INTRODUCTION

1.1 General

In Greek atmosphere means *atmos,* "vapour" ; *sphaira,* "sphere" i.e. gaseous envelope covering a planet. It is the ocean of air in which we move and have our being, which flows around us and sustains life on Earth. The ever changing sky has always inspired and intrigued mankind. Depending on the good graces of the weather for so many of his pursuits, man recognised early the necessity of studying the weather. The farmer watched the sunset and the motions of the clouds to determine if the next day would bring rain. The mariner watched the same signs and as ships ranged around the world mariners prepared weather charts. A disastrous flood, a drought or a long severe winter arouses even today the desire to trace back the event to some specific cause. For practical and observational reasons, attention has been largely concentrated in the past on the study of the processes in the lowest layer (up to about 10-15 km) of the atmosphere which give rise to weather.
Investigation of the upper air began in 1749 when Alexander Wilson attached a thermometer to a kite. With the development of the balloon in the late 18th century, scientific ballooning began with manned flights. Extensive application to research started in 1892 when Gustave Hermite and George Besançon began to use small unmanned balloons (balloon sondes) carrying instruments. In 1894, Albert Rotch used large kites tethered by steel wire, but meteorological kite flying was gradually abandoned.

Between 1899 and 1902 balloon experiments led Richard Assmann and L.P. Tisserence de Bort to the discovery of the stratosphere, and the first two decades of the 20th century saw an immense development of the balloon sounding technique, yielding considerable information about the lowest layer of the atmosphere. In the period 1927-36 advances in radio techniques made possible the development of the radiosonde. This instrument, attached to a free balloon, sends radio signals that can be translated into numerical values of temperature, humidity, and pressure. During World War II and later, radiosonde techniques were further developed, radar was applied to wind measurements, meteorological instrumentation for aircraft was greatly advanced, and the sounding rocket came into use. Regular
meteorological rocket soundings commenced in 1962. Satellites are now being employed for determining the temperature profiles of the atmosphere up to about 30-40 km by infrared radiation measurements.

1.2 Various techniques of sounding the atmosphere

Detailed exploration of the atmospheric structure awaited the development of suitable vehicles for the transport of instrumentation into the relatively inaccessible region, stratosphere and mesosphere. Radiosonde method has been widely employed all over the globe. The rubber balloons used for routine meteorological soundings burst near the tropopause. The American 'Darex' and the Japanese 'Totex', each 1200 gm, have been found to reach altitudes of about 30-35 km. On account of its strong neck and sturdy structure, a 'Totex' balloon is preferred when higher rate of ascent, 24 km hr\(^{-1}\) is desired and the launching is to be carried out in rough weather and gusty wind conditions although its cost is higher and it attains a relatively lower altitude. The trajectory of the hydrogen gas filled balloon released with radiosonde and reflector is tracked by radar and telemetery system and the meteorological parameters recorded. Small corner
aluminium reflectors of 250 gm are used for rawin ascents. At the Thumba Equatorial Rocket Launching Station (TERLS) there are two radiosonde systems working on 401 MHz and 1680 MHz. The Soviet 'RKZ-2' radiosonde system working on 1780 MHz was also employed.

