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ABSTRACT

A multitude of rocket observations were conducted during IQSY which, for the first time, established a synoptic picture of the entire stratosphere, at least in selected regions of the globe, and gave an insight into the seasonal and large scale zonal and meridional behavior of the mesosphere. These massive rocket observations were supplemented by observations from the ground (sodium glow) from satellites (temperature patterns in the stratosphere) and by a number of fundamental theoretical investigations (e.g., treatment of radiative equilibrium, large scale horizontal eddies, gravity waves, tidal oscillations, etc.). Results from these observations and analyses produced some sketchy, though important, inferences of interactions especially between the lower stratosphere and the upper mesosphere. But, perhaps more importantly, they established an understanding of the physics and dynamics of the "middle atmosphere". In the future this understanding will permit the tracing of interactions through this region and across its lower and upper boundaries and will perhaps lead to the delineation of cause and effect of these interactions.

INTERACTIONS BETWEEN THE UPPER AND LOWER ATMOSPHERE*

INTRODUCTION

A number of energy exchange processes, both on horizontal and vertical scales, have been identified in the stratosphere and mesosphere during the IQSY. These processes are the most probable mechanisms through which interactions between the upper atmosphere (thermosphere/ionosphere) and lower atmosphere (troposphere) might take place. Energy is transferred, either radiatively or dynamically, and changes and variations in the structure of the affected region of the atmosphere are produced by these interactions which occur on a wide range of time and distance scales. For example, large scale planetary waves in the lower stratosphere are apparently driven by smaller scale motions in the troposphere. These waves carry energy to high latitudes in the stratosphere in winter to compensate for the energy deficit there caused by radiation (Newell 1966). The waves are superimposed on the mean circulation and are especially pronounced in winter. They have been observed throughout the stratosphere and in the lower mesosphere (Newell 1963, Warnecke 1965). At tropical latitudes, interactions are evidenced by the well known quasi-biennial oscillation, a variation in the circulation of the stratosphere with a period of approximately 26 months (Reed 1965a). On smaller scales, both in time and distance, there is evidence that energy propagation takes place through the upper stratosphere, mesosphere and lower thermosphere in the form of gravity and tidal waves (Hines 1965, Friedman 1966, Lindzen 1967a) and through turbulent exchange (Justus 1965). These interactions take place on a time scale of several hours while horizontal planetary waves have periods ranging from several days up to several months.

Generally, we cannot observe interactions directly, but rather, we infer them from measurements of such parameters as the variation of temperature, pressure, density or wind with time, location and altitude. Such inferences could be misleading if not made properly. If, for example, we attempt to infer the speed and direction of the vertical propagation of kinetic energy from temporal variations of temperature or wind with height, we must realize that we are observing only the propagation of phase. In fact, in some cases such as in gravity wave propagation, the directions of phase and energy propagation may be in opposite directions (Hines and Reddy 1967). A similar situation may hold in the vertical propagation of wind and temperature variations associated with the quasi-biennial oscillation. In that case, downward propagation of these variations is observed (from the middle stratosphere to the tropopause), however, the actual

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source of energy driving these variations may very well be found at lower levels, in the upper troposphere (Newell 1964, Tucker 1966).

Before the IGY and IQSY interactions between the upper and lower atmosphere have been speculated upon. However, only indirect and statistical evidence was available, at best. Since IGY, and especially during the IQSY, measurements were made in greater quantity and under more suitable conditions. These measurements provided a better understanding of the radiational and dynamical processes which might be the basis for many previously suspected, and statistically inferred interactions. It is not necessary to review here the entire observational and analytical progress made during IQSY since Murgatroyd, et al. (1965) have already made such a review for the earlier phase of the IQSY program. The purpose of this presentation is to illuminate the most important findings of the IQSY period and to emphasize those additional phenomena which were explored after that review was published. Foremost among those are the tidal oscillations of temperature and wind in the upper stratosphere and mesosphere, and the possible occurrence of gravity waves which seems to be indicated by extreme fluctuations of temperatures in the mesosphere at high latitudes during winter.

INVESTIGATIONS DURING THE POST-IGY AND IQSY PERIOD

During and immediately after the IGY, a "climatology" of the upper stratosphere and mesosphere had been established. This climatology was expressed in a number of standard and reference atmospheres (CIRA 1961, U. S. Standard Atmosphere 1962). They described the seasonal variation of temperature, pressure and density with height on a large and rather coarse scale, and depicted the overall, large scale, behaviour of the thermally driven circulation in that region: the anti-cyclonic summer easterlies and the intense wintertime polar vortex. During the IGY, the inter-seasonal transition between these two circulation regimes became also rather well known. The structure of the temperature and pressure field as observed during that period was not entirely in agreement with the production of potential energy computed purely on the basis of radiation (Murgatroyd and Goody 1958). It was obvious that the discrepancy was due to energy transports by dynamical processes, however, it was unknown whether these occurred via a simple, mean meridional circulation such as proposed by Murgatroyd and Singleton (1961) or whether more complex interactions, produced by eddies and waves, were responsible for the discrepancy.

The major discrepancy was the latitudinal temperature gradient in the middle and upper mesosphere. Observed temperatures were about 80 - 100° colder over the winter hemisphere than over the summer hemisphere (Fig. 1). Theory, based solely on radiation considerations, required exactly the opposite temperature gradient. Another discrepancy was the magnitude of the temperature difference between summer and winter at the stratopause and in the upper stratosphere. In that region observations showed that at high latitudes temperatures were 20 - 25° higher in summer than in winter (Fig. 1). Radiative computations required a much larger temperature difference between the two seasons at these heights.

The simple, single meridional cell conceived by Murgatroyd and Singleton (1961) postulated that the summer mesosphere be cooled by upward motion and the winter mesosphere be heated by downward motion. Meridional circulation would be maintained from the equator to the poles in the lower stratosphere, and from summer pole to winter pole in the upper stratosphere and mesosphere. An alternate explanation was advanced by Kellogg (1961) who demonstrated that the downward transport of atomic oxygen at high latitudes in winter could produce considerable chemical heating to balance, and indeed reverse, the radiatively computed temperature gradient. However, observational evidence obtained during the IQSY indicated that the variability of the winter mesosphere is so pronounced, that major, short term disturbances must be superimposed on the mean motions postulated by these earlier investigations. Synoptic scale disturbances observed at lower altitudes (below 70 km) in winter, as well as the first substantial observations of oscillations in the tropical stratosphere and mesosphere also required a reassessment of the dynamics of the "Middle Atmosphere". This reassessment came about during IQSY because of two largely interrelated efforts:

a. Observational. A large number of small meteorological rocket soundings were conducted over many areas of the world, including, especially, North and South America, the Atlantic and the Pacific Oceans, and the Polar Regions. Well over 1,000 such soundings were carried out during the period of the IQSY with small meteorological rockets measuring primarily wind and frequently temperature up to the lower mesosphere (Meteorological Rocket Network 1960). These soundings have provided us with a relatively detailed picture of the general circulation of the middle and upper stratosphere and of the variations due to synoptic as well as tidal oscillations in that circulation field (Webb 1964, Reed et al. 1966). Larger rocket probes were also launched into the mesosphere and lower thermosphere. These amounted to approximately 200 to 300 for the same period. These larger probes obtained measurements of pressure, density and wind by means of chemical release, acoustic grenade, falling sphere, pitot tube, and similar methods (IQSY 1964, Smith et al. 1967a). Results from these soundings have been especially helpful in exploring the short term variations and interactions, such as gravity waves and turbulent exchange. They have also produced a new insight into the physics and formation of noctilucent clouds (Theon et al. 1967a) and into the general circulation of the mesosphere (Nordberg et al. 1965a). Finally, fields of temperatures, averaged over a height slab of the middle stratosphere, were derived from satellite observations of thermal radiation emitted by carbon dioxide in the 15 micron band (Nordberg et al. 1965b). Features of the circulation of the middle stratosphere could be inferred daily, on a global scale from these observations by TIROS and NIMBUS (Kennedy and Nordberg 1967, Warnecke 1967). These space techniques, combined with many ground based observations of upper atmosphere phenomena such as air glow (Hunten and Godson, 1967) have produced a vast amount of material on the upper atmosphere. However, a commensurate analytical and theoretical effort was necessary to put these observations into proper perspective.

b. Theoretical and Analytical. Interactions in this region of the atmosphere are produced by radiative and dynamic processes. Radiative processes in the stratosphere and mesosphere were treated rather fundamentally by Murgatroyd and Goody (1958). Since then Manabe and Strickler (1964), Leovy (1964a), Kondratiev (1966), and Lindzen and Goody (1965) have appreciably refined this original treatment. Manabe and Strickler (1964) have included the effect of clouds, water vapor and convective adjustment in their calculations of equilibrium temperatures in the troposphere and stratosphere, Leovy (1964a) and Kondratiev (1966) refined the computation of radiative transfer by mesospheric ozone and CO_2 respectively and Lindzen and Goody (1965) have combined the considerations of radiative and photochemical equilibrium. These investigations were much more detailed than the basic work by Murgatroyd and Goody (1958) but, they have not produced any fundamental disagreements with the conclusions reached in that work. New concepts of the dynamics of the stratosphere and mesosphere, especially for the winter Hemisphere and for the tropics had to be developed to fully explain and exploit the observations.

Leovy (1964b) refined the single cell, mean meridional motion concept of Murgatroyd and Singleton and advanced a possible, but not very likely single cell dynamics consistent with earlier observations. Newell (1963 and 1965) introduced the concept of transport of momentum and kinetic energy toward high latitudes by means of horizontal, planetary scale eddies throughout the stratosphere. Hines (1965, 1967) interpreted the variable temperature structure of the winter mesosphere in terms of gravity wave propagation and feeding of energy from the troposphere into the thermosphere. Reed et al. (1966) interpreted the diurnal variations in the observed meridional circulation of the stratosphere as tidal in nature, produced by solar heating, and Lindzen (1967a) provided a comprehensive theory for the world wide diurnal variations of temperature, pressure and wind with height up to the mesopause based on the solar thermal tide. Finally, Reed (1965a) furnished a thorough description of the quasi-biennial oscillation and found, from analysis of the tropical rocket results (1965b), that this oscillation diminishes in the upper stratosphere and is replaced there by a semiannual, tidal oscillation. Possible driving mechanisms of the quasi-biennial oscillation by tropospheric eddies were advanced by Newell (1964) and Tucker (1966). Each of these findings shall be examined briefly in this review.

