon the viewed area size requirement. It was determined that conditional statistics for points near in time or distance to an initial point were also required.

## 1.3 Data Types

As indicated in the tasks outlined above, we have assembled two types of cloud cover data for use in computer simulations. Unconditional cloud cover statistics are frequency distributions of fractions of the sky covered, expressed in percent frequency. Because the diurnal and annual variations of cloud cover are important in most regions, the unconditional data are stratified or subdivided into distributions for each month and for 3-hour intervals throughout the day.

Conditional distributions are required for many potential applications of the data. These answer questions like, "What is the probability that the cloud cover over a certain area is 10/10 if it has already been observed that the cloud cover over a similar area 200 miles away is 10/10?" This probability is clearly higher than the unconditional probability of 10/10 at either point. We have assembled estimates of statistics from which such conditional probabilities can be generated, both in the space and time domains. Insufficient data were available to stratify these by time of day. A seasonal stratification has been provided.

Later sections of this report will elaborate on the nature and uses of these two types of statistics.

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# 2. REQUIREMENTS FOR CLOUD DATA

Nearly all earth-oriented experiments from space, whether they be photographic, manned sightings, or experiments using other electromagnetic sensors, are cloud sensitive to some degree. For example, if an experiment involves use of a camera-bearing orbiting platform as a means of photographing a specific area of the world to determine growth of some particular crop, the mission must operate during a particular season or month and succeed in photographing the desired area through cloudless skies. It may be possible to accept a photographic montage of the required area made up of pieces taken on a number of successive orbital passes some time apart; here the amount of film that must be expended to assure coverage becomes important, along with the elapsed time between adjacent pictorial segments.

Since space experiments are necessarily expensive and require a great deal of planning and operational control, computer simulation has become common. These simulations permit organization of orbits, communications, power profiles, and time lines for the conduct of experiments and of multi-experiment missions. Many simulation programs permit the inclusion of contingencies on a statistical or Monte Carlo basis. The presence of cloud over a ground target represents a contingency of more frequent occurrence than most; however, the incorporation of the cloud cover contingency has had to await the generation of suitable statistics and suitable procedures. The present study represents a first effort to provide an adequate set of data and procedures.

## 2.1 Simulation Requirements

Computer simulation may be used for a variety of purposes. A number of generic examples are described below.

### 2.1.1 Experiment Feasibility

Once the feasibility of sensors and associated equipment is established, it still remains to be demonstrated that experimental objectives have a reasonable chance of success in the real cloudy world. It is not sufficient to know that the earth is about 45% cloud covered if the sensing system requires a cloud-free area of considerable size; far fewer than 55% of candidate targets will be cloud free, and those that qualify will tend to cluster in a few climatologically cloud-free areas. Determination of the number and area distribution of such cloud-free areas to be encountered on the mission, and the statistical variability of that number, requires the application of suitably organized cloud statistics. (A sample solution is given in Section 9.2 of this report.)

### 2.1.2 Experiment Equipment Design

If the results of feasibility determination appear favorable, it is next desirable to specify appropriate features of the experimental equipment in such fashion that the experimental return is maximized. Continuing our example of the experiment requiring a large clear area, it may be desired to choose the activation of the experiment by: (1) an onboard timer, operating at regular intervals without consideration of the cloud field; (2) a controller programmed to activate the experiment at certain specific times derived from forecasts based on independently acquired meteorological satellite data; (3) an optical cloud sensor that activates the experiment when conditions are right; (4) an astronaut, alerted by forecast, using optical gear to identify and verify freedom from cloud. A cost-performance trade-off analysis would have to consider that alternatives (1) and (2) require some means of determining that the field of view was in fact cloud free if it is not obvious from the data themselves. Alternative (3) may be unsuitable if the sensor threshold results in experiment activation under the marginal conditions that would be encountered just before the spacecraft moves over a truly clear area. Here the question becomes one of establishing a suitable delay to maximize the probability of success.

It is clear that the alternatives have been listed in order of probable cost and of probable yield of good data. Cost effectiveness can only be judged by actual simulation of the performance of the experiment in each mode.

### 2.1.3 Experiment Time Line Preliminary Profiles (looking at one experiment at a time)

Continuing the example of the experiment requiring a large cloud-free area, let us assume that alternative (4), requiring astronaut attention for each execution, has been tentatively chosen. As a first approach to mission planning, simulating the performance of this experiment as if it did not compete for astronaut attention can give a clear idea of frequency and duration of calls for attention and of the interaction between the astronaut's physical capabilities and experiment performance. A possible outcome of this situation would be a decision to return to alternative (2) with a capability for astronaut override when he is available.

2.1.4 Experiment Integration (time line profiles looking at many instruments which comprise a single mission)

Some spacecraft systems, notably manned missions, must be organized so that not all experiments can be operated simultaneously. This restriction may result from mutual interference, peak power restrictions, limitation of on-board recording, telemetry capacity, or simply competition for attention of astronauts or ground controllers. A part of experiment integration then involves the establishment of time line rules which permit reasonable data yields while conforming to all constraints. A first approach might be to establish a set of fixed time lines that obey the constraints and then by simulation to evaluate the data return expected; if satisfactory, the time lines can stand. A more sophisticated approach, certainly essential in manned missions, is by simulation to evolve a set of objective techniques for the day-by-day or orbit-by-orbit construction of time lines based on observation and/or prediction of cloud cover. The data return from such fluid time lines is likely to be materially greater than from a more rigid system. The requirement for suitable cloud statistics in either case is self-obvious.

2.1.5 Mission Analysis and Optimization (this includes such items as logistics, data handling, sleep cycles, communications, integration with other contingencies, fuel stores, etc.)

The final synthesis of a manned mission occurs through the "mission simulation program" or a hierarchy of such programs. It is here that required adjustments can be made to make the mission reach its objectives within the constraints of saftey, payload, and the other system limitations. The complexity of such programs suggests that cloud-contingent elements be simulated on a sampled basis rather than throughout the mission. If possible, the results of the time line generator should be included.

2.1.6 Dynamic Programming (the real-time reprogramming of future mission activities based on cumulative mission accomplishment, current status, and a simulation of future activities to determine the optimum program)

A truly sophisticated mission simulation program will include simulation of dynamic programming. At any given point in the mission, the different experiments will have satisfied various fractions of their mission objectives as a result of cloud and other contingencies encountered. Simulation of the remainder of the mission can lead to an optimized strategy to maximize the total mission achievement. The same set of strategies can then be transferred to the real time dynamic programming of the mission. Here, a mixture of short-range forecast and cloud climatology provides the cloud background for simulation.

Simulation thus can be seen to require a set of cloud climatological data of fairly universal application. While other uncertainties in simulation preclude the necessity of extreme accuracy, the climatological data should have at least the following properties:

1. Provide global coverage
2. Provide cloud cover distributions in a readily useable, standard form
3. Give distributions by season, time of day, and some readily defined climatological region or grid
4. Provide expression of the spatial and temporal coherence of cloud cover
5. Provide for the expression of cloud cover distributions on a variety of scales of observation.

2.2 Design Objectives

The design objectives of the study discussed in this report were the preparation of a set of cloud statistics, on a world wide basis, for use in simulation of earth oriented experiments. To accomplish these objectives, we have performed a statistical analysis of cloud amounts for monthly, seasonal and annual reference periods, for various times of day, for selected stations which typify the various cloud types and frequencies over the globe. In addition to the task of assembly of such a bank of statistical data, we have also collected for each of the selected cloud climatological regions a set of both time and space conditional probabilities. Preliminary techniques for modifying these distributions for variable distances, times, and scales have been established.

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## 3. DESIGN OF CLOUD CLIMATOLOGICAL REGIONS

The practical use of cloud statistics in computer simulation routines dictates the subdivision of the earth into nominally homogeneous cloud climatic regions. The number of such regions is arbitrarily set by consideration of the data volume that must be handled by the computer and by the amount of suitable data available to us. Since tabulations are required of the diurnal variation of cloud cover, of spatial conditional cloud distributions, and of temporal conditional distributions, the number of regions was kept relatively small.

This section describes how 29 regions were defined from standard climatology. This information was obtained from general cloud summaries, both conventional and satellite observations, and cloud data from selected stations.

### 3.1 Climatological Systems and Cloud Cover Information Used

#### 3.1.1 Standard Climatological Classification Systems:

1. "Climatic Types of the Earth," after Köppen, (Haurwitz and Austin, (1944)).
2. "Climates of the Earth," Trewartha (1943).
3. "Distribution of the Principal Climates of the Earth," Thornthwaite (1941).

#### 3.1.2 General Cloud Summaries:

1. "Mean Monthly Cloudiness in Percentage of Sky Cover," (based on conventional data). Landsberg (1945).
2. "Global Cloud Cover for Seasons," (based on satellite data), Clapp (1964).
3. "Northern Hemisphere Monthly Cloud Charts," (based on all available data), USAF -ETAC (1967).
4. "Analysis of Mean Cloud Amounts for all Landmarks, Winter and Summer Seasons," (based on satellite data), Barnes, et al (1967).
5. "Average Monthly Cloud Cover for the Global Tropics," (based on satellite data), Sadler (1966).

3.1.3 Cloud Data for Individual Stations

1. "Mean Sky Cover, Sunrise to Sunset, Monthly and Annual, for the United States," (based on conventional data), United States Weather Bureau (Office of Climatology, 1961).

2. "The Annual and Diurnal Variations of Cloud Amounts and Cloud Types at Six Arizona Cities," (based on conventional data), Sellers (1958).

3. "Mean Monthly Cloud Cover Over the USSR," (based on conventional data), Elliott (1960).

4. "Uniform Summary of Surface Weather Observations," for selected stations (conventional data summaries), National Weather Records Center.

3.2 Design Procedures

The procedures employed in the design of the cloud climatological regions are summarized below:

1. The climatological classification system of Köppen was transposed to a large base map of the earth.

2. Climatological boundaries determined by criteria based on temperature alone were deleted.

3. Over land areas, the regions were redrawn to conform more closely with the systems designed by Trewartha and Thornthwaite. These systems are somewhat simpler than Köppen's, and the Thornthwaite system is based more strongly on precipitation differences, which would be related (at least to some degree) with cloudiness. The Köppen system was the only one extending over ocean areas.

4. Boundaries of the initial map, based on the above general climatological considerations, were redrawn with reference to world-wide maps of mean monthly cloud amounts.

5. Further modifications were made in tropical areas, based primarily on the satellite observations summarized by Sadler. Since conventional data are particularly sparse throughout the extensive tropical ocean areas, the climatological regions were redrawn to conform closely with those derived from the satellite data. These regions were derived from mean monthly cloud amount charts by differentiating regions with considerable, moderate, and little cloudiness throughout the year, and regions with various magnitudes of seasonal change in cloud amount.

6. Similar but less extensive modifications were made in extratropical areas, based on the ETAC cloud summaries. Seasonal distributions of mean monthly cloud amounts were plotted for several grid points in areas where climatological region boundaries were uncertain. From comparisons between these distributions, the boundaries were redrawn.

7. Final adjustments to the climatological region boundaries were made in selected areas from comparisons of the seasonal distributions of mean monthly cloud amounts for individual stations. For example, the design of the regions within the United States was completed in this way.

8. To facilitate computer programming, the climatological region map was adjusted to consist of straight line boundaries, falling on even degrees of latitude and longitude. The resulting regionalization is shown in Figure 3-1.

9. Predominant cloud types and estimated diurnal cloud amount distributions, based on general climatological considerations, were assigned to each region.

10. The cloud climatological regions were numbered consecutively from 01 through 29. As seen in Figure 3-1, most regions are repeated two or more times throughout the world.

For the interested reader, each of these procedures are discussed in some detail in the paragraphs below.

### 3.2.1 Use of Standard Climatological Classification Systems

The initial procedure in the design of the climatological regions was the preparation of a preliminary climatological map based on the standard classification systems. A combination of the Trewartha (1943) and Thornthwaite (1941) systems was used over land areas; Köppen's more complex system (Haurwitz and Austin, 1944) provided the only information over the oceans. The Thornthwaite system is based more strongly than the others on precipitation differences, and so is more applicable to the design of a cloud climatology. In any case, classifications based on temperature differences alone were disregarded.

### 3.2.2 Modifications Based on Cloud Cover Information

The preliminary climatological map was modified through information provided by existing cloud amount summaries, based both on conventional and satellite data. These modifications were limited, in general, to the area between 60°N and

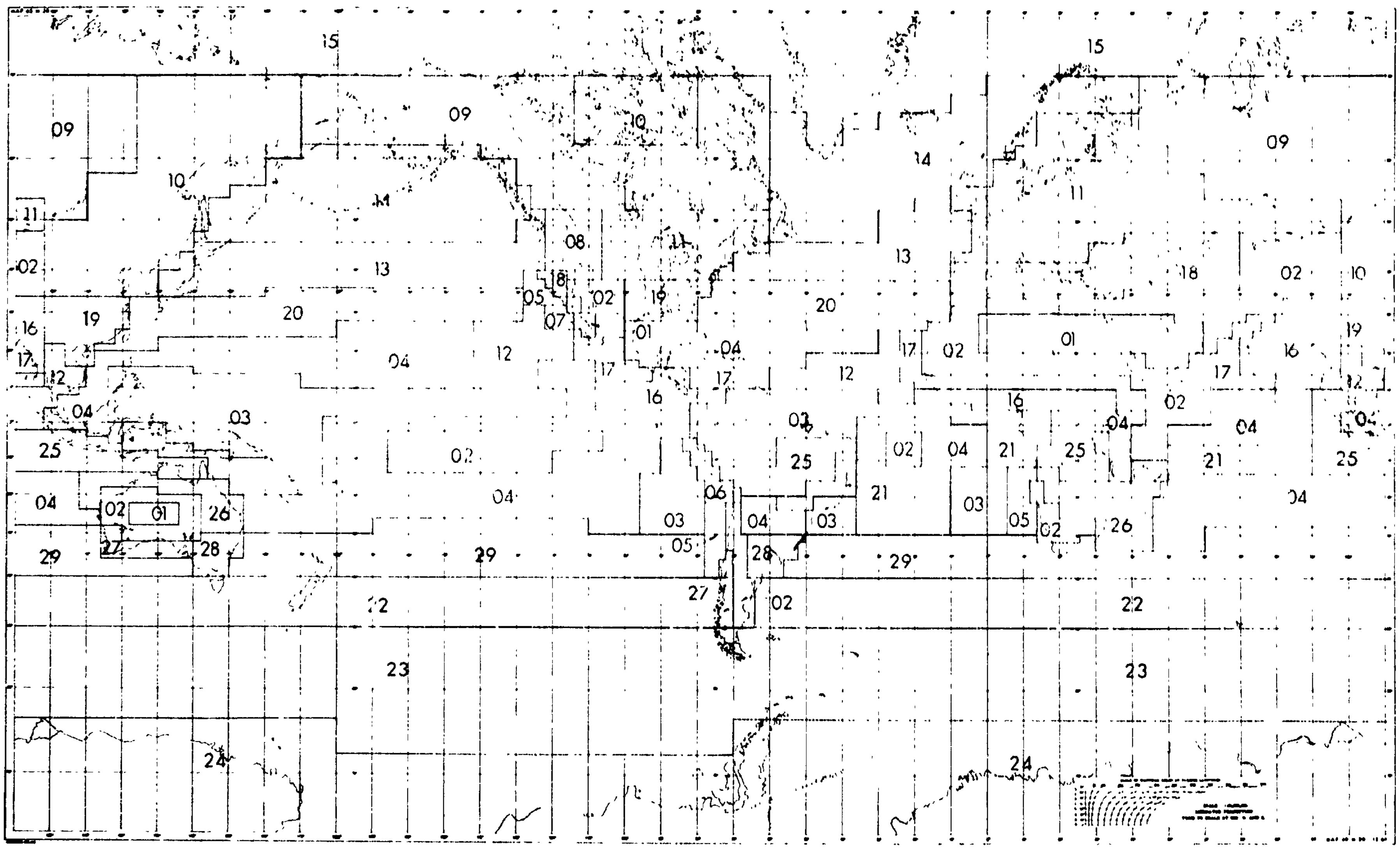


Figure 3-1 Region Location Map for World Wide Cloud Cover Data

$60^{o}S$, the area of primary interest. Furthermore, few cloud data were available from the polar regions. World-wide charts of mean monthly cloud amounts, prepared by Landsberg (1945), and seasonal charts from Clapp (1964), were used as references. Further modifications in tropical areas were derived from Sadler's data (Sadler, 1966) and in extratropical areas from the ETAC (USAF, 1967) data. Detailed studies over limited areas (Office of Climatology, 1961), (Sellers, 1958), (Elliot, 1960) and data summaries for individual stations provided the information for final adjustment of boundaries.

Due to the large amount of ocean in tropical areas, cloud summaries based on conventional data are of limited value. Therefore, the design of the climatological regions in tropical areas was based primarily on satellite-observed cloudiness, as studied by Sadler (1966). Results of the study by Barnes, et al (1967) were also referred to in specific areas.

Sadler determined the mean cloud cover for each 2-1/2$^{o}$ block between $30^{o}N$ and $30^{o}S$ from once per day satellite observations from May 1966 through February 1967. The cloud amounts were extracted from nephanalyses, and since TIROS data were used for the earlier months, complete daily global coverage was seldom available. Mean monthly cloud amounts for each block were computed from the daily values. In the design of the climatological regions, global analyses of these mean monthly cloud amounts were used.

Limitations to the use of the Sadler study include the relatively short data period, the availability of only one observation per day, and the large size of the areas from which cloud amounts were extracted. The significance of the 2-1/2$^{o}$ blocks, as compared to the smaller area viewed by a ground observer, will be discussed further in Section 7. Despite these limitations, however, this study was believed to provide the most meaningful data available for the design of cloud climatological regions in the tropics.

Since no satellite cloud studies of the scope of the Sadler study were available for extratropical areas, studies based on conventional data were referred to for modification of the original climatological regions. Northern Hemisphere cloud charts, obtained from ETAC (USAF, 1967) provided the principal data source. These charts, prepared from the Global Weather Central daily analyses for 0000 GMT and 1200 GMT, give monthly mean cloudiness and frequency of occurrence of clouds at each of the 1977 GWC grid points.

### 3.2.3 Application to Simulation Programs

For application to computer simulation programs, the climatological region map was adjusted to consist of straight-line boundaries. To accomplish this, the earth's surface was considered to be made up of $2^{\circ} \times 2^{\circ}$ blocks, and the boundaries were drawn to conform to the blocks. This trade-off for simplification of programming significantly affects climatological accuracy only in areas where the natural boundaries are determined by coastlines or mountain barriers. Among such areas are the west coasts of North and South America (see Figure 3-1).

The mean monthly cloud cover was the principal factor in differentiating between climatological regions. The absolute cloud amount, the season of maximum cloudiness, and the magnitude of the seasonal change were all taken into account. Some consideration was also given to cloud type, with each region being designated as having predominantly convective cloudiness (tropics) or predominantly synoptic scale cloudiness (extratropical areas). For example, areas off the west coasts of continents where widespread stratus is common, were so designated. Studies such as those by London (1957) and Seide (1954) provided some guidance in assigning cloud types. Through general climatological considerations and cloud summaries for specific stations, the probable diurnal variation in cloud amount was also determined for each region.

Separate climatological regions have generally been designed for land and ocean areas. Certain regions, however, such as numbers 03 and 04, contain mostly ocean, but also some continental land areas and many islands. Since these are tropical regions, considerable difference in the cloud regimes, particularly in the diurnal variations, might be expected. In such regions the input statistics were necessarily derived from land stations, and, therefore, properly apply to land areas. In extratropical areas, statistics for ocean regions were summarized from ocean ship stations. Also, in the design of the climatological regions, mountainous areas were not designated. In such areas, cloud regimes could be significantly different (generally greater cloud amounts) than indicated by the statistics for that particular region.

As can be seen in Figure 3-1, many regions have a relatively narrow meridional dimension, a reflection of more rapid changes in cloud climatology with latitude than with longitude. The results of the conditional probability computations for a north-south group of stations, discussed in Section 4.2.4, tend to confirm the choice of narrow regions.

### 3.3 Descriptions of Regions

A description of each cloud climatological region is given in Table 3-1. It must be remembered that these descriptions are generalizations, based primarily on seasonal distributions of mean monthly cloud amount. The final cloud statistics for each region were derived from a representative station, as discussed in Sections 4 and 5. These statistics involve cloud amount frequency distributions, and therefore are in a more detailed form than is presented by the general descriptions given in Table 3-1.

Table 3-1

General Description of Climatological Regions

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| Region Number | General Description | Location | Seasonal Change in Cloud Amount | Mean Monthly Cloud Amount Jun-Aug (in Percent) | Mean Monthly Cloud Amount Dec-Mar (in Percent) | Predominant Cloud Type | Diurnal Variation in Cloud Amount | Hour of Maximum Cloud Amount (Local Time) |
| 01 | Essentially Clear | Major Desert Area | Small | < 20 | < 20 | -- | Small | ---- |
| 02 | Little Cloudiness | Sub-Desert Areas | Small | <40 | < 40 | -- | Small | ---- |
| 03 | Tropical Cloudy | Near Equator | Small | >60 | >60 | Convective | Large | 1600 |
| 04 | Tropical Moderate Cloudiness | North or South of Region 03 | Small | ~50 | ~50 | Convective | Large | 1600 |
| 05 | Desert Marine | Over Ocean - off West Coasts | Small | ~50 | ~50 | Stratiform | Large | 0800 |
| 06 | Desert Marine Cloudy Winter | Over Ocean - West of Peru | Extreme | >70 | < 30 | Stratiform | Large | 0800 |
| 07 | Desert Marine Cloudy Summer | Over Ocean - West of Baja California | Extreme | >70 | < 30 | Stratiform | Large | 0800 |
| 08 | Mid Latitude - Clear Summer | North America | Extreme | <40 | ~70 | Synoptic Scale | Small | ---- |
| 09 | High Latitude - Cloudy Summer | North America, Asia | Moderate | ~70 | ~50 | Synoptic Scale | Small | ---- |
| 10 | High Latitude - Clear Winter | Asia, North America | Extreme | ~70 | <30 | Synoptic Scale | Small | ---- |
| 11 | Mid Latitude - Land | Northern Hemisphere | Moderate | ~50 | ~70 | Synoptic Scale | Small | ---- |
| 12 | Tropical - Cloudy Summer | North of Region 03 | Moderate | >60 | ~50 | Convective | Large | 1600 |
| 13 | Mid Latitude - Ocean | Northern Hemisphere | Moderate | ~60 | >70 | Synoptic Scale | Small | ---- |

Table 3-1 Cont'd

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| 14 | High Latitude - Ocean | Northern Hemisphere | Moderate | >80 | ~70 | Synoptic Scale | Small | ---- |
| 15 | Polar | Northern Hemisphere | Small | ~60 | ~60 | Synoptic Scale | Small | ---- |
| 16 | Tropical - Seasonal Change | North of Region 03 | Extreme | >70 | ≤ 40 | Convective | Large | 1600 |
| 17 | Tropical - Clear Winter | Northern Hemisphere Near Region 16 | Moderate | ~50 | <30 | Convective | Large | 1600 |
| 18 | Mediter-ranean | Northern Hemisphere Europe, Western North America | Extreme | ~30 | -- | Convective | Small | ---- |
| | | | | -- | ~60 | Synoptic Scale | Small | ---- |
| 19 | Sub Tropical | Northern Hemisphere ~30N | Moderate | <50<br>-- | --<br>~60 | Convective<br>Synoptic Scale | Large<br>Small | 1600<br>---- |
| 20 | Sub Tropical - Ocean | Northern Hemisphere ~30N | Moderate | ~50<br>-- | --<br>>60 | Convective<br>Synoptic Scale | Small<br>Small | ----<br>---- |
| 21 | Tropical - Cloudy Summer | South of Region 03 | Moderate | ~50 | >60 | Convective | Large | 1600 |
| 22 | Mid Latitude Ocean | Southern Hemisphere | Moderate | >70 | ~ 60 | Synoptic Scale | Small | ---- |
| 23 | High Latitude - Ocean | Southern Hemisphere | Moderate | ~70 | > 80 | Synoptic Scale | Small | ---- |
| 24 | Polar | Southern Hemisphere | Small | ~60 | ~ 60 | Synoptic Scale | Small | ---- |
| 25 | Tropical - Seasonal Change | South of Region 03 | Extreme | <40 | > 70 | Convective | Large | 1600 |
| 26 | Tropical - Clear Winter | South of Region 25; Africa, Australia | Moderate | <30 | ~50 | Convective | Large | 1600 |
| 27 | Mediter-ranean | Southern Hemisphere Australia, Chile | Extreme | -- | ~30 | Convective | Small | ---- |
| | | | | ~60 | -- | Synoptic Scale | Small | ---- |
| 28 | Sub Tropical Land | Southern Hemisphere ~30S | Moderate | --<br>~60 | < 50<br>-- | Convective<br>Synoptic Scale | Large<br>Small | 1600<br>---- |
| 29 | Sub Tropical - Ocean | Southern ~30S | Moderate | --<br>>60 | ~50<br>-- | Convective<br>Synoptic Scale | Small<br>Small | ----<br>---- |

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# 4. DATA SOURCES

## 4.1 Unconditional Distributions

### 4.1.1 Data Search

Following completion of the initial climatological region selection, discussed in Section 3, data were obtained for approximately 100 observing stations distributed throughout the world. For as many regions as possible, single representative stations were selected from this sample, and unconditional cloud statistics were derived from the data summaries for this stations. As discussed more fully in Section 5, the cloud climatologies for several Southern Hemisphere regions were taken as being seasonal reversals of similar Northern Hemisphere regions. For some regions, where representative data could not be obtained, these statistics were modified from those of other regions, based on climatological considerations.

An initial selection of stations was made to obtain data to represent the cloud climatic regions. The initial search was based on station locations indicated on Northern and Southern Hemisphere upper air Raob and Rawinsonde network charts (NWRC, 1962, and NWRC, 1963. Station names and coordinates were checked in the Weather Station Index (U. S. Naval Oceanographic Office, 1964). A visit to the National Weather Records Center, revealed that useable data were not available for several of the originally selected stations. Wherever possible, nearby stations were substituted. The final data sample consisted of 108 stations.

### 4.1.2 Data Form

Cloud observations from different parts of the world are summarized in various forms. In addition, observational times, and even observing techniques, vary from place to place. The data summaries from which the unconditional distributions were derived where three basic forms: (1) Revised Uniform Summary of Surface Weather Observations (A-F), (2) Original Uniform Summary of Surface Weather Observations (A and B), and (3) NIS*or N-Summary. Of the 108 stations, the Revised Uniform Summaries were available for 33, the Original Uniform Summaries for 23, and the NIS Summaries for 52 stations. Most of the NIS Summaries were designated as Old Type N-Summaries. In addition, ten years of raw data (on magnetic tape) were obtained for six ship stations. Unconditional distributions were derived directly from these data

* National Intelligence Survey

The Revised Uniform Summaries provided the most useable data. For these stations, cloud amounts are summarized in tenths by percentage frequency; frequencies are given for three-hourly groups for all months. The stations for which the Revised Uniform Summaries are available are concentrated in only a few climatological regions, particularly those within the United States. These summaries also exist, however, for several United States Air Force bases throughout the world.

Original Uniform Summaries for most stations are in a similar form, except the number of observations is given instead of the percentage. For some stations, however, the cloud amounts are not broken down by tenths, but by categories such as clear, scattered and low broken; for these summaries, it was necessary to assign a cloud amount to each category.

The N-type Summaries were in the least useable form, since the summarizing procedures vary from station-to-station. The most common form gives the mean number of days per month with the following sky covers: 0-1/8, 0-2/8, 3-6/8, and 6-8/8. Moreover, the data are generally available for only a few hours of the day. These summaries, therefore, required considerable reworking to be of use for the intended application.

#### 4.1.3 Representative Stations

The stations representative of each region, from which the unconditional statistics were derived, are given in Table 4-1* The type of data summary available and the number of years of observation are also given. The climatological regions for which the statistics were modified from other regions are so indicated.

### 4.2 Conditional Distributions

Cloud statistics conditional with regard to time and to space were compiled for each climatological region. From the temporal conditional distributions, the cloud amount probability distribution for "tomorrow" can be determined given a cloud amount "today." Similarly, from the spatial conditional distributions, the cloud amount probability distribution for a location at a specified distance from a base location can be determined for a given cloud amount at the base location.

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* Validation of representativeness of the stations can be found in Section 5.1.3 and Appendix A.

Table 4-1

Representative Stations for Unconditional Distributions

| REGION NUMBER | STATION | COORDINATES | TYPE OF DATA | YEARS OF RECORD |
|---|---|---|---|---|
| 1 | Dhahran, Saudi Arabia (Airfield) | 26-17N 50-09E | 2 | 11 |
| 2 | Tripoli, Libya (Wheelus AFB) | 32-54N 13-17E | 1 | 19 |
| 3 | Angeles, Luzon, P. I. (Clark AFB) | 15-11N 120-33E | 1 | 21 |
| 4 | Tampa, Florida (MacDill AFB) | 27-51N 82-30W | 1 | 23 |
| 5 | Los Angeles, California (WBAS) Hours 10-19 (May-October) Modified | 33-56N 118-23W | 1 | 19 |
| 6 | Talara, Peru 01 and 22 Hours-Synthetic | 04-32S 81-14W | 2 | 5 |
| 7 | Synthetic Data | | | - |
| 8 | Mountain Home, Idaho (AFB) | 43-03N 115-51W | 1 | 20 |
| 9 | Fort Yukon, Alaska (WB) | 66-35N 145-18W | 2 | 18 |
| 10 | Harbin, China | 45-45N 126-38W | 3 | 7 |
| 11 | Belleville, Illinois (Scott AFB) | 38-33N 89-51W | 1 | 27 |
| 12 | Ban Me Thuot, Vietnam (City Airport) | 12-41N 108-07E | 1 | 10 |
| 13 | Ship D (Atlantic) | 44-00N 41-00W | 4 | 10 |
| 14 | Adak, Alaska (NS) | 51-53N 176-38W | 1 | 25 |
| 15 | Resolute, NWT, Canada | 74-41N 94-55W | 2 | 7 |
| 16 | Fort Kobbe, Canal Zone (Howard AFB) | 08-55N 79-36W | 1 | 19 |
| 17 | Bangalore, India (Hindustan Airport) | 12-57N 77-38E | 3 | 7 |
| 18 | San Francisco, California (WBAS) | 37-37N 122-23W | 1 | 18 |
| 19 | Shreveport, Louisiana (Parksdale, AFB) | 3[illegible]-30N 93-40W | [illegible] | 27 |
| 20 | Ship V (Pacific) | 31-00N 164-00E | 4 | 10 |
| 21 | Seasonal Reversal of Region 12 | | | |
| 22 | Seasonal Reversal of Region 13 | | | |
| 23 | Seasonal Reversal of Region 14 | | | |
| 24 | Seasonal Reversal of Region 15 | | | |
| 25 | Seasonal Reversal of Region 16; Hours [illegible], 13, 16 for May - September Modified | | | |
| 26 | Seasonal Reversal of Region 17 | | | |
| 27 | Seasonal Reversal of Region 18 | | | |
| 28 | Seasonal Reversal of Region 19 | | | |
| 29 | Seasonal Reversal of Region 20 | | | |

**Legend for Type of Data:**

(1) Revised Uniform Summary (A-F)
(2) Original Uniform Summary (A and B)
(3) NIS Summary
(4) Raw Data (Ship Stations)

Satellite observed cloud amounts were used to derive the conditional statistics because the effort involved in summarizing raw conventional cloud data from various parts of the world would have been prohibitive. Satellite observations were obtained for most of the climatological regions; probability distributions for the remaining regions were adopted from the statistics available for hopefully comparable regions.

4.2.1 Data

For tropical areas, between about 30°N and 30°S, little new data extraction was necessary, as use could be made of data on hand from previous studies. From a study of the cloud obscuration of terrestrial landmarks to be used in the Apollo Navigation System (Barnes, Beran, and Glaser, 1967), daily satellite-observed cloud amounts were available for 100 landmarks (stations) in the tropics. Although these stations were not evenly distributed, observations were available for most tropical climatological regions. The cloud amounts in this data sample were extracted from within circular areas of one degree latitude diameter.

Data collected in the study by Sadler (1966), see Section 3.2.2, were also examined for possible use in deriving the conditional probability statistics. As discussed in Section 4.2.2, these data were found to be not useful for these purposes.

In extratropical areas, cloud amounts were extracted for several locations (stations) within each major climatological region. The statistics for some regions, particularly those of smaller size, were modified from the results for other regions. The stations for which data were extracted, generally five to ten for each region, were usually oriented along an east-west line providing uniform distributions for the computations with regard to distance. As in tropical regions, the cloud amounts were for one degree circular areas.

Summer and winter (Northern Hemisphere) data samples were obtained. The summer sample, obtained from Nimbus II AVCS photography consisted of all available observations during June, July, and August 1966, the period of operation of this satellite. The winter sample consisted of observations taken during December, January, and February, 1966-67, by the ESSA-3 satellite. A limited data sample was also obtained from the ESSA-5 satellite, for June, July, and August 1967. For discussions of short sample periods, etc., see Section 5.1.2.

Although the nominal camera resolution of the Nimbus AVCS photography is 0.5 miles, compared with two miles for the ESSA satellites, the improved picture quality of the ESSA photography provided data of at least comparable value. The summer 1967 sample from ESSA-5 provided an opportunity for a limited comparison with the Nimbus data for a similar period in 1966.

#### 4.2.2 Temporal Conditional Distributions

Computations for temporal conditional distributions were carried out for time periods of 24 and 48 hours. Observations from several stations within the same climatological region were combined to provide a more meaningful data sample. In most regions, from five to seven stations were used. In addition, probabilities were computed on a seasonal rather than monthly basis, to further increase the sample size. Even so, samples were materially smaller than desirable.

The results indicated little conditionality past 24 hours, therefore, only the 24 hour probabilities were included in the final statistics. Methods were developed for computing temporal conditional statistics in other increments of time (see Section 6).

For regions 13 and 20, temporal conditional distributions have been compiled from raw ocean ship observation data during processing of these data for unconditional distributions. It is reassuring to find that these compilations are similar in kind to those obtained from much shorter samples of satellite data.

The statistics derived from the Sadler satellite data sample were strongly biased toward middle cloud amounts (3, 4, 5 octas), and therefore, were not used. These results emphasized the magnitude of the sampling area size problem, discussed in detail in Section 7.

#### 4.2.3 Spatial Conditional Distributions

In each regional group of stations, a "base" station was selected to become the "given" for each of the other stations in the group. In the tropical data sample the stations were not evenly distributed. The stations selected for the extratropical regions were evenly distributed in an east-west direction. In both samples, distances between stations varied from approximately 100 to 1,000 nm. As with the temporal distributions, seasonal compilations were made to increase the size of the data sample.

In addition to the compilation of conditional cloud frequency distributions, correlation coefficients were computed as a guide to the significance of the statistics. In general the correlations were found to decrease rapidly with distance, characteristically reaching a value of 0.6 at an average distance of about 200 nm.

4.2.4 North-South Data Sample

As discussed above, the spatial conditional data points for most of the climatological regions were oriented in an east-west direction. To examine the effect of this orientation, a sample was also obtained for a group of five stations oriented north-south, from region 11 for a single season. The data were extracted from ESSA-5 photography for the summer of 1967.

The resulting unconditional cloud frequency distribution for the five stations combined is, of course, very similar to that obtained for a group of east-west stations in the same region. Temporal conditional distributions are also similar to those computed for the east-west sample. In the spatial domain, however, the correlation between stations appears to decrease with distance more rapidly in the north-south group of stations. While the correlations are similar in the two groups for stations about 120 nm apart, a much lower correlation was obtained in the north-south sample for stations about 300 nm apart (a correlation coefficient of 0.14, compared to 0.64 for the east-west group).

The decrease in correlation in the north-south direction probably reflects the more rapid changes in cloud climatology with latitude than with longitude. This result tends to confirm the choice of a narrow latitudinal dimension for many of the climatological regions.

# 5. DESCRIPTION OF DATA

## 5.1 The Basic Statistics - Unconditional Distributions

### 5.1.1 Discussion of Data Sources

For purposes of simulation of earth observation from space on a global basis, the earth's surface has been divided into 29 regions, chosen to have reasonably homogeneous cloud cover distributions. The problems of delineation of homogeneous regions are discussed in Section 3. Region boundaries have been arbitrarily set to fall on even $2^{\circ}$ lines of latitude and longitude to simplify computer determination of the region in which a selected surface point occurs.

A single observing station with a reasonable length of good record is used to characterize the region, even where areas of the same regional designation occur widely separated from each other about the globe. Tests indicate that this is a reasonable procedure if the chosen station is in fact representative of the region (see Section 5.1.3). However, in some regions the paucity of summarized data makes necessary the adoption of cloud cover distributions without validation.

Cloud cover distributions, as discussed in Section 4.1, are summarized in different ways by the various meteorological services, and there are somewhat varying instructions to the observer. As will be appreciated from the considerations of Section 7, a major factor affecting representativeness of individual distributions is the field of view available to - or used by - the observer. Restricted fields will tend to produce more U-shaped distributions.

Because of the problems of representativeness and of probable cloud amount overestimation (see Section 5.1.2) it seems unnecessary to present cloud cover distributions in much detail. Reduction of the number of classes into which the cover is distributed permits greater data compaction and speedier computation. Five cloud cover categories have been designated, as displayed in Table 5-1. The allocation of cloud to category is based on consideration of simulation requirements (see Section 2).

Table 5-1
Cloud Category Designation

| Category | Tenths | Eighths (Octas) |
|---|---|---|
| 1 | 0 | 0 |
| 2 | 1, 2, 3 | 1, 2 |
| 3 | 4, 5 | 3, 4 |
| 4 | 6, 7, 8, 9 | 5, 6, 7 |
| 5 | 10 | 8 |

It will be noted that the intervals are unequal in size and that the categorization from data in tenths differs slightly from that from data in eighths. The bulk of the data available was expressed in tenths of sky cover; about 25% of the summaries were expressed in eighths. It is possible to adjust distributions to make the data expressed in eighths absolutely comparable to those expressed in tenths, but this involves some assumption as to the distribution of cloud cover within a cloud cover group. Moreover, the magnitude of any adjustment would surely be smaller than the error inherent in assuming that a chosen station is representative of its region.

In the two regions with N-type summaries (see Table 4-1), the available data are not only expressed in eighths but in a grouped form that does not explicitly give the frequency of clear or overcast. In these cases, the frequencies were estimated by plotting and extrapolating the available data (also see Appendix A).

Other than cloud climatological region, the factors having the greatest effect on cloud cover distribution are season and solar time. Accordingly, the cloud distributions are given for each month of the year and at three-hour intervals in the solar day. In those cases where an equivalent cloud climatological region occurs in both hemispheres, the seasons are inverted by shifting six months, and a new regional designation is provided. Validation tests have shown this to be a reasonable procedure, better than accepting data from a location known to be unrepresentative.

### 5.1.2 Data Quality

Cloud cover data obtained from surface observations are not strictly comparable to cloud cover as it would be seen from space (see Section 5.5). The surface observer usually has a limited field of view, maximum radius of about 30 miles, dependent upon ambient visibility and obstructions. However, the observer tends to weight the inner few miles rather heavily, as he is told that half of the dome of the sky occurs above an elevation angle of 30°.

The observer's view of cloud sides, particularly in the half of the dome of the sky below 30°, causes him to overestimate the cloud cover in most types of scattered or broken cloud situations. Studies of the degree of overestimation have been made by Appleman (1962), Lund (1965 and 1966), McCabe (1965), and Watson (1965), among others.

Because of the heterogeneity of our data sources and the lack of useful data on cloud type versus cloud cover, we have made no effort to compensate for this known overestimation. The degree to which the mean cloud cover is affected by overestimation is very much dependent upon the nature of the observed cloud distribution. Regions that exhibit "U" or "J" shaped distributions, with low probability of broken cloud, will not be greatly overestimated. Regions of bell-shaped cloud cover distribution, where broken cloud is preponderant, will suffer significantly more overestimation than other regions.

Certain compensating factors make it undesirable to attempt broken cloud-amount correction in any event. Photographic-type observation is perturbed by cloud shadows. The amount of shadow extending beyond the vertical projection of the cloud is controlled by many of the same factors that lead to the observer's overestimate of cloud amount.

Wide-angle photography or infrared scanning will also suffer reduced coverage from views of cloud sides in the portions of the field of view removed from the spacecraft subpoint. In this case, other atmospheric effects that accompany partial cloud cover may work to reduce coverage even more sharply than the ground observer's cloud cover overestimate would indicate.

Coverage by radiometers or radars will be limited by the interaction of the wings of the acceptance beam (beyond the half-power points) with clouds. Characteristic earth surface spot sizes are sufficiently large in most cases to compare with inter-cloud gaps, so that the fraction of the surface available uncontaminated by cloud may be distinctly smaller than the cloud cover would indicate.

In manned experiments where it is required that the astronaut find a ground target, it is usually necessary that the target be acquired when it has approached a depression angle of about 45°. This gives a sufficient opportunity for study or instrumental observation as the spacecraft passes overhead. The combined effects of the perspective view of cloud sides and the confusion resulting from the differing relative motion of cloud layers and the ground, very likely reduce the probability of successful acquisition and tracking to a value comparable to that predicted from the ground observer's overestimate of cloud cover. We hope that controlled experiments can be performed in the Apollo Applications program to evaluate these effects.

5.1.3 Data Validation

Certain assumptions have been made in laying out our approach to the data presentation. We here will examine their validity.

5.1.3.1 Regional Homogeneity

Wherever possible, cloud cover distributions for all stations available within a region have been compared with samples of the tabulated statistics of the chosen stations. Usually, comparisons were made for a winter and a summer month, and for two times of day, usually early morning and late afternoon. Such comparisons were made for 15 of the 20 basic regions.

Figure 5-1 shows the cloud distribution for Region 11, which covers the northeastern United States and North Central Europe. Distributions for six stations are shown, ranging in apparent climate from that of Minot, North Dakota, through Kennedy Airport at New York City, to Furth, Germany. The "prototype" we have chosen for the region is Scott AFB, at Belleville, Illinois. It can be seen that winter cloud cover is remarkably similar at all stations; summer cloud cover is more variable, particularly in the incidence of clear and overcast skies. However, the character of the summer distributions are quite similar.

Figure 5-2 shows distributions for Region 1, comprising desert areas. Dhahran is the "prototype." The data have been graphed in the only common form available. Distributions are so similar the year around that we did not reverse the seasons for Alice Springs, Australia, although a slight improvement in representativeness would have resulted from such a reversal.

Appendix A presents all distributions used for validation.

5.1.3.2 Seasonal Reversal

In 9 cases, prototype data from the Northern Hemisphere, available in suitable form, were used to define the cloud climatologies of Southern Hemisphere regions, where suitable data were not available. The other 11 regions either occur in only one hemisphere, or occur in both hemispheres without need of seasonal transposition. We have verified the validity of the procedure in three of the seasonal reversal cases. Figure 5-3 compares the cloud cover distribution of Adak, in the Aleutians, with Campbell Island, South of New Zealand, and Laurie Island, in the South Orkneys east

## REGION 11

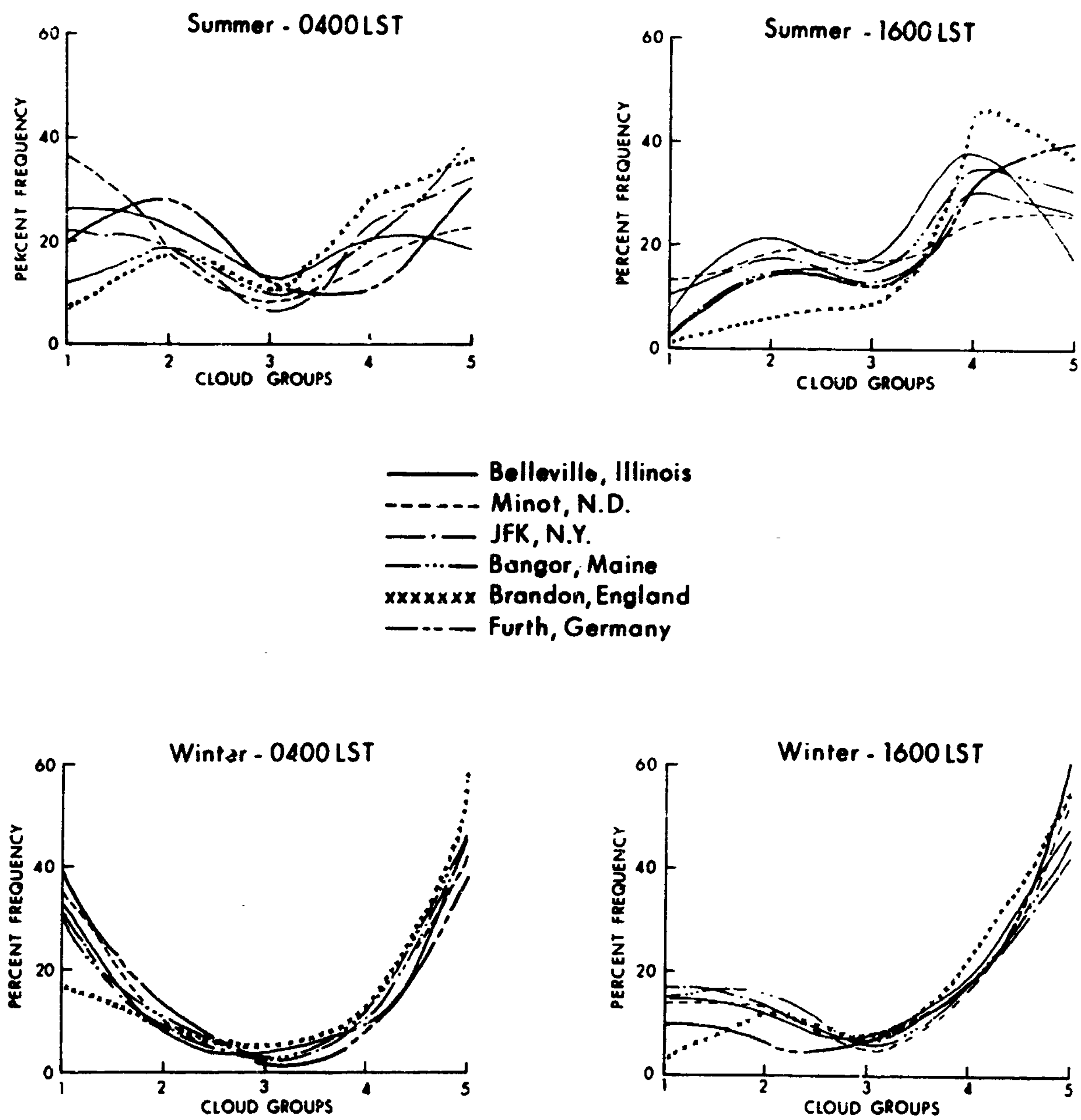


Figure 5-1 Cloud Cover Distributions Demonstrating Regional Homogeneity for Region 11

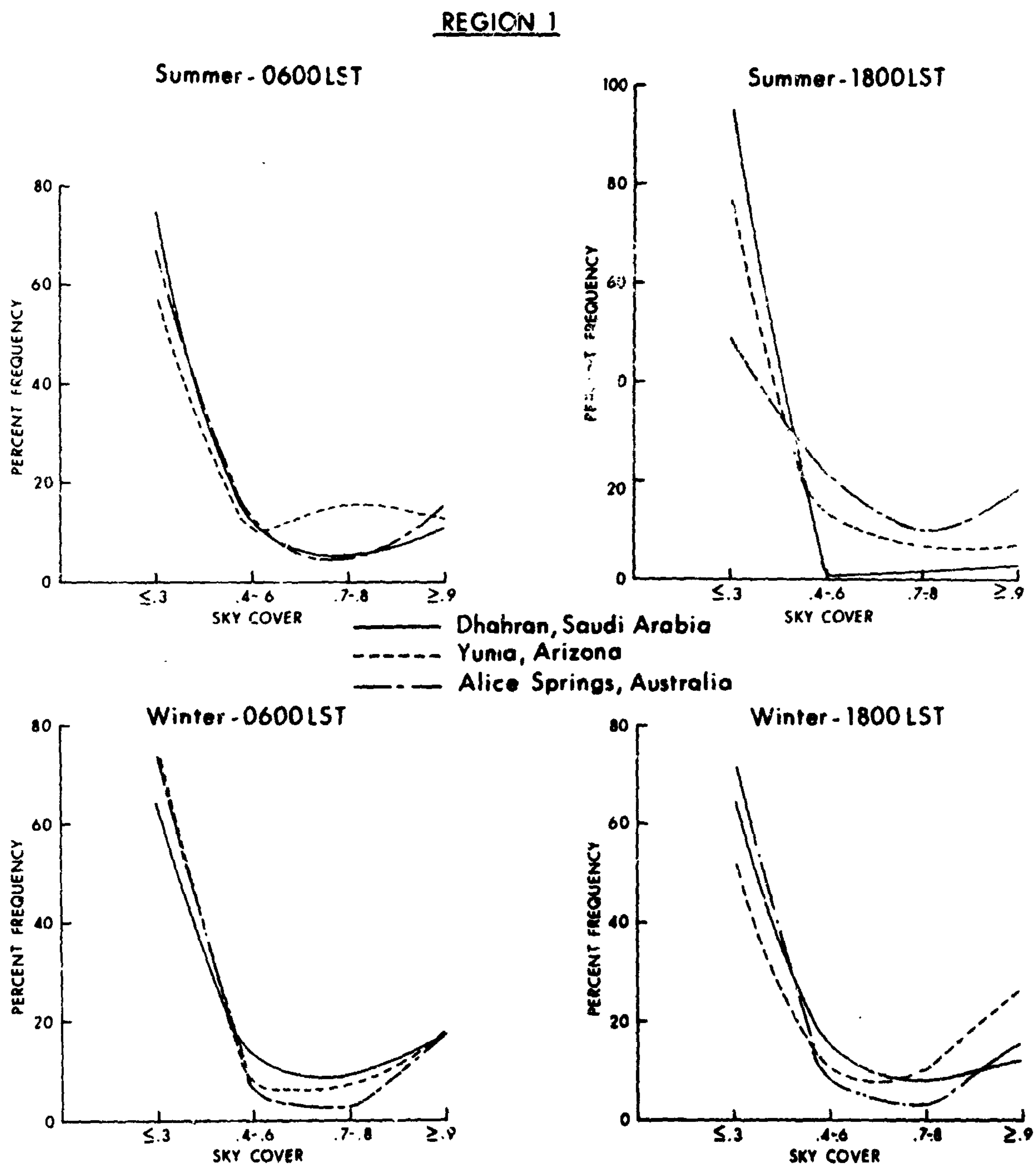


Figure 5-2 Cloud Cover Distributions Demonstrating Regional Homogeneity for Region 1

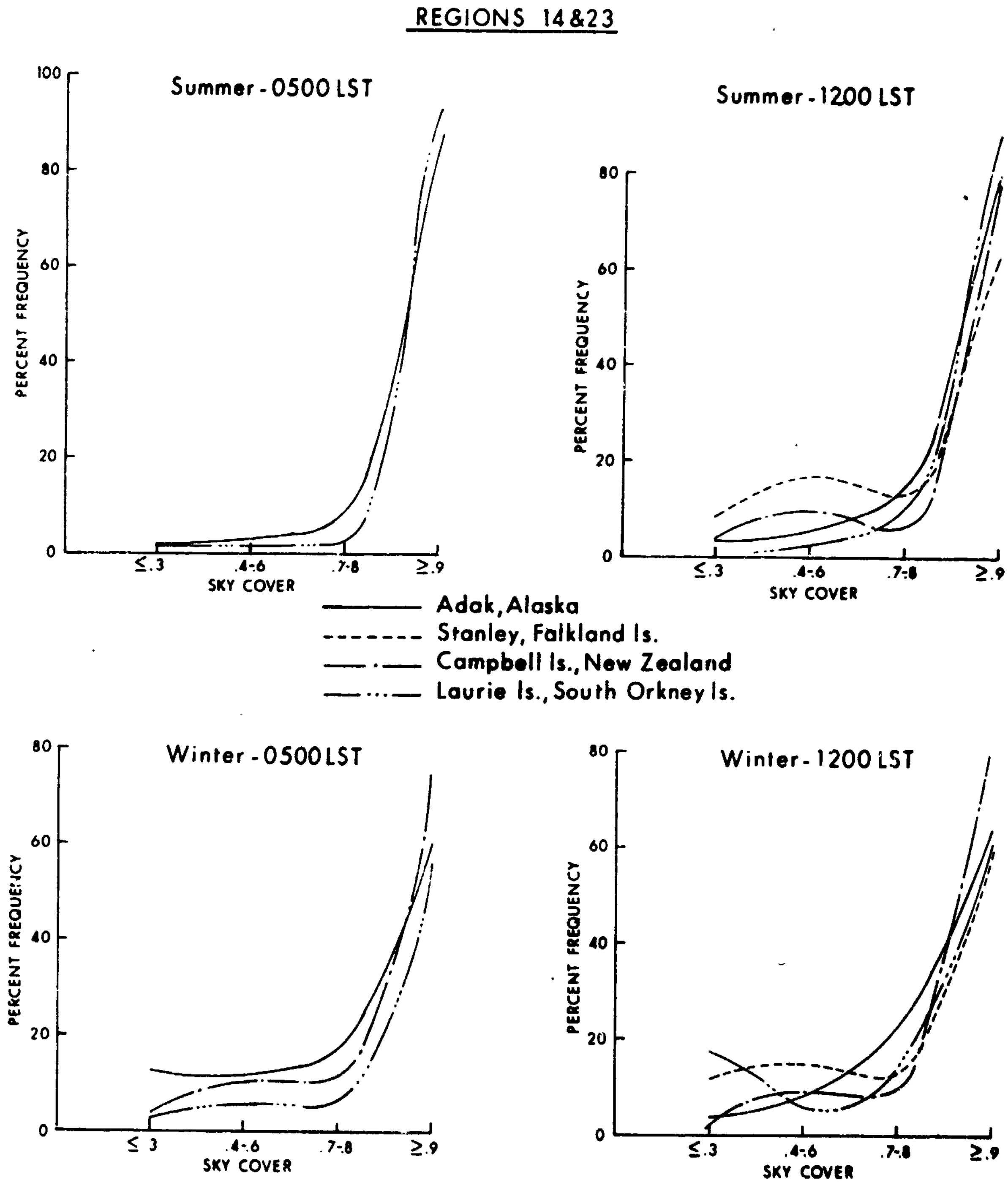


Figure 5-3 Cloud Cover Distributions Demonstrating Regional Homogeneity and Seasonal Reversal of Regions 14 and 23.

of the tip of South America. Daytime observations were also available from Stanley, in the Falkland Islands. It can be seen that with the possible exception of Laurie Island and Stanley in the winter, exposed to Antarctic polar outbreaks, agreement is excellent.

Appendix A gives the distributions used for validation of the seasonal reversal.

5.1.3.3 Length of Record

One criterion for the selection of the prototype station for a region was that, if possible, it have a record of at least 10 years duration.* Since single months were summarized, this implies a target of 300 observations for each time of day. About half of the stations used had hourly observations, which were averaged in groups of three adjacent hours, to give the eight 3-hourly distributions.

The necessity of long record was made amply clear by an experiment performed with satellite data read from the mosaics of ESSA-5 and Nimbus II. Cloud cover was read from 60-mile diameter circles centered on the stations shown in Figure 5-4, for the summer season (June, July and August). Data from ESSA-5 were observed at 1500 local time, the Nimbus II data at noon. Ground-based observations indicate only little diurnal change between these hours. Yet, as seen in Figure 5-4, the distributions are fairly dissimilar. A sample application of the $\chi^2$-test shows it improbable that distributions were drawn from the same population.

The dissimilarity may come from any of several sources. First, it may be that resolution difference between ESSA-5 and Nimbus II affects the distribution. However, it would be expected that resolution difference would principally effect the relative number of clear days, which are not greatly different.

Each sample consists of 85 observations (a few days are missing). Distribution of this number of observations into 5 groups would of course give a certain expected variability. However, the effective number of independent observations is fewer than 85 because of the day-to-day persistence of the weather, so that increased sample-to-sample variability may be expected.

The year-to-year variability in cloud cover is also significant. We suspect it may be the principal contributor in cloud cover variability, since we find the variability within the same year from one point to another in the same region to be fairly small. This is typified by the distributions shown in Figure 5-5 drawn from marginal totals of joint distributions leading to spatial conditional distributions.

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* Four of the stations used did not meet the 10 year data criterion. However, only one of these four stations had less than 7 years record, and that station (Bangalore, India) had a 5 year record.

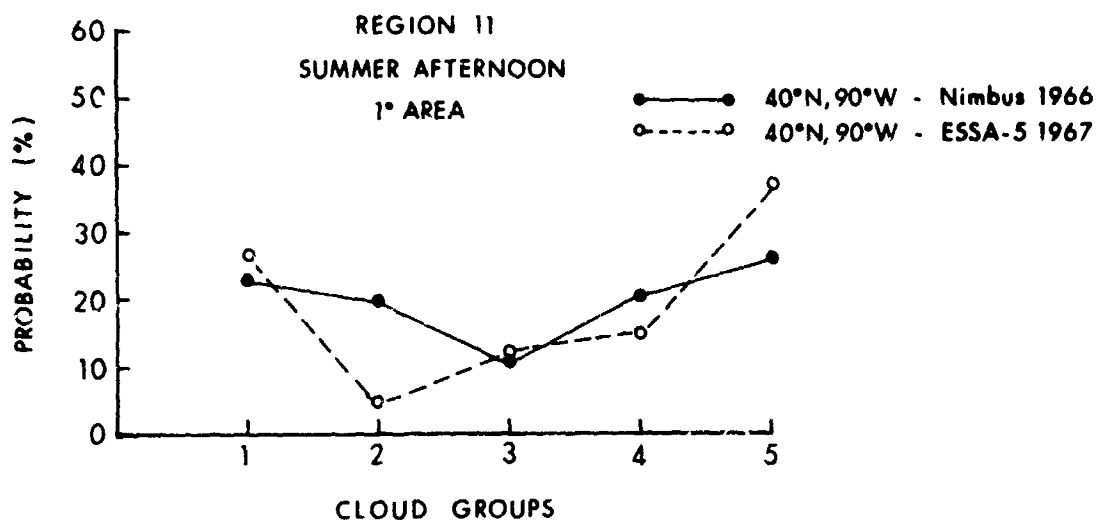


Figure 5-4 Comparison Between Cloud Cover Distributions for Two Different Years

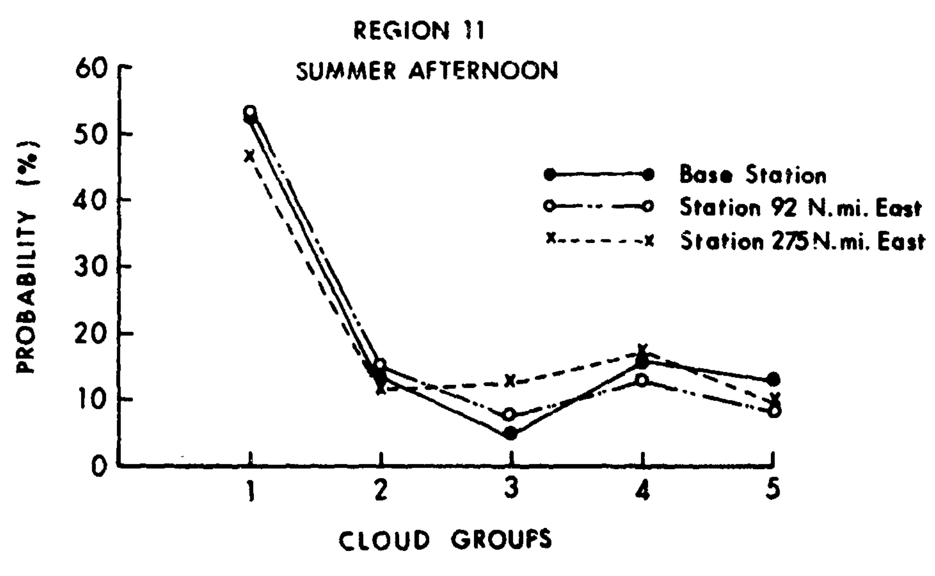


Figure 5-5 Comparison of Cloud Cover Distributions within the Same Region

## 5.2 Conditional Distributions

### 5.2.1 Conditional Probabilities

The conditional probability of the occurrence of event x if event y is already known to have occurred is written as $P(x|y)$ and is defined as

$$P(x|y) = P(xy) / P(y)$$

where $P(xy)$ represents the probability of the joint occurrence of the events x and y and $P(y)$ is the marginal total $\sum_x P(xy)$.

Presentation of the conditional probabilities in the form of an n times n entry table, n being the number of cloud categories (5 in the present case). Characteristically, the diagonal elements of the table, representing the probability of the same cloud group occurring in both the given and the dependent location, are the largest.

### 5.2.2 Spatial Conditionals

Figure 5-6 gives a schematic of the variation of conditional cloud probability of clear skies (cloud group 1) as a function of distance from the given station. At zero distance, the probability is zero for other given cloud groups, 100% for cloud group 1. As the distance between locations increases, the probability tends toward the unconditional probability of clear sky. Some difficulty occurs in defining the conditional probability in situations where the areas over which the cloud cover is described overlap; however, most applications do not require information at this range.

Figure 5-6 has been drawn to illustrate effects that are noted, not universally in real data. When the distance between points somewhat exceeds the probable radius of clear areas in the region, the conditional probability $P(1|1)$ may fall below the unconditional level, to return at some later point. In a few cases, oscillations occur out to some distance, which may result either from insufficient data or from synoptic scale waves. Similarly, the conditional probability of clear skies in the vicinity of an area of scattered cloud may exceed the unconditional probability of clear. Some of the conditional relationships found are somewhat mystifying and can most easily be ascribed to chance variations resulting from data insufficiency (see Section 5.2.5.1).

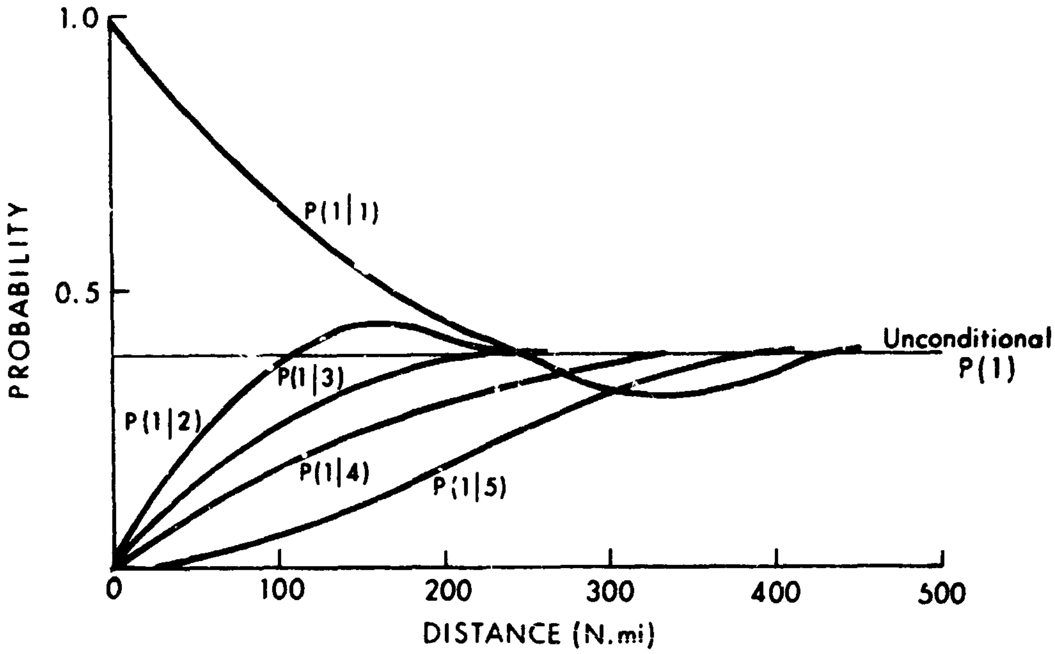


Figure 5-6 Schematic of the Variation of Conditional Probability with Distance

## 5.?.3 Use of Spatial Conditional Distributions

We are not prepared at this time to define a generalized mathematical function describing the decay of conditional probability with distance. In its place we have adopted a simplified procedure to permit general use of the data without invoking data volumes and computational complexities that cannot be justified by the quality of the available conditional data. For each region and month, distributions are presented at a nominal distance of 200 nm. In general, the data have been taken without modification from pairs of satellite observations approximately 200 nm apart. Whenever possible, data from the same region are grouped to increase sample sizes; unfortunately, this was seldom possible.

The data are intended to be used by assuming a straight line probability decay between unity and the 200 nm value for on-diagonal conditionals ($P(3|3)$, etc.), between zero and the appropriate 200 nm value for off-diagonal conditionals ($P(3|2)$, etc.).