The development of rockets capable of carrying instruments much higher above the earth's surface has now made it possible to make direct measurements of atmospheric winds, temperature, pressure and density above the balloon altitudes. The investigation of the upper atmosphere necessitated the development of small and less expensive meteorological rockets which could be fired on a routine basis for synoptic studies. The British 'Skua', the Polish 'Meteor-1', the United States 'Lokidart', 'Judidart' and 'Arcas', the Japanese 'MT-135' and 'MT-160' and the Australian 'Kookaburra' meteorological rocket systems are now being regularly used for sounding the upper atmosphere (Webb, 1969). For the present investigation of the upper atmospheric structure, the Soviet 'M-100' meteorological rocket sounding system was employed which is discussed separately in Chapter - II.
The M-100 rocket sounding system incorporates parachute and chaff as wind sensors and four tungsten-rhenium (40 microns) wire thermometers as temperature sensors. The two-stage M-100 rocket measures 8.906 m, has a diameter of 25 cm and weighs about 480 kg when fully charged. It can reach a maximum altitude of 100 km when launched vertically with a solid propellant made of nitrocellulose base. For meteorological investigations it is usually fired at 83° effective elevation with a payload of about 66 kg. The steeple portion containing the temperature sensors opens around 60 sec after the lift off. The whole payload is separated at 70 sec around 70 km and it attains an apogee of about 90 km around 140 sec from the take-off. About 400 gm of chaff, in a special container divided into two parts, is ejected at rocket apogee. The chaff consists of aluminium-coated glass fibres with a diameter of about 0.025 mm. After ejection from the M-100 rocket, it is tracked by a high sensitivity Meteor-2 radar. Conventionally, three or four fibre glass chaff bundles are ejected at intervals of ten km in downward direction starting from 90 km and the different chaff clouds are tracked by a single radar system. Also, at apogee the parachute consisting of a non-reflecting hemispherical mylar with a surface area of 35 m² exerts a stabilising influence on the payload and
fully opens during descent at an altitude of 60-65 km around 200 sec after the take-off. The parachute is tracked by the Meteor-1 radar operating at 1780 MHz in the transponder mode. Atmospheric winds are derived from the drift of the trajectory of the descending parachute and chaff. An unbalanced wheatstone bridge arrangement is used for telemetering the atmospheric temperature data from the 40 μm tungsten-rhenium wire thermometers to the ground. Two telemetry receivers with panoramic and photographic attachments record the temperature data along with the timing pulses from the take-off. The reduction and processing of the meteorological data obtained from the M-100 rocket sounding system and the various corrections applied are discussed in Chapter - III.

Various types of rocket-borne wind and temperature sounding instruments are now used throughout the world to study the atmospheric structure in the region from about 20 to 100 km. Wind profiles are determined on a routine basis as high as 65 to 85 km with passive radar targets 'chaff', inflatable sphere 'Robin' and parachutes. The two main temperature sensors used in the rocket payloads for temperature measurements are thermistor and wire resistance types. Other techniques for measuring the atmospheric winds and temperatures are falling sphere, grenade, vapour cloud
(Sodium, Trimethyl Aluminium and Barium) and pitot tubes which are limited due to their complexity, cost and accuracy. The wide range of environmental conditions which characterise the stratosphere and mesosphere preclude the application of any one measuring system over the entire range of interest. Consequently, various techniques have to be used for sounding the terrestrial atmosphere. Bollermann (1970) has given a survey of the various techniques used for atmospheric sounding.

1.3 Present state of knowledge

Since the establishment of the Meteorological Rocket Network (MRN) there has been a substantial increase in the number of measurements of atmospheric structure by sounding rockets. An attempt is made to summarise some of the important results obtained so far.

1.3.1 Earlier studies of the atmospheric structure

Our initial knowledge of the atmospheric structure came from a variety of instrumentation systems. A good deal of information on atmospheric winds and temperatures was deduced indirectly from other experiments based on phenomena such as observations of solar spectrum. In addition certain naturally occurring phenomena such as meteors, aurora and
noctilucent clouds have provided valuable information so that with the help of theoretical considerations a general picture of winds and temperatures over the globe could be built up to considerably higher levels, for example as given by Kellog and Schilling (1951), Pant (1956) and Deb (1953). Investigations such as those of Murgatroyed (1957), Batten (1961) and Finger, Towoles and Mason (1963) have established that in summer an anticyclonic vortex develops around the poles but in winter the circulation changes to a cyclonic circumpolar vortex. These vortices develop earlier and more rapidly at higher levels and penetrate downward and equatorward with advance of season.

The 50 mb (about 20 km) constant pressure chart shows in summer a warm high situated near the pole, the temperature and contour height decreasing steadily towards the equator. The thermal winds are therefore easterly. Although at 50 mb itself the actual winds are light, at higher levels (around 25 km) a marked easterly circulation prevails at all latitudes. In winter, a cold low is located near the pole. Temperature and contour height rise rapidly from the pole up to about 50°N where a ridge is noticeable. Winds are already westerly at 50 mb and continue to increase in speed upwards. Equatorward of 50°N the westerlies weaken and even change at low latitudes to easterlies.
The easterly zonal flow of summer, although weak, is steady, being affected only by occasional mild perturbations. On the other hand the stronger winter circulation is dynamically unstable. Not only are both zonal wind and wind shear larger than in summer, but also the vertical temperature gradient continues to be negative even above the tropopause, at high latitudes. Consequently, the Richardson number becomes small. As a result of baroclinic instability it is found that disturbances of wave number usually 2 or 3 (which set in through essentially barotropic development) get accentuated. Sometimes the polar cyclonic vortex shrinks (the low latitude anticyclonic belt advances poleward) and local anticyclones develop which shift towards the winter pole at some latitudes. On other occasions, there is a complete reversal of the circulation and of the normal winter-time meridional temperature gradient. In the latter kind of circulation disturbance, which may be termed 'major' the stratosphere seems capable of generating its own kinetic energy, and operating as a heat engine; in the former or 'minor' kind, the stratosphere is probably a sink of kinetic energy consuming energy perhaps supplied by the troposphere below (Julian, 1967). These break-downs rarely occur when the winter circulation is at its early stage but are common during winter and the final spring reversal periods. They closely precede sudden stratospheric warmings.
1.3.2 Synoptic studies in the Northern Hemisphere

