ANTARCTIC SEA ICE: 1972–1975*

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The areal extent and variability of sea ice is one of the most important of the numerous components that interact to produce global climatic patterns, even for areas far removed from the polar zones. Sea ice in the south-polar region exhibits significant seasonal and interannual variations that from a practical viewpoint are important for Antarctic coastal navigation and fishery operations. The impact of these variations on global climate can have other far-reaching consequences.

The presence of an ice cover effectively halts the exchanges of energy and mass between ocean and atmosphere and, therefore, must influence the behavior of the atmosphere. The sea ice becomes, as far as interface processes are concerned, an extension of the Antarctic continental ice sheet. During the time of minimum ice extent (usually March), ice occupies approximately 6 percent of the total hemispheric area; at the time of maximum extension (usually September), ice covers nearly 33 million square kilometers, or almost 13 percent of total hemispheric area. Fluctuations of this magnitude must profoundly influence the global energy balance and associated circulation patterns. Any global or hemispheric climate model should therefore contain sea-ice cover as a variable.

Until recently, reliable estimates of the extent and the variability of Antarctic sea ice were difficult to obtain. Early maps depicted ice boundaries based on data that were poorly distributed in both space and time. Accordingly, these maps exhibit significant differences. With the deployment of earth-monitoring satellites in the early 1960's, observation improved markedly. Nevertheless, the chosen orbital paths and a reliance on visible and near-infrared imaging did not allow continuous or complete coverage. Development of the Electrically Scanning Microwave Radiometer (ESMR) and its placement on the polar-orbiting Nimbus V satellite in December, 1972, provided scientists with complete coverage of ice extent on a daily basis, regardless of cloud cover or light conditions. This valuable tool provides an accurate means of monitoring short-period, seasonal, and interannual fluctuations of the Antarctic sea ice. This study examines the temporal and spatial variations of the ice boundary and calculates the statistics that describe the boundary and its variations. These analyses will form the basis for future comparisons.

Historical Perspective

Philosophers of ancient Greece believed that a vast landmass, heavily populated and possessing abundant natural resources, must be located south of the equator so as to balance the known landmass to the north. Concurrently, the Greek theory of an earth divided into three climatic zones, torrid, temperate, and frigid, postulated that the equatorial zone was impassable because of extreme heat. Exploration of the large southern continent was subsequently discouraged for hundreds of years.1

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Once the equator was crossed in 1475, interest in the legendary land, labeled “Terra Australis Incognita” on maps of the 1500s, was rekindled. Magellan’s passage through the straits that bear his name and Dutch voyages around Cape Horn in 1615 suggested the remoteness of the Antarctic continent. In 1768 Captain James Cook set sail from Plymouth, England, with instructions from the British Admiralty to sail to 40° south latitude in search of the southern continent. Cook discovered no continent at this latitude. Returning to the southern hemisphere four years later with instructions to sail as far south as he wished, Cook and his crew were the first to circumnavigate Antarctica. During the three summer seasons that were required to complete that voyage, the Antarctic continent was never sighted. Although Cook did not prove the existence of Antarctica, his sightings of numerous icebergs and sea ice laid to rest the lingering myth of a vast land rich in culture and resources.

Among the discoveries made by Cook were the huge populations of fur-bearing seals inhabiting the subpolar islands. The active sealing industry that followed in the early 1800s attracted fleets of ships and necessitated observation of icebergs and sea-ice patterns in the vicinity of the sealing grounds. Yet inaccurate reports and the highly competitive nature of the sealers slowed progress in charting the ice margins and coastlines. In 1819 the Russian explorer, Thaddeus von Bellingshausen, probably became the first person to see the continent proper, although he did not report his sighting as such.

