

1.0 CORRECTIONS

1. Page 4: In section 2.2.1.1 the words "increase or decrease in the distance and" should be deleted.
2. Page 8: The word "periodic" should be "aperiodic".
3. Page 16: The reference "(Heath 1977)" should be "(Heath et al 1977)".
The reference "(Bhalme 1984)" should be "(Bhalme et al 1984)".
The reference "(Ananthakrishnan 1984)" should be "(Ananthakrishnan et al 1984)".
4. Page 19: The reference "(Base 1976)" should be "(Base et al 1976)".
The reference "(Wigley 1980)" should be "(Wigley et al 1980)".
The reference "Newell (1979)" should be "Newell et al (1979)".
The reference "Ramanathan (1979)" should be "Ramanathan et al (1979)".
5. Page 25: In the second paragraph the name "Dumon" should be "Dumont".
6. Page 35: The word "dominancce" should be "dominance".
7. Page 37: The word "preceded" should be "followed".
8. Page 39: The reference "Aharon (1980)" should be "Aharon et al (1980)".
9. Page 40: The reference "Bindscadler (1982)" should be "Bindschadler et al (1982)".
10. Page 48: The reference "(Gruber 1984)" should be "(Gruber et al 1984)".
11. Page 60: The reference "Abel (1979)" should be "Abel et al (1979)".
12. Page 71: The reference "Hunt (1982)" should be "Hunt et al (1982)".

13. Page 138: The reference "(England 1984)" should be "(England et al 1984)".
14. Page 148: The graph here shows the original data and a smooth curve representing the first harmonic of the Fourier reconstruction. The full reconstruction using the 9 components listed is shown in the attached graph. The axis scales and labels are the same.
15. Page 190: The name "Jackobowitz" should be "Jacobowitz".
16. Page 194: The text "change (" should be deleted.

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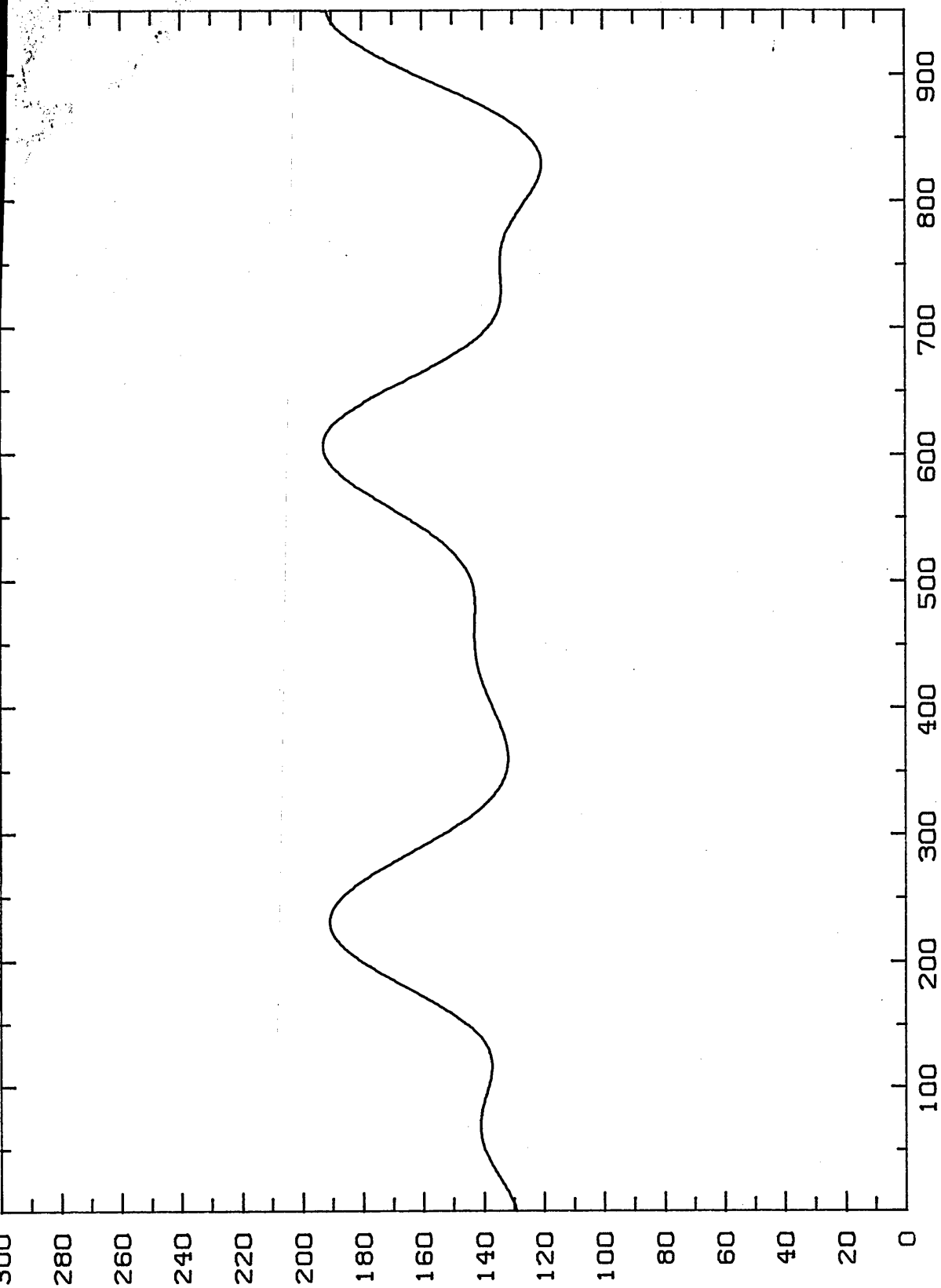


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Remote Sensing Studies Of Antarctica
Using Radiation Budget Measurements

by

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ABSTRACT

Radiation budget data of the Earth's atmosphere which is available from satellite platforms, is useful for the determination of the Earth's weather and climate.

Previous studies have concentrated on detailed analyses of data over short periods of time, ie less than 3 years, and often on a global scale. This study considers the period from June 1974 to February 1983 using data from the NOAA polar orbiting satellites. Particular attention is paid to the data from the Southern Hemisphere and Antarctica.

Studies of the radiation budget for the period were carried out to determine its variability. Results indicate that on a large scale the atmosphere is not very variable on a decadal time-scale, the maximum extent being about 30 Watts per metre squared. However abnormally high or low values can be identified on smaller spatial and temporal scales. The location and time of these anomalies, and their interrelationships are useful in determining the mechanisms that drive the global circulation. This has been investigated for areas related to the Antarctic region.

Radiation budget data was also used for ice and cloud cover derivation. The ice and cloud cover in the Southern Hemisphere were calculated using image processing techniques. These data are useful for correlation with other variables that affect climate in the Southern Hemisphere.

Teleconnections between the equatorial regions and the higher Southern latitudes have been determined using an objective lagged cross correlation technique.