IQSY RESULTS

a. Synoptic Disturbances in the Mean Stratosphere and Mesosphere Circulation

Rocket probes conducted over North America and the North Atlantic demonstrated that variations in the temperature and wind field at high latitudes, especially during the winter season, are associated with planetary scale synoptic disturbances throughout the stratosphere and in the mesosphere up to levels of about 70 km (Warnecke and Nordberg 1965 and Theon et al. 1967b). These disturbances which are either transient with a duration of several days or stationary throughout the winter season are superimposed on a mean circulation and temperature field which, especially in the stratosphere and near the stratopause, varies regularly with season. The seasonal variation in the circulation has been described by Webb (1964). Mean temperatures in the upper stratosphere are also in phase with the seasonal variation of solar elevation. Fig. 2 illustrates this fact for the temperature variation at high northern latitudes where stratopause temperatures resulting from acoustic-grenade soundings at Ft. Churchill and Pt. Barrow are shown as "normal" if the measured temperature profile was relatively smooth and displayed a clear temperature maximum at the stratopause level. If the observed temperature profile was variable and showed multiple temperature maxima in the upper stratosphere and lower mesosphere, or if there was a marked deviation of temperature from the smooth profile in a narrow layer, then the maximum temperature measured near 50 km is shown in Fig. 2 as "warming". Pt. Barrow and Churchill were the only high latitude sites where sufficient observations were made during IQSY to construct such an annual picture. "Warming" deviations for 1965/66 were most numerous during the winter and especially during January and February. However, deviations also occur as early as October. No substantial deviations from the overall seasonal pattern occur during the summer months. These large temperature deviations are probably dynamically induced and are connected to the development of planetary scale eddies observed in the wind fields of the upper stratosphere.

Analyses of Northern Hemisphere winter observations by Theon et al. (1967b) have demonstrated that small variations in the position of the Aleutian anti-cyclone, a well known standing eddy over the North Pacific, can produce a transient stratospheric warming at 50 km at Pt. Barrow. Fig. 3 shows three observed temperature profiles over Pt. Barrow during late January and early February 1965. The upper stratosphere and the stratopause were substantially warmer on 4 February than either in the previous or subsequent soundings. Maps of the circulation at 50 km were drawn on the basis of these rocket soundings at Pt. Barrow, and Churchill, and on the basis of Meteorological Rocket Network data over the remainder of the North American continent as well as in the British Isles. They indicate clearly that the Aleutian anti-cyclone existed on all three days, at least up to 50 km (Fig. 4). On 4 February the anti-cyclone had shifted eastward so that Pt. Barrow came under the strong influence of the warm air mass causing the high temperatures observed in the sounding (Fig. 3). Subsequently, the warm ridge receded westward and the polar vortex again dominated the Pt. Barrow region bringing colder temperatures on 8 February. Similar analyses of observations conducted during 1962 (Warnecke and Nordberg 1965) have shown that the mean zonal circulation and its seasonal reversal, as well as disturbances of the type described above extend well into the mesosphere up to about 70 km.

Deviations from the solar controlled patterns of mean temperatures in the stratosphere were observed on a global scale during 1963/64 by the TIROS VII satellite. The temperatures observed by the satellite are not true temperatures at a given stratospheric level, they are not even mean temperatures in a given layer of constant thickness, but rather, they are temperatures relating to a weighted average in the lower and middle stratosphere ranging from about 15 to 30 km. The weights applied to varying height levels vary, depending on latitude and season, in a rather complex manner, as these temperature fields are derived from the satellite observed radiation intensities emitted by the atmosphere in the 15 micron carbon dioxide band. Nevertheless, it has been demonstrated that these temperature fields serve well to describe the state of the middle stratosphere especially in areas where no other observations are available such as in the Southern Hemisphere (Nordberg, et al. 1965b and Kennedy and Nordberg 1967). Examples of these TIROS VII satellite temperature observations are shown in Figures 5 and 6. Isotherms during the Northern Hemisphere winter (Fig. 5) deviate very strongly from the zonal pattern which would be expected on the basis of radiative energy balance alone. As has been well known for many years, the region over the North Pacific remains quite warm throughout the entire winter, while the region over the European and Asian continent cools in accordance with the seasonal pattern. The warm region is associated with the Aleutian anticyclone and provides a standing eddy of wave number one in the Northern Hemisphere circulation throughout the entire winter season. Fig. 6 illustrates a similar situation during the Southern Hemisphere winter. Here, an analogous disturbance in the zonal temperature field is observed over the Australian sector of the Southern Hemisphere. There is a strong temperature gradient with longitude at high southern latitudes during winter. In general, warmer temperatures are found in the Australian sector and the adjacent regions of the Pacific or Indian Oceans, while the region around South America and the adjacent Atlantic Ocean, generally, remains cooler. This was observed during both the winters of 1964 and 1965. However, Kennedy and Nordberg (1967) showed that in contrast to the Northern Hemisphere, the Southern Hemisphere eddy, which is also of wave number one, is considerably more transient in nature. Although the Australian sector seems to be the preferred location for the warm ridge, there is considerable movement in its position from week to week. In the Northern Hemisphere, the center of the ridge is essentially locked into position near the Gulf of Alaska.

While the Tiros observations were restricted to a latitude belt between 65° N and 65° S due to the inclination of the satellite's orbit, it was possible to extend this method of observation into the polar regions with Nimbus II observations during 1966. Nimbus II observations (Fig. 7) demonstrate the asymmetry in the isotherms around the South Pole during the height of the winter in early June 1966. As in the Tiros observations, the Australian sector shows a strong warm ridge while a cold trough extends far northward on the opposite side of the Southern Hemisphere and the warm ridge again oscillates widely around its mean position of about 140° E. A rather symmetrical polar votex was established eventually during early July 1966. The Tiros observations in 1964 and 1965 (Fig. 6) showed that eddy disturbances in the temperature field became strongest during September and October.

Newell (1966) has shown that these transient or standing eddies of the type described above may be fed by energy from the troposphere and could be instrumental in transporting heat and momentum to high latitudes in the stratosphere during winter. Even the increased program of rocket soundings and these first satellite observations of global temperature fields in the stratosphere, however, are still too few to perform a thorough quantitative analysis of correlation products between the components of transport vectors of heat and momentum. Nevertheless, the observed disturbances in the zonal circulation and temperature field agree qualitatively with the theoretical picture developed by Newell. The large departures of high latitude winter temperatures from the smooth annual temperature cycle (Fig. 2) observed with periods of several days in the upper stratosphere and at the stratopause are most probably related to these planetary scale eddies. At higher altitudes, in the mesosphere, eddies on a much shorter time scale may add to the winter heating and cause the departures from smoother temperature lapse rates expected on the basis of radiative processes. Such short period eddies will be discussed below.

During summer, the absence of any major deviations from a smooth vertical temperature profile and the absence of any horizontal, planetary scale eddies in the rocket wind observations indicate that in that season the mean circulation, interacting with radiative heating and cooling, may account for the energy balance in the stratosphere and mesosphere (Leovy 1964a and b).

b. Short Term Eddies in the High Latitude Winter Mesosphere

Temperature profiles observed during the IQSY and later have demonstrated the likelihood of another interaction process which could transfer considerable amounts of energy between various altitude levels in the upper stratosphere and mesosphere at high latitudes in winter. Figures 8 and 9 illustrate the contrast in the temperature profiles between winter and summer at Pt. Barrow, Alaska.

In winter, temperatures above 60 km are extremely variable, and average temperatures are relatively warm. In summer, there is a remarkably smooth and steep lapse rate between 50 and 80 km which results in very cold mesopause temperatures. Pt. Barrow was chosen for this illustration because it is the highest latitude site for which sufficient observations exist to make such a comparison. Additional observations from Wallops Island (38°N) and Churchill (59°N) indicate that this drastic contrast between seasons is most pronounced at Pt. Barrow (71°N) and is smallest at Wallops Island, at a latitude of 38°N (Theon et al. 1967b). Soundings in sufficient numbers have not yet been made to delineate the detailed behaviour of these wavelike winter disturbances in the mesosphere temperatures (Fig. 8). For example, it has not been possible yet to study the direction of phase or energy propagation in these waves. Such investigations are now underway. It can be definitely determined, however, from the IQSY soundings at Pt. Barrow as well as from the other sites, that the amplitude of the temperature oscillation is of the order of ±15° C at the highest latitude (Pt. Barrow), and that the vertical spacing between successive temperature maxima or minima generally ranges from 10 to 15 km. This amplitude is considerably larger than the adiabatic heating which would be produced by compression due to gravity waves described by Hines (1965). However, the vertical wavelength (10-15 km) and period (about 2 hrs) in the observed temperature fluctuations are consistent with Hines' gravity wave theory.

The possibility that these wavelike temperature variations are driven by lower altitude sources of larger scale such as, for example, perturbations in the tropospheric jet stream or in the stratospheric polar vortex, is also consistent with analyses by Charney and Drazin (1961). Charney and Drazin found that conditions for upward propagation of perturbations at lower altitudes are most favorable when meridional circulation replaces the zonal flow or when zonal flow is weak. This is the case at Pt. Barrow throughout most of the winter season and indeed it is at Pt. Barrow where the temperature waves are observed most prominently. A more strongly westerly circulation prevails at Ft. Churchill and Wallops Island where these waves occur less frequently and at a lesser amplitude. The easterly zonal circulation, which prevails in summer, will cause total reflectance of the upward propagation vector of these disturbances preventing their penetration into the stratosphere and mesosphere. Indeed, no temperature waves are observed in summer (Fig. 8). The fact that this wavelike temperature structure is observed at times when the zonal circulation has weakened is also consistent with earlier, statistically derived indications of interactions between the lower and upper atmosphere where the strongest correlations between lower levels (troposphere and stratosphere) and higher levels (ionosphere) were found to exist during late winter (Bauer 1958, Shapley and Beynon 1965).

Waves of yet smaller scales, which could be sustained by upward propagating gravity waves, thermal tides or by turbulence inherent in the upper mesosphere and lower thermosphere may serve as an efficient process for feeding energy across the mesospause into the lower thermosphere. Such processes have been evident in observations of vapor trails from rocketborne releases of chemicals of meteor trails. According to Roper (1966) the energy transferred by these turbulent waves may be of equal or greater importance than the energy deposited in this region by radiative processes. Observations of all these phenomena combined with their analytical interpretations demonstrate without doubt that interactions between the lower and upper atmosphere are produced by short period waves. Present and future investigations will demonstrate to what extent the various mechanisms, gravity waves, tidal waves and internal turbulence, are responsible for the energy transfer.

c. Tidal Oscillations in the Global Stratospheric Circulation

Reed (1966) has analyzed Meteorological Rocket Network wind observations and found that oscillations in the stratospheric circulation follow a 24 hour diurnal cycle. These findings demonstrate a further mechanism for the vertical propagation of energy in the stratosphere and mesosphere on a large geographic scale. The tidal pattern is especially apparent in the meridional wind components measured at various latitudes and longitudes by the Meteorological Rocket Network sondes. The schematic picture derived by Reed (Fig. 10) indicates a strong poleward motion at noon and an equatorward motion at midnight superimposed on the stratospheric mean circulation. This tidal wind component is still evident at higher latitudes where meridional motions associated with synoptic, planetary scale eddies are otherwise dominant. The tidal component in the zonal circulation is always directed away from the sub-solar point (Fig. 10).