With the advent of pelagic whaling one hundred years later came the first serious consideration of the general distribution of Antarctic sea ice. In 1923 the British Colonial Office organized the Discovery Committee to further oceanographic research. During the next twenty years the committee funded numerous expeditions to the Antarctic. Based upon observations recorded during some of these expeditions and supplemented by reports from whaling ships, H. E. Hansen in 1934 was able to publish the first maps of sea-ice distribution. The maps depicted conditions between 40°W and 110°E for four summer seasons during the period from 1929 to 1934. In 1936 Hansen published an atlas that showed the mean positions of the ice edge in November, December, January, and March, except for the Pacific sector, where mean positions were shown for January and March only. It was reported by J. A. Heap that, in some areas, Hansen mapped the ice boundary by connecting simultaneous positions of whaling ships that were in the vicinity of the ice edge. In 1940 N. A. Mackintosh and H. F. P. Herdman published the definitive work on sea-ice limits, showing the mean position of the ice edge for all twelve months. Many atlases still use modified versions of these original maps. The decline of the whaling industry and the advent of World War II resulted in a decrease in sea-ice research, and the succeeding twenty-five years produced little in the way of significant modifications to the understanding of the sea-ice extent on the southern oceans.

The launching of earth-orbiting satellites in the late 1950s heralded a new era in

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3 Friis, op. cit. [see footnote i above] p. 241.
4 Friis, op. cit. [see footnote i above] p. 297 and Wiggins, op. cit. [see footnote 2 above].
the study of polar ice conditions. From the vantage point of space, it became possible to view large sections of Antarctica simultaneously or from mosaics obtained over a few hours. The first weather satellite to occupy a near-polar orbit was Nimbus I, launched in August, 1964. Earlier satellites were not capable of continuous polar observation because of their orbital patterns. In addition, the reliance on visible and near-infrared wavelengths precluded observation during the "polar night" or in the presence of cloud cover.

The first continuous monitoring on a year-round basis of south-polar sea ice became possible with the launch of Nimbus V on December 11, 1972. The nearly circular polar orbit (1089 kilometers X 1102 kilometers) permitted complete global surface coverage in twelve hours, regardless of cloud cover or light conditions. This research is concerned with the analysis of these data.

THE DATA

The original measurements for this study were made by an ESMR mounted aboard Nimbus V. The receiver is sensitive to radiation from 19.225 to 19.475 GHz or the equivalent of a central wavelength of 15.5 millimeters, except for a 10 MHz gap in the center of the band.9 The radiation in these frequencies depends upon the emissivity and the physical temperature of the earth's surface and is affected by high humidities and large liquid droplets in the atmosphere. Because humidity is low and the number and size of liquid particles are small in polar regions, the radiation recorded by the receiver can be assumed to be emitted from the surface layer. Furthermore, the radiation is unaffected by the presence of cloud or darkness.

The resulting output, known as the brightness temperature, is more a function of the surface emissivity than of the physical temperature. At 15.5 millimeters the emissivity of old ice is about 0.8, of first-year ice about 0.95, and of sea water about 0.4. Therefore, these different surfaces are distinguishable.10

In order to obtain as reliable and complete a coverage of the Antarctic region as possible, NASA scientists divided the original records into three-day intervals that are averaged in both time and space. The final product is a uniform 293 by 293 square array of cells overlaying a stereographic projection of the south-polar region with the outer edges tangent to 50°S. The average length of a cell side is 31.5 kilometers at the pole and 28.05 kilometers at 50°S.

Even with averaging, several three-day arrays are missing completely, and cells and groups of cells within other arrays contain no data. Consequently, some initial interpolation was performed. It consisted of averaging surrounding cells and was successful in the majority of cases. Of a possible 299 maps for the period December 19, 1972, to June 4, 1975, 219 are retained for study. Two major gaps appear, February 26 to May 29, 1973, and August 1 to September 5, 1973 (Figs. 1 and 2).

Based on work by NASA scientists, the 155K brightness isotherm is assumed to coincide with the 15-percent ice-cover isopleth in Antarctic waters.11 It was found that

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the $155K$ brightness isotherm also follows the outer edge of a steep gradient in brightness temperature. Two-dimensional differentiation reveals this zone to have a rate of change of brightness between one-half and one kelvin per kilometer with a width between 120 and 150 kilometers. Until further ground-truth studies have been conducted, it is assumed that this zone coincides with that of broken pack ice having an areal density between 15 to 85 percent. In the following, the ice boundary is assumed to be synonymous with the $155K$ brightness isotherm.