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CHAPTER 1

INTRODUCTION

1.1 THE IMPORTANCE OF CLIMATE

The study of the Earth's atmosphere can be divided into two categories, weather and climate. Climate is a measure of the mean state of the atmosphere over a period of time varying from a week to thousands of years; weather concerns itself with periods less than this. At the shortest climatic time scales the mean period is a week to ten days (see section 5.6.2 for further discussion). In order of increasing time scale examples are: the persistent cloud bands over the South Pacific ocean from year to year, the 'Little ice age' (1400 -1800 AD), and the little optimum, when global temperatures were higher (800 - 1200 AD), and the great ice ages (300 - 250 Myr BP), when ice sheets covered large areas of the Earth. The last of these are long term climatic issues and are not examined here (Even longer climatic time scales exist covering many thousands or even millions of years.)

The study of climate is important because of the way it influences the environment in which we live by changing the effectiveness of agricultural areas on the Earth or the demand for energy. Over long periods (millions of years) dramatic changes in living conditions on the Earth may result, making life impossible. The movement of the land masses (continental drift) has changed global temperatures through the fortuitous placing of a land mass, Antarctica, over the South Pole. Changes in orbital characteristics are also thought to have had effects on the Earth's climate. Shorter term changes in climate (a few years) also affect activities on the Earth, for example the drought in the Sahel region of Africa has had a significant effect on the food supply in the area. There are a number of factors which affect the climate over the shorter term (a few years). Changes in the way radiant energy is distributed in the atmosphere by the introduction of dust (from volcanos) or by modifications in the opacity (by changing carbon-dioxide concentrations) may all have significant effects. The climatic state itself may not be stable, oscillations in the atmospheric-oceanographic conditions (such as the El nino) cause periodic changes in the 'normal' year to year measurements of sea surface temperatures. Because of the variability of climate conditions on the Earth, factors which tend to stabilise changes are of some importance. The Antarctic continent and the associated sea ice and ice sheets act as a large heat sink and source and thus may tend to stabilise large changes in the Earth's climate. (See Chapter 3 for further discussion of the Antarctic's importance.)

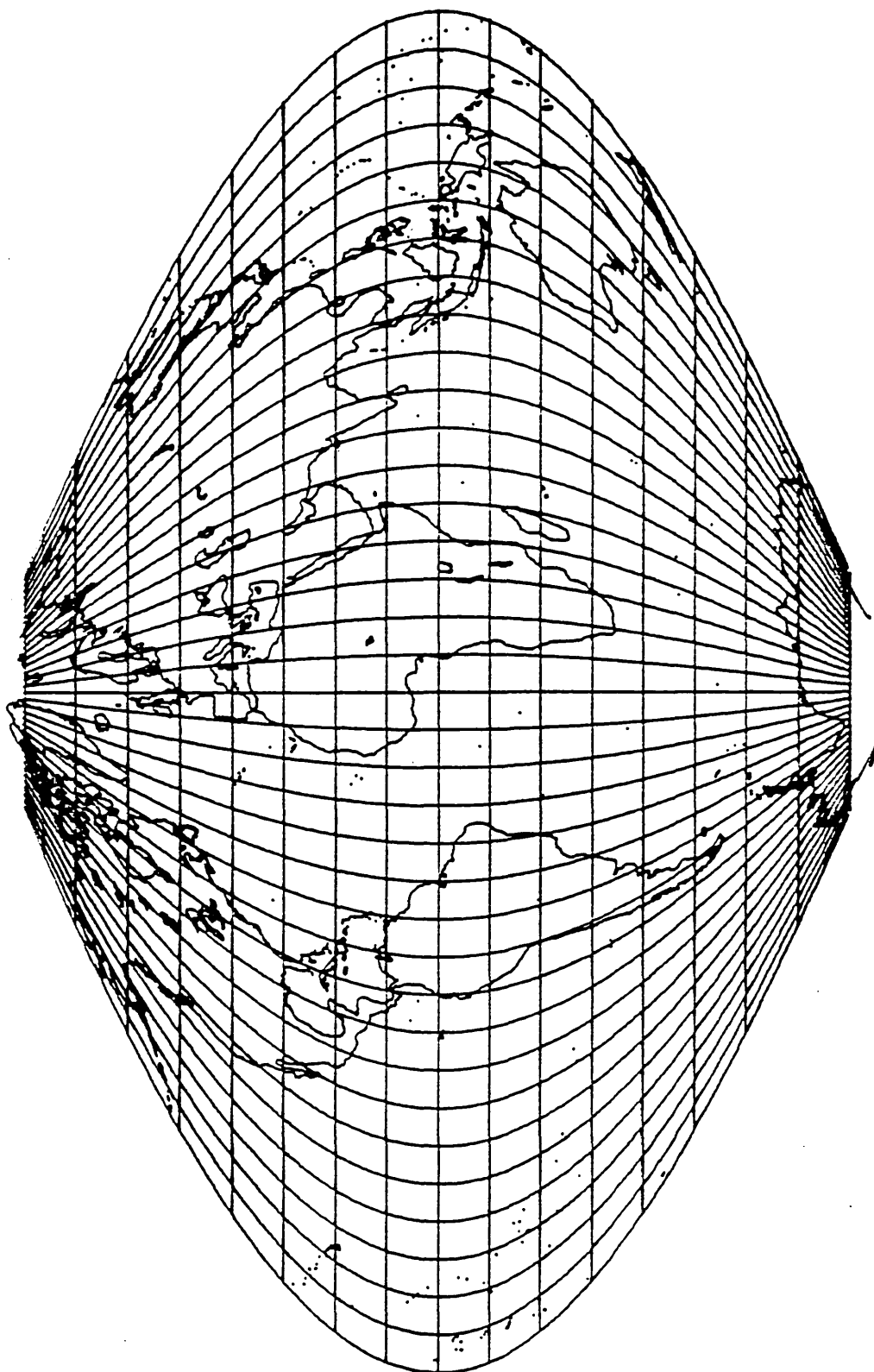


Figure 1.1. The World. An equal area projection.

1.2 SATELLITE CLIMATE STUDIES

Satellites are uniquely positioned in various orbits around the Earth to observe the weather and climate. Instruments on board these orbiting platforms can measure radiation from the atmosphere and over a period of time, investigators can build up an understanding of the climatic state of the atmosphere through the interpretation of the data sent back to Earth. Satellite studies of the Earth's radiation budget are an important element in the overall observation of the forces driving the terrestrial climate. Observations of radiation budget parameters have been made for almost two decades by a variety of satellites (von der Haar 1971, Gruber 1978, Raschke 1973 and Stephens 1981). In this thesis data from the NOAA (National Oceanic and Atmospheric Administration) polar orbiters is used to investigate the climatic state for periods ranging from ten days to ten years.