Some authors (Miers and Byers 1965) have speculated that this 24 hour oscillation in the stratospheric circulation may be caused by a "diurnal bulge" resulting from 15° to 20° C higher stratopause temperatures at noon than at midnight. Such large temperature differences between noon and midnight at the stratopause were found in some Meteorological Rocket Network observations (Byers and Miers 1965), however, they have been disputed by others (Theon et al. 1967b, Finger and Wolf 1966, Lindzen 1967b). The results reported by Theon, et al. 1967b, indicate that stratopause temperatures at Wallops Island at noon are certainly not higher than at midnight (Fig. 11) and that diurnal variations in the stratopause temperatures could, at some locations, be such that night time temperatures are higher than day time temperatures. There is no doubt that the diurnal oscillation in the stratospheric circulation is a tidal phenomenon induced by solar heating of the atmosphere. However, the observations at this time do not support the rather simple picture that the wind variations are caused by a coherent temperature increase at the stratopause at noon and a temperature decrease at midnight. The question of diurnal temperature variations at the stratopause still remains open after these IQSY observations and present rocketsonde observations as well as recent theoretical investigations (Lindzen 1967a) will hopefully lead to more definite conclusions.

d. Tidal Variation in Temperature Structure at Low Latitudes

Based strictly on the input of solar energy into the atmosphere and harmonic analysis of tidal oscillations, Lindzen (1967a) has comprehensively described the complex picture of diurnal temperature, pressure and wind variations with height, season and latitude in the stratosphere and mesosphere. Lindzen's findings are essentially in agreement with the analysis of observations of the tidal oscillations in the stratospheric circulations by Reed, discussed above. As expected, temperature variations due to this diurnal, 24 hour tide, are very complex and are far from being uniform at various heights and latitudes. They are a maximum near the equator and a minimum at high latitudes. Temperature variations are largest (±60° C) at high altitudes, near the mesopause. Recent temperature observations as a function of time of the day at Natal, Brazil, 6° S, agree essentially with Lindzen's tidal theory. These results have been reported by Smith et al. (1967b) and one example is shown in Fig. 12. The temperature differences between two soundings each at sunrise and sunset on Oct. 1 and Oct. 2 at Natal are compared to the temperature differences predicted by Lindzen for these times at this latitude. At all altitudes the diurnal temperature variations are in phase with Lindzen's predictions and the magnitude of the temperature variations are at least of the same order as predicted. This demonstrates that, at low latitudes, short term temperature variations throughout the stratosphere and mesosphere are controlled by the diurnal tide. However, even at low latitudes, these variations do not at all levels produce higher temperatures during the day and lower temperatures at night. It has not yet been determined how much energy is transferred between levels of the stratosphere and mesosphere by these diurnal tidal variations. The assessment of this is certainly one of the important next steps to take in the analysis of interactions in that region of the atmosphere.

e. The Quasi-Biennial Variation in the Stratosphere

Newell (1966) has shown that transient eddies in the upper troposphere are probably responsible for feeding energy into lower stratosphere to drive the circulation there. Similar mechanisms, namely, synoptic oscillations in the tropospheric circulation have been suggested as the possible driving force for the observed Quasi-biennial Stratospheric Oscillation (Tucker 1966, Newell 1964). This oscillation, with a period of approximately 26 months in both wind and temperature in the lower stratosphere has been described by Reed (1965a) and could be yet another manifestation of interaction processes, in this case, between the upper troposphere and the lower stratosphere in the tropics. A thorough description, if not the full explanation, of this peculiar phenomenon must be considered as one of the major accomplishments of the IQSY in this portion of the atmosphere.

The best illustration of the Quasi-biennial Stratospheric Oscillation in wind direction is presented in Reed's classical diagram, reproduced in Fig. 13. It shows that the oscillation was maintained continuously from 1953 to 1964. Later investigations by Reed (1965b), which are based on Meteorological Rocket Network results, showed that the oscillation diminishes markedly with altitude (Fig. 14). Reed's analysis demonstrated that the oscillation is most pronounced in the lower stratosphere and can be detected as high as about 35 km. Above that altitude, however, a strong semi-annual oscillation replaces the quasi-biennial oscillation. This decrease in the amplitude of the oscillation with height is consistent with the theories which postulate driving the oscillation from a tropospheric source.

CONCLUSIONS

In contrast with the static picture of the "middle atmosphere", derived during and after the IGY, a dynamic picture has evolved as a result of the observations conducted during IQSY. This dynamic picture indicates that interactions between levels of the stratosphere and mesosphere and across the tropopause and mesopause do indeed exist. In some cases there is evidence, and in many cases there is speculation, that these interactions are fed from below. At high latitudes, transient and standing horizontal eddies, on a planetary scale, seem to be a most prominent mechanism for transferring energy both from lower altitudes to high altitudes and from low latitudes to high latitudes in winter. Although there is still some doubt about the precise quantity of energy and momentum transferred by these eddies, numerous observations of stratospheric and mesospheric temperature and wind patterns obtained during the IQSY leave no doubt about their existence. Another mechanism for transferring energy contained in perturbations of the tropospheric and/or stratospheric circulation into the mesosphere may be found in short period waves. These waves are also limited to the winter period at high latitudes. They exist especially in areas where the zonal circulation is weak. The waves are manifested by oscillations in the temperature structure of the mesosphere at an amplitude of about ±20° and a vertical wavelength of about 10-15 km. Neither large scale horizontal eddies nor short period waves are observed in the stratosphere and mesosphere during the summer season.

At low latitudes, the well known quasi-biennial oscillation may be an indication of interactions between the upper troposphere and lower stratosphere.

Observed diurnal oscillations in the global circulation of the stratosphere and in the temperature of the stratosphere and mesosphere at low latitudes are most probably induced by thermal tides due to solar heating. However, in this case, the nature of the interactions between levels has not been sufficiently studied to draw any definite conclusions regarding the energy transferred by these tides.

Ironically, and perhaps expectedly, the rather extensive findings in that region of the atmosphere during the IQSY have not produced any results with regard to the originally stated objective of the IQSY, namely, to find a relationship between variations in the atmospheric structure and solar activity. More importantly, in this region of the atmosphere, the cooperation and coordination of experimental as well as theoretical investigations, which was possible through the organized IQSY effort, has produced results of unprecedented quantity and quality in this short time period. Thus, the exploration of interlevel interactions in the stratosphere and mesosphere, which in the past was mainly based on correlative speculation, has now gained a vast amount of observations and a solid theoretical foundation from which an understanding of the basic physics of these interactions can be deduced.

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FIGURE CAPTIONS

1. Average temperature profiles derived from 11 acoustic grenade soundings in winter and 15 acoustic grenade soundings in summer at Churchill, Canada (59°N), Pt. Barrow, Alaska (71°N), and Kronogard, Sweden (66°N) during the years 1962 to 1965. [Reproduced from Science, Theon, et al., (1967a)].

2. Annual variation of stratopause temperatures at Pt. Barrow, Alaska and Churchill, Canada measured by acoustic grenade rocket soundings.

3. Temperature profiles measured by acoustic grenade soundings at Pt. Barrow, Alaska during winter 1965.

4. Pressure and wind field at 50 km derived from acoustic grenade soundings at Pt. Barrow, Alaska, Churchill, Canada, and Wallops Island, Virginia (38°N) and from meteorological rocket soundings at other locations on 27 January 1965. Pressure is indicated in millibars. [Reproduced from Journal of Atmospheric Sciences, Theon, et al., (1967b)].

5. Stratospheric temperature fields derived from measurements of radiation emitted at 15 microns by carbon dioxide measured with the TIROS VII satellite during the period 6 to 15 January 1964 (°K).

6. Stratospheric temperature fields derived from measurements of radiation emitted at 15 microns by carbon dioxide measured with the TIROS VII satellite during the period 2 to 11 September 1963 (°K).

7. Stratospheric temperature fields derived from measurements of radiation emitted at 15 microns by carbon dioxide measured with the NIMBUS II satellite over the Southern Hemisphere on 10 June 1966 (°K).

8. Temperature profiles obtained with acoustic grenade soundings at Pt. Barrow, Alaska during summer 1965.

9. Temperature profiles obtained with acoustic grenade soundings at Pt. Barrow, Alaska during winter 1967.

10. Schematic model of diurnal tidal motions in the stratosphere and lower mesospheres. Single arrows denote horizontal motions; double arrows, vertical motions. Wind arrows are not drawn to scale. [Reproduced from Journal of Atmospheric Sciences, Reed, et al., (1966)].

11. Temperature profiles measured with acoustic grenade soundings at Wallops Island, Virginia during noon and midnight on 30 September 1966.

12. Sunrise temperature minus sunset temperature (ΔT) versus altitude obtained from two pairs of pitot-tube rocket soundings on 1 Oct. and 2 Oct. 1966 at Natal, Brazil (6°S), compared to corresponding differences derived theoretically by Lindzen (1967a).

13. Wind speeds and directions versus time and height in the tropical stratosphere after Reed (1965a). Cyclic variation with period of about 26 months propagating downward is demonstrated. [Reproduced from cover of Bulletin of American Meteorological Society, Reed, (1965a)].

14. Zonal wind velocity at Ascension Island (8°S). Solid circles give individual observations; open circles monthly means. [Reproduced from JAS, Reed, (1965b)].