**Spatial Analysis of the Pack-Ice Boundary**

Once the ice-sea boundary has been identified, various approaches may be applied to describe its form. The simplest and most complete description is a map containing all the original data. More useful procedures are ones that summarize the most important features such as mean extents, asymmetries, embayments, promontories, and polynyas. The major approach taken in this research has been to follow statistical reasoning to describe the wealth of data on the original maps. It turns out that many of the summarizing statistics have useful physical interpretations.

Statistical description of data involves the specification of the central tendency and of the magnitude and the form of the variability. If the data are independent and normally distributed, then the two statistics (the mean and the variance) are sufficient descriptors. In the case of nonnormality, higher moments will be necessary. For sequenced data, such as those identifying a boundary, the location of one point is not independent of those on either side. Consequently, this interdependence needs to be specified as, for example, through the calculation of the autocovariance function. This indicates the degree of relationship between a single point and other points at successively increasing distances. Unfortunately, the autocovariance function is not easily interpretable. On the other hand, the Fourier coefficients obtained from fitting a Fourier series to this function are equivalent to the proportion of variance accounted for by that particular sinusoidal curve. The same information may be obtained by fitting a Fourier series to the original data, and the step of calculating the autocovariances is unnecessary.

The mathematical requirements for such a procedure are that the original function be periodic and that it be single-valued. That the boundary is periodic is clear because it is the same regardless of the number of times that it is followed backward or forward around Antarctica. A variable observed around the earth is one of the few examples of true periodicity. The requirement that the boundary be single-valued is not fulfilled if the independent variable is taken as the longitude; there are frequent instances where the boundary curves back and forth across the same meridian or where polynyas produce several boundaries. The solution here has been to generate two series: one of maximum ice extent (minimum latitude = MINL) and one of minimum continuous ice extent (maximum latitude = MAXL).

Because the $155K$ brightness isotherm appears within the continent of Antarctica and in lower latitudes, especially around the southern tip of South America, these regions are initially masked out. Then each remaining cell edge is interrogated for $155K$. For a given integer longitude (for example, $41.50^\circ$E to $42.49^\circ$E), the MAXL and the MINL are retained.

The resulting series are good representations of the actual boundary only when

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SELECTED HARMONICS OF THE MINIMUM LATITUDE OF THE ICE-SEA BOUNDARY

FIG. 1—Minimum latitude of the ice-sea boundary. The seven time plots display the mean latitude of the boundary, the total variance, the percent of variances in each of the first four harmonics, and their combined total as a percentage.
Fig. 2—Maximum latitude of the ice-sea boundary. The seven time plots display the mean latitude of the boundary, the total variance, the percent of variances in each of the first four harmonics, and their combined total as a percentage.
and where they coincide. The coincidence occurs in winter for the whole boundary and throughout the year in longitudes between 20°E and 70°E off Enderby Land and between 130°E and 160°E off eastern Wilkes Land. At other times, the series are envelopes for the boundary, a circumstance that to some extent limits their usefulness. In addition to the ice–sea boundary, the continental outline, including the ice shelves, is digitized for maximum and minimum latitude extensions. These are combined to produce an outline (Fig. 3) that reveals some differences from the original base map.12 The harmonic analysis technique has been discussed in relation to weather elsewhere, so that further elaboration will not be given here.13 The results of the analysis reveal

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that the first seven harmonics are sufficient to describe more than 70 percent of the MINL boundary throughout the observation period and more than 90 percent of the winter seasons. In other words, the remaining 173 components are generally very small and unimportant. Apparently they account for the random elements in the 360-item series. Because of space limitations, only the first four harmonics and their sums as percentages of the total variance are given with the means in Figures 1 and 2.

**THE MEAN AND AREA**

The first amplitude produced by Fourier analysis is the mean of the data, the average of the latitudes observed at the 360 meridians, and is hereafter called the zonal average. The continental outline with ice shelves has a mean of 71.14°S for MINL and 71.65°S for MAXL. Both the MINL and the MAXL boundary averages clearly display annual fluctuations. The curves are smooth and similar from year to year. For the MINL, the highest latitude reached is between 68°S and 69°S in each of the three Februarys and the lowest is 60°S in September and early October for 1973 and 1974. Similar statements may be made for the MAXL in which the magnitudes are from 69°S to 70°S and 61°S. Actual extremes during the recorded period were 59.93°S on September 4, 1974, and 68.84°S on February 19, 1975, for the MINL series (Figs. 4 and 5) and 60.60°S on October 3, 1973, and 69.77°S on February 16, 1975, for the MAXL series.