1.3 THESIS OUTLINE

This thesis considers a number of aspects of climatic variability and remote sensing, with particular reference to Antarctica. Chapter 1 is a brief introduction to climate (as opposed to weather), what it is, its study, especially from satellite platforms, examples of climate changes and variability and how these can affect our environment. Chapter 2 discusses the basic present day climate on a global scale indicating the important variables which need to be considered in a study of climatic change. Long term as well as short term effects are considered briefly and a distinction is drawn between the variables which modify climate from inside the system and those which modify from the outside. Chapter 3 begins with an exposition of Antarctic

history and explorations, up to the present date. A description is given of the location, geographical qualities and meteorological and climatic properties of this continent, in preparation for the work which is concerned with the same. The problems of using satellite data for such studies are discussed in general and specifically for the NOAA polar orbiters in chapter 4, together with the instrumentation and regression techniques used to derive the physical parameters. Consideration is also given of the errors which are likely to be found in the data set and their magnitude. Chapter 5 considers the logistical aspects of using the data. Some description of the hardware and software used throughout is given and some of the specific problems encountered in the analysis of the data are described. Chapter 6, 7 and 8 discuss the processing of the data to produce useful physical quantities and their interpretation, whilst chapter 9 presents the main results of these analyses. Chapter 6 is concerned primarily with the mean measured climatological state and the statistical deviations from this state. Useful quantities are evaluated and displayed, such as global albedo for the past 9 years. The algorithms used are also described. The image processing techniques used to derive cloud and ice areas, and the results of these analyses are explained in chapter 7. In chapter 8 an objective method of measuring the correlation of different areas of OLR anomalies is described, taking into account phase shifts. The algorithms and results obtained using this lagged cross-correlation (LCC) technique are explained. The results are shown and the conclusions derived from them given.

CHAPTER 2

GLOBAL CLIMATE

2.1 INTRODUCTION

The Earth-atmosphere system can be regarded as a heat engine with the Sun as an external energy source. Some of the incident energy is rapidly lost from the system either through reflection within the atmosphere and at the surface, or re-radiation in the infra-red region of the spectrum. The distribution of radiation in the Earth's atmosphere can be understood in terms of two distinct regions of the spectrum, the visible and the infra-red.

Infra-red radiation is absorbed and emitted by atmospheric constituents in amounts depending on the density and temperature of the emitter or absorber. Some of the factors influencing the infra-red radiation are (in order of importance) water vapour, carbon-dioxide, ozone, and aerosols. Some of these gases particularly carbon-dioxide and water vapour, significantly increase the atmospheric opacity (a measure of the atmospheres ability to allow radiation to pass through) in increasing concentrations, thus allowing less infra-red radiation from the

surface to escape to space (increasing the green house effect), and thus increasing atmospheric temperatures.

Visible radiation (the ultimate source of which is the Sun) is affected by albedo (a measure of reflectivity). In the atmosphere water vapour, in the form of clouds, is the major factor affecting albedo, aerosols (small suspended particles) also have some effect. Snow and ice also have high albedo. The seasonal effect of these, on albedo, is however somewhat reduced by the low Solar input to high latitudes where the majority of snow and ice is to be found.

Radiation budget observations may be used to analyse the current distribution and magnitudes of energy sources and sinks, relating these to the present climate. Variations in sea ice extent may be used to determine climatic state as melting represents a significant sink of energy. They may also be used to investigate the effect of factors such as changing cloudiness on the local energy balance, and hence provide information on possible future climatic change.

2.2 GLOBAL CLIMATE VARIABILITY

The variability of the global climate can be divided into two sections, those changes due to external influences and those due to internal.

2.2.1 External Factors

External influences on climate, are due to modifications to the Solar input to the Earth-atmosphere system and are thus due to orbital variations, (which change the distance or orientation of the Earth to the Sun's rays) or changes in the Solar output.

2.2.1.1 Orbital Changes

Ignoring for the moment the seasonal and daily variations in the Solar input due to the Earth's orbit and spin, it is thought that variations in the orbital parameters, such as precession of the equinoxes and obliquity changes could be a major influence in the long term climate of the Earth through the increase or decrease in the distance and orientation of the Earth to the Sun. (Hays 1976, Berger 1977). These changes (rotation of the Earth orbit - precession, and orbital plane changes - obliquity changes) have the right sort of time scales (hundreds of thousands of years) and appear to match the period between peaks in climate indices. However these factors are not significant on the short time scale (a few hundred years) and are not important to the study in this thesis.

2.2.1.2 Solar Variability

The Solar spectrum peaks at about 0.47 micron, the visible part of the spectrum and the region in which the human eye is most sensitive. This is the region with the largest energy input to the atmosphere. Integration at all frequencies of the Solar spectrum (which extends from X-rays to radio waves) constitutes the total energy input to the atmosphere. By measuring this Solar input the so called Solar constant can be calculated. The Solar constant is of vital importance to radiation budget studies and its value is continuously re-evaluated. It is also thought that from time to time - of the order of million of years - the Solar system passes through dust clouds that exist in interstellar space, thus reducing the effective Solar constant.

The Sun is known to have many time dependant features. The major variation in the Sun's activity, called the sunspot cycle, is observed to have a period of about 22 years. This 22 year periodic change in the Sun's activity may be measured by the number of active regions visible on the Sun (sunspots) officially measured as the Zurich sunspot number. Sunspots are regions on the Sun's surface that are slightly cooler than their surroundings (thus appearing darker) where magnetic fields are concentrated. The number of sunspots observed are known to peak about every eleven years. Every eleven years the polarity of the leading sunspot, in sunspot pairs in any particular hemisphere, changes, thus the reason for the 22 year period. The sunspots themselves are not thought to have any direct effect on the Earth, but they are an indication of Solar activity. Changes in the brightness of the corona - an outer tenuous layer in the Sun's atmosphere - also occur with the same periodicity. These are known to affect communications on Earth through the interaction of high energy particles - emitted during periods of high activity - and the Earth's magnetic field.

Variations in the Ultraviolet (UV) part of the spectrum (120 to 400 nm) are also related to the Solar cycle; increased Solar UV is measured during a Sunspot maximum period (Heath 1977), and this change in solar UV may affect the Earths' climate by increasing ozone concentration in the upper atmosphere which in turn causes the green house effect to be more or less effective. (Chamberlain 1981, Simon 1981).

Many authors, (Bhalme 1984; Bhalme 1981; Currie 1974; Ananthakrishnan 1984) have attempted to correlate the eleven and twenty-two year sunspot cycle with major meteorological events on Earth such as floods and drought, the monsoon index in India and surface air temperatures. Although no mechanism for the influence of the sunspot cycle on the Earths climate has yet been determined, statistical analyses seem to indicate that there is some relationship between the two.

Shorter term variations in the radiation input to the atmosphere, that are well understood and are due to the elliptical orbit of the Earth around the Sun and the 23.5 degree tilt of the Earth's spin axis, are called the seasons. There are also diurnal changes (due to Earth spinning on its axis every 24 hours).