The straight line is to terminate at the appropriate unconditional value. Since the sum

$$\Sigma P(y|x) = 1 \text{ for any } x$$

it is necessary that all conditional probabilities defined by a given cloud cover be replaced by the equivalent unconditionals if the straight line process places one conditional probability on the wrong side of its matching unconditional level. Thus, if at a distance of 250 nm.

$$P(1|5) > P(1), \text{ then } P(1|5) = P(1),\ P(2|5) = P(2),\ P5|5 = P(5), \text{ etc.}$$

Or if $P(5|5) < P(5)$, the same substitutions are required.

The probable effect of this mode of use can be assessed from Figure 5-6. The diagonal conditionals may be overestimated at distances other than 200 nm. The region of underestimate is usually small. The off-diagonal conditionals may be affected either way, depending upon the shape of the curve.

Experiments using these data for purposes of validation suggest that the weakest part of the procedure lies in the substitution of unconditionals when the conditional distribution cannot properly be defined by the straight line approximation. In Figure 5-6, the straight line approximation to $P(1|2)$ passes $P(1)$ at about 180 nm. If $P(2|2)$ (not shown) is still materially above $P(2)$ at 200 nm, the effect of coherence will have been lost. We hope in future efforts to substitute a modified procedure which would permit good expression of conditional probabilities at fair distances while guarding against the type of an absurdity that can result from extrapolation of straight line approximations.

5.2.4 Temporal Conditionals

The behavior of temporal conditional cloud probability with time is not dissimilar from that of the spatial conditionals with distance. The bulk of our data was derived from sun-synchronous satellite observations, and thus represent observations taken at 24 hour intervals, It was found that, in general, 24-hour persistence can be demonstrated, as indicated by the diagonal values of the conditional probability table, exceeding the matching unconditional value. In a number of cases, however, apparent antipersistence occurred, where relatively improbable cloud events showed no tendency to persist 24 hours. Much of the apparent antipersistence is probably real, some the result of short data samples, and some the result of the cloud cover underestimate in satellite data. A survey was made of cases of antipersistence to see whether these were real or artifacts in the data. Table 5-2 summarizes a January sample of all 29 regions; 5 diagonal conditional probability elements were examined in each region at the 24-hour interval. The hypothesis is made that if antipersistence is a real rather than random effect, a suitable stratification of the data should show definite trends. Accordingly, the count of numbers of cases of antipersistence (diagonal less than the 1300 local unconditional probability) was stratified according to whether the region was primarily continental or maritime, Northern Hemisphere, Tropical, or Southern Hemisphere. A $\chi^2$ test performed on the tabulation gives a 1% probability that this distribution could arise by chance.

This demonstration, by geographic stratification, that the occurrences of antipersistence are probably real, at least in part, also lends some confidence to our estimates of persistence for the remaining (80%) of the cases.

Table 5-2

Geographic Stratification of Cases of Apparent 24-hour Antipersistence
(note: 5/35 indicates 5 out of 35 cases, etc.)

| | Continental | Maritime |
|---|---|---|
| Northern Hemisphere | 5/35 | 5/15 |
| Tropics | 6/10 | 7/40 |
| Southern Hemisphere | 3/10 | 3/35 |

We have given some validation to the 24-hour satellite estimates of conditional distributions by examination of temporal distributions generated from raw ocean weather ship data. These were compiled from observations made at 6 hour intervals, so that the behavior of the conditional distributions at shorter intervals can be assessed. Figure 5-7 shows characteristic diagonal values for ocean ship Victor in winter. Like most ocean weather stations, it is in a region (20) of rapidly moving weather systems, where clear skies are rare. Broken clouds and overcast are about equally probable.

It can be seen that the straight line approximation to P(5|5) results in a fairly substantial overestimate of persistence. An even poorer approximation is provided for P(2|2) and P(3|3) which becomes antipersistent even at 6 hours, presumably from diurnal effects. (It has been found from the ocean weather ship data that diurnal effects are material at sea, textbook lore notwithstanding.) It should be appreciated that this case, selected from the Northern Hemisphere maritime winter season, is one of the worst cases.

Almost all potential mission simulation applications of the cloud climatology data "fly" over the same area at intervals of less than 4 hours, about 12-hours, about 24 hours, or more. Of these, only the conditional probabilities at the 12 hour interval may be seriously misrepresented by the straight line approximation. This could be of material consequence, for example, in overestimating the probability of success of sequential day-night surface temperature comparisons by infrared radiometry. Accordingly, some care is required in 12-hour applications. We do believe,

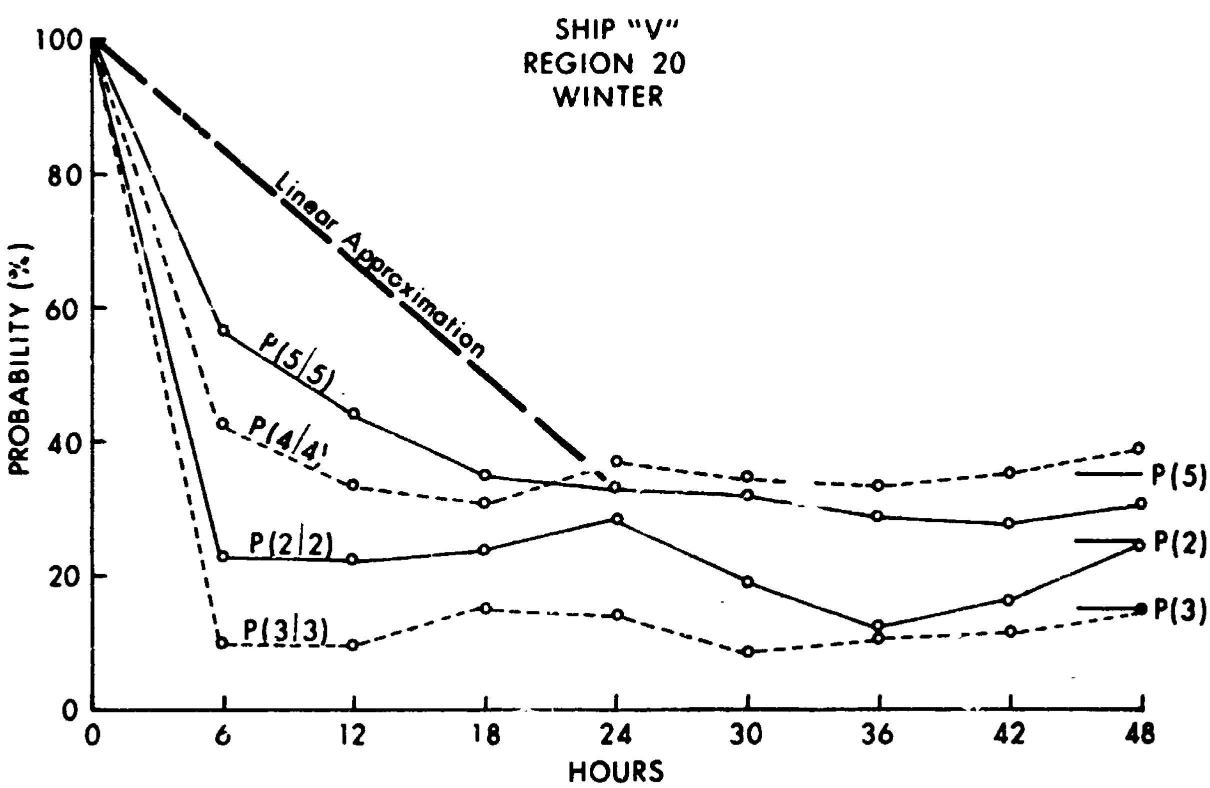


Figure 5-7 Variation of Temporal Conditions with Time

however, that the straight line approximation will generally give better simulation results than an assumption of independence. It is hoped that in the near future conditional data can be developed for a substantial selection of regions at intervals of 6 hours or less; permitting a less crude description of temporal conditionality.

A procedure for dealing independently with diurnal effects while maintaining temporal conditional relations is outlined in Section 6. 5

5. 2. 5 Quality of Conditional Distributions

5. 2. 5. 1 Data Quantity

The problems of data quantity can be appreciated from consideration of the way in which the conditional probabilities are generated. The starting point is a 25-element joint frequency table. Our characteristic data samples had 85 to 90 pairs of observations. In a number of joint distributions, a few elements along the diagonal contained most of the entries, leaving a scattering elsewhere. At first it seemed that the best solution to this problem in the absence of greater data amounts, would be to group data from several regions. However, because the regions were defined by their cloud climatological dissimilarity, it was found that this procedure would result in serious distortion of joint probabilities along the diagonal, thus destroying the major part of the significance of the distribution. To put this observation on a firmer statistical basis, $\chi^2$ tests of homogeneity were performed to see if candidates for grouping could be considered as being drawn from the same parent distribution. The results indicated that in spite of the small-sample sizes, the null hypothesis of homogeneity could not be accepted. As an example, the first test was performed on distributions for Regions 11 and 18 in winter, yielding $\chi^2 = 46.0$ with 24 degrees of freedom, significant past the 1% level.

A further consideration mitigating the effect of small sample size is that the frequency of reference to an element in the conditional probability table should be in direct proportion to the number of observations that were used to define that element. Thus, the variance that can be tolerated in estimating the probability of the frequently occurring joint events is greater than in the case of the more probable events. By the same token, care should be taken in applications of these statistics that the results do not depend critically upon the occurrence of improbable joint events, the probability of which may be poorly estimated. As an example, if in our satellite data sample only one case of clear sky occurred, the conditional probability table would dictate that any clear day must be followed by whatever cloud cover succeeded the clear day in the data sample, all other transistions being excluded. The probability of two successive clear days would be zero.

5.2.5.2 Quality of Source Data

The satellite data were "observed" by a skilled meteorological technician with extended experience in the handling and interpretation of satellite TV data. Data sources were mosaics of Nimbus II AVCS data prepared by Allied Research for the Goddard Space Flight Center and similar machine-prepared mosaics of data from ESSA-3 and ESSA-5. Variations in exposure and processing of Nimbus II data made consistent quantitative judgment of cloud cover quite difficult, adding an element of variability beyond that to be expected from normal subjective judgment.

The area from which cloud was to be read was delineated by a transparent template placed over the cloud field in a position dictated by the machine-superposed geographical grid marks. These are frequently in error by a degree or more, with occasional major errors resulting from failure of picture time coordination. Except for cases of obvious gross error, the technician was instructed to use the grid for reference even where it disagreed with landmark evidence.

A few tests were run to assess the probable error of this class of manual data extraction, which is really not different in kind from cloud cover estimation by ground observers. It was found that data extracted under the same ground rules were reasonalby consistent (see Fig. 5-5), but that the unconditional (marginal) distributions could be materially changed by altering instructions to the data extractor.

Not unexpectedly, the marginal distributions of the satellite data were found to give much smaller cloud covers than the corresponding conventionally observed cloud data. The greatest departures came from the Nimbus II data sample, where it was apparently difficult to differentiate thin cloud and small clouds. Table 5-3 compares the unconditional frequencies in the worst case found. While it is probable that Tampa and the part of the Gulf of Mexico immediately to its west may be cloudier than the more maritime parts of the region used in the satellite sample, the differences are still extreme. The explanation must lie in the prevalence of sub-resolution size cumulus, resulting in a shift from the scattered and partly covered groups into clear; and the one degree satellite sample size which may almost universally exceed the size of the large cumulus and cumulonimbus providing overcasts at Tampa, thus shifting them into cloud cover classes vacated by the unresolved small cumulus.

Table 5-3

Comparison Between Data Samples
For Region 04 - Summer Season

| Cloud Amount in Octas | August Tampa | Percentage Nimbus II (1966) | Frequency ESSA-5 (1967) |
|---|---|---|---|
| 0 | 3% | 52% | 35% |
| 1-2 | 28 | 31 | 32 |
| 3-5 | 15 | 11 | 16 |
| 6-7 | 21 | 4 | 12 |
| 8 | 33 | 2 | 14 |

Section 6.8 will discuss how the overestimated cloud cover of the ground observer, in the unconditional distributions, the underestimated satellite cloud cover used in the temporal and spatial conditional distributions, and the overestimates of cloud coherence and persistence resulting from the use of the straight line approximation all tend to compensate each other in characteristic applications.

An overall assessment of the quality of the conditional probabilities cannot be made without reference to their intended use. The techniques to be described in Section 6 have been selected to make effective use of the appropriate properties of the conditional distributions with only occasional apparent minor errors arising from their relative inaccuracy and bias toward clear skies (see Section 5.4). Used in the recommended fashion in appropriate simulation situations, we believe that these data will give results materially more realistic than those derived from simple assumptions on cloud climatology.

5.3 Data Confidence

A table of data confidence levels, prepared for all 29 regions, is presented as Table 5-4. In this table we have assigned a confidence code for both the unconditional and conditional cloud statistics and in the case of the conditional statistics for both space and time. This confidence code is a simple 1 through 3 system, where 1 denotes good data obtained directly from long-period record in the case of the unconditional statistics and from computed conditional statistics for the specific map region

Table 5-4

Data Confidence Factor

| Climatological Region | Unconditional Statistics | Conditional Statistics | |
|---|---|---|---|
| | | Space | Time |
| 1 | 1 | 1 | 2 |
| 2 | 1 | 1 | 1 |
| 3 | 1 | 1 | 1 |
| 4 | 1 | 1 | 1 |
| 5 | 2 | 3 | 3 |
| 6 | 2 | 3 | 3 |
| 7 | 3 | 3 | 3 |
| 8 | 1 | 1 | 1 |
| 9 | 1 | 1 | 1 |
| 10 | 2 | 1 | 2 |
| 11 | 1 | 1 | 1 |
| 12 | 1 | 1 | 2 |
| 13 | 1 | 2 | 2 |
| 14 | 1 | 1 | 1 |
| 15 | 1 | 1 | 1 |
| 16 | 1 | 1 | 1 |
| 17 | 2 | 2 | 2 |
| 18 | 1 | 1 | 1 |
| 19 | 1 | 1 | 1 |
| 20 | 1 | 1 | 1 |
| 21 | 1 | 1 | 2 |
| 22 | 1 | 2 | 2 |
| 23 | 1 | 1 | 1 |
| 24 | 1 | 1 | 1 |
| 25 | 2 | 1 | 1 |
| 26 | 2 | 2 | 2 |
| 27 | 1 | 1 | 1 |
| 28 | 1 | 1 | 1 |
| 29 | 1 | 1 | 1 |

**Legend**

**1 Good (Unmodified)**
**2 Fair (Modified)**
**3 Poor (Synthetic)**

in question in the case of the conditional statistics. A code of 2 denotes a confidence level of fair, indicating principally that the statistics for these regions have been modified from long term record data or from computed conditional statistics for other regions, based on climatology and good meteorological judgment. A confidence code of 3 indicates relatively poor data, that in some cases has been synthesized, based on firm meteorological considerations, because no satisfactory cloud data for that region exists.

### 5.4 Comparison Between Satellite Observed and Surface Observed Cloud Cover

A recent study carried out at Allied Research (Barnes et al, 1967) has shown that satellite observed cloudiness is generally less than surface observed cloudiness. In this study, which used Nimbus II and ESSA-3 AVCS data, cloud amounts were estimated for one degree latitude circles, centered on specific landmarks to be used in the Apollo program.

#### 5.4.1 Comparison with Normal Cloud Amounts for Selected Landmarks

Satellite observed cloud amounts were compared with normal ground observed cloudiness for 1500 LST, for a sample of the stations shown in Section 9.1. The ground observed cloud amount is greater than the satellite observed in all except one instance (see Table 5-5). The average difference in percentage mean is 20 with the maximum difference for any station being 44.

#### 5.4.2 Comparison with Concurrent Observations

The ESSA-3 observations were compared with concurrent observations for a sample of landmarks. For the five month period, the average difference between the normal mean cloud amount and the satellite observed cloud amount is 16% (Table 5-6); the average difference between the concurrent ground and satellite observed cloudiness for the nine landmarks is also 16%; the maximum difference for any landmark is 23%. For a three and one-half month summer sample, the differences were somewhat greater. In all cases, the cloud cover estimated from the satellite photographs was less than that estimated from the ground. Other comparisons were also made, with similar results.

Table 5-5

Comparison Between Actual Satellite Observed and Normal Ground Observed Cloud Amount. (ESSA-3 Sample) From Barnes et al (1967)

| Landmark Index No. | Reporting Ground Station | S (%) | G (%) | G-S (%) |
|---|---|---|---|---|
| 3 | Miami | 36 | 53 | 17 |
| 334 | Jacksonville | 40 | 55 | 15 |
| 317 | Galveston | 51 | 58 | 7 |
| 20 | Kingston, Jamaica | 34 | 58 | 24 |
| 300 | San Diego | 29 | 39 | 10 |
| 510 | Yuma | 16 | 30 | 14 |
| 60 | Georgetown | 41 | 78 | 37 |
| 336 | Talara (Dec. Msg.) | 26 | 40 | 14 |
| 96 | Ben Guerir | 18 | 51 | 33 |
| 81 | Recife | 18 | 62 | 44 |
| 85 | Dakar | 24 | 41 | 17 |
| 524 | Cairo | 18 | 45 | 27 |
| 801 | New Delhi | 05 | 25 | 20 |
| 811 | Accra | 24 | 45 | 21 |
| 814 | Kyushu | 58 | 52 | -6 |

Mean G-S = 20

Range of Values = -6 to 44

S = Satellite Observed Amount: Mean for Period 9 October 1966 - 28 February 1967

G = Ground Observed Amount: Normal Mean for 1500 LST October - February

Table 5-6

Comparisons Between Satellite Observed, Normal Ground Observed, and Actual Ground Observed Cloud Amounts; Mean Sunrise-Sunset Cloud Amounts Used. (ESSA-3 Sample)

| Landmark Index Number | Reporting Ground Station | S (%) | NG (%) | AG (%) | NG-S (%) | AG-S (%) |
|---|---|---|---|---|---|---|
| 3 | Miami | 36 | 53 | 59 | 17 | 23 |
| 334 | Jacksonville | 40 | 57 | 60 | 17 | 20 |
| 330 | Tampa | 30 | 53 | 52 | 23 | 22 |
| 50 | New Orleans | 51 | 56 | 58 | 5 | 7 |
| 316 | Corpus Christi | 43 | 59 | 63 | 16 | 20 |
| 512 | Abilene | 25 | 50 | 44 | 25 | 19 |
| 511 | El Paso | 29 | 39 | 34 | 10 | 5 |
| 510 | Yuma | 16 | 31 | 30 | 15 | 14 |
| 300 | San Diego | 29 | 45 | 42 | 16 | 13 |
| | | | Mean Difference = | | 16 | 16 |

S = Satellite Observed Amount, Mean for 9 October 1966 - 28 February 1967

NG = Normal Ground Observed Amount, Mean Sunrise to Sunset Value for October 1966 - February 1967

AG = Actual Ground Observed Amount, Mean Sunrise to Sunset Value for October 1966 - February 1967

5.4.3 Comparison of Distributions

Distribution of ground-observed (tabulated) data and of satellite data are compared in four regions in Figure 5-8 (summer) and Figure 5-9 (winter). It is seen that the distributions are quite different in the summer, some features being inexplicable except perhaps by the short satellite data sample. In the winter, the distributions are quite similar except in Region 4, where poor resolution of small clouds has affected the data, and perhaps Region 9, where the data analyst's attempt to separate cloud and snow may have been unsuccessful.

5.4.4 Discussion

The landmarks used in this study were located between 35N and 35S, where cloudiness is predominately cellular (convective). Furthermore, for the sample of stations in the United States the greatest differences were observed during summer, when a larger percentage of the cloudiness is cellular. It appears that a part of the difference arises because small cellular clouds are not resolved by the satellite camera systems (i. e., satellite underestimate). A significant part is, however, due to the overestimation of cloudiness in surface observations.

Previous investigators have found indications that observers may overestimate cloud cover. Appleman (1962) compared cloud amounts extracted from aerial photographs with surface observations, and Barnes (1966) compared cloud amounts extracted from TIROS nephanalyses with surface observations. In both of these studies cloud amounts extracted from the conventional data were greater.

In a study to determine clear lines-of-sight through the atmosphere, McCabe (1965) states that, since half the sky dome over which an observer integrates his total sky cover is less than 30° above the horizon, the observer's view is often blocked more by the sides of clouds than by their bases. Lund (1965) has computed the average "earth cover" for Tampa in August, based on a cloud model with typical cloud dimensions. His computed "earth cover" is as much as 40% less than the observed average cloud cover.

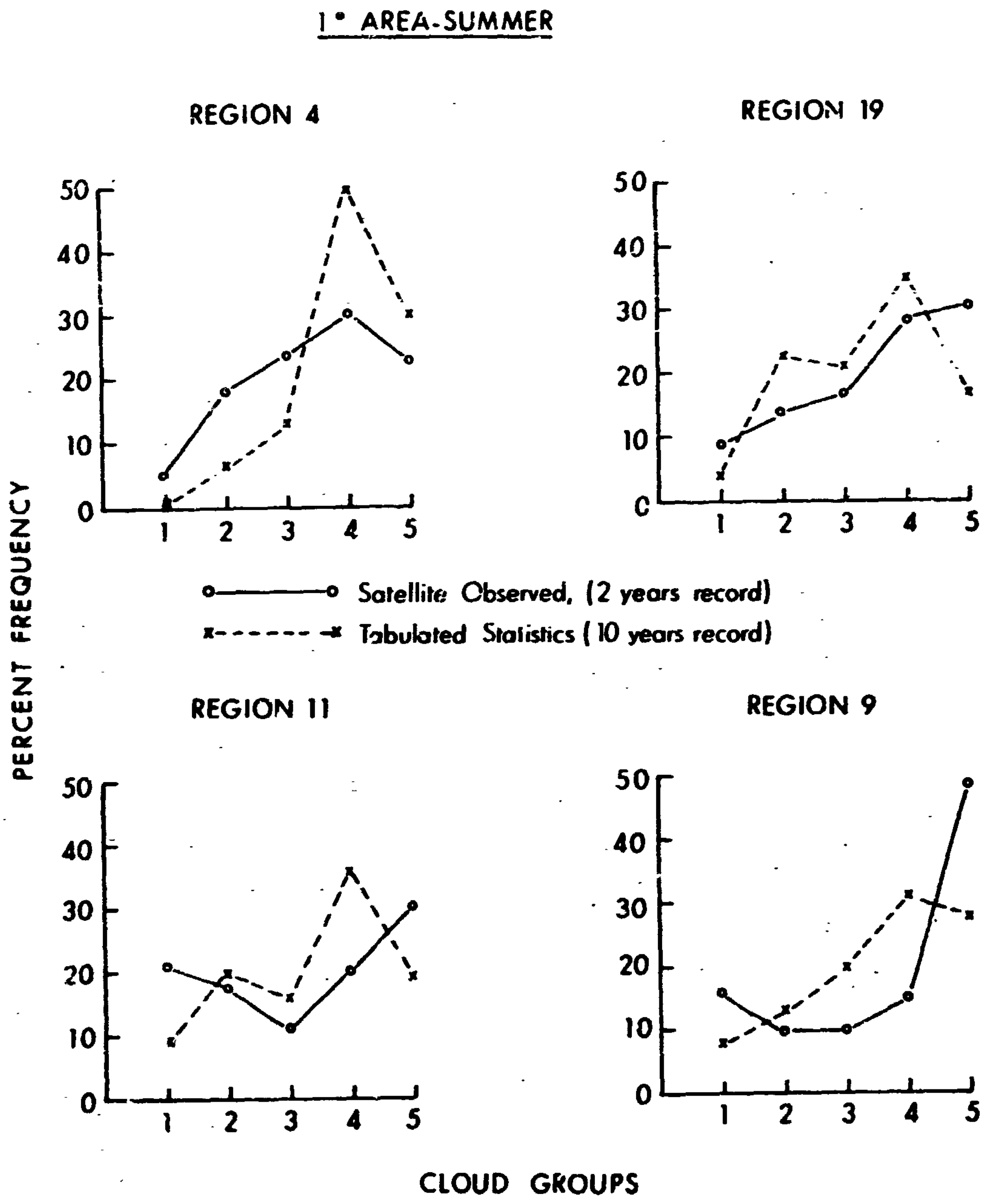


Figure 5-8 Comparison of Ground Observed (Tabulated) and Satellite Data for Four Regions in Summer

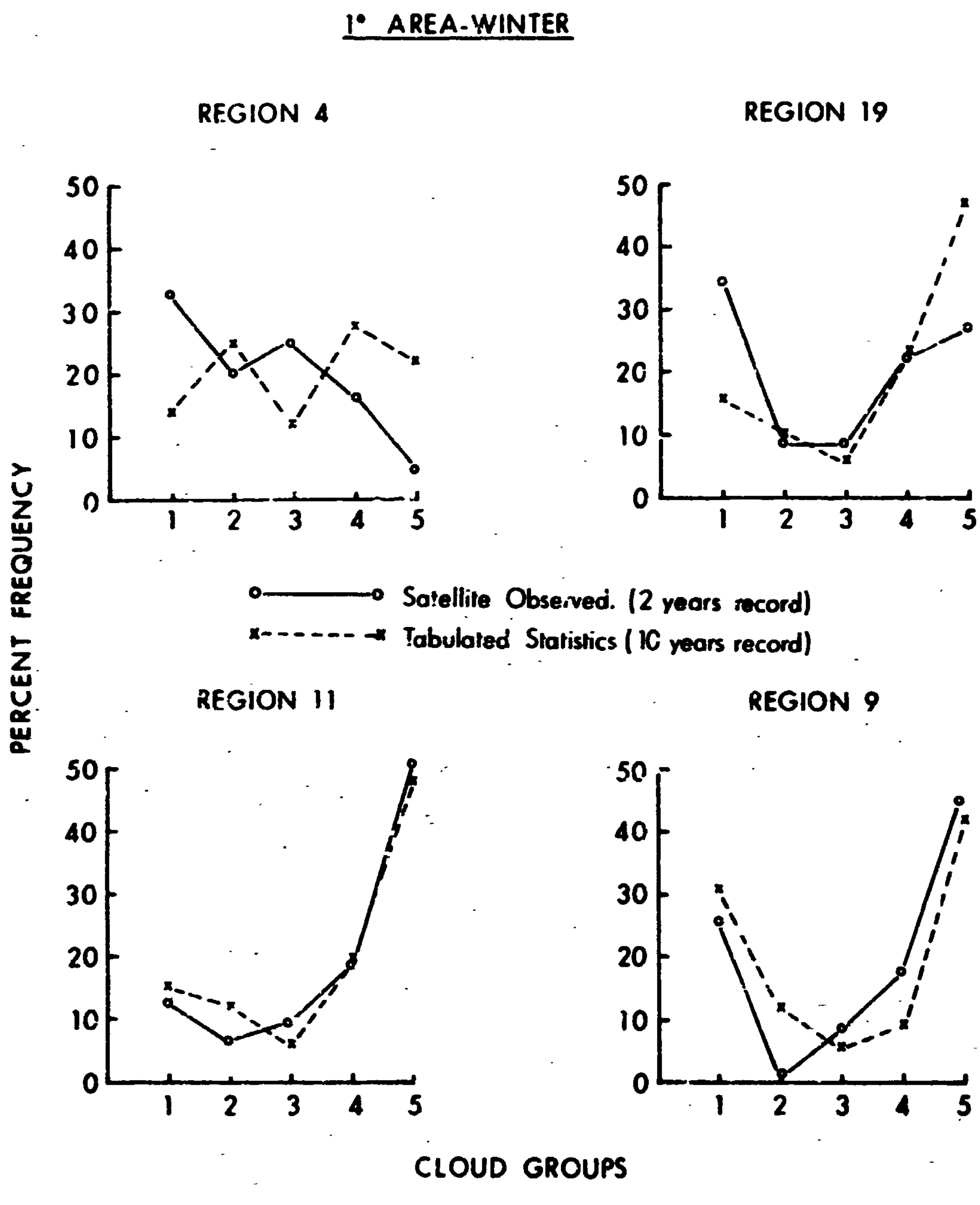


Figure 5-9 Comparison of Ground Observed (Tabulated) and Satellite Data for Four Regions in Winter

In summary, cloud amounts extracted from satellite photography have been found to be generally less than those from surface observations. The true cloudiness very likely lies between these two estimates, due to: (1) satellite observations underestimating cloud cover, especially because small cumulus cells cannot be detected at existing camera resolutions; and (2) surface observations overestimating cloud cover, because the observer looks at the sides of clouds as well as their bases. Further studies comparing concurrent satellite and surface observations are needed to establish more realiably the magnitudes of the errors and determine the influences of cloud amount and cloud type; one such study is currently underway at Allied Research under Contract No. NAS 5-10478.

5.5 Example of Tabulated Cloud Cover Data

Table 5-7 presents an example of the tabulated data in a convenient format. Computer printouts of the entire data blank and the map region card decks can be found in Appendix B.

Table 5-7

Example of Tabulated Cloud Cover Distributions

CLIMATOLOGICAL REGION NUMBER 1 STATISTICS FOR MONTH 1

| | UNCONDITIONAL PROBABILITIES TIME (LST) | | | | | | | | | CONDITIONAL PROBABILITIES 24 HOUR TEMPORAL | | | | | | | 200 NM SPATIAL | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 01 | 04 | 07 | 10 | 13 | 16 | 19 | 22 | GIVEN | | 1 | 2 | 3 | 4 | 5 | GIVEN | | 1 | 2 | 3 | 4 | 5 |
| 1 | .62 | .63 | .49 | .44 | .42 | .39 | .46 | .59 | | 1 | .85 | .08 | .05 | .02 | .0 | | 1 | .81 | .07 | .03 | .09 | .0 |
| 2 | .14 | .12 | .17 | .16 | .18 | .19 | .18 | .15 | | 2 | .78 | .12 | .05 | .05 | .0 | | 2 | .70 | .10 | .0 | .20 | .0 |
| 3 | .06 | .07 | .10 | .09 | .07 | .10 | .10 | .08 | | 3 | .75 | .10 | .10 | .05 | .0 | | 3 | .57 | .29 | .0 | .14 | .0 |
| 4 | .11 | .10 | .14 | .20 | .22 | .20 | .17 | .10 | | 4 | .80 | .05 | .05 | .05 | .05 | | 4 | .50 | .0 | .07 | .29 | .14 |
| 5 | .07 | .08 | .10 | .11 | .11 | .12 | .09 | .08 | | 5 | .80 | .08 | .05 | .05 | .02 | | 5 | .0 | .0 | .0 | .01 | .99 |

CLIMATOLOGICAL REGION NUMBER 2 STATISTICS FOR MONTH 1

| | UNCONDITIONAL PROBABILITIES TIME (LST) | | | | | | | | | CONDITIONAL PROBABILITIES 24 HOUR TEMPORAL | | | | | | | 200 NM SPATIAL | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 01 | 04 | 07 | 10 | 13 | 16 | 19 | 22 | GIVEN | | 1 | 2 | 3 | 4 | 5 | GIVEN | | 1 | 2 | 3 | 4 | 5 |
| 1 | .37 | .38 | .22 | .18 | .17 | .17 | .23 | .31 | | 1 | .73 | .06 | .04 | .11 | .06 | | 1 | .63 | .11 | .02 | .21 | .03 |
| 2 | .19 | .16 | .20 | .21 | .21 | .19 | .22 | .20 | | 2 | .70 | .10 | .10 | .05 | .05 | | 2 | .50 | .0 | .0 | .0 | .50 |
| 3 | .10 | .08 | .11 | .10 | .12 | .13 | .12 | .12 | | 3 | .60 | .13 | .0 | .14 | .13 | | 3 | .20 | .0 | .20 | .20 | .40 |
| 4 | .22 | .23 | .33 | .35 | .32 | .33 | .26 | .24 | | 4 | .43 | .04 | .06 | .25 | .22 | | 4 | .22 | .0 | .22 | .22 | .34 |
| 5 | .12 | .15 | .14 | .16 | .18 | .18 | .17 | .13 | | 5 | .29 | .07 | .03 | .35 | .26 | | 5 | .25 | .0 | .12 | .13 | .50 |

CLIMATOLOGICAL REGION NUMBER 3 STATISTICS FOR MONTH 1

| | UNCONDITIONAL PROBABILITIES TIME (LST) | | | | | | | | | CONDITIONAL PROBABILITIES 24 HOUR TEMPORAL | | | | | | | 200 NM SPATIAL | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 01 | 04 | 07 | 10 | 13 | 16 | 19 | 22 | GIVEN | | 1 | 2 | 3 | 4 | 5 | GIVEN | | 1 | 2 | 3 | 4 | 5 |
| 1 | .17 | .18 | .15 | .04 | .01 | .01 | .04 | .09 | | 1 | .17 | .16 | .17 | .42 | .08 | | 1 | .30 | .20 | .20 | .20 | .10 |
| 2 | .24 | .25 | .21 | .19 | .11 | .13 | .18 | .22 | | 2 | .05 | .18 | .24 | .42 | .11 | | 2 | .0 | .25 | .25 | .50 | .0 |
| 3 | .12 | .13 | .13 | .16 | .16 | .17 | .13 | .13 | | 3 | .02 | .15 | .27 | .39 | .17 | | 3 | .0 | .0 | .46 | .46 | .08 |
| 4 | .27 | .23 | .33 | .32 | .41 | .39 | .34 | .34 | | 4 | .03 | .09 | .21 | .50 | .17 | | 4 | .0 | .0 | .05 | .73 | .22 |
| 5 | .20 | .21 | .28 | .29 | .31 | .30 | .31 | .22 | | 5 | .05 | .04 | .18 | .52 | .21 | | 5 | .0 | .0 | .0 | .41 | .59 |

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## 6. CLOUD MODEL AND DATA MANIPULATION

### 6.1 Introduction

For the present purposes the cloud cover of the earth's surface is defined as the fraction of definite area covered by the vertical projection of the clouds within the area. In general, the same cloud cover prevails over a number of contiguous areas. As seen on the grand scale from weather satellites, most clouds form part of large scale organized cloud systems. These systems maintain their identity from day-to-day, while moving at speeds characteristic of synoptic systems. The cloud systems, and subsystems within them, move and deform continuously. New systems are born, only occasionally explosively, while old systems dissipate more gradually. Accordingly, the cloud cover over one area cannot be considered independently of that over another nearby area, nor is the cloud cover today necessarily independent of that yesterday.

Computer simulation of earth observation from space involves "flying" the mission over many samples of the cloud field that might be observed. The use of real cloud fields, described by satellite observations or surface observations, would seem appropriate However, it is difficult to obtain a sufficient sample to get reasonable statistical stability.

During the early phases of our study of simulation applications of cloud cover data, consideration was given to possible techniques of generating sequences of computer maps of cloud cover that would have suitable properties of spatial and temporal coherence. This approach was rejected on grounds of impracticability because of the large amount of computation involved, the large memory requirements to obtain sufficient density, and the waste of computed data that would occur in the subsequent simulation. In its place, we have adopted a procedure of computing conditional cloud statistics "to order," following the path of the simulation. The simulation of cloud then takes the form of a simple Markhov chain proceeding from each potential earth observation to the next (see Section 6.8 for discussion of the properties of this chain).

### 6.2 The Cloud Model

The cloud model to be used for simulation results from the following considerations:

a) Each observation from space has associated with it a certain characteristic area of the earth's surface over which the cloud cover must be described to evaluate the success of the observation. This may vary from a few acres for ground truth sites to some 50,000 square miles for atmospheric sounding experiments. The requirements for finding a small area, whether by an astronaut in real time or later in the data presentation, increases the minimum size of area to be considered, since geographic "lead-ins" are required. A practical minimum area is perhaps a 30 mile diameter circle, corresponding (fortunately) to the ground observer's field of view

b) The cloud cover distribution is a strong function of the size of the area over which the cloud is described, ranging from a bimodel 0 and 100% for a very small area to a possible constant 40% for the globe as a whole. Evidence from this study suggests that the distribution changes quite rapidly with viewed area size over the range of interest.

c) Most earth oriented-observations will be made from fairly low orbit, ranging from 150 to perhaps 600 miles. Thus, the attempted observations will occur in a sequential chain in orbit order, or in the form of isolated diverted attempts to observe specific targets. Observations from earth synchronous height would also be made in organized sequence.

d) The same point may be observed at intervals of about one orbit, two orbits, 12 hours, 24 hours, or much longer. The success of certain experiments may depend on the ability to make unbroken sequential observations.

e) Computer simulation of cloud contingent events may take one of two forms: (1) derived statistical distributions of certain parameters of mission or experiment success; (2) Monte Carlo simulation of the contingent parts of the mission or experiment. Hybrid applications may also occur; it may be desirable to work out probability distributions of the observational success consequences of cloud cover, then perform a Monte Carlo simulation using observational success as the random variable rather than cloud cover. Such a hybrid system could have been used in the simulation example of Section 9. 1.

The cloud "model" adopted to meet these requirements and those of computational convenience has the following description:

a) The earth is divided into a number of regions, described by 29 regional types. The cloud distributions, conditional and unconditional, are the same everywhere within each region.

b) Regional boundaries are also impermeable boundaries between cloud systems so that there is no conditionality across boundaries. This is literally true for many boundaries, and seems to be effectively true for many of the others.

c) Because cloud cover must always be interpreted in terms of its effect on observation before it can be used effectively in simulation, only 5 categories are used to describe cloud cover. The most important events, clear and overcast, are given unique categories

d) Diurnal and seasonal cloud variations for most regions are so strong that unconditional tabulations at 3-hour intervals and by month are given.

e) Spatial and temporal conditional distributions are given for one distance (200 nm) and one time interval (24 hours). Only two seasons are represented, and no account is taken of any diurnal changes in the conditional distributions.

f) The assumption is made that spatial conditionality is independent of direction (it isn't). Serious consequences of this assumption are avoided by the limited meridional extent of most regions and the impermeability of region boundaries.

g) Conditional distributions for distances and times other than those presented are to be found by straight line interpolation (or extrapolation) between the given elements and the degenerate (0 or 1) conditionality at zero distance or time.

h) Joint probability distributions of dependent events are to be found by

$$P(a\,b) = P(a) \cdot P(b|a)$$

However, since $P(a)$ and $P(b|a)$ are drawn from different populations, $P(a\,b) \neq P(b\,a)$. Further, the two marginal distributions $P'(a) = \sum_b P(a\,b)$ and $P'(b) = \sum_a P(a\,b)$ will not be equal.

i) Sample cloud covers are generated by a simple Markhov chain process; the cloud cover of the first point encountered in a region is found from a random sample from the appropriate unconditional distribution. Subsequent cloud covers are found from random samples from an appropriately scaled distribution conditional on the cloud cover of the prior sample. If the space between observations exceeds 800 miles or 36 hours, a new unconditional start is made to the chain.

### 6.3 Glossary of Terms

We have chosen for convenience to keep track of the various scaled and unscaled probability distributions by use of a set of FORTRAN mnemonics which are somewhat descriptive of the content of the distribution. Table 6-1 defines these mnemonics. These terms will be used throughout the remaining sections to designate the various distributions. Techniques for computing the distributions will be described in the remainder of Section 6 and 7.

Table 6-1

Definition of Terms

| | |
|---|---|
| UNCON | Unconditional Distribution for Sampling Area Size 30-60 nm. |
| SCOND | Spatial Conditional Distribution for Sampling Area Size 30-60 nm and Distance 200 nm from UNCON. |
| TCOND | Temporal Conditional Distribution for Sampling Area Size 30-60 nm and 24-hours after UNCON. |
| SUNCON | Scaled Unconditional Distribution for Enlarged Sampling Area Size. |
| CONNEW | Conditional Distribution Scaled for Enlarged Sampling Area Size. |
| CONDIS | Spatial Conditional Distribution Scaled for Distance Other than 200 nm. |
| CONTIM | Temporal Conditional Distribution Scaled for Time Other than 24-hours. |
| SCSCON | Spatial Conditional Distribution Scaled for Both Enlarged Area Size and Distance Other than 200 nm. |
| SCTCON | Temporal Conditional Distribution Scaled for Both Enlarged Area Size and Time Other than 24-hours |
| TSCON | Conditional Distribution Scaled for Both Time and Distance for 30-60 nm Sampling. |
| TSSCON | Conditional Distribution Scaled for Time, Distance and Enlarged Sampling Area Size. |
| DICON | Pseudo-Conditional Distribution Matrix Generated while Scaling TCOND for Diurnal Effects. |
| DITCON | Diurnally Scaled Temporal Conditionals. |

6.4 Scaling for Distance

Data for 200 miles distance from the initial point are tabulated in the data bank. We present here the mathematical technique for scaling these conditional statistics for distances other than 200 nm. As mentioned in paragraph 6.2, the assumption is made that the conditional probabilities decay linearly with distance. This decay will be demonstrated and discussed in paragraph 6.4.1 below.

The procedure for scaling for distance based on the linear assumption is thus a relatively simple one. Two conditions are imposed. The first concerns the area within 200 miles i.e., scaling for distances less than 200 miles, the second is for scaling beyond 200 miles. For scaling within 200 miles, one uses the following two formulas. For probabilities on the diagonal on the 5 x 5 conditional matrix i.e., 1 given 1, 2 given 2, etc. one uses

$$P(C) = 1 - \frac{\text{Scale (d)}}{200} \text{ (1-SCOND)} \qquad (1)$$

If the value in question is not on the diagonal i.e., probability of 1 given 2, 1 given 3, etc. the following formula is used for scaling

$$P(C) = \frac{\text{Scale (d)}}{200} \text{ (SCOND)} \qquad (2)$$

When the required distance is greater than 200 nm, the following condition is also imposed. For values on the diagonal, the scaled values (scaled using the formulas immediately above) must remain greater than the unconditional probability of the diagonal value, i.e., the scaled probability of 2 given 2 must be greater than the unconditional probability of 2. If this test fails, the entire horizontal line of the 5 x 5 matrix is replaced with the unconditional statistics as demonstrated in Table 6-2 below. In a similar manner for values not on the diagonal, the scaled values must remain below the unconditional probability of the given cloud group, i.e., $P(2|1)$ and $P(2|3)$ etc. must be smaller than the unconditional probability of 2. If this test fails, the entire horizontal line of the 5 x 5 matrix is also replaced by the unconditional statistics. Thus if either the diagonal value is less than the unconditional value or if the non-diagonal value on any given line is greater than the unconditional value, the whole line is replaced by the unconditional statistics. This amounts to saying that if either of these tests fail, the cloud cover statistics for this cloud category beyond this point are no longer conditional upon the first point but rather assume the unconditional distributions.

Table 6-2

Examples of Scaling for Distances Greater than 200 nm

Region 19 January - 1600 L

| Cloud Group | UNCON | SCOND (≈200 nm) | | | | | CONDIS (350 nm) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 |
| 1 | .16 | .76 | .05 | .05 | .05 | .09 | .58 | .09 | .09 | .09 | .16 |
| 2 | .10 | .17 | .17 | .08 | .08 | .50 | .30 | -.45 | .14 | .14 | .87 |
| 3 | .06 | .13 | .12 | .15 | .30 | .30 | .23 | .21 | -.50 | .52 | .52 |
| 4 | .21 | .14 | .09 | .14 | .45 | .18 | .24 | .16 | .24 | .04 | .32 |
| 5 | .47 | .13 | .06 | .12 | .16 | .53 | .23 | .10 | .21 | .28 | .18 |

TEST FOR CONDITIONALITY

1) Are Diagonal values greater than corresponding UNCON - Ans. No

2) Are all Non-Diagonal values in each row less than or equal to corresponding UNCON -Check

Cloud Group 1 Yes
2 No
3 No
4 No
5 No

If NO replace Matrix values with UNCON

| | New CONDIS (350 nm) | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| G 1 | .58 | .09 | .09 | .09 | .16 |
| I 2 | .16 | .10 | .06 | .21 | .47 |
| V 3 | .16 | .10 | .06 | .21 | .47 |
| E 4 | .16 | .10 | .06 | .21 | .47 |
| N 5 | .16 | .10 | .06 | .21 | .47 |

### 6.4.1 Validation of Scaling for Distance Procedure

Region 11 has been chosen to exemplify the decay of the conditional probabilities with distance. Figures 6-1 through 6-5 are graphs showing the decay of the conditional probabilities with distance for winter and summer. In Figure 6-1 for example, the decay of P(1|1) etc. demonstrated. Note that the linear assumption of decay (a straight line drawn between probability 1.0 and the value nearest 200 miles) approximates the decay of P(1|1), P(2|2), P(3|3), etc. The poorest approximation occurs in the middle cloud groups, in particular P(3|3). Note, however, that beyond approximately 200 miles, most of the statistics are approximated by the unconditional probability.

### 6.4.2 Example for Scaling for Distance

Two examples are presented below to demonstrate the scaling of the conditional probability distributions (as tabulated in the data bank) for distances other than 200 nm. In example one (Table 6-2) the scaling has been accomplished for a distance of 350 nm. Note that, in this case, the additional test for SCALE greater than 200 nm (see paragraph 6.4 above) has been imposed. The difference in the 5x5 matrix shown at the top of the Table (SCOND) values and those shown at the bottom (new CONDIS) values are significant.

In Table 6-3 we show an example of scaling for distances less than 200 miles (160 nm). The additional test for conditionality with regard to the unconditional probabilities is not imposed in this case. Note the increase in the values on the diagonal of the 5x5 matrix between the SCOND and the CONDIS matrices shown in Table 6-3. Thus as one moves closer than 200 nm the conditional probabilities become more diagonalized (i.e., the cloud cover at the second point is more dependent on cloud cover at the first point) when the distances are less than 200 nm.

## 6.5 Scaling for Time

Scaling the conditional distributions for time is handled in a somewhat similar way to that for distance. In this case, we assume that the statistics are no longer conditional (see paragraph 6.5.1 below) for times beyond 36 hours.

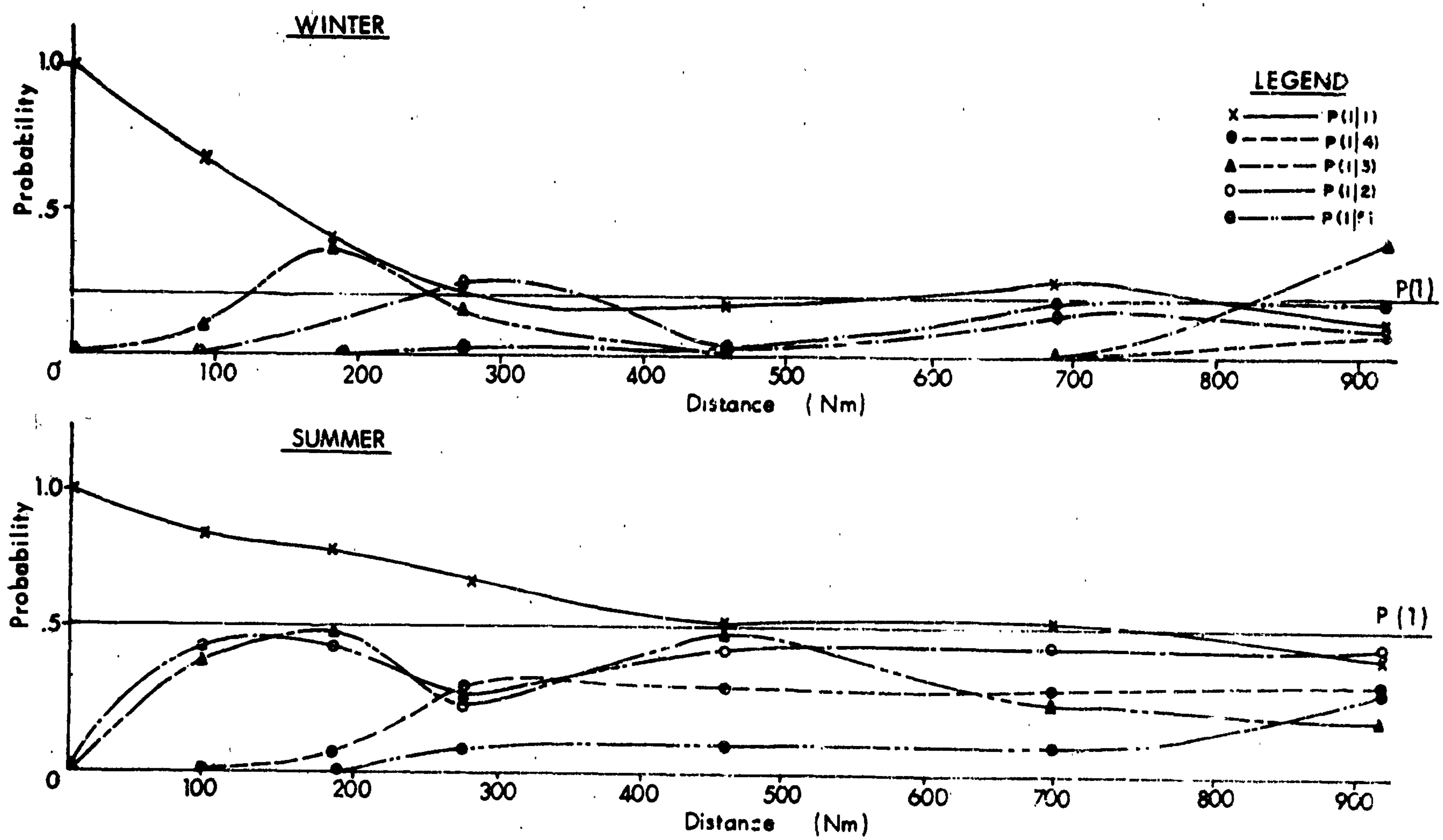


Figure 6-1 Decay of Conditional Probabilities with Distance for Region 11

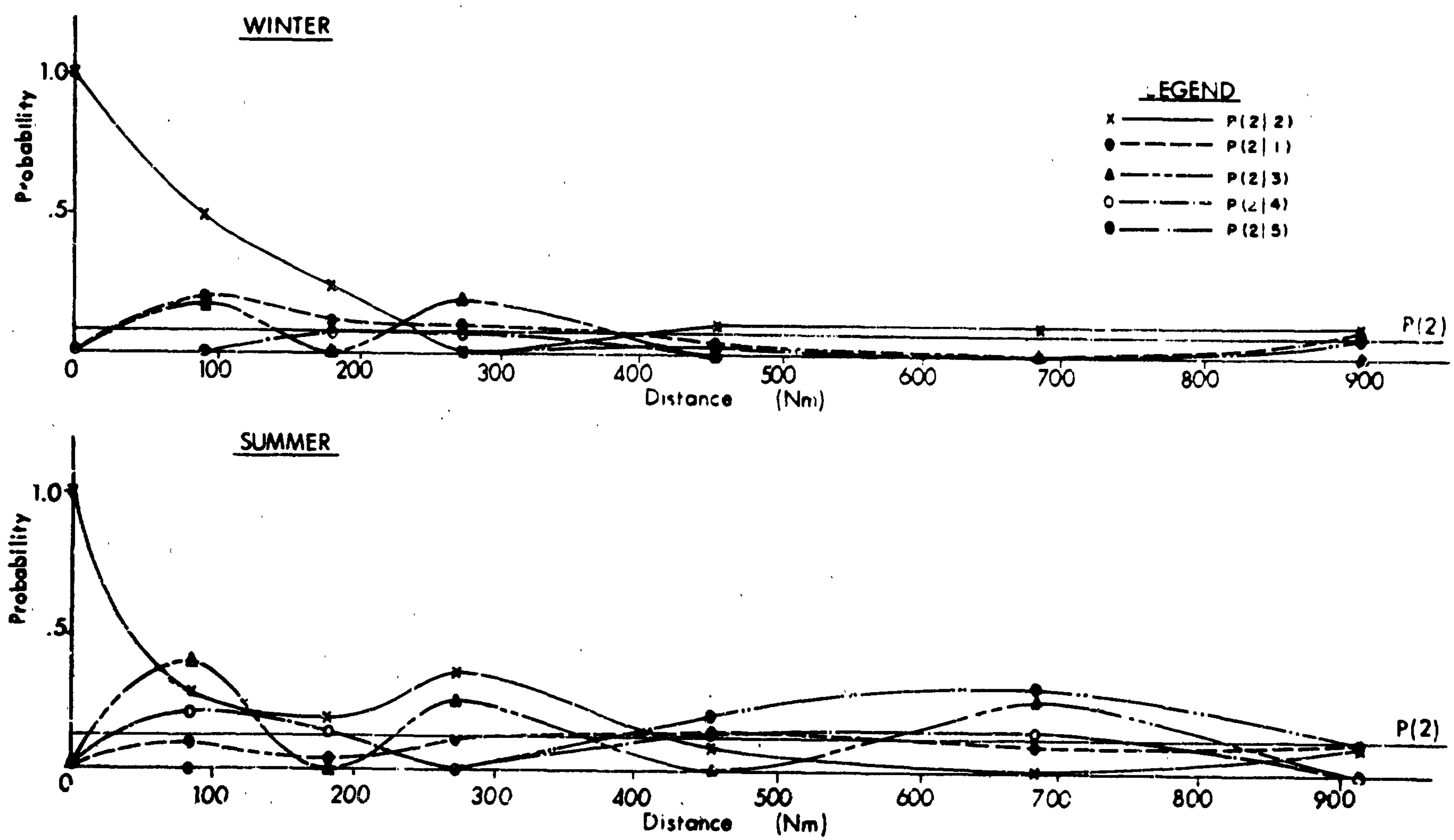


Figure 6-2 Decay of Conditional Probabilities with Distance for Region 11

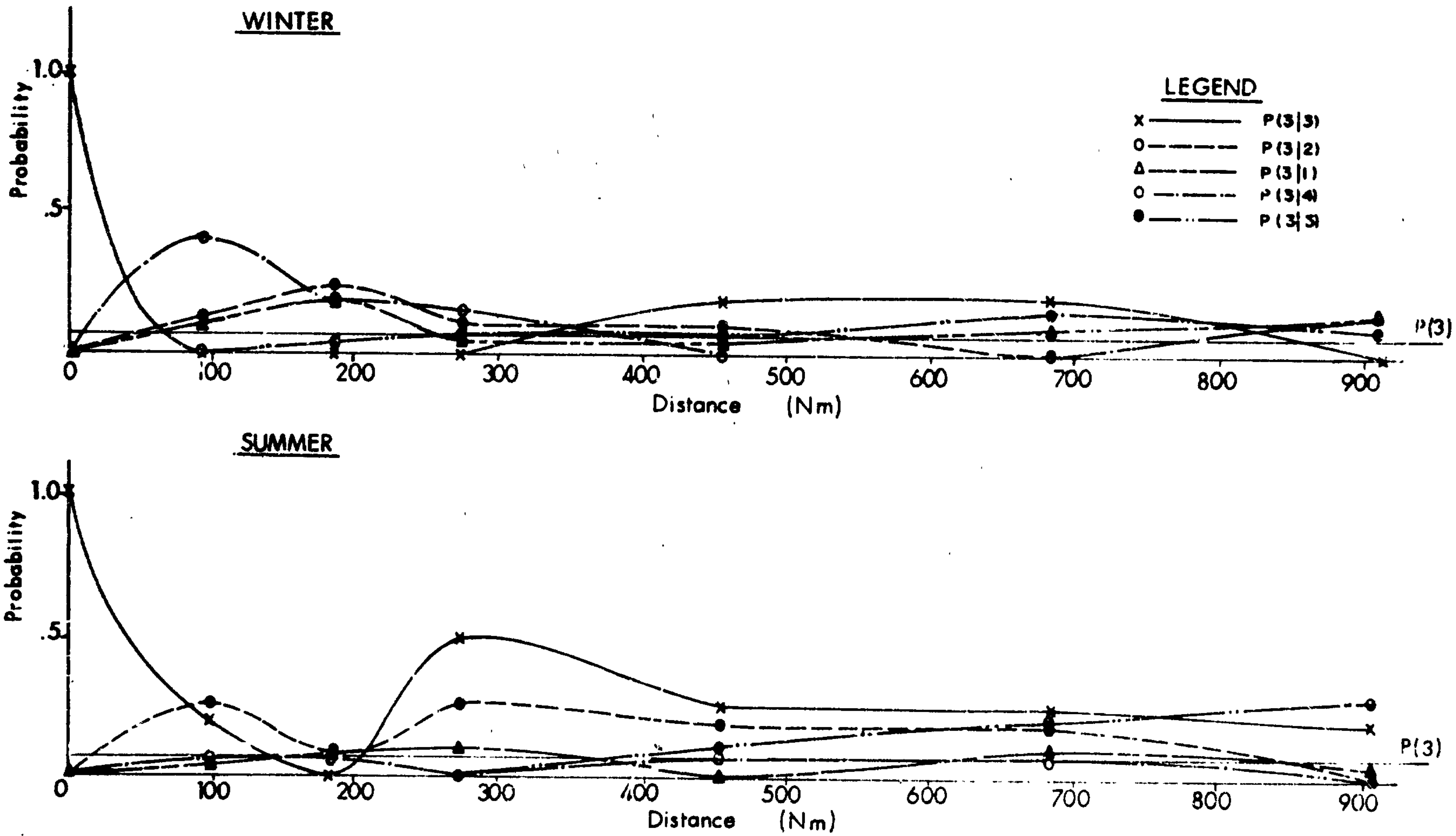


Figure 6-3 Decay of Conditional Probabilities with Distance for Region 11

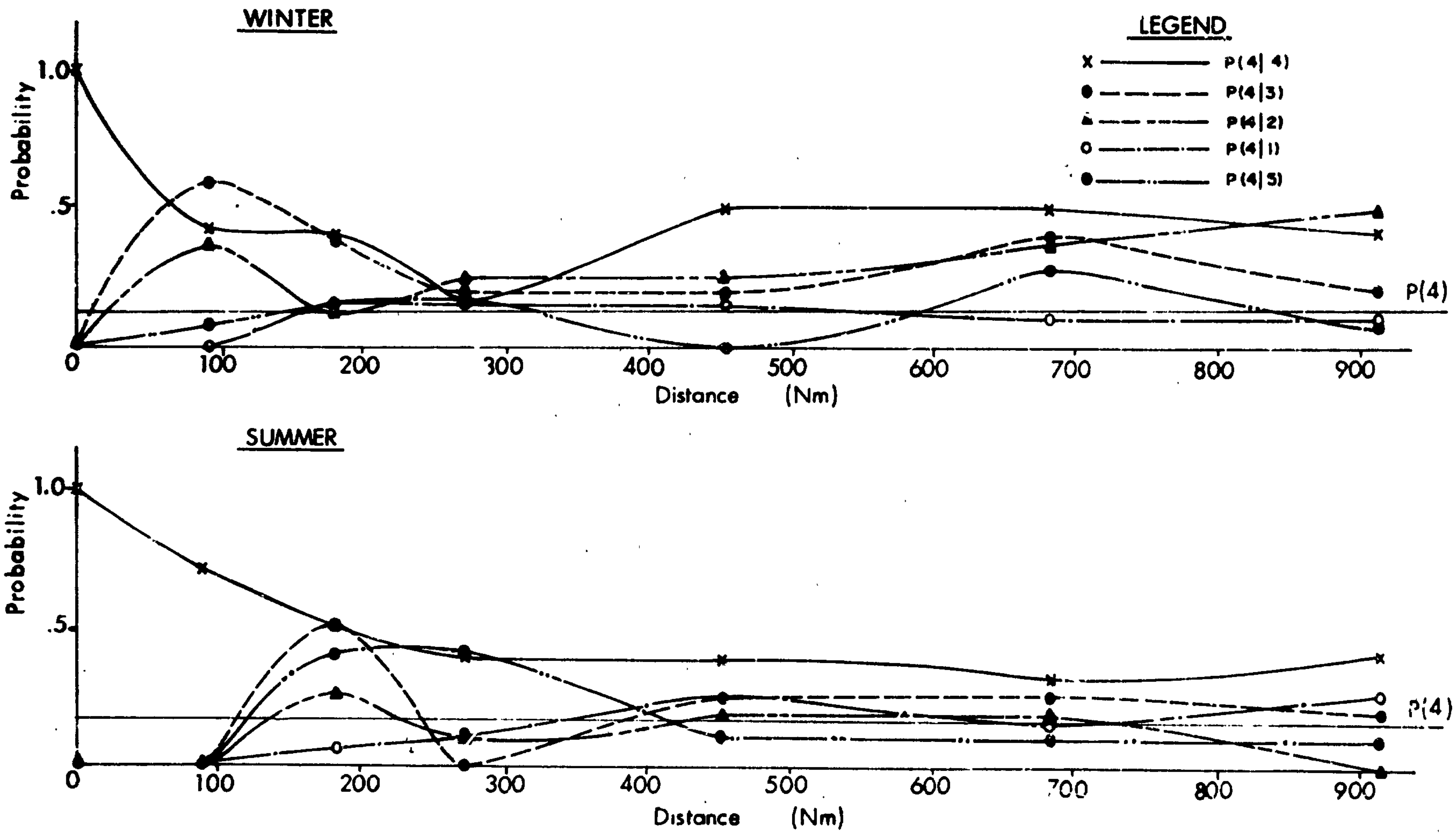


Figure 6-4 Decay of Conditional Probabilities with Distance for Region 11

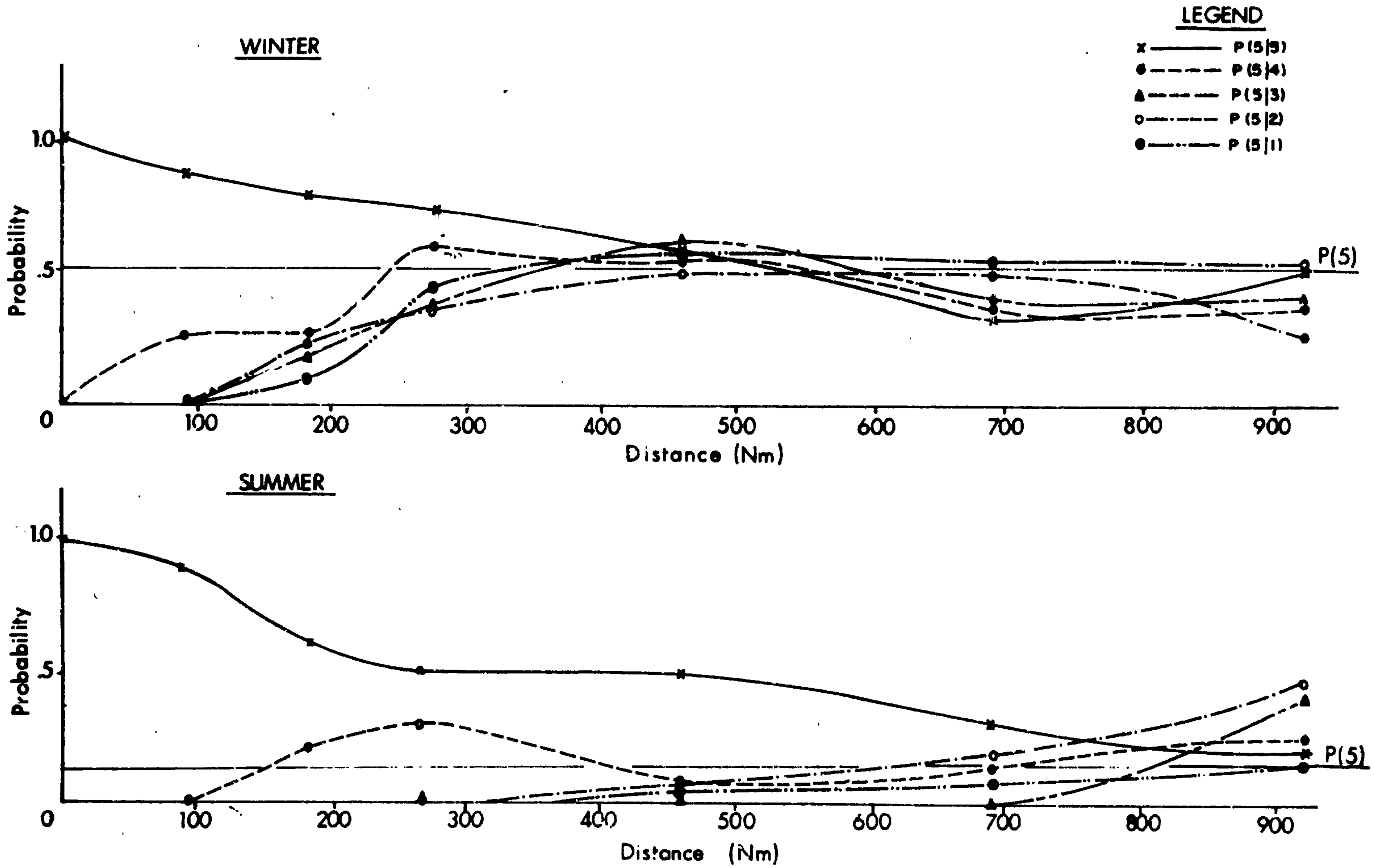


Figure 6-5 Decay of Conditional Probabilities with Distance for Region 11

Table 6-3

Example of Scaling for Distance Less Than 200 nm
Region 19 January 1300 L

| Cloud Group | UNCON | SCOND | | | | | | | CONDIS (160 nm) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | | | 1 | 2 | 3 | 4 | 5 |
| 1 | .15 | .76 | .05 | .05 | .05 | .09 | G | 1 | .81 | .04 | .04 | .04 | .07 |
| 2 | .12 | .17 | .17 | .08 | .08 | .50 | I | 2 | .14 | .34 | .06 | .06 | .40 |
| 3 | .04 | .13 | .12 | .15 | .30 | .30 | V | 3 | .10 | .10 | .32 | .24 | .24 |
| 4 | .17 | .14 | .09 | .14 | .45 | .18 | E | 4 | .11 | .07 | .11 | .56 | .15 |
| 5 | .52 | .13 | .06 | .12 | .16 | .53 | N | 5 | .10 | .05 | .10 | .13 | .62 |

ON the diagonal

$$P(C) = 1 - \frac{\text{Scale (T)}}{24} (1 - \text{TCOND})$$

OFF the diagonal

$$P(C) = \frac{\text{Scale (T)}}{24} (\text{TCOND})$$

The first formula is used for values which lie on the diagonal of the 5 x 5 matrix while the second formula is used for those which lie off the diagonal (similar to the discussion in paragraph 6.4 above).