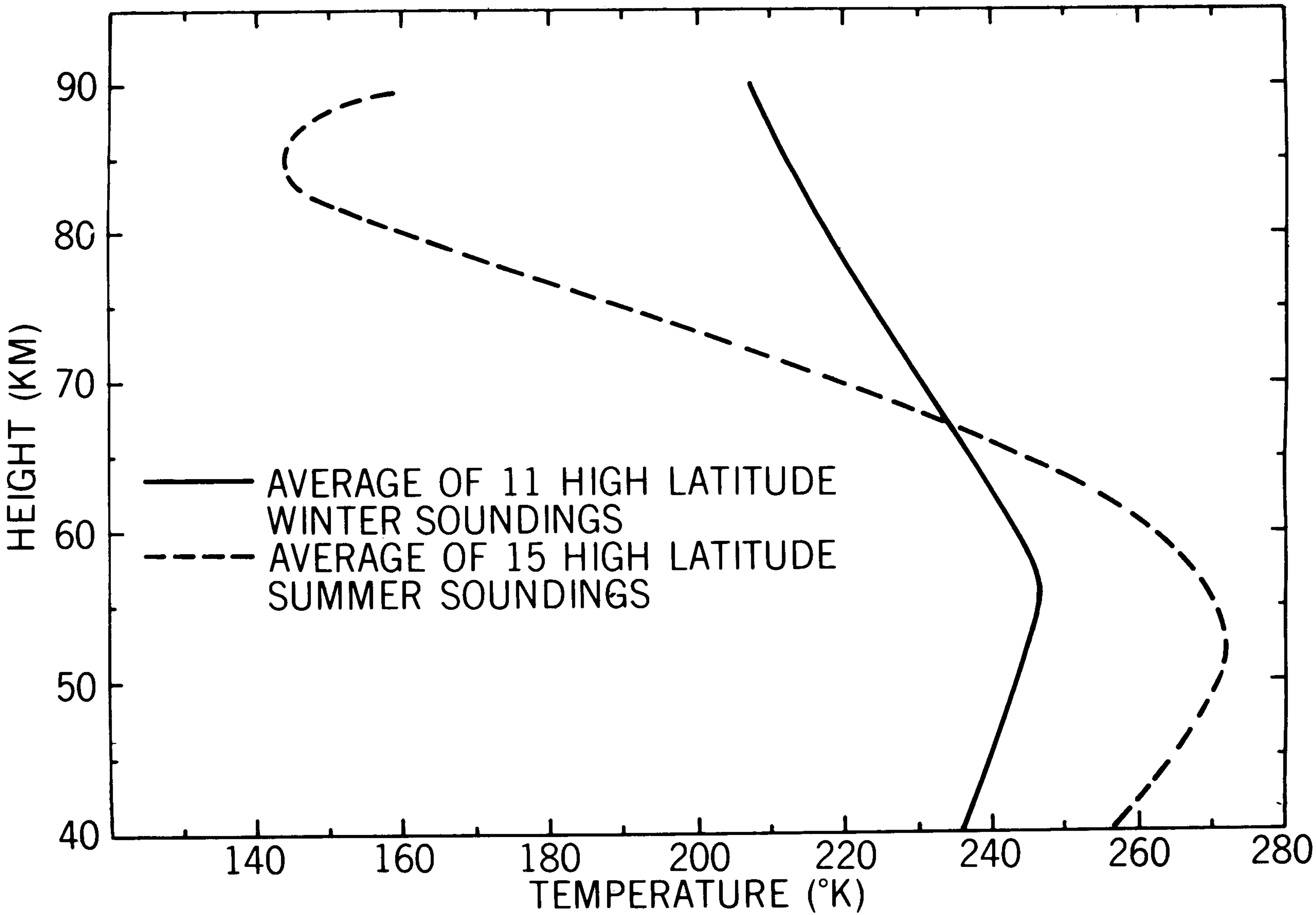

90
80
70
60
50
40
HEIGHT (KM)
AVERAGE OF 11 HIGH LATITUDE
WINTER SOUNDINGS
AVERAGE OF 15 HIGH LATITUDE
SUMMER SOUNDINGS
140
160
180
200
220
240
260
280
TEMPERATURE (°K)

Figure 1

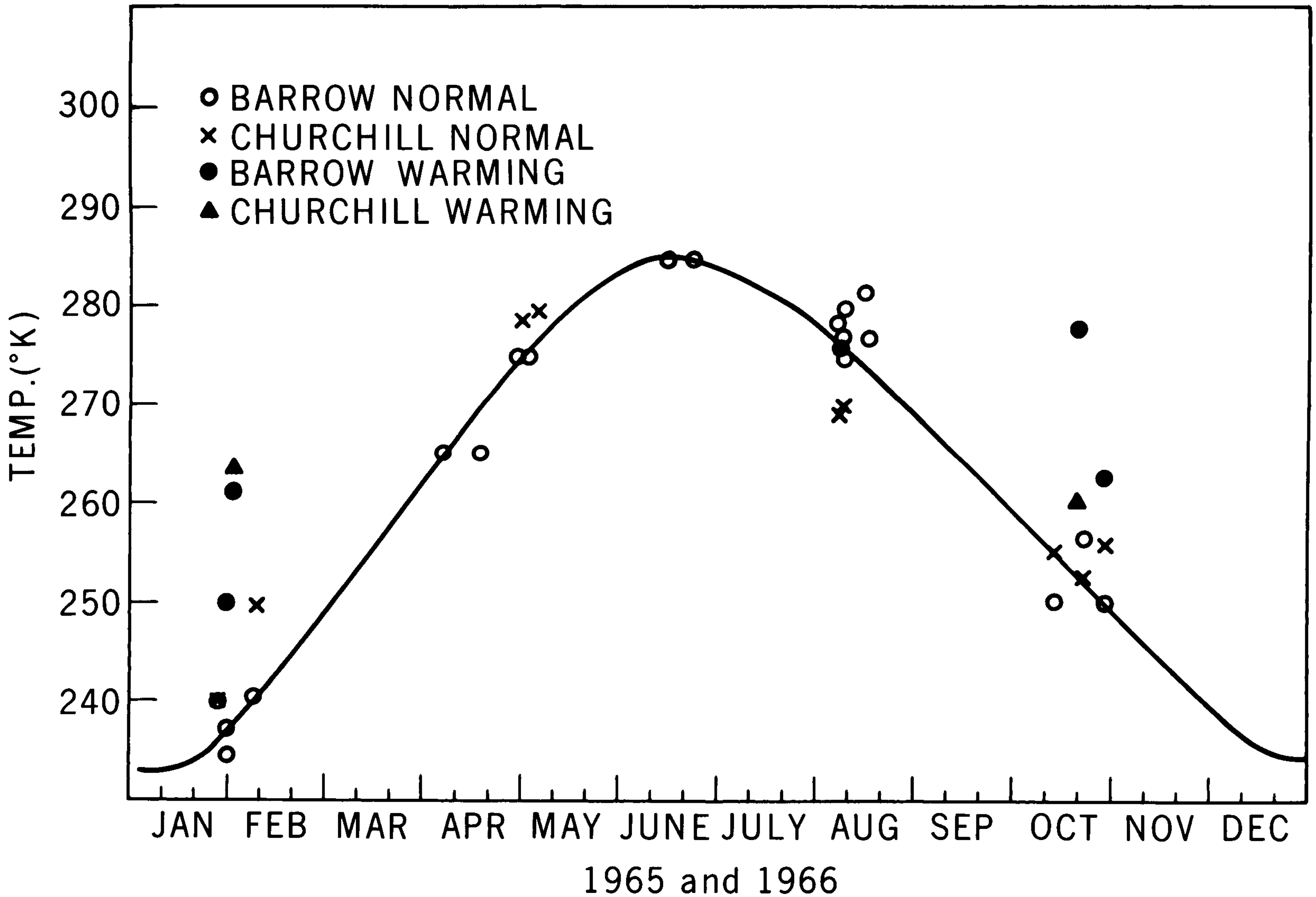
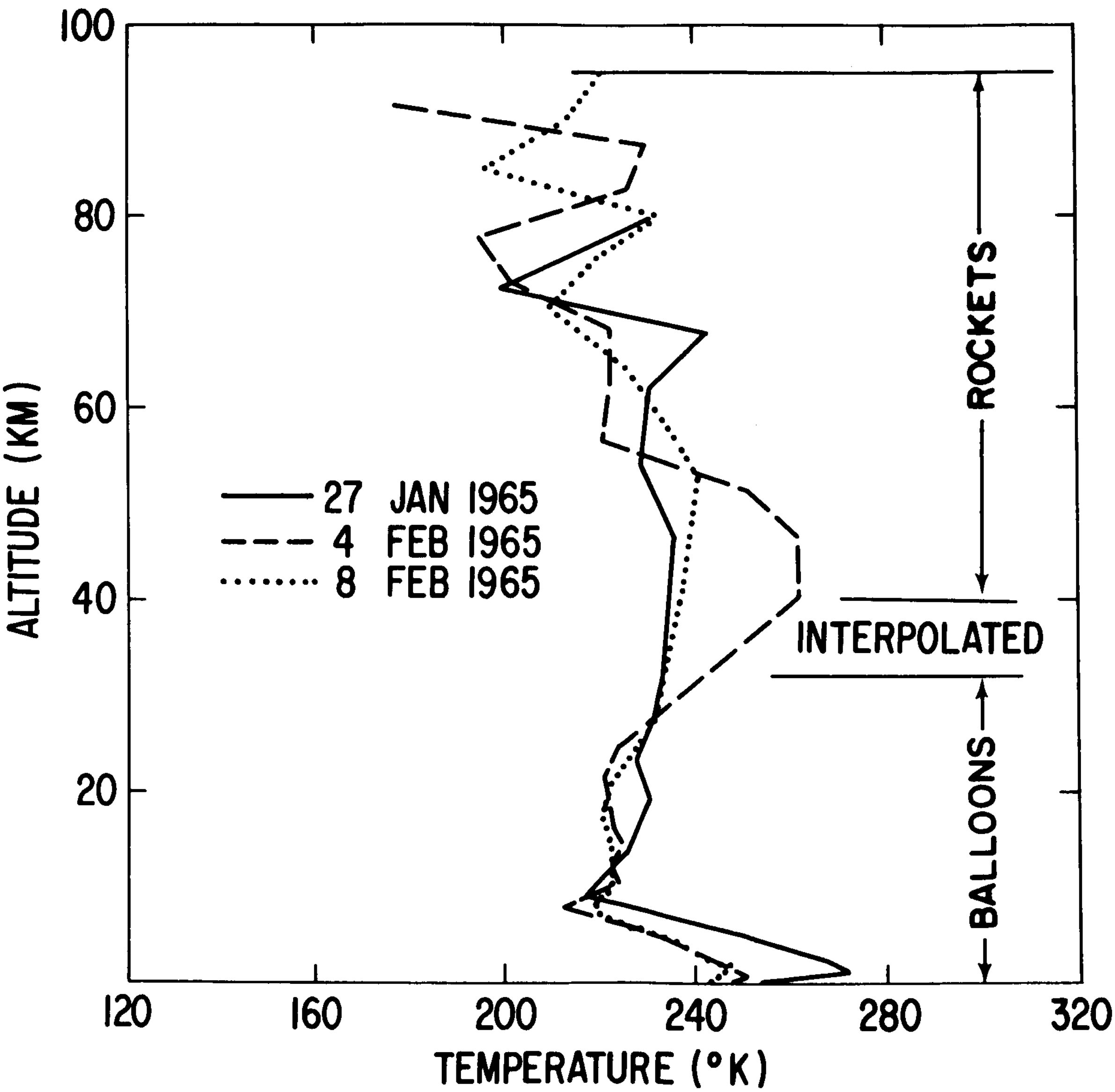

BARROW NORMAL
CHURCHILL NORMAL
BARROW WARMING
CHURCHILL WARMING
300
290
280
270
260
250
240
TEMP.(°K)
JAN FEB MAR APR MAY JUNE JULY AUG SEP OCT NOV DEC
1965 and 1966

Figure 2



100
80
60
40
20
ALTITUDE (KM)
120
160
200
240
280
320
TEMPERATURE (°K)
27 JAN 1965
4 FEB 1965
8 FEB 1965
ROCKETS
INTERPOLATED
BALLOONS