2.2.2 Internal Factors

Internal influences on the global climate are many and complex, as they interact with each other in many ways. Here, only the major factors are considered. These are broadly divisible into natural and anthropogenic.

2.2.2.1 Natural Variations

Many factors in the Earth-atmosphere system work to change the climatic state. Volcanoes increase the atmospheric load of particles, causing changes in atmospheric turbidity world wide which affect the incident Solar radiation at the surface. These particulate loads stay in the atmosphere for many years. Oceans which have stored in them large amounts of energy and cover two thirds of the Earths surface, influence the atmosphere by interaction at the sea surface. Oceans also have a much longer overturning time than the atmosphere; very deep currents (abysall currents) can bring to the surface cold water from a period in the Earths climatic history many hundreds of years ago causing changes in the winds and thus the distribution of water vapour over the globe. Oscillations in the atmospheric state such as the El Nino-Southern Oscillation (ENSO), caused by changes in sea surface temperatures, affect remote regions through interactions of this kind. (Lau 1983).

2.2.2.2 Human Influence

Industrialised society through its influence on the atmosphere and oceans may be having an effect on the global climate. A large variety of pollutants are expelled into the atmosphere, of which carbon-dioxide is the best known. However the effects of agricultural fertilizers on the nitrogen cycle and the distribution of ozone, could have serious consequences for the global climate.

Major factors influencing the atmospheric opacity in the troposphere are water vapour and carbon-dioxide. It is now well known that the atmospheric burden of carbon-dioxide is increasing. The measurements made at Mauna Loa in Hawaii, studied by Keeling (1976), show an increasing trend since 1958 up until 1976. The increase is from about 316 parts per million by volume to 336 per million by volume in 1976, with an annual cycle superimposed on the long term trend. The annual cycle is primarily due to the growing season; growing plants use more carbon-dioxide. The increasing secular trend is believed to be anthropogenic in source.

Our present technological industrialised society consumes large amounts of fossil fuels, which when combusted release carbon-dioxide into the atmosphere. This chemical reaction brings carbon and oxygen together to release carbon-dioxide. It is estimated by Kandell (1980) that 180×10^9 tons of carbon-dioxide have been released into the atmosphere in the twentieth century. Half of this increase is thought to have been absorbed by the oceans and the biosphere. Large scale deforestation is a further major factor in the increase of atmospheric carbon-dioxide in two ways; firstly it reduces the biosphere's ability to absorb carbon-dioxide and secondly the wood cut down may well be used to add to the atmospheric load of

carbon-dioxide. The oceans absorb large amounts of atmospheric carbon-dioxide, (which may be taken down 100m or more), but assuming present trends the carbon-dioxide concentration in the atmosphere will be increased two-fold by the year 2030 (Base 1976).

The effect of increasing amounts of carbon-dioxide gas in the atmosphere could cause a runaway greenhouse effect (Wigley 1980). The problem is far from clear cut, as articles by Idso (1984), who suggests an inverse greenhouse effect for increasing carbon-dioxide concentrations, and Newell (1979) show. Many modelling efforts have been directed to establishing just what effect the measured concentration changes of carbon-dioxide are having. (Schlesinger 1983). 2

The problem is that changes in the flux input to the atmosphere modify the surface temperature field. The modified surface temperatures in turn change the circulation and this can be catastrophic for agriculture, causing flooding in low lying regions of the world (due to an increase in sea level). Some authors, among them Idso (1984) have suggested that changes in the agricultural zones may be of net benefit to man. Ramanathan (1979), has estimated that a 4 W/m^2 change in the surface flux will give rise to a change of one degree in temperature at the surface, averaged over the globe. There will of course be local changes which are larger or smaller than the average. This change in temperature may cause changes in the circulation but it is not clear whether the effect of this change will tend to increase the surface temperature or decrease it. There are a number of feedback mechanisms to be considered:

- o As pointed out by Budyko (1966) a small perturbation of summer temperatures in the Arctic sustained over a year or two can easily dissipate 4 m of sea ice for a part of a summer. Once the ice has gone annual temperature will

rise to 5 degrees centigrade (Due to the reduced albedo of sea water) and if the top 30 m of ocean form a storage layer the surface may never re-freeze (Goody 1980).

- o Positive temperature trends can cause enhanced evaporation at the surface, and increase the atmospheric load of water vapour. This rise in water vapour concentration causes the infra-red opacity of the atmosphere to increase thus trapping more radiation in the troposphere. This process itself would raise ground temperatures.
- o The cloud cover may be expected to increase, due to the increased water vapour concentration in the atmosphere, and cause more radiation to be reflected back to space. This last mechanism is a negative feedback and will tend to stabilise the situation unlike the other two mechanisms which are positive feedbacks and are unstable.

Since the effects are primarily radiative, if the atmospheric carbon-dioxide is having an effect it should be observable as a flux change, either as a change due to surface temperature increase or global cloudiness.

Lastly mention should be made of the effect of nuclear war on the atmosphere. It is now clear that the aerosol increase in the atmosphere would precipitate catastrophic global circulation changes and cause what has been termed the 'nuclear winter'. It seems however that such considerations are irrelevant in these circumstances.

CHAPTER 3

ANTARCTICA

3.1 THE ANTARCTIC

Antarctica is derived from the Greek *ἄντι*, meaning opposite and *ἄρκτος* meaning bear. Not surprisingly then it is found at the South pole, opposite the Northern constellation of Ursa Major (the big bear) that contains the (north) pole star. The Antarctic continent is a land mass of area 14 million square km, located directly over the south pole. 55% of the land is in excess of 2000 metres in height (See fig 3.1). The main land mass is the Antarctic plateau, while the largest mountain range, the Sentinel, contains the highest mountain, the Vinson massif (5140 m) at 78.6 degrees South, 85.4 degrees West. The plateau and most of the surrounding areas are covered in snow and ice all the year round. This ice cap contains 90% of the total world snow and ice. There are five main ocean sectors around the Antarctic continent, in order of increasing longitude they are: The Weddell sea (50W - 60E), the Indian ocean (12E - 90E), the Pacific ocean (90E - 160E), the Ross sea (160E - 130W), and the Bellinghausen-Amundsen sea (130W - 60W). The land beneath the

snow and ice has been shown to be composed of two main tectonic plates making up roughly east and west Antarctica. The meeting place of these two plates marks the position of the faulted mountain range.