In each of the time series the late-winter peak extension of ice lasts longer than the short late-summer minimum. Based on the mean for the whole series, the summer lasts approximately 160 days and the winter lasts 205 days. In addition, for each of the examples the curves are asymmetric, an indication that the spring-summer removal is more rapid than the autumn-winter growth. The former takes about 120 days, whereas the latter is almost 150 days.

A more objective measure of some of these findings is obtained through the fitting of the mean and an annual sinusoid by least squares to the time series of zonal averages. For the MINL, an overall mean of 63.75°S and an annual range of 8.66 degrees are produced. The phase places the occurrence of the highest latitude at March 1 and the lowest at September 1. However, because of the above-mentioned asymmetry ten to fifteen days should be subtracted from and added to these dates respectively for the actual extremes. For MAXL the overall mean is 64.85°S and the annual range is 8.80 degrees. The occurrence of the highest and lowest latitudes is eleven days earlier than for the MINL of the ice-sea boundary.

The zonal average may be used to calculate the area of the ice, if the earth is assumed to be a sphere. Then the area of a polar cap is given by Area = 2πr² (1-sin φ), where r = 6371 kilometers for the earth and φ is the latitude. Applying the equation to the mean latitude of the continent (MAXL = 71.65°S, MINL = 71.14°S), estimates of between 13 million and 13.69 million square kilometers respectively are obtained. These figures are close to those usually quoted for Antarctica; W. Schwerdtfeger, for example, uses 14 million square kilometers.14

As indicated above, the zonal mean value is calculated in the normal manner with each observation of latitude having equal weight. If the results are to be used to obtain area, lower latitudes should have greater weight than higher latitudes because they represent proportionately larger sectors of the polar cap. A sine transformation

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applied to the continental outline produces 70.66°S for MINL and 71.17°S for MAXL and gives areas of 14.39 million square kilometers for MINL and 13.65 million square kilometers for MAXL. The recomputed areas are approximately 5 percent greater than the originals. For a sample of ice boundaries, which are generally less irregular than the continent, the areas calculated via the sine transformation are only about 2 percent larger.

The extreme areas of the ice calculated from the simple zonal averages are 34.32 million square kilometers (September 4, 1974) and 17.20 million square kilometers (February 19, 1975) for MINL and 32.84 million square kilometers (October 3, 1973) and 15.73 million square kilometers (February 16, 1975) for MAXL. If it is assumed that the continent including the ice shelves occupies 13.5 million square kilometers, these estimates show that the area covered by the pack ice varies between 3 and 20
The minimum ice extent as represented by the 155K brightness isotherm. Similar figures were given by Schwerdtfeger who relied on the work of A. F. Treshnikov. \textsuperscript{15}

**The Centroid**

The second amplitude of harmonic analysis refers to the amplitude of a single sinusoid around the earth. When a sinusoid is plotted on a polar projection, it becomes a circle with a radius of the zonal mean. The circle is centered off the geographic pole by the amplitude in a direction given by the phase. On the assumption that the ice is continuous within the boundary used, this center is also the centroid of the ice.

The calculations set the centroid of the continent for MINL at 71°E and 86.2°S and for MAXL at 73°E and 85.7°S (Fig. 3), approximately 420 and 480 kilometers respectively from the pole. The difference is due to the curving coastlines of the peninsula and of the eastern Ross Sea and to the islands of the peninsula. These shield the ocean areas on their poleward sides. The circles also represent the area of the continent that must lie between the two extremes. Their positions demonstrate
and quantify the well-known asymmetry of the continent. In terms of land and water contrasts alone, such a bias must have a significant influence upon the atmosphere. This is enhanced by the relief, which is not under investigation here but which also has a similar bias.