Figure 3

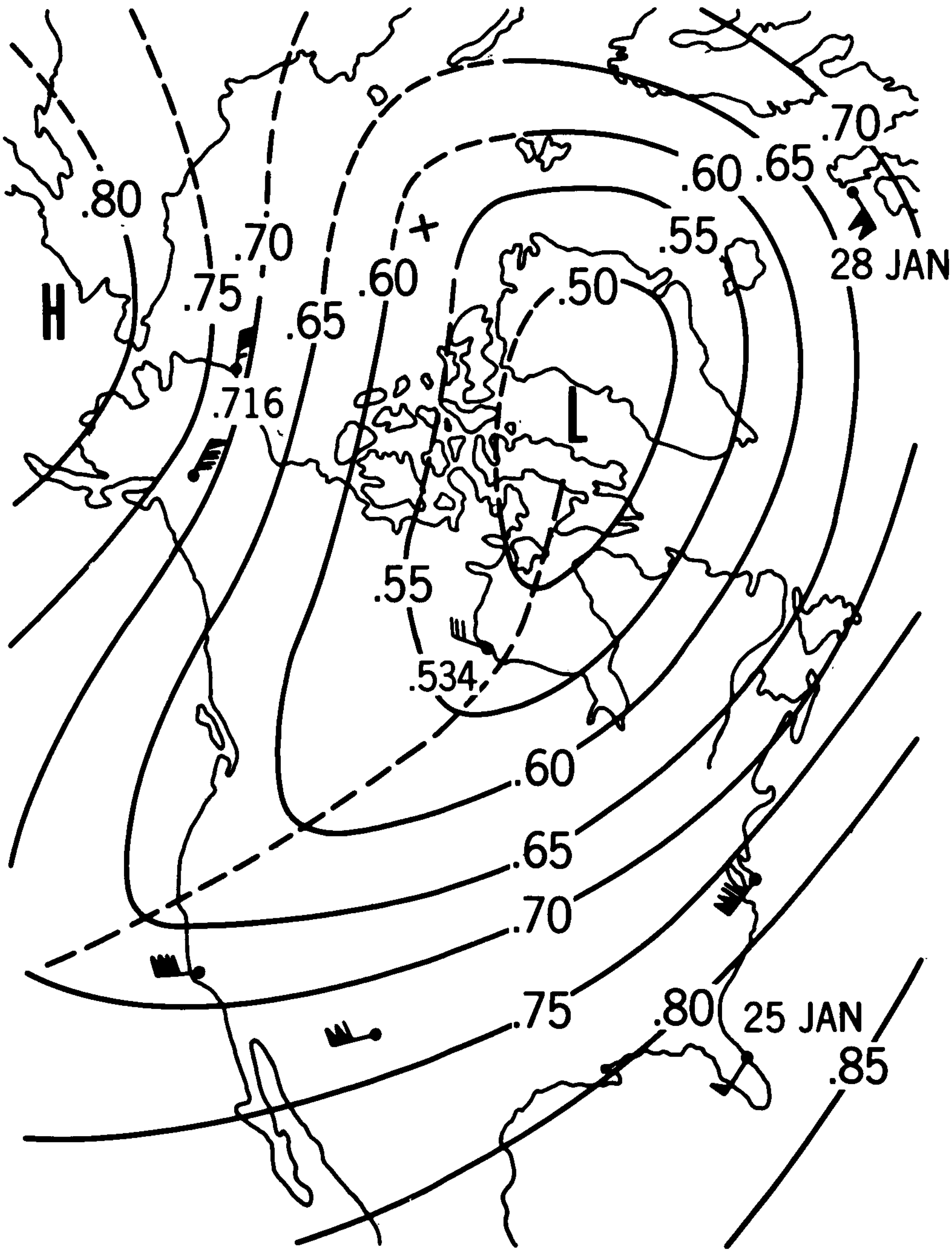
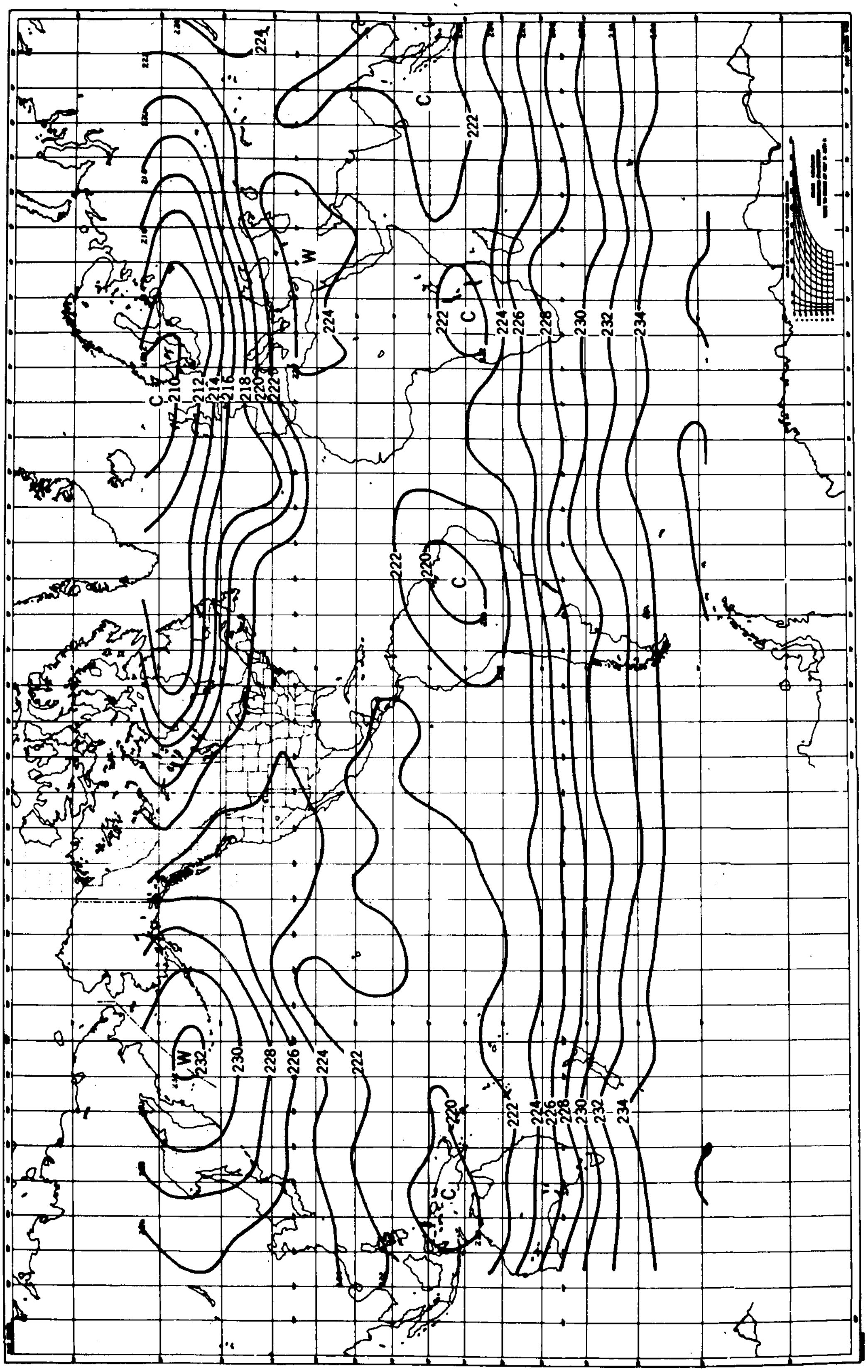

.80
.70
.75
H
.65
.60
.716
.50
.60
.65
.70
.55
28 JAN
L
.55
.534
.60
.65
.70
.75
.80
25 JAN
.85

Figure 4



224
222
C
W
224
222
C
224
226
228
230
232
234
C
210
212
214
216
218
220
222
222
220
C
W
232
230
228
226
224
222
220
C
222
224
226
228
230
232
234