In the Northern Hemisphere, a regular feature of the summer months is a polar anticyclone which reaches peak intensity in July. Summer conditions are generally steady and symmetrical in longitude. Thereafter the system decays slowly and by the end of August high latitude cyclonic activity may be expected to appear at 36 km. As the cyclone cools the anticyclonic circulation retreats southward reaching low latitudes by late October so that most of the hemisphere is involved in an apparently steady nearly circumpolar westerly circulation. This situation is usually soon terminated by a warming with anticyclonic activity appearing over the Aleutian area possibly before the end of October. A typical winter situation is difficult to define on account of the non-steady conditions. The Aleutian anticyclone generally intensifies and displaces the polar low towards northern Europe or Eurasia. It may later fill in and subsequently intensify.

When the temperature gradient between the high and low pressure systems increases, strong northerly winds develop over North Canada. The main changes that occur in the winter and early spring are associated with pulsations and displacements of the Aleutian high and with the occurrence
of stratospheric warmings. The final phase occurs in late March or early April when a cyclone usually dominates the polar area again for a brief period before a warm polar anticyclone develops in response to spring time radiational heating. Up to 30 km complete coverage in longitude has been provided for the Northern Hemisphere since the IGY by high-level balloons. Infra-Red (IR) sensing by satellites of \( CO_2 \) emissions in the 15\-\( \mu \)m spectral region has more recently provided a new tool for synoptic studies in both the Northern and Southern Hemispheres. A single-channel radiometer in TIROS VII provided observational results over one seasonal cycle of the temperature field smoothed in altitude with maximum weighting at 20 km. Over 70 percent of the total received radiation originated at altitudes between 10 and 30 km (Kennedy and Nordberg, 1967). The differences between the summer and winter synoptic situations were in general agreement with the rocketsonde results. Synoptic charts have been prepared by Johnson and McInturff (1970) from the NIMBUS 3 results.

1.3.3 Synoptic studies in the Southern Hemisphere

In the Southern Hemisphere the number of available observations on the atmospheric structure have always been sparse. For CIRA 1965 the number of launchings carried out
were 30 for Ascension Island at 8°S, 22 for Woomera at 31°S and just 14 for McMurdo Sound at 78°S. At Woomera, the seasonal wind pattern appeared similar to that at 30°N sites judged by these few observations which did not cover all months of the year. From the few available observations at McMurdo Sound it appeared that midwinter warmings of the Antarctic were similar in many respects to Arctic warmings, the circumpolar vortex tending to elongate and split (Quiroz, 1966). The observations were, however, not sufficient to show whether the winter flow was disrupted in the Southern Hemisphere to the same extent as in the Northern Hemisphere.

Different Southern Hemisphere winters, particularly at balloon altitudes, have behaved in quite different ways in terms of the detailed temperature structure but they have not shown the large amplitude variability found in the Arctic. In late winter, August and September, warm cells, principally in the Australian Sector, produce perceptible perturbations in the otherwise zonal flow, which develop into the final warming. Asymmetries in atmospheric heating and circulation between the two hemispheres may be expected to arise from the very different distributions of land and sea, although the effects in the stratosphere and mesosphere may not be large. Total ozone amounts which were measured at 17 stations during the IGY showed quite a distinct asymmetry. The maximum
concentration in the Southern Hemisphere occurred at 50 to 55° latitude throughout the year with decreasing concentration towards the pole, whereas in the Northern Hemisphere the maximum occurred at 60° to 70° moving to above 80° during spring (MacDowell, 1960). The upwards extension of such asymmetries has been uncertain due to the small number of observations.