A relationship between the continental boundary and the pack-ice boundary may be expected. A plot of the centroids of all the MINL (Fig. 6) shows that they all fall in
Table I—Selected Components of Harmonic Analysis of the Continental Outline

<table>
<thead>
<tr>
<th>MEAN LATITUDE</th>
<th>TOTAL VARIANCE</th>
<th>WAVE NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% P A % P % P % P % P % P % P</td>
<td>1 2 3 4 5 6 7 1-7</td>
</tr>
<tr>
<td>MINL 71.14</td>
<td>18.74</td>
<td>38 71 3.8 20 11 10 24 2 -15 9 5 6 22 4 -7</td>
</tr>
<tr>
<td>MAXL 71.65</td>
<td>18.45</td>
<td>50 73 4.3 17 4 13 16 1 -15 6 0 1 19 2 -9</td>
</tr>
</tbody>
</table>

Key to units:
- Variance = Degrees of latitude squared
- % = Percent of the total variance in the respective harmonic
- P = Phase, distance of the first peak (maximum latitude of the boundary) in degrees of longitude clockwise from 180°
- A = Amplitude in degrees of latitude
- 1-7 = Total of harmonics 1 to 7

the western two-thirds of the eastern hemisphere between longitudes 15°E and 120°E. In the extreme, they lie as far as 500 kilometers from the pole, the continental centroid being similarly distant. However, this extreme occurs in winter when the ice margin is farthest from the continent and therefore may be expected to be least affected by it. In summer, the pack-ice centroid is as little as 70 kilometers from the pole, an indication that the pack ice, especially during periods of minima, is located so as to offset the asymmetry of the more permanent ice and land.

The clustering of the centroids in Figure 6 suggests that there are two distinct groups: one in a linear pattern within plus or minus fifteen degrees of 30°E stretching out to 85.5°S, and the other in a sector between 60°E and 120°E reaching to 87.5°S. The first group is produced during the expansion of the ice between June and October and during the contraction phase from September to the end of the year. The late-summer and autumn periods give rise to the second clustering around 90°E. These centroids show a fairly consistent annual pattern over the two-and-a-half years of observation, a circumstance suggesting that the factors affecting the boundary position are stable from year to year.

The MAXL series reveals a similar but less-consistent pattern (Fig. 7). The range is still 0.8 to 4.5 degrees between longitudes 15°E to 120°E, although linear extension along 30°E of 1973 did not occur in 1974. The change in the movement of the centroid between these years can be associated with the existence of a polynya and an embayment in the ice east of the Antarctic Peninsula throughout the winter of 1974.

The Variance and Its Decomposition

The spatial variance of the boundary is a measure of the variability in terms of north–south deviations from the mean latitude. These may occur as large-scale displacements or as smaller embayments and peninsulas. For the continental outlines of MINL and MAXL, the calculated total variances are approximately 18.5 degrees squared (Table I). If the series is normally distributed, then it can be stated that 68 percent of the coastlines will lie within one standard deviation (square root of the variance) of the mean. For the continent, the figure is 71.4°S plus or minus 4.3 degrees. The boundary is not normally distributed, and these limits account only for about 58 percent of the observations. Nevertheless, the variance is a statistic that may be used as a basis for a comparison of variability.

For the ice-sea boundary there is less uniformity from year to year in the total variance than in the mean. The range for the MINL boundary is 5.3 to 15.3 degrees
squared. The series displays a broad maximum of 13 to 15 degrees squared during the winter of 1973 but shows only a minor increase to 9 to 11 degrees squared in 1974 (Fig. 1). Shorter-period peaks of 11 to 12 degrees squared coincide with the minimum ice in each of the three years. Other irregular fluctuations are also present.

The least-squares fits of the mean and the annual curves to the time series of spatial variances yield estimates for MINL of an overall average of 9.30 degrees squared with an annual range of 2.9. The maximum for the annual curve occurs on November 15, that is, at the end of the long, winter maximum just as the rapid decrease of the mean ice amount begins. This feature gains greater emphasis in the MAXL series. It contains significant peaks of 23.3 degrees squared in 1973 and 22.8 in 1974. Each peak develops suddenly at the end of November and lasts through the early-summer decrease in ice. The least-squares-fitted curves to MAXL produce a mean of 11.7 and a range of 9.7 degrees squared.