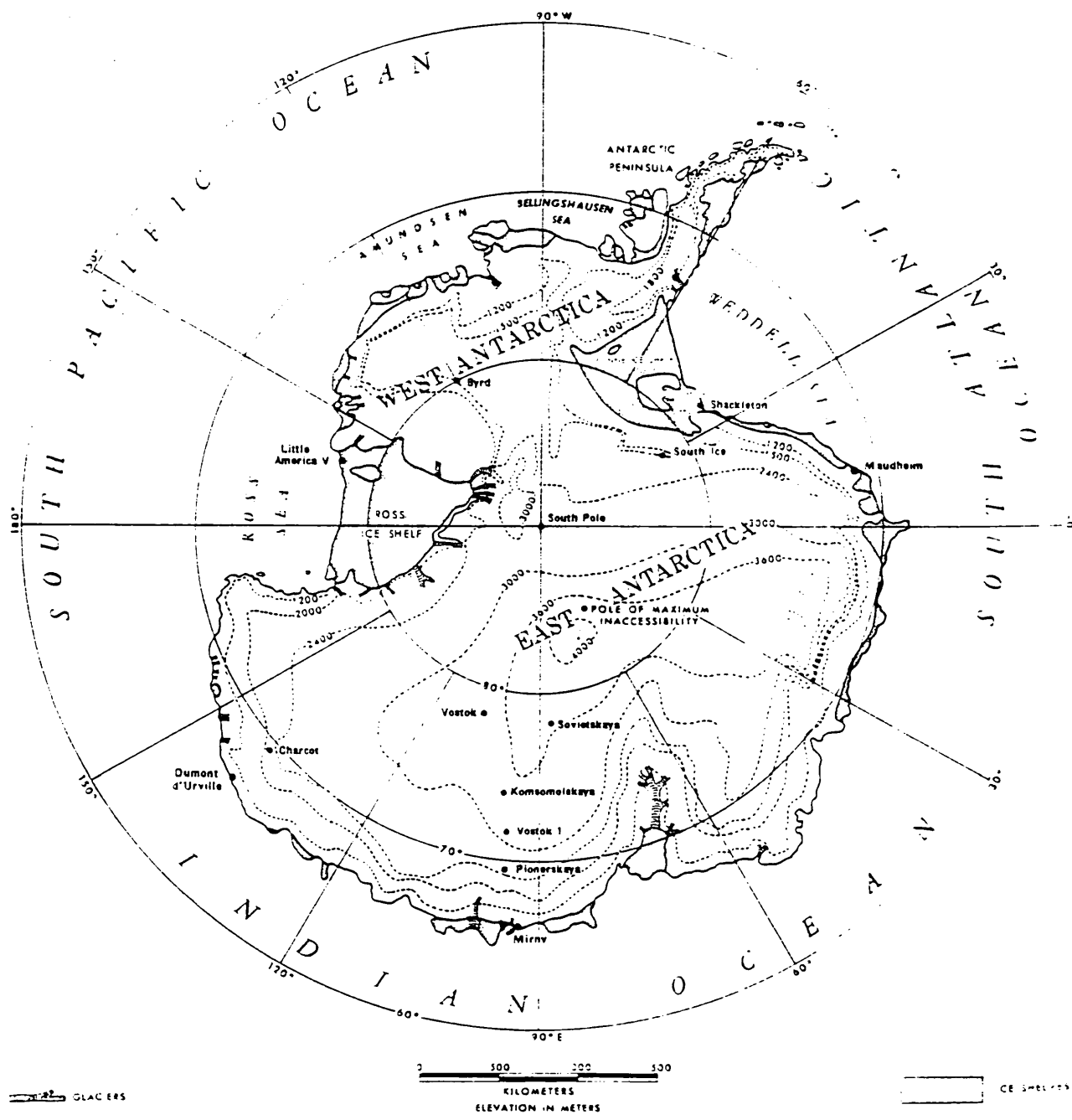


Figure 3.1. The Antarctic. Manned stations (1957) indicated.

The largest ice shelves are located in the Weddell sea (Ronne ice shelf) and the Ross sea (the Ross ice shelf). There are no trees on the mainland or indigenous human population. The land plants consist mostly of mosses lichens and fungi which inhabit the small percentage of open ground on the mainland. In contrast the marine life is very rich, consisting mostly of penguins, whales and seals.

3.2 DISCOVERY AND EXPLORATION

It was the Greek philosophers who first predicted the existence of climatic zones in the Southern Hemisphere, similar to those in the Northern Hemisphere. The exploration of the Southern seas began with the discovery of related islands, Bouvet Island, (54 degrees 10 minutes South), by Bouvet de Lozier (1739), Kerguelen Island, Crozet and Prince Edward island, by Y.J. Kregueler-Tremarec (1772). Before this time journeys into the Southern oceans had been forced by bad weather, where early reports originate of the huge ice floes.

In 1772, J. Cook, in the Resolution, began a search for a continent in the Southern ocean, but he did not discover it and in 1775 after landing on South Georgia, (an island now considered part of the Antarctic territory), he sailed back to Great Britain. Cook remarks that while travelling South the winds changed direction from Westerlies to Easterlies with a coincident drop in pressure. Postulated to explain these pressure and wind changes were cyclones (low pressure areas) in the Southern Hemisphere which follow tracks around the South Pole. A different explanation for the winds suggested cold air subsidence northward from the Antarctic continent. The Coriolis force then causes the air to divert. We now know that Cook was observing

the change from the strong zonal wind near the Antarctic to the trades nearer the equator. Cook also proved that Terra Australis, (The Southern land), was not part of the great Southern continent by sailing round the island now known as Australia. In 1820, Edward Bransfield, was the first to chart the position of the Antarctic mainland. Fabian von Bellinghausen headed a Russian expedition in 1819 and in 1823 James Weddell, with Peter Kemp, and John Biscoe sailed into the sea, now named after him, in search of new sealing and whaling areas.

The first scientific expedition, led by a Frenchman, Dumont d'Urville, sailed to the area now known as the Adelie coast in 1835 to take magnetic readings among other things. Other expeditions followed in 1838 (Charles Wilkes- American), and in 1839, (Captain J. Clark Ross- British), who conducted magnetic surveys and located two mountain peaks in Antarctica, mount Erebus and Terror which were named after the 2 ships in his survey. A period of about 30 years followed when little was done with regard to Antarctic exploration or scientific investigation.

The most important piece of information which most ships recorded, and is of use to modern analysis is the extent of the pack ice beyond which ships could progress no further. The edge of the ice matches quite closely the position of the Antarctic convergence, where the warm tropical waters meet the cold outflow. A large number of measurements regarding wind direction, temperature etc, were made by whaling ships or others which were in the southern oceans as commercial traffic, rather than on exploratory or scientific expeditions. However, in 1869 the Suez canal became available to shipping thus allowing the long journey around the tip of South Africa to be avoided. This reduced traffic in the Southern ocean (In 1914 the Panama canal also opened reducing traffic to the present low level).