Since 1966, additional data in the southern Hemisphere have been obtained from the Experimental Inter-American Meteorological Rocket Network (EXAMETNET). In view of the large ocean areas in the Southern Hemisphere, shipboard launchings have provided a means of extending coverage in latitude (Finger and Woolf, 1967 a), (Theon and Horvarth, 1968). Vertical distribution of the main meteorological parameters and large-scale processes in the stratosphere and mesosphere has been discussed by Gaigerov et al in a paper presented at 13th COSPAR Meeting, Leningrad, 1970. It was found that the summer anticyclonic circulation is symmetric about the pole and is practically the same in both hemispheres, the winter circulation in the Southern Hemisphere is less perturbed than in the Northern Hemisphere and that during the transitional season, April and October the two zonal flows are from the west.
Zonal flows at times of the year other than April and October are in opposite directions in the two hemispheres except at low latitudes where they merge along a sub-tropical ridge line in the winter hemispheres. When the sub-tropical ridge is displaced southward due to deepening of the middle latitude trough, westerlies replace easterlies in the sub-tropics. At mid or high latitudes during wintertime the meridional wind speeds at times may be comparable with the zonal wind speeds. At other times, meridional wind velocities are generally small compared with zonal velocities and consequently their seasonal pattern is not so readily apparent as that for the zonal winds.

1.3.4 Transient and standing eddies

A distinction can be made between transient eddies which give rise to time variations in the meridional wind at a particular site and standing eddies which are related to the longitudinal variations in the time-averaged value. When evaluated for the troposphere in terms of appropriate standard deviations, both transient and standing eddies were found to be largest in the vicinity of the mid-latitude jet stream at 10 km altitude (Newell, Wallace and Mahoney, 1966). The standing eddies are smaller in summer than winter, and even in winter their standard deviations are small in
comparison with those of the transient eddies, which show little seasonal change and have a maximum standard deviation of 15 ms$^{-1}$. Transient eddies in the lower stratosphere tend to increase with latitude and values of the order of 10 ms$^{-1}$ were found in the above study at high latitudes. Polewards of 30$^\circ$ latitude, a seasonal variation in the transient eddy velocity was present. With regard to height dependence, transient eddies were least in the region of 24 km. Above 24 km the longitudinal coverage by balloon observations has been inadequate for zonal averaging and analysis of standing eddies and the meridional circulation. Above the transient eddy minimum at 24 km, values were found to increase to a maximum at 50 km or more and to reach 25 ms$^{-1}$ at high latitude in winter. Seasonal dependence is prominent in stratospheric transient eddies in comparison with the tropospheric ones possibly due to the seasonal reversal of the stratospheric vortex. Standing eddies are expected to be an important feature of the circulation at rocket heights as well as at balloon heights. A more detailed analysis of these parameters of meridional flow awaits a better global distribution of data.

1.3.5 Diurnal variations

The increased amount of data from meteorological rocket soundings has revealed the existence of diurnal tidal motions with amplitudes of several ms$^{-1}$. Diurnal components
are more readily resolved in meridional winds than zonal winds, which are subject to large seasonal variations. At 50 km a diurnal amplitude of 8 ms⁻¹ has been found using summer data over a number of years, the maximum south-to-north flow occurring close to noon (Groves, 1967). Diurnal variations in meridional flow have also been resolved at Ascension Island and high latitude sites (Reed, McKenzie and Vyverberg, 1966). The main thermal drives for the diurnal tide, insolation absorption by O₃ and H₂O, have been described by Lindzen (1967). It is apparent that a complicated wind field is set up by relatively simple thermal drives. The results are a first approximation which may possibly be improved when the thermal drives are better known. At midlatitudes, the phase of the 24-hour tide changes rapidly with latitude and is therefore sensitive to the relative thermal input between low and high latitudes that is assumed. Seasonal changes in the thermal input will also have an effect.

The amplitude and phase of the diurnal variation in the zonal wind components at 30°N has also been obtained (Reed, Oard and Sieminski, 1969). Except near 40 km, the phase difference between the two components is about 90° corresponding to a clockwise rotation of the wind vector with time. Seasonal variations in tidal components for 31.5°N have been investigated by Groves and Makarious (1968).
Quite significant variations of phase with season occur particularly in the diurnal component where phases may change rapidly with height. Attempts have been made to observe diurnal variations in stratosphere temperatures but the amplitudes obtained have been consistently greater than those predicted by tidal theory. A limited sample of rocketsonde temperature and wind data gathered during a series of launchings at Wallops Island suggests that the diurnal range of observed temperature consists of components that can be ascribed to the real diurnal variation and radiation error of the rocketsonde instrument (Finger and Woolf, 1967b). Corresponding diurnal dependences will also be present in pressures and densities. Diurnal variations derived from temperatures measured at White Sands, 32°N, have given an amplitude of 4 to 7 percent in pressure and 3 to 5 percent in density for the 52-58 km layer (Thiele, 1966). Although these variations are small, they are comparable with the seasonal variation at latitudes of less than 30°.