The sudden increase in the variance is explained by the rapid development of polynyas. They appear first in the MAXL series. If they open into embayments to join the main ice–sea boundary, they produce a sudden increase in variance in the MINL data. These features will be discussed in more detail.

The decomposition of the total variances into various harmonics (scales) produces a large number of components. As indicated earlier, however, only the larger scales need to be considered in the majority of cases. For example, for both the continental MINL and MAXL series the first 13 waves account for 95 percent of the total variance, and no waves greater than number 13 in either series individually account for as much as 0.5 percent. Only the first seven harmonics are listed in Table I. For the ice–sea boundary, only the first four harmonics are given in Figures 1 and 2.

Wavenumber 1 has already been discussed for its importance in describing the centroid of the boundaries. Each of the next three waves is composed of the number of symmetric maxima and minima as its wavenumber indicates. Thus wavenumber 5 for the continental MINL (Table I) has five maxima, located at 175°W, 103°W, 31°W, 41°E, and 113°E and contributes 9 percent of the total variance. In general, the waves tend to decline in importance from the lower to the higher wavenumbers. For the continent, wavenumber 4 is weak and therefore breaks this pattern.

From data from the MINL series (Fig. 1), it is apparent that during the winter wavenumber 1 accounts for more than 70 percent of the total variance. Minima of approximately 5 percent occur in late spring and of 7 percent in early autumn. A minor maximum of 25 percent separates the minima in summer. The fluctuations, of course, describe the fairly uniform boundary of the ice in winter (Fig. 4). Summer is a period when a more regular boundary again appears (Fig. 5). Wavenumber 2 is important in spring and again in summer when it accounts for more than 30 percent of the variance. Wavenumber 3 has peaks in autumn and spring. So does wavenumber 4 but with smaller magnitudes.

The MAXL series presents a somewhat different picture. The total percentage of variance explained by the first seven harmonics is generally lower, especially in 1974. As has been noted, the annual maximum is missing in wavenumber 1 for 1974, and it is not made up by increased percentage contributions from the next higher wavenumbers. Wavenumber 2 is weaker in 1974, but this is offset by a stronger wavenumber 4 that year. Wavenumber 3 does not present spring peaks as noted for the MINL series.

In general, it may be concluded that the outer ice boundary may be described sufficiently well by the first seven harmonics plus the mean. In other words, the 360
LATITUDE OF MAXIMUM AND MINIMUM ICE EXTENT AT LONGITUDE 180°

Fig. 8—Maximum and minimum latitudes of ice extent at longitude 180°
observations may be reduced to 15 (8 amplitudes and 7 phases). The same conclusion may be made for the inner boundary only for the winter of some years.

**Meridian Time Series**

The data for this study may be thought of as a three-dimensional matrix with two spatial and one temporal dimensions. Thus far, the temporal analysis has been based on the collapsing of the spatial components to single statistics such as the mean, the variance, or the spectral elements. An alternative approach is to transpose this matrix or to look at specific spatial locations through time. Here the MINL and MAXL series are converted into time series for specific meridians. Although all 360 longitudes are analyzed, 180°, 90°W, 0°, and 90°E are reasonably representative of the others and are plotted (Figs. 8, 9, 10, and 11).

Several distinct patterns may be recognized and are present in the four examples. Annual oscillations appear very strongly at longitudes 180° and 0°, whereas they are weak at 90°W and 90°E. MINL and MAXL were essentially the same at 0° between December, 1972, and June, 1974, but they diverged for the winter of 1974, when MAXL remains almost constant. At 180° the series diverged during the summer. At 90°W very little distance separated the two series throughout the period, and at 90°E separation occurred only in early summer. The asymmetry, already noted in the mean series, can be discerned at 90°W, although it is much more sharply defined around 50°E and 110°W. The tendency for constant magnitudes at higher latitudes in the MAXL series is due to the coincidence of the pack-ice boundary with either the continental or the multiyear pack-ice boundaries.