6.5.1 Example of Scaling for Time Less than 24 Hours

Data are presented in Table 6-4 exemplifying a scaling of the TCOND (time conditionals) for an observation 20 hours after the initial observation. The formulas presented in paragraph 6.5 (above) have been used to scale the TCOND values. This results in a new 5 x 5 conditional distribution (CONTIM). Note that as time decreases from 24 to 20 hours the values of the parameters on the diagonal increase.

6.6 Diurnal Change

The 24-hour conditional distributions, and any scaling of them for other time intervals, contain no direct provision for introducing the effect of diurnal variation, which in some regions is the principal factor affecting cloud cover. A recommended procedure is as follows:

1. Generate a pseudo-conditional distribution (DICON) between the unconditional distributions at the local times of the first and second cloud events. This can be done by first forming a joint probability distribution between UNCON (A), the unconditional distribution of event A, and UNCON (B) the unconditional distribution of event B (later in time than A). The assumption is made that the event B corresponding to a specific event A is the one occurring at the same cumulative probability level in the unconditional distribution at the second time as does the event A in the unconditional distribution at the first time. This satisfies the intuition that diurnal

Table 6-4

**Example of Scaling for Time Less Than 24 Hours**

**Region 19 January 1300 L**

| Cloud Group | UNCON | TCOND | | | | | | | CONTIM (20 hours) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | | | 1 | 2 | 3 | 4 | 5 |
| 1 | .15 | .52 | .07 | .06 | .18 | .17 | G | 1 | .60 | .06 | .05 | .15 | .14 |
| 2 | .12 | .33 | .18 | .08 | .19 | .22 | I | 2 | .28 | .32 | .06 | .16 | .18 |
| 3 | .04 | .21 | .18 | .11 | .32 | .18 | V | 3 | .18 | .15 | .26 | .26 | .15 |
| 4 | .17 | .23 | .10 | .05 | .35 | .27 | E | 4 | .19 | .08 | .04 | .46 | .23 |
| 5 | .52 | .23 | .04 | .07 | .20 | .46 | N | 5 | .19 | .03 | .06 | .17 | .55 |

Table 6-5

Computation of a Pseudo-Conditional Distribution for Diurnal Variation

| | Cloud Category | UNCON EVENT (A) Prob. | Cum. | (B) Prob. | Cum. |
|---|---|---|---|---|---|
| | 1 | .2 | .2 | .3 | .3 |
| (A) | 2 | .5 | .7 | .3 | .6 |
| | 3 | .2 | .9 | .2 | .8 |
| | 4 | .05 | .95 | .1 | .9 |
| | 5 | .05 | 1.0 | .1 | 1.0 |

| | Cloud Category | Event (A) Probability | Rated Probability | UNCON Joint Cell Number | Rated Probability | Event (B) Probability | Cloud Category |
|---|---|---|---|---|---|---|---|
| | 1 | .2 | .2 | 1-1 | .2 | .3 | 1 |
| | | | .1 | 2-1 | .1 | | |
| | 2 | .5 | .3 | 2-2 | .3 | .3 | 2 |
| (B) | | | .1 | 2-3 | .1 | | |
| | 3 | .2 | .1 | 3-3 | .1 | .2 | 3 |
| | | | .1 | 3-4 | .1 | | |
| | 4 | .05 | .05 | 4-5 | .05 | .1 | 4 |
| | 5 | .05 | .05 | 5-5 | .05 | .1 | 5 |

Table 6-5 (cont'd)

**JOINT PROBABILITY**

| | | (B) 1 | 2 | 3 | 4 | 5 | Total= UNCON(A) |
|---|---|---|---|---|---|---|---|
| (C) (A) | 1 | .2 | 0 | 0 | 0 | 0 | .2 |
| | 2 | .1 | .3 | .1 | 0 | 0 | .5 |
| | 3 | 0 | 0 | .1 | .1 | 0 | .2 |
| | 4 | 0 | 0 | 0 | 0 | .05 | .05 |
| | 5 | 0 | 0 | 0 | 0 | .05 | .05 |

**DICON**

| | | $C_{(B)}$ 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| (D) $C_{(A)}$ | 1 | 1.0 | 0 | 0 | 0 | 0 |
| | 2 | .2 | .6 | .2 | 0 | [illegible] |
| | 3 | 0 | 0 | .5 | .5 | [illegible] |
| | 4 | 0 | 0 | 0 | 0 | 1.0 |
| | 5 | 0 | 0 | 0 | 0 | 1.0 |

change is superposed on more gross synoptic scale variability, so that if event A represents a lesser cloud cover than normal, the succeeding event B should also represent a smaller cloud cover than normal at that time. As an aid to the reader, we define $P_A(1)$, $P_A(2)$, etc. to be the probability of cloud group 1, 2, etc. for event A, and $P_B(1)$, $P_B(2)$, etc. to be the corresponding probabilities for event B.

The cloud categorization intervals fall at different cumulative probabilities in the distributions of events A and B. Thus it is necessary to divide up the intervals of the distribution of event A and assign them to intervals of the distribution of event B, assuming uniform distribution within an interval. To form the joint probability matrix shown in Table 6-5(C), we find the fractional part of $P_A(1)$ that is contained in (jointly distributed with) $P_B(1)$. In the example shown in Table 6-5(B), all of $P_A(1)$, 0.2, is contained in $P_B(1)$. Thus, 0.2 is entered in the joint probability matrix at position A = 1, B = 1 (cell number of joint table). Since $P_B(1)$ is 10% greater than $P_A(1)$, this additional 0.1 in $P_B(1)$ could not have occurred jointly with $P_A(1)$. Therefore, it is placed in the matrix (Table 6-5(C)) at position A = 2, B = 1.

In a similar way, we rate (jointly distribute) $P_A(2)$ with $P_B(2)$ and find that only 0.3 are contained in both. Therefore, 0.3 is located in the joint matrix at A = 2, B = 2 Again there is an additional part to be allocated; this time 0.1 of $P_A(2)$ must have ocurred with $P_B(3)$; it is thus entered in the matrix at A = 2, B = 3. (For Monte Carlo computational procedures, it may be more convenient to work with the UNCON cumulative probabilities.)

This process is continued for all categories as shown. These individual entries, divided by the marginal total UNCON (A), become the entries in DICON ($C_B$ $C_A$).

If any element of UNCON (A) is zero, a suitable flag should be entered in the cell number of the joint distribution into which an entry would fall if that element were very small. In forming the DICON matrix, by division through each row by the corresponding element of UNCON (A), the rule is "flag divided by zero is 1.0." This results in an appropriate entry in DICON to take care of the eventuality of a "forbidden" event A materializing as a result of other manipulations. If an element of UNCON (B) is zero, no special provisions are required, as the resulting distribution will "lock out" that category.

2) Form the diurnal - temporal conditional distribution (DITCON) by

$$\text{DITCON}\ (a_i | b_j) = \sum_{k=1}^{5} \text{DICON}\ (a_i | c_k) \cdot \text{CONTIM}\ (c_k | b_j)$$

where CONTIM is the scaled derived temporal conditional appropriate to the time interval.

3) Use DITCON in place of the temporal conditional in question. The DITCON operation is not required for time intervals of less than 2 hours or approximately 24 hours.

If it is desired that the resulting distribution avoid total lockout of cloud categories of zero probability in UNCON (2), the formula for DITCON may be reversed

$$\text{DITCON}\ (a_i | b_j) = \sum_{k=1}^{5} \text{CONTIM}\ (a_i | c_k) \cdot \text{DICON}\ (c_k | b_j)$$

The two formulas differ in the effective order in which the operations of diurnal change and temporal conditionality are performed. The first procedure, recommended for most applications, performs the conditionality operation first.

As noted earlier, the straight line estimate of temporal conditional distribution at time intervals less than 24 hours tends to overestimate the persistence, i. e., produces a distribution too strongly diagonalized. A large part of this overestimate may be due to the ignored diurnal change. The DITCON operation reduces the diagonalization in a fashion directly related to the degree of diurnal change, lending some confidence to its validity.

## 6.7 Scaling for Both Time and Distance

Certain simulation situations may require that a point or area on the earth be observed on a given orbit and a second nearby point be observed on a somewhat later orbit. For this situation, where the time difference between the first and the second observation is less than 36 hours and where the distance between the two observed points is less than 800 miles, the conditional probabilities must be scaled for both time and distance concurrently. The following procedure has been established to accomplish this concurrent scaling for time and distance.

### 6.7.1 Procedure for Scaling for Time and Distance

a) Separately calculate CONDIS and CONTIM for the appropriate distance and time, respectively, from SCOND and TCOND. Perform DITCON diurnal operation on CONTIM if required.

b)

$$\text{TSCON}\,(a_i \mid b_j) = \sum_{k=1}^{5} \left[\text{CONDIS}\,(a_i \mid c_k) \cdot \text{CONTIM}\,(c_k \mid b_j)\right]$$

for $a_i$ from 1 to 5 and $b_j$ from 1 to 5.

c) If the conditionals have been modified for viewed area size (see Section 7), substitute TSSCON, SCSCON, and SCTCON for TSCON, CONDIS, and CONTIM respectively.

### 6.7.2 Example for Scaling for Time and Distance

An example of scaling for time and distance is presented in Table 6-6. At the top of the Table (labeled A) are data scaled according to the procedure demonstrated in paragraph 6.7.1. Here the scaling is for 24 hours and 200 nm for a sampling area size of 60 nm. In part B of Table 6-6 the data are scaled for 20 hours, 160 nm and for a sampling area size of 60 nm. In part C of Table 6-6 an example is shown where the time has been scaled to 20 hours, the distance to 160 nm and the sampling area size has also been changed and enlarged to 150 nm.* These matrices can be compared with the unscaled data shown in Tables 6-2 for distance and 6-4 for time.

---

* Procedures for enlarging the sampling area size are discussed in Section 7.

Table 6-6

Example of Scaling for Time and Distance

A - Scaled for Time = 24 Hours, Distance = 200 nm
Sampling Area Size = 60 nm

| | | | | |
|---|---|---|---|---|
| .46 | .07 | .09 | .16 | .22 |
| .35 | .09 | .10 | .17 | .29 |
| .27 | .09 | .11 | .23 | .30 |
| .28 | .08 | .11 | .24 | .29 |
| .28 | .07 | .11 | .20 | .34 |

B - Scaled for Time = 20 Hours, Distance = 160 nm
Sampling Area Size = 60 nm

| | | | | |
|---|---|---|---|---|
| .53 | .07 | .07 | .14 | .19 |
| .31 | .14 | .09 | .16 | .30 |
| .23 | .11 | .14 | .25 | .27 |
| .25 | .08 | .10 | .31 | .26 |
| .24 | .06 | .10 | .19 | .41 |

C - Scaled for Time = 20 Hours, Distance = 160 nm
Sampling Area Size = 150 nm

| | | | | |
|---|---|---|---|---|
| .15 | .09 | .20 | .24 | .32 |
| .11 | .10 | .18 | .28 | .33 |
| .09 | .10 | .17 | .27 | .37 |
| .07 | .08 | .17 | .29 | .39 |
| .06 | .08 | .17 | .24 | .45 |

## 6.8 Markhov Chains

### 6.8.1 Introduction

The cloud model we have adopted calls for generation of cloud fields or cloud statistics as Markhov chains. It is of interest to outline some of the properties of the Markhov chain and to examine the behavior of the chain used with our cloud distributions.

A simple first order Markhov process is defined as a stochastic process for which the current value of the random variable depends upon any set of previous values, but only through the most recent value. The probability of the joint event is:

$$p(x_1, x_2, x_3, \ldots, x_n) = p(x_1) \prod_{v=2} p(x_v | x_{v-1})$$

so that a Markhov process is defined by the initial unconditional distribution $p(x_1)$ and the succeeding set of conditional distributions.

The use of a simple Markhov process as a cloud model needs some defense. Internal evidence within our statistics, such as the appearance of what we have termed antipersistence in the conditional distributions at some distances, suggest that the simple Markhov chain model cannot be a complete description of the processes at work. We believe, however, that it is an adequate model for most purposes, subject to the provisos that the chains should not be permitted to get too long, and that not too much faith be put in the ability of the model to estimate the probability of relatively improbable joint events. Perhaps its greatest virtue is its flexibility of application and the relatively small computational problem involved in its use.

### 6.8.2 Behavior of Markhov Chains Using Cloud Data

Use of our data in the recommended manner in Markhov chains helps compensate for some of the known deficiencies of the data. The Markhov process using our data is not stationary in the sense that the expectation and variance of any sample is not independent of its position within the chain. The first element of the chain, drawn from the ground-observed unconditional distributions, is known to be biased toward greater cloud amounts. The subsequent conditional links are based on satellite-observed parent populations known to be biased toward lesser cloud amounts. Thus, the first member of the chain has a "pessimistic" expectation. Succeeding events along the chain have progressively more optimistic expectations, finally converging on the expectation of the parent satellite distribution. Thus, a chain of an appropriate length will have an overall expectation of mean cloud cover near the "true" value. Since we do not know the "true" expectation, there is no immediately satisfactory way of defining a chain length which will have the desired expectation.

The variance of the entire chain would appear to be greater than the "true" variance because of the trend of the expectation. However, the artifice of the straight line approximation to the conditional distribution at less than 200 miles or 24 hours, which in general overestimates the diagonal elements of the scaled conditional distribution, operates to reduce the variance of individual events along the chain. Since these variances are greater in most regions than the contribution to variance from the trend of the expectation, reasonable compensation may occur for chains of moderate length.

### 6. 8. 3 Use of the Markhov Chain in Simulation

The following procedures are recommended for the use of the Markhov chain.

1. Generating a Distribution of Joint Events

Order the events in one region in a logical chain in space and time. Section 6. 9 gives some suggestions for the more difficult situations. Normally the chain should be limited to 3 or 4 dependent events, if for no other reason than to keep the subsequent computation and memory requirements within bounds. Then the joint distribution is given by

$$P(a_i, b_j, c_k, \ldots\ldots) = P(a_i) \cdot P(b_j | a_i) \cdot P(c_k | b_j) \ldots$$

where the $P(b_j | a_i)$ etc. are conditional distributions scaled for space and/or time between each pair of observational events. Note that $5^n$ storage areas and $5^{n!}$ multiplications are involved in creating the joint distribution, where n is the number of events in the chain, and the cloud cover is distributed in 5 categories.

Normally the joint distribution is used by forming certain marginal or joint totals; i. e. ,the cloud sequences 1-1-5, 1-1-4, 5-1-1, and 4-1-1 may all have the same observational success consequence, and would be grouped together. Such groupings can be done during computation, significantly reducing storage required for interim products.

2. Monte Carlo Simulation

The computational load involved in analytically handling even fairly short Markhov chains suggests that solution by random sampling (Monte Carlo) techniques may frequently be preferred even where analytical expansion is possible. This is particularly true where the ocurrence of improbable events does not significantly affect the results. In many other simulation situations, the decision processes underlying the observations may be so complex as to defy tractable analytic expression. Monte Carlo sampling then offers a straightforward procedure for arriving at a reasonably confident estimate of the probability of joint events.

The Procedure:

Order the events as before. Here, there is no fundamental objection to branching chains as a means of keeping the chain length short. Compute the scaled conditional distributions between each pair of observational trials. Sum all distributions, including the unconditional distribution of the first observational trial, to form cumulative distributions. Generate a random number uniformly distributed in the range 0-1. Find the cumulative class interval of the unconditional distribution into which the random number falls. This class is the cloud category of the first event, which is appropriately recorded. Estimating the impact of the cloud category on observational success may require a further random process.

The cloud category just found becomes the "given" for the next observational trial. Another random number is generated, and compared with the cumulative distribution conditional on the previous cloud cover. This results in another cloud cover, and the process is repeated to the end of the chain. The entire sampling process must then be repeated a large number of times. The number of samplings depends upon number of categories into which the final distribution of observational success is to be divided and an a priori estimate of the probability of the least probable joint event of interest. The number of samplings should be sufficient to give at least 5 such events.

Section 9. 1 gives an example of a practical Monte Carlo simulation of a f rly complex situation.

## 6.9 Ordering of Events - The Characteristic Velocity

Because of the basic Markhov chain model we have adopted, the ordering of observation events is important. As a general rule, the events should be ordered in a chain of greatest proximity within the region. The chain is broken when the trial of observations passes out of the region, but is resumed if the region is revisited within 36 hours.

Organization into a chain becomes more complex when subsequent orbits cross each other inside the region. The chain logically branches at the point of crossing, which of itself causes no mathematical problems. Care must be taken, of course, to maintain the proper order of conditionality.

Figure 6-6 shows a path of conditionality for a characteristic situation. Three orbits overlap within a region. Observations are attempted over a series of areas centered on the subpoint. The path of conditionality leads from the original unconditional entry of the first orbit to its intersection with the second orbit, where a three-way branch occurs. The path of conditionality runs backward along part of the second orbit, causing no logical difficulty, since we have postulated that spatial dependence is independent of direction. Although time is also nominally running backward, orbital speed is sufficient to make all observations on one orbit practically synchronous.

At the branch point, it may be necessary to go from orbit 1 to orbit 2 via a temporal conditional transformation if the orbital period is 2 hours or more. The same process occurs at the branch point between orbits 2 and 3.

At the intersection of orbits 1 and 3, a potential ambiguity occurs. The same area will be observed 3 to 5 hours after it was first observed, but along a conditional path of some length from the first observation. A decision must be made whether to terminate the orbit 3 chain before the intersection and to continue orbit 3 dependent on the prior observation on orbit 1, or to continue the chain across orbit 1. In the present case, the requirement to keep the chain short may compel the first alternative.

In other cases, however, many such decisions may be required, and little _a priori_ information may be available on the path of conditionality. The example in Section 9.1 is such a case. In these situations, a mechanical process of ordering the events is required.

In the general case, the observational events may be randomly ordered in space and time. We wish to establish a means of comparing space and time so that we can trace a path among the events that orders them in logical proximity. To do

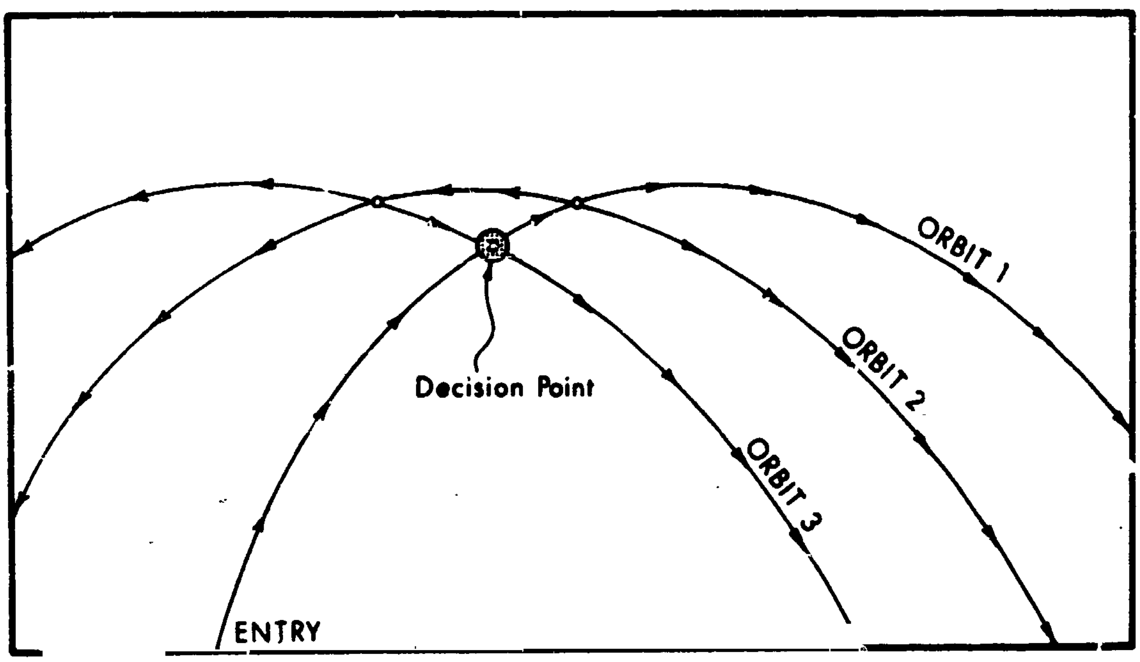


Figure 6-6 Path of Conditionality within a Region

this we have defined a quantity to be called the characteristic velocity. This is a quantity, having the dimensions of a velocity, which multiplies the time base of the linear decay of conditionality of the temporal conditional distribution to make it congruent with the spatial conditional distribution.

There is, of course, no single such velocity. An estimate of a characteristic velocity is found by the following process.

1) Find the highest conditional probability on the diagonal of SCOND. Call it SMAX.

2) Read the corresponding element of TCOND. Call it TMAX.

3) Then $V = \frac{200}{24} \frac{(1 - TMAX)}{(1 - SMAX)}$ Knots

Typical characteristic velocities are of the order of 20 knots, giving a feeling of physical reality to the definition.

Application of the characteristic velocity in ordering a chain is as follows:

1) Sort the observation events by region. Within each region, the initial order should be the order of probable encounter.

2) Assign a local time of encounter to each event.

3) Compute an equivalent distance between the first event and all others; a convenient formula is

$$S^2 = 3600 \left[(\Delta\, LAT)^2 + (\Delta\, LONG)(COS(LAT))^2\right] + (V\, \Delta\, t)^2$$

where the terms are self evident.

4) The event having the smallest value of $S^2$ becomes number 2 in the chain.

5) The process is repeated using event 2 as the starting point.

6) If branching is to be considered, is the smallest value of $S^2$ found in (5) larger than the second smallest found in (3)? If so, a branch is originated and it will be necessary to make subsequent comparisons along both branches.

7) Continue the process starting at (5) until all points are ordered. Unless it is obvious that branching is required, it is probably best avoided to reduce program logic and computation volume.

The example of Section 9.1 gives a complete demonstration of the use of these procedures.

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# 7. ENLARGING THE SAMPLE AREA SIZE

## 7.1 Introduction

Earlier sections have referred to the change in cloud cover distribution resulting from change in the area size over which the cloud cover is defined. It has been pointed out that dramatic changes take place over the very range of sample areas that are to be used in earth-oriented experiments, and thus in simulation. It is required, therefore, that a reasonably effective method be found for generating suitable cloud cover distributions for enlarged sampling areas from already available information - the available cloud statistics. Collection of adequate samples of raw satellite data seems prohibitive, at least until suitable compilations of digitized data become available.

The general features of the change of cloud cover distribution with size of sample area can be readily visualized. The cloud cover over a point can have but two values - clear and overcast. The cloud cover over the entire earth seems to stay reasonably constant at perhaps 40%. Intermediate sized areas have cloud distributions which pass from the U shape of small areas to more bell-shaped distributions at rates which depend upon the prevalence of large-scale cloud systems. The temperate zones, in which large cloud systems are the rule, show characteristically U or J-shaped distributions at the 30 mile scale size of the ground observer. Tropical regions may already exhibit bell-shaped distributions at this scale.

The effect of scale size on the distribution can be seen from the examples of Figure 7-1, which are taken from limited samples of satellite data. A distribution originally bell-shaped at $1^{\circ}$ area becomes more so at $3^{\circ}$ and $5^{\circ}$, at the expense of the already rare clear areas; overcasts also become less probable. A J-shaped distribution tends toward a skewed bell-shape. A U-shaped distribution first becomes binodal, then bell-shaped with increase in sample area scale. In all cases, the probability of clear sky becomes quite small at a $5^{\circ}$ (300 nm) scale.

The effect of increasing the sample area size can be demonstrated by a simple computational exercise of doubling the sampling area.

The cloud distribution in the two areas can be expressed as the joint distribution of the two sets of events. The initial computation will assume independence between events in the two areas. Table 7-1 outlines the computation of the joint distribution from synthetic data.

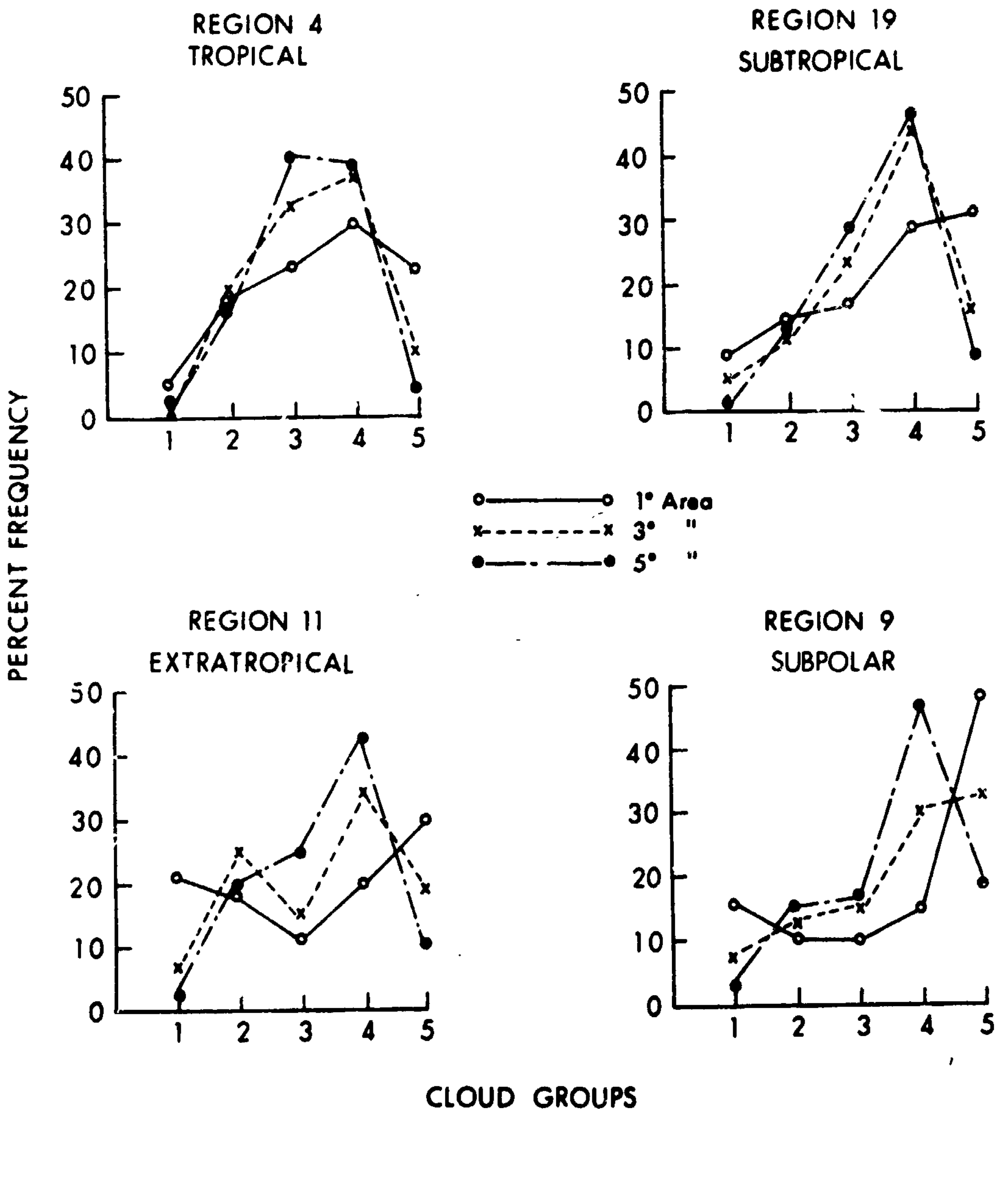


Figure 7-1 Comparison of Cloud Cover Distributions as Sampling Area Size Increases

The joint distribution is defined by:

PJOINT (a, b) = UNCON (a) · UNCON (b)

Each element of the PJOINT matrix corresponds to an average cloud cover over the doubled area. These cloud covers can be reclassified according to the original cloud cover grouping scheme (Table 5-1). Table 7-2 gives the cloud group assignment of each location in the PJOINT matrix. This location matrix is universally useful in area size computations, and is called KWHERE.

To obtain the cloud cover group values at each location in the KWHERE matrix the cloud amounts of the joint events were averaged. For example, cloud cover 1 for the enlarged area can only result if both areas, used in the average, had cloud cover 1. For all of the upper left to lower right diagonal values in the KWHERE matrix (Fig. 7-2), the averaged cloud covers remain the same; i. e. cloud cover 2, averaged with 2, results in cloud cover 2, 3 given 3 in 2, etc. The non-diagonal values are derived by averaging the mean cloud amounts from each group i. e., group 3 with a mean of 3. 5 tenths and group 1 with 0 tenths averages to 1. 75 tenths. Translated back to cloud groups, this is group 2. Thus, cloud group 2 is shown in the KWHERE matrix at 3 given 1 and 1 given 3. Similarly, for all other non-diagonal values.

Conversion of PJOINT to the unconditional distribution scaled for the doubled area size, SUNCON, is achieved by the operation of adding together all elements of PJOINT having the same entry in the matching location of KWHERE. The result, shown in Table 7-3, is rather startling. The previously U-shaped UNCON has become the strongly peaked SUNCON.

This extreme change in cloud cover distribution with a relatively small change in area size results from the untenable assumption of independence between cloud events in contiguous areas. Lets us repeat the computation, now using a synthetic set of conditional probabilities to describe the dependence of events in the second area on those in the first. Table 7-4 outlines the computation.

PJOINT (a, b) = UNCON (b) • CONNEW (a|b)

is the general case; CONNEW is the spatial conditional distribution appropriately scaled to the distance between centers of the areas.

Table 7-1

Computation of Joint Distribution, Independent Data

| Cloud Group | UNCON | PJOINT 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| 1 | .3 | .09 | .03 | .03 | .06 | .09 |
| 2 | .1 | .03 | .01 | .01 | .02 | .03 |
| 3 | .1 | .03 | .01 | .01 | .02 | .03 |
| 4 | .2 | .06 | .02 | .02 | .04 | .06 |
| 5 | .3 | .09 | .03 | .03 | .06 | .09 |

Table 7-2

Cloud Group Location Matrix

| Cloud Group | KWHERE 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | 1 | 2 | 2 | 3 | 3 |
| 2 | 2 | 2 | 2 | 3 | 3 |
| 3 | 2 | 2 | 3 | 4 | 4 |
| 4 | 3 | 3 | 4 | 4 | 4 |
| 5 | 3 | 3 | 4 | 4 | 5 |

Table 7-3

Cloud Cover Distribution for Doubled Area, Independent Events

| Cloud Group | UNCON | SUNCON |
|---|---|---|
| 1 | .3 | .09 |
| 2 | .1 | .15 |
| 3 | .1 | .41 |
| 4 | .2 | .26 |
| 5 | .3 | .09 |

Table 7-4

Computation of Cloud Cover Distribution for Doubled Area, Dependent Events

| Cloud Group | UNCON | CONDIS | | | | | PJOINT | | | | | SUNCON |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | |
| 1 | .3 | .5 | .3 | .1 | .1 | 0 | .15 | .09 | .03 | .03 | 0 | .15 |
| 2 | .1 | .1 | .5 | .2 | .1 | .1 | .01 | .05 | .02 | .02 | .01 | .23 |
| 3 | .1 | .1 | .2 | .5 | .1 | [illegible] | .01 | .02 | .05 | .01 | .01 | .17 |
| 4 | .2 | .1 | .1 | .2 | .5 | .1 | .02 | .02 | .04 | .10 | .02 | .30 |
| 5 | .3 | 0 | .1 | .1 | .3 | .5 | 0 | .03 | .03 | .09 | .15 | .15 |

Even though CONDIS is only moderately diagonalized, the resulting SUNCON distribution more closely resembles its parent UNCON distribution. Figure 7-2 compares the SUNCON distributions ($P_{2A}$) with UNCON ($P_{1A}$).

Let us now consider the more general case of viewed area size several times the area on which the statistical distributions are based.

## 7.2 An Approach to Scaling for Enlarged Sampling Area Size.

The information at our disposal for the task of enlarging the sampling area size is the unconditional distribution, valid for a sampling area of 30-50 nm diameter, and the spatial conditional distribution, defined for areas about 60 nm diameter with centers separated by about 200 nm. A straight line interpolation or extrapolation has been adopted to find conditional distributions at other distances. No information is available to define the conditional dependence of cloud events within an area on more than one of its neighbors.

Let us initially investigate some properties of a straight chain of 50-60 mile square areas, corresponding to a diameter of a larger circle. Let each member of the chain be dependent only on the first member. The straight line approximation to the scaling of the spatial conditional distribution then gives rise to individual PJOINT distributions, the elements of which are linear interpolations between the unit diagonal PJOINT of the first member of the chain, and PJOINT of the last. It can be seen that the distribution of the total cloud cover in this chain can be described by PJOINT of the last element, internally summed as before by reference to the KWHERE locator matrix.

Lacking data for two-way conditionality, we have taken the distribution of cloud cover in the diametric strip as the distribution for the entire circle. Pragmatic success of this procedure has led us to seek the properties of cloud cover that contribute to its success. Cloud systems are usually of larger scale than even the enlarged sampling areas. The cloud cover, rather than being randomly distributed in the sampling area, simply appears as a gradient across the area. This then reduces the calculation of the cloud distribution over the entire area to a one-dimensional linear problem, similar to the procedure we have adopted. We have reasonable verification of the success of the procedure, as outlined in later paragraphs.

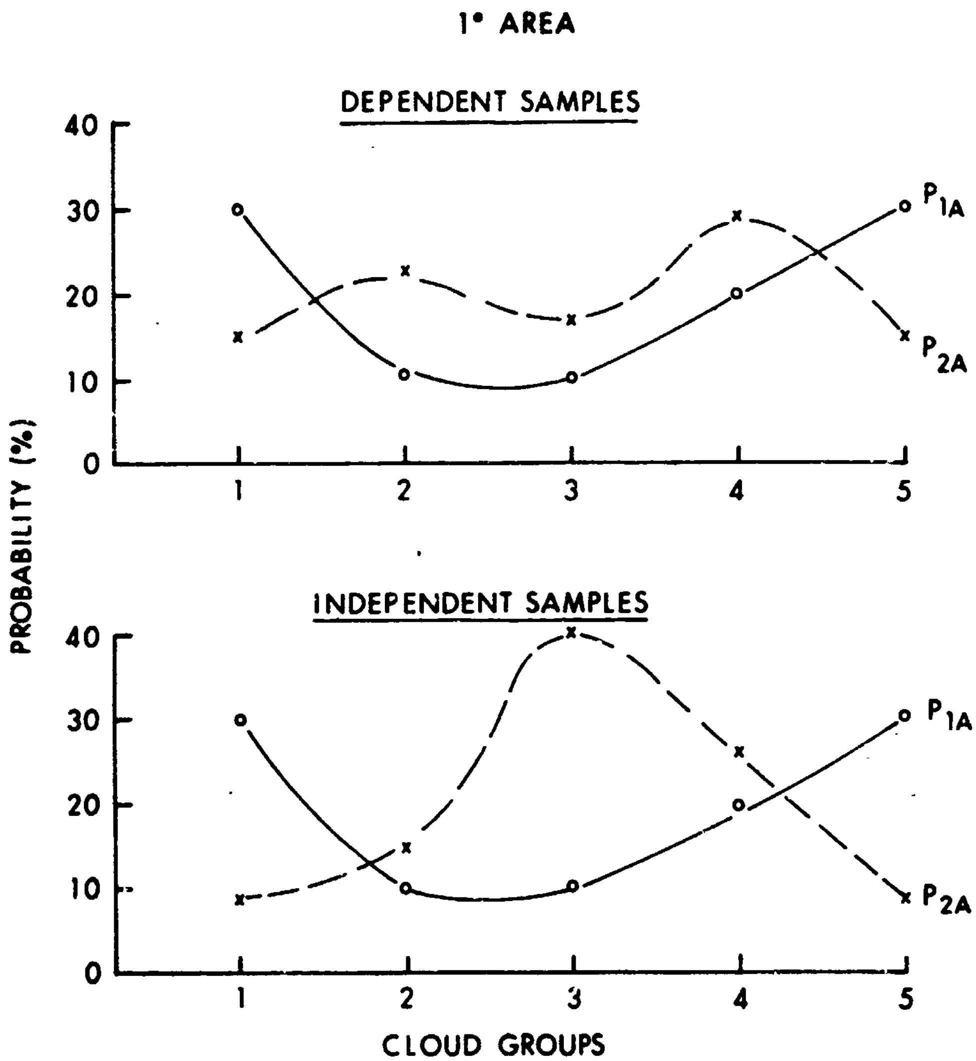


Figure 7-2 Change in Shape of Cloud Cover as Sampling Area Size Doubles

## 7.3 Procedure for Computation of Unconditional Distribution Scaled for Sample Area Size.

We recapitulate the procedure for finding SUNCON.

1) Tabulate the unconditional and conditional distributions for the required regions, month and time of day.

2) Scale the conditional statistics, using the procedures detailed in Section 6, to a distance which corresponds to the diameter of the required enlarged viewed area.

3) The unconditional distribution UNCON is multiplied into the conditional distribution matrix CONNEW.

4) The resultant joint distribution matrix is PJOINT summed using the KWHERE matrix for reference.

5) A new unconditional distribution, SUNCON, applicable to the enlarged viewed area size results.

## 7.4 Validation of Scaling UNCON for Sampled Area Size

A few special data extractions from satellite data have been made to validate the sampled area scaling process. These validations have been made for summer samples from Regions 4, 19, 11, and 9. Figure 5-8, shows the comparison between the UNCON data and the satellite observed distribution from which SCOND was composed. Agreement is indifferent at best, so these data should provide a critical test of the capability of our procedures to produce reasonable values of SUNCON from the available data.

Computations and satellite data extractions have been made for $3^{\circ}$ (180 nm) areas. Figure 7-3 compares the satellite-observed and computed results. Agreement is fair, the major disagreements arising from the larger discrepancies in source distributions. Comparison with Figure 5-8 shows that the computed distribution is a better approximation to the observed than either parent distribution. $\chi^2$ tests show no evidence that, in a sample of 90 trials, the calculated and observed distributions did not come from the same population.

## 7.5 Computational Procedure for Enlarging the Area Size for Conditional Distributions

The procedure for enlarging sampling area size for conditional distributions is similar to, but more involved than the procedure for the unconditional distributions.

Referring to Figure 7-4, we are given unconditional distributions for the area represented by "a" and conditional statistics for an area "c" some distance $\Delta$ from area "a". What we wish to compute is the conditional probability distribution for new enlarged area B given the unconditional probabilities for new enlarged area A (both areas have been enlarged to the new diameter $\alpha$). Thus what is required is to first expand area "a" to area A using the techniques described in paragraph 7.3 above. Then to obtain the new 5 x 5 conditional probability matrix for area B, given A we define:

$$P(A, B) = \text{joint probability of cloud cover in A and B}$$

The computational algorithm for accomplishing this multiplication of probabilities is to perform the multiplications indicated in Figure 7-4 where a schematic form for the matrices has been used. In this Figure the designators have the same meaning as defined in Section 6, CONNEW is the expanded sampling area space conditionals (SCOND), etc. The joint probability of events in all four areas is:

$$P(abcd) = P(a) \cdot P(b|a) \cdot P(d|b) \cdot P(c|d)$$

where the order of conditionality is somewhat arbitrary.

We define the cloud cover in area A to be the average of the cloud cover in a and b while the cloud cover in B is the average cloud cover in c and d. Thus, we can write formally:

$$P(A, B) = P(\overline{ab}, \overline{cd})$$

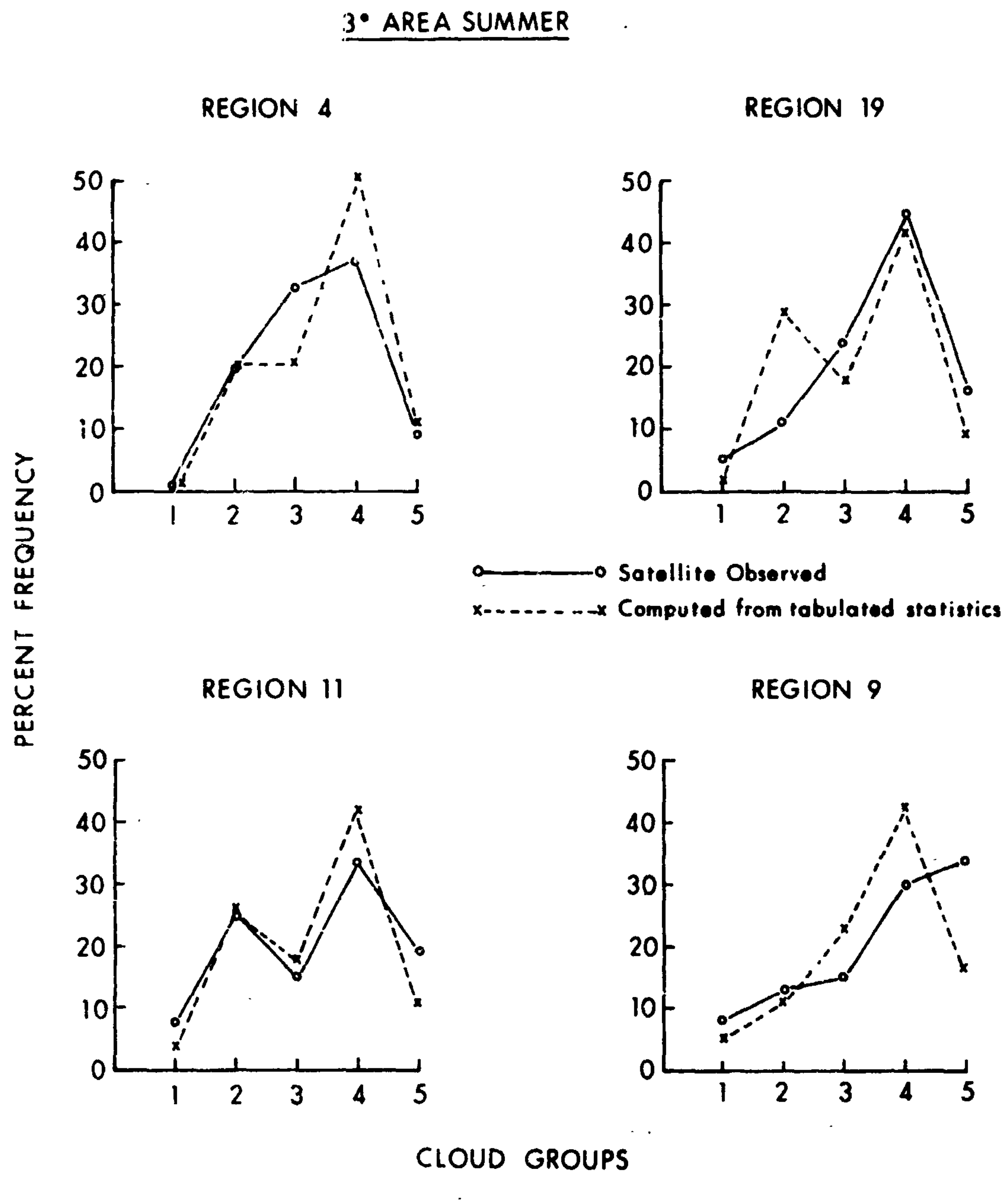


Figure 7-3 Comparison of Satellite-Observed and Computed Distributions for 3° Areas During the Summer

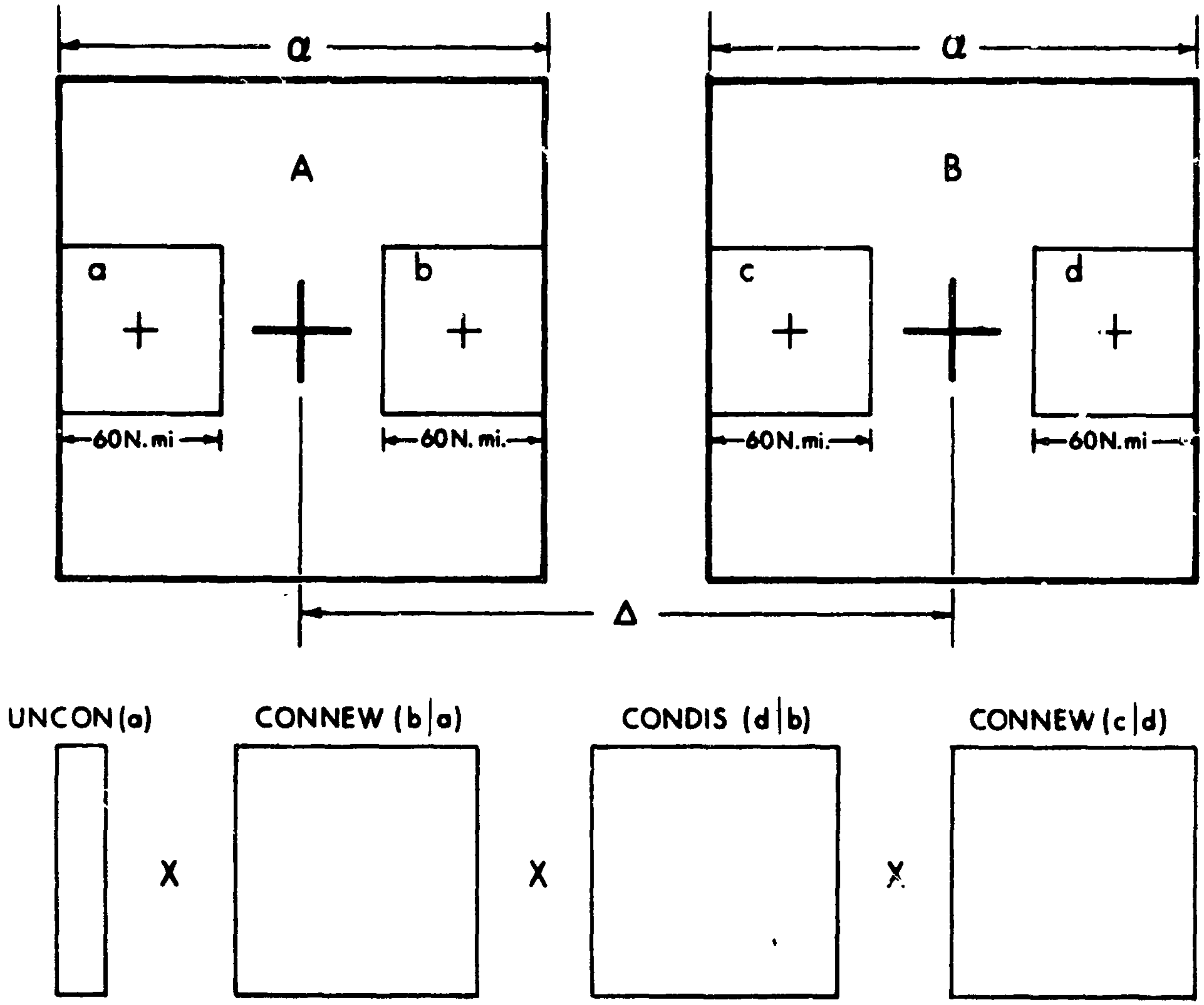


Figure 7-4 Scheme for Computation of Spatial Conditional Distribution of Enlarged Sample Areas

To find $P(\overline{ab}.\overline{cd})$, the KWHERE locator matrix is used 4-dimensionally. This involves assigning values to $\overline{ab}$ from the a and b locations in the 4-dimensional PJNT matrix, and to $\overline{cd}$ from the c and d locations. The result is the two dimensional joint probability table P (A, B). This is transformed to the conditional probability by division by the marginal total.

$$P(B|A) = \frac{P(A,B)}{\sum_B P(A,B)}$$

The process of finding temporal conditional distributions of enlarged sample areas is identical, with the exception that CONTIM is substituted for CONDIS. CONNEW (c|d) should be computed for the local time of event B, and the DITCON operation (Section 6.6) should be performed in finding CONTIM.

7.6 Examples of Conditional Distributions for 180 Nautical Mile Sampling Areas

No suitable data are immediately available for validation of the procedure for computing conditional distributions of enlarged areas, so reliance must be placed on examination of sample calculations for reasonableness.

Examples of conditional and unconditional distributions scaled for time and distance were presented in Section 6 above. Here we present examples of conditional distributions scaled for larger sampling area size.

Table 7-5 presents unconditional and conditional statistics for a sampling area size of 60 nm extracted directly from the tabulated data for Region 19. This data is for 1300 local time for the month of January. Table 7-6 presents the distributions resulting from application of the techniques described in Paragraphs 7.3, 7.5 above for an enlarged sampling area of 180 nm. Note the differences in the two conditional matrices, particularly those values which lie on the diagonal. As might be expected, the middle cloud group, 3, becomes a more probable joint event.

The SUNCON distribution, found as a by-product, (one of the marginal totals $\sum_A P(A,B)$), has some interesting properties. The probability of clear skies is little changed. The probability of partial cloud almost vanishes in SUNCON, while the slight probability of cloud group 3 in UNCON is replaced with a fairly high probability in SUNCON. Most noteworthy is the drop in the probability of overcast, matched by a distinctly lowered conditional 5|5 in SCSCON. None of these features violate our sense of what may be expected, and thus the new distributions may be accepted as providing more information than no knowledge at all, even if they have not been demonstrated to be "correct."

Some comment is required on the use of these derived distributions in simulation. Each conditional distribution derived for our enlarged sample area represents a 3-step Markhov chain. Two of the steps are formally removed by the averaging process involved, but the variance of elements within the distribution is still at least 3/2 the variance of the elements of the conditional distributions from which it was derived. In the extreme case, if the variance of the distribution entering the computations becomes large, all states of the joint probability matrix become equally probable and the distributions are defined only by the averaging process. Table 7-7 presents the "noise" distribution. The conditional distribution will show no conditionality; thus all rows will be identical to the unconditional. None of the computations we have performed have shown any tendency to revert to this distribution, except for those tropical regions where the parent distribution is already of this form.

Table 7-5

Unconditional and Conditional Distributions for a 60 nm Sampling Area Size at 200 nm Separation

| Cloud Group | UNCON (60) | SCOND 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| 1 | . 15 | . 76 | . 05 | . 05 | . 05 | . 09 |
| 2 | . 12 | . 17 | . 17 | . 08 | . 08 | . 50 |
| 3 | . 04 | . 13 | . 12 | . 15 | . 30 | . 30 |
| 4 | . 17 | . 14 | . 09 | . 14 | . 45 | . 18 |
| 5 | . 52 | . 13 | . 06 | . 12 | . 16 | . 53 |

Table 7-6

Unconditional and Conditional Distributions for a 180 nm Sampling Area Size at 180 nm Separation

| Cloud Group | SUNCON (180) | SCSCON 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| 1 | . 12 | . 34 | . 10 | . 30 | . 13 | . 13 |
| 2 | . 08 | . 14 | . 12 | . 24 | . 29 | . 21 |
| 3 | . 21 | . 09 | . 09 | . 21 | . 31 | . 30 |
| 4 | . 29 | . 03 | . 05 | . 16 | . 44 | . 32 |
| 5 | . 30 | . 03 | . 07 | . 20 | . 20 | . 50 |

Table 7-7

Distribution Resulting from Averaging of Equiprobable Joint Events.

| Cloud Category | Probability |
|---|---|
| 1 | . 04 |
| 2 | . 28 |
| 3 | . 36 |
| 4 | 28 |
| 5 | . 04 |

# 8. ENGINEERING AND SIMULATION APPLICATIONS

The set of data, techniques, and procedures that have been assembled are intended for a variety of applications in the study and simulation of earth-oriented experiments from low orbit. We will list, in no particular order, a number of such applications by category. In most cases the mode of application depends upon the details of the specific problem.

## 8.1 Design of Experiments

Viewed Area Size. Trade off of entrance aperture of field of view against speed of response and problem of sorting good from cloud-contaminated data. Particularly important for radiometric instruments.

Control Systems. Selection of experiment control system and mode of deployment based on benefit/cost studies over cloudy skies.

Data Volumes. Where film is the medium, it is important to estimate the number of exposures over partly cloudy skies required for mission success. Section 9.2 explores this further. The same class of problem may occur with on-board telemetry storage of less capacity than the maximum data taking rate can use.

Probability of Success. An experiment may be cloud sensitive and require a reasonably coherent chain of observations to achieve a reasonable level of success. An example is infrared observation of apparent diurnal surface temperature changes to estimate the condition of ground cover. Simulation or computation of probability distributions may be desired to ascertain whether the experiment is worth consideration.

Alternate Techniques. The cloud data may be used to evaluate alternate instrumentation for the same general observational purpose. The control system design is one feature of this.

Cost/Benefit. Earth resource satellite system costs and benefits cannot be properly evaluated in the absence of cloud information. While the sophistication of the techniques presented in this report exceeds that of usual techniques for estimating benefits, cloud information at some level is essential.

Orbit Analysis Each experiment has an orbit inclination, height, precession rate, and time and season of injection into orbit that will give optimum results. It does not follow that an orbit optimized for the experiment without reference to cloud interference will also be the optimum orbit in the presence of cloud. By defining a suitable measure of experiment success, it should be possible, by trial and error if necessary, to find a good, if not optimum, orbi for the experiment over the real cloudy world.

8.2 Mission Integration and Design

Mission integration involves assembly of a number of experiments, the spacecraft, its power, control, communication, and, for manned missions. the life support system and the astronauts into a total mission-oriented system. A large number of tradeoffs are required. For example, the various candidate experiments may well have divergent requirements for orbit, spacecraft attitude control, etc. From this large set of compromises, a workable physical design must emerge. In addition to the design of the physical system, such features as astronaut skills, the orbit, time in orbit, and time, azimuth, and season of injection must be determined. The object of the integration design activity is to maximize probable mission return as defined by some composite measure of mission success. Constraints of physical realization, economic limits, astronaut safety, range safety, available boosters, etc., limit the degree of freedom.

A major tool for manned mission optimization is a form of mission simulation computer program which can adjust the free parameters of the mission to establish either the most feasible mission, or to select the optimum mission design in the realm of feasibility. To date, these programs have not considered the earth's cloud cover except in the most elementary way. Most unclassified, earth-oriented satellite systems to date have been meteorologically oriented and have not required optimization with respect to the behavior of the earth's cloud cover. Future earth resources systems, manned or unmanned, will doubtlessly require such treatment before the mission can be fully defined.

The mission integration programs generally use various deterministic techniques to arrive at the optimum solutions. The introduction of the earth's cover, which creates a contingency at each possible observation event, requires techniques which have yet to be fully explored. However, data now available from the activity reported here can be used in unsophisticated form to improve the realism of simulation for integration.

## 8.3 Mission Simulation

Given the space system defined by the integration activity, a computer mission simulation can be performed. While this function may be included in the package of integration programs, it can be separately considered. A number of applications can be found for mission simulation programs that embody cloud data in a realistic fashion.

Time Lines. Mission integration will have made up a set of time lines, or rules for finding time lines, of all the various functions on the spacecraft. The time lines are important in establishing control sequences, data acquisition and dump profiles, power profiles, etc. For manned systems they also must involve astronaut sleep-work cycles, skill mixes, etc.

In earth-oriented missions where the attempt at observation by some sensors is contingent on suitable cloud cover or a forecast of cloud cover, time lines become stochastic processes operating within certain constraints. This in turn partially randomizes mission parameters dependent upon the time lines of individual experiments. We are not aware of any attempt to deal with this situation, which can now be effectively simulated through use of cloud data.

Since the concept of only partially constrained random time lines is likely to be abhorrent to the system design engineers as well as to mission controllers, an alternate approach is to seek fixed time lines that maximize the probability of mission success (measured in some suitable way) in the cloudy world. Again, we are not aware of any procedures that go materially beyond a simple assumption of 50% success in the performance of an observation.

Probability of Mission Success. The observation mission has a set of *a priori* objectives; the degree of success in meeting these objectives can either be measured quantitatively or be described by a simple success-failure characterization. Having defined the mission, it is of interest to estimate the probability distribution of some measure or measures of success.

Section 9.1 describes simulation of a mission in which the number of observations made is critical to the success of the mission. It is necessary to be sure that there is a high probability that clouds will permit at least the minimum number of observations to be made. There is, of course, a finite probability of no observations at all.

Section 9. 2 presents an abridged "simulation" of a photographic mission, in which an estimate is made of the probability that at least p percent of a target area can be photographed in n passes. This also will give the frequency distribution of the number of blind exposures required to give probability P of covering at least p percent of the target area. A slight extension of the example would give the frequency distribution of the number of exposures and the mission length required to give probability P of covering at least p percent of the area if exposure is inhibited when the cloud cover exceeds a value C. This could be traded off against blind photography to ascertain whether the additional complexity of controlled photography is worth while.

Mission Performance Analysis. Mission simulation gives the simulator the opportunity to trace the events of the mission, and based on this information to perform certain adjustments to the mission that are outside the province of the mission integration program. Various statistics can be amassed which will help to better define the characteristics of the mission before flight. Here again, realistic inclusion of cloud cover information will result in a more realistic analysis of the performance of earth-oriented missions.

8. 4 Experiment Scheduling

The scheduling of experiments both before launch and in real time can be expedited by reference to cloud statistics which can give an assessment of the performance expectation and variance resulting from that schedule. This is similar to time lining, but here refers strictly to the experiments.

8. 5 Dynamic Programming

During flight, a mission assessment program should keep track of the present status and fractional achievment of the mission to date. It is then possible to simulate future events, based on certain priorities and scheduling rules, out to the end of the mission. The priorities and scheduling rules may be optimized to maximize mission performance, and the new rules would then be adopted. The accumulated effect of contingencies, both of weather and of the mission, may require further revision of these priorities and rules at a later time. This process, which we feel is essential to expensive missions such as the eventual Apollo Applications system, we call dynamic programming.

# 9. EXAMPLES OF ENGINEERING APPLICATIONS

## 9.1 An Application Using Monte Carlo Techniques

### 9.1.1 Introduction

During early 1967 a study was performed by Allied Research Associates, Inc. of cloud effects on optical sighting of land features from Apollo manned missions. A specific objective was to determine the probability distribution of the number of sightings of certain specified landmarks during Apollo's first two and one-half revolutions of the earth. Three different launch times and azimuths were studied (Barnes et al 1967). These will be referred to as "missions."

The cloud data originally used was read from meteorological satellite picture compilations over the actual landmarks to be sighted. The initial data sample for the study was provided by the Nimbus II satellite, which operated from 15 May through 31 August 1966. Because the early failure of Nimbus II resulted in only three-and-one-half months of data, an additional four and one-half months of data were extracted from the ESSA-3 satellite. ESSA-3 observations from 9 October 1966 through 28 February 1967 were utilized. Nearly complete daily global coverage was available during the operation of both satellites.

Since the Nimbus II period is essentially representative of the Northern Hemisphere summer and the ESSA-3 period of the winter, the two samples were treated separately.

A Monte Carlo flight simulation was performed by "flying" each mission over each day's data sample. The Monte Carlo approach was made imperative because of the interrelationship between the attempts at sighting successive landmarks; if a landmark is sighted, it is necessary to continue to track it until it approaches the rear horizon. Realignment of the periscope sights and computer functions takes an additional length of time, so that a number of potential landmarks may pass unobserved following a successful sighting. Handling this situation analytically is impracticable, at least without the insights provided by the results of the Monte Carlo simulation.

We have reproduced the same set of Monte Carlo simulations using the global data generated in this contract, and using the techniques of data application recommended in this report. Results are similar in nature, but somewhat different in numerical magnitude. The differences are readily accounted for, and suggest that simulation using our present data gives results reasonably close to the "truth."

Because of the value of this example in demonstrating the application of our data to a real simulation problem, it will be described in detail. The reader is referred to Barnes, Beran and Glaser (1967) for a complete description of the satellite-data based simulation (which differs only in data sources and handling), and for an extended discussion of the quality of those data which leads us to the belief that the present simulation is more realistic.

9.1.2 Landmarks

9.1.2.1 Description

One hundred landmarks have been selected by the Apollo Project. The landmarks are located between 35°N and 35°S, with the majority of them found at land-sea interfaces. The landmarks are plotted on a base map in Figure 9-1. Approximately three-fourths of the landmarks were used for the mission simulations.

9.1.2.2 Landmark Order Numbers

Each of the one hundred landmarks was designated by an index number, which served only as its identification and was not necessarily related to when the landmark would be sighted by an Apollo spacecraft. Three separate missions, each consisting of-two-and-one-half revolutions and each containing about 30 possible landmarks, were defined. Some of the landmarks were repeated within a mission and some were repeated on more than one mission. For programming purposes, an order number was assigned to each landmark as it appeared within an Apollo mission; the landmark order within a mission conformed to the order in which it would be sighted. If the landmark was repeated later in the mission, it was given a new number consistent with its new position. When a landmark was used on more than one mission, it was given different mission numbers and order numbers, again consistent with its position in a mission. Table 9-1 shows the order of possible sightings in two of the three missions.

After the order number within each mission had been established, the time that Apollo would be over each landmark became a function of the vehicle launch time and the orbital elements. A launch time for each mission was provided, along with the hour (local time) that the spacecraft would be over each landmark.