Diurnal variations in wind components above 60 km have been most extensively observed by the radar-meteor method. The 24 hour, 12 hour and 8 hour solar components are usually extracted by harmonic analysis. Amplitudes and phases can be expected from theoretical considerations to be both latitudinally and seasonally dependent. At latitudes
50 to 55°N, the 12 hour component is found to be the main periodic variation exceeding the 24 hour component by a factor of 3 to 4. In contrast to the 24 hour component, seasonal changes in the 12 hour component follow a regular pattern. For most of the year, the phase of the zonal component leads that of the meridional component by about 3 hours corresponding to a clockwise rotation of the wind vector. Muller (1966) and Sprenger, Greisiger and Schminder (1969) have discussed the diurnal variations above 60 km. For altitudes above 90 km, tidal period winds have been sought by analysis of data from chemical releases (Hines, 1966) and (Woodrum, Justus and Roper 1969). In spite of the attenuation of the upward tidal energy flux, the decrease of ambient density with height tends to maintain velocity amplitudes so that tidal components still contribute significantly to the total wind vector.

1.3.6 Seasonal variations

One of the main variation of the stratospheric and mesospheric structure is the seasonal variation (Belmont and Dartt, 1970). At mid and high latitudes, there is a well established pattern of easterlies in summer and stronger westerlies in winter. The easterlies recur very regularly each year but the westerlies show year-to-year variations
in the winter and early spring. At low latitudes, the summer-time easterlies at 40 km extend across the equator into the winter hemisphere, giving rise to a semiannual variation. Due to the presence of the quasi-biennial oscillation the annual cycles are significantly modified. The semi-annual variation was quite well represented by the CIRA 1965 zonal wind model, considering the small amount of low-latitude data then available. Using the data from Ascension Island and other sites up to September 1964, the semi-annual variation was estimated to have a maximum amplitude of 30 m s\(^{-1}\) near 50 km with the core of the summer easterlies located at 15° latitude (Reed, 1966). The levels of maximum easterlies at several low-latitude sites have been studied by Rao and Joseph (1969) and the structure of the semi-annual variation at different longitudes has been investigated by Quiroz and Miller (1967).

There is a seasonal asymmetry between the Northern and the Southern Hemispheres. The easterlies from the Southern Hemisphere penetrate further into the Northern Hemisphere than do the Northern Hemisphere easterlies into the Southern Hemisphere. The Southern Hemisphere westerlies extend further towards the equator than the Northern Hemisphere westerlies as part of the same asymmetry. Although data are lacking at mid and high latitude in the Southern Hemisphere, both
winter and summer regimes in the Southern Hemisphere appear to be more intense or more extensive in latitude than their Northern Hemisphere counterparts. A hemispheric asymmetry also appears in temperature data at maximum balloon altitudes. Differences of up to \(15^\circ\)K have been reported for the same season in opposite hemispheres but annual means differ by only 2 to \(3^\circ\)K between the two hemispheres for the same latitude (Smith, McMurray and Crutcher, 1961). Southern Hemisphere data are still too few for separate consideration of the two hemispheres over a wide range of latitude.

Chemical trail releases and ground-based techniques have now provided new data for higher altitudes. In 1964, zonal wind patterns for January and July were extended to 120 km for latitudes up to 75\(^\circ\)N using Adelaide radio-meteor results and chemical release data from Wallops Island, Eglin AFB and Woomera, Australia (Kantor and Cole, 1964). In 1969 the model was updated at low latitudes on the basis of the wind results from the Barbados gun-launched probes (Murphy, 1969). Although equatorial winds appear to be from the east at heights of 95 ± 15 km throughout the year, a slight shifting of the wind belt north and south of the equator results in a seasonal reversal being observed at the Barbados latitude (Groves, 1969).
Murgatroyd (1965) has developed mean latitudinal cross sections of zonal winds for both the equinoxes and solstices using data obtained by the radio-meteor and E-layer drift techniques. In summer the easterlies changed to westerlies in the E-layer, and above 120 km a return to easterlies was thought to be indicated by sodium trail data. This description agrees with the July profile, but in winter the westerlies were taken to extend to only 100-110 km before reversing to easterlies, whereas the January profile shows them extending to 120 km.