Divergence of the two series is the result of the development of polynyas or embayments. In the four examples they are most significant at 180° and 0° where they appear suddenly first in the MAXL series and, in some cases, later in the MINL series. At 180° the coast of the embayment curved back and forth so that open water extended all the way along the meridian only for a few days in the summer of 1972–1973 and the latter part of the 1974–1975 summer. At 0° during the winter of 1974 open water remained in high latitudes throughout the season, but in each of the three summers the whole meridian up to 68°S experienced less than 15 percent ice for approximately five months. An unusual minor maximum in the 90°W series during July, 1973, was the result of a large feature in the western hemisphere boundary and has no simple explanation.

All four examples reveal small-scale fluctuations of the boundary, especially during the long winter seasons. These amount to 0.1 to 0.3 degrees of latitude per day, usually with alternating signs. The changes that accompany the opening and the closing of embayments (MINL series) are much larger and are approximately 3 degrees per day for the 0° longitude.

A study of all meridians reveals that the maximum extension of the pack ice occurs off the Antarctic Peninsula at approximately 30°W and also in the vicinity of 10°E. Actual extremes for these sectors were 53.96°S on July 17, 1973, and 52.86°S on September 21, 1973. Similar extremes in sequence occurred in 1974. Subjective review of the maps for the winter periods suggests that there is a rotation of the outer pack ice clockwise around the pole by several degrees. It is recognizable in most regions, but especially near 0° and 145°W as noted previously by S. F. Ackley and T. E. Keliher.
LATITUDE OF MAXIMUM AND MINIMUM ICE EXTENT AT LONGITUDE 90°W

Fig. 9—Maximum and minimum latitudes of ice extent at longitude 90°W.
Fig. 10—Maximum and minimum latitudes of ice extent at longitude 0°
Fig. 11—Maximum and minimum latitudes of ice extent at longitude 90°E.
Enclosed water areas, polynyas, are important features of the pack-ice-distribution maps and, as has been demonstrated, frequently control the various boundary statistics. Moreover, because there are order-of-magnitude differences between the latent and sensible heat fluxes over an ice surface as compared to an open-water surface, these polynyas must be regarded as significant elements in the energy and wave exchanges between the surface and the atmosphere in the Antarctic.

Typical of a growth period of the polynyas is the interval between November 20 and December 18, 1973. After the period of maximum ice extent (early October), the ice field began to shrink, and the ice–sea boundary assumed a more “jagged” appearance with small polynyas appearing within the ice early in November. On November 20 both the Ross Sea polynya (77°S, 180°E) and the polynya in the lee of the Antarctic Peninsula (63°S, 8°E) reappeared. The latter polynya expanded rapidly during the next twenty-one days until it merged with the ocean on December 11 (Fig. 12). Initially, the Ross Sea polynya expanded quickly until December 6, after which growth was confined to the vicinity of 180°. This same pattern of enlargement was noted in the preceding year. On December 23 this polynya opened to the ocean. Smaller ice-free areas were again present on the eastern margin between 60°E and 120°E at 65°S to 70°S latitude and within the pack ice between 20°W and 120°W at approximately 75°S latitude. In particular, these polynyas form near the boundary between the permanent and seasonal ice fields. Polynyas near the eastern margin merged with the sea as the ice receded, but various small polynyas on the western side persisted throughout the period of minimum ice extent until they disappeared between March 20 and April 7, 1974, when the ice fields once again started to expand.

The winter season of 1974 is especially interesting because a large polynya in the lee of the Antarctic Peninsula developed and remained throughout the winter. As the ice field increased in area with the approaching winter, particularly rapid growth of the pack ice was observed to approximately 57°S to 58°S latitude between 0° and 50°W longitude around and to the lee of the Antarctic Peninsula. However, between 0° and 10°E longitude minimal expansion occurred, forming an embayment in the ice field. As the areal extent of pack ice continued to increase, eastward growth of the ice field in the lee of the peninsula began to close off the embayment, except for a narrow channel connecting the ice-free zone with the ocean. The enclosure was complete by July 21 with the formation of a large, elongated polynya between 10°W and 5°E longitude at approximately 65°S latitude. Within three days the polynya had increased in size to approximately 280,000 square kilometers. Then, the size of the polynya remained nearly constant, although slight changes in shape did occur.