Figure 5

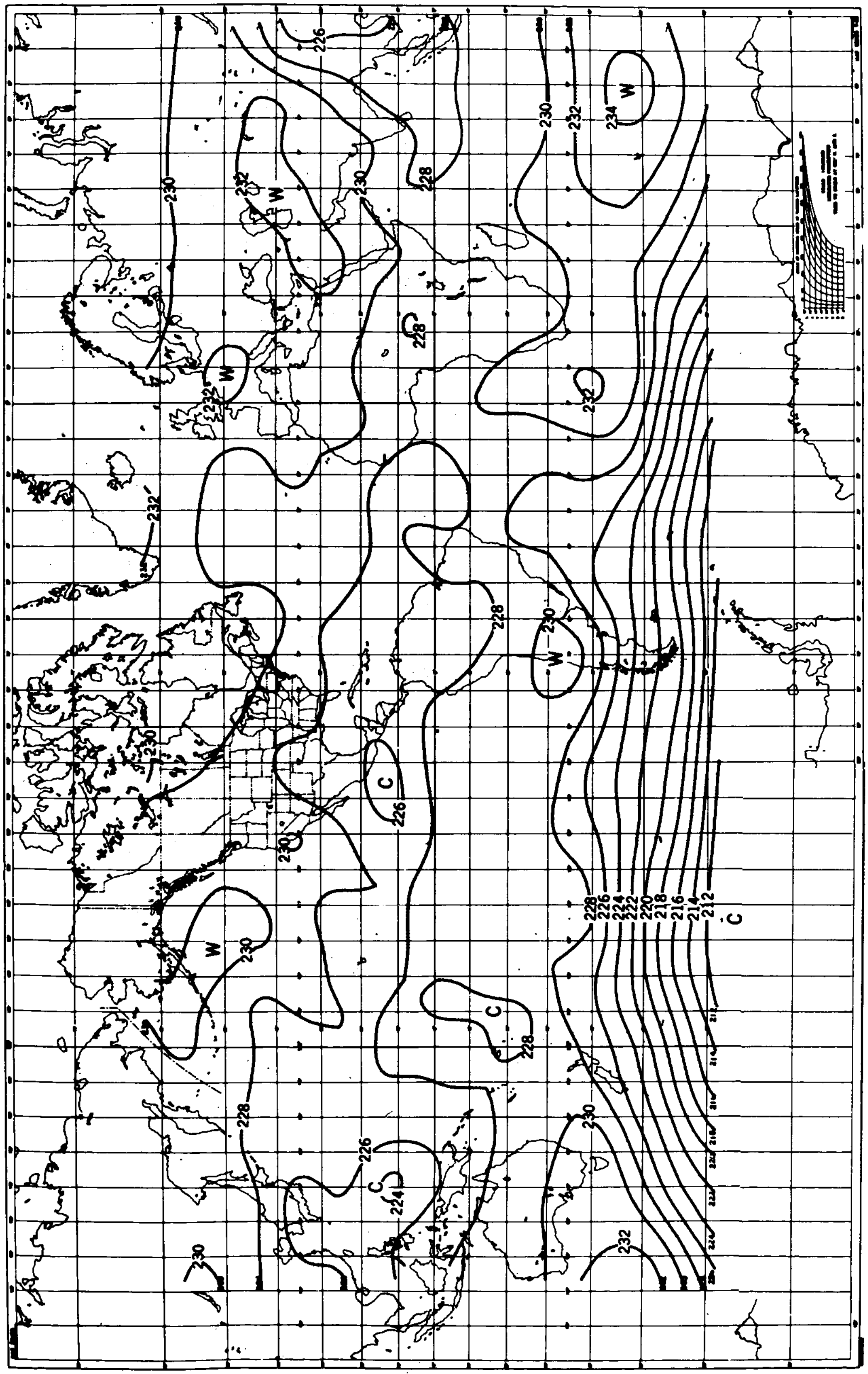


Figure 6

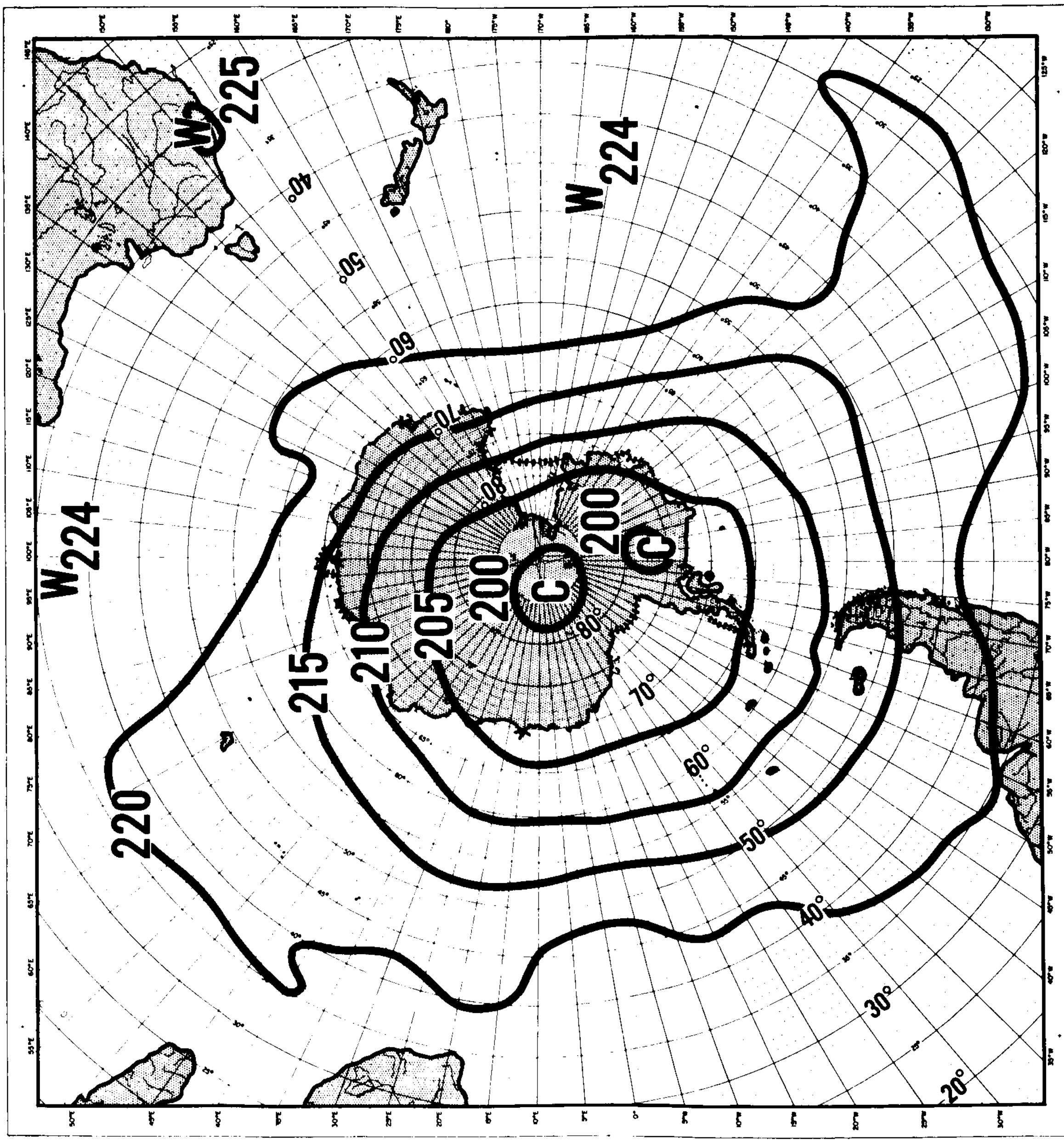


Figure 7

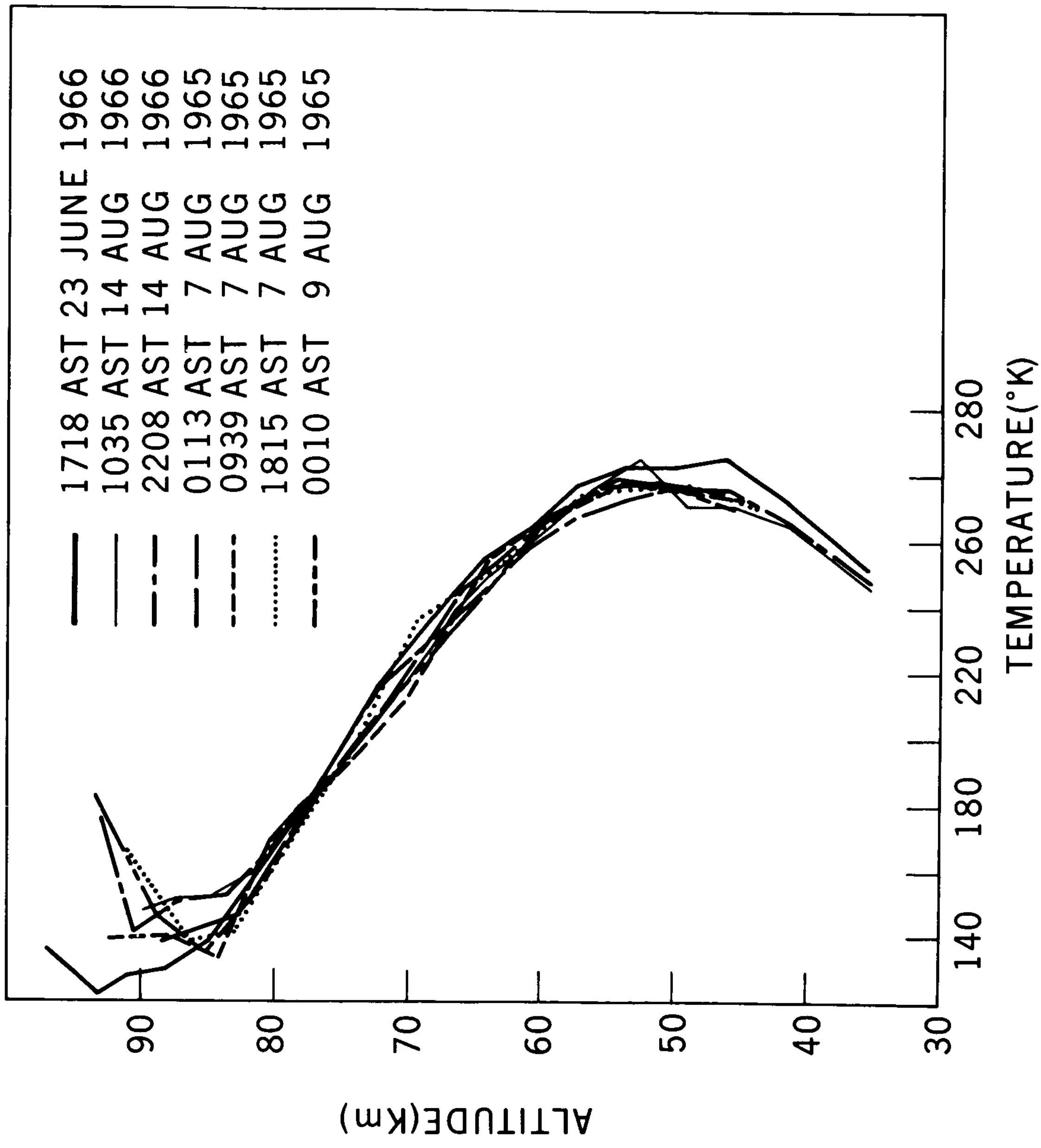

1718 AST 23 JUNE 1966
1035 AST 14 AUG 1966
2208 AST 14 AUG 1966
0113 AST 7 AUG 1965
0939 AST 7 AUG 1965
1815 AST 7 AUG 1965
0010 AST 9 AUG 1965
TEMPERATURE(°K)
ALTITUDE(Km)
140
180
220
260
280
30
40
50
60
70
80
90