In 1895 the Royal Geographical Society began sponsoring interest in the Antarctic, and in 1898, C.E. Borchogrevink spent the first winter on the continent; valuable scientific work was done. The low pressures measured were of note. The lowest value measured was 926 mb. A number of explorers commented on the fact that their barometers were useless because they could not register these low pressures, as the needles were impinging on the wooden case of the barometer. The British National Antarctic expedition was co-sponsored by the Royal Society and the Royal Geographical Society in 1901-1904. A ship, the Discovery was dispatched and in 1902 a settled base, at Edward VII peninsula, was set up and used as a centre for scientific studies and exploration. During this expedition measurements of salinity were made. The measurements involved taking samples of water by lowering baskets over the side, to a depth sufficient to penetrate the surface layer. There was often a difference of several degrees in water temperature, and a large change in salinity. A sled journey, by R.F.Scott, E.Shackleton and E.A.Wilson succeeded in reaching 82 degrees 17 minutes South on the 20th of December 1902.

Another expedition was led by E. Shackleton in 1908. In the Nimrod, Shackleton landed on Ross island and it was during this expedition that T.W.E. David sledged to the magnetic pole (72 degrees 25 minutes South). Scott (in the Terra Nova), and Amundsen (in the Fram), both arrived at the Ross sea in 1911. Amundsen set off for the pole and reached it on the 14th of December. Scott led a second exploration (1910 -1913), which was based at Cape Evans and Cape Adare. Geomagnetism, meteorology, atmospheric electricity, and geology were studied. Sir George Simpson, meteorologist with Scott's expedition, was the first to make upper air soundings in the Antarctic. Scott, Wilson, Bowers, L.E.G.Oates and Edgar Evans left for the South pole soon after. On January 18th 1912 they reached the South pole, and set off on their return journey; they were caught by

bad weather conditions on the way back, none of them survived. In 1914 Shackleton took part in the Imperial Trans-Antarctic expedition, (intending to cross the Antarctic plateau from the Weddell sea to the Ross sea by way of the South pole). The ship, the Endurance, was trapped in the ice and eventually crushed on October 27th 1915. The survivors were eventually rescued from Elephant island, which they had sailed to in their 12 foot boats, on August 30th 1916.

In 1928 an airplane was used for the first time by Admiral Byrd during his expedition. Observations were made in glaciology, geology, meteorology, the ionosphere and cosmic rays were also studied. The expedition lasted until 1930. A second journey by Byrd took place between 1933-1935 when the Ross ice shelf thickness was established for the first time using seismic methods. There followed a break in activity due to World War II. In 1947-1948, and 1949-1952 major expeditions were mounted. The one in 1949-1952 was a joint British - Norwegian - Swedish campaign; studies were made of meteorology, geology, solar radiation and surface energy balance.

However the overwhelming impression of the southern oceans that all explorers took back with them was of the icebergs which, with the ice flows, play an extremely important part in the radiation regime of the Southern Hemisphere. This is discussed in detail in the sections below. (For references see footnote 1).

Footnote (1) - A number of references were used in this section: (Cook 1777, Ponting 1979, Royal Society 1908, Royal Society 1960, Brittanica 1959)

3.2.1 IGY And After

The meteorology of the Southern Hemisphere was first studied in detail during the International Geophysical Year, (IGY), which began in 1957. During the IGY studies were carried out in a large number of disciplines including solar activity, meteorology, geomagnetism, oceanography, glaciology, etc. The study of the Antarctic was given special emphasis for a number of reasons; adequate observations of the Southern Hemisphere's meteorology could only be made if the Antarctic (which is after all a large part of the Southern Hemisphere), had observation stations active throughout the IGY (the south pole station was also the end point of the pole-to-pole observations required). The Antarctic was also the major area of study for glaciologists, since the continent is the largest area of snow and ice on the Earth. The meteorology of Antarctica was considered vital to the understanding of the Southern Hemisphere circulation in general so synoptic observations were also made; and the first weather maps prepared for the Antarctic were produced during the IGY. Much of the lack of measurements in the Southern hemisphere in more recent times is due to the reduced shipping traffic in the Southern oceans. However during the IGY a special dispensation was given to whaling ships (van Loon 1977) which returned valuable information on the state of the atmosphere. The meteorological observations were considered unique due to the unusual conditions generally found in Antarctica. Since the majority of the Earth's magnetic field lines cross the Earth's surface at the poles study of geomagnetic phenomena is best carried out there. Observations of the ionosphere and the Aurora Australis were made to determine the mechanisms linking these phenomena and Solar activity (the IGY was also during a sunspot maximum).

In 1959 twelve countries were signatories to the Antarctic treaty which pledged no military activity and scientific cooperation for 30 years in the Antarctic territories. Several stations that had been manned during the IGY were abandoned. Also in 1959 a Special Committee on Antarctic Research (SCAR) was set up which is still active today. Work done by the UK included studies in the fields of geomagnetism, seismology, meteorology, glaciology and biology. Theoretical studies of Antarctic climatology rely on a large number of experimental measurements. In the earliest days these were made by explorers of the Southern oceans. Today there are many permanent stations in the region which make regular measurements of temperature, pressure, cloud cover, and whose personnel release weather balloons to determine the vertical temperature profile (BAS 1983). These valuable ground truth measurements are significantly augmented by independent satellite observations which cover large areas not serviced by ground personnel. The intercalibration is useful for determining the relationship between these two different types of measurements. (See discussion on errors for cloud comparison in section 7.1.3) An example of the excellent use of satellites in the study of the Southern Hemisphere is the work by Zwally (1983). The microwave instrument aboard NIMBUS was used to determine sea-ice extent and concentration. However these measurements are still relatively new; the work by Zwally spans a period of only 3 years, 1973-1976.

Recent improvements in communications have also taken place between the stations in Antarctica and the meteorological centres in the United Kingdom. To avoid problems with ionospheric storms disrupting HF (High Frequency) communications, use of the DCP (Data Collection Platform) on board METEOSAT-1 has recently been made. This technique has improved the rate at which Antarctic meteorological data gets into the world weather database from 18 months (the journey time by ship) to less than a day. More details of the DCP system as used by the British Antarctic

Survey, (BAS) are given in a paper by Limbert (1983).

3.3 METEOROLOGY AND CLIMATE

Antarctic meteorology requires special study for many reasons arising from its topography and from the special nature of the surface and extent of the snow fields. A number of differences between the Northern and Southern Hemispheres should be borne in mind throughout this discussion:

- o Antarctica is the largest ice covered land mass in both Hemispheres with extremes of low temperatures which have often prompted people to call this vast continent the "Refrigerator of the Southern Hemisphere".
- o The ratio of sea to land masses is vastly different from that in the Northern Hemisphere. This can quite clearly be seen in a graph of land area in a zonal band versus latitude. (See for example figure 3.2 taken from van Loon (November 1972)).