Conclusions

These analyses of the three-day-average brightness maps of Antarctica, obtained from the Nimbus V ESMR in the 15.5 millimeter band, have produced a number of important findings. They apply strictly to the period of observation, December, 1972, to June, 1975, but many have more general applicability. Most refer to the 155K isotherm that is assumed to be representative of the 15-percent ice-cover isolphe.

First, the overall mean latitude for the outer ice boundary is 63.75°S, yielding an area of approximately 26 million square kilometers. The continent is estimated to have a mean outer boundary of 71.14°S or an area of 13.69 million square kilometers, so that the average area of pack ice is approximately 12.5 million square kilometers.
Second, the time variation of the spatial mean latitude of the boundary is a relatively smooth function, having maxima each year of 68° to 69°S and minimum of 60°S. Extremes occurred on September 4, 1974, with an average latitude of 59.93°S and an area of 34.32 million square kilometers, and on February 19, 1975, with an average latitude of 68.84°S and an area of 17.20 million square kilometers. The average area of pack ice varies between 3 million and 20 million square kilometers.

Third, the colder seasons are relatively long (205 days) compared to the warmer seasons (60 days) when the division is made on the basis of the mean extent of the ice.

Fourth, the time variation of the spatial mean latitude is asymmetric. The spring-summer removal of ice is relatively fast (120 days) compared to the autumn-winter increase of 150 days. The maximum latitude (summer) occurs in February, and the minimum latitude (winter) occurs in September-October. The asymmetry is ex-
plained by the growth of polynyas that open rapidly and produce suddenly large embayments in the outer boundary.

Fifth, the continent, including the ice shelves and the ice cover to the pack boundary, has centroids varying between 0.8 and 4.6 degrees north of the South Pole in the 15°E to 120°E sector. The continental centroid has a deviation of approximately four degrees from the geographic pole along the 72°E longitude. Pack ice at its minimum extent, which may be expected to conform to the continental outline, has the same orientation, but a much smaller amplitude. The pack ice at minimum extension tends to make Antarctica more symmetrical. Maximum deviations from the geographic pole are produced by the winter ice. The centroids lie four to five degrees from the pole along meridians between 15°E and 45°E. The pack in winter is strongly asymmetrical with an orientation that appears to be unrelated to the continent.

Sixth, the spatial variance of the outer boundary averages 9.30 degrees squared and, except for peaks of 11 to 12 degrees squared in the summers, shows no consistent pattern. The winter of 1973 contained a broad peak, but that season in 1974 did not. The inner boundary, however, displays sudden sharp peaks in the springs followed by high magnitudes during the summers. These may be explained by the development of large polynyas in spring and the existence of an irregular broken boundary in summer.

Seventh, spatial harmonic analysis reveals that the off-centeredness, or wave-number 1, accounts for 70 percent of the variance in winter. Together with the next six wavenumbers, which are generally in descending order of importance, more than 70 percent of the total variance can be explained in summer and more than 90 percent in winter. Therefore, the 360 boundary points for the MINL series may be replaced by 15 Fourier coefficients.

Eighth, the temporal variation of the ice in different sectors is well represented by the meridian time graphs that make it possible to distinguish regions with large and rapid movement (longitude 180° and 0°) from those with smaller fluctuations. In the extreme cases where polynyas open to the ocean in spring, the boundary may change location by as much as an average of three degrees latitude per day (330 kilometers per day). The more frequent and widespread smaller changes are less than one-tenth of this amount.

Ninth, different meridians experience maximum ice extension at different times, a pattern that suggests a clockwise rotation around the pole.

Tenth, two large polynyas, one centered at 180° and 75°S and the other at 8°E and 63°S, dominate the spring periods until the polynyas join the ocean to produce large embayments. In 1974 the polynya in the lee of the Antarctic Peninsula never closed.

The calculated magnitudes in these findings will be different for other periods, but the general conclusions should not change significantly. For example, the area of the ice may be expected to double between the summer minimum in February and the winter maximum in September. The asymmetry in growth and decay and the location of the centroid along approximately 30°E in winter should remain. The pack-ice boundary will tend to be much more irregular in the break-up period than at other times. The polynyas will exist throughout some winter seasons but will dominate the spring. The results of this study form a base with which future ice-boundary variations may be compared and with which computer simulation studies of sea-ice growth and decay in Antarctica may be evaluated.