Figure 8

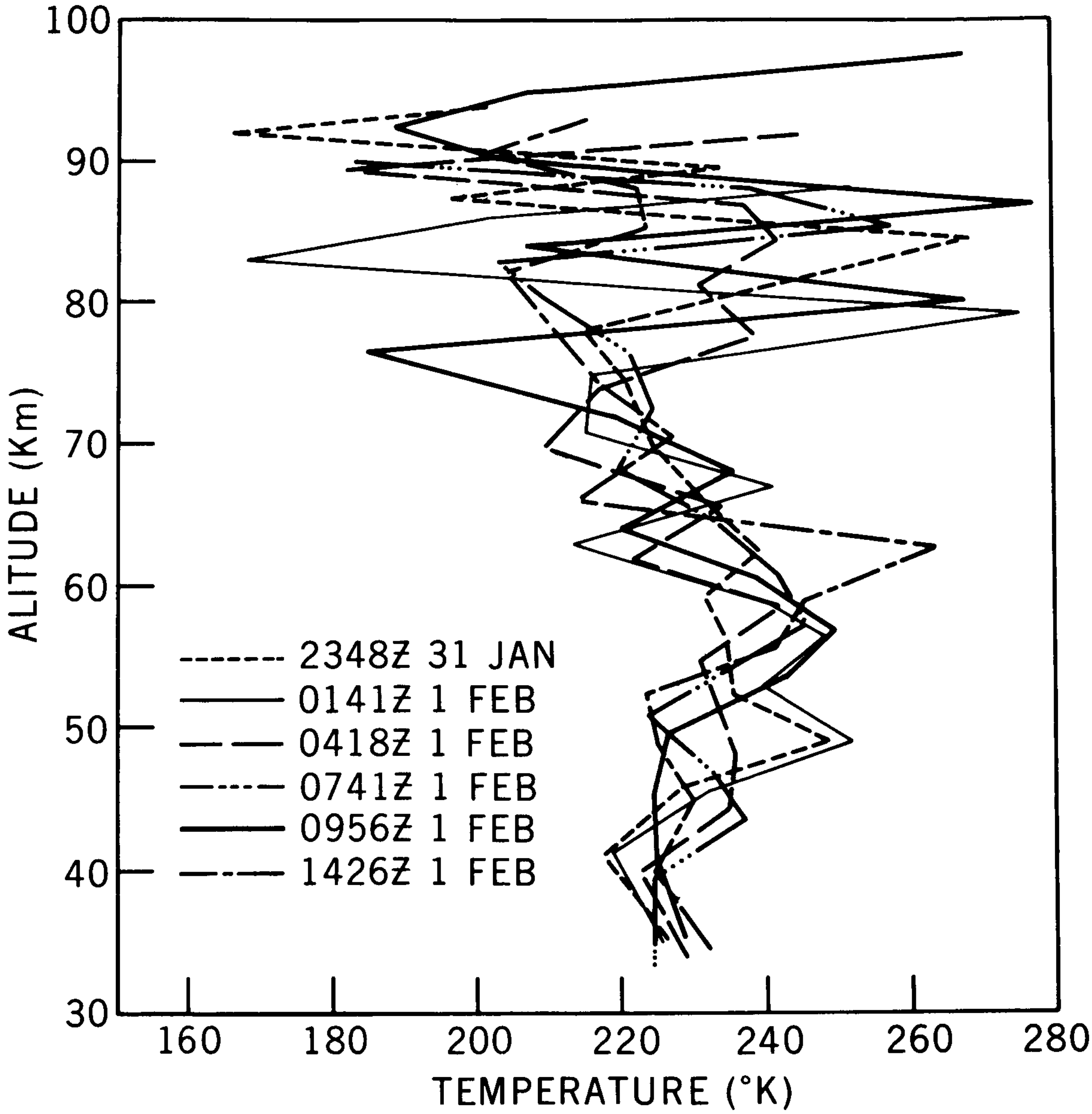

100
90
80
70
60
50
40
30
ALITUDE (Km)
160
180
200
220
240
260
280
TEMPERATURE (°K)
2348Z 31 JAN
0141Z 1 FEB
0418Z 1 FEB
0741Z 1 FEB
0956Z 1 FEB
1426Z 1 FEB

Figure 9

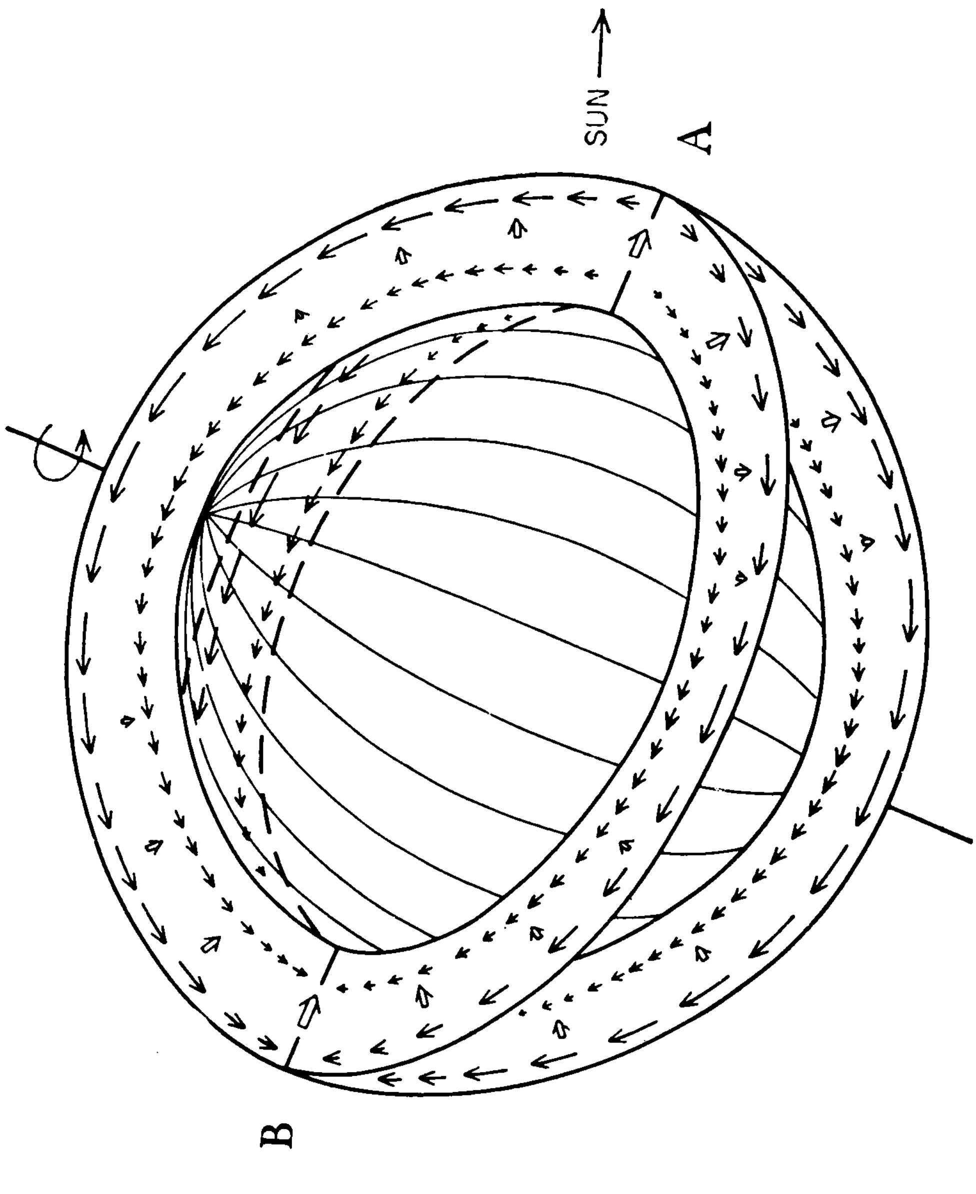


Figure 10

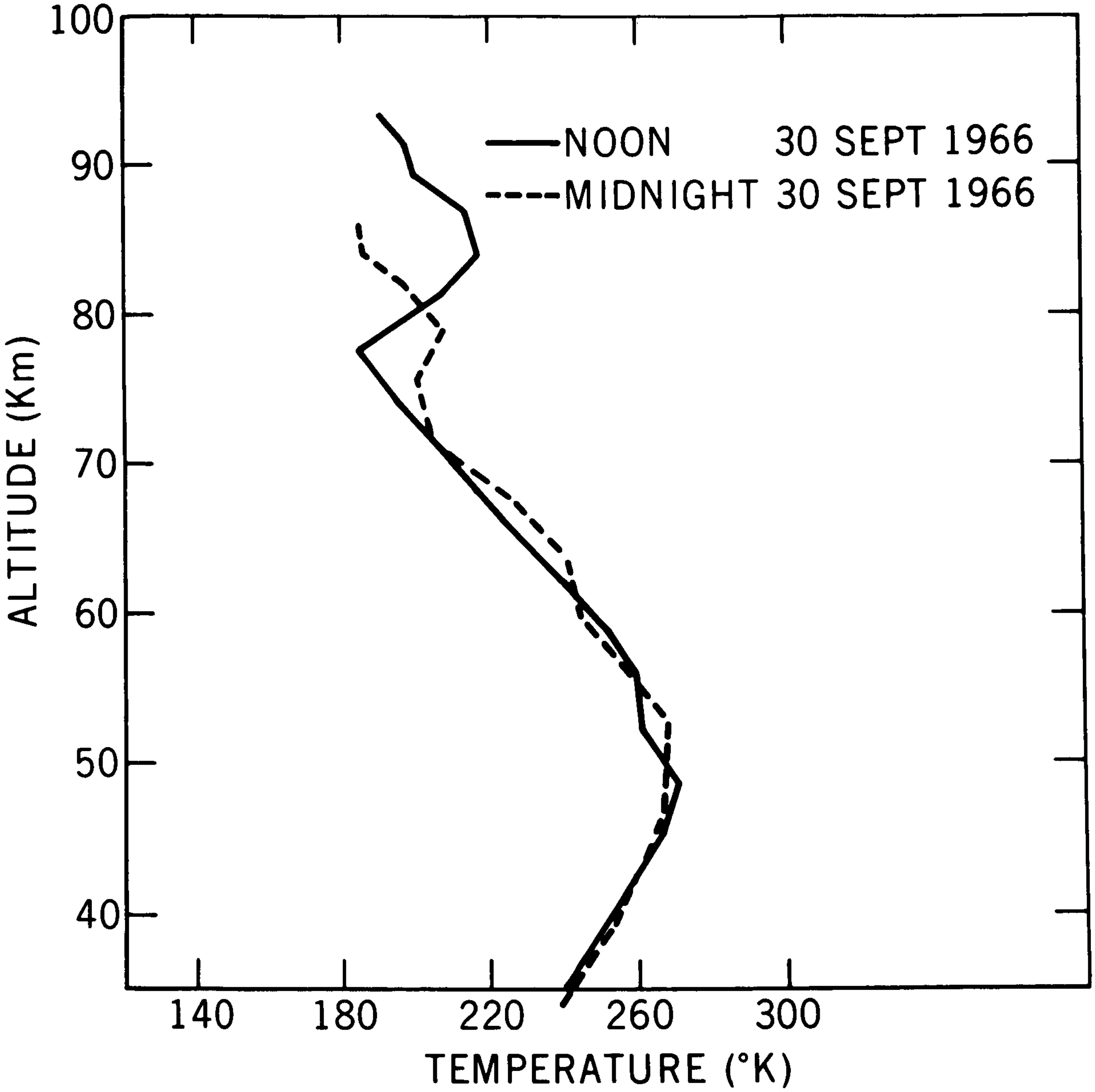

100
90
80
70
60
50
40
ALTITUDE (Km)
NOON 30 SEPT 1966
MIDNIGHT 30 SEPT 1966
140
180
220
260
300
TEMPERATURE (°K)