The analysis of the meridional circulation in the stratosphere and the mesosphere is rather more difficult than zonal circulation on account of the smaller flow velocities involved. In the upper mesosphere, however, meridional components are often observed which equal or exceed zonal components. Tidal components contribute significantly at these heights to both zonal and meridional components but even when these have been extracted as with the radar-meteor technique, prevailing meridional velocities of the order of tens of ms\(^{-1}\) remain. A prominent feature of the meridional components is the flow from the summer hemisphere to the winter hemisphere at 85 to 105 km, the heights accessible for observation by the radar-meteor technique. Observations are, however, needed at other longitudes to obtain the zonally
averaged meridional flow.

1.3.7 **Quasi-biennial oscillation**

Superimposed on the annual cycle of winds described above, there is in the equatorial stratosphere, a quasi-biennial oscillation (QBO) of period nearly 26 months. This is associated with oscillations of a similar period in temperature and ozone (Ebden, 1960), (Ramanathan, 1963) and (Staley, 1963). The quasi-biennial wind oscillation has its maximum amplitude near the equator where it is far more prominent than the annual oscillation. With increasing latitude, the amplitude decreases, becoming small near the 30° latitude circle. In the vertical, there is a rapid increase in amplitude from near zero values close to the tropopause, to a maximum at about 25 km. Further upwards, the amplitude decreases slowly with height to about half the maximum value at 50 km. The QBO is characterised by a downward propagation of phase at the rate of approximately 1 km per month. The variation of amplitude or phase with longitude is not significant.

Long period variations in the zonal wind have recently been studied on a global basis using 1950-64 balloon data from 200 stations (Dartt and Belmont, 1970). The primary variation is the QBO of the equatorial stratosphere and its extension to higher latitudes. The first observations of the QBO above
30 km were obtained from rocket soundings at Ascension Island, 8°S between October 1962 and October 1964 as discussed by Reed (1965). The zonal wind oscillation was found to decrease in amplitude with increasing altitude above the 25 km level and to propagate downwards in phase at a rate of 2 km per month. Angell and Korshover (1965) showed that at temperate latitudes the amplitudes increased with height so that above 55 km the QBO zonal wind oscillation was larger than at tropical latitudes and the downwards propagation of phase was faster than at low latitudes, being 5 or more km per month. A review of the QBO has been given by Rahmatullah (1965).

The QBO in wind is accompanied by a corresponding temperature oscillation, the latter being relatively more difficult to trace. At 80 mb level the temperature amplitu'ee is 3 to 4°C and this decreases upwards to about 2°C at 30 mb. The temperature oscillation goes through a minimum at about 17°N. At 30°N, the phase change from equator is π radians, the amplitude attaining a secondary maximum of only about 1°C. Further north the amplitude decreases becoming insignificant near 40-50°N. Geostrophic equilibrium is obtained within this oscillation in the low latitude stratosphere and the temperature and wind oscillations are found to obey well the thermal wind relationship.
Ramanathan (1963) has observed a two year ozone periodicity: a year of high ozone in high latitudes occurring when there is low ozone in low latitudes. Rising and sinking motions of a cellular type in the meridional plane are suggested to explain the ozone variation. This agrees with a similar suggestion by Reed (1964) to explain the temperature QBO. Sparrow and Unthank (1964) found that the periods of westerly winds at Christchurch, New Zealand coincide with minimum ozone amounts at Aspendale and Brisbane in Australia. The downward progress of the temperature wave with time has led Angell and Korshover (1962) to infer that the likely cause is small scale eddy heat flux. Tucker (1965) has found a sinusoidal oscillation in the eddy flux gradient which is consistent with the QBO in wind. Difference between the tropical and temperate parts of the oscillation have also been reported for the Southern Hemisphere from an analysis of 1958-66 balloon data over Australia (Tucker and Hopwood, 1968). The maximum amplitude which occurs at about 25 km in the tropics was not found in the southern latitudes below 30.5 km, the effective altitude limit of observations. The presence of a QBO in other atmospheric parameters at low latitudes is not so apparent as in the zonal wind.
Stratospheric warmings