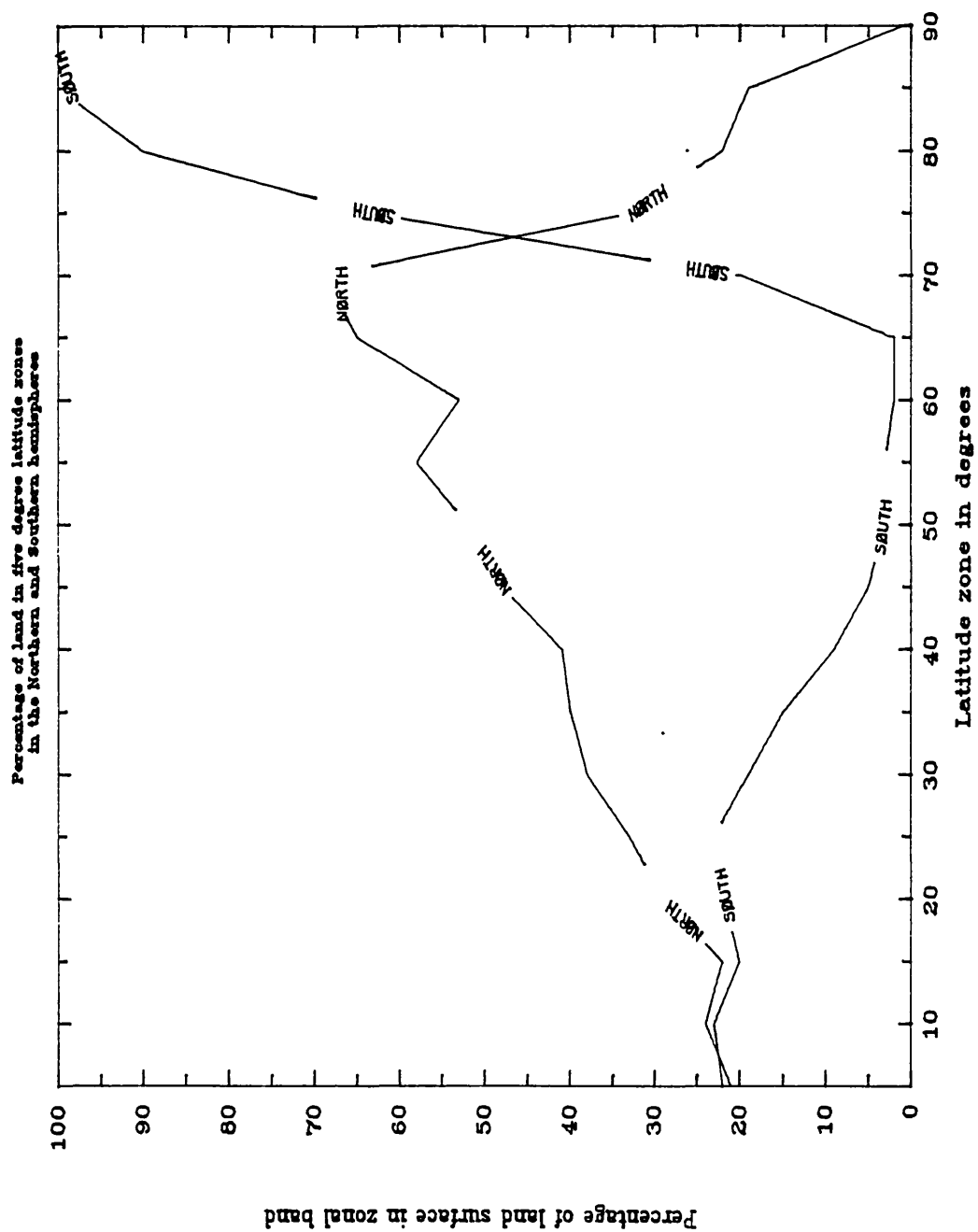


Figure 3.2. Graph of area versus latitude.

- o A large portion of the land mass in the Southern Hemisphere is concentrated over the pole. In the Northern Hemisphere there are no significant land masses above seventy degrees north.
- o The Northern Hemisphere is a bowl while the Southern Hemisphere is a plateau around which the zonal flow tends to be diverted.

This almost mirror image of the Northern Hemisphere is the reason for the very strong zonal flow around the Antarctic. A little to the south of the maximum strength of the zonal flow a region of high cyclone frequency occurs (between 60 and 50 degrees south). These low pressure regions move eastward and southward and are a common feature near the Antarctic. Many of the cyclones cross the coast but do not proceed very far before dissipating.

The Antarctic region can be divided into two distinct regions of interest. The 'normal' meteorological elements comprising the plateau (the Antarctic inland area), the Antarctic coastal regions and the Southern Hemisphere circulation and the exceptional meteorological elements; the Southern ocean and associated sea-ice near the continent.

3.3.1 The Antarctic Plateau

The first of these, the Antarctic plateau, is technically classed as a desert because of its small amount of precipitation. It is a large area of raised land (about three-thousand feet in height) comprising about 55% of the land area of the continent. (See figure 3.2). The Antarctic plateau is very cold. The maximum temperatures around its various stations are all below zero! The coldest temperatures measured were at a Russian station, Vostok where an all time low was measured at 184 K, (-89 Celsius), while the mean annual temperature is measured at 217 K, (-56 Celsius). Periods of intense cold occur when the rare 'warm' air advections fail for long periods of time. The wind chill factor (a measure of rate at which heat is taken away from a body) is approximately constant over the entire continent, the warmer temperatures away from the plateau being made up for by the stronger winds.

Because of the height of the interior of the plateau few depressions can penetrate to deposit their moisture there. Fronts that do pass over the interior are difficult to identify with any certainty because similar phenomena which occur in the interior resemble their effects on the local scale. An increase in surface winds for example can reduce a surface inversion in a matter of a few hours and this can be mistaken for a front due to the rapid rise in temperature. They are also difficult to see on synoptic pressure charts because only 500 mb charts are available for the continent (it is at a height corresponding to about 700 mb). In general fronts do not seem to have the same characteristics over the Antarctic as they do over other places on the Earth. This is due to the very large stable layer of cold air which is permanently resident over the plateau.

Strong inversions are a common feature on the plateau, it is common for inversions to persist for a whole year. These are caused by intense radiative heat loss from the surface. Snow being both a good reflector in the visible and a good radiator in the infra-red. It is the strong inversion which causes the very cold temperatures that are recorded there. Inversions can be dissipated by surface winds (as mentioned above) but these soon return (within a day) (Dalrymple 1966). On the plateau there are only very small diurnal and seasonal changes in meteorological phenomena. This is because of the extremely stable layer of cold air. The diurnal forcing of the atmosphere is also much weaker in the polar regions.

3.3.2 Other Antarctic Regions

Measurements of precipitation are difficult if not impossible but it is estimated that $< 5\text{cm}$ of water equivalent falls on the plateau (it is higher on the periphery). In contrast to the relative calmness of the plateau the coastline exhibits much of the most extreme weather to be found in Antarctica. A notable feature of the coastal regions are the katabatic (down slope) winds. In the interior the katabatic winds are weak but at the edge of the plateau they can be very strong and long lasting, due to the increased slope.

Cloud cover on the plateau is also difficult to ascertain especially at night or when it is snowing but it is estimated at about 2 tenths cover. The maximum cloud amount is observed during the transition season from summer to winter. The Antarctic peninsula is a major factor in Antarctic ocean currents due to its perturbation of the zonal flow. It is ridged with high mountains and therefore also perturbs the atmospheric flow.