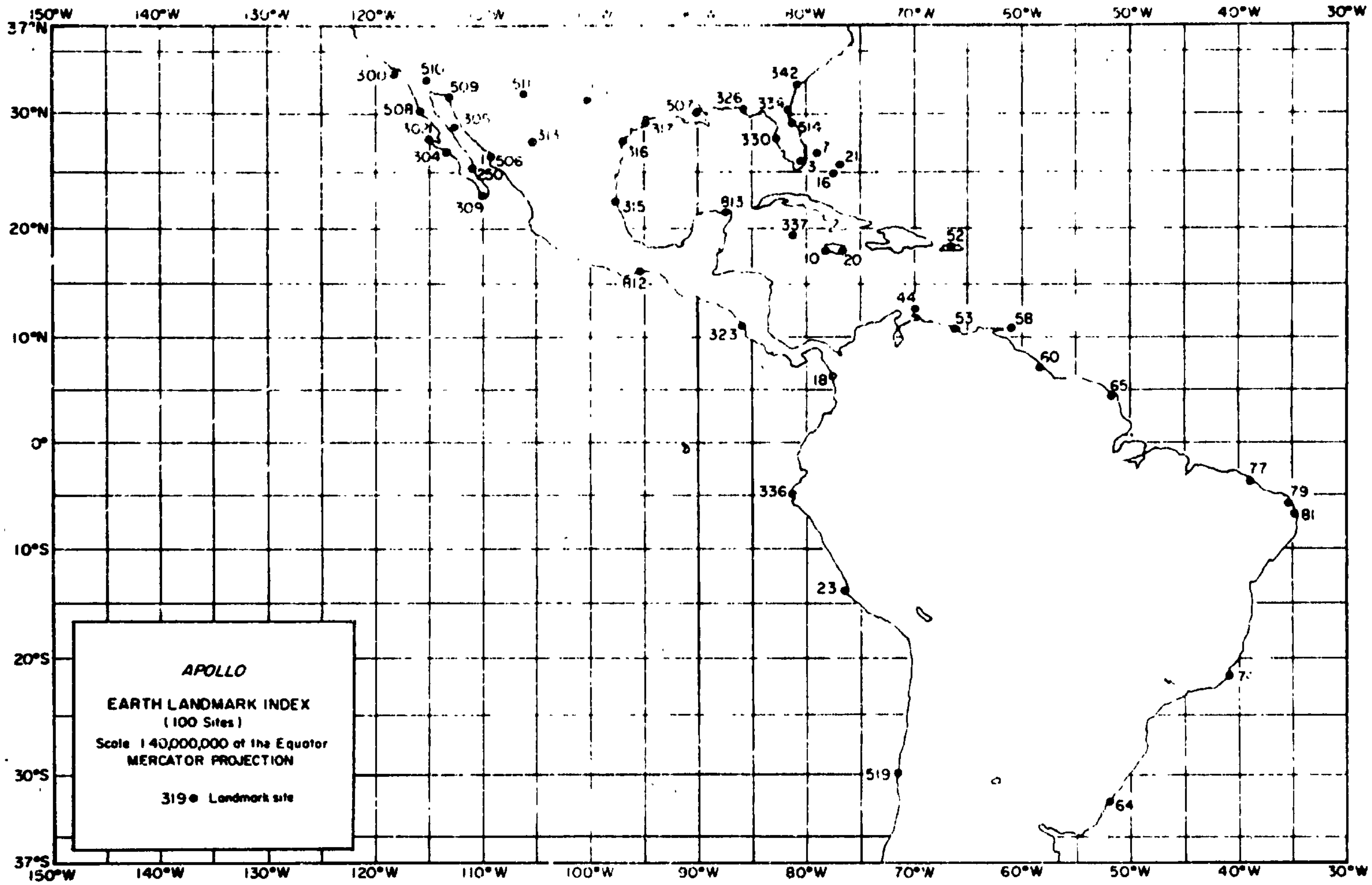


Figure 9-1 Locations of Landmarks

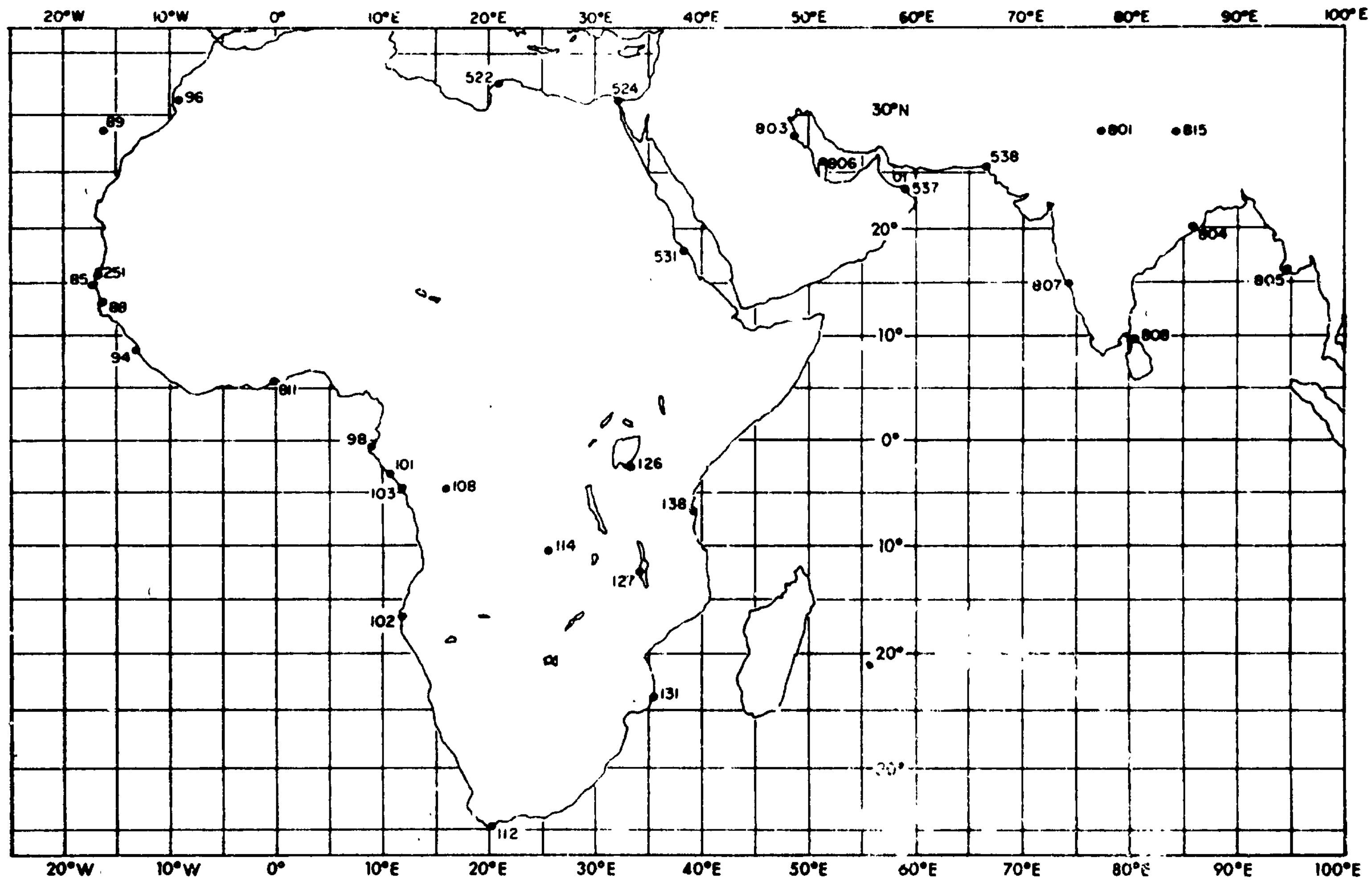


Figure 9-1 Cont'd

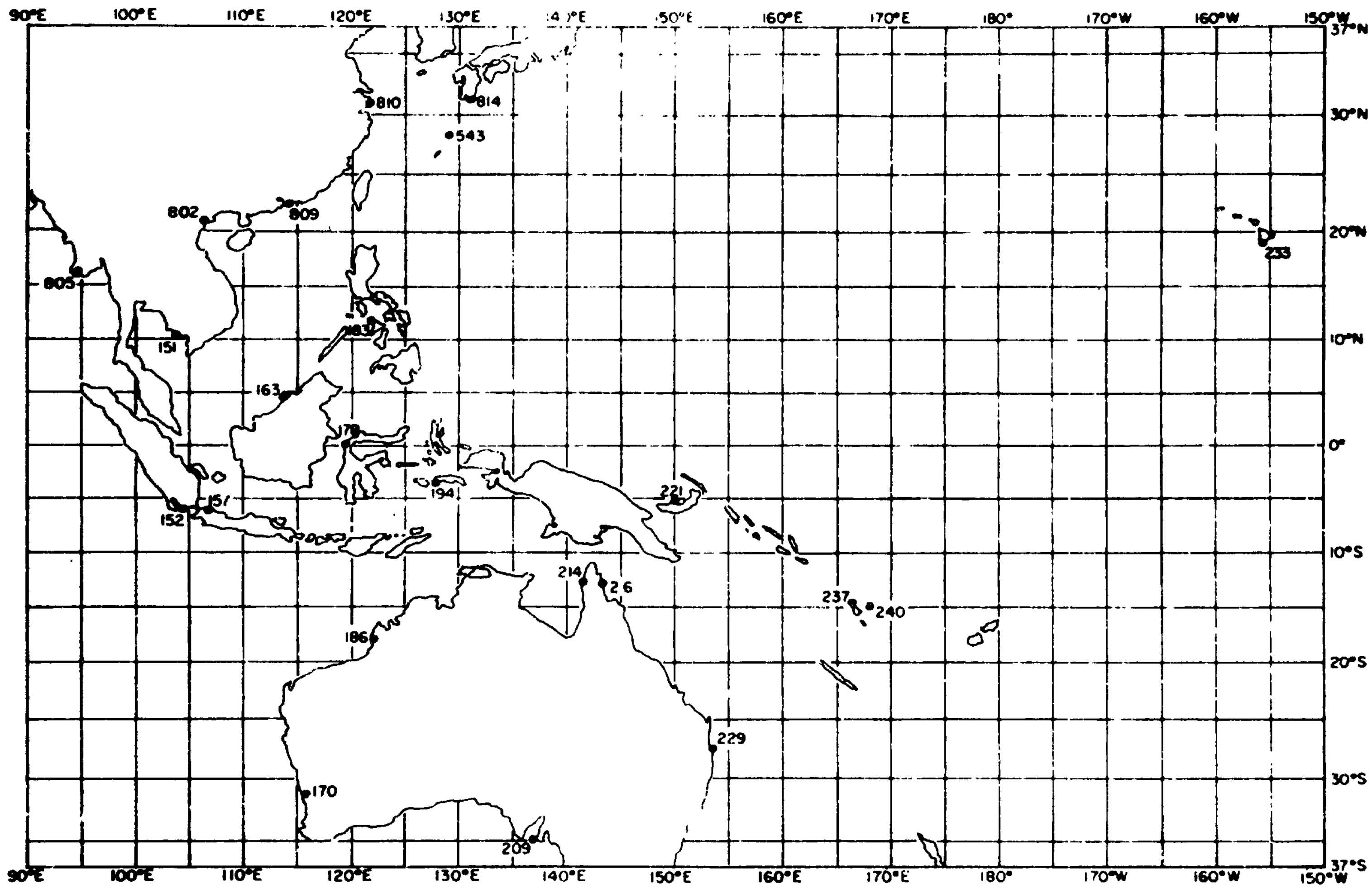


Figure 9-1 Cont'd

Table 9-1

Order of Landmarks in Each Mission

| Order Number | Mission Number 1 | Mission Number 3 |
|---|---|---|
| 1 | 126 | 524 |
| 2 | 138 | 801 |
| 3 | 304 | 802 |
| 4 | 250 | 183 |
| 5 | 506 | 221 |
| 6 | 313 | 237 |
| 7 | 317 | 240 |
| 8 | 507 | 524 |
| 9 | 326 | 803 |
| 10 | 334 | 538 |
| 11 | 342 | 804 |
| 12 | 85 | 805 |
| 13 | 251 | 151 |
| 14 | 88 | 163 |
| 15 | 811 | 178 |
| 16 | 98 | 194 |
| 17 | 101 | 214 |
| 18 | 103 | 216 |
| 19 | 108 | 96 |
| 20 | 114 | 522 |
| 21 | 233 | 524 |
| 22 | 508 | 806 |
| 23 | 510 | 537 |
| 24 | 509 | 807 |
| 25 | 511 | 808 |
| 26 | 512 | 152 |
| 27 | 507 | 157 |
| 28 | 326 | 186 |
| 29 | 334 | 229 |
| 30 | 514 | - |
| 31 | 102 | - |

9. 1. 2. 3 Landmark Grouping

To simulate landmark sighting on an Apollo mission, the requirements placed upon the astronaut must be considered. For a successful sighting, the astronaut must point an optical device at a specific landmark and take a certain number of "fixes" during the time he is over the landmark. When he attempts to sight a landmark, one of two possible events can occur: (1) he is successful in his attempt to find the landmark and he proceeds with the prescribed sighting procedure; (2) he is unsuccessful, because cloud obscures the landmark, and he re-orients the sighting mechanism for a try on a new landmark. These events require a different, but predictable amount of time during which the spacecraft will have passed over a certain number of landmarks that cannot be used. In other words, it would be unrealistic to say that each of the landmarks could be sighted on each mission. Rather some grouping of landmarks, based on successful and unseccessful tries, is required.

A listing of landmarks was assembled, containing the next independent landmark (independence being a function of the time required for sighting, or to try a sighting) for both successful and unsuccessful sighting attempts. Direct application of this listing would have resulted in some landmarks never being used, because they were bypassed in both the "successful" and "unsuccessful" columns. Further grouping, and a random process of selecting the station to be tried within a group, were required to insure that each landmark had an equal chance of being sighted during a mission.

The general approach was to arrange the landmarks in a manner which would make all landmarks accessible from some previous group. The assumption was made that the next landmark after a successfully acquired and marked land feature would have to pass under the spacecraft at least eight minutes later. If the first landmark was sought, but not acquired, the next sought landmark must be at least four minutes away. These time estimates were based upon simulated operation of the orbital navigation program and associated sighting procedures. Time to process data and re-position the optics were the important contributions.

To determine a set of groups which would contain the "used" and "unused" landmarks, a "logic tree," shown in Figure 9-2, was prepared. The order numbers, for mission number 1, are listed down the center of the diagram. The lines drawn from the order number lead to the next independent landmark; successful tries are on the left, unsuccessful tries are on the right. Starting with order number 1, the line on the left, representing success, extends over and down to order number 3; the line on the right, representing failure, goes over and down to order number 2.

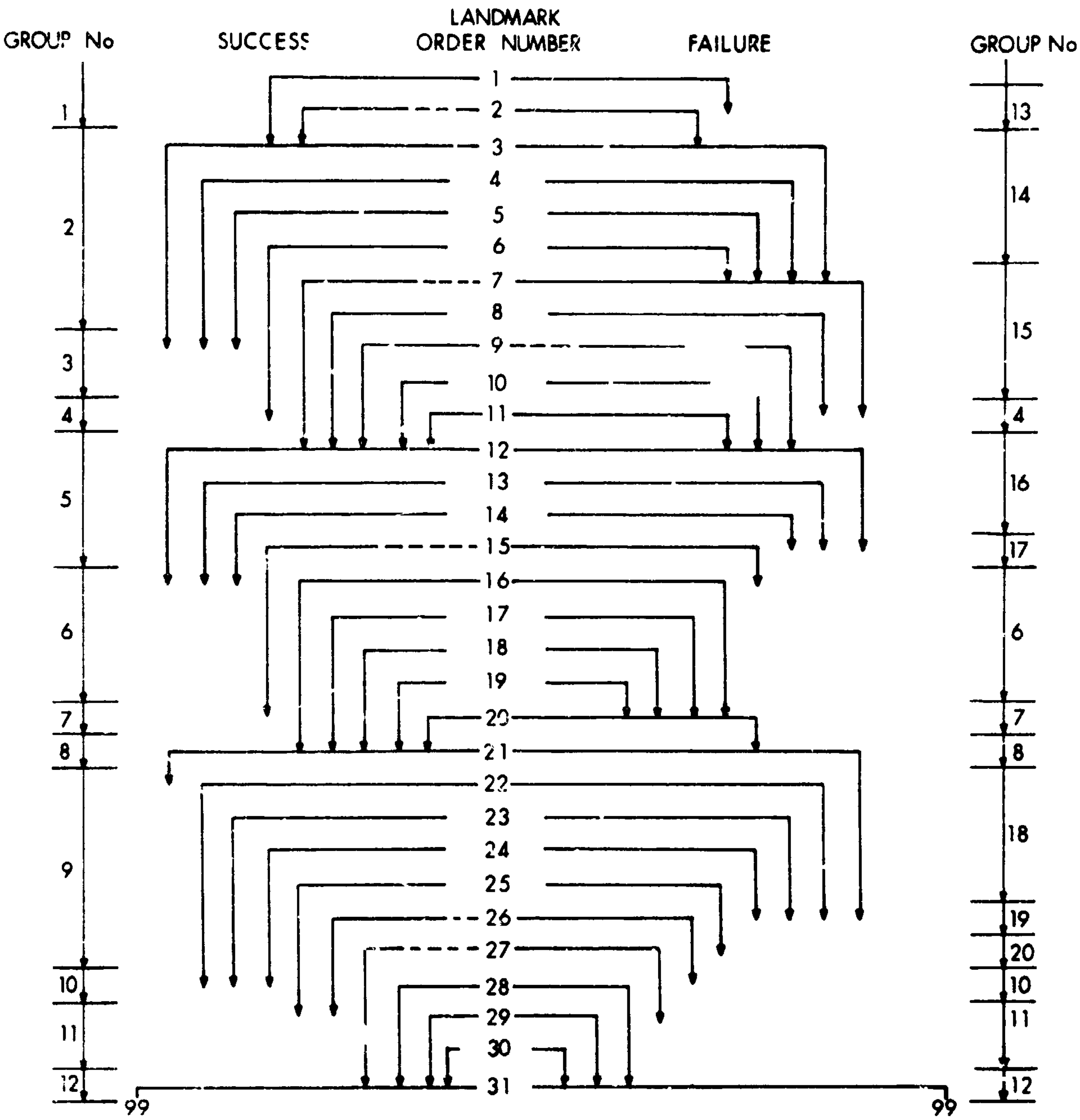


Figure 9-2 Logic Tree for Landmark Grouping in Mission Number 1

From order number 2, the right and left line both go to order number 3. The dashed line of the success side indicates that it was impossible to get to number 2 through a previous success; a previous failure, however, would have led to order number 2, so the solid line on the failure side extends all the way to the number. Order number 3 leads to number 9 for success and to number 7 for failure. Since either success or failure on a previous number would have led to number 3, the lines extend all the way to the number. As with number 3, order number 4 leads to number 9 for success and to 7 for failure; however, since there is no possible way to reach number 4 from a previous number, the lines leading away from 4 do not extend all the way to the number.

The procedure of drawing lines from the order number to the next independent order number for both success and failure was continued until the diagram was complete. When examining the logic tree, the reader should keep in mind that a dashed line at the beginning of a leader represents a landmark that can only be reached by an opposite result from a previous number (i. e. , a dashed line on the success side means the number was reached by a previous failure and a dashed line on the failure side means the number was reached by a previous success). If the leader lines do not extend all the way to the numbers, it means that the landmark cannot be reached by any route.

The logic tree provided the basis for grouping the landmarks. Starting on the success side and working down, each order number that could not be reached by a previous success, occurring under an order number that could be reached from above, was grouped along with the one that could be reached. Referring to Figure 4-2, order number 3 can be reached by a previous success, but order numbers 4, 5, 6, 7, and 8 cannot be reached by a previous success. A group was, therefore, made up of 3, 4, 5, 6, 7 and 8 Number 9 could be reached from a previous success, so it is the beginning of a new group. Number 10 is the only landmark under 9 which cannot be reached by a previous success, therefore the next group is made up of order numbers 9 and 10.

This process was continued until all order numbers had been grouped on the success side. The same procedure was then repeated for the failure side of the logic tree. The groupings determined by this procedure are shown along the sides of the logic tree (Fig. 9-2). The groups are numbered in ascending order starting with the first successful group and continuing down the left side of the diagram, then to the first failure group and number down the right side. The first group on the failure side, containing order number 1, does not require a group number, as it will automatically be included in the first trial during the simulated flight. Certain groups on the failure side are given the same group number as one of the success groups, since they contain the same landmarks. The 99, which appears at the bottom of the diagram, indicates that the mission has been completed.

This procedure was repeated for the remaining missions. Listings for each mission, prepared in this way, are shown in Table 9-2, and include: (1) the groups for each mission, (2) the number of landmarks in each group, and (3) the order number of the landmarks within a group. An array showing the "go to" group for each order number within each mission was also prepared, as is shown in Table 9-3

### 9.1.3 Sighting Probability

The probability of sighting a landmark in a region of cloudiness of amount described by one of our cloud groups was assumed to be 95% for cloud group 1 (clear), and descending linearly to 40% for group 3 and then to 4% for group 4. As discussed earlier in this report, the probability of sighting a landmark is probably smaller than this would indicate, but this error is compensated in great measure by the ground observer's overestimation of cloud amount in partial cloud cover situations.

A somewhat different sighting probability curve was used in the original simulation using satellite cloud cover data. There, it was known that cloud underestimates were the rule, particularly in regions of scattered small clouds. Accordingly, a probability of sighting of 80% was assigned to clear skies, descending linearly to zero for 75% cloud cover. For reasons to be discussed in Section 9.1.5, this continues to somewhat overestimate the probability of sighting a landmark.

### 9.1.4 The Simulation Program

Figure 9-3 presents a gross block diagram of the simulation program using our cloud statistics in recommended fashion. The change in source data required a near-total rewriting of the program; care has been taken, however, to preserve the identical logic of landmark and landmark group sequencing. Listings of the original program and of the program described here can be made available by Allied Research Associates, Inc. to those interested in tracing the procedures in detail. A description of the program follows:

Table 9-2a

Groups in Mission I and Order Number* of Landmarks Within Each Group

| Group Number | Number of Landmarks in Group | Order Number* of Landmarks in Group | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | 2 | 1 | 2 | | | | |
| 2 | 6 | 3 | 4 | 5 | 6 | 7 | 8 |
| 3 | 2 | 9 | 10 | | | | |
| 4 | 1 | 11 | | | | | |
| 5 | 4 | 12 | 13 | 14 | 15 | | |
| 6 | 4 | 16 | 17 | 18 | 19 | | |
| 7 | 1 | 20 | | | | | |
| 8 | 1 | 21 | | | | | |
| 9 | 6 | 22 | 23 | 24 | 25 | 26 | 27 |
| 10 | 1 | 28 | | | | | |
| 11 | 2 | 29 | 30 | | | | |
| 12 | 1 | 31 | | | | | |
| 13 | 1 | 2 | | | | | |
| 14 | 4 | 3 | 4 | 5 | 6 | | |
| 15 | 4 | 7 | 8 | 9 | 10 | | |
| 16 | 3 | 12 | 13 | 14 | | | |
| 17 | 1 | 15 | | | | | |
| 18 | 4 | 22 | 23 | 24 | 25 | | |
| 19 | 1 | 26 | | | | | |
| 20 | 1 | 27 | | | | | |

* See Table 9-1

Table 9-2b

Groups in Mission 3 and Order Number* of Landmarks Within Each Group

| Group Number | Number of Landmark in Group | Order Number* of Landmarks in Group | | |
|---|---|---|---|---|
| 1 | 1 | 1 | | |
| 2 | 1 | 2 | | |
| 3 | 2 | 3 | 4 | |
| 4 | 3 | 5 | 6 | 7 |
| 5 | 2 | 8 | 9 | |
| 6 | 1 | 10 | | |
| 7 | 1 | 11 | | |
| 8 | 2 | 12 | 13 | |
| 9 | 1 | 14 | | |
| 10 | 2 | 15 | 16 | |
| 11 | 2 | 17 | 18 | |
| 12 | 1 | 19 | | |
| 13 | 2 | 20 | 21 | |
| 14 | 1 | 22 | | |
| 15 | 2 | 23 | 24 | |
| 16 | 1 | 25 | | |
| 17 | 2 | 26 | 27 | |
| 18 | 1 | 28 | | |
| 19 | 1 | 29 | | |
| 20 | 1 | 3 | | |
| 21 | 1 | 4 | | |
| 22 | 1 | 5 | | |
| 23 | 2 | 6 | 7 | |
| 24 | 1 | 8 | | |
| 25 | 1 | 9 | | |
| 26 | 2 | 11 | 12 | |
| 27 | 1 | 13 | | |
| 28 | 1 | 15 | | |
| 29 | 1 | 16 | | |
| 30 | 1 | 20 | | |
| 31 | 1 | 21 | | |
| 32 | 2 | 22 | 23 | |
| 33 | 2 | 24 | 25 | |

* See Table 9-1

Table 9-3a

Next Independent Group for Each Landmark in Mission Number 1

| Landmark Order Number | If Sighted Go to Group Number | If Not Sighted Go to Group Number |
|---|---|---|
| 1 | 2 | 13 |
| 2 | 2 | 14 |
| 3 | 3 | 15 |
| 4 | 3 | 15 |
| 5 | 3 | 15 |
| 6 | 4 | 15 |
| 7 | 5 | 4 |
| 8 | 5 | 4 |
| 9 | 5 | 16 |
| 10 | 5 | 16 |
| 11 | 5 | 16 |
| 12 | 6 | 17 |
| 13 | 6 | 17 |
| 14 | 6 | 17 |
| 15 | 7 | 6 |
| 16 | 8 | 7 |
| 17 | 8 | 7 |
| 18 | 8 | 7 |
| 19 | 8 | 7 |
| 20 | 8 | 8 |
| 21 | 9 | 18 |
| 22 | 10 | 19 |
| 23 | 10 | 19 |
| 24 | 10 | 19 |
| 25 | 11 | 20 |
| 26 | 11 | 10 |
| 27 | 12 | 11 |
| 28 | 12 | 12 |
| 29 | 12 | 12 |
| 30 | 12 | 12 |
| 31 | 99* | 99* |

* 99 indicates the mission is completed

Table 9-3b

**Next Independent Group for Each Landmark in Mission Number 3**

| Landmark Order Number | If Sighted Go to Group Number | If Not Sighted Go to Group Number |
|---|---|---|
| 1 | 2 | 2 |
| 2 | 3 | 20 |
| 3 | 4 | 21 |
| 4 | 4 | 22 |
| 5 | 5 | 23 |
| 6 | 5 | 24 |
| 7 | 5 | 24 |
| 8 | 6 | 25 |
| 9 | 7 | 6 |
| 10 | 8 | 26 |
| 11 | 9 | 27 |
| 12 | 10 | 9 |
| 13 | 11 | 28 |
| 14 | 11 | 29 |
| 15 | 12 | 11 |
| 16 | 12 | 11 |
| 17 | 12 | 12 |
| 18 | 12 | 12 |
| 19 | 13 | 30 |
| 20 | 14 | 31 |
| 21 | 15 | 32 |
| 22 | 16 | 33 |
| 23 | 17 | 33 |
| 24 | 17 | 17 |
| 25 | 18 | 17 |
| 26 | 19 | 18 |
| 27 | 19 | 18 |
| 28 | 19 | 19 |
| 29 | 99* | 99* |

* 99 indicates the mission is completed.

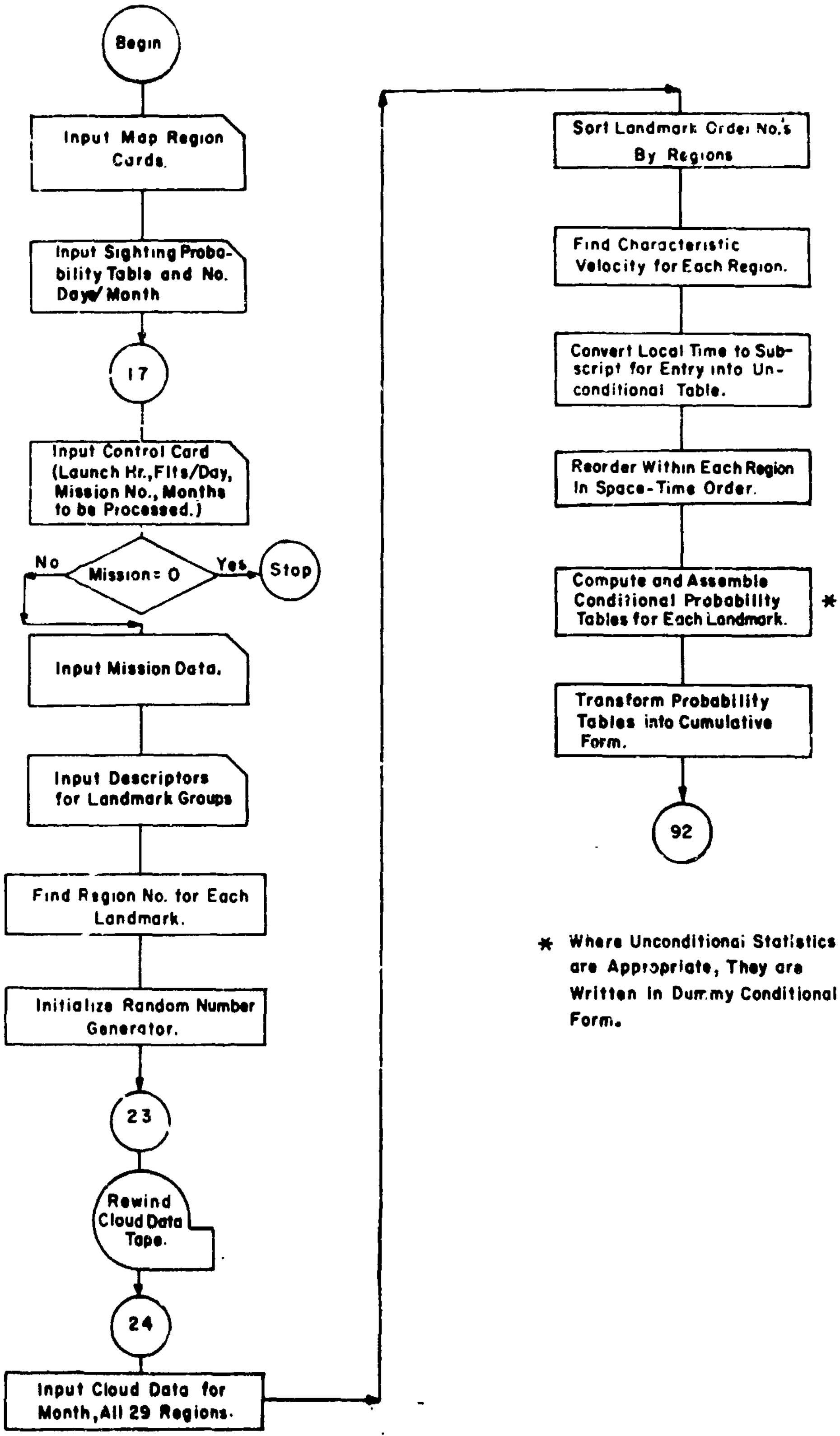


Figure 9-3 Block Diagram of a Possible Monte Carlo Program to Generate Probability Distribution of Photographic Coverage

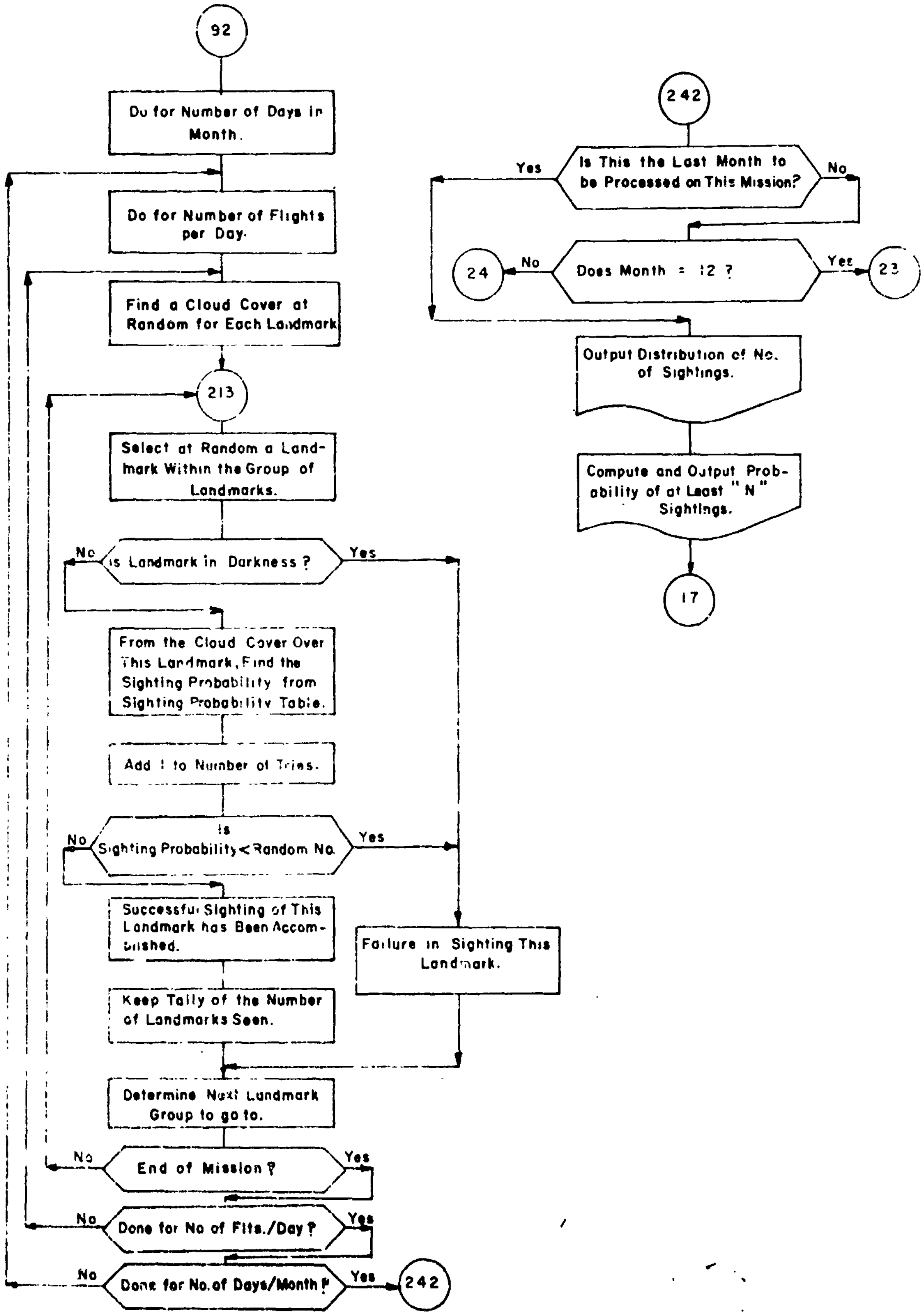


Figure 9-3 Cont'd

Required data is entered from cards. These data consist of: the set of descriptors that permit the map region subprogram to identify the region in which each landmark falls; sighting probabilities connected with each cloud group; a calendar that identifies the number of days in each month; a control card containing which launch hour, number of flights/day, mission number, and the months to be processed; the location of each landmark; the landmark group assignments; and description(s) of the landmark sequence(s) based on time(s) and azimuth(s) of launch. The global cloud cover statistics are on magnetic tape, having been transferred from a card deck in a prior operation.

The landmark subprogram is called repeatedly to assign a cloud climate region to each landmark. At this point the landmarks are ordered in order of potential encounter. The random number generator subroutine is initialized in an appropriate fashion to assure an independent set of random numbers for each run.

Assembly of statistics for a sample from one month can now be done. The appropriate month's section of the cloud data tape is read into memory.

1) Preparatory to organizing data in form suitable for establishing a chain of conditional statistics within each region, the landmarks are sorted by region. Within each region, they still occur in order of encounter in each mission.

2) The "characteristic velocity" for each region is computed by finding the largest spatial conditional value on the diagonal of the region's spatial conditional table, locating the corresponding entry in the temporal conditional table, and entering the appropriate formula (see Section 6. 9).

3) The local time at each landmark is found from the time after the known hour of launch at which each landmark is encountered. This local time is converted to a row subscript to find the unconditional distribution appropriate to the time of day.

4) They are then reordered by space-time proximity in a straight chain starting with the first encounter in each region. This is done by computing an equivalent distance for each landmark from the first, using

$$d^2 = V^2 (\Delta t)^2 + (\Delta s)^2$$

where V is the characteristic velocity, $\Delta t$ is the time difference between landmark encounters, and $\Delta s$ is the great circle distance between landmarks, calculated from their latitudes and longitudes. The landmark having the lowest $d^2$ is ordered as number two, and then serves as the origin of another set of $d^2$ calculations to find its successor. The entails (n - 1)! computations, where n is the number of landmarks in a region.

In the present case, the number of landmarks in each region was sufficiently small to keep this $d^2$ operation from becoming time-consuming. In other situations where large numbers of points may fall within a region, it will be desirable to introduce logic to break the list into statistically independent segments. Nearby points may also be grouped together as always having the same cloud cover. These expedients will keep the length of the Markhov chains reasonably short; as pointed out earlier, the quality of our present statistics cannot justify chains appreciably longer than 5 or 6 elements. In the present program, one chain of 9 landmarks occurred within Region 19. Grouping, which occurred naturally because some of the landmarks were in fact repeats of the same landmark encountered on a previous orbit, reduced the effective chain length to 5.

Each landmark is to have a conditional cloud probability table associated with it, conditional on the cloud cover at the landmark which preceded it in the space-time order in the region. The cloud cover of the first landmark in each region is, of course, not conditional on any predecessor. We have arbitrarily set the limit of statistical dependence in space-time at 800 nm, so that the cloud cover at any landmark separated from its predecessor by more than this amount would also be drawn from the unconditional table appropriate to the hour of encounter. Also, in a number of cases the range of validity of the spatial conditional tables did not extend to the physical distance involved, requiring the substitution of unconditional statistics. For convenience in processing, the 5 entry unconditional tables are written in a dummy 5 x 5 conditional form, with all rows identical.

Compilation of the conditional cloud probability tables follows the procedures of Section 6. In the present case, the time intervals are quite short, and therefore major contribution to the content of the derived conditional tables comes from the spatial separation of landmarks.

For convenience in subsequent processing, the conditional tables, real or dummy, are summed from left to right to form cumulative probability tables.

Simulated flight now occurs. For consistency with the prior simulation, a day of the month and number of iterated flights per day (10) are maintained, although 300 iterations of one day would of course be statistically identical.

First, a cloud cover is assigned to each landmark. This is done by formally considering the entire string of landmarks, now ordered by region and by proximity within regions, as a long Markhov chain with transition probabilities defined by the conditional probability table, real or dummy, associated with each landmark. A random number is drawn, uniformly distributed in the range 0-1. It is compared with the entries in the associated conditional probability table in the row defined by the cloud cover found previously. The random number will fall on a cumulative probability corresponding to one cloud group, which then is the designation of the cloud cover at the landmark. To start the chain a dummy cloud group "1" is provided.

As described earlier, the landmarks are grouped logically to describe their exclusive accessibility; only one landmark of a group can be used. A random number is generated to decide which landmark of the group is to be attempted. A check is made to see whether the landmark is in darkness; if so, a failure is registered and the flight proceeds to the next group. If in light, the sighting probability is drawn from the appropriate table. As noted earlier, the sighting probability is one minus the median cloud cover for the cloud group. A random number, uniformly distributed in the range 0-1, is drawn and compared with the sighting probability. If the random number equals or exceeds the sighting probability, a sighting failure has occurred and is so tabulated; otherwise, the landmark has been sighted and is appropriately tabulated.

The next group of landmarks to be attempted is determined, based on the success or failure of sighting of the specific landmark, and the process is repeated until the end of the mission. A summary is made of which landmarks were sighted, and the mission is repeated ten times, each time over a fresh cloud field. The whole operation is repeated for the entire month.

The simulation then proceeds to the next requested month until all requested months have been processed for the mission. Tabulation and outputting of the results obtained in each month is then initiated for the entire mission. The frequency distributions of landmarks sighted are converted, for convenience, to the (reverse) cumulative probability of seeing at least n landmarks. The simulation then proceeds to the next mission.

The organization of the program expedites computer computation. A characteristic run, covering nine months of data, two missions, each flown 300 times a month, required 0.89 minutes on IBM 360/75-50, including compiling the Fortran IV source deck and outputting to tape.

9.1.5 Results of Simulation

The product of the simulation program is a tabulation of the frequency distribution of the number of landmarks sighted per mission, and a tabulation of the cumulative probability of seeing at least n landmarks. Table 9-4 displays a few frequency

Table 9-4

Frequency Distributions of Landmark Sightings

Mission 1

| | Cloud Statistics Simulation | | | | Satellite Data Simulation | | | |
|---|---|---|---|---|---|---|---|---|
| | Month | | | | Month | | | |
| n | Nov | Feb | June | Aug | Nov* | Feb* | June† | Aug† |
| 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 9 | 7 | 4 | 0 | 5 | 2 | 0 | 0 |
| 2 | 47 | 36 | 14 | 13 | 27 | 18 | 2 | 1 |
| 3 | 87 | 67 | 51 | 30 | 47 | 65 | 20 | 8 |
| 4 | 80 | 83 | 89 | 74 | 86 | 92 | 45 | 39 |
| 5 | 56 | 56 | 78 | 97 | 78 | 63 | 89 | 67 |
| 6 | 16 | 26 | 52 | 75 | 45 | 29 | 85 | 103 |
| 7 | 3 | 5 | 11 | 15 | 11 | 10 | 53 | 73 |
| 8 | 0 | 0 | 1 | 6 | 1 | 1 | 6 | 19 |

Mission 3

| n | Nov | Feb | June | Aug | Nov* | Feb* | June† | Aug† |
|---|---|---|---|---|---|---|---|---|
| 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 11 | 8 | 0 | 0 | 1 | 2 | 0 | 0 |
| 3 | 37 | 12 | 6 | 0 | 3 | 5 | 0 | 0 |
| 4 | 55 | 44 | 20 | 7 | 3 | 10 | 1 | 0 |
| 5 | 85 | 58 | 53 | 19 | 12 | 36 | 3 | 4 |
| 6 | 59 | 66 | 95 | 71 | 44 | 67 | 12 | 7 |
| 7 | 22 | 49 | 67 | 96 | 62 | 73 | 30 | 48 |
| 8 | 12 | 33 | 44 | 77 | 71 | 50 | 61 | 70 |
| 9 | 8 | 6 | 9 | 32 | 62 | 23 | 81 | 77 |
| 10 | 0 | 1 | 6 | 8 | 35 | 14 | 66 | 75 |
| 11 | 0 | 1 | 0 | 0 | 6 | 0 | 34 | 21 |
| 12 | 0 | 0 | 0 | 0 | 1 | 0 | 9 | 8 |
| 13 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 |
| 14 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |

* Data from ESSA-3 † Data from Nimbus II

tabulations selected to show seasonal variability. Matching tabulations are also presented of the results of performing the same simulation using daily satellite data. Figures 9-4 to 9-7 show the cumulative plots for Mission 1, comparing the results of simulations based on satellite data and on the cloud statistics. The plots have been made on probability paper to suitably expand the scales.

It is seen that Mission 1 results are quite similar for the two data sources, particularly in the months of November and February, when data were taken from ESSA-3. There seems to be a constant difference of about 1/2 landmark sighting between the two sources. The slopes are similar, indicating that the variance in number of sightings is about the same in each case. The June and August simulations, which use satellite data from Nimbus II, show a difference of about one landmark sighting

While these differences may not seem great, they are operationally fairly important. Validation studies of the satellite data, performed in support of the original simulation effort, indicate that gross underestimates of cloud cover have occurred in regions normally having heavy convective cover, particularly of small size. At the extreme, Georgetown, Guyana, was apparently underestimated in the Nimbus II sample by 61%. Stations like San Diego, Talara, Peru, and Benguerir, Moracco, had their mean cloud cover rather accurately estimated; they are, of course, in regions of coastal stratus. On the average, the underestimate was judged to be about 25%. It is not easy to translate the effect of cloud cover underestimates into their effect on the simulation, since an increased number of failures permits an increase in the number of trials. On Mission 1, flown over satellite data, an average of 9.0 trials per mission occurred. Flown over the cloud statistics, 10.0 trials were attempted. The percentage of successful sightings were 63 and 42 respectively. The suggestion is strong, therefore, that the simulation based on our cloud statistics is closer to "truth."

The ESSA-3 results are considerably closer to those obtained from cloud statistics. This can be accounted for as a combination of two effects. The ESSA-3 data, while nominally of the same resolution, had better contrast than the Nimbus data. This contrast difference makes it easier for the data abstractor to note detail indicating the presence of cloud of size smaller than the minimal resolution element. The bulk of Mission 1 landmarks are in the Northern Hemisphere; ESSA-3 data were used in the Northern Hemisphere winter, Nimbus II in the summer. Seasonal effects on cumulus convection may have also contributed to the 1/2 landmark difference between satellites (assuming the statistical data to be a stable normal).

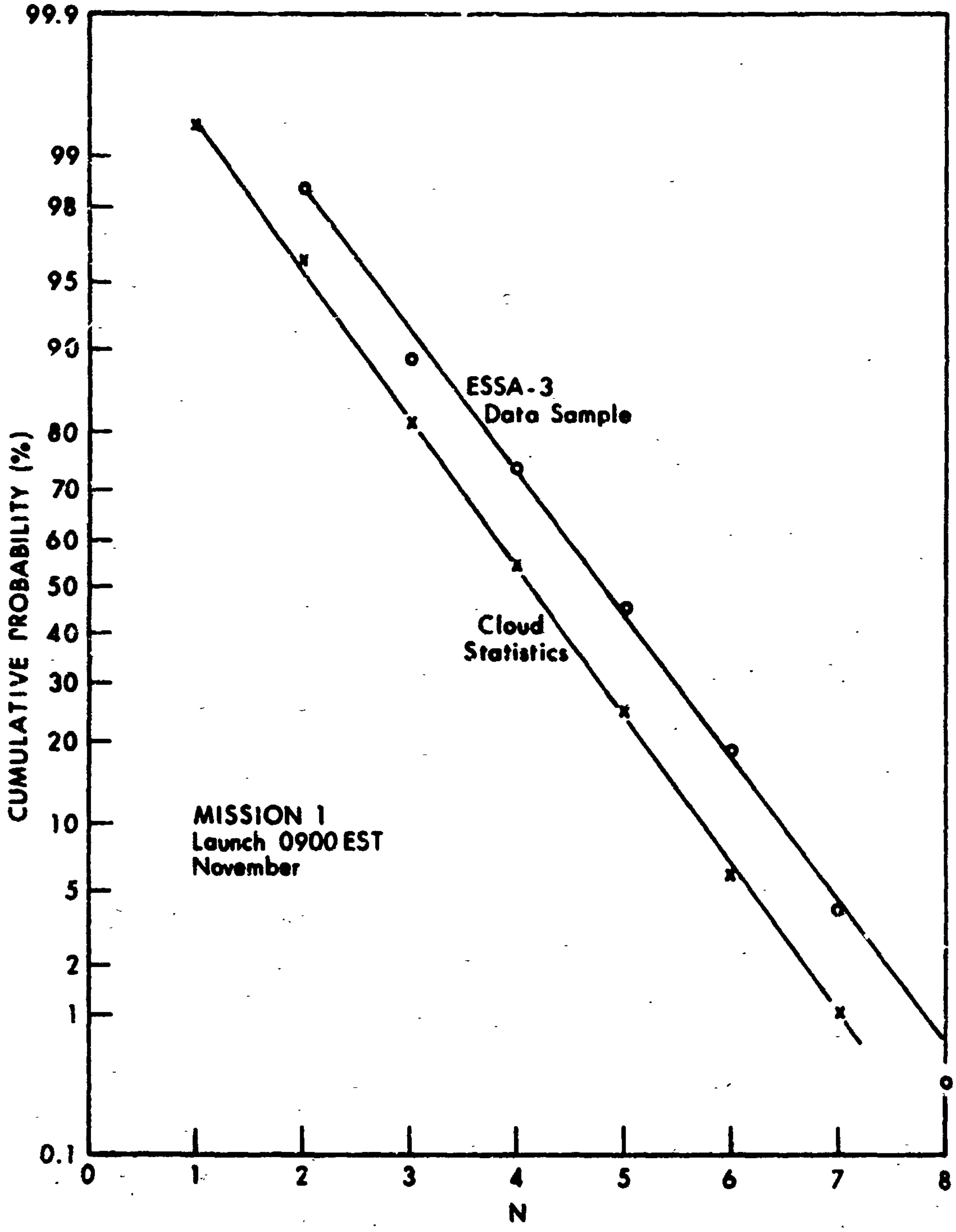


Figure 9-4 Probability of Sighting at Least N Landmarks

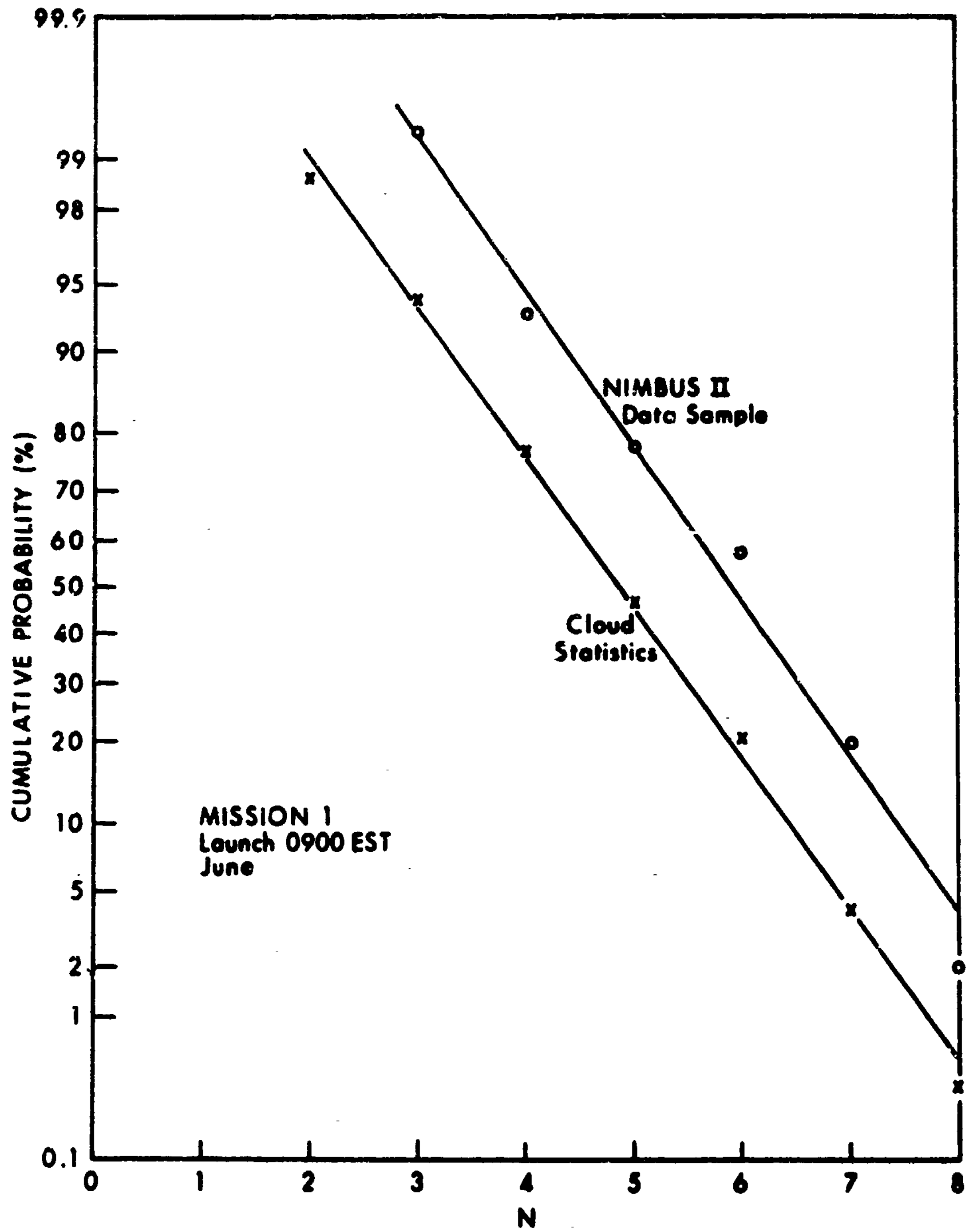


Figure 9-5 Probability of Sighting at Least N Landmarks

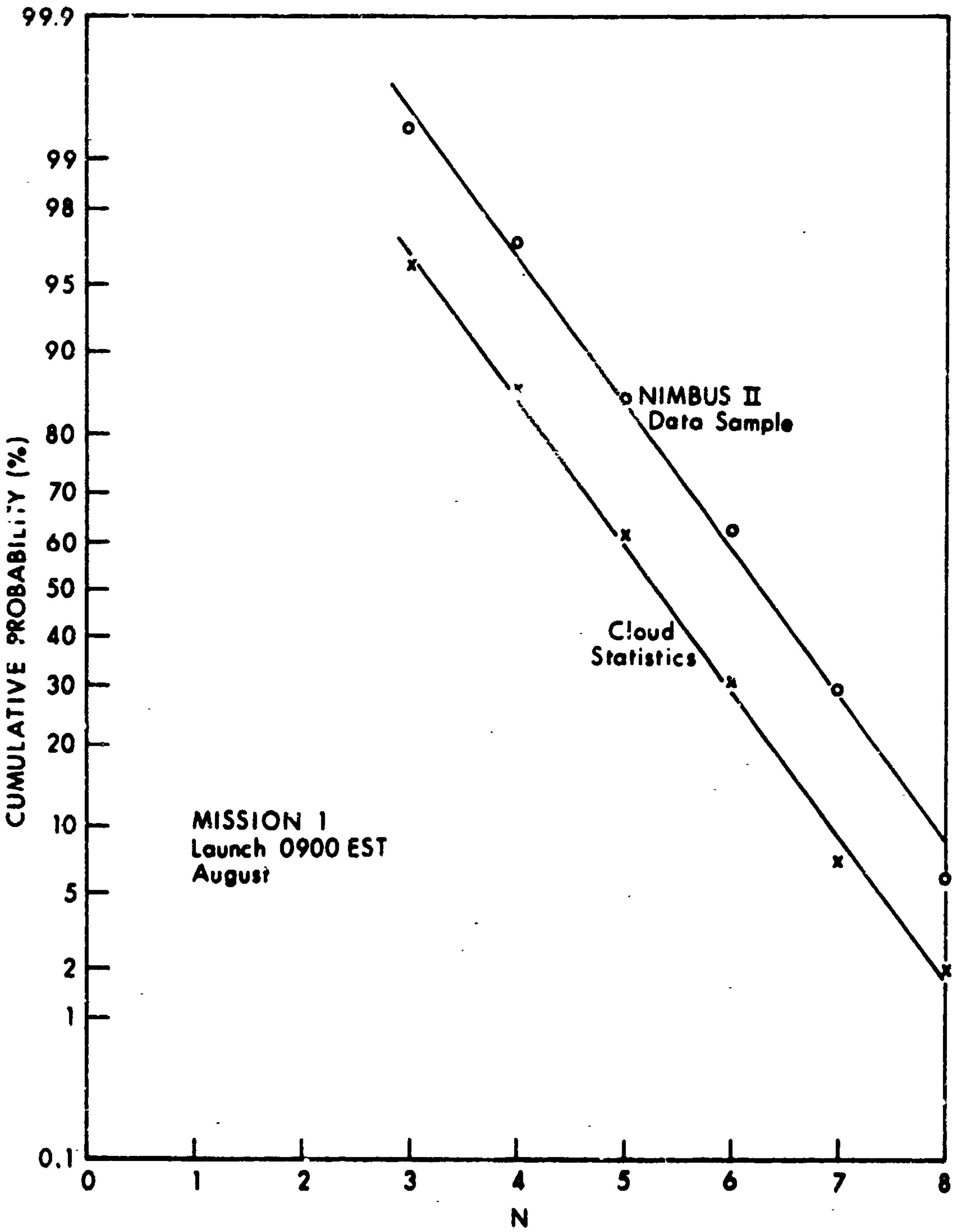


Figure 9-6 Probability of Sighting at Least N Landmarks

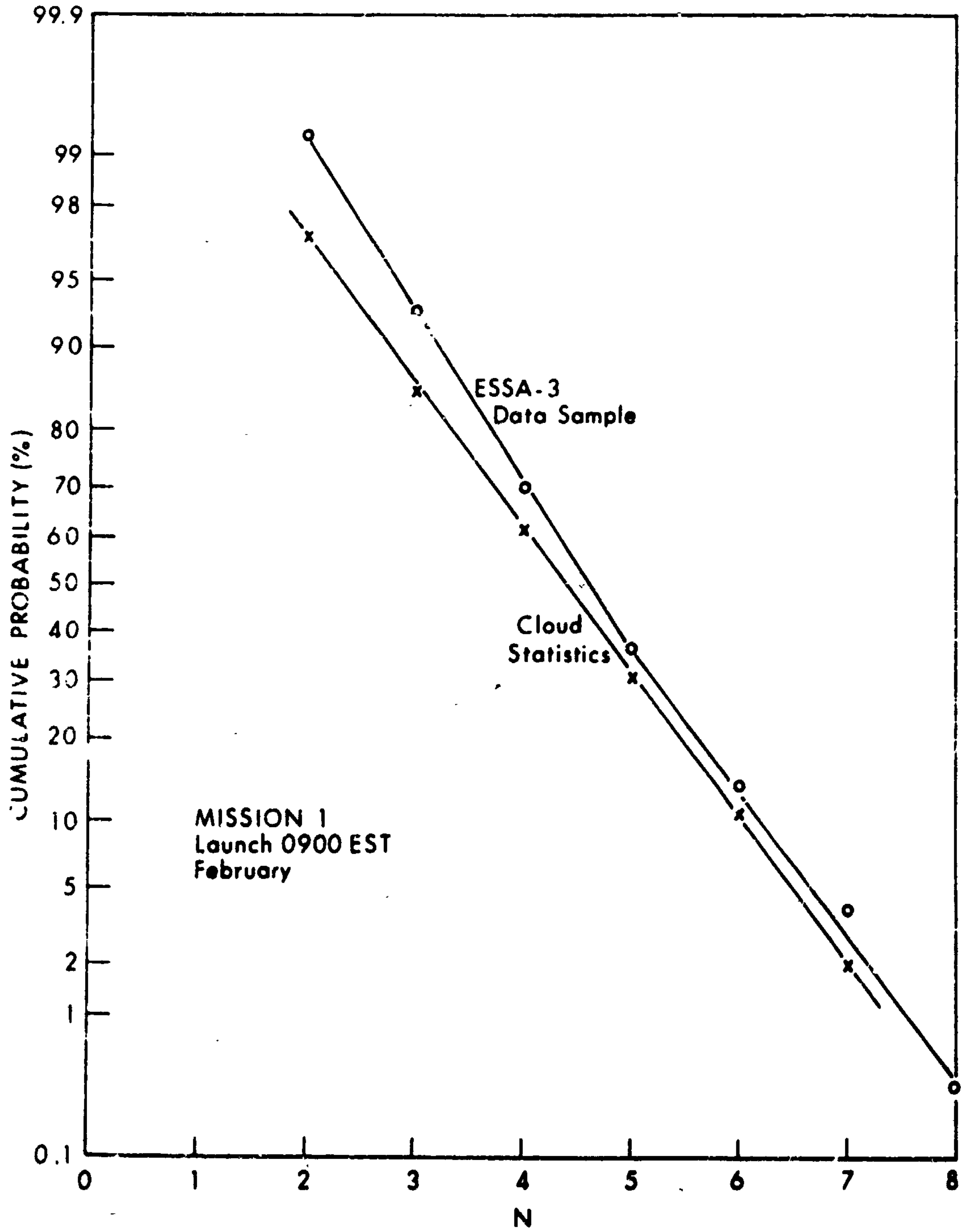


Figure 9-7 Probability of Sighting at Least N Landmarks

Figure 9-8 is included as an example of the error that can result from cascading biases. Mission 3 was designed in an attempt to demonstrate that a suitable choice of launch hour and azimuth could cause the spacecraft to pass over a combination of landmarks of low cloud amount during daylight hours, with the landmarks separated in such fashion that a maximum number of opportunities for observation would occur. The cloud cover estimates came from the satellite data. Using the same data for simulation resulted in an apparent eminent success. However, the simulation using cloud statistics was materially less optimistic - by nearly 3 landmark sightings in the case plotted. However, comparison with the Mission 1 data shows that the increase in the number of opportunities resulted in an increase of about 2 landmarks sighted, at any probability level, with some increase in the variance of the number sighted.

It will have been noted that when plotted on probability paper, the center sections of the cumulative probability curves become essentially straight lines. This suggests that the probability distribution of successful landmark sightings approximates the Bernoulli or binomial distribution. This is not surprising, since they arise from the sampling of a finite number of success-failure alternatives. However, there is nothing in the statistics that gives an a priori estimate of the parameters of the distribution. For example, the distribution obtained from our cloud statistics has a mean of 3.61 sightings and a standard deviation of 1.26 sightings. The Bernoulli formulas,

$$\bar{X} = sp$$

$$\sigma^2 = spq$$

$$q = 1 - p$$

where $\bar{X}$ is the mean number of successes in s trials, p is the probability of success on any one trial, and q is the probability of failure, yield p = .562 and s = 6.4. A program trace indicates that in fact the average number of sighting trials was 10.1, with a probability of success p = .368.

This computation of Bernoulli distribution parameters is primarily intended to demonstrate that the Monte Carlo procedure yields distributions which cannot be readily generated from elementary considerations. However, it may be of interest to speculate on the significance of the derived parameters. The diminished number

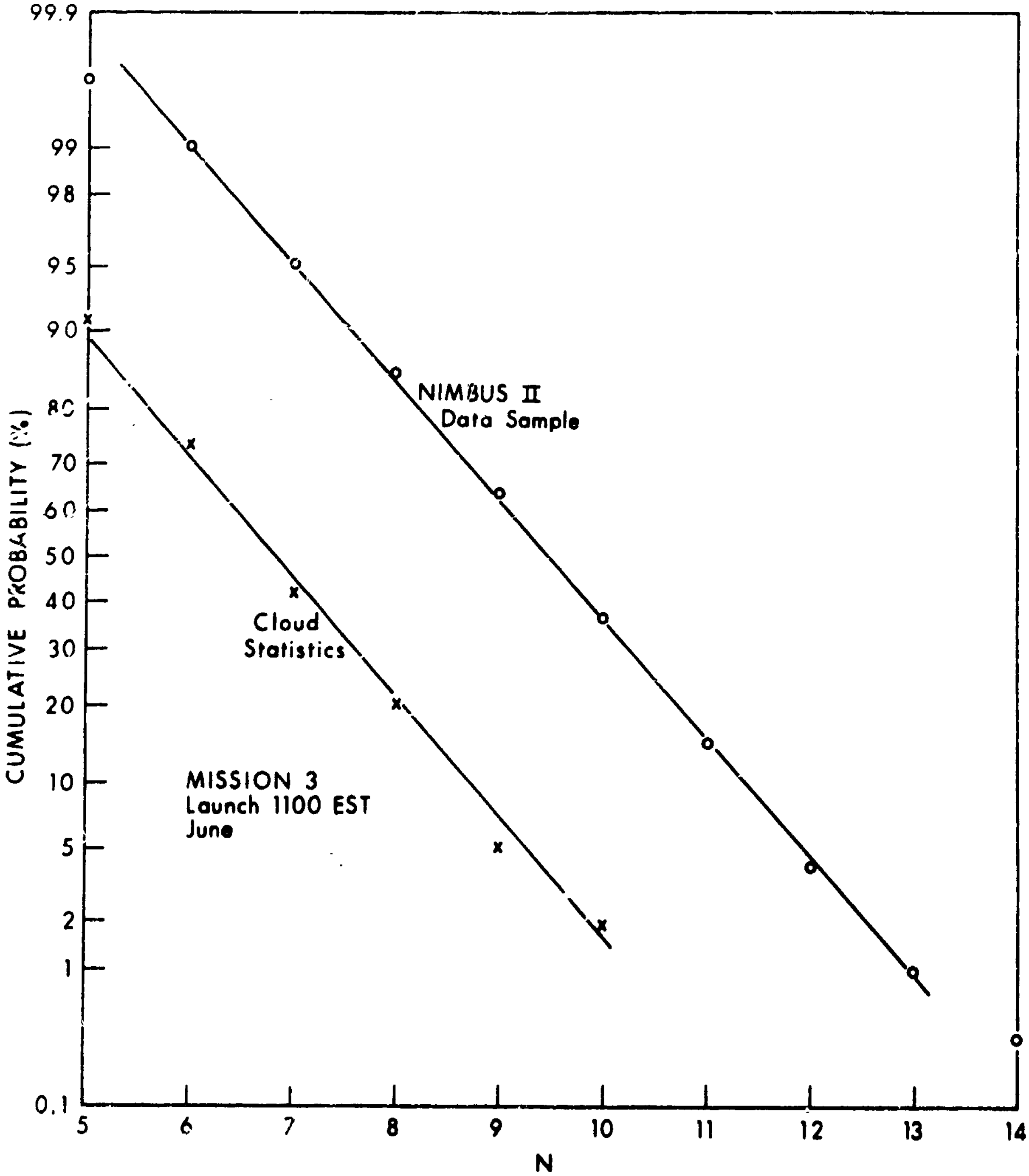


Figure 9-8 Probability of Sighting at Least N Landmarks

of apparent samples may result in part from cloud coherence. Of the 31 landmarks to be sighted in daylight on Mission 1, 17 had cloud covers described by conditional distributions. Thus the number of independent samples was smaller than the number of trials.

As pointed out earlier, the number of trials is related to the number of failures. This tends to reduce the variance of the distributions, which upon consideration of the formulas for the mean and variance of the Bernoulli distribution, can be seen to cause a decrease in the apparent number of samples and thus an increase in the apparent probability of success.

The distributions have some further properties of interest. First, it is possible, even if not very probable, to have no landmark sightings at all. Mission 1 has an apparent absolute maximum of 8 sightings, resulting from the distribution of landmarks and daylight along the orbital track. Mission 3 would appear to have a maximum of 14 sightings, a number never reached using cloud statistics as a simulation base.

### 9.2 A Typical Simulation Problem

Let us suppose we are designing a photographic mission for mapping or for agricultural surveillance. A prime target area of size 300 x 300 miles is contained within one cloud region. The proposed orbit provides coverage of the area with favorable illumination every 3 days. (We make this stipulation to avoid the use of temporal conditional statistics.) If the area is fairly cloudy, we are willing to piece together our map from cloud-free segments of the photographic coverage, although we would, of course, prefer to find the entire area cloudless and complete our mission on a single pass. The questions that may be asked are:

1) How many passes are required to give a probability of 95% (or some other level) of at least one clear pass over the area?

2) If the number of passes required to reasonably assure one clear pass is excessive, what is the amount of pieced-together coverage expected in N passes?

3) How many passes are required to give a 90% (or some other level) probability that at least 90% (or some other fraction) of the area can be photographed?

All of these questions can be answered from a probability distribution of piecewise coverage (which includes total coverage) as a function of the number of passes. To arrive at this distribution, we make the dubious assumption that the cloud in the area are always completely randomly scattered over the whole area, so that the incremental photographic coverage of each pass is:

$$P(i) = (1 - B)(1 - C)$$

where B is the already photographed fraction of the area, and C is the cloud cover encountered on the pass. By induction, the fraction of the area photographed is:

$$B(N) = 1 - \prod^{N} C_n$$

where $C_n$ is the cloud cover encountered on pass number n, N is the total number of passes.

The unconditional cloud distribution for the 300 mile area should be generated from the basic unconditional and spatial conditional data. For ease of computation, we have assumed a distribution which might be typical of a 300 mile square area in southeastern U. S. in summer or spring, at noon, as shown in Table 9-5.