As was first observed by Scherhag (1960) and later by others (Sheppard, 1963), the temperature in the stratosphere rises suddenly in mid-winter, especially in the region 30-40 km where temperature may rise in a typical case from \(-50^\circ C\) to \(-5^\circ C\) in less than 48 hours. The warmings occur first in the vicinity of the stratopause around 48 km and appear to travel gradually down to the tropopause. The energy transformations associated with the stratospheric warmings have been discussed by Teweles (1965). The zonally available potential energy which originates primarily from latitudinal variation in solar heating and which may be expressed in terms of the mean meridional temperature gradient is converted into eddy potential energy by perturbations of wave number 2 appearing through essentially barotropic development in the strong westerlies. Eddy available potential energy may also be generated in situ by latitudinal differences in albedo and heat capacity of adjacent land and sea areas. Under conditions favourable for the formation of vortices, eddy potential energy is converted into eddy kinetic energy. While some of the eddy kinetic energy passes through a cascade process into shorter and shorter wavelengths until finally dissipated as frictional heat, a considerable fraction is converted into zonal kinetic energy. With the intense closed low centres
below the Arctic circle, the zonally averaged flow at high latitudes is easterly. The thermal winds associated with the layers where this flow increases with height require higher temperature on the side of polar darkness. Thus a portion of the zonal kinetic energy has been converted into zonal potential energy through the mechanism of eddies and an indirect meridional circulation. This potential energy is rapidly destroyed by radiative heat loss from the warm air in the polar region, with the ultimate result that the hemispheric circulation is left operating with a much lower energy than before.

A survey of Northern Hemisphere stratospheric warmings has been given by Kreister (1968). There are two general categories of warmings, 1: mid-winter warmings, which may be divided into minor and major warmings and 2: final warmings which may be divided into early or late final warmings. A major stratospheric warming occurred in December 1967 which was unusual in that it began one month earlier than previous early warmings (Johnson, 1969). Midwinter warmings in the Northern Hemisphere in the first quarter of 1966 have been analysed by Labitzke (1969) at the 30 km and 35 km levels where balloon observations are available at many longitudes. The mean temperature differences between these two levels for January were in very good
agreement with the CIRA 1965 differences. For February, however, when a major warming occurred, temperature differences as well as temperatures were longitudinally dependent, indicating a rapid change with height in the form of the longitudinal dependence. Such vertical structure is clearly apparent in the NIMBUS 4 observations with westward tilts of a few degrees longitude per kilometer height (Barnett et al. 1971). Midwinter stratospheric warmings in the Northern Hemisphere occur locally 3 to 4 times during November to February or March. The final warming occurs in spring between mid-February to mid-April when there is rapid and large general rise in temperature throughout the depth of the stratosphere and the cold low near the poles is replaced by a warm high. It is also observed that during final warming stratospheric temperature overshoots a little before settling down to the early summer temperature value.

Longitudinal variations in density are associated with those in temperature and may significantly affect the re-entry heating and dynamics of space vehicles. For the December 1967 warming, horizontal density gradients in the Arctic regions as large as $0.04 \text{ g m}^{-3} \text{ deg}^{-1}$ latitude occurred at 40 km (typical density $3 \text{ g m}^{-3}$), corresponding to an increase in the normal latitude gradient by about a
factor of three. Strong winds are associated with stratospheric warmings as horizontal temperature gradients increase. The highest wind speed recorded in the stratosphere so far appears to be $198 \text{ ms}^{-1}$ over Heiss Island on 1st February 1966 which occurred at the relatively low height of 39 km (Quiroz, 1969).

It may be mentioned that in the Southern Hemisphere only occasional midwinter warmings of the 'minor' type (tropospheric-stratospheric compensation mechanism) have been reported to take place and no major warming energetically and dynamically similar to those in the Southern Hemisphere has been satisfactorily observed (Julian, 1967). The final warming in the Antarctic stratosphere, however, is well marked. Antarctic stratospheric warmings have now also been observed by satellites IR radiometry. TIROS VII was operational for the winter 1963 and detected one midwinter minor warming and two later winter warmings at latitudes of less than $60^\circ$ which moved eastwards from Australia and the South Indian Ocean (Shen, Nicholas and Belmont, 1968). The Southern Hemisphere winter of 1969 was observed by the polar-orbiting NIMBUS 3 up to the 30 mb (23km) level as discussed by Miller, Finger and Gelman (1970). A warm area developed in the Indian Ocean and moved to the South Pacific Ocean during August passing south of Australia where the decrease in westerly flow was
observed at balloon levels. This eastwards drift appears to have been shared by the temperature field over the whole South Polar region.