Figure 11

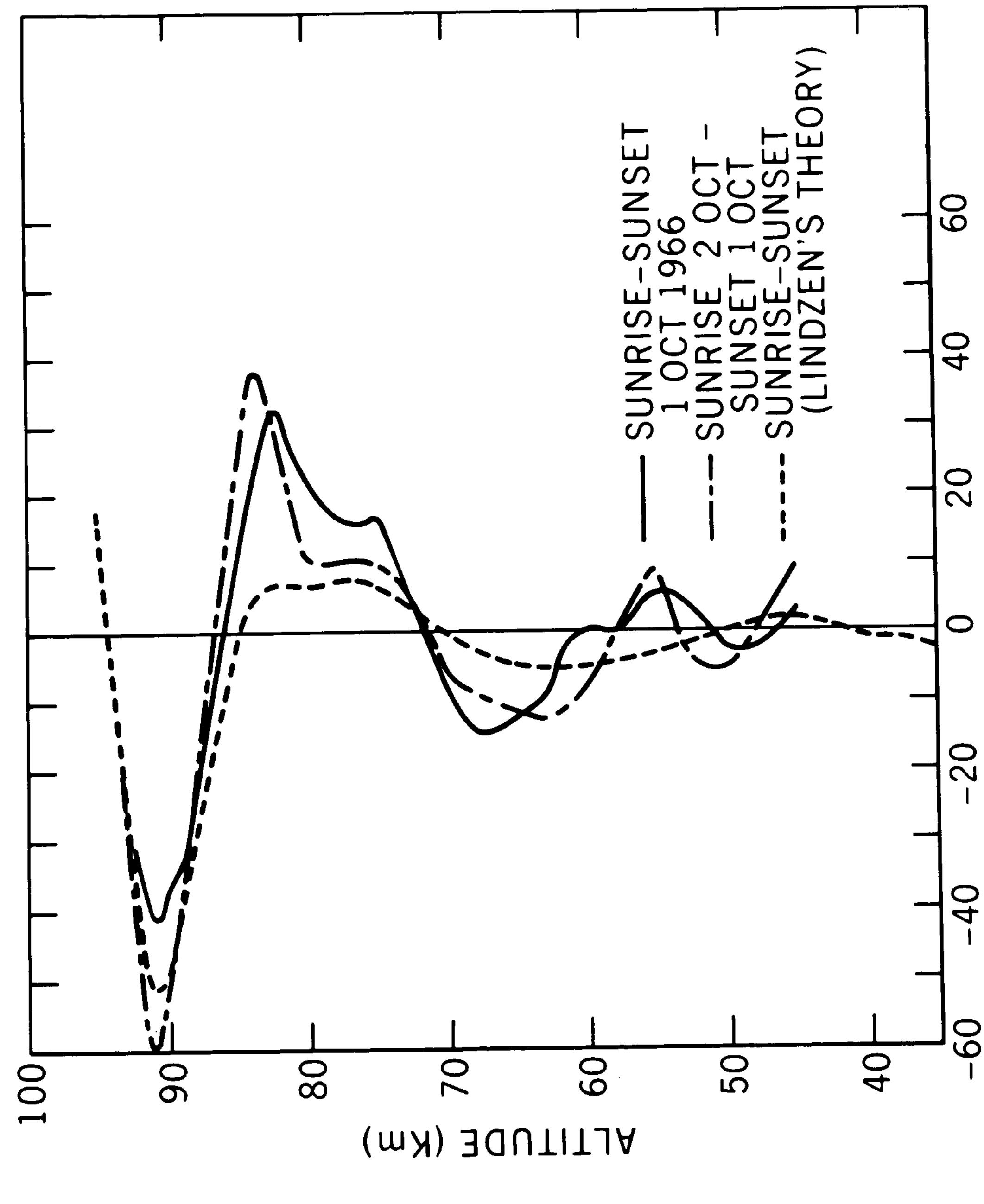

SUNRISE–SUNSET
1 OCT 1966
SUNRISE 2 OCT –
SUNSET 1 OCT
SUNRISE–SUNSET
(LINDZEN'S THEORY)
ALTITUDE (Km)
100
90
80
70
60
50
40
ΔT (°K)
−60
−40
−20
0
20
40
60

Figure 12

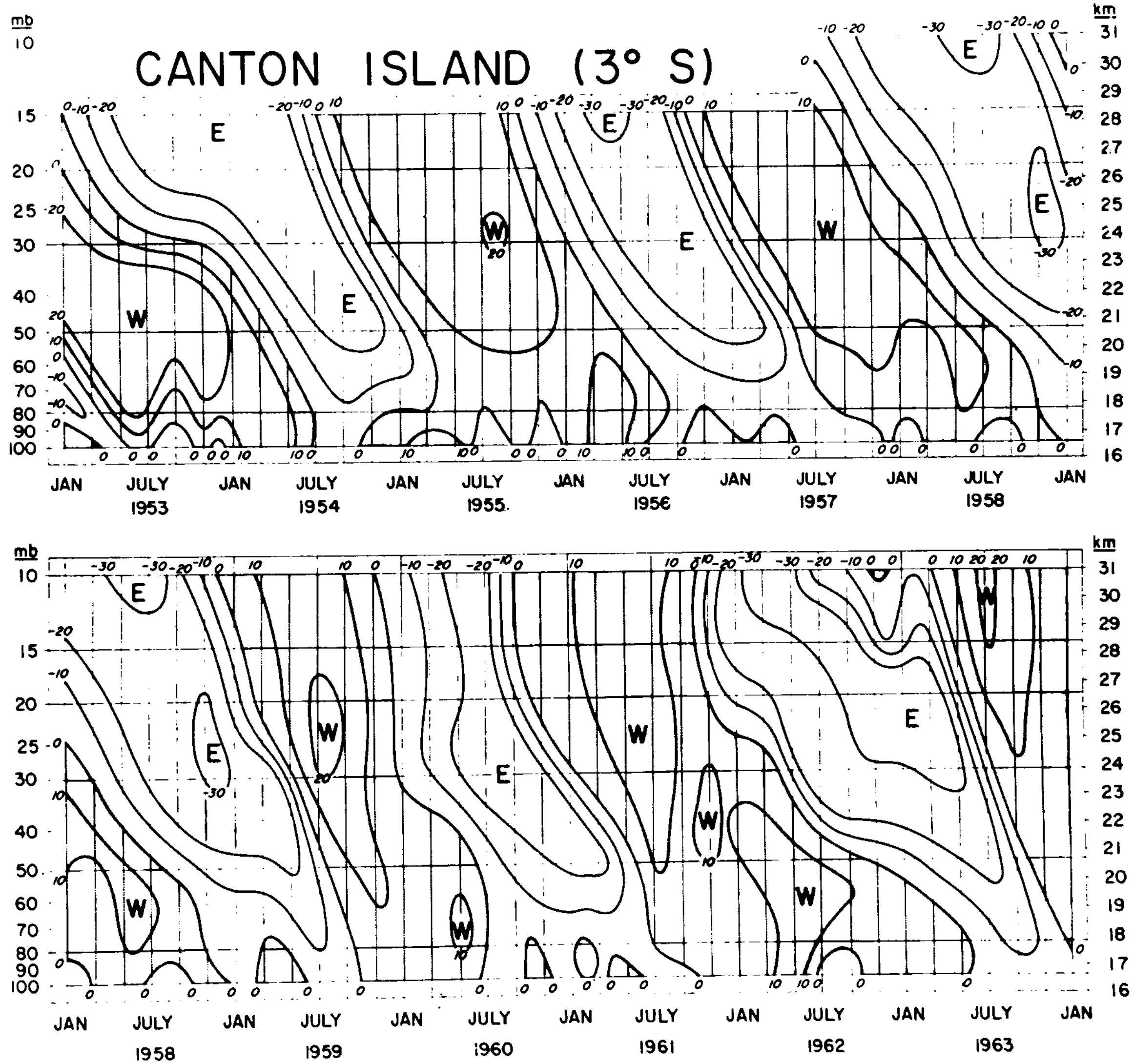
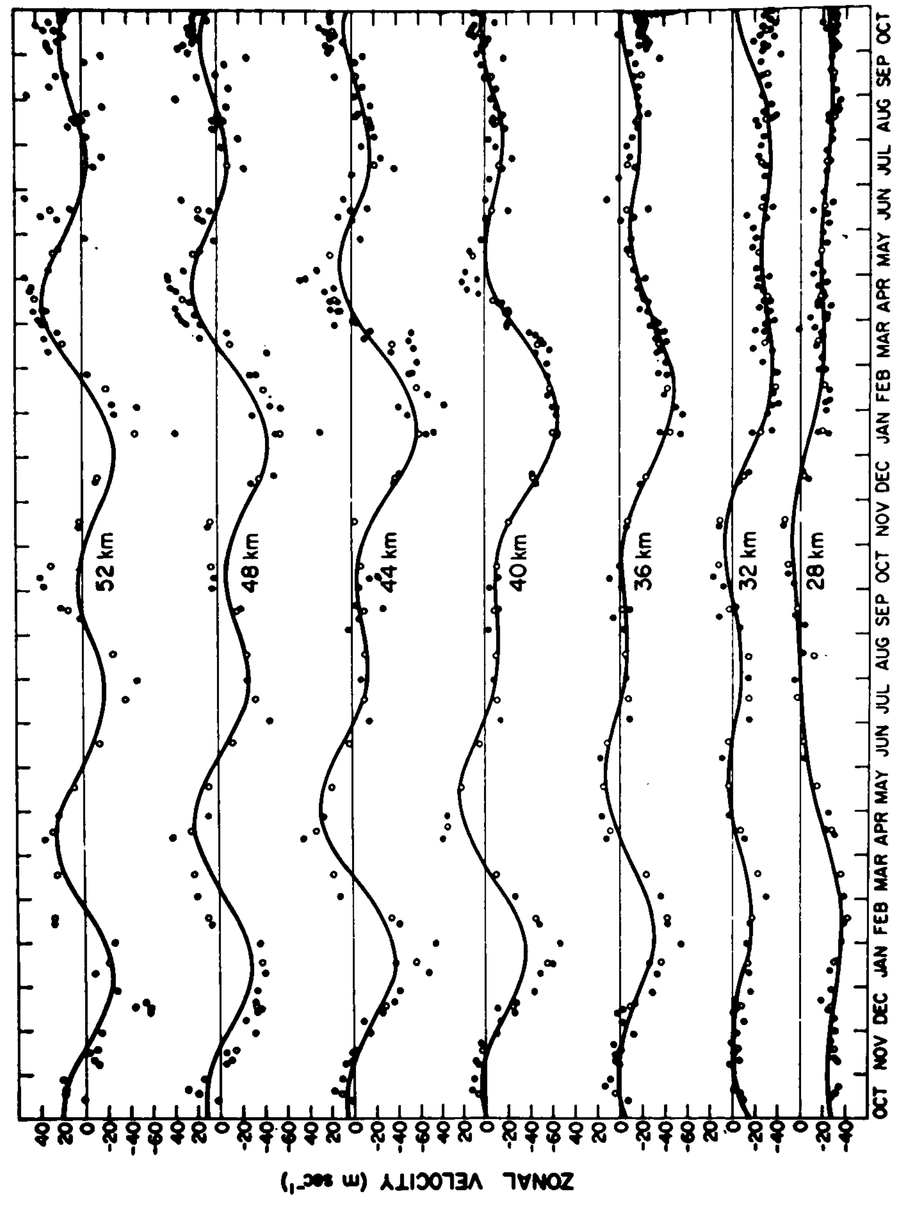

CANTON ISLAND (3° S)
mb
km
JAN
JULY
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963

Figure 13



ZONAL VELOCITY (m sec⁻¹)
52 km
48 km
44 km
40 km
36 km
32 km
28 km
OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT
1962
1963
1964

Figure 14