Table 9-5

An Assumed Distribution

| Group | Mean Cloud Cover | Probability |
|---|---|---|
| 1 | 0 | .1 |
| 2 | .25 | .2 |
| 3 | .55 | .3 |
| 4 | .75 | .2 |
| 5 | 1.00 | .2 |

A direct approach to the problem is through elementary combinatory analysis. First, it should be noted that if cloud group 1 occurs at least once in a sequence of N passes, the photographic coverage is 100%. Accordingly, the probability of 100% coverage is:

$$P_{100\%} = 1 - [1 - P(1)]^N$$

where P(1) is the probability of occurrence of clear sky over the whole area. From this the answer to question (1) for the assumed distribution is that 28 passes must be programmed to provide 95% probability of encountering clear skies. Under the postulated conditions, this will take nearly 3 months.

The remaining four cloud groups can occur in any combination, and under our assumption will always give less than 100% coverage. The number of combinations, N at a time, of the four cloud groups (see, for example, page 59 of Niver (1965)) is:

$$C(4 + N - 1, N) = \frac{(N + 3)!}{3!N!}$$

Table 9-6 shows the number of such combinations.

Table 9-6

Combinations of 4 Things With Replacement

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| N | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| C | 4 | 10 | 20 | 35 | 56 | 84 | 120 | 165 | 220 | 286 |

By a systematic listing it is possible to generate all possible combinations. Table 9-7 lists the combinations for N = 3.

The various combinations are not equiprobable. The number of ways each combination can occur is:

$$W = \frac{N!}{a!b!c!d!}$$

Table 9-7

Computation of Probability Distribution of
Photo Coverage, 300 x 300 Mile Area, Region 11,
Number of Passes = 3

Probability of at Least One Cloud Group 1 = .271

| Cloud Group Combination | W | W Π P($C_n$) | Cumulative Probability | B (3) |
|---|---|---|---|---|
| | | | .271 | |
| 222 | 1 | .008 | .279 | .984 |
| 223 | 3 | .036 | .315 | .967 |
| 224 | 3 | .024 | .339 | .95 |
| 225 | 3 | .024 | .363 | .938 |
| 233 | 3 | .054 | .417 | .924 |
| 234 | 6 | .072 | .489 | .89 |
| 235 | 6 | .072 | .561 | .863 |
| 244 | 3 | .024 | .585 | .84 |
| 245 | 6 | .048 | .660 | .80 |
| 255 | 3 | .024 | .738 | .75 |
| 333 | 1 | .027 | .612 | .834 |
| 334 | 3 | .054 | .714 | .758 |
| 335 | 3 | .054 | .792 | .687 |
| 344 | 3 | .036 | .828 | .648 |
| 345 | 6 | .072 | .900 | .56 |
| 355 | 3 | .036 | .944 | .45 |
| 444 | 1 | .008 | .908 | .488 |
| 445 | 3 | .024 | .968 | .36 |
| 455 | 3 | .024 | .992 | .2 |
| 555 | 1 | .008 | 1.00 | 0.0 |

where a, b, c, d are the number of times cloud groups 2, 3, 4 and 5 occur in the combination. Table 9-7 gives the corresponding W for each combination. The probability of the event represented by any combination is then W times the joint probability of the individual events of each pass, or

$$W \prod^{N} P(C_n)$$

where $P(C_n)$ is the probability of the cloud group represented by the $n^{th}$ element of the combination. Table 9-7 also lists the probability of each combination.

The next step is to generate cumulative probabilities. Since we are interested in the probability of obtaining at least a certain degree of photographic coverage, we start from a base of the probability in N passes of 100% photo coverage, adding the probabilities of combinations with successively smaller area coverage. As will be noted from close examination of the example of Table 9-7, the area coverages do not necessarily fall in descending order with the logic we have used for ordering the combinations.

Figure 9-9 shows the results of such computations. The curves for N = 2, 3, and 4 were generated by the process described. The curves for N = 5, 6 and 10 are rather gross extrapolations from those curves, using a process similar to that used (properly) for finding the probability of N cloud-free passes. For convenience of display, the curves are plotted on "probability paper." The fact that they are nearly straight shows that the probability distribution of areas photographed in N passes is nearly Gaussian in the range of interest.

To the extent that the distributions are Gaussian, the most probable photo coverage can be estimated from the 50% level (ignoring the probability spike at 100% coverage). Table 9-8 shows the estimate of most probable coverage.

Table 9-8

Most Probable Photographic Coverage

| No. of Passes: | 1 | 2 | 3 | 4 | 5 | 6 | 7 or more |
|---|---|---|---|---|---|---|---|
| Coverage, % | 55 | 75 | 88 | 94 | 97 | 99 | 100 |

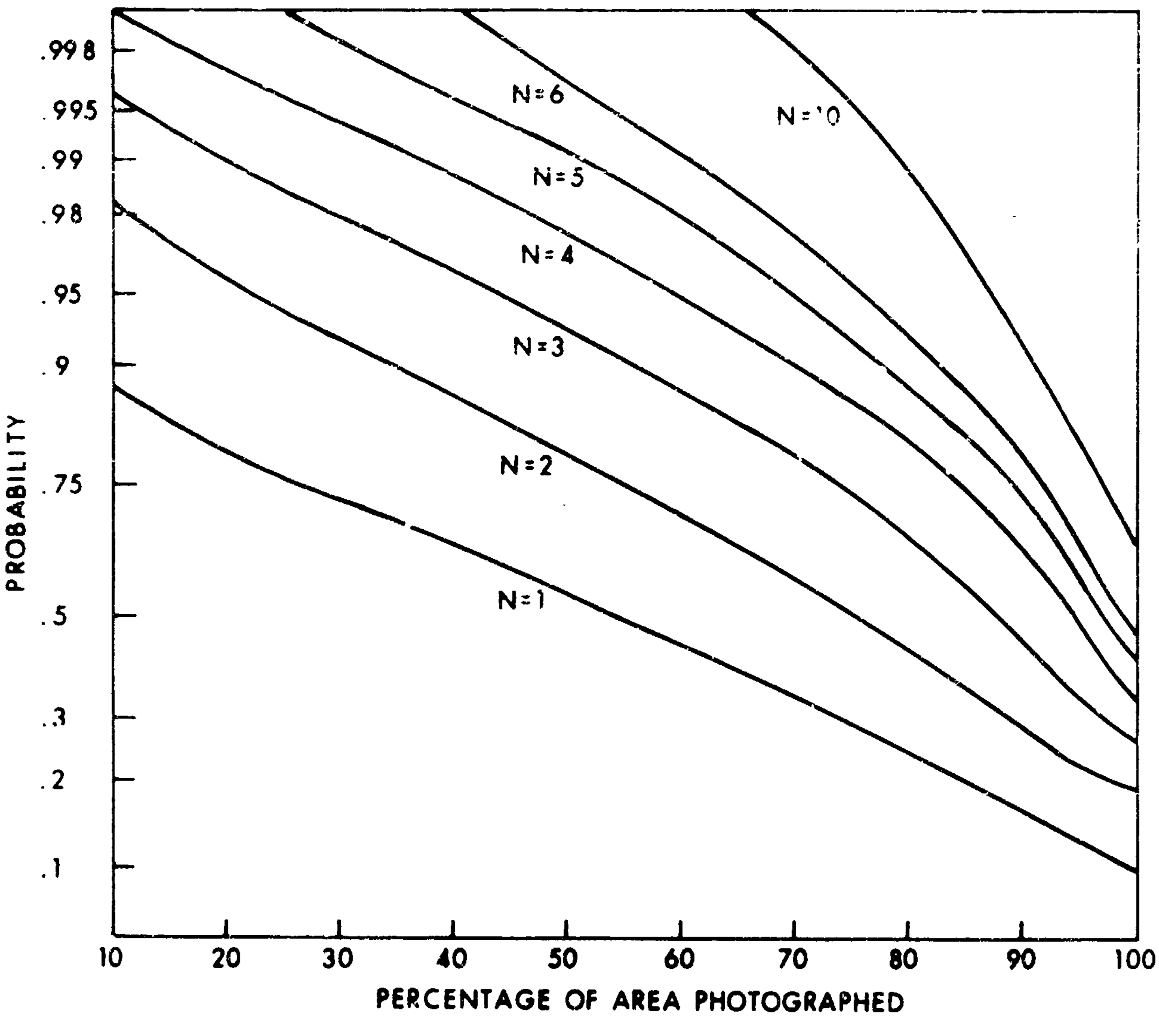


Figure 9-9 Probability of Photographing a Given Percentage of a Target Area

Exact computation by the combinatory procedures outlined here is feasible on a large computer up to N = 10 or 12. However, before that point, it is probably more expedient to resort to Monte Carlo procedures.

Use of Monte Carlo permits easy injection of a rather important effect which we have neglected in the combinatorial approach. The assumption was made that partial cloud cover is always sufficiently dissected to make valid an analytic description of the incremental photo coverage of each pass. In truth, the incremental photo coverage has a probability distribution which can be estimated from a consideration of the ways in which the cloud cover might be distributed over the area. One obvious result of a distribution of incremental photo coverage is the appearance of a finite probability of achieving 100% photo coverage even though no single pass was clear.

It may be seen, then, that neglect of the distribution of partial cloud cover has resulted in a pessimistic estimate of the probability of total coverage.

A Monte Carlo procedure would facilitate the introduction of temporal conditional probabilities, as would be required if the interval between cases of suitable orbit position and illumination is 24 hours or less. The combinatorial approach also permits use of conditional probabilities, but since the order in which a combination of cloud covers occurs now affects the probability of occurrence, the computation becomes considerably more voluminous.

While we have not programmed a Monte Carlo approach to this problem, it may be of interest to explore how one would be organized. The ground rules remain the same, but now we remove the restriction on time interval and will insert a provision for a random distribution of incremental photo coverage.

The first order of business is to compute area-scaled tables of unconditional and of temporal conditional cloud cover by the procedures outlined in Section 6. For sun-synchronous orbits, the temporal conditional table would be computed for 24 hours. Orbits of lesser inclination might require several tables at differing intervals. If at all possible, it is desirable to operate from pre-computed tables to avoid additional computer load. We will assume a sun-synchronous orbit and a single temporal conditional table. All tables are organized as cumulative probabilities in ascending order of cloud cover.

Figure 9-10 is a gross block diagram of the program. Iteration number Q and pass number n are initialized. The first draw is made from the unconditional table by finding which cloud group probability interval contains the random number RAN. If the cloud group is number 1 (clear), 100% photo coverage has occurred; there is no need for further photography, and 100% is noted in the tabulation for each number of passes.

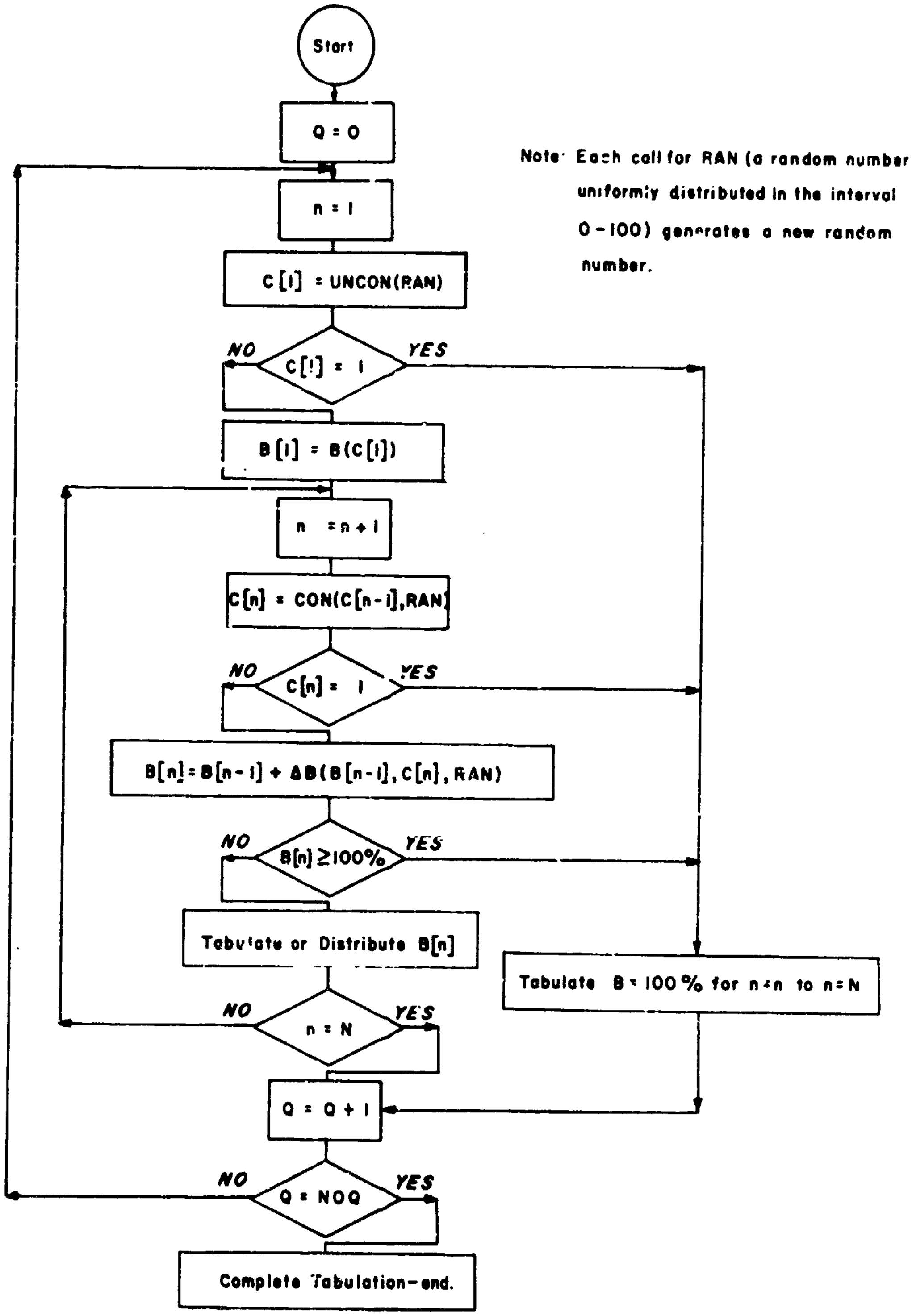


Figure 9-10 Block Diagram of a Possible Monte Carlo Program to Generate Probability Distribution of Photographic Coverage

If the cloud group is other than number 1, a photo coverage is assigned. The pass over the area is initiated. The new cloud cover is now generated from the line in the conditional probability table corresponding to the previous cloud cover. If cloud group 1 occurs, 100% cumulative coverage is tabulated for the pass and all subsequent passes.

The incremental photo coverage is computed as a stochastic function of existing coverage and the cloud group. The form of the function depends upon the dissection of the cloud cover, which can be estimated from the original cloud cover distribution observed from the ground. Formulation of the statistics of incremental coverage can be the subject of a separate investigation.

The incremental coverage may result in total coverage. If it does, the process is aborted as before. If not, the coverage achieved is tabulated under pass number n. The process is repeated for the N passes of interest. Then the whole process is repeated NOQ times. In similar simulations, we have found NOQ of 100 to 300 give excellent convergence with very short computer times required.

## 10. RECOMMENDATION FOR FUTURE WORK

Throughout the later sections of this report we have indicated areas in which imporved functional descriptions, techniques, or data could have improved the utility of the global cloud cover data bank. These recommendations are summarized here into two categories; first, those recommendations for improving the statistical base, second those recommendations with regard to further applications of the world-wide cloud cover data.

### 10.1 Recommendations for Improving the Statistics

a) Further explore the differences between ground-based statistics and corresponding observations from space, so that improved utility of the ground based data can be obtained in the simulation of earth-oriented space experiments.

b) Derive an improved functional description of the conditional probability as a function of distance and time. This improved functional relationship will eliminate the straight line extrapolation procedure now required for distances different from 200 nm and times different from 24 hours.

c) Examine in more detail the directional conditionality of the cloud cover distributions.

d) Increase the sample size from which the conditional statistics are drawn It may be possible to synthetically correct the conditional probabilities to make the joint probability matrix symetrical (i. e., conditional statistics should be drawn from the same population as the unconditional statistics). It might also be possible to use digital ATS or ESSA-5 satellite data to obtain this goal with a greater precision. Such data tabulation is not difficult, but a large computer would be required.

e) Add more seasons to the conditional probability data i. e., obtain spring and fall distributions as well as summer and winter.

f) Refine the regional distribution and in particular some of the regional boundaries where required.

g) Include a means for incorporating cloud system motion (where simulation requirements demand).

h) Obtain raw data for one or more of the conventional stations and prepare conditional distributions from long-term records. These can then be used as guide posts for the data derived from the satellite observations. The computer program for these summations and correlations is already available at Allied Research.

i) Obtain further meteorological satellite data for use in checking the enlarged sampling area size computational procedure.

10.2 Recommendations for Future Applications of the Data

a) Organize the potential applications of the cloud data in a systematic fashion, so that a relatively small number of stock procedures can be prepared (distinguish between situations which do and do not require Monte Carlo procedures).

b) Determine what cloud amount is significant for various specific objectives or experiments.

c) Organize a group to provide expert information on applications.

d) Prepare procedures for forecast and forecast varification in overall system simulations.

e) Prepare an actual simulation of a chosen example drawn from the real world.

f) Study the role of simulation in dynamic experiment programming.

g) Prepare techniques for the use of the statistics in cloud prognosis.

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# APPENDIX A
# SOURCE DATA

## APPENDIX A

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## APPENDIX A

## SOURCE DATA

This appendix describes in some detail the methods and procedures followed in obtaining the cloud cover data tabulated for use with computer simulation routines. In the Final Report (the report to which this is an appendix) the proposed uses for these data are described, as well as suggested engineering applications and demonstrations of their use. The Final Report presents the objectives of the study and the assumptions involved in the tabulation of the data. Thus, we include here only a brief statement of the objectives and ground rules which governed the data search, and a review of the data sources which were used.

### 1. OBJECTIVES

The basic objective of the world-wide cloud cover study was the creation of a master file of tabulated cloud statistics and cloud distributions for regions representing all of the earth's surface. The requirement was that these statistics be tabulated and made available either on IBM punched cards or magnetic tape, so that statistical analyses of cloud amounts could easily be performed for monthly, seasonal, and annual reference periods for selected areas on the earth.

In addition, conditional statistics were required to take account of the time and space dependence of the cloud regime at one point on that of another point nearby in either space or time. The tabulated statistics include provisions for taking account of the diurnal variation in cloud cover throughout the day and night.

Several secondary objectives also existed. For example, a comparative analysis was necessary to evaluate the relationship between cloud cover as it might be viewed from a satellite versus that observed from the ground, so that the probability that the earth's surface can be observed from a satellite can be inferred from ground-observed data. An engineering interpretation of the tabulated cloud statistics and cloud distributions in terms of requirements for an earth satellite sensor operation was performed to demonstrate the use of and to validate the tabulated statistics.

Several guidelines were provided in the contractual statement. These included the following:

1. A minimum number of stations should be selected for the purpose of charaterizing the monthly, seasonal, and annual distributions of cloud types for selected regions which typify the diverse cloud types and frequencies.

2. The statistical data will be drawn from existing records, where possible, and extrapolated, interpolated and evaluated for appropriate areas over the earth.

3. Day-night and monthly reference periods may be feasible.

In addition to these stated guidelines, it became obvious early in the performance of the work that much could be gained from trips to NASA centers and to various NASA contractors to determine requirements for cloud cover data in current mission planning and simulation endeavors. The details of the data presentation system have resulted from information gained from such visits.

## 2. UNCONDITIONAL CLOUD COVER DISTRIBUTIONS

Unconditional cloud statistics (in the form of frequency distributions of the fraction of the sky covered, expressed in percent frequency) were prepared for use in computer simulations. Ideally, it would have been desirable to process the individual cloud cover observations from a large number of observing stations in a consistent fashion to obtain a reasonably homogeneous form of summarization. Since available resources were limited, however, existing summaries had to be used wherever possible. A limited amount of raw cloud data was summarized.

### 2.1 Data Search

Twenty-nine cloud climatic regions were selected to represent the entire earth's surface. It was hoped that for many of these regions a single station could be used to represent the cloud climatology; however, it was also desirable to obtain data for more than one station for most regions, so that an indication of the homogeneity of the region and "representativeness" of the station could be established. Cloud summaries were obtained for approximately 100 observing stations distributed throughout the world. The initial selection was made from station locations indicated on Northern and Southern Hemisphere upper air Raob and Rawinsonde network charts, based on the idea that better quality cloud observations would be available from such stations. A visit to the National Weather Records Center (NWRC) revealed that useable summaries were not available for several of the originally selected stations. Whenever possible, summaries from nearby stations were substituted. The final data sample consisted of 108 land stations, plus six ocean weather ships.

2.2 Form of the Existing Data Summaries

Cloud observations from different parts of the world are summarized in various forms. Observational times, and even observing techniques, vary from place to place. The data summaries from which the unconditional statistics were derived were in three basic forms: (1) Revised Uniform Summary of Surface Weather Observations (A-F); (2) Original Uniform Summary of Surface Weather Observations (A and B); and (3) NIS* or N-Summary. Of the 108 stations, the Revised Uniform Summaries were available for 33, the Original Uniform Summaries for 23, and the NIS Summaries for 52 stations. Most of the NIS Summaries were designated as Old Type N-Summaries. Also, ten years of raw data (on magnetic tape) were obtained for six ship stations, and unconditional statistics were derived directly from these data.

The Revised Uniform Summaries provided the most useable data (see Fig. A-1). For these stations, cloud amounts are summarized in tenths by percentage frequency; frequencies are given for three-hourly groups for all months. The stations for which the Revised Uniform Summaries are available are concentrated in only a few climatological regions, particularly those within the United States. These summaries also exist, however, for several United States Air Force bases throughout the world.

Original Uniform Summaries for most stations are in a somewhat similar form, except the number of observations is given instead of the percentage. A second difference is that the cloud cover is summarized by groups, as shown in Figure A-2. For some stations, however, the cloud amounts are not summarized by tenths, but by categories, such as clear, scattered and low broken. For these summaries, it was necessary to assign a cloud amount to each category (see Fig. A-3).

The N-Type Summaries were in the least useable form, since the summarizing procedures vary from station to station. The most common form (sometimes called NIS Summary #17) gives the mean number of days per month with the following sky covers: 0-1/8, 0-2/8, 3-5/8 and 6-8/8 (see Fig. A-4). Moreover, the data are generally available for only a few hours of the day. These summaries, therefore, required considerable reworking to be of any use.

* NIS Summaries are prepared by the National Intelligence Survey

DATA PROCESSING DIVISION
ETAC, USAF
ASHEVILLE, N.C. 28801

# SKY COVER

41213 — NHA TRANG VIETNAM APT — 57-61,66 — MAR

STATION — STATION NAME — PERIOD — MONTH

PERCENTAGE FREQUENCY OF OCCURRENCE
(FROM HOURLY OBSERVATIONS)

| MONTH | HOURS (L.S.T.) | PERCENTAGE FREQUENCY OF TENTHS OF TOTAL SKY COVER 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | MEAN TENTHS OF SKY COVER | TOTAL NO. OF OBS. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MAR | 00-02 | 2.6 | 3.6 | 4.8 | 12.5 | 16.1 | 16.1 | 9.7 | 3.6 | 8.1 | 14.9 | 4.8 | 5.3 | 248 |
| | 03-05 | 4.1 | 6.1 | 2.6 | 12.2 | 18.1 | 11.3 | 13.9 | 1.5 | 8.5 | 17.0 | 4.6 | 5.4 | 459 |
| | 06-08 | .7 | 5.0 | .7 | 6.5 | 15.1 | 7.9 | 13.2 | 1.8 | 15.9 | 28.5 | 4.7 | 6.5 | 555 |
| | 09-11 | 1.4 | 2.9 | 1.3 | 8.1 | 17.1 | 14.7 | 13.5 | 1.3 | 19.8 | 15.8 | 4.1 | 6.0 | 556 |
| | 12-14 | .5 | 4.0 | 1.8 | 8.9 | 19.7 | 14.3 | 20.3 | 2.7 | 13.4 | 11.9 | 2.5 | 5.6 | 553 |
| | 15-17 | | 6.5 | 1.3 | 11.2 | 21.6 | 17.2 | 12.0 | 2.2 | 13.0 | 11.4 | 3.6 | 5.5 | 552 |
| | 18-20 | 1.3 | 7.5 | 1.0 | 11.0 | 18.5 | 13.0 | 11.3 | 3.3 | 16.5 | 11.5 | 5.3 | 5.6 | 400 |
| | 21-23 | 6.5 | 8.5 | 4.0 | 12.6 | 20.2 | 8.9 | 10.9 | 2.0 | 10.5 | 12.6 | 3.2 | 4.9 | 247 |
| TOTALS | | 1.9 | 5.3 | 1.8 | 9.9 | 18.3 | 13.1 | 13.6 | 2.2 | 13.9 | 15.9 | 4.1 | 5.7 | 3570 |

Figure A-1 Sample Form of Revised Uniform Summary of Surface Weather Observations

1210WS FORM JUL 64 0-9-5 (Dot 50) PREVIOUS EDITIONS OF THIS FORM ARE OBSOLETE

DATA PROCESSING DIVISION
CLIMATIC CENTER, USAF
AIR WEATHER SERVICE(MATS)
ASHEVILLE, NORTH CAROLINA

# SKY COVER

## FREQUENCY OF OCCURRENCE

48456 BANGKOK THAILAND/DON MUANG — MAR
STATION — STATION NAME — MONTH
54 55 56 57 58 59 60 61 62 63
YEARS

| MONTH | HOURS (L.S.T.) | FREQUENCY OF TENTHS OF TOTAL SKY COVER BY GROUPS: 0 | 1-2 | 3 | 4-5 | 6-7 | 8-9 | 10 | MEAN TENTHS OF SKY COVER | SUM OF TENTHS OF SKY COVER | TOTAL NO. OF OBSERVATIONS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 00 | 7 | 11 | 74 | 120 | 36 | 52 | 7 | 4.8 | 1485 | 307 |
| | 01 | 8 | 17 | 71 | 112 | 35 | 59 | 5 | 4.8 | 1476 | 307 |
| | 02 | 6 | 22 | 70 | 110 | 26 | 68 | 5 | 4.9 | 1493 | 307 |
| | 03 | 3 | 14 | 63 | 121 | 29 | 68 | 9 | 5.1 | 1564 | 307 |
| | 04 | 4 | 13 | 56 | 135 | 26 | 66 | 7 | 5.0 | 1548 | 307 |
| | 05 | 4 | 10 | 46 | 141 | 44 | 56 | 6 | 5.1 | 1567 | 307 |
| | 06 | 2 | 4 | 36 | 132 | 56 | 70 | 7 | 5.5 | 1692 | 307 |
| | 07 | 1 | 1 | 16 | 98 | 68 | 115 | 8 | 6.4 | 1958 | 307 |
| | 08 | 1 | 4 | 37 | 93 | 58 | 108 | 6 | 6.0 | 1844 | 307 |
| | 09 | 4 | 7 | 31 | 99 | 48 | 113 | 5 | 6.0 | 1842 | 307 |
| | 10 | 1 | 9 | 14 | 96 | 55 | 125 | 7 | 6.3 | 1942 | 307 |
| | 11 | 1 | 10 | 17 | 86 | 60 | 127 | 5 | 6.3 | 1930 | 306 |
| | 12 | 2 | 8 | 20 | 79 | 49 | 143 | 6 | 6.5 | 1981 | 307 |
| | 13 | 1 | 4 | 24 | 68 | 52 | 150 | 7 | 6.6 | 2014 | 306 |
| | 14 | 1 | 3 | 27 | 78 | 56 | 137 | 5 | 6.4 | 1975 | 307 |
| | 15 | 2 | 4 | 40 | 85 | 55 | 111 | 10 | 6.1 | 1872 | 307 |
| | 16 | 2 | 6 | 49 | 94 | 47 | 98 | 10 | 5.8 | 1781 | 306 |
| | 17 | 2 | 8 | 51 | 112 | 40 | 85 | 9 | 5.6 | 1715 | 307 |
| | 18 | 2 | 15 | 36 | 110 | 32 | 104 | 8 | 5.8 | 1770 | 307 |
| | 19 | 2 | 11 | 27 | 99 | 43 | 109 | 16 | 6.1 | 1875 | 307 |
| | 20 | 2 | 13 | 35 | 108 | 46 | 88 | 15 | 5.7 | 1760 | 307 |
| | 21 | 3 | 13 | 48 | 103 | 58 | 69 | 13 | 5.5 | 1675 | 307 |
| | 22 | 5 | 10 | 61 | 107 | 49 | 61 | 14 | 5.2 | 1609 | 307 |
| | 23 | 6 | 10 | 68 | 109 | 42 | 60 | 10 | 5.1 | 1551 | 305 |
| TOTALS | | 72 | 227 | 1017 | 2495 | 1110 | 2242 | 200 | 5.7 | 41919 | 7363 |

Form 1210WS 0-9 (Dot 80) Apr 62

Figure A-2 Sample Form of Original Uniform Summary of Surface Weather Observations

# SKY CONDITIONS

## FREQUENCY OF OCCURRENCE

ADEN ARABIA SHEIKH OTHMAN (STATION NAME) — JAN (PERIOD)

| STATION | YEAR | MONTH | HOUR (L S T) | CLEAR | SCATTERED | HI BKN OR HI OVC WITH SCTD OR NO LOW CLOUDS | LOW BROKEN | LOW OVERCAST | TOTAL NO OF OBSERVATIONS |
|---|---|---|---|---|---|---|---|---|---|
| 31401 | | 01 | 01 | 23 | 22 | 1 | 8 | 8 | 62 |
| | | | 02 | 24 | 22 | 3 | 8 | 5 | 62 |
| | | | 03 | 23 | 19 | 1 | 16 | 3 | 62 |
| | | | 04 | 23 | 16 | 3 | 17 | [illegible] | 62 |
| | | | 05 | 23 | 16 | 2 | 16 | 5 | 62 |
| | | | 06 | 23 | 13 | 1 | 15 | 3 | 62 |
| | | | 07 | 6 | 33 | 2 | 15 | 6 | 62 |
| | | | 08 | 5 | 28 | 2 | 25 | 2 | 62 |
| | | | 09 | 3 | 35 | | 19 | 5 | 62 |
| | | | 10 | 1 | 22 | 2 | 29 | 8 | 62 |
| | | | 11 | 1 | 16 | | 38 | 7 | 62 |
| | | | 12 | | 22 | 2 | 33 | 5 | 62 |
| | | | 13 | 2 | 32 | 3 | 1[illegible] | [illegible] | 62 |
| | | | 14 | 7 | 33 | 5 | 13 | 4 | 62 |
| | | | 15 | 11 | 30 | 4 | 6 | 2 | 62 |
| | | | 16 | 15 | 33 | 5 | 3 | | 62 |
| | | | 17 | 24 | 28 | 9 | 1 | | 62 |
| | | | 18 | 30 | 23 | 8 | 1 | | 62 |
| | | | 19 | 25 | 26 | 10 | 1 | | 62 |
| | | | 20 | 33 | 22 | 5 | 4 | | 62 |
| | | | 21 | 35 | 15 | 4 | 6 | 2 | 62 |
| | | | 22 | 28 | 19 | 3 | [illegible] | [illegible] | 62 |
| | | | 23 | 24 | 23 | 4 | 6 | 5 | 62 |
| | | | 24 | 23 | 24 | 3 | [illegible] | 4 | 62 |
| TOTALS → | | | | 412 | 590 | 67 | 31[illegible] | [illegible] | 14[illegible] |

LOW CLOUDS ARE HEREIN DEFINED AS THOSE REPORTED BELOW 10,000 FEET
HIGH CLOUDS ARE HEREIN DEFINED AS THOSE REPORTED AT OR ABOVE 10,000 FEET

**Figure A-3** Sample Form of Original Uniform Summary of Surface Weather Observations

AWS MC FORM 105 1 NOV 51 PREVIOUS EDITIONS OF THIS FORM MAY BE USED

AIR WEATHER SERVICE | N SUMMARY # 17
CLIMATIC CENTER | 08 LST
DATA PROCESSING DIVISION

MEAN NUMBER OF DAYS WITH INDICATED
TOTAL AND LOW CLOUD AMOUNTS

86217 ASUNCION PARAGUAY

25 16 S 57 38 W 21[illegible] FT

JAN 49-OCT 59,DEC 59-SEP 60,NOV 60-MAR 61,MAY 61-AUG 61,JUL 62-SEP 63,NOV 63-APR 64

| MONTH | MEAN TOTAL CLD IN OKTAS | MEAN NUMBER OF DAYS WITH TOTAL CLOUD AMOUNT 0-1/8 | 0-2/8 | 3-5/8 | 6-8/8 | TOTAL OBS | MEAN NUMBER OF DAYS WITH LOW CLOUD AMOUNT* 0-1/8 | 0-2/8 | 3-5/8 | 6-8/8 | TOTAL OBS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| JAN | 4.0 | 9.3 | 14.0 | 4.7 | 12.4 | 40 | 20.1 | 21.9 | 3.6 | 5.5 | 319 |
| FEB | 4.1 | 8.0 | 10.0 | 6.5 | 11.5 | 56 | 20.9 | 22.0 | 1.7 | 4.2 | 310 |
| MAR | 4.1 | 9.3 | 12.5 | 5.6 | 13.0 | 67 | 21.4 | 22.2 | 2.2 | 6.7 | 340 |
| APR | 4.1 | 10.2 | 13.6 | 4.0 | 12.5 | 53 | 22.5 | 23.4 | 1.5 | 5.1 | 322 |
| MAY | 4.8 | 7.8 | 11.6 | 2.4 | 17.0 | 64 | 19.2 | 20.5 | 3.5 | 6.9 | 341 |
| JUN | 5.1 | 8.1 | 9.4 | 2.7 | 17.9 | 67 | 15.7 | 16.8 | 4.8 | 8.3 | 335 |
| JUL | 4.2 | 11.4 | 14.7 | .9 | 15.3 | 103 | 20.9 | 21.8 | 2.3 | 7.0 | 352 |
| AUG | 4.5 | 11.1 | 12.1 | 2.6 | 16.3 | 95 | 22.9 | 24.2 | 1.5 | 5.4 | 340 |
| SEP | 5.1 | 7.3 | 10.0 | 2.7 | 17.3 | 99 | 18.6 | 19.1 | 2.2 | 8.7 | 336 |
| OCT | 4.1 | 11.2 | 13.7 | 3.6 | 13.7 | 86 | 20.1 | 21.3 | 2.7 | 7.0 | 332 |
| NOV | 4.8 | 7.1 | 8.8 | 5.8 | 15.4 | 72 | 22.0 | 23.2 | 2.5 | 4.2 | 311 |
| DEC | 4.5 | 7.8 | 10.2 | 6.3 | 14.4 | 88 | 23.5 | 24.7 | 2.9 | 3.5 | 337 |
| ANN | 4.5 | 108.3 | 140.5 | 47.8 | 176.6 | 890 | 247.6 | 261.0 | 31.4 | 72.5 | 3975 |

*LOW CLOUD AMOUNT IS FROM THE SYNOPTIC CODE SYMBOL N WITH A LOWER CASE H SUBSCRIPT AND NORMALLY REPRESENTS THE FRACTION OF THE CELESTIAL DOME COVERED BY THE CLOUD TYPE REPORTED FOR THE LOW LAYER OR IF NONE FOR THE MIDDLE LAYER REGARDLESS OF HEIGHT.

Figure A-4 Sample Form of NIS Summary No. 17

A second form of the N-Summary has the following categories: $\leq 3/10$, 4-6/10, $\geq 7/10$ and $\geq 9/10$. Here again the number of observations in each category are tabulated for certain hours of the day (these reporting hours also vary from station to station) (see Fig. A-5).

A third form of the N-Summary has categories of $\leq 2/10$, 3-6/10, $\geq 7/10$ and $\geq 9/10$ (see Fig. A-6).

As can be noted from the foregoing, some of the summarization formats are mutually exclusive. Thus, criteria had to be established, so that representative station selection could be made. For simulation purposes there is a strong requirement that clear skies, overcast skies and skies having less than 3/10 cloud cover be separately delineated. Any summarization scheme must, therefore, include the possibility of tabulating these three cloud groups. One of the principal factors involved in choosing the old A and B and revised A and B summaries as the preferred data sources, was the ease of obtaining these cloud cover groupings.

2.3 Final Selection of Stations

The stations representative of each region from which the unconditional statistics were derived are given in Table A-1. The type of data summary available and the number of years of observation are also given. The climatological regions for which the statistics were modified from other regions are so indicated.

2.4 Regional Homogeneity

A second criterion for picking a representative station for each region comes from the implied requirement that the station must indeed be representative of a homogeneous area. Thus, wherever possible, all of the stations within a region from which we had summaries have been compared, one with the other. These comparisons were usually made for a winter and summer month and for two times of the day, usually early morning and late afternoon. Such comparisons were made in 15 of the 20 basic regions (tabulated in Table A-2). These comparisons are shown in Figures A-7 to A-21. Here, we will only mention briefly the comparison for two regions and leave the comparison of the remaining regions to the reader. The overall homogeneity as demonstrated in these Figures is

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Asheville, N. C.

## SUMMARY NO. 17
### Total and Low Cloud Amounts

COCOS 96996
12 05S 96 53E

06 HR JAN 1949-DEC 1955,
LESS JAN-MAR, MAY-JUN 1953
12 HR JAN 1949-DEC 1955,
LESS JUN, DEC 1949, MAY 1950,
SEP 1952, OCT 1953-FEB 1954
18 HR JAN 1949-DEC 1955

| Month | | Mean Total Cloud Amount | Mean No. Days with Total Cloud Amount | | | | No. of Obs. | Mean No. Days with Low Cloud Amount | | | | No. of Obs. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ≤ 3/10 | 4-6/10 | ≥ 7/10 | ≥ 9/10 | | ≤ 3/10 | 4-6/10 | ≥ 7/10 | ≥ 9/10 | |
| JAN | 01 | 4.9 | 8.6 | 6.4 | 16.0 | 12.8 | 126 | 13.6 | 8.2 | 9.2 | 8.0 | 128 |
| FEB | 02 | 5.3 | 5.4 | 6.9 | 15.7 | 11.3 | 114 | 11.3 | 9.3 | 7.5 | 6.0 | 112 |
| MAR | 03 | 4.9 | 5.2 | 11.9 | 13.9 | 8.4 | 125 | 12.4 | 12.4 | 6.1 | 3.9 | 127 |
| APR | 04 | 5.0 | 5.0 | 11.2 | 13.7 | 9.2 | 107 | 10.7 | 13.5 | 5.9 | 4.5 | 107 |
| MAY | 05 | 5.2 | 4.0 | 11.3 | 15.8 | 11.0 | 124 | 11.0 | 11.0 | 9.0 | 4.9 | 127 |
| JUN | 06 | 5.3 | 3.4 | 10.4 | 16.2 | 12.8 | 115 | 11.6 | 10.1 | 8.3 | 4.9 | 116 |
| JUL | 07 | 4.9 | 4.3 | 12.2 | 14.5 | 10.0 | 145 | 11.8 | 10.7 | 8.5 | 4.3 | 145 |
| AUG | 08 | 5.0 | 5.1 | 11.5 | 14.4 | 10.6 | 140 | 12.3 | 11.8 | 6.9 | 5.1 | 139 |
| SEP | 09 | 5.0 | 5.3 | 10.4 | 14.3 | 10.4 | 136 | 10.8 | 12.8 | 6.4 | 4.2 | 136 |
| OCT | 10 | 5.1 | 6.0 | 9.1 | 15.9 | 12.2 | 140 | 11.2 | 11.5 | 8.3 | 5.8 | 138 |
| NOV | 11 | 5.5 | 4.9 | 7.6 | 17.5 | 12.2 | 142 | 8.8 | 11.6 | 9.6 | 6.2 | 140 |
| DEC | 12 | 4.5 | 8.3 | 10.0 | 12.7 | 9.1 | 146 | 13.4 | 11.3 | 6.4 | 4.0 | 146 |
| ANN | | 5.1 | 65.5 | 118.9 | 180.6 | 130.0 | 1560 | 138.9 | 134.2 | 92.1 | 61.8 | 1561 |
| HOUR 1ST | 06 | 60.6 | | | | | | | | | | |

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| STATION NO. | SUMMARY NO. |
|---|---|
| 96996 | 17 |

Figure A-5 Sample Form of N-Summary No. 17

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Asheville, N. C.

## SUMMARY NO. 17

**Total and Low Cloud Amounts**

SWAN ISLAND WEST INDIES WBO
N 17 24 W 83 56

JAN-DEC 1948
HRS 04, 10, 16, & 22 LST

TOTAL CLOUD AMOUNT NOT REPORTED PRIOR TO JANUARY 1946

| Month | | Mean Total Cloud Amount (tenths) | Mean No. Days with Total Cloud Amount ≤ 2/10 | 3-6/10 | ≥ 7/10 | ≥ 9/10 | No. of Obs. | Mean No. Days with Low Cloud Amount ≤ 2/10 | 3-6/10 | ≥ 7/10 | ≥ 8/10 | No. of Obs. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| JAN | 01 | 5.7 | 5.0 | 12.0 | 14.0 | 9.0 | 31 | 10.0 | 15.0 | 6.0 | 6.0 | 31 |
| FEB | 02 | 3.6 | 12.6 | 10.6 | 4.8 | 2.9 | 29 | 15.4 | 10.6 | 1.9 | 1.0 | 29 |
| MAR | 03 | 3.2 | 13.0 | 13.0 | 5.0 | | 31 | 18.0 | 11.0 | 2.0 | 1.0 | 31 |
| APR | 04 | 3.7 | 11.0 | 13.0 | 6.0 | 3.0 | 30 | 18.0 | 11.0 | 1.0 | | 30 |
| MAY | 05 | 4.8 | 7.2 | 14.5 | 9.3 | 6.2 | 30 | 18.6 | 12.4 | | | 30 |
| JUN | 06 | 6.1 | 6.0 | 10.0 | 14.0 | 11.0 | 30 | 21.0 | 9.0 | | | 30 |
| JUL | 07 | 5.2 | 9.0 | 11.0 | 11.0 | 8.0 | 31 | 26.0 | 5.0 | | | 31 |
| AUG | 08 | 4.1 | 15.0 | 6.0 | 10.0 | 5.0 | 31 | 24.6 | 6.4 | | | 29 |
| SEP | 09 | 5.1 | 7.0 | 12.0 | 11.0 | 4.0 | 30 | 20.0 | 8.0 | 2.0 | 1.0 | 30 |
| OCT | 10 | 5.3 | 8.0 | 12.0 | 11.0 | 8.0 | 31 | 17.0 | 12.0 | 2.0 | 2.0 | 31 |
| NOV | 11 | 2.5 | 20.0 | 7.0 | 3.0 | 3.0 | 30 | 23.3 | 6.7 | | | 27 |
| DEC | 12 | 1.8 | 22.7 | 6.2 | 2.1 | | 30 | 21.1 | 8.7 | 1.2 | | 25 |
| ANN | | 4.3 | 136.5 | 127.3 | 101.2 | 60.1 | 364 | 233.0 | 115.8 | 16.1 | 11.0 | 354 |
| HOUR LST | 04 | 51.1 | | | | | | | | | | |

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Figure A-6 Sample Form of N-Summary No. 17

## Table A-1

### Representative Stations for Unconditional Distributions

| REGION NUMBER | STATION | COORDINATES | TYPE OF DATA | YEARS OF RECORD |
|---|---|---|---|---|
| 1 | Dhahran, Saudi Arabia (Airfield) | 26-17N 50-09E | 2 | 11 |
| 2 | Tripoli, Libya (Wheelus AFB) | 32-54N 13-17E | 1 | 19 |
| 3 | Angeles, Luzon, P.I. (Clark AFB) | 15-11N 120-33E | 1 | 21 |
| 4 | Tampa, Florida (MacDill AFB) | 27-51N 82-30W | 1 | 23 |
| 5 | Los Angeles, California (WBAS) Hours 10-19 (May-October) Modified | 33-56N 118-23W | 1 | 19 |
| 6 | Talara, Peru 01 and 22 Hours-Synthetic | 04-32S 81-14W | 2 | 5 |
| 7 | Synthetic Data | | | – |
| 8 | Mountain Home, Idaho (AFB) | 43-03N 115-51W | 1 | 20 |
| 9 | Fort Yukon, Alaska (WB) | 66-35N 145-18W | 2 | 18 |
| 10 | Harbin, China | 45-45N 126-38W | 3 | 7 |
| 11 | Belleville, Illinois (Scott AFB) | 38-33N 89-51W | 1 | 27 |
| 12 | Ban Me Thuot, Vietnam (City Airport) | 12-41N 108-07E | 1 | 10 |
| 13 | Ship D (Atlantic) | 44-00N 41-00W | 4 | 10 |
| 14 | Adak, Alaska (NS) | 51-53N 176-38W | 1 | 25 |
| 15 | Resolute NWT, Canada | 74-41N 94-55W | 2 | 7 |
| 16 | Fort Kobbe, Canal Zone (Howard AFB) | 08-55N 79-36W | 1 | 19 |
| 17 | Bangalore, India (Hindustan Airport) | 12-57N 77-38E | 3 | 7 |
| 18 | San Francisco, California (WBAS) | 37-37N 122-23W | 1 | 18 |
| 19 | Shreveport, Louisiana (Barksdale, AFB) | 32-30N 93-40W | 1 | 27 |
| 20 | Ship V (Pacific) | 31-00N 164-00E | 4 | 10 |
| 21 | Seasonal Reversal of Region 12 | | | |
| 22 | Seasonal Reversal of Region 13 | | | |
| 23 | Seasonal Reversal of Region 14 | | | |
| 24 | Seasonal Reversal of Region 15 | | | |
| 25 | Seasonal Reversal of Region 16; Hours 10, 13, 16 for May - September Modified | | | |
| 26 | Seasonal Reversal of Region 17 | | | |
| 27 | Seasonal Reversal of Region 18 | | | |
| 28 | Seasonal Reversal of Region 19 | | | |
| 29 | Seasonal Reversal of Region 20 | | | |

**Legend for Type of Data:**

- (1) Revised Uniform Summary (A-F)
- (2) Original Uniform Summary (A and B)
- (3) NIS Summary
- (4) Raw Data (Ship Stations)

Table A-2

Tabulation of Regions to Which Regional Homogeneity was Established from Conventional Data

| Region | Number of Stations |
|---|---|
| 1 | 3 |
| 2 | 2 |
| 3 | 5 |
| 4 | 6 |
| 9 | 3 |
| 10 | 2 |
| 11 | 6 |
| 12 | 5 |
| 13 | 3 |
| 14/23 | 4 |
| 16/25 | 5 |
| 17/26 | 4 |
| 18 | 4 |
| 19 | 2 |
| 20 | 6 |

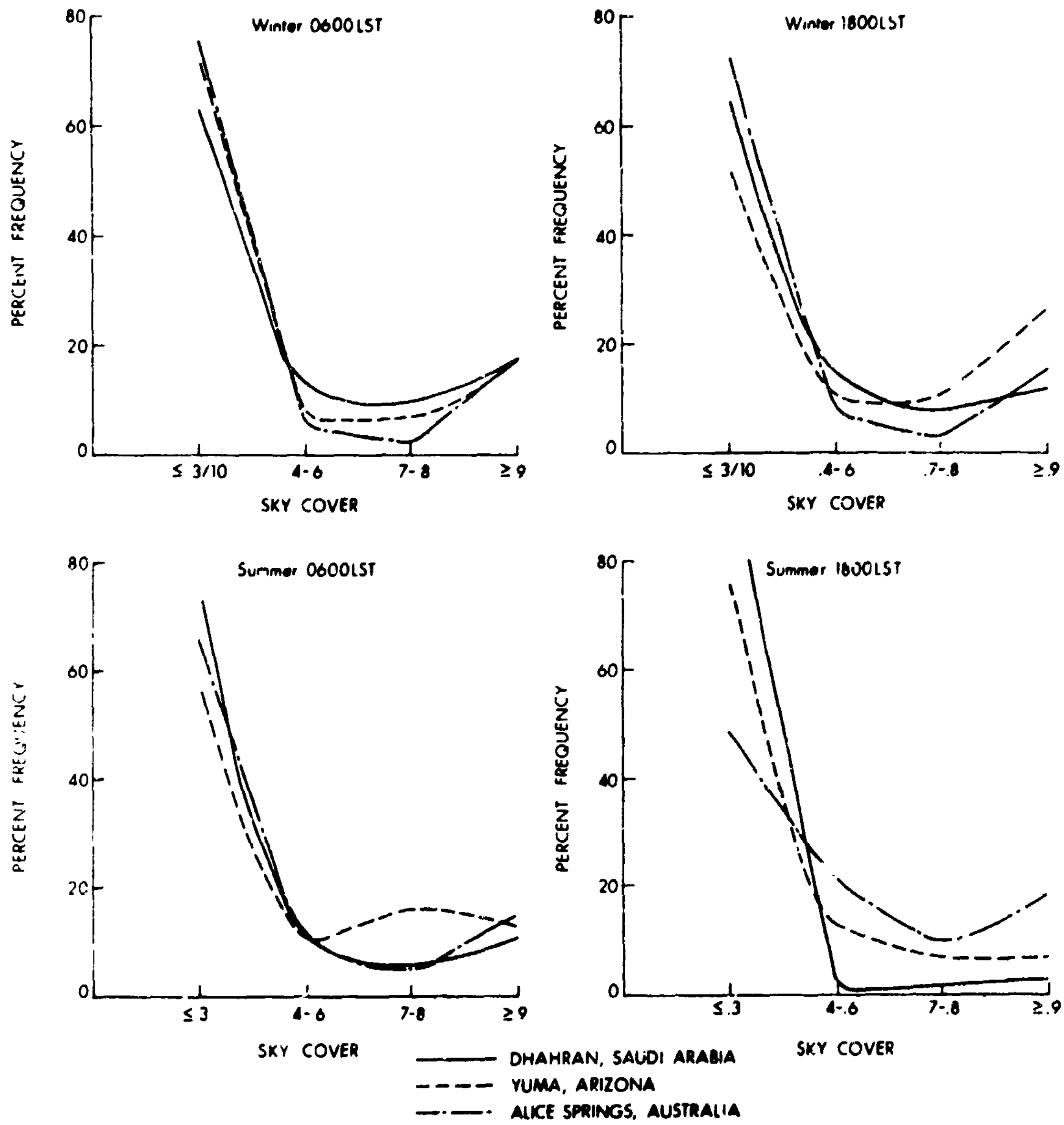


Figure A-7 Cloud Cover Distributions Demonstrating Regional Homogeneity for Region 1

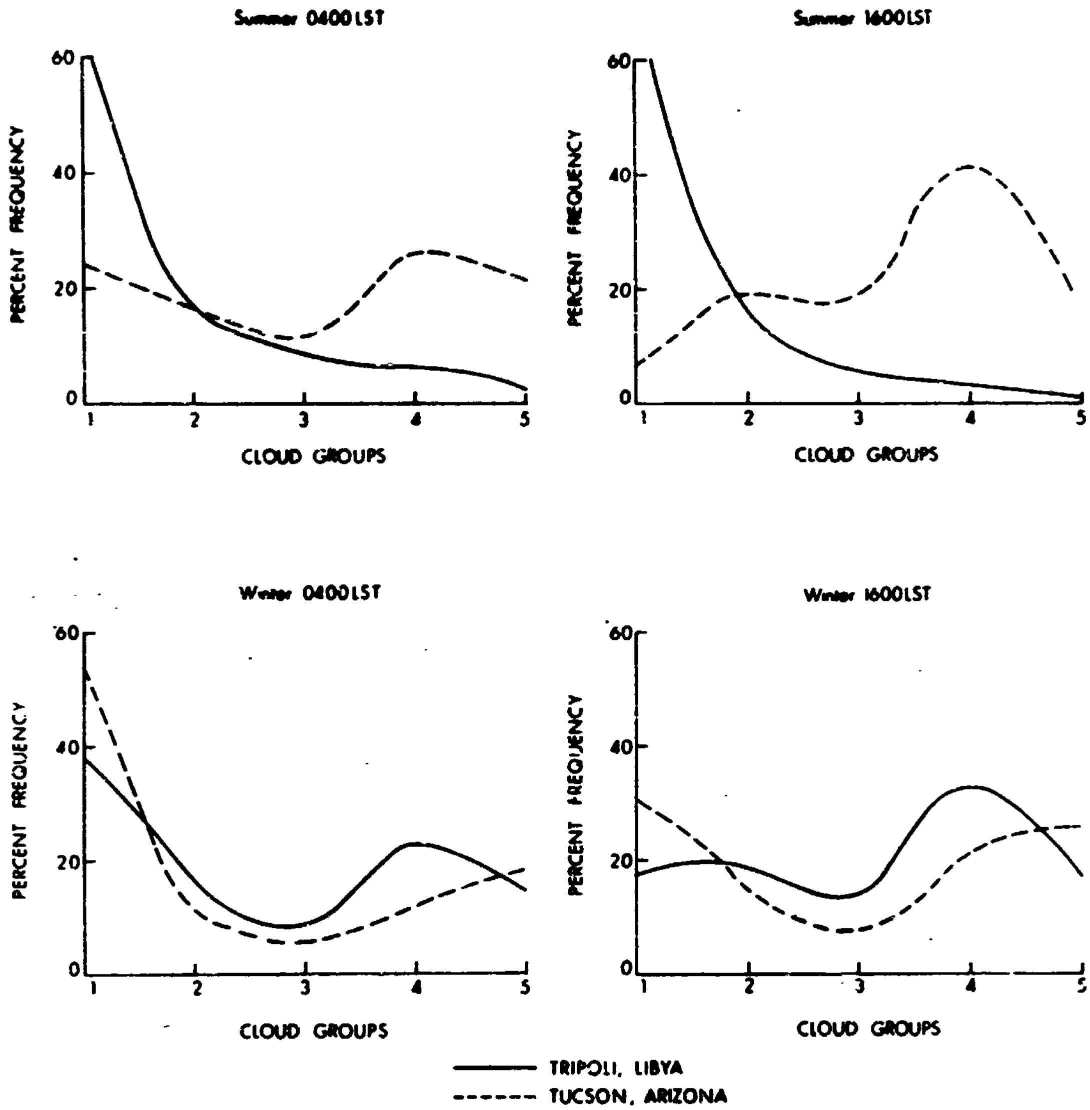


Figure A-8 Cloud Cover Distributions Demonstrating Regional Homogeneity for Region 2

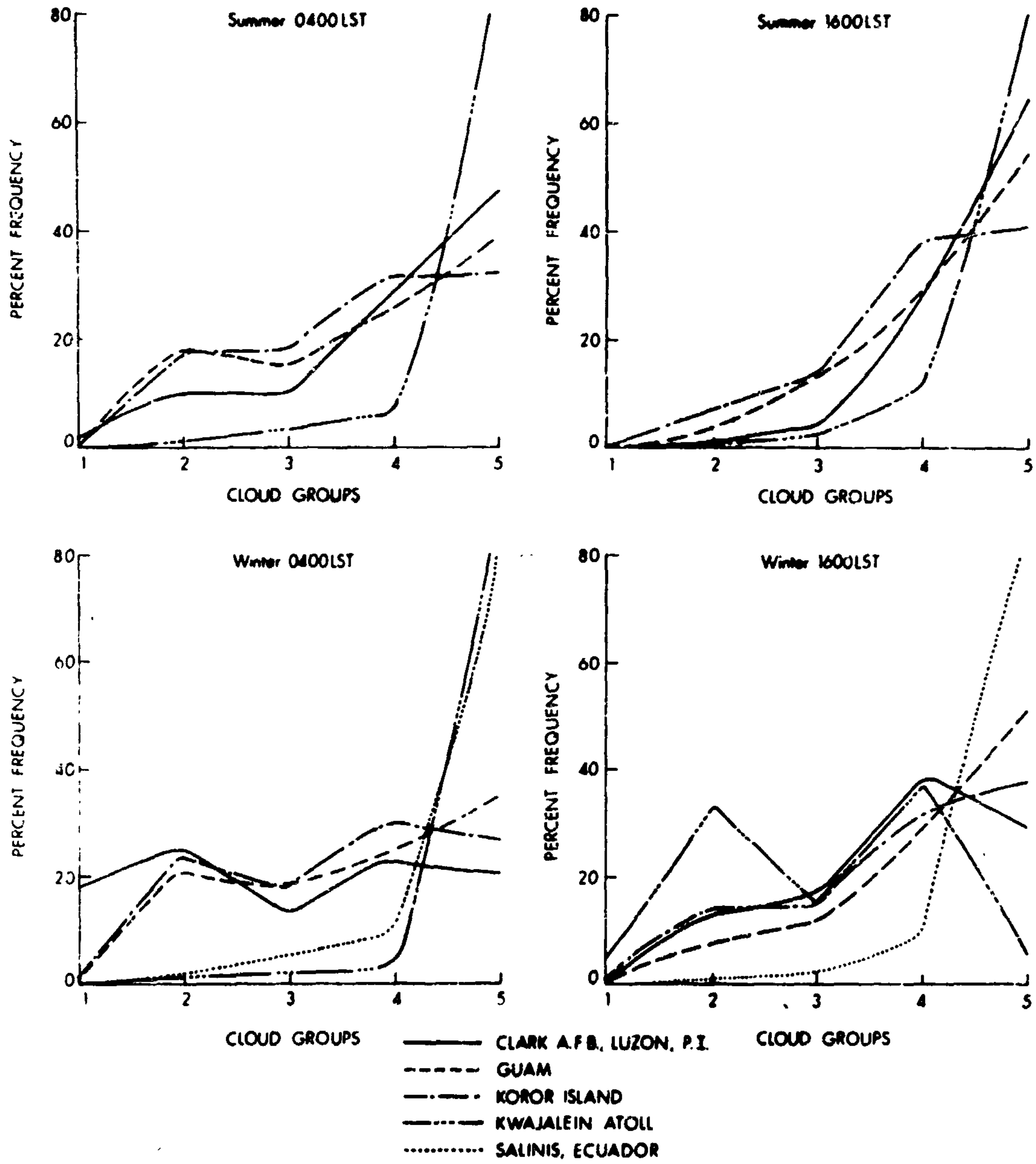


**Figure A-9 Cloud Cover Distributions Demonstrating Regional Homogeneity for Region 3**

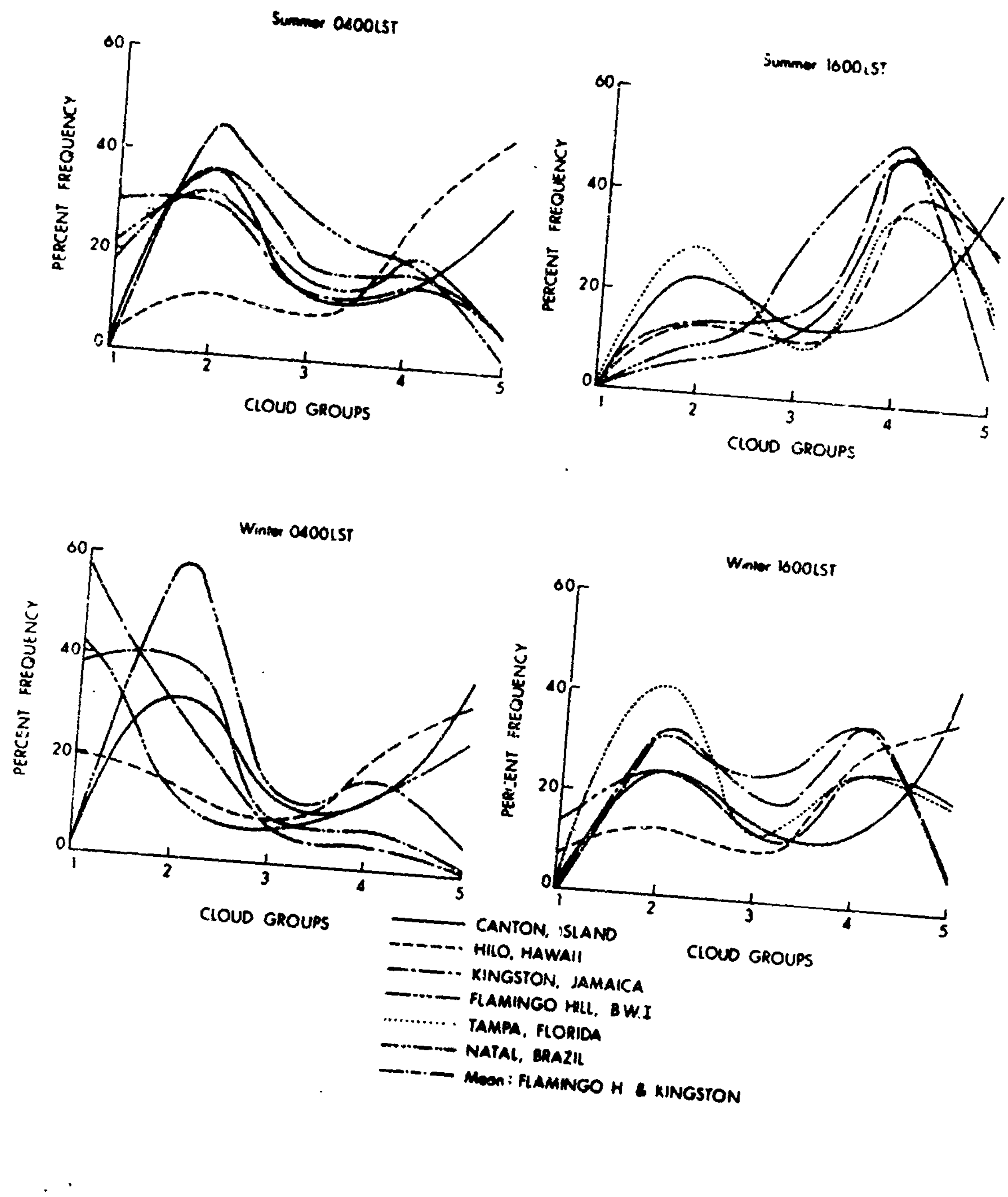


Figure A-10 Cloud Cover Distributions Demonstrating Regional Homogeneity for Region 4

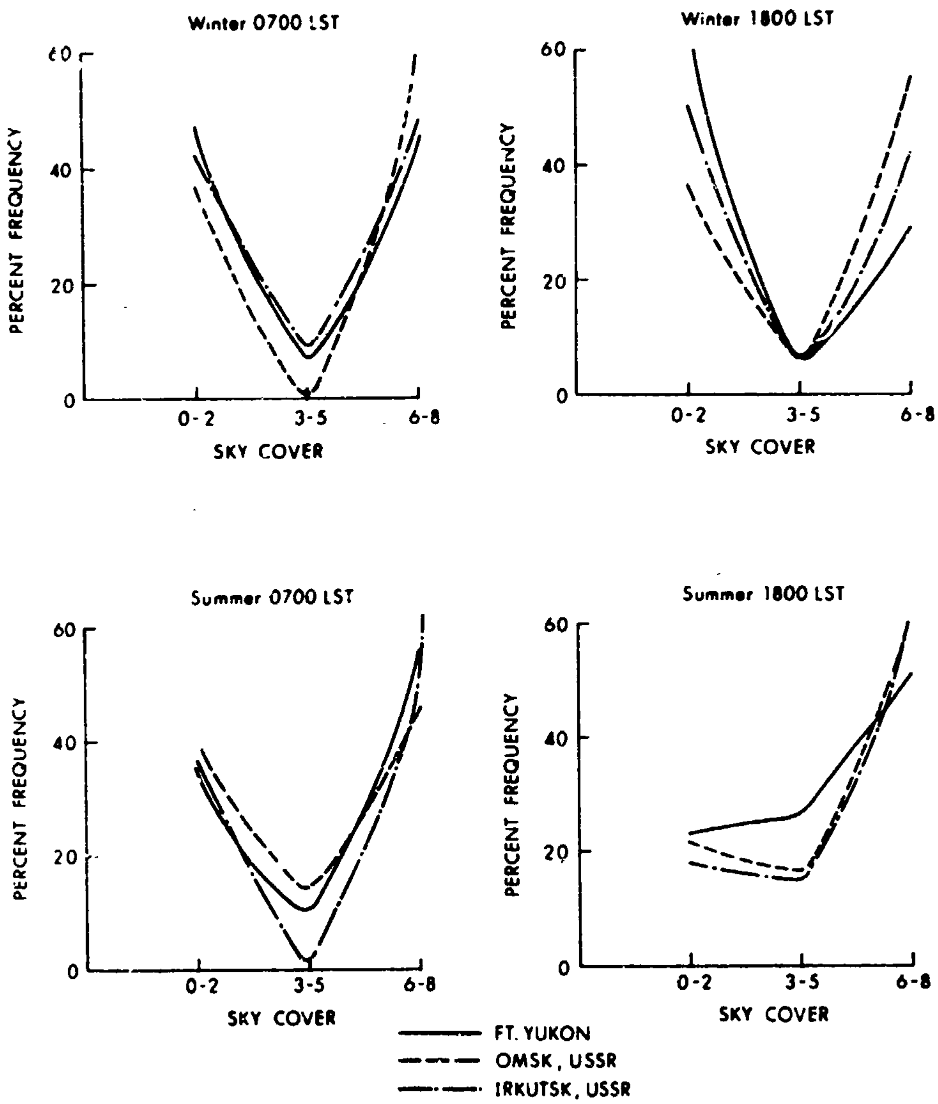


Figure A-11 Cloud Cover Distributions Demonstrating Regional Homogeneity for Region 9