Some interesting explanations have been advanced to account for the stratospheric warmings. It is curious that the source level of sudden warmings (close to the stratopause) coincides with the portion of the ozone layer heated most strongly by solar radiation. Yet, the explanation perhaps favoured most is that local subsidence associated with the break-down of the winter circulation is responsible for the warmings. Willet (1968), however, basing his arguments on the outstanding differences between observed phenomena in the Arctic and Antarctic stratosphere considers the explanation in terms of latitudinal transport, vertical mixing and dynamic heating rather unsatisfactory. According to him, the marked correlation of auroral activity with Arctic and Antarctic regimes and sudden changes of stratospheric temperature and total ozone indicate a dependence on the variability of the solar wind (solar corpuscular) invasions causing and controlling auroral, magnetic, ozonal as well as thermal phenomena.

1.3.9 Dependence on solar activity

Sprenger and Schminder (1969) have shown that the prevailing zonal wind component increased with increasing solar activity from about 15 ms$^{-1}$ towards the east at solar
minimum to nearly 40 ms\(^{-1}\) towards the east at solar maximum indicating a possible solar-cycle dependence. Other components also appear to have been affected. Evidence of a possible solar-cycle dependence in other atmospheric parameters has also been cited. Winter temperatures at 80 km at Fort Churchill, 59\(^{\circ}\)N show an average decrease of about 30\(^{\circ}\)K between solar maximum and solar minimum, and summer temperatures also show a small decrease (Groves, 1968). Meteor counting rates (Lindblad, 1967) and falling-sphere densities (Lindblad, 1968) have also been analysed showing a solar-cycle effect at mesospheric heights.

An intriguing feature of the global temperature field in the meso-stratospheric region is that while at the stratopause level the atmospheric temperature falls as should be expected but at the mesopause level it is reversed with the dark winter pole being warmer than the summer pole. To explain this reversal several causes have been considered, for example: recombination of atomic oxygen brought down from higher levels (Kellog, 1961), up-gradient transfer of energy by eddies (Sheppard, 1963), degradation of energy of internal gravity waves (Hines, 1963) and release of energy from auroral particles (Maeda, 1963). However, a completely satisfactory solution for this problem is yet to come.
The Indian Space Research Organisation, Government of India entered into a joint agreement with the Hydrometeorological Service of the USSR for collaborative meteorological rocket soundings of the upper atmosphere from Thumba Equatorial Rocket Launching Station (8°32'N, 76°52'E) using Soviet M-100 rockets. The Indo-Soviet collaborative meteorological programme commenced from Thumba on December 9, 1970 and is being continued with the M-100 rocket soundings weekly once on Wednesdays. The author worked at Thumba, assisted in the execution of the collaborative programme and directly participated in the collection of the M-100 rocketsonde data.

Under the joint Indo-Soviet agreement, the author participated in the Soviet Antarctic Expedition during 1971-73, circumnavigated the Antarctic continent, wintered at the South Polar Ice-cap and also took part in a 1500-km tractor-driven sledge odyssey from the coastal observatory Mirny (66°33'S, 93°01'E) to the geomagnetic South Pole Vostok (78°27'S, 106°48'E at 3488 m above M.S.L.) which is the world's coldest place (Caffin, 1975).
In particular, the author worked at the Soviet Antarctic station Molodezhnaya (67°40'S, 45°51'E) and carried out meteorological rocket soundings of the upper atmosphere over Antarctica during 1971-73. In this programme M-100 rockets were launched weekly once (twice in the southern winter regime May to August) from Molodezhnaya as part of the synoptic study to understand the Arctic-Antarctic circulation and the atmospheric structure in the Eastern Hemisphere. Results of the exploration of atmospheric structure over Antarctica are discussed in Chapters IV & V. A study of the equatorial atmospheric structure is made in Chapter VI and a comparison of the South Polar atmospheric structure results with those obtained at Thumba Equatorial Rocket Launching Station for the corresponding periods is given in Chapter VII. The results obtained from the Eastern Meridional Network (along 70°E) are compared with the corresponding results from the Western Meridional Network (along 70°W) in Chapter VIII. A summary of the work done and principal conclusions drawn from this investigation are given in Chapter IX.

Some of these studies have been published in the following papers:
Papers published