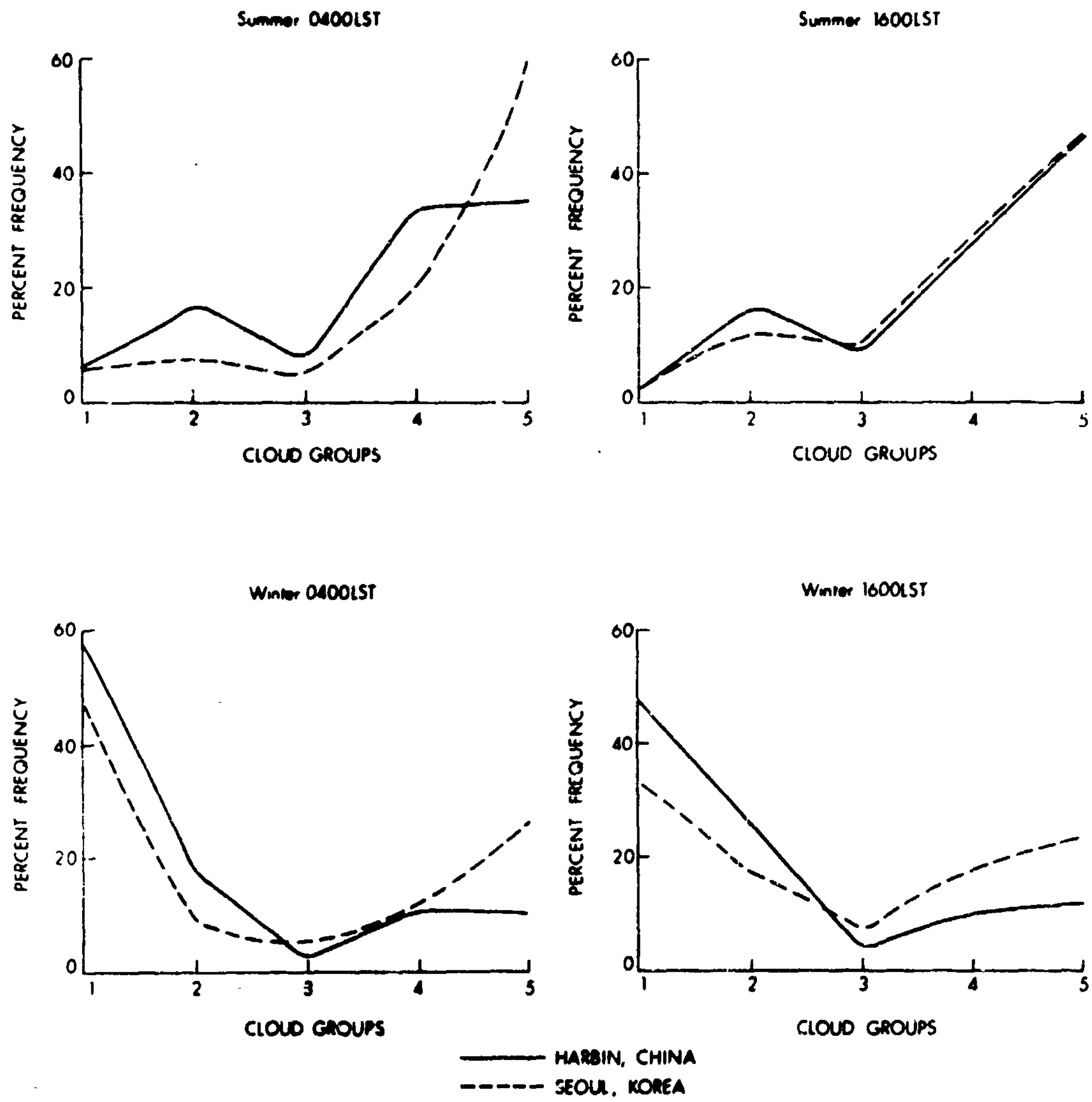


Figure A-12 Cloud Cover Distributions Demonstrating Regional Homogeneity for Region 10

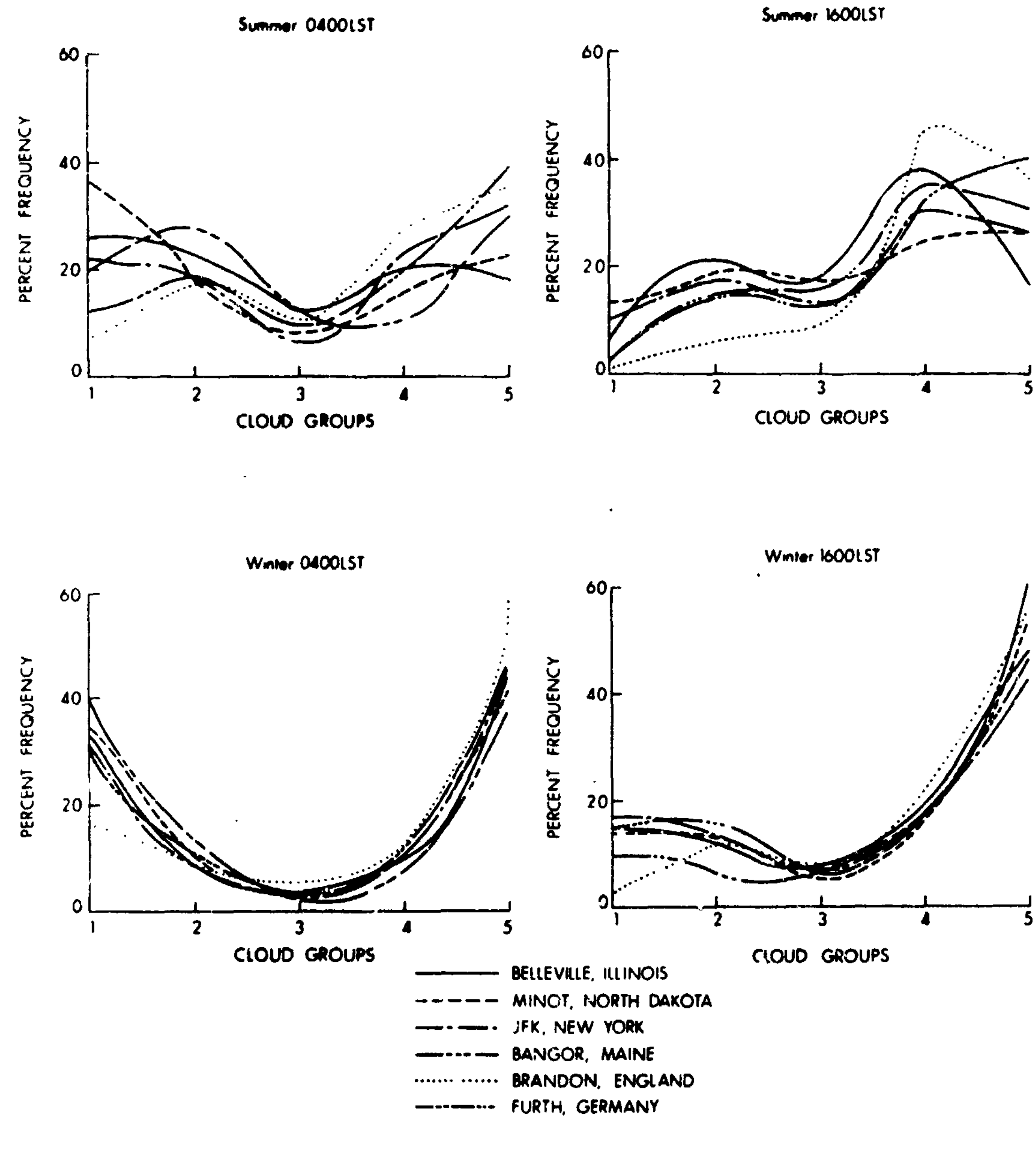


Figure A-13 Cloud Cover Distributions Demonstrating Regional Homogeneity for Region 11

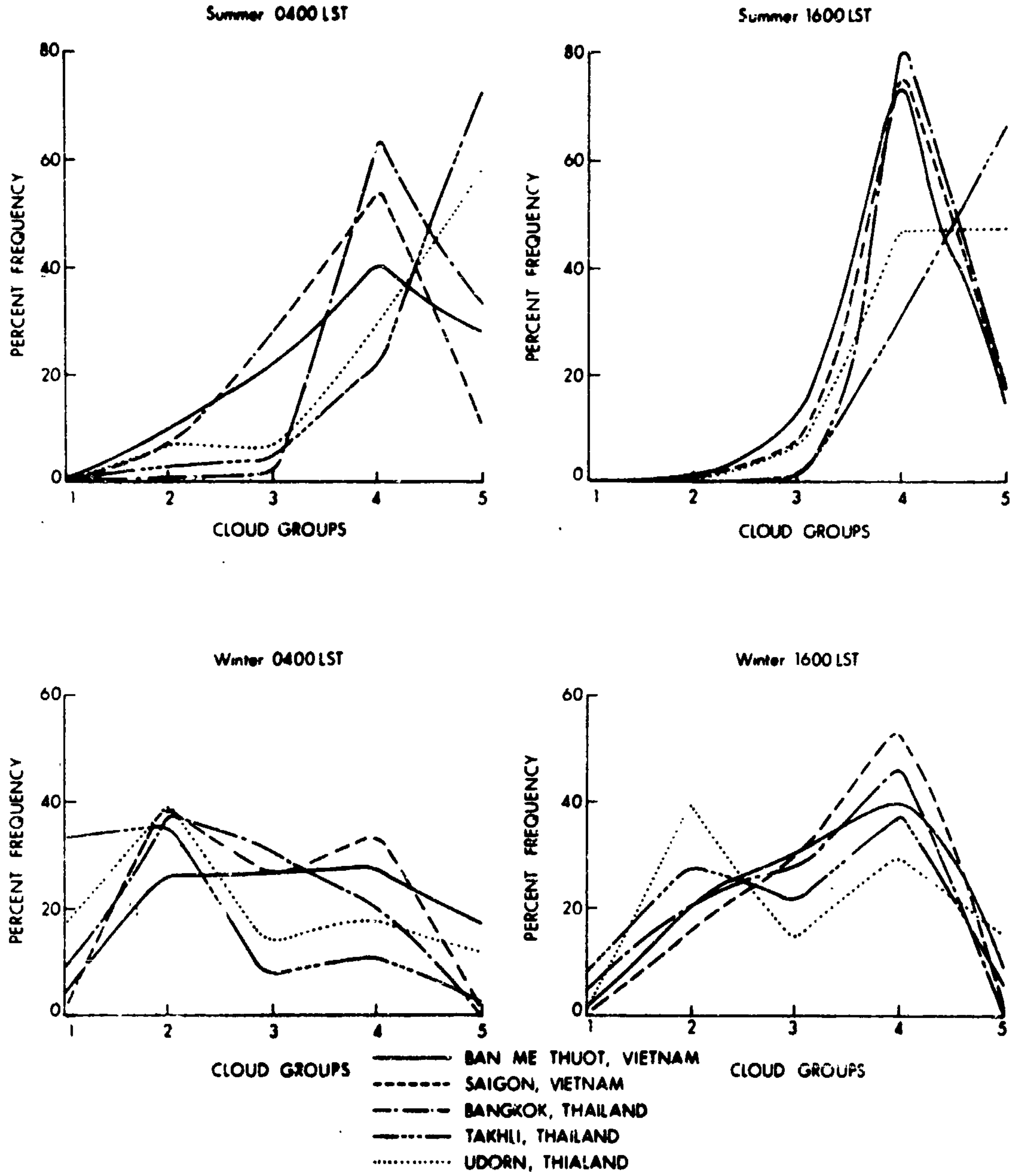


Figure A-14 Cloud Cover Distributions Demonstrating Regional Homogeneity for Region 12

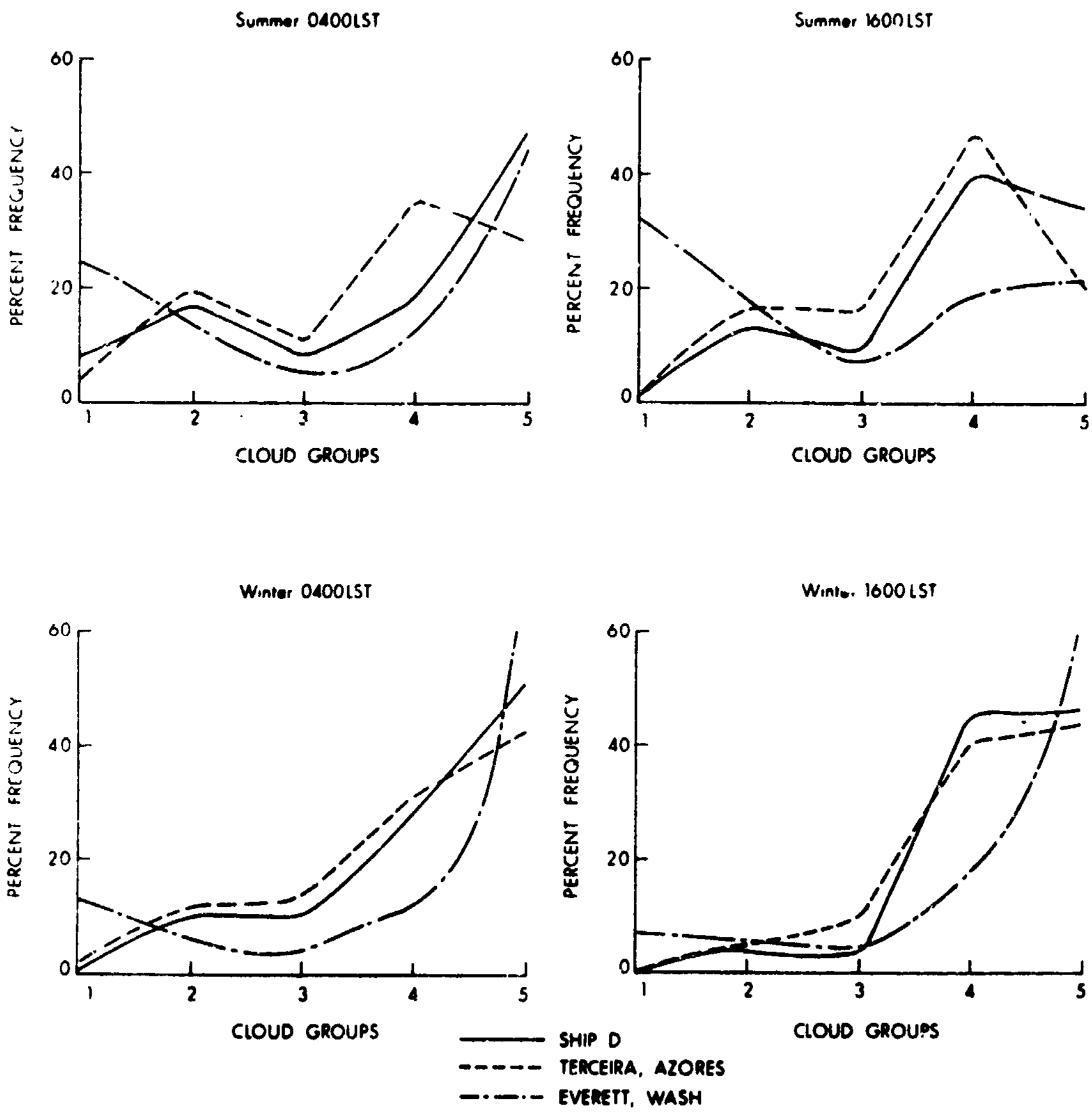


**Figure A-15 Cloud Cover Distributions Demonstrating Regional Homogeneity for Region 13**

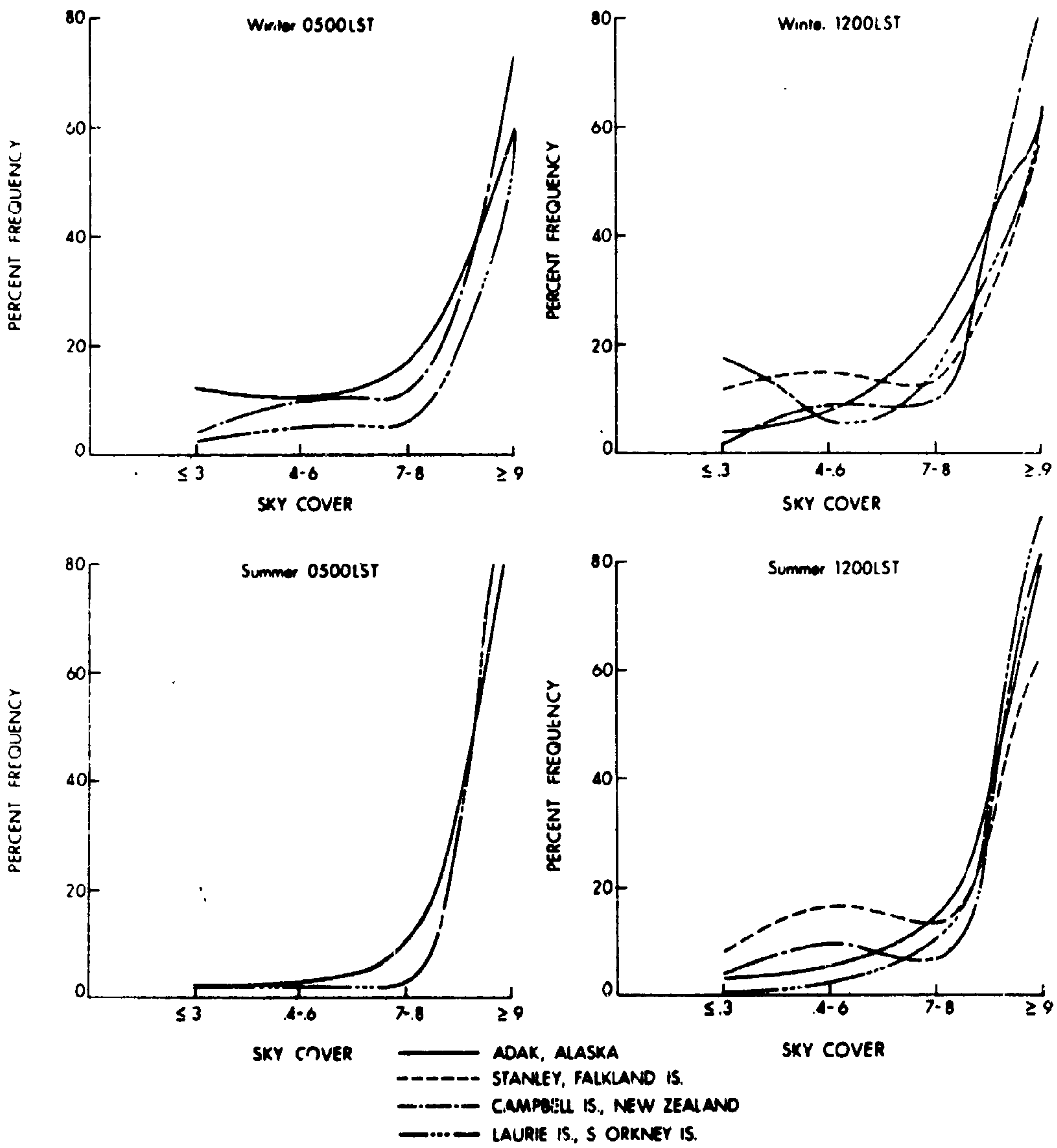


Figure A-16 Cloud Cover Distributions Demonstrating Regional Homogeneity for Regions 14 and 23

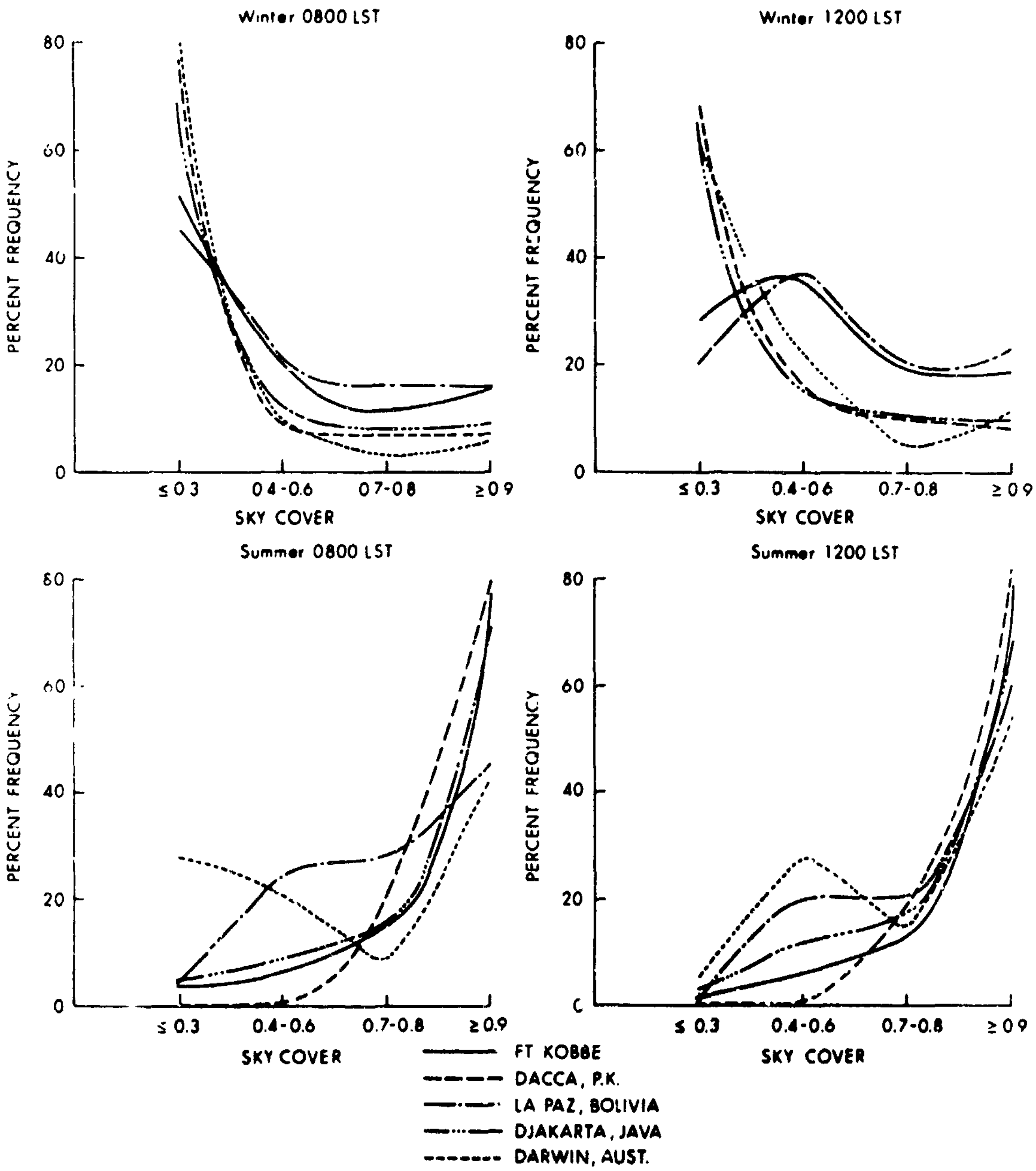


Figure A-17 Cloud Cover Distributions Demonstrating Regional Homogeneity for Regions 16 and 25

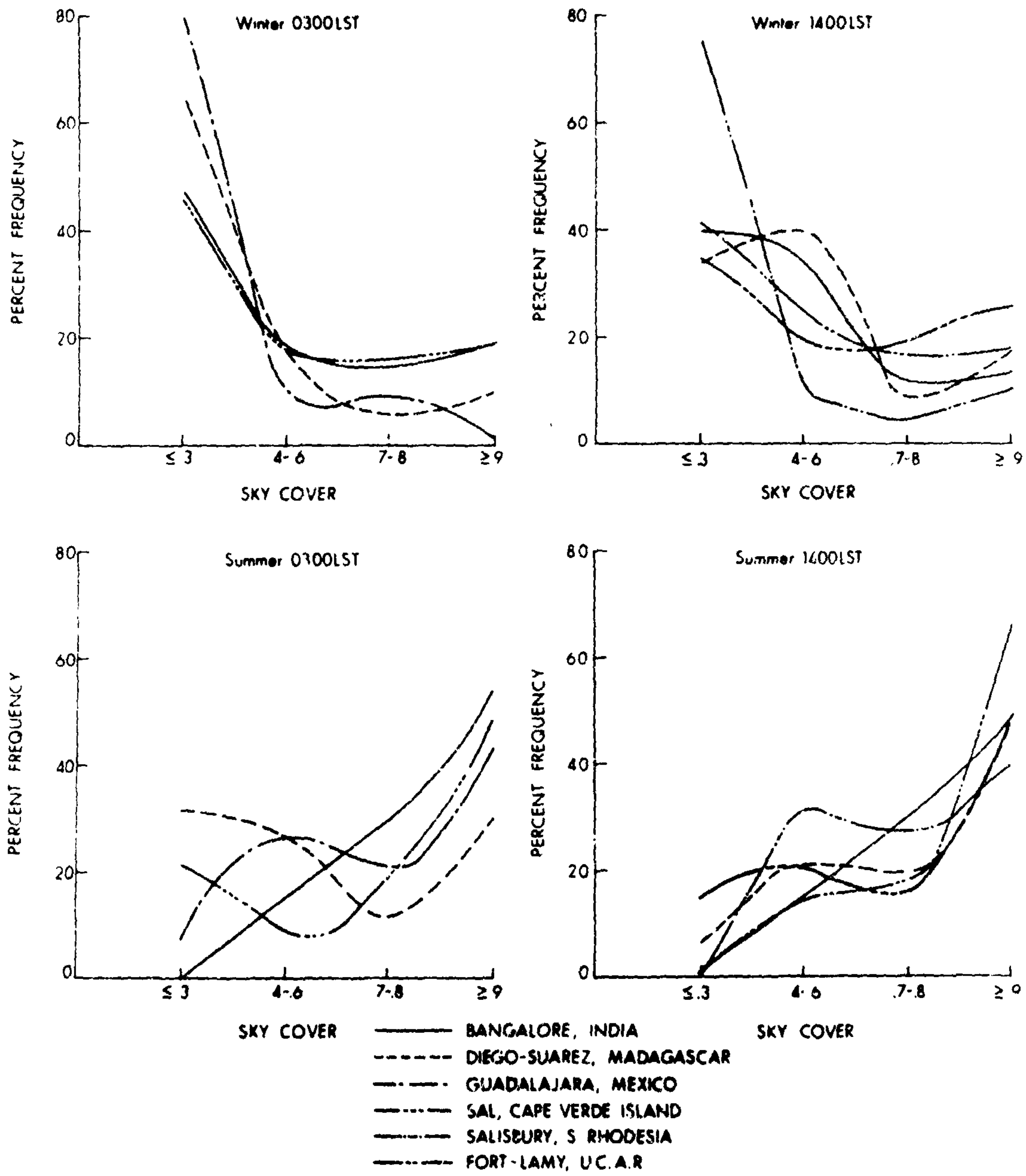


Figure A-18 Cloud Cover Distributions Demonstrating Regional Homogeneity for Regions 17 and 26

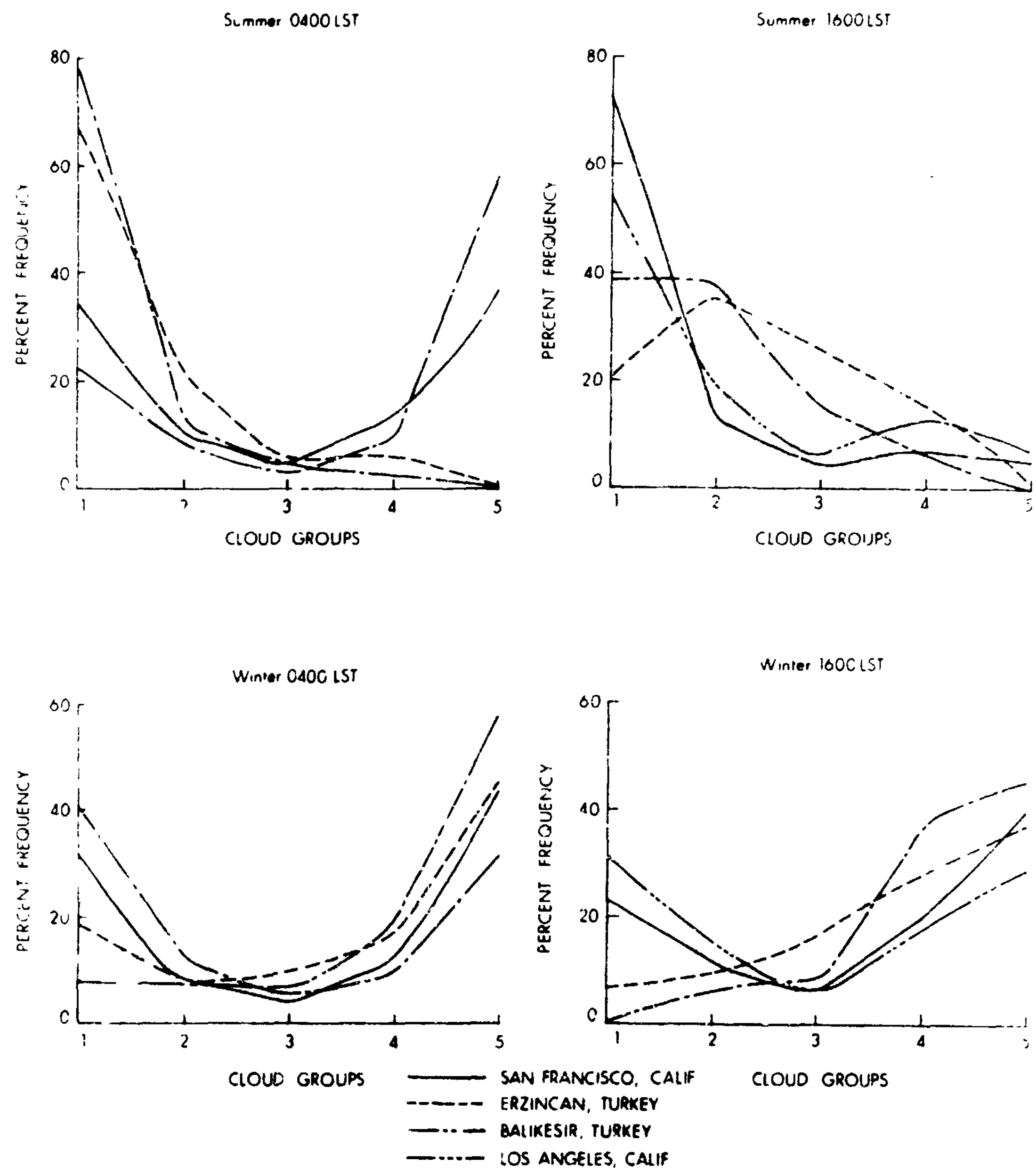


Figure A-19 Cloud Cover Distributions Demonstrating Regional Homogeneity for Region 18

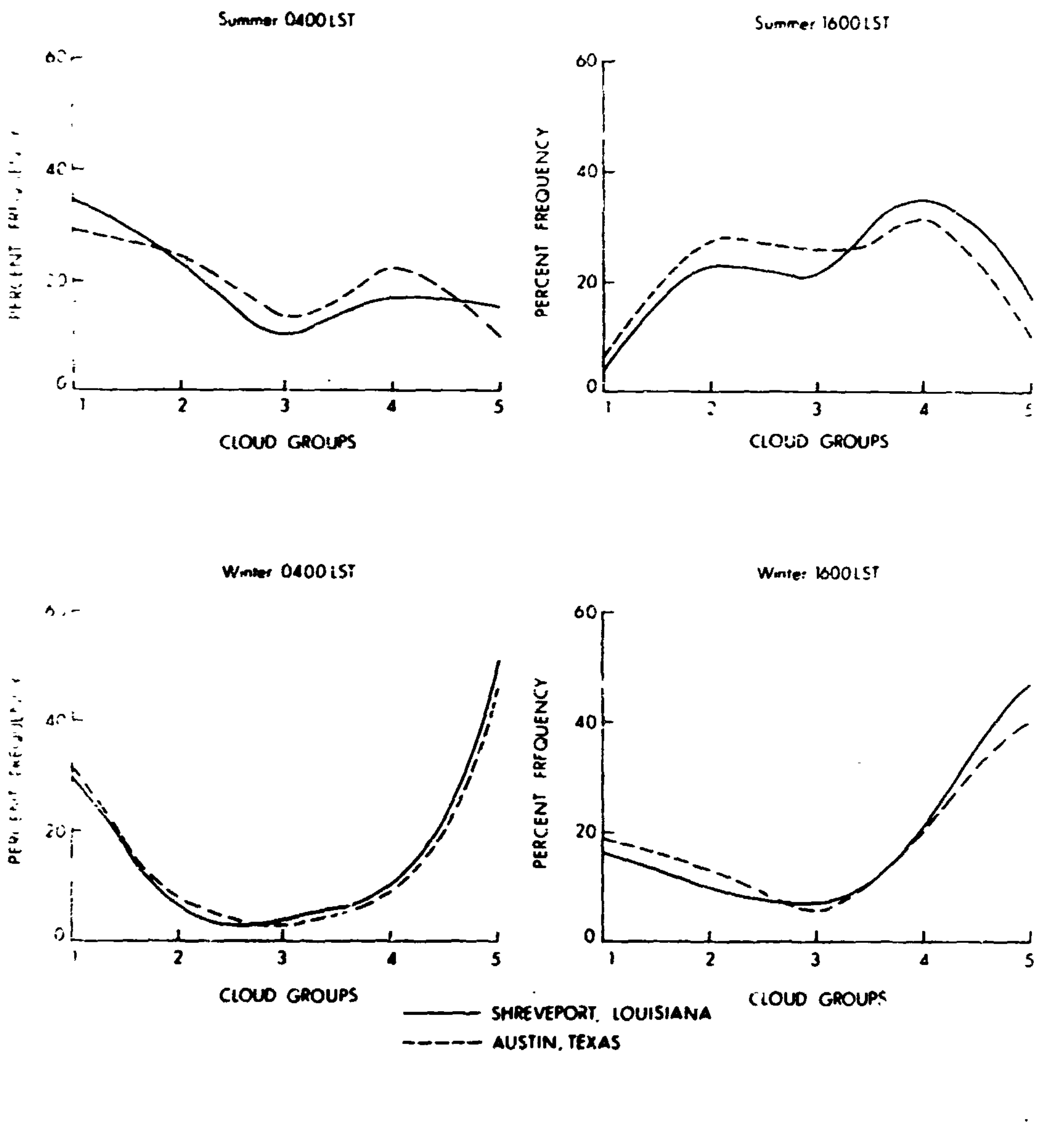


**Figure A-20 Cloud Cover Distributions Demonstrating Regional Homogeneity for Region 19**

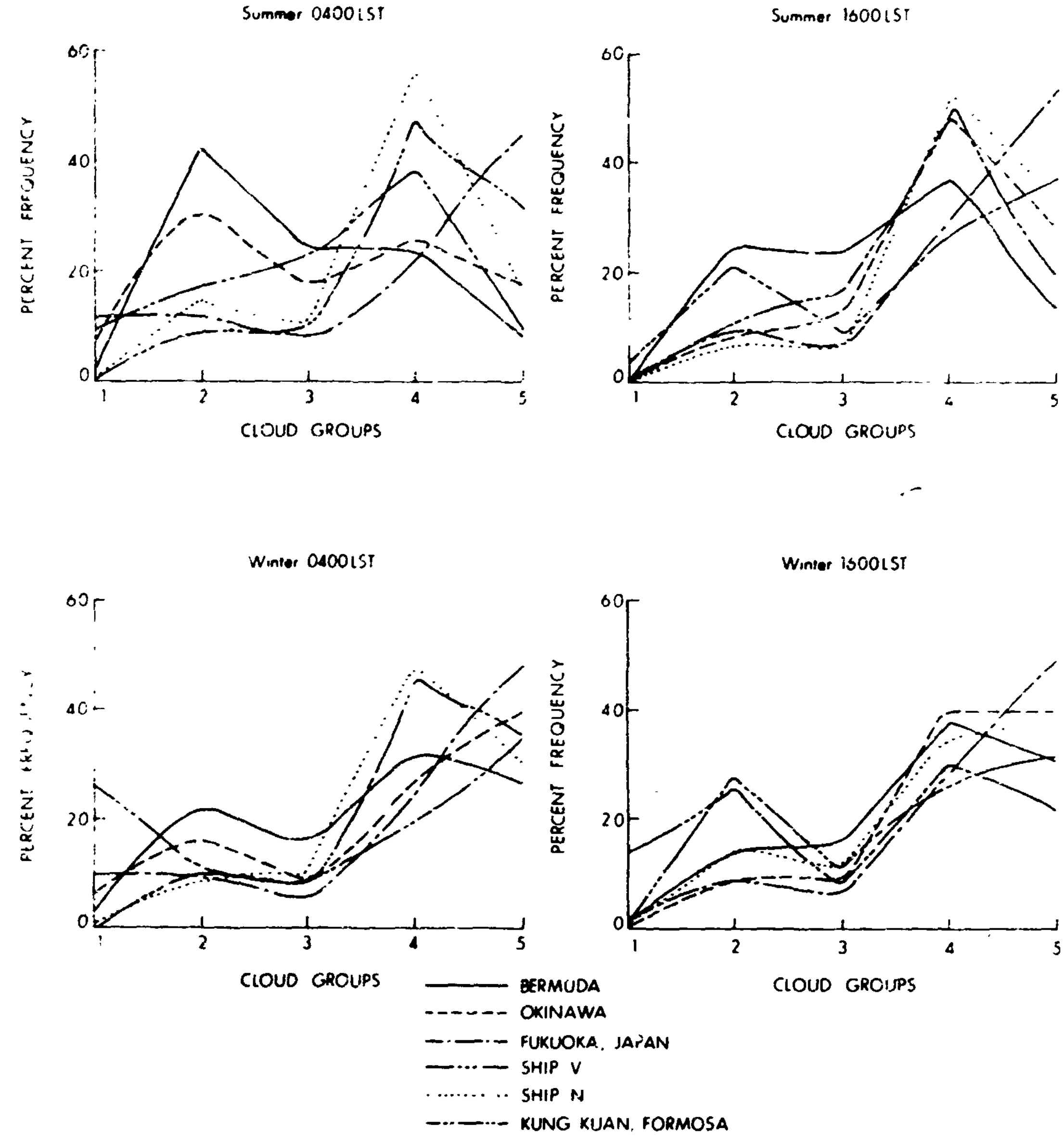


**Figure A-21 Cloud Cover Distributions Demonstrating Regional Homogeneity for Region 20**

considerably better than one might intuitively expect considering the large extent of the regions, their diversity and separation around the globe, and their separation into Northern and Southern Hemisphere (reversed) regions.

Figure A-10 shows the cloud distribution for Region 11, which covers the northeastern United States and North Central Europe. Distributions for six stations are shown, ranging in apparent climate from that of Minot, North Dakota, through Kennedy Airport at New York City, to Furth, Germany. The "prototype" we have chosen for the region is Scott AFB, at Belleville, Illinois. It can be seen that winter cloud cover is remarkably similar at all stations; summer cloud cover is more variable, particularly in the incidence of clear and overcast skies. However, the characters of the summer distributions are quite similar.

Figure A-7 shows distributions for Region 1, comprising desert areas. Dhahran is the "prototype." The data have been graphed in the only common form available. Distributions are so similar the year around that we did not reverse the seasons for Alice Springs, Australia, although a slight improvement in representativeness would have resulted from such a reversal.

## 2.5 Seasonal Reversal

In nine cases prototype data from the Northern Hemisphere available in suitable form were used to define the cloud climatologies of Southern Hemisphere regions where suitable data were not available. The remaining eleven regions either occur in only one hemisphere or occur in both hemispheres without need of seasonal transposition. We have verified the validity of the seasonal procedure in three of the cases. These are shown in Figures A-16 to A-18. Note, for example, (Fig. A-16) the comparison of the cloud cover distribution of Adak, in the Aleutians, with those of Campbell Island, south of New Zealand, and Laurie Island, in the South Orkneys east of the tip of South America. Daytime observations were also available from Stanley in the Falkland Islands. It can be seen, with the possible exception of Laurie Island and Stanley in the winter (which are exposed to Antarctic Polar outbreaks), the agreement is excellent.

## 2.6 Special Tabulations

For two of the regions (13 and 20) no oceanic data could be obtained from standard summaries. In addition it was desirable to check the validity of using certain other land stations (or island stations) to represent certain mostly maritime regions. Since no data tabulations in form suitable for obtaining cloud cover distributions were available, the raw data were obtained and tabulated for the ocean ships. Ten years of data for six ocean vessels (as shown in Table A-3) were obtained, and special tabulations prepared, to obtain frequency distributions of our five cloud cover groups. These frequency distributions were obtained for the eight times of day in a similar manner to the other tabulated data (see data for regions 13 and 20 in Appendix C), so that the diurnal variation could be represented. In addition, temporal conditional statistics were obtained for six hourly periods running from six hours to 48 hours. The results of these temporal conditional distributions will be discussed in Section 3 below.

Data from two of these weather ships has been selected to represent regions 13 and 20. In addition, a comparison was made for: (1) Ship C, Ship M, and Adak (the prototype data) for Region 14 (see Fig. A-22 for a summer and winter sample at 0400 and 1400 local time); (2) Ship D and other stations in Region 13 (see Fig. A-15); and (3) Ships N and V with four other stations in Region 20 (see Fig. A-21). In Region 14 (Fig. A-22), note the extremely good agreement of all samples (stations) in cloud groups 1 and 2, and the near zero probability of clear skies.

## 2.7 Synthetic Data

There is no station from which to get data for Region 7. Thus a synthetic set of statistics for this region had to be generated. These synthetic data were prepared using data from adjacent regions modified by using the known special climatology of Region 7 (see also Table 3-1 of the final report). This modification highlights the large diurnal variations in cloud amount and the persistent occurrence of stratiform type cloud in the summer period.

Region 6, which includes Peru and other parts of South America, had no reliable observations in the middle of the night (2200 and 0100 hours local time). Thus synthetic data was generated for these two hourly periods based on good meteorological judgment and the diurnal variations inherent in this climatic region.

Table A-3

Location of Ocean Ships for Which Special Data Tabulations Were Made

| Ocean Ship | Latitude-Longitude | Climatological Regions |
|---|---|---|
| C | 52.8N - 35.5W | 14 |
| D | 44N - 41W | 13 |
| K | 45N - 16W | 13 |
| M | 66N - 2E | 14 |
| N | 30N - 140W | 20 |
| V | 31N - 164E | 20 |

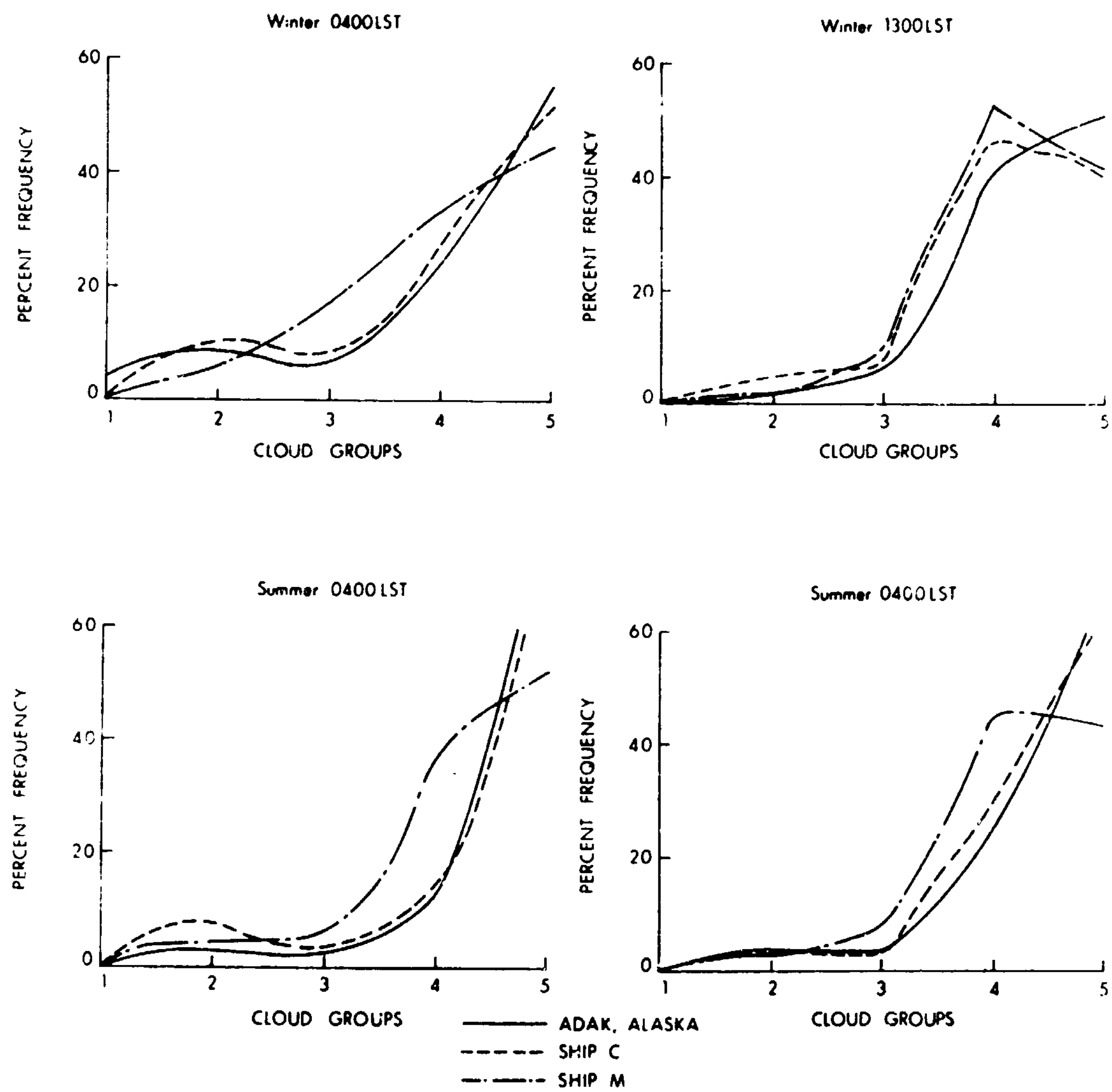


Figure A-22 Maritime Cloud Cover Distributions Demonstrating Regional Homogeneity for Region 14

Region 25 required that hours 1000, 1300 and 1600 local time for the months of May through September be modified to account for known cloud climatological variations which were not direct seasonal reversals of Region 16. Thus in this region, synthetic data were generated for these hours and for these months.

Region 5 also required a modification in the mid-day hours for the period May to September. During other times of the day and seasons, the data closely resembled those for Region 18.

In Regions 10, 17 and 26, NIS Summaries had to be used, for which the frequency of clear and overcast were not uniquely specified. The frequencies of occurrence of the category 1 (clear) and category 5 (overcast) were generated from plots of the existing summarized data for each time of day. Data for the appropriate categories were then extrapolated from the plots.

## 3. CONDITIONAL DISTRIBUTIONS

It is important for simulation purposes to know the probability of occurrence of an event at some later time or at some short distance from an initial point. Such spatial and temporal conditional distributions cannot be derived from existing summaries. Therefore, raw data for each of the stations representing the 29 regions must be obtained. The use of raw conventional data from various parts of the world to generate these distributions would involve an effort which was prohibitive. Therefore, satellite observations for short periods of time were obtained for most of the climatological regions; statistics for the remaining regions were modified from the statistics computed directly for the regions with data. A second reason for using satellite data to estimate the conditional distributions was that data sufficient to describe tropical regions were already available.

Conditional probability distributions with regard to time and space were derived for each climatological region. From the statistics with regard to time, the probable cloud amount frequency distribution for tomorrow can be determined for a given cloud amount today. Similarly, from the statistics with regard to distance, the probable cloud amount frequency distribution for a location at a specified distance from a base location can be determined for a given cloud amount at the base location.

3.1 Data

For tropical areas, between about 30°N and 30°S, little data extraction was necessary, as use could be made of data on hand from previous studies. From a study of the cloud obscuration of terrestrial landmarks to be used in the Apollo Navigation System, Barnes et al (1967), daily satellite observed cloud amounts were available for 100 landmarks (stations) in the tropics. Although these stations were not evenly distributed, observations were available for most climatological regions. The cloud amounts in this data sample were extracted from within circular areas of one degree latitude diameter.

The statistics derived from a satellite data sample collected by Sadler (1966) were strongly biased toward middle cloud amounts (3, 4, 5 octas), and therefore, were not used. These results emphasized the magnitude of the sampling area size problem, discussed in detail in Section 7 of the Final Report.

In extratropical areas, cloud amounts were extracted for several locations (stations) within each major climatological region. The statistics for some regions, particularly those of smaller size, were modified from the results for other regions. The stations for which data were extracted, generally five to ten for each region, were oriented in an east-west direction, providing uniform distributions for the computations with regard to distance. As in tropical regions, the cloud amounts were for one degree circular areas.

Summer and winter (Northern Hemisphere) data samples were obtained. The summer sample, obtained from Nimbus II AVCS photography, consisted of all available observations during June, July, and August 1966, the period of operation of this satellite. The winter sample consisted of observations taken during December, January, and February, 1966-67, by the ESSA-3 satellite. A limited data sample was also obtained from the ESSA-5 satellite, for June, July, and August 1967.

Although the nominal camera resolution of the Nimbus AVCS photography is 0.5 miles, compared with two miles for the ESSA satellites, the improved picture quality of the ESSA photography provides comparable data. The summer 1967 sample from ESSA-5 provided an opportunity for a limited comparison with the Nimbus data for a similar period in 1966.

## 3.2 Temporal Conditionals

Computations for temporal conditional distributions were carried out for time periods of 24 and 48 hours. Only three months of record for each of two seasons were available; thus, observations from several stations within the same climatological region were combined to provide a more meaningful data sample. In most regions, from five to seven stations were used. In addition, probabilities were computed on a seasonal rather than monthly basis, to further increase the sample size. Even so, samples were materially smaller than desirable.

The results indicated little conditionality past 24 hours, so only the 24 hour probabilities were included in the final statistics (see Section 3.2.1 below). Methods were developed for computing temporal conditional statistics in other increments of time (see Section 6 of the Final Report).

For regions 13 and 20, temporal conditional distributions were compiled from raw ocean ship observation data during processing of these data for unconditional distributions. It is reassuring to find that these compilations are similar in kind to those obtained from much shorter samples of satellite data.

### 3.2.1 Decay of Temporal Conditionals with Time

For all but 2 of the 20 basic regions, temporal conditional data were computed from sun-synchronous satellite observations, and thus represented observations taken at 24 hour intervals. For these data, it was found that there was little conditionality beyond 24 hours. Examples for Regions 11 and 9 are shown for winter and summer in Figure A-23.

For two regions (13 and 20) we were able to compute temporal conditional distributions for each 6 hour interval from 0 to 48 hours.

Figure A-24 presents winter and summer distributions of the diagonal values of the conditional matrix for Ship D (Region 13) and Ship V (Region 20). Both of these ships, like most weather stations, lie in a region of rapidly moving weather systems where clear skies are rare. Broken clouds and overcast are about equally probable. It can be seen that the straight line approximation to $P(5|5)$ results in a fairly substantial overestimate of persistence in the winter season. In the summer season, however, the straight line assumption to $P(5|5)$ is a reasonable approximation. Even poorer approximations are provided for $P(2|2)$ and $P(3|3)$, which becomes essentially antipersistent after six hours.

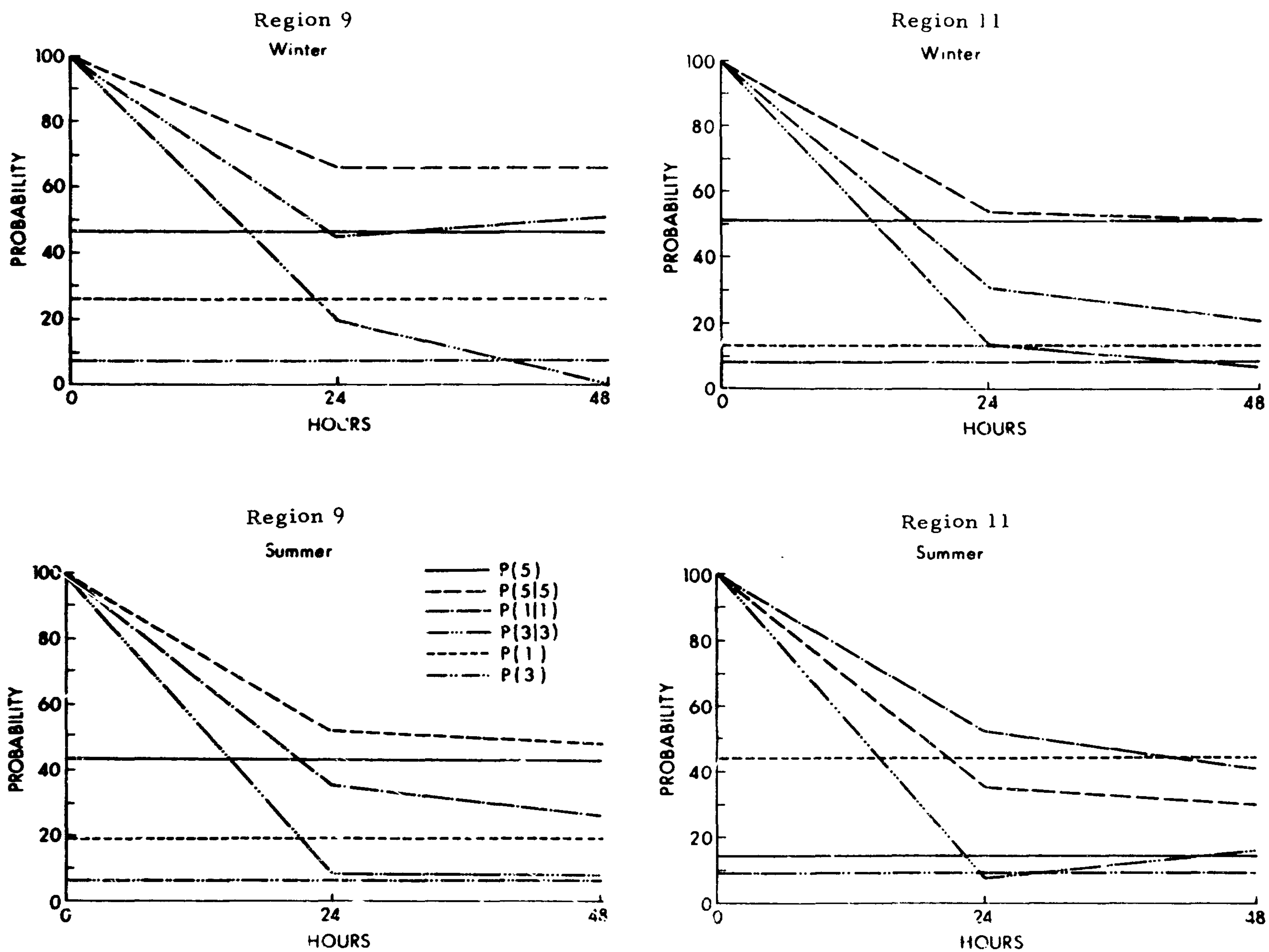


Figure A-23 Comparison of Decay of Temporal Conditionals with Time for Regions 9 and 11

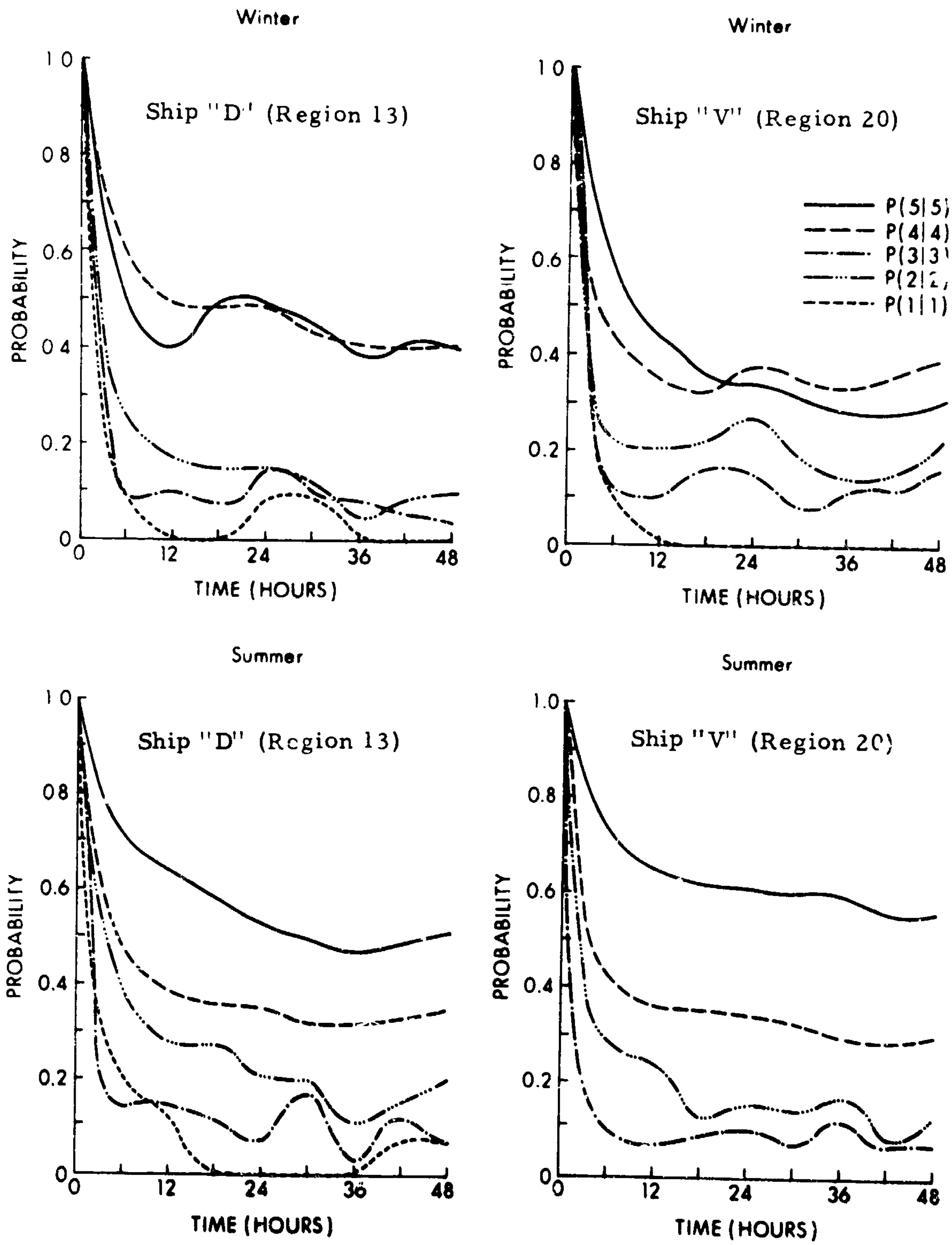


Figure A-24 Comparison of Decay of Temporal Conditionals with Time for Regions 13 and 20

### 3.3 Spatial Conditionals

In each region studied, a "base station" (a fixed location) was selected to become the "given" for each of the other stations in the group. In the tropical data sample the stations were not evenly distributed. The stations selected for the extratropical regions were evenly distributed in an east-west direction. In both samples, distances between stations varied from approximately 100 to 1,000 nm. As with the temporal distributions, seasonal compilations were made to increase the size of the data sample.

#### 3.3.1 Decay of Spatial Conditionals with Distance

Figure A-25 gives a schematic of the variation of conditional probability of clear skies (cloud group 1) as a function of distance from the given station. At zero distance the probability is zero for other given cloud groups, 100% for cloud group 1. As the distance between locations increases, the probability tends toward the unconditional probability of clear sky (P(1)). Some difficulty occurs in defining the conditional probability in situations where the areas over which the cloud cover is described overlap; however, most applications do not require information of this range.

The decay of the spatial conditionals with distance is shown in Figures A-26 to A-30 for Region 11, and in Figures A-31 to A-35 for Region 19. The figures presented in this form show the real data in a similar fashion to the hypothetical case shown in Figure A-25. In this form, the data should show convergence to the unconditional probability as indicated by the horizontal straight line on each of the figures.

These figures have been drawn to illustrate effects that are noted in the real data. When the distance between points somewhat exceeds the probable radius of clear areas in the region, the conditional probability P(1|1) may fall below the unconditional level to return at some later point. In a few cases, oscillations occur out to some distance, which may result from either insufficient data or from synoptic scale waves. Similarly, the conditional probabilities of clear skies in the vicinity of an area of scattered clouds may exceed the unconditional probability of clear. Some of the conditional relationships found are somewhat mystifying and can most easily be ascribed to chance variations resulting from data insufficiency (see

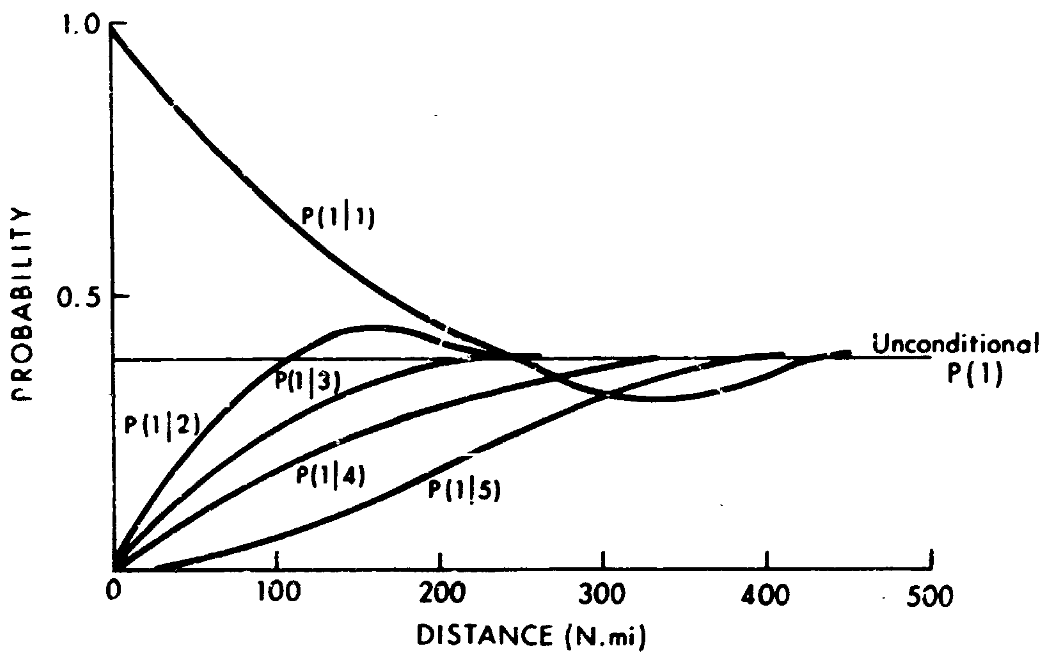


Figure A-25 Schematic of the Variation of Conditional Probability with Distance

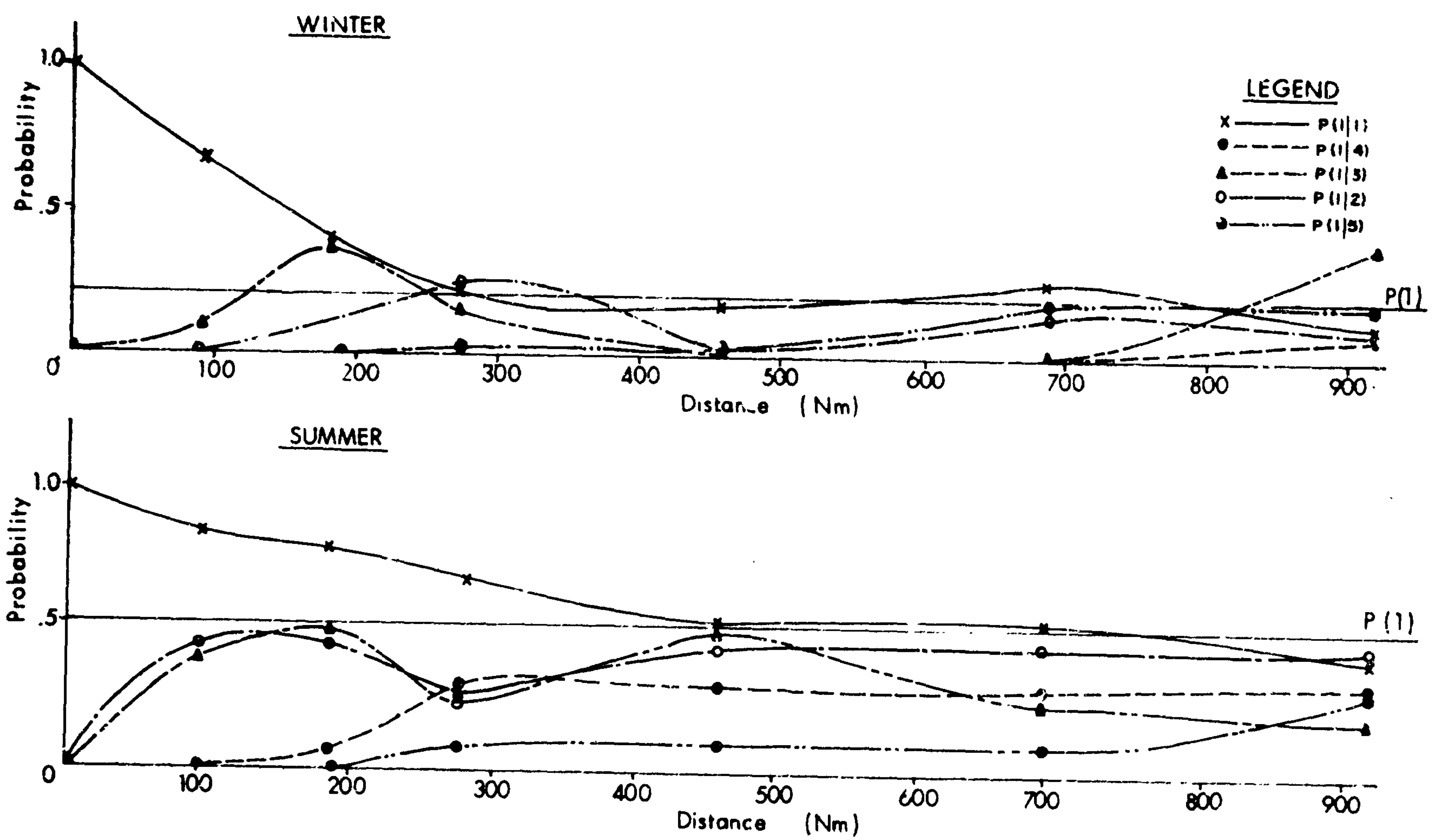


Figure A-26 Decay of Conditional Probabilities with Distance for Region 11

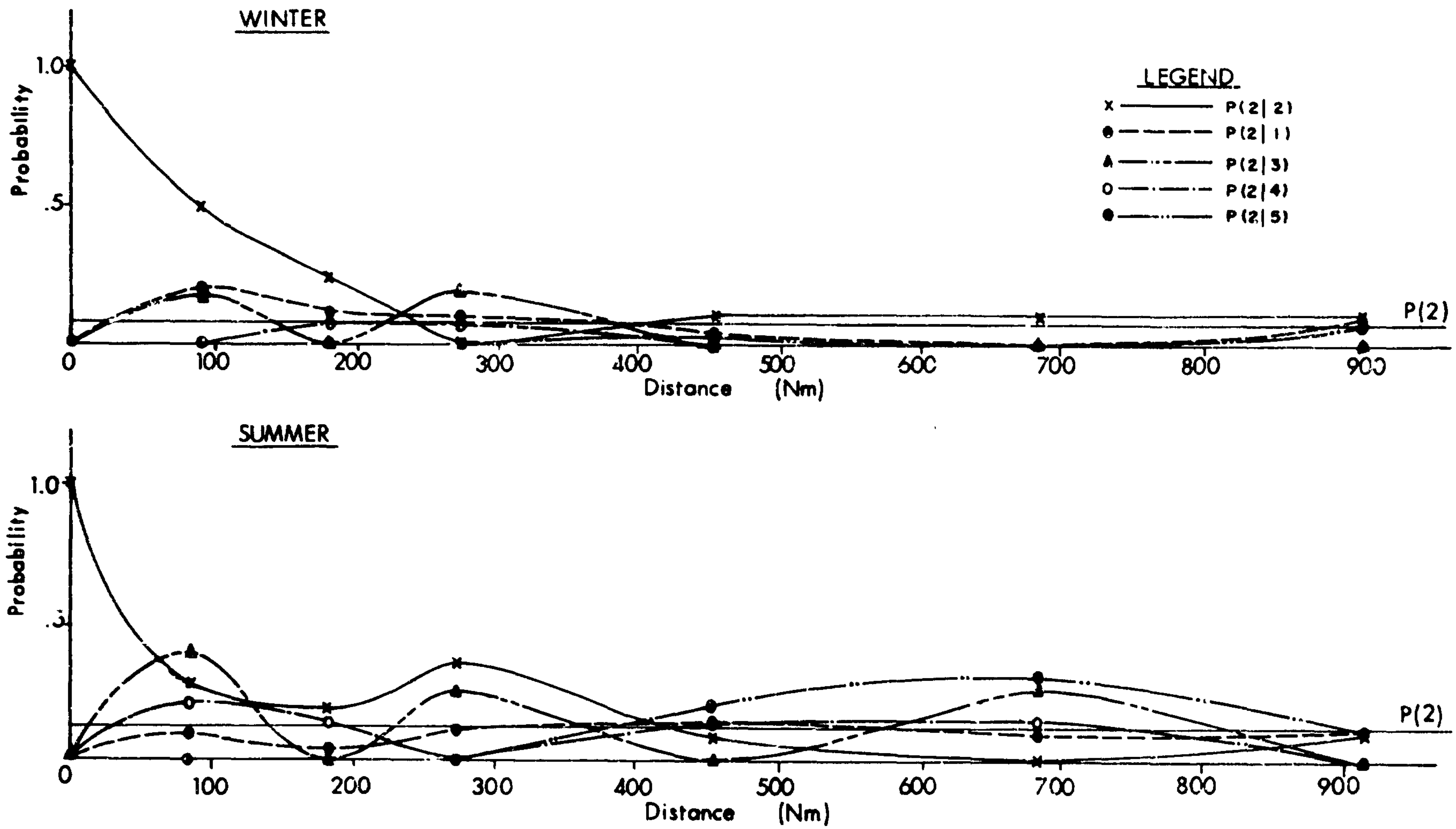


Figure A-27 Decay of Conditional Probabilities with Distance for Region II

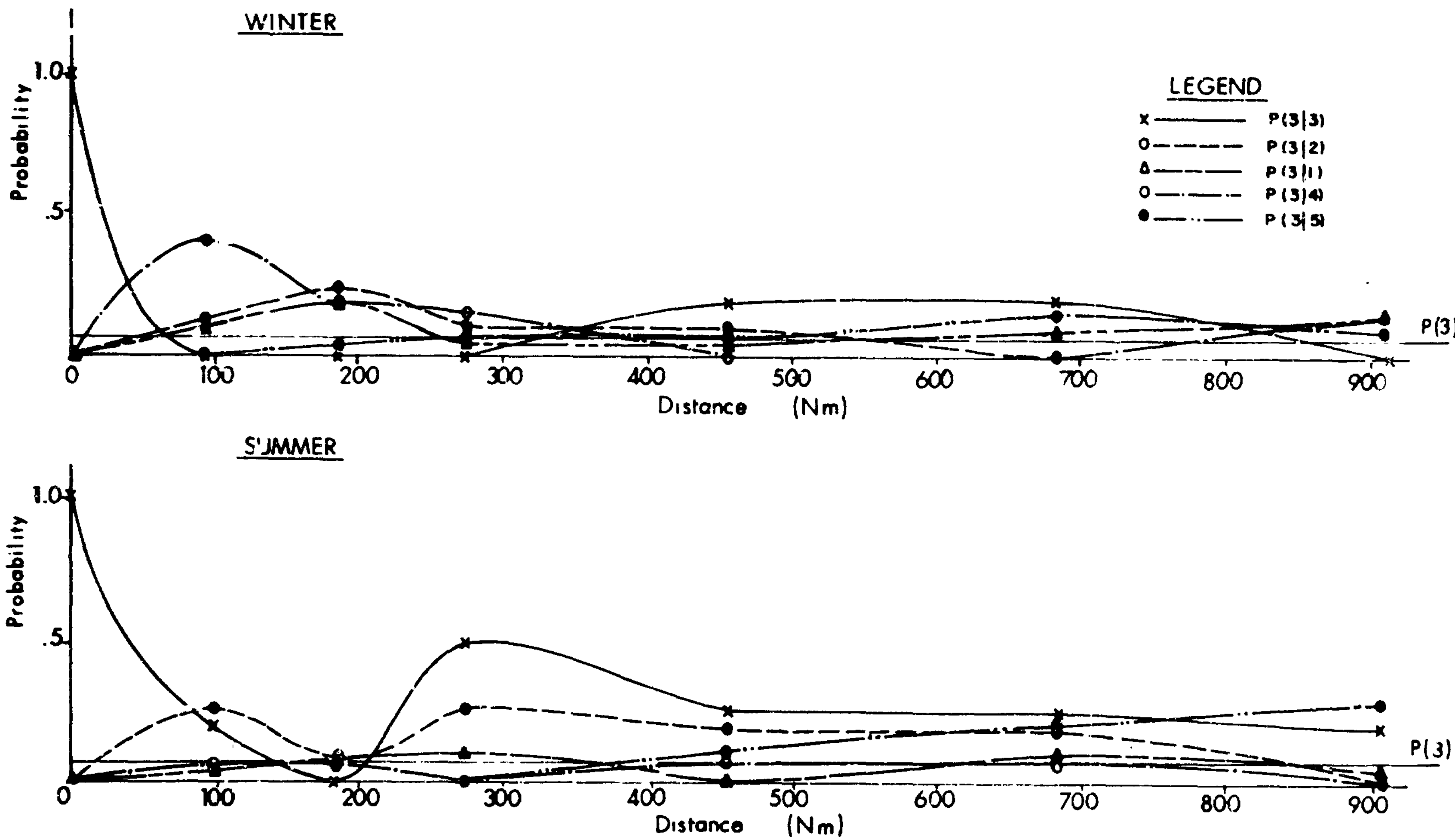


Figure A-28 Decay of Conditional Probabilities with Distance for Region 11

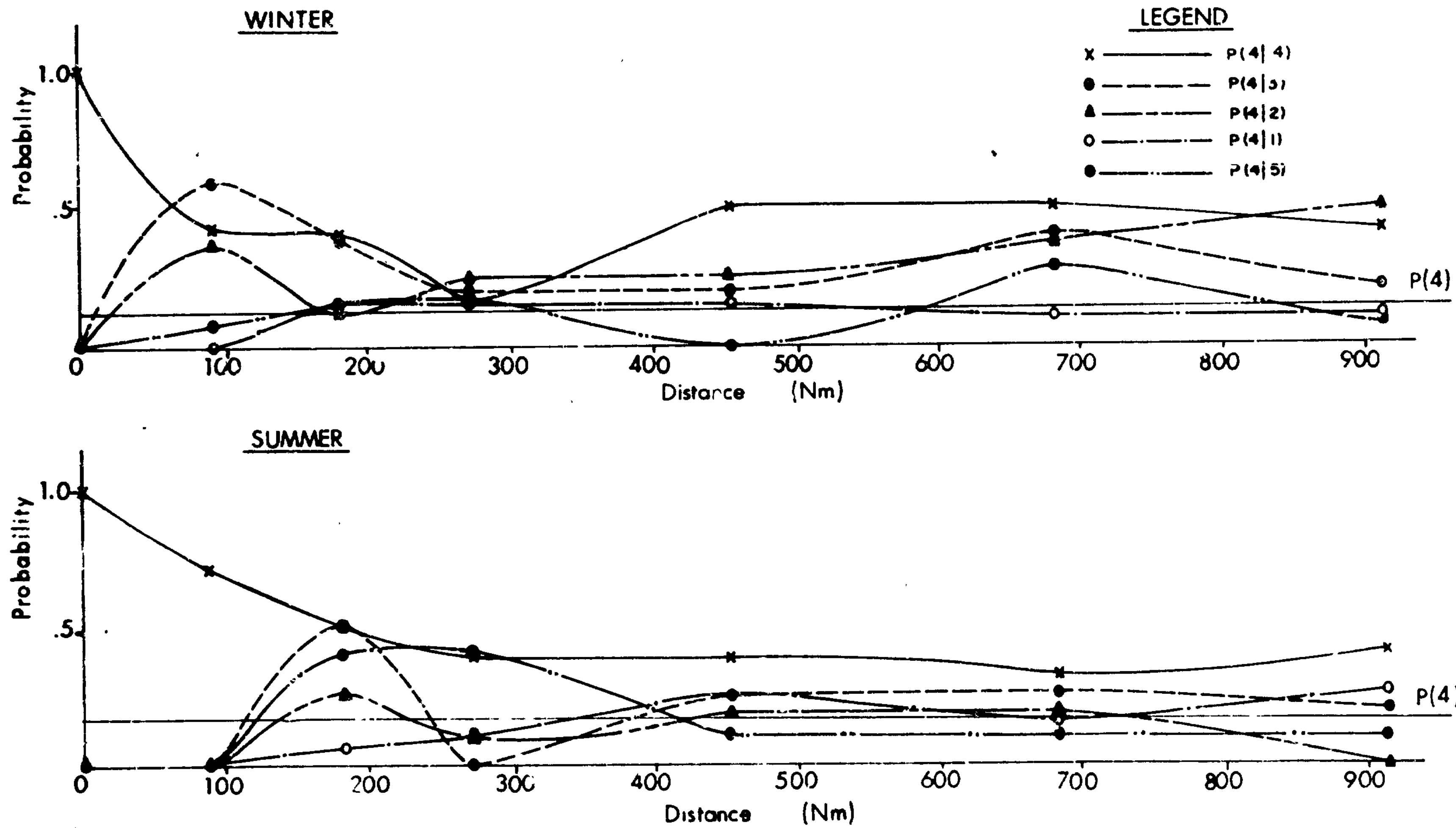


Figure A-29 Decay of Conditional Probabilities with Distance for Region 11

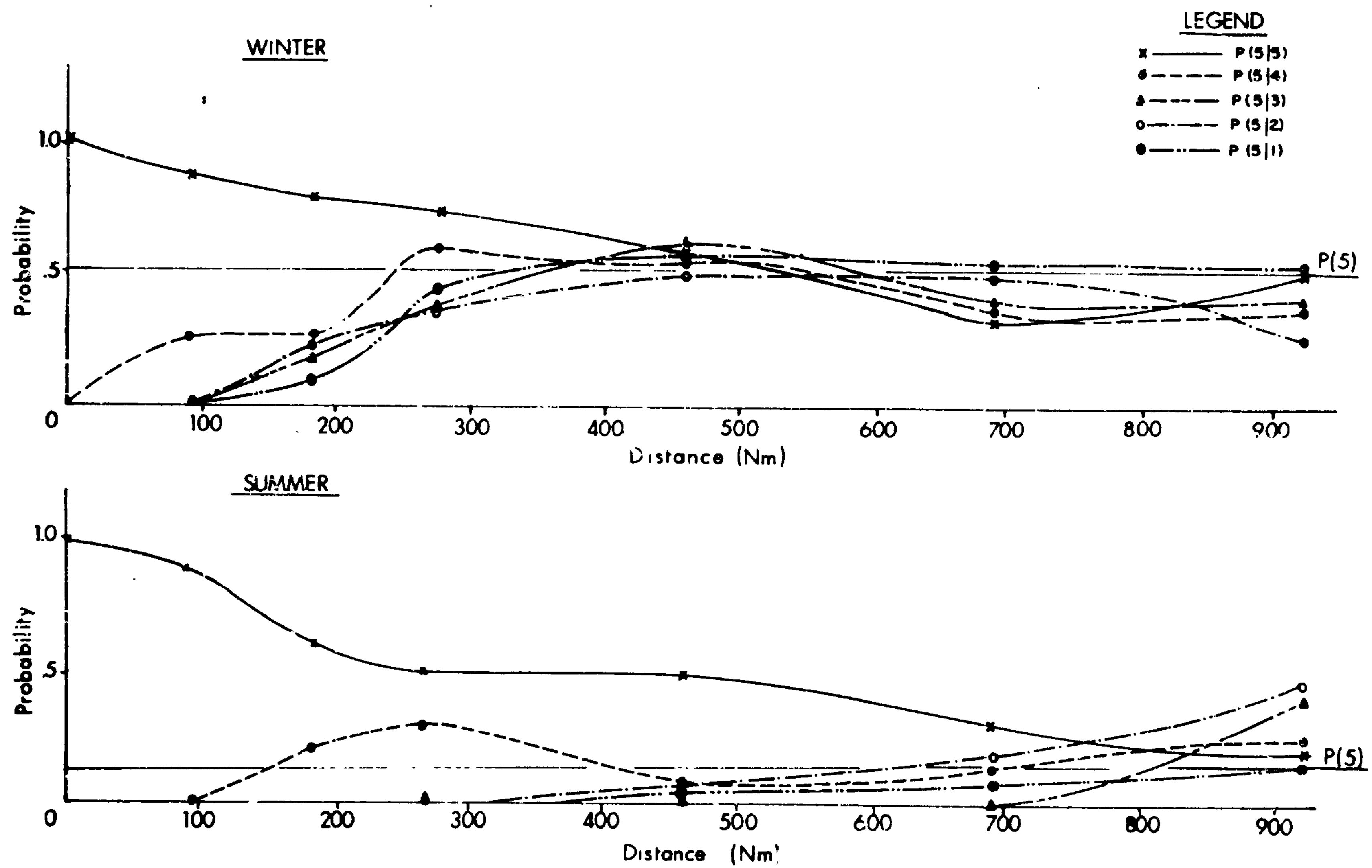


Figure A-30 Decay of Conditional Probabilities with Distance for Region 11

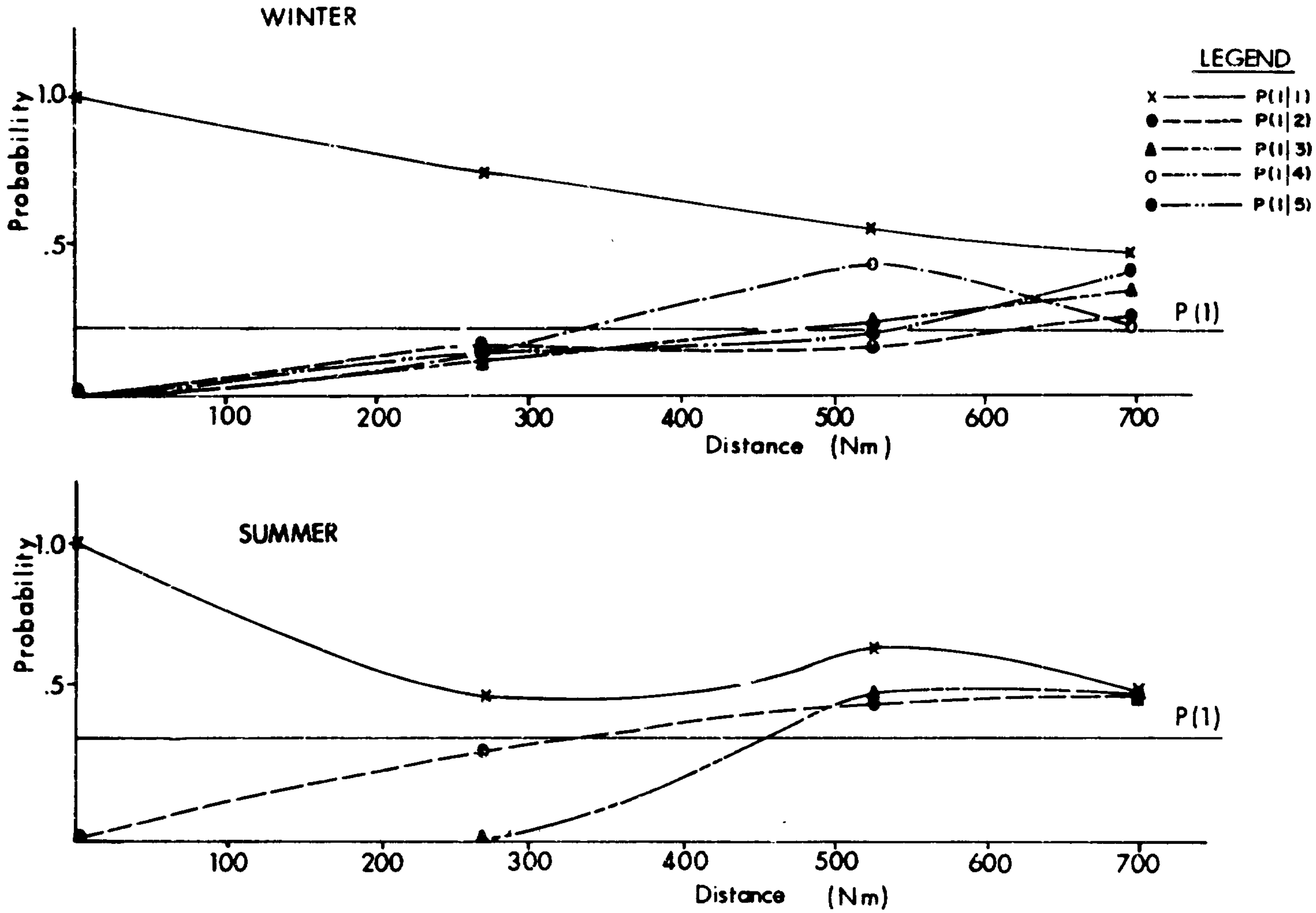


Figure A-31 Decay of Conditional Probabilities with Distance for Region 19

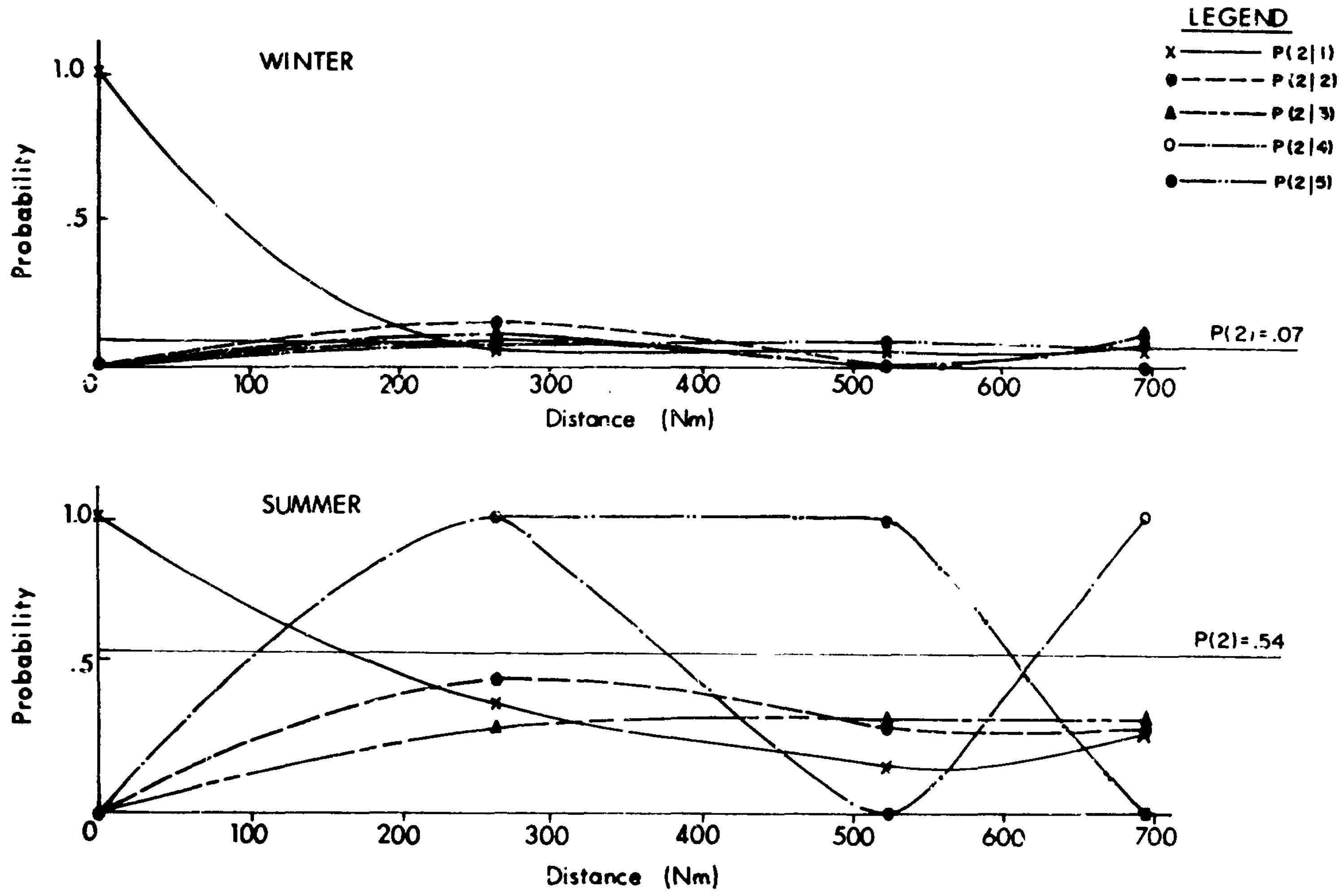


Figure A-32 Decay of Conditional Probabilities with Distance for Region 19

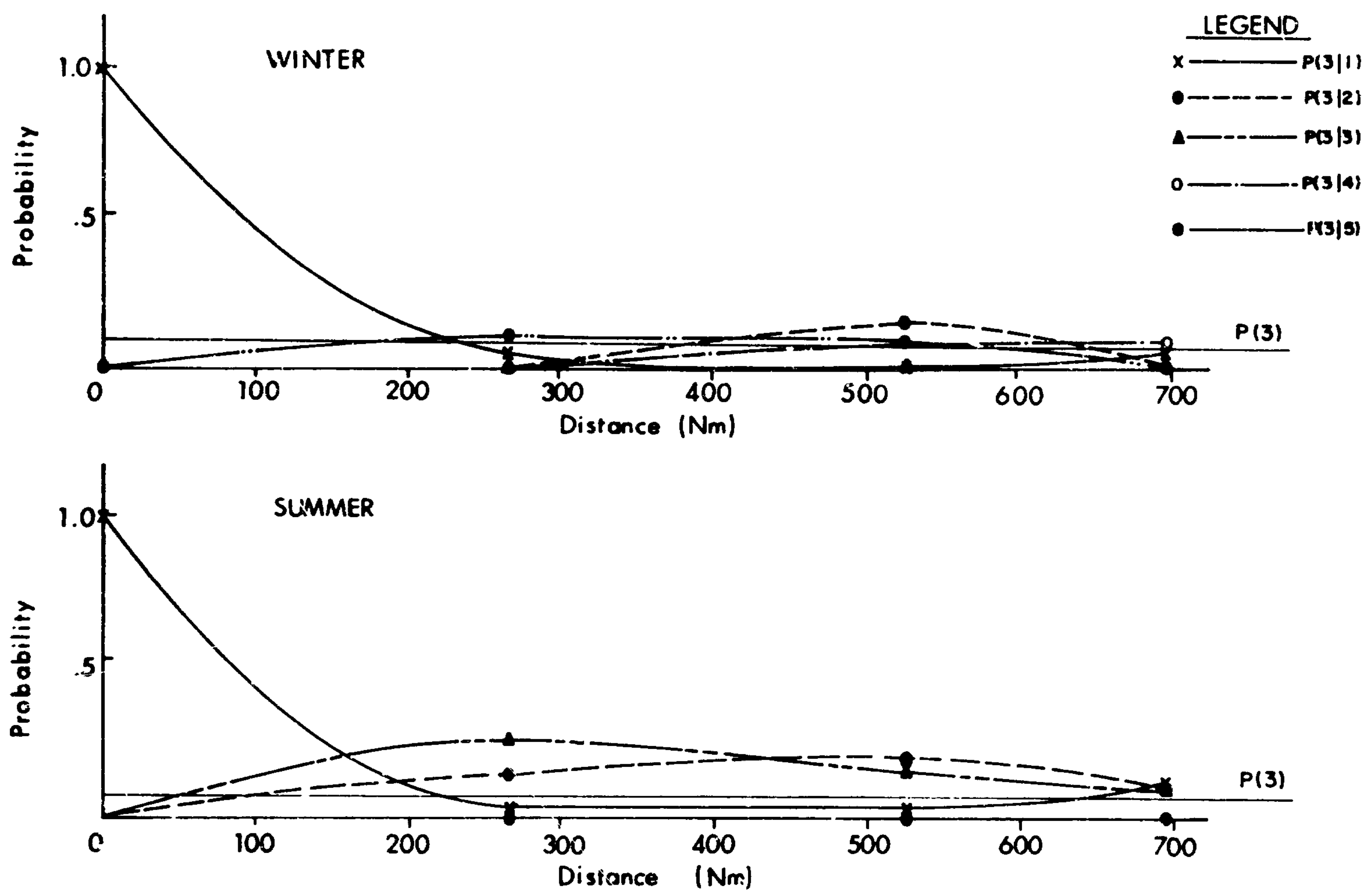


Figure A-33 Decay of Conditional Probabilities with Distance for Region 19

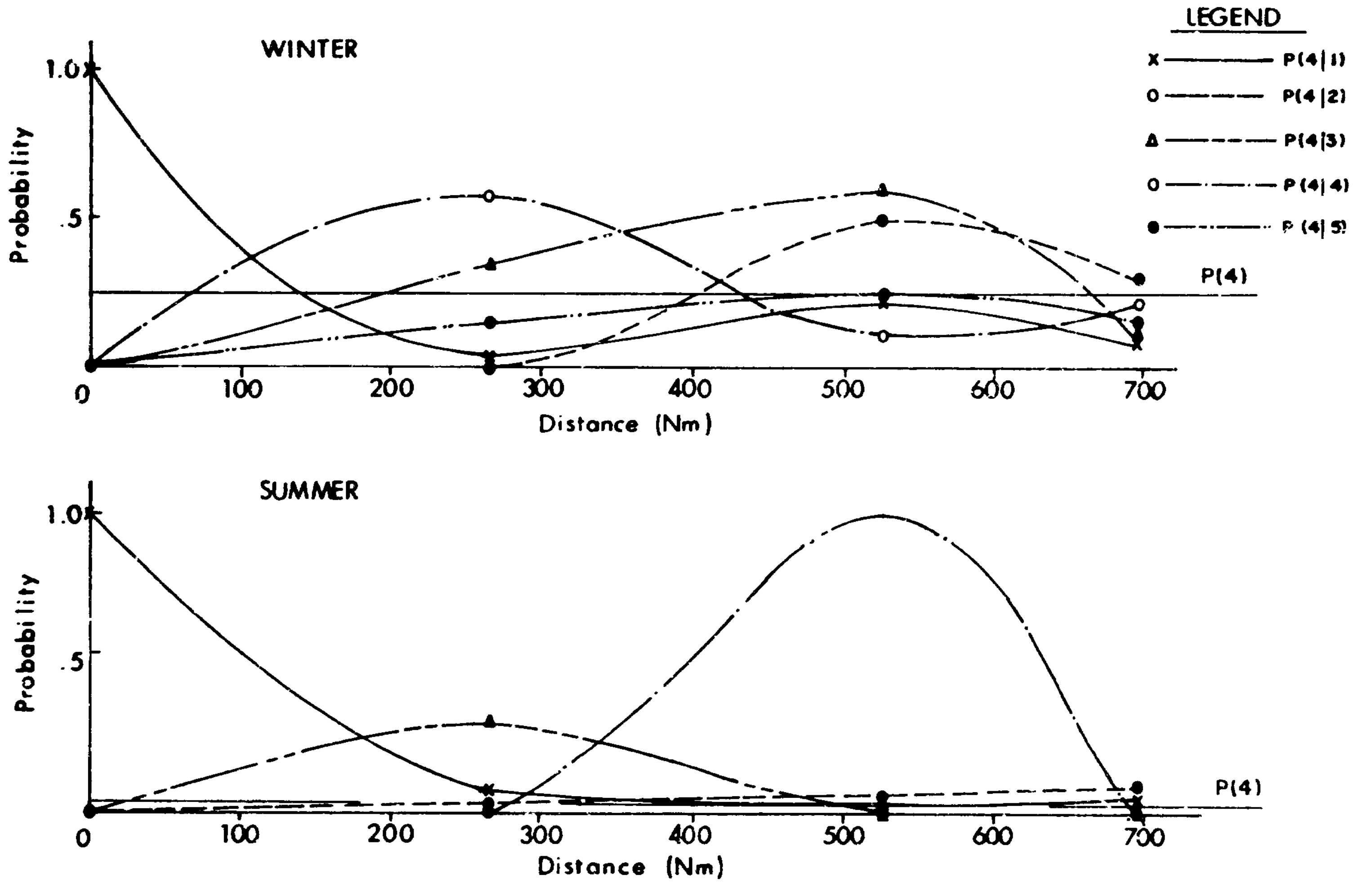


Figure A-34 Decay of Conditional Probabilities with Distance for Region 19

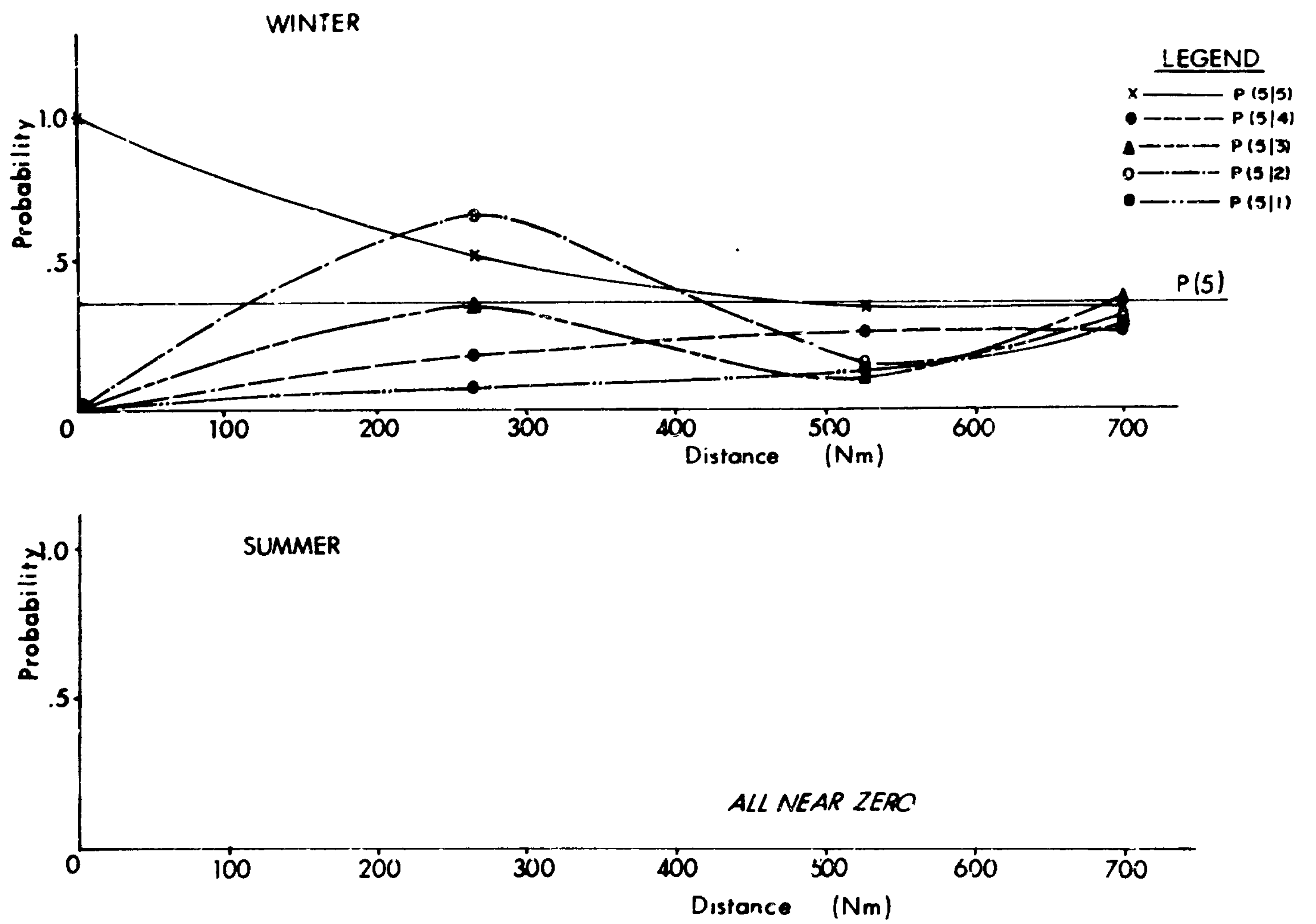


Figure A-35 Decay of Conditional Probabilities with Distance for Region 19

Section 5.2.5.1 of the Final Report). Some of these strange behaviors are particularly noticeable in the summer season of Figures A-32 and A-34. Good convergence is demonstrated for the winter season in Figures A-32 and A-33. In general, the convergence to the unconditional probability is better during the winter season than during the summer.

An alternate way of presenting the same data such that the sum of all the probabilities at any given distance must equal one are shown in Figures A-36 through A-40 for Region 11.

Because of the smallness of the data sample and the requirement that the data bank be kept relatively small from a computational point of view, we have not defined, at this time, a generalized mathematical function describing the decay of conditional probability with distance. In its place we have adopted a simplified procedure to permit general use of the data without invoking data volumes and computational complexities that cannot be justified by the quality of the available conditional data. For each region and month, distributions are presented at a nominal distance of 200 nm. In general the data have been taken without modification, from pairs of satellite observations approximately 200 nm apart. Whenever possible the data from the same region are grouped to increase sample sizes; unfortunately, this was seldom possible. The data are intended to be used by assuming a straight line probability decay between unity and the 200 nm value for on-diagonal conditionals (P(3|3), etc.), and between zero and the appropriate value for off-diagonal conditionals (P(3|2), etc). The straight line is to terminate at the appropriate unconditional value. For further discussion of the use of spatial conditional distributions, see Section 5.2.3 of the Final Report.

### 3.3.2 Correlation Analysis

During the course of the computation of the probable cloud frequency distributions for pairs of stations to obtain conditional probabilities with distance, correlation coefficients were computed for both the one degree satellite data and the two and one-half degree satellite data obtained from Sadler (1966). As might be expected from the data shown in the foregoing several figures, the correlations were found to decrease rapidly with distance reaching a value of approximately 0.6 at an average distance of about 200 nm. For most regions in the tropics and extratropics the correlation coefficient is a well behaved function of distance, out to about 200 nm.

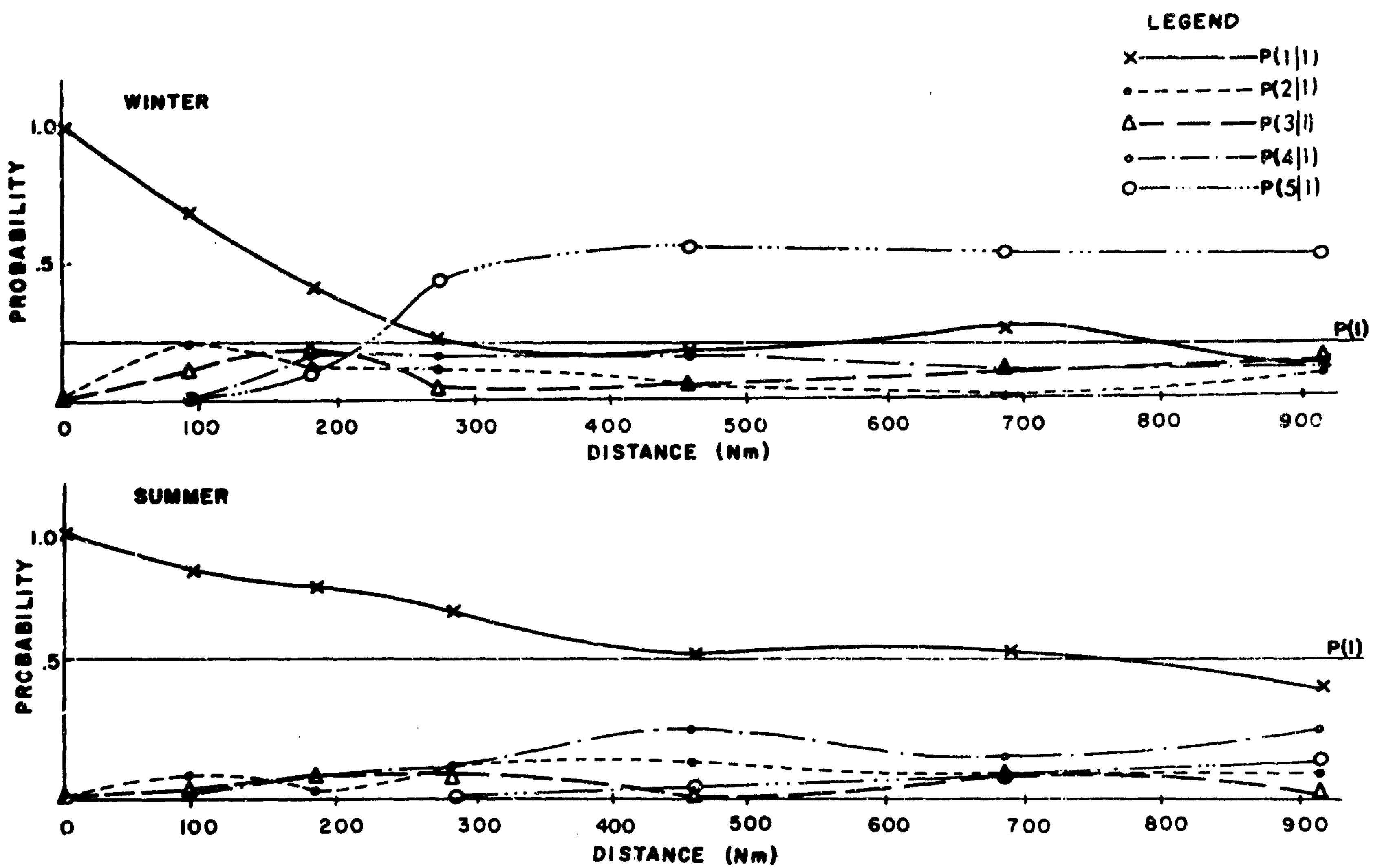


Figure A-36 Decay of Conditional Probabilities with Distance for Region 11 (Probability of cloud group 1-5 given cloud cover 1)

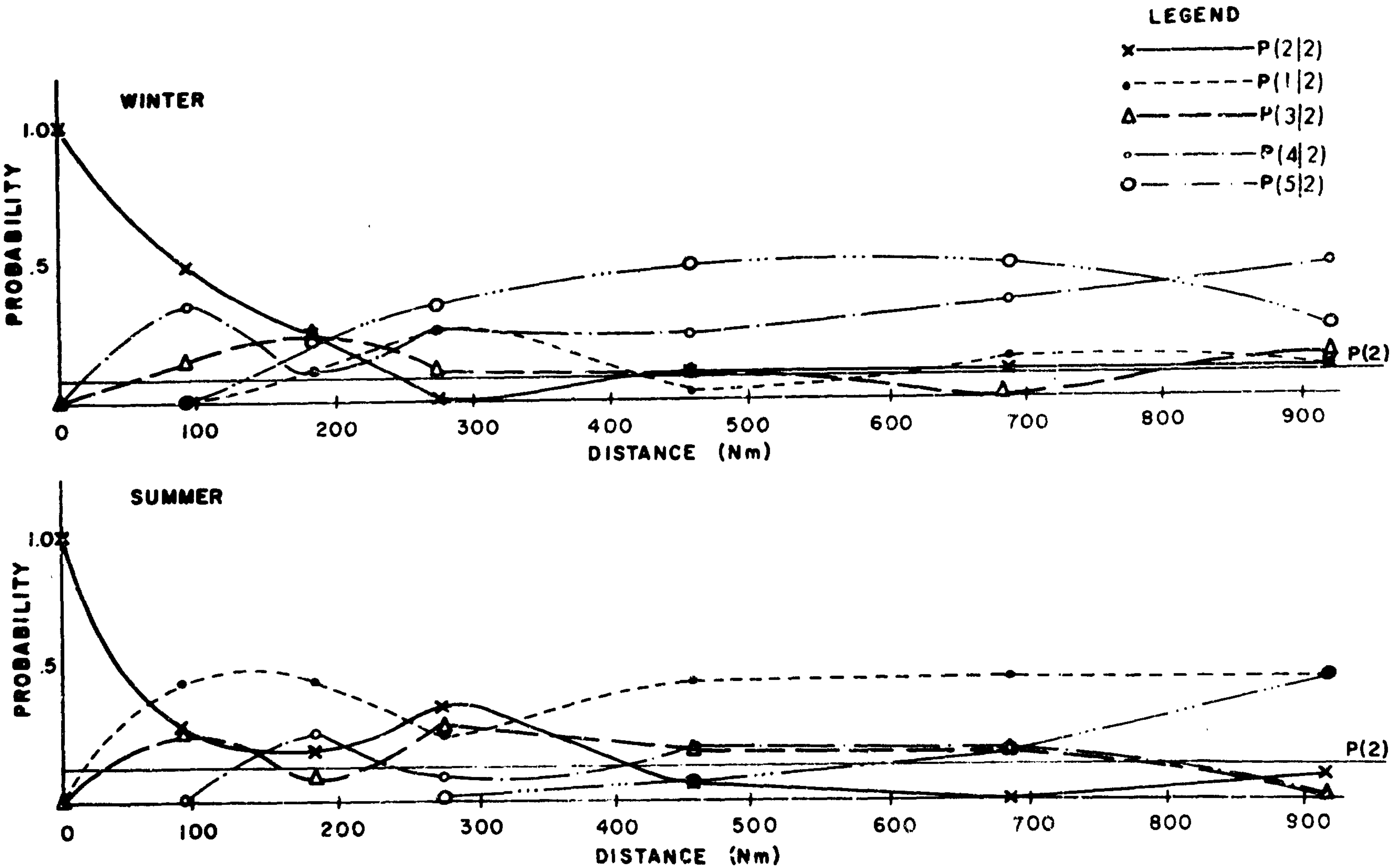


Figure A-37 Decay of Conditional Probabilities with Distance for Region II

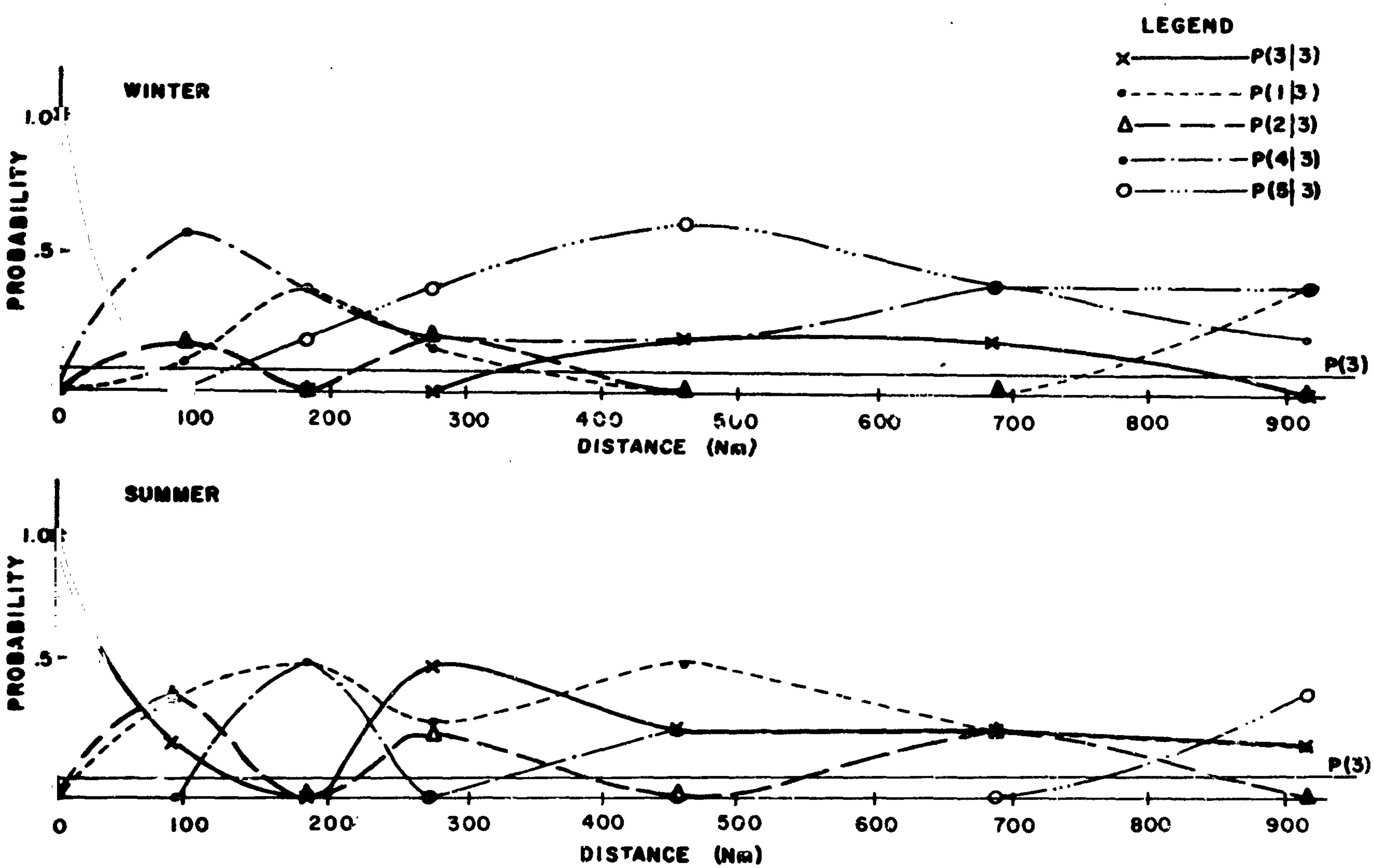


Figure A-38 Decay of Conditional Probabilities with Distance for Region 11

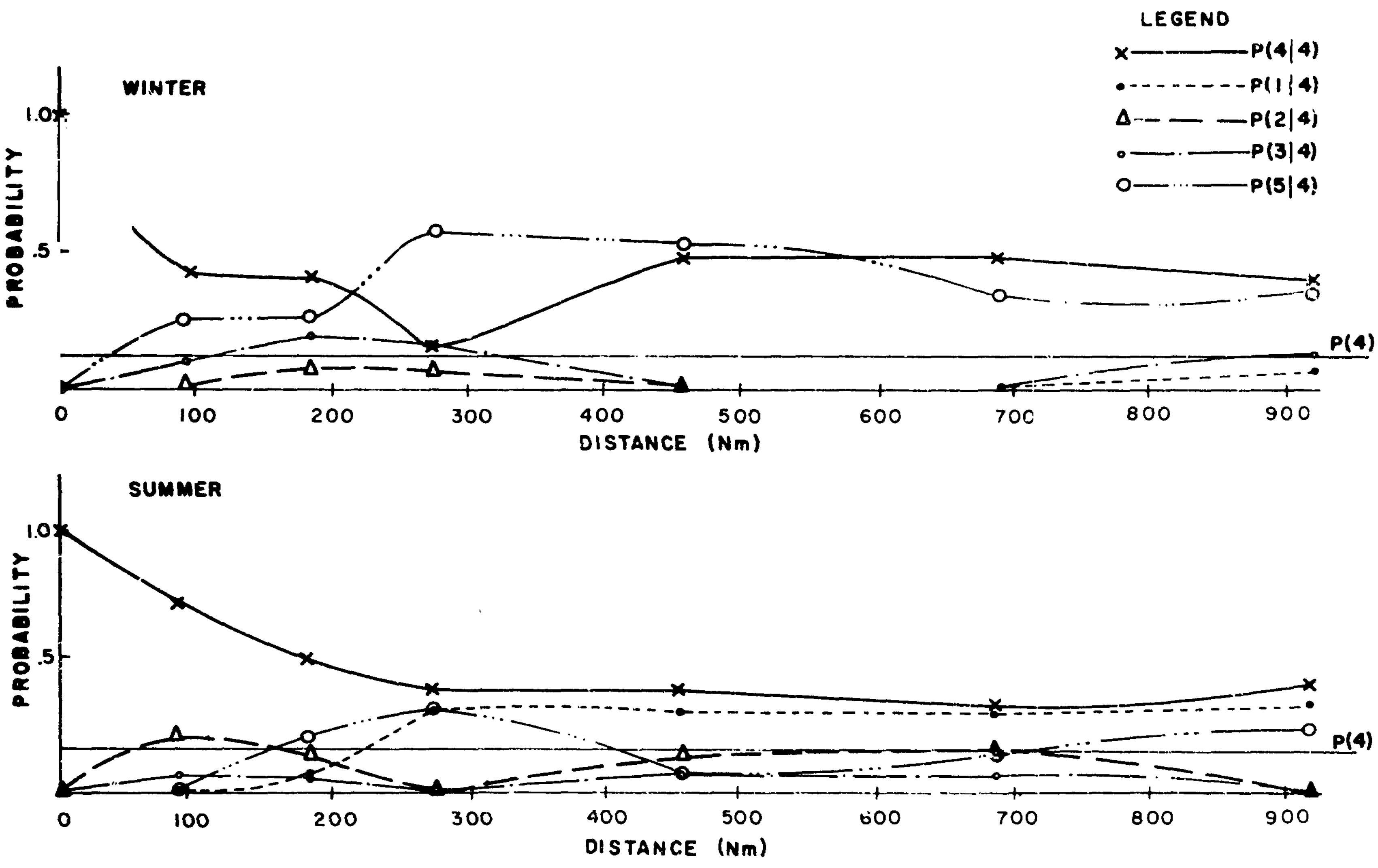


Figure A-39 Decay of Conditional Probabilities with Distance for Region 11

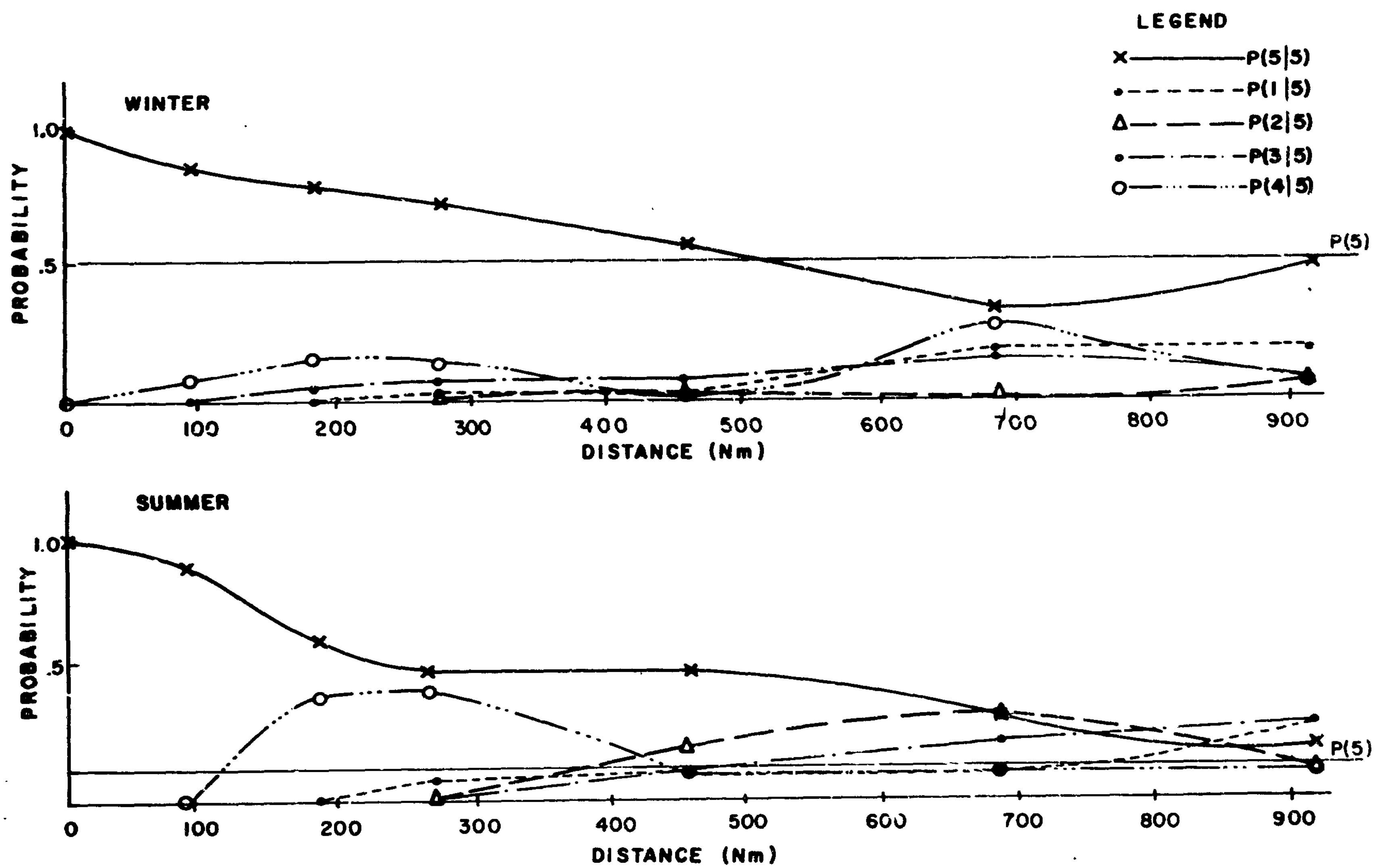


Figure A-40 Decay of Conditional Probabilities with Distance for Region 11

In some regions, the correlation coefficient is well behaved out to distances of 400 to 500 miles (where the values are often below 0.4). In all regions beyond 500 miles, the correlation coefficient becomes not well behaved and in all cases the coefficients are very small.

### 3.3.3 North-South Data Sample

As discussed above, the data points for most of the climatological regions were oriented in an east-west direction. A sample was also obtained, however, for a group of stations oriented north-south. Available resources limited this sample to a single region and single season, with the data being extracted from ESSA-5 photography for the summer of 1967, for a group of five stations, four being in Region 11 and one in Region 9.

The resulting cloud frequency distribution for the five stations combined is very similar to that obtained for a group of east-west stations in the same region. Conditional probabilities both with regard to space and to time are also similar to those computed for the east-west sample. In the computations with regard to distance, however, the correlation between stations appears to decrease more rapidly in the north-south group of stations. While the correlations are similar in the two groups for stations about 120 nautical miles apart, a much lower correlation was obtained in the north-south sample for stations about 300 nautical miles apart (a correlation coefficient of 0.14, compared to 0.64 for the east-west group).

The decrease in correlation in the north-south direction probably reflects the more rapid changes in cloud climatology with latitude than with longitude. Although a larger data sample is required before conclusive results can be obtained, these results tend to confirm the choice of a narrow latitudinal dimension for many of the climatological regions.

## 3.4 Quality of Conditional Distributions

### 3.4.1 Data Quantity

The problems of data quantity can be appreciated from consideration of the way in which the conditional probabilities are generated. The starting point is a 25-element joint frequency table. Our characteristic data samples had 85 to 90 pairs of observations. In a number of joint distributions, a few elements along the diagonal contained most of the entries, leaving a scattering elsewhere. At first it seemed that the best solution to this problem in the absence of greater data amounts, would be to group data from several regions. However, because the regions were defined by their cloud climatological dissimilarity, it was found that this procedure would result in serious distortion of joint probabilities along the diagonal, thus destroying the major part of the significance of the distribution. To put this observation on a firmer statistical basis, $\chi^2$ tests of homogeneity were performed to see if candidates for grouping could be considered as being drawn from the same parent distribution. The results indicated that in spite of the small sample sizes, the null hypothesis of homogeneity could not be accepted. As an example, the first test was performed on distributions for Regions 11 and 18 in winter, yielding $\chi^2 = 46.0$ with 24 degrees of freedom, significant past the 1% level.

A further consideration mitigating the effect of small sample size is that the frequency of reference to an element in the conditional probability table should be in direct proportion to the number of observations that were used to define that element. Thus, the variance that can be tolerated in estimating the probability of the frequently occurring joint events is greater than in the case of the more probable events. By the same token, care should be taken in applications of these statistics that the results do not depend critically upon the occurrence of improbable joint events, the probability of which may be poorly estimated. As an example, if in our satellite data sample only one case of clear sky occurred, the conditional probability table would dictate that any clear day must be followed by whatever cloud cover succeeded the clear day in the data sample, all other transitions being excluded. The probability of two successive clear days would be zero.

### 3.4.2 Quality of Source Data

The satellite data were "observed" by a skilled meteorological technician with extensive experience in the handling and interpretation of satellite TV data. Data sources were mosaics of Nimbus II AVCS data prepared by Allied Research for the Goddard Space Flight Center and similar machine-prepared mosaics of data from ESSA-3 and ESSA-5. Variations in exposure and processing of Nimbus II data made consistent quantitative judgment of cloud cover quite difficult, adding an element of variability beyond that to be expected from normal subjective judgment.

The area from which cloud was to be read was delineated by a transparent template placed over the cloud field in a position dictated by the machine-superposed geographical grid marks. These are frequently in error by a degree or more, with occasional major errors resulting from failure of picture time coordination. Except for cases of obvious gross error, the technician was instructed to use the grid for reference even where it disagreed with landmark evidence.

A few tests were run to assess the probable error of this class of manual data extraction, which is really not different in kind from cloud cover estimation by ground observers. It was found that data extracted under the same ground rules were reasonably consistent, but that the unconditional (marginal) distributions could be materially changed by altering instructions to the data extractor.

Not unexpectedly, the marginal distributions of the satellite data were found to give much smaller cloud covers than the corresponding conventionally observed cloud data. The greatest departures came from the Nimbus II data sample, where it was apparently difficult to differentiate thin cloud and small clouds. Table A-4 compares the unconditional frequencies in the worst case found. While it is probable that Tampa and the part of the Gulf of Mexico immediately to its west may be cloudier than the more maritime parts of the region used in the satellite sample, the differences are still extreme. The explanation must lie in the prevalence of sub-resolution size cumulus, resulting in a shift from the scattered and partly covered groups into clear; and the one degree satellite sample size which may almost universally exceed the size of the large cumulus and cumulonimbus providing overcasts at Tampa, thus shifting them into cloud cover classes vacated by the unresolved small cumulus.

Table A-4

Comparison Between Data Samples
For Region 04 - Summer Season

| Cloud Amount In Octas | August Tampa | Percentage Nimbus II (1966) | Frequency ESSA-5 (1967) |
|---|---|---|---|
| 0 | 3% | 52% | 35% |
| 1-2 | 28 | 31 | 32 |
| 3-5 | 15 | 11 | 16 |
| 6-7 | 21 | 4 | 12 |
| 8 | 33 | 2 | 14 |

Section 6.8 of the Final Report discusses how the overestimated cloud cover of the ground observed, in the unconditional distributions, the underestimated satellite cloud cover used in the temporal and spatial conditional distributions, and the overestimates of cloud coherence and persistence resulting from the use of the straight line approximation all tend to compensate each other in characteristic applications.

An overall assessment of the quality of the conditional probabilities cannot be made without reference to their intended use. The techniques (described in Section 6 of the Final Report) have been selected to make effective use of the appropriate properties of the conditional distributions with only occasional apparent minor errors arising from their relative inaccuracy and bias toward clear skies (see Section 5.4 of the Final Report). Used in the recommended fashion in appropriate simulation situations, we believe that these data will give results materially more realistic than those derived from simple assumptions on cloud climatology.

### 3.5 Data Confidence

A table of data confidence levels, prepared for all 29 regions, is presented as Table A-5. In this table we have assigned a confidence code for both the unconditional and conditional cloud statistics and in the case of the conditional statistics for both space and time. This confidence code is a simple one through three system, where one denotes good data obtained directly from long-period record in the case of the unconditional statistics and from computed conditional statistics for the specific map region in question in the case of the conditional statistics. A code of two denotes a confidence level of fair, indicating principally that the statistics for these regions have been modified from long term record data or from computed conditional statistics for other regions, based on climatology and good meteorological judgment. A confidence code of three indicates relatively poor data, that in some cases has been synthesized, based on firm meteorological considerations, because no satisfactory cloud data for that region exists.

# APPENDIX B
# FINAL DATA FORMAT AND COMPUTER SUBROUTINES

## APPENDIX B

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## APPENDIX B

## FINAL DATA FORMAT AND COMPUTER SUBROUTINES

This appendix presents a brief disucssion of (1) the map region and data card decks, (2) printouts of these data decks, and (3) discussions of a few computer sub routines to be used in data manipulation. For example, subroutines for obtaining map region from the latitude and longitude of a desired point on the earth, and for scaling distributions for distances other than 200 nm or times different from 24 hours are discussed. Formulas for enlarging sampled area size are also presented.

### 1. WORLD-WIDE CLOUD COVER CARD DECK DESCRIPTION

Two decks of cards contain all input data necessary to use the world-wide cloud statistics. The first deck contains map region numbers and boundaries (Fig. B-1). The second contains twelve months of cloud statistics for each of the 29 regions.

#### 1.1 Map Deck

Data for the first deck were extracted from the map in Figure B-1 in the following manner.

Boundaries of each region fall on even numbered latitudes and longitudes. The area between 70 degrees south and 70 degrees north is divided into 70 swaths at odd numbered latitudes which extend from 0 degrees to 360 degrees eastward from Greenwich. The areas above 70 degrees north and below 70 degrees south require other logic since one region number defines the entire area. By scanning eastward from Greenwich along each swath, the number of the region previously encountered and the value of its terminating longitude (numbers between 0 and 360) were recorded and punched on cards. The maximum number of terminating longitudes in one swath was nineteen. Two cards were used to catalogue one swath even though data for some swaths did not extend into the second card. The card setup is illustrated in Figure B-2.

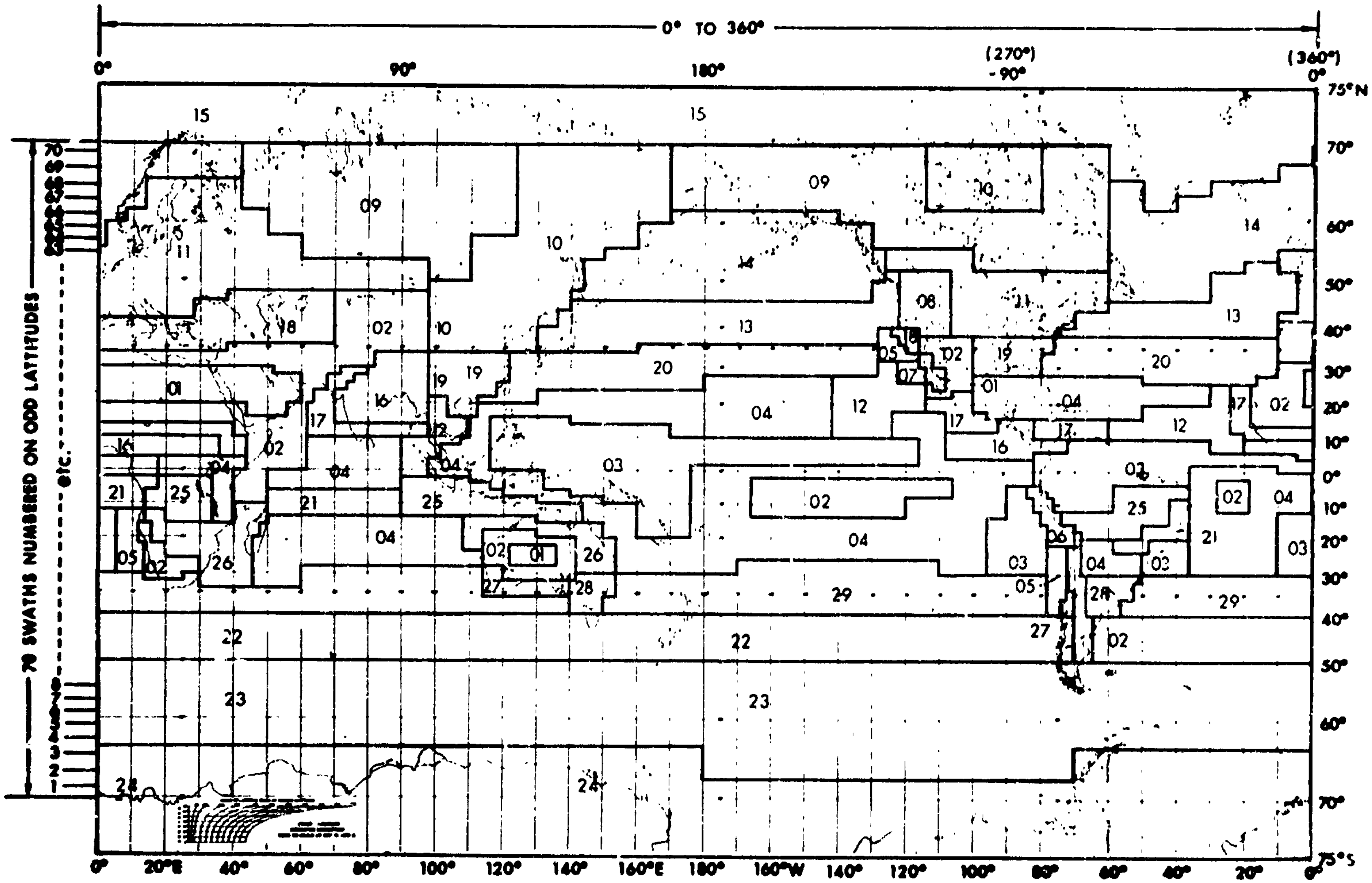


Figure B-1 Map Region Designation for Use with Map Deck Extraction Subroutine

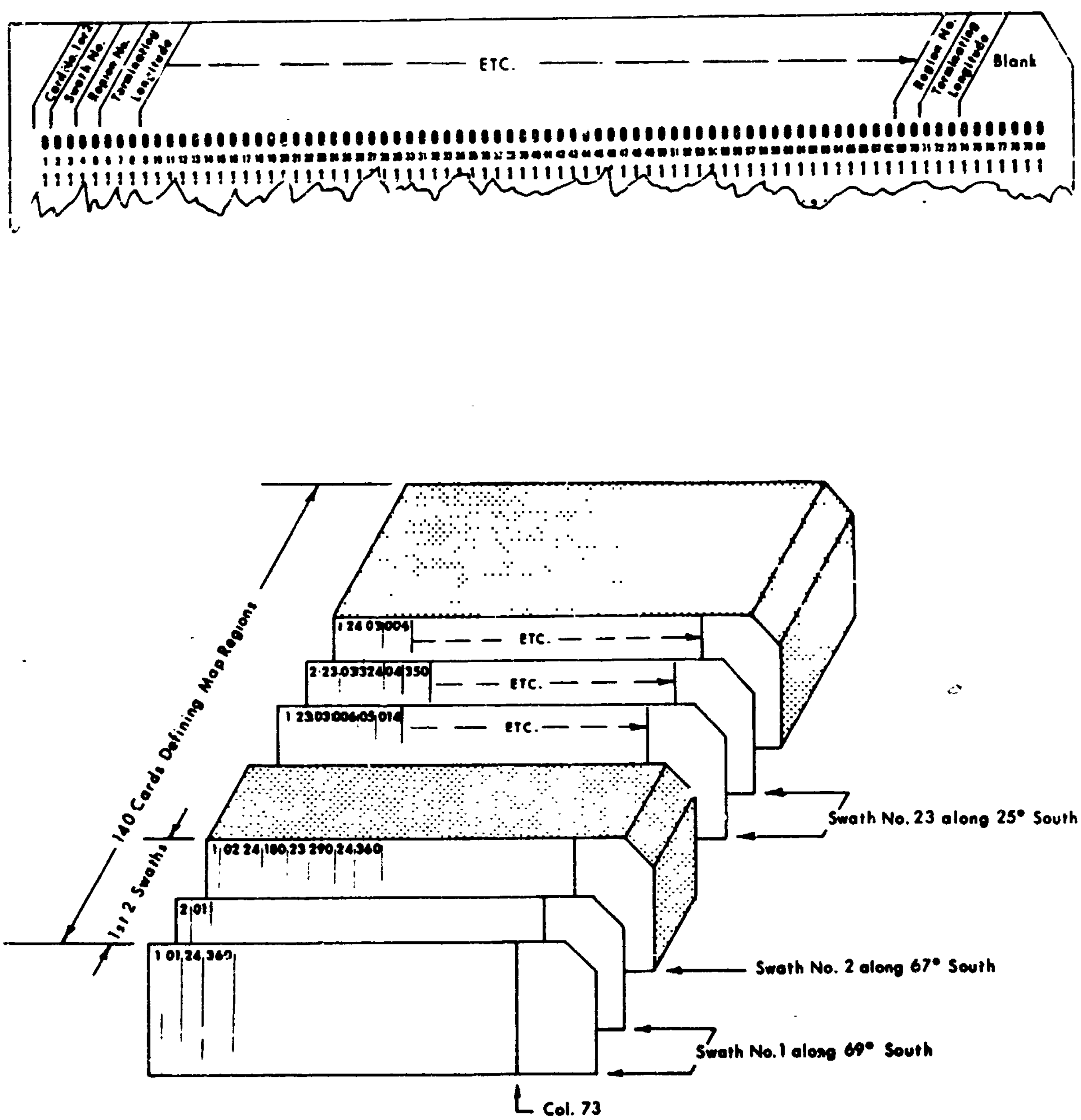


Figure B-2 Data Card Systems for Defining Climatic Regions.

The flow chart in Figure B-5 is of a subroutine that may be used to extract the region numbers from a given latitude-longitude location on earth In this subroutine it is assumed that the cards have been read into an array made up of 70 rows and 38 columns and that values of latitude are negative south, positive north, and longitude negative west, positive east.

1. 2 The Data Deck

The second deck, containing the cloud statistics, is illustrated in Figure B-3. Figure B-4 further demonstrates the individual card setup for the statistical data. As can be seen, 5 cards make up 3 matrices, the first being the unconditional probabilities for five cloud groups and eight local times. The second matrix is the 24 hour temporal statistics and the third is the 200 nm spatial statistics with the five given cloud groups listed on the left and the corresponding five cloud groups listed on the top.

A complete listing of all the map region data cards and cloud statistic data cards may be found in Section 2. 1 and 2. 2 of this appendix.

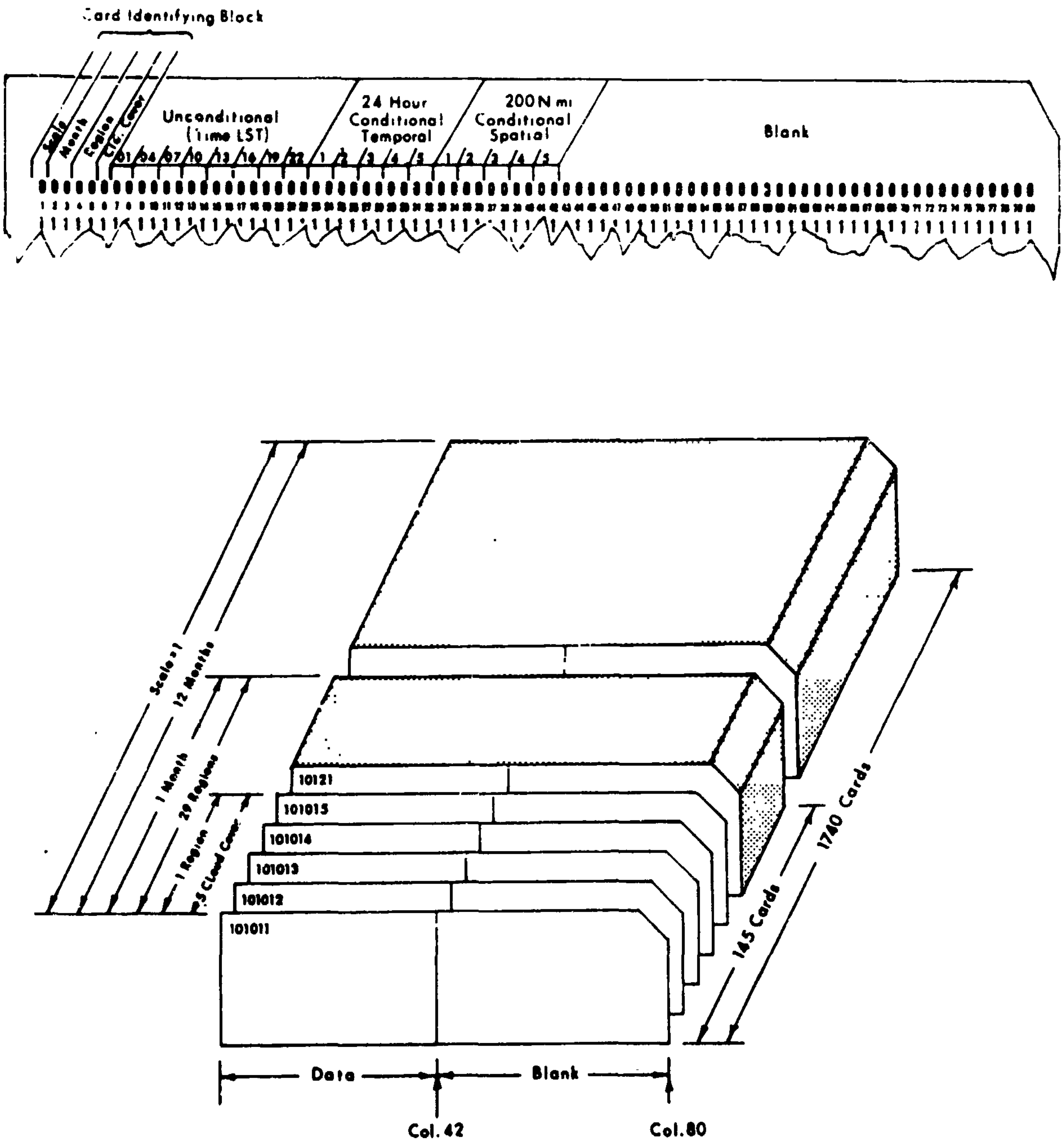


Figure B-3 Data Card Systems for Cloud Statistics.

| Scale | Month | Region | Cloud Code | Unconditional Probabilities | Conditional Probabilities: 24 Hr. Temporal | Conditional Probabilities: 200 N.M. Spacial | |
|---|---|---|---|---|---|---|---|
| 1 | 01 | 01 | 1 | 6263494442394659 | 8508050200 | 8107030900 | Card No. 1 |
| 1 | 01 | 01 | 2 | 1412171618191815 | 7812050500 | 7010002000 | Card No. 2 |
| 1 | 01 | 01 | 3 | 0607100907101008 | 7510100500 | 5729001400 | Card No. 3 |
| 1 | 01 | 01 | 4 | 1110142022201710 | 8005050505 | 5000072914 | Card No. 4 |
| 1 | 01 | 01 | 5 | 0708101111120908 | 8008050502 | 0000000199 | Card No. 5 |

Card Column 1 — Card Column 42

CLIMATOLOGICAL REGION NUMBER 1 STATISTICS FOR MONTH 1

UNCONDITIONAL PROBABILITIES TIME (LST) — Matrix 1

| Cloud Code | 01 | 04 | 07 | 10 | 13 | 16 | 19 | 22 |
|---|---|---|---|---|---|---|---|---|
| 1 | .62 | .63 | .49 | .44 | .42 | .39 | .46 | .59 |
| 2 | .14 | .12 | .17 | .16 | .18 | .19 | .18 | .15 |
| 3 | .06 | .07 | .10 | .09 | .07 | .10 | .10 | .08 |
| 4 | .11 | .13 | .14 | .20 | .22 | .20 | .17 | .10 |
| 5 | .07 | .08 | .10 | .11 | .11 | .12 | .09 | .08 |

CONDITIONAL PROBABILITIES 24 HOUR TEMPORAL — Matrix 2

| Cloud Codes (GIVEN) | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | .85 | .08 | .05 | .02 | .0 |
| 2 | .78 | .12 | .05 | .05 | .0 |
| 3 | .75 | .10 | .10 | .05 | .0 |
| 4 | .80 | .05 | .05 | .05 | .05 |
| 5 | .80 | .08 | .05 | .05 | .02 |

CONDITIONAL PROBABILITIES 200 NM SPATIAL — Matrix 3

| Cloud Codes (GIVEN) | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | .81 | .07 | .03 | .09 | .0 |
| 2 | .70 | .10 | .0 | .20 | .0 |
| 3 | .57 | .29 | .0 | .14 | .0 |
| 4 | .50 | .0 | .07 | .29 | .14 |
| 5 | .0 | .0 | .0 | .01 | .99 |

*Computerized Listing of the First Five Cards in the Statistical Deck*

Figure B-4 Punched Card Setup for Statistical Data.

## 2. COMPUTER LISTING OF CARD DECKS

### 2.1 Listing of the Map Region Cards

```
10124360
201
102241602329024360
202
103241602329024360
203
10423360
204
10523360
205
10623360
206
10723360
207
10823360
208
10923360
209
11023360
210
111222900229622360
211
112222900229622360
212
113222900229622360
213
114222900229622360
214
115222900229622360
215
1162914028150292820528627290022942830429360
216
1172914028150292820528627290022942830429360
217
11829114271402815429282052882729002294283082936 0
218
1192903026046040602911427140281542928205288022942830829360
219
1202901402026290302604604060291142712002142281542928205288022942831029360
220
1210300605014020302604604060291142712002142261540419029250042640328205288
2210229204310033240435003360
1220300605014020302604604114021220113602142261540419029250042640328205288
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2250435003360
```

```
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236
13703018040440206204090120980411603244042780336O
237
1381603617044020620409012102041160324404252162780335616360
238
139160361704402062040901210204116032440425216288033301234016360
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24402360
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24601360
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24701360
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24901360
1500105202072170801609819122202321223807246012520226019280203500235801360
250
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252
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```

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254
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255
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256
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2. 2 Listing of Cards Containing Cloud Distributions

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112175101319111517150716175017001040401OC,
112181373423222425373850091121095414111506
112182090809101214120925201721173838121200
112183040405040605040419222717153317083309
112184101017172020131324162129101717303105
112185404446473836343610111333330010105030
112191383626222221323852070618177605050509
112192080811111215110833180819221717080850
112193030304050506050321181132181312153030
112194121114172119141223100535271409144518
112195394245454039383923040720461306121653
11220101010001022020008082338237605050509
112202060807161916150602181128411717080850
112203060811171113131001161043301312153030
112204454445233032294601101139391409144518
112205383937433837413801121038391306121653
112211020000000000000118320935065025250000
112212111209030000030911311538052936002807
112213152421140811171403122253100036184600
112214284555718175532308152046110712205407
112215441915121114275307072249150000105040
112221010402010101020100270540271010253520
112222141715081011121000201123461420401610
112223070908080708050601150632461710174016
112224332323333233343801140735430202123450
112225454752505047474502090730520105060781
112231000101000001000004061218601010204020
112232020101010202020120051525351420401610
112233020101020302010209031821491710174016
112234131417212525241605061231460000123454
112235838380767070738102040518710000020791
112241090506040407061035070518356018040711
112242080607091212110731040723355610340000
112243020102030404040532080832202709102727
112244131320242319171721080725390510005035
112245687565605758626111060526520004073554
112251040200000000000218320935063020202010
112252181204010001021011311538050025255000
112253131508040302041303122253100000464608

```
112254313641373834292908152046110000057322
112255343547585963554607072249150000004159
112261050000000000040660160808083525251005
112262080602020000040812452810050545351005
112263151305070505101405343128020535451005
112264454238465053555405332634020510403510
112265273955454542271816175017000505353520
112271453532445353505284050406018705020501
112272111311151615151345290422007020100000
112273040506060708060464280100075000173300
112274111216141415151148111922006010101010
112275293535211009142020200040205015101510
112281493219130607224554390501014837040704
112282162019171524261941421205003148140502
112283070910172522110920471815000033343300
112284141925353829221220202725080015255010
112285142027181618191505152025350010152550
112291000101000201000001140014714837040704
112292080708061012050501150940353148140502
112293040405040602040402210937310033343300
112294343532302427333501070334550015255010
112295545354605858565600070428610010152550
```

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## 3. COMPUTER SUBROUTINES

The following sections briefly describe several proposed subroutines for data handling or data manipulation.

### 3.1 Subroutine for Extracting Region Numbers

Figure B-5 is a flow chart of a subroutine that may be used to extract region numbers from a given latitude-longitude location on earth. The routine assumes that the cards (see Fig. B-2) have been read into an array made up of 70 rows and 38 columns and that values of latitude are negative south, positive north, and longitude negative west, positive east. Table [illegible] is a FORTRAN Program printout of this subroutine.

Table B-1

FORTRAN Printout of Map Region Subroutine

```
      SUBROUTINE REGION
      COMMON PLAT,PLONG,MAP(70,38),IREGON
C               ENTER WITH A LATITUDE & NORTH - SOUTH, LONGITUDE OF 0 TO
C               180 DEGREES & EAST - WEST.
C               RETURN WITH THE CLIMATOLOGICAL REGION NUMBER WHERE THE
C               COORDINATES RESIDE.
      IF(ABS(PLAT).GE.70.0) GO TO 11
    1 ILAT = (PLAT&71.0)/2.0 & .5
      ILONG = PLONG
      IF(ILONG.LT.0) ILONG = ILONG&360
      DO 7 I=2,38,2
      IF(MAP(ILAT,I).LT.ILONG) GO TO 7
      IREGON = MAP(ILAT,I-1)
      GO TO 12
    7 CONTINUE
      RETURN
   11 IREGON = 15
      IF(PLAT.LT.0.0) IREGON = 24
   12 RETURN
      END
```

Dimension Map (70, 28)

Enter With:
PLAT - Some Latitude, + N, -S
PLONG - Some Longitude

Return With:
Region number where the point resides

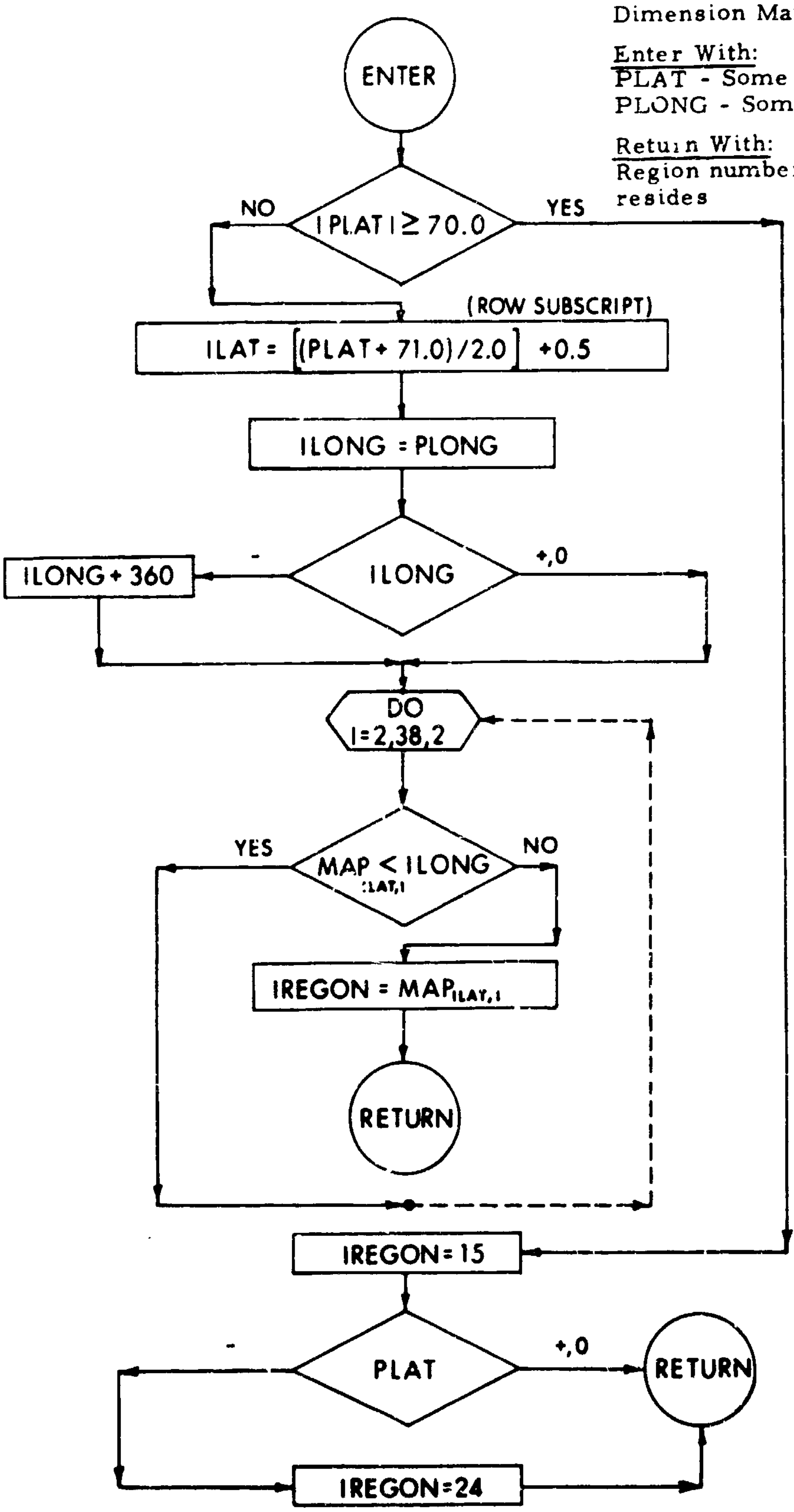



Figure B-5 Flow Chart for Map Region Subroutine.

3.2 Proposed Computer Subroutine for Scaling Temporal or Spatial Conditional Distributions

Figure B-6 is a flow chart and FORTRAN version of a subroutine for scaling the conditionals for distance or time. Table B-2 lists the necessary definitions, inputs, restrictions, etc. Table B-3 provides a list of terms and definitions which are used throughout the following paragraphs.

The scaling procedure is described in detail in Section 6.2 of the Final Report. The following paragraphs have been extracted from this discussion, to outline the basis for this subroutine.

3.2.1 Scaling for Distance

Data for 200 miles distance from the initial point are tabulated in the data bank. We present here the mathematical technique for scaling these conditional statistics for distances other than 200 nm. The assumption is made that the conditional probabilities decay linearly with distance.

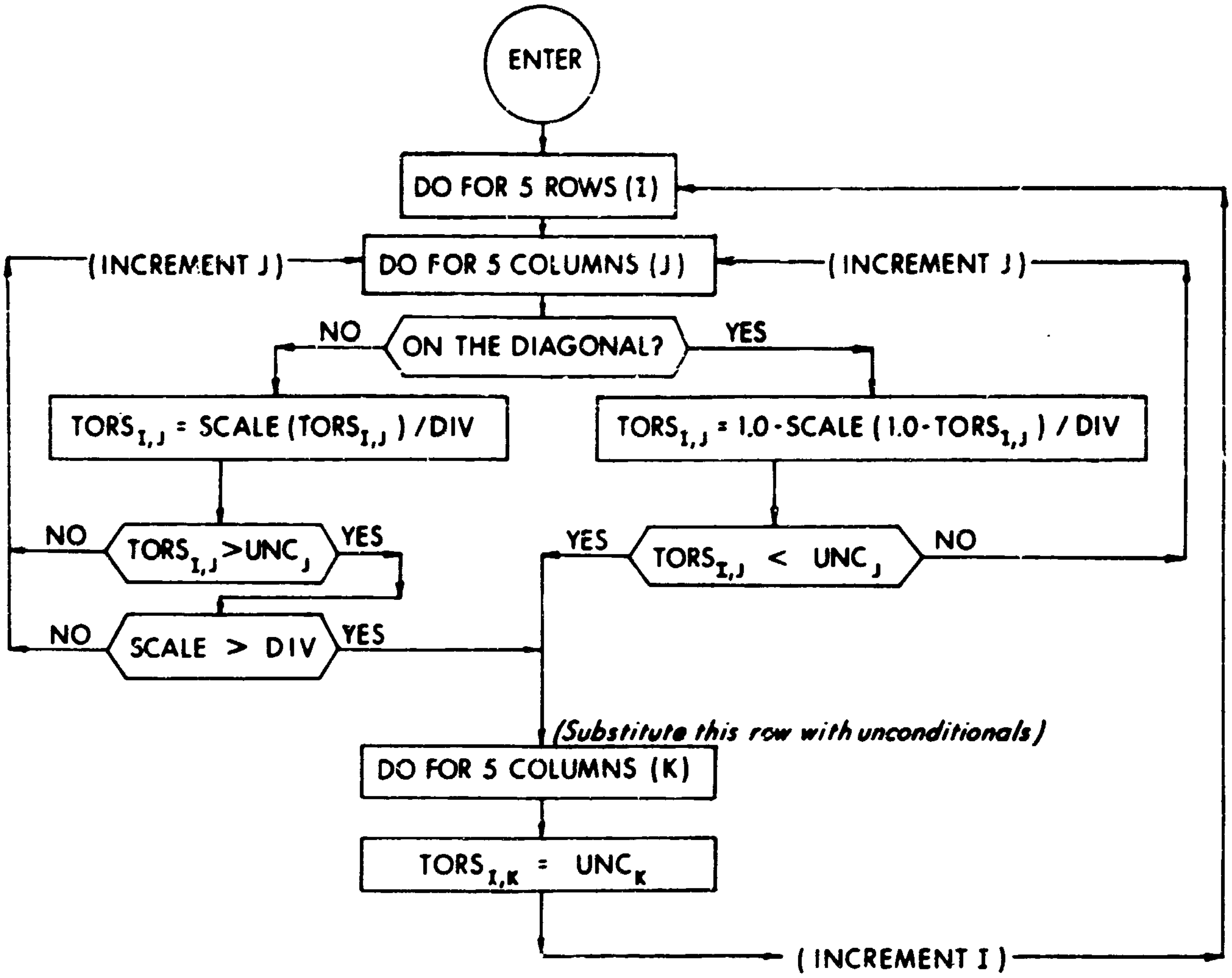
The procedure for scaling for distance based on the linear assumption is thus a relatively simple one. Two conditions are imposed. The first concerns the area within 200 miles, i.e., scaling for distances less than 200 miles; the second is for scaling beyond 200 miles. For scaling within 200 miles, one uses the following two formulas. For probabilities on the diagonal of the 5 x 5 conditional matrix, i.e., 1 given 1, 2 given 2, etc., one uses

$$P(C) = 1 - \frac{\text{Scale (d)}}{200} \text{ (1-SCOND)} \tag{1}$$

If the value in question is not on the diagonal, i.e., probability of 1 given 2, 1 given 3, etc, the following formula is used for scaling

$$P(C) = \frac{\text{Scale (d)}}{200} \text{ (SCOND)} \tag{2}$$

When the required distance is greater than 200 nm the following condition is also imposed. For values on the diagonal, the scaled values (scaled using the formulas immediately above) must remain greater than the unconditional probability of the diagonal value, i.e., the scaled probability of 2 given 2 must be greater than the unconditional probability of 2. If this test fails, the entire horizontal line of the 5 x 5 matrix




FORTRAN IV Version of SCALNG (KA=I, KB=J, KD=K for reference to above chart.)

```
      SUBROUTINE SCALNG
      COMMON /AREA2/TORS(5,5),UNC(5),SCALE,DIV
      DO 4 KA=1,5
      DO 2 KB=1,5
      IF(KA.EQ.KB) GO TO 1
      TORS(KA,KB) = SCALE*TORS(KA,KB)/DIV
      IF(TORS(KA,KB).GT.UNC(KB) .AND. SCALE.GT.DIV) GO TO 3
      GO TO 2
    1 TORS(KA,KB) = 1.-SCALE*(1.-TORS(KA,KB))/DIV
      IF(TORS(KA,KB).LT.UNC(KB)) GO TO 3
    2 CONTINUE
      GO TO 4
    3 DO 4 KD=1,5
      TORS(KA,KD) = UNC(KD)
    4 CONTINUE
      RETURN
      END
```

**Figure B-6 Flow Chart and Fortran Printout for Scaling Subroutine.**

Table B-2

Subroutine for Scaling

IDENTIFICATION:

Title: Subroutine SCALNG

PURPOSE:

This is a subroutine that may be used for linear scaling of temporal or spatial conditional statistics derived from the world-wide cloud cover study.

USAGE:

Calling Sequence:

CALL SCALNG (TORS (5, 5), UNC(5), SCALE, DIV)

Where (1) TORS is a 5 x 5 matrix of temporal or spatial conditional statistics to be linearly scaled. Rows of this matrix are defined as the 5 given cloud groups increasing from top to bottom.

(2) UNC is a 1 x 5 matrix of selected unconditional probabilities that can be used for substitution into appropriate rows of the conditional matrix should certain tests justify.

(3) SCALE is some number expressed in nautical miles when scaling spatial conditionals, or hours when scaling temporal conditionals

(4) DIV is equal to 200 when scaling for spatial conditionals, or 24 when scaling for temporal conditionals.

RESTRICTIONS:

SCALE should never be less than or equal to the sampling area size from which the spatial statistics were derived when scaling spatial conditionals (i. e., ~ 60 nm).

COMMENT:

Return with the scaled conditionals in TORS.

Table B-3

Definition of Terms

| | |
|---|---|
| UNCON | Unconditional Distribution for Sampling Area Size 30-60 nm. |
| SCOND | Spatial Conditional Distribution for Sampling Area Size 30-60 nm and Distance 200 nm from UNCON. |
| TCOND | Temporal Conditional Distribution for Sampling Area Size 30-60 nm and 24-hours after UNCON. |
| SUNCON | Scaled Unconditional Distribution for Enlarged Sampling Area Size. |
| CONNEW | Conditional Distribution Scaled for Enlarged Sampling Area Size. |
| CONDIS | Spatial Conditional Distribution Scaled for Distance Other than 200 nm. |
| CONTIM | Temporal Conditional Distribution Scaled for Time Other than 24-hours. |
| SCSCON | Spatial Conditional Distribution Scaled for Both Enlarged Area Size and Distance Other than 200 nm. |
| SCTCON | Temporal Conditional Distribution Scaled for Both Enlarged Area Size and Time Other than 24-hours |
| TSCON | Conditional Distribution Scaled for Both Time and Distance for 30-60 nm Sampling. |
| TSSCON | Conditional Distribution Scaled for Time, Distance and Enlarged Sampling Area Size. |
| DICON | Pseudo-Conditional Distribution Matrix Generated while Scaling TCOND for Diurnal Effects. |
| DITCON | Diurnally Scaled Temporal Conditionals. |

is replaced with the unconditional statistics. In a similar manner for values not on the diagonal, the scaled values must remain below the unconditional probability of the given cloud group, i. e., $P(2|1)$ and $P(2|3)$ etc. must be smaller than the unconditional probability of 2. If this test fails, the entire horizontal line of the 5 x 5 matrix is also replaced by the unconditional statistics. Thus if either the diagonal value is less than the unconditional value or if the non-diagonal value on any given line is greater than the unconditional value, the whole line is replaced by the unconditional statistics. This amounts to saying that if either of these tests fail, the cloud cover statistics for this cloud category beyond this distance are no longer conditional upon the first point but rather assume the unconditional distributions.

### 3. 2. 2 Scaling for Time

Scaling the conditional distributions for time is handled in a somewhat similar way to that for distance. In this case, we assume that the statistics are no longer conditional for times beyond 36 hours. To scale the time conditionals the following formulas are used:

ON the diagonal

$$P(C) = 1 - \frac{\text{Scale (T)}}{24}(1 - \text{TCOND})$$

OFF the diagonal

$$P(C) = \frac{\text{Scale (T)}}{24}(\text{TCOND})$$

The first formula is used for values which lie on the diagonal of the 5 x 5 matrix while the second formula is used for those which lie off the diagonal (similar to the discussion in paragraph 3. 2. 1 above).

3.3 Scaling for Diurnal Change

The 24-hour conditional distributions and any scaling of them for other time intervals, contain no direct provision for introducing the effect of diurnal variation, which in some regions is the principal factor affecting cloud cover. A recommended procedure is as follows:

1. Generate a pseudo-conditional distribution (DICON) between the unconditional distributions at the local times of the first and second cloud events. This can be done by first forming a joint probability distribution between UNCON (A), the unconditional distribution of event A, and UNCON (B) the unconditional distribution of event B (later in time than A). The assumption is made that the event B corresponding to a specific event A is the one occurring at the same cumulative probability level in the unconditional distribution at the second time as does the event A in the unconditional distribution at the first time. This satisfies the intuition that diurnal change is superposed on more gross synoptic scale variability, so that if event A represents a lesser cloud cover than normal, the succeeding event B should also represent a smaller cloud cover than normal at that time. As an aid to the reader, we define $P_A(1)$, $P_A(2)$, etc to be the probability of cloud group 1, 2, etc. for event A, and $P_B(1)$, $P_B(2)$, etc. to be the corresponding probabilities for event B.

The cloud categorization intervals fall at different cumulative probabilities in the distributions of event A and B. Thus it is necessary to divide up the intervals of the distribution of event A and assign them to intervals of the distribution of event B, assuming uniform distribution within an interval. To form the joint probability matrix shown in Table B-4(C), we find the fractional part of $P_A(1)$ that is contained in (jointly distributed with) $P_B(1)$. In the example shown in Table B-4(B), all of $P_A(1)$, 0.2, is contained in $P_B(1)$. Thus, 0.2 is entered in the joint probability matrix at position A = 1, B = 1 (cell number of joint table). Since $P_B(1)$ is 10% greater than $P_A(1)$, this additional 0.1 in $P_B(1)$ could not have occurred jointly with $P_A(1)$. Therefore, it is placed in the matrix (Table B-4(C) at position A = 2, B = 1.

In a similar way, we rate (jointly distribute) $P_A(2)$ with $P_B(2)$ and find that only 0.3 are contained in both. Therefore, 0.3 is located in the joint matrix at A = 2, B = 2. Again there is an additional part to be allocated: this time 0.1 of $P_A(2)$ must have occurred with $P_B(3)$; it is thus entered in the matrix at A = 2, B = 3. (For Monte Carlo computational procedures, it may be more convenient to work with the UNCON cumulative probabilities.)

Table B-4

Computation of a Pseudo-Conditional Distribution for Diurnal Variation

UNCON EVENT

| | Cloud Category | (A) Prob. | (A) Cum. | (B) Prob. | (B) Cum. |
|---|---|---|---|---|---|
| (A) | 1 | .2 | .2 | .3 | .3 |
| | 2 | .5 | .7 | .3 | .6 |
| | 3 | .2 | .9 | .2 | .8 |
| | 4 | .05 | .95 | .1 | .9 |
| | 5 | .05 | 1.0 | .1 | 1.0 |

UNCON

| | Cloud Category | Event (A) Probability | Event (A) Rated Probability | Joint Cell Number | Event (B) Rated Probability | Event (B) Probability | Cloud Category |
|---|---|---|---|---|---|---|---|
| (B) | 1 | .2 | .2 | 1-1 | .2 | .3 | 1 |
| | | | | 2-1 | .1 | | |
| | 2 | .5 | .1 | | | | |
| | | | .3 | 2-2 | .3 | .3 | 2 |
| | | | .1 | 2-3 | | | |
| | 3 | .2 | .1 | 3-3 | .1 | .2 | 3 |
| | | | .1 | | .1 | | |
| | | | | 3-4 | | | |
| | 4 | .05 | .05 | | .1 | .1 | 4 |
| | | | | 4-5 | .05 | | |
| | 5 | .05 | .05 | 5-5 | .05 | .1 | 5 |

Table B-4 (cont'd)

| | | JOINT PROBABILITY (B) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | Total= UNCON(A) |
| | 1 | .2 | 0 | 0 | 0 | 0 | .2 |
| | 2 | .1 | .3 | .1 | 0 | 0 | .5 |
| (C) | 3 (A) | 0 | 0 | .1 | .1 | 0 | .2 |
| | 4 | 0 | 0 | 0 | 0 | .05 | .05 |
| | 5 | 0 | 0 | 0 | 0 | .05 | .05 |

| | | DICON $C_{(B)}$ | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| | 1 | 1.0 | 0 | 0 | 0 | 0 |
| | 2 | .2 | .6 | .2 | 0 | 0 |
| (D) | 3 $C_{(A)}$ | 0 | 0 | .5 | .5 | 0 |
| | 4 | 0 | 0 | 0 | 0 | 1.0 |
| | 5 | 0 | 0 | 0 | 0 | 1.0 |

This process is continued for all categories as shown. These individual entries, divided by the marginal total UNCON (A), become the entries in DICON ($C_B$ $C_A$).

If any element of UNCON (A) is zero, a suitable flag should be entered in the cell number of the joint distribution (See example in Table B-5) into which an entry would fall if that element were very small. In forming the DICON matrix, by division through each row by the corresponding element of UNCON (A), the rule is "flag divided by zero is 1.0." This results in an appropriate entry in DICON to take care of the eventuality of a "forbidden" event A materializing as a result of other manipulations. If an element of UNCON (B) is zero, no special provisions are required, as the resulting distribution will "lock out" that category.

2. Form the diurnal - temporal conditional distribution (DITCON) by

$$\text{DITCON}\,(a_i|b_j) = \sum_{k=1}^{5} \text{DICON}\,(a_i|c_k) \cdot \text{CONTIM}\,(c_k|b_j)$$

where CONTIM is the scaled derived temporal conditional appropriate to the time interval.

3) Use DITCON in place of the temporal conditional in question. The DITCON operation is not required for time intervals of less than 2 hours or approximately 24 hours.

If it is desired that the resulting distribution avoid total lockout of cloud categories of zero probability in UNCON (B), the formula for DICON may be reversed:

$$\text{DITCON}\,(a_i|b_j) = \sum_{k=1}^{5} \text{CONTIM}\,(a_i|c_k) \cdot \text{DICON}\,(c_k|b_j)$$

The two formulas differ in the effective order in which the operations of diurnal change and temporal conditionality are performed. The first procedure, recommended for most applications, performs the conditionality operation first.

As noted earlier, the straight line estimate of temporal conditional distribution at time intervals less than 24 hours tends to overestimate the persistence, i.e., produces a distribution too strongly diagonalized. A large part of this overestimate may be due to the ignored diurnal change. The DITCON operation reduces the diagonalization in a fashion directly related to the degree of diurnal change, lending some confidence to its validity.

Table B-5

Computation of a Pseudo-Conditional Distribution for Diurnal Variation With a Zero UNCON Entry

**UNCON**

| Cloud Category | Event (A) Probability | Event (A) Rated Probability | Joint Cell Number | Event (E) Rated Probability | Event (E) Probability | Cloud Category |
|---|---|---|---|---|---|---|
| 1 | .4 | .3 | 1-1 | .3 | .3 | 1 |
| | | .1 | 1-2 | .1 | | |
| 2 | .3 | .2 | 2-2 | .2 | .3 | 2 |
| | | .1 | 2-3 | .1 | | |
| 3 | .2 | .1 | 3-3 | .1 | .2 | 3 |
| | | .1 | 3-4 | .1 | | |
| 4 | 0 | 0 | 4-4 | 0 | .1 | 4 |
| 5 | .1 | .1 | 5-5 | .1 | .1 | 5 |

**JOINT PROBABILITY**

(B)

| (A) | 1 | 2 | 3 | 4 | 5 | Total |
|---|---|---|---|---|---|---|
| 1 | .3 | .1 | 0 | 0 | 0 | .4 |
| 2 | 0 | .2 | .1 | 0 | 0 | .3 |
| 3 | 0 | 0 | .1 | .1 | 0 | .2 |
| 4 | 0 | 0 | 0 | * | 0 | 0* |
| 5 | 0 | 0 | 0 | 0 | .1 | .1 |

**DICON**

$C_{(B)}$

| $C_{(A)}$ | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | .75 | .25 | 0 | 0 | 0 |
| 2 | 0 | .67 | .33 | 0 | 0 |
| 3 | 0 | 0 | .5 | .5 | 0 |
| 4 | 0 | 0 | 0 | 1.0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 1.0 |

3.4 Scaling for Both Time and Distance

Certain simulation situations may require that a point or area on the earth be observed on a given orbit and a second nearby point be observed on a somewhat later orbit. For this situation, where the time difference between the first and the second observation is less than 36 hours and where the distance between the two observed points is less than 800 miles, the conditional probabilities must be scaled for both time and distance concurrently. The following procedure has been established to accomplish this concurrent scaling for time and distance

3.4.1 Procedure for Scaling for Time and Distance

a) Separately calculate CONDIS and CONTIM for the appropriate distance and time, respectively, from SCOND and TCOND. Perform DITCON diurnal operation on CONTIM if required

b)

$$\text{TSCON}\,(a_i|b_j) = \sum_{k=1}^{5} \text{CONDIS}\,(a_i|c_k) \cdot \text{CONTIM}\,(c_k|b_j)$$

for $a_i$ from 1 to 5 and $b_j$ from 1 to 5

c) If the conditional have been modified for viewed area size (see Section 3.5), substitute TSSCON, SCSCON, and SCTCON for TSCON, CONDIS, and CONTIM respectively.

3.5 Suggested Procedures for Enlarging the Sample Area Size

The change in cloud cover distribution resulting from change in the area size over which the cloud cover is defined is discussed in detail in Section 7 of the Final Report. It was pointed out that dramatic changes take place over the very range of sample areas that are to be used in earth-oriented experiments, and thus in simulation. It is required, therefore, that a reasonably effective method be found for generating suitable cloud cover distributions for enlarged sampling areas from already available information - the available cloud statistics. Collection of adequate samples of raw satellite data seems prohibitive, at least until suitable compilations of digitized data become available.

The general features of the change of cloud cover distribution with size of sample area can be readily visualized. The cloud cover over a point can have but two values - clear and overcast. The cloud cover over the entire earth seems to stay reasonably constant at perhaps 40%. Intermediate sized areas have cloud distributions which pass from the U-shape of small areas to more bell-shaped distributions at rates which depend upon the prevalence of large-scale cloud systems. The temperate zones, in which large cloud systems are the rule, show characteristically U or J-shaped distributions at the 30 mile scale size of the ground observer. Tropical regions may already exhibit bell-shaped distributions at this scale. A distribution originally bell-shaped at a $1^{\circ}$ area becomes more so at $3^{\circ}$ and $5^{\circ}$, at the expense of the already rare clear areas; overcasts also become less probable. A J-shaped distribution tends toward a skewed bell-shape. A U-shaped distribution first becomes binodal, then bell-shaped with increase in sample area scale. In all cases, the probability of clear sky becomes quite small at $5^{\circ}$ (300 nm) scale.

The effect of increasing the sample area size can be demonstrated by a simple computational exercise of doubling the sampling area. In this exercise, the cloud distribution in the two areas can be expressed as the joint distribution of the two sets of events. The initial computation will assume independence between events in the two areas. Table B-6 outlines the computation of the joint distribution from synthetic data. The joint distribution is defined by:

$$\text{PJOINT}(a, b) = \text{UNCON}(a) \cdot \text{UNCON}(b)$$

Each element of the PJOINT matrix corresponds to an average cloud cover over the doubled area. These cloud covers can be reclassified according to the original cloud cover grouping scheme (1 through 5). Table B-7 gives the cloud group assignment of each location in the PJOINT matrix. This location matrix is universally useful in area size computations, and is called KWHERE.

Conversion of PJOINT to the unconditional distribution scaled for the doubled area size, SUNCON, is achieved by the operation of adding together all elements of PJOINT having the same entry in the matching location of KWHERE. The result, shown in Table B-8, is rather startling. The previously U-shaped UNCON has become the strongly peaked SUNCON.

Let us initially investigate some properties of a straight chain of 50-60 mile square areas, corresponding to a diameter of a larger circle. Let each member of the chain be dependent only on the first member. The straight line approximation of the scaling of the spatial conditional distribution then gives rise to individual PJOINT distributions, the elements of which are linear interpolations between the unit diagonal PJOINT of the first member of the chain, and PJOINT of the last. It can be seen that the distribution of the total cloud cover in this chain can be described by PJOINT of the last element, internally summed by reference to the KWHERE locator matrix (see Section 7 of the Final Report)

This extreme change in cloud cover distribution with a relatively small change in area size results from the untenable assumption of independence between cloud events in contiguous areas. Let us repeat the computation, now using a synthetic set of conditional probabilities to describe the dependence of events in the second area on those in the first. Table B-9 outlines the computation.

In the general case,

$$\text{PJOINT (a, b)} = \text{UNON (b)} \cdot \text{CONNEW (a b)}$$

where CONNEW is the spatial conditional distribution appropriately scaled to the distance between centers of the areas.

Even though CONNEW is only moderately diagonalized, the resulting SUNCON distribution more closely resembles its parent UNCON distribution.

Let us now consider the more general case of viewed area size several times the area on which the statistical distributions are based.

3.5.1 An Approach to Scaling for Enlarged Sampling Area Size.

The information at our disposal for the task of enlarging the sampling area size is the unconditional distribution, valid for a sampling area of 30-60 nm diameter, and the spatial conditional distribution, defined for areas about 60 nm diameter with centers separated by about 200 nm. A straight line interpolation or extrapolation has been adopted to find conditional distributions at other distances. No information is available to define the conditional dependence of cloud events within an area on more than one of its neighbors.

Let us initially investigate some properties of a straight chain of 50-60 mile square areas, corresponding to a diameter of a larger circle. Let each member of the chain be dependent only on the first member. The straight line approximation of the scaling of the spatial conditional distribution then gives rise to individual PJOINT distributions, the elements of which are linear interpolations between the unit diagonal PJOINT of the first member of the chain, and PJOINT of the last. It can be seen that the distribution of the total cloud cover in this chain can be described by PJOINT of the last element, internally summed by reference to the KWHERE locator matrix (see Section 7 of the Final Report).

Table B-6

Computation of Joint Distribution, Independent Data

| Cloud Group | UNCON | PJOINT 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| 1 | .3 | .09 | .03 | .03 | .06 | .09 |
| 2 | .1 | .03 | .01 | .01 | .02 | .03 |
| 3 | .1 | .03 | .01 | .01 | .02 | .03 |
| 4 | .2 | .06 | .02 | .02 | .04 | .06 |
| 5 | .3 | .09 | .03 | .03 | .06 | .09 |

Table B-7

Cloud Group Location Matrix

| Cloud Group | KWHERE 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | 1 | 2 | 2 | 3 | 3 |
| 2 | 2 | 2 | 2 | 3 | 3 |
| 3 | 2 | 2 | 3 | 4 | 4 |
| 4 | 3 | 3 | 4 | 4 | 4 |
| 5 | 3 | 3 | 4 | 4 | 5 |

Table B-8

Cloud Cover Distribution for Doubled Area, Independent Events

| Cloud Group | UNCON | SUNCON |
|---|---|---|
| 1 | .3 | .09 |
| 2 | .1 | .15 |
| 3 | .1 | .41 |
| 4 | .2 | .26 |
| 5 | .3 | .09 |

Table B-9

Computation of Cloud Cover Distribution for
Doubled Area, Dependent Events

| Cloud Group | UNCON | CONDIS | | | | | PJOINT | | | | | SUNCON |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 | |
| 1 | .3 | .5 | .3 | .1 | .1 | 0 | .15 | .09 | .03 | .03 | 0 | .15 |
| 2 | .1 | .1 | .5 | .2 | .1 | .1 | .01 | .05 | .02 | .02 | .01 | .23 |
| 3 | .1 | .1 | .2 | .5 | .1 | .1 | .01 | .02 | .05 | .01 | .01 | .17 |
| 4 | .2 | .1 | .1 | .2 | .5 | 1 | .02 | .02 | .04 | .10 | .02 | .30 |
| 5 | .3 | 0 | .1 | .1 | .3 | .5 | 0 | .03 | .03 | .09 | .15 | .15 |

### 3.5.2 Procedure for Computation of Unconditional Distribution Scaled for Sample Area Size

We recapitulate the procedure for finding SUNCON.

1) Tabulate the unconditional and conditional distributions for the required regions, month and time of day. (These scaled conditionals are called CONNEW.)

2) Scale the conditional statistics, using the procedures detailed in Section 6 of the Final Report, to a distance which corresponds to the diameter of the required enlarged viewed area. (These scaled conditionals are called CONNEW.)

3) The unconditional distribution UNCON is multiplied into the conditional distribution matrix CONNEW

4) The resultant joint distribution matrix is PJOINT summed using the KWHERE matrix for reference.

5) A new unconditional distribution, SUNCON, applicable to the enlarged viewed area size, results.

### 3.5.3 Computational Procedure for Enlarging the Area Size for Conditional Distributions

The procedure for enlarging sampling area size for conditional distributions is similar to, but more involved than the procedure for the unconditional distributions.

Referring to Figure B-7, we are given unconditional distributions for the area represented by "a" and conditional statistics for area "c" some distance $\Delta$ from area "a". What we wish to compute is the conditional probability distribution for new enlarged area B given the unconditional probabilities for new enlarged area A (both areas have been enlarged to the new diameter $\alpha$). Thus, what is required is to first expand area "a" to area A using the techniques described in paragraph 3.5.2 above. Then, to obtain the new 5 x 5 conditional probability matrix for area B, given A, we define:

$$P(A, B) = \text{joint probability of cloud cover in A and B}$$

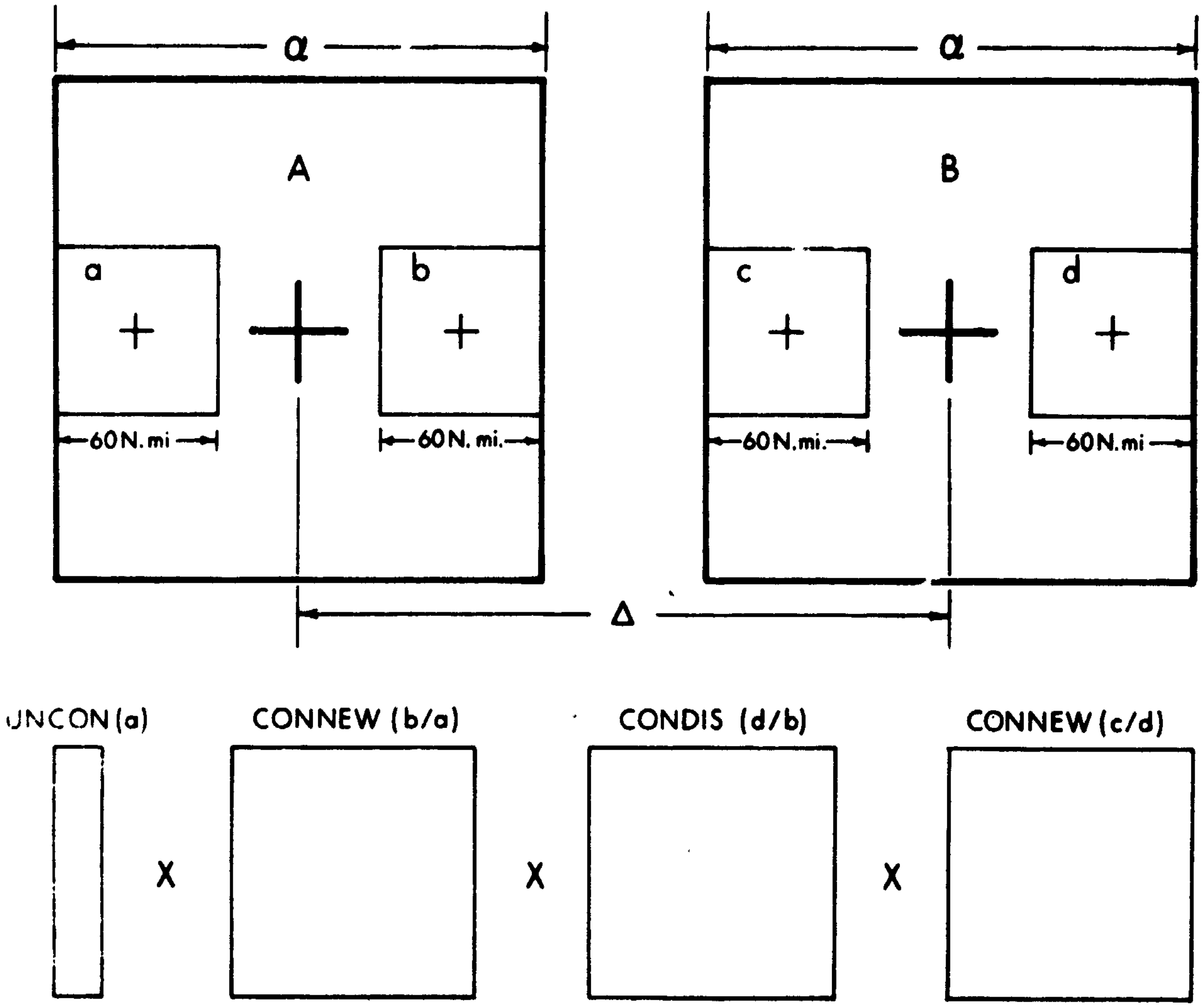



Figure B-7 Scheme for Computation of Spatial Conditional Distribution of Enlarged Sample Areas.

The computational algorithm for accomplishing this multiplication of probabilities is to perform the multiplications indicated in Figure B-7, where a schematic form for the matrices has been used. In this figure, where CONNEW is the expanded sampling area space conditionals, etc., the joint probability of events in all four areas is:

$$P(abcd) = P(a) \cdot P(b|a) \cdot P(d|b) \cdot P(c|d)$$

where the order of conditionality is somewhat arbitrary.

We define the cloud cover in area A to be the average of the cloud cover in a and b, while the cloud cover in B is the average cloud cover in c and d. Thus, we can write formally:

$$P(A, B) = P(\overline{ab}, \overline{cd})$$

To find $P(\overline{ab}, \overline{cd})$, the KWHERE locator matrix is used 4-dimensionally. This involves assigning values to $\overline{ab}$ from the a and b locations in the 4-dimensional PJNT matrix, and to $\overline{cd}$ from the c and d locations. The result is the two dimensional joint probability table P(A, B). This is transformed to the conditional probability by division by the marginal total.

$$P(B|A) = \frac{P(A, B)}{\sum_B P(A, B)}$$

The process of finding temporal conditional distributions of enlarged sample areas is identical, with the exception that CONTIM is substituted for CONDIS. CONNEW (c|d) should be computed for the local time of event B, and the DITCON operation (Section 3.3) should be performed in finding CONTIM.

### 3.5.4 Example of Computation Procedure for Enlarging Area Size for Conditional Distributions

We choose as an example the expansion of the conditional statistics for Region 19 (southeastern U.S.) for mid-day in January. The tabulated data for 30-50 nm area and 200 nm distance are shown on page C-7. The conditional distribution is scaled for α and Δ as shown in Figure B-7 and described in Section 3.2.1 For this example 180 nm was chosen for both α and Δ. The input values for the computation discussed in Section 3.5.3 and illustrated in the lower half of Figure B-7 are shown in Table B-10.

Table B-10 Input Values for Example of Computational Procedure for Enlarging Area Size for Conditional Distributions

| Cloud Group | UNCON(a) | | CONNEW (b\|a) | | | | | | CONDIS (d\|b) | | | | | | CONNEW (c\|d) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | b | | | | | | d | | | | | | c | | | | | |
| | | | 1 | 2 | 3 | 4 | 5 | | 1 | 2 | 3 | 4 | 5 | | 1 | 2 | 3 | 4 | 5 | |
| 1 | .15 | | .784 | .045 | .045 | .045 | .081 | | .784 | .045 | .045 | .045 | .081 | | .784 | .045 | .045 | .045 | .081 | 1 |
| 2 | .12 | | .153 | .253 | .072 | .072 | .450 | | .153 | .253 | .072 | .072 | .450 | | .153 | .253 | .072 | .072 | .450 | 2 |
| 3 | .04 | a | .117 | .108 | .235 | .270 | .270 | b | .117 | .108 | .235 | .270 | .270 | d | .117 | .108 | .235 | .270 | .270 | 3 |
| 4 | .17 | | .126 | .081 | .126 | .505 | .162 | | .126 | .081 | .126 | .505 | .162 | | .126 | .081 | .126 | .505 | .162 | 4 |
| 5 | .52 | | .117 | .054 | .108 | .144 | .577 | | .117 | .054 | .108 | .144 | .577 | | .117 | .054 | .108 | .144 | .577 | 5 |

To find the joint probability

$$P(A, B) = P(\overline{ab}, \overline{cd})$$

we use the summation matrix (KWHERE) twice i.e., use the KWHERE matrix for the set a, b and again for the set c, d (Table B-11) Entries in the joint probability matrix P (A, B) =PJNT (A, B) are derived by reference to Table B-11. For example if KWHERE (a, b) = 1, B =1; if KWHERE (c, d) = 1, A = 1. Reference to Table B-11 indicates that the only way KWHERE (a, b) can equal 1 is for a = 1 and b = 1. Similarly for KWHERE (c, d) = 1, c = 1 and d = 1. Thus, the only entry in PJNT (A, B) at A = 1, B = 1 results when a = b = c = d = 1.

Refer again to Table B-11. Entries in PJNT (1, 2) result if A = 1 which again implies that c = 1 and d = 1. However, B = 2 can be obtained in seven ways, i. e.

| | | | | | | |
|---|---|---|---|---|---|---|
| b = 2 | b = 3 | b = 1 | b = 2 | b = 3 | b = 1 | b = 2 |
| a = 1 | a = 1 | a = 2 | a = 2 | a = 2 | a = 3 | a = 3 |

Similarly for A = 1, B = 3, we find c = 1 and d = 1 while a and b are paired in in nine possible ways (all "three" entries in KWHERE (a, b). This procedure is followed to find all of the subentries in PJNT (A, B). To find each entry in PJNT (A, B) we must sum the subentries obtained by multiplying the appropriate values as extracted from Table B-10 (according to the following formula for all possible combinations of a, b, c, d (as obtained just above).

$$P(abcd) = P(a) \cdot P(b|a) \cdot P(d|b) \cdot P(c|d)$$

For PJNT (1, 1)

$P(a) = P(1) = .15$
$P(b|a) = P(1|1) = .78$
$P(d|b) = P(1|1) = .78$
$P(c|d) = P(1|1) = .78$

**Thus, PJNT (1, 1) = . 15 x . 78 x . 78 x . 78 = . 072**
**Enter this value in Table B-12A at PJNT (1, 1)**

Table B-11

Four Dimensional Locator Matrix (KWHERE)

KWHERE (a, b)

| Cloud Group | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | 1 | 2 | 2 | 3 | 3 |
| 2 | 2 | 2 | 2 | 3 | 3 |
| 3 | 2 | 2 | 3 | 4 | 4 |
| 4 | 3 | 3 | 4 | 4 | 4 |
| 5 | 3 | 3 | 4 | 4 | 5 |

KWHERE (c, d)

| Cloud Group | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | 1 | 2 | 2 | 3 | 3 |
| 2 | 2 | 2 | 2 | 3 | 3 |
| 3 | 2 | 2 | 3 | 4 | 4 |
| 4 | 3 | 3 | 4 | 4 | 4 |
| 5 | 3 | 3 | 4 | 4 | 5 |

**B = KWHERE (a, b)**

**A = KWHERE (c, d)**

For PJNT (1,2), the values from Table B-10 are

$$\left.\begin{array}{l} a = 1 \\ b = 2 \\ c = 1 \\ d = 1 \end{array}\right\} .15 \times .045 \times .153 \times .784 = .00081$$

$$\left.\begin{array}{l} a = 1 \\ b = 3 \\ c = 1 \\ d = 1 \end{array}\right\} .15 \times .045 \times .117 \times .784 = .00062$$

$$\left.\begin{array}{l} a = 2 \\ b = 1 \\ c = 1 \\ d = 1 \end{array}\right\} .12 \times .153 \times .784 \times .784 = .0112$$

$$\left.\begin{array}{l} a = 2 \\ b = 2 \\ c = 1 \\ d = 1 \end{array}\right\} .12 \times .253 \times .153 \times .784 = .0036$$

$$\left.\begin{array}{l} a = 2 \\ b = 3 \\ c = 1 \\ d = 1 \end{array}\right\} .12 \times .072 \times .117 \times .784 = .00079$$

$$\left.\begin{array}{l} a = 3 \\ b = 1 \\ c = 1 \\ d = 1 \end{array}\right\} .04 \times .117 \times .784 \times .784 = .00288$$

$$\left.\begin{array}{l} a = 3 \\ b = 2 \\ c = 1 \\ d = 1 \end{array}\right\} .04 \times .108 \times .153 \times .784 = .00051$$

The sum of these seven values (.0204) is entered in Table B-12A at PJNT (1,2). The remaining entries are found in a similar way. The result is shown as Table B-12B. If PJNT contains a row of zeros insert "1" in the diagonal position.

The marginal totals in both directions are important. The marginal totals resulting from summing over A gives SUNCON (The scaled unconditional distribution) while the marginal totals resulting from summing on B are used as divisors to obtain P(A|B) or SCSCON. Each entry in a row of PJNT (A, B) is divided by the marginal sum to obtain a row of entries in SCSCON. See Table B-12C where .072/.212 = .341 etc. The values in SCSCON matrix are the distance conditionals scaled to a 180 nm viewed area and 180 nm distant from the unconditional event.

Table B-12

Resultant Joint Probability Matrix and Scaled Conditional Probabilities

(A) PJNT (A, B)

| Cloud Group | B 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | .072 | .0204 | | | |
| 2 | | | | | |
| 3 | | | | | |
| 4 | | | | | |
| 5 | | | | | .099 |

(B) PJNT (A, B)

| Cloud Group | B 1 | 2 | 3 | 4 | 5 | Σ B |
|---|---|---|---|---|---|---|
| 1 | .072 | 021 | .064 | .027 | .028 | .212 |
| 2 | .012 | .010 | .021 | .025 | .018 | .086 |
| 3 | .018 | 018 | .092 | 063 | .059 | .200 |
| 4 | .009 | 17 | .048 | .131 | .095 | .300 |
| 5 | .006 | .014 | .040 | .041 | .010 | 201 |
| Σ A | .117 | .080 | .215 | .289 | .300 | |

SUNCON

(C) SCSCON = P(B | A)

| Cloud Group | B 1 | 2 | 3 | 4 | 5 | Σ B |
|---|---|---|---|---|---|---|
| 1 | .341 | .097 | 302 | .130 | .130 | 1.0 |
| 2 | .139 | 120 | .244 | .286 | .211 | 1.0 |
| 3 | .092 | 089 | 211 | 314 | 294 | 1 0 |
| 4 | .031 | .056 | .160 | 436 | .317 | 1.0 |
| 5 | .028 | 071 | .198 | 204 | 499 | 1.0 |