This large orographic barrier is known to affect the path of cyclones as they pass the peninsula. This makes the Weddell sea area a region in which cyclones are rarely found, in fact it is generally an anticyclonic area. Cold air from the plateau damming against the peninsula seems to be a major factor in the determination of the ice floe direction (Ackley 1979), (see section below). This ridge is in fact the meeting place of two air streams one warmer than the other. The warmer air stream comes from the South Pacific while the colder air stream is a katabatic wind which comes down the slopes from the Antarctic plateau. In fact 4 distinct types of synoptic situation have been found to occur in this region (BAS 1983). The dominance of one or other of these is thought to be the deciding factor in the winter's severity. The local climate depends on small changes in the temperatures in the Antarctic peninsula, the changes causing one or other of the air streams to be dominant.

3.4 THE IMPORTANCE OF ANTARCTICA

The Antarctic is essentially a large expanse of ice and snow. It is largely through this property that it is regarded as a large heat sink in the Southern Hemisphere. Its short term effects on the global circulation are through its interactions in the Southern Hemisphere with the pressure and wind fields. Sometimes the sea-ice variations drive the circulation and sometimes the circulation drives the sea-ice growth and decay. The situation involves the interplay of wind, ocean circulation, and temperature distribution and all the mechanisms involved have not been elaborated. Because of the effect that sea-ice has on the atmosphere and oceanic circulation the extent of the ice from year to year is of vital importance. The areal distribution and concentration would be a useful starting point for those wishing

to establish the physical mechanism that links the atmosphere to the sea-ice distribution.

3.4.1 Antarctic Sea-ice

The southern ocean, which can be regarded as bound to the north by the Antarctic convergence, consists of the southern ends of the Atlantic, Pacific and Indian oceans. This ocean is unique because of the circumpolar flow that occurs there. It is also known to produce bottom water and to export it equatorward (Heezan 1972). Sea-ice comes in many forms, from the first stage of ice formation, which consists of fine ice particles (grease ice) to thick multi-year floes (there are about 20 different named types of sea-ice). Sea-ice in the Southern Hemisphere reaches a maximum area of about 25 million square kilometres - in September - (4% of the hemispheres area) and in the Northern Hemisphere about 15 million square kilometres (3% of the hemispheres area) (Goody 1980). (However note that although the area of sea-ice is 50% more than the area of snow and ice on the Antarctic the volume of ice in Antarctica is 1000 times greater than that in the sea). Antarctica if melted would represent a 70m rise in sea level while the rest of the sea-ice would represent <8m (Barry 1981). Sea-ice has a number of effects on the local radiation budget regime which need to be considered. Ice (especially if it is covered in snow), is a very good insulator. The albedo of sea-ice (60-70%) is very high, certainly much higher than that of sea (~6%)! Sea-ice represents a very large store of energy, in the form of latent heat of melting. There are also mechanical effects to be considered. Waves can influence the position and concentration of sea-ice. Sea-ice also affects the pressure fields and hence the wind strength and direction.

The position of the Antarctic convergence can accurately be measured from ocean salinity or temperature measurements. This is because the act of freezing salt water causes the expulsion of salt into the remaining unfrozen water thus increasing the density of the unfrozen water. Water which is not of an Antarctic source has a lower salinity. Sea-ice is also thought to have a major influence on the climate of the continent through the action of cyclones which are induced by large temperature differences between sea and sea-ice (Schwerdtfeger 1970). A great deal of effort has been put into understanding the way the area of the sea-ice grows because it has implications for a large number of meteorological factors. Studies using numerical models have shown that the Antarctic sea ice has a much larger effect on climate than that in the Arctic (variation in sea-ice area in the Southern Hemisphere is six times greater than for the Northern Hemisphere (Simmonds 1979)). A numerical study by Barry (1981) has shown that during the melt (January to February) the ice area anomalies are preceded by atmospheric changes, implying atmospheric forcing by ice. During ice increases the situation is reversed; atmospheric changes seem to force the sea-ice area (Barry 1981). Similar results have been shown by Cavalieri (1981). An enhancement of the circumpolar trough has also been observed to coincide with periods of rapid sea-ice area change.

The role of cracks in sea-ice, or leads, is one of the factors which complicates matters and ties the problem of estimating heat budgets in models to sea currents and winds, since these induce stresses in sea-ice, causing leads and ridges to form. Leads only make up about 1% of the area of an ice shelf but they replace a -30 degrees C surface with one at 1.9 degrees C. This and the insulating properties of the sea-ice cause the heat exchange with the atmosphere through these leads to be comparable with that through the 99% of remaining sea-ice (Maykut 1978). Wind fields also play a major role in advecting sea ice in the Weddell area.

The area of sea-ice in the Southern Hemisphere in winter is typically of the order of 25 million square km, while in summer the area is only about 5 million square km (a few places on the coastline are ice free), (Zwally 1983). This very large change in ice area is thought to be some indication of climate variability (Ackley 1979). It is also expected that during colder climatic periods the area of sea-ice will be larger (Lamb 1972). Furthermore it appears that > 50% of this change takes place during a very short period of time (July - September)

The Weddell sea has the largest area of variable sea ice throughout the season (Zwally 1984). The sea flow in this area is dominated by a cyclonic gyre (a clockwise rotation in the Southern Hemisphere) which contains the coldest water in the seas near the Antarctic. Recently areas of open sea inside large ice-sea areas, polynya, have been observed and mapped by the ESMR instrument on NIMBUS. (Zwally 1981). These negative sea-ice anomalies have been associated with coincident positive anomalies in the Ross sea (Barry 1981). The very large polynya observed in the Weddell sea is thought to be caused by a combination of oceanic and wind field factors (Parkinson 1982).

Observations of ice berg dynamics have given valuable insight into the way in which ice fields grow and shrink. Modern measurements track large ice bergs from satellites (Swithinbank 1977). In comparison early measurements of this type were due to trapped ships (Wordie 1921). Measurements of the position of fronts have shown that these seem to occur roughly where the ice edge is. The flow of broken ice, wind and currents northward out of the Weddell sea has prompted sailors to call this area the hell hole of Antarctica. It is indeed an area of strong sea currents and winds with loose pack ice being advected northward.

In the long term the Antarctic is important for a number of reasons, both for its influence on ice ages and as a region in which climate studies can be carried out. The glaciologists need measurements to know if their models, that can predict the coming of an ice age, accurately reflect the true situation.

3.4.2 Ice Ages

Ice ages are periods in the Earth's climatic history when global temperatures are much lower (1 - 2 centigrade). The Earth seems to pass from periods of cold (ice ages) to periods of relative warmth (inter glacial periods). During ice ages the distribution of ice over the world increases dramatically. There are two mechanisms that are postulated to explain these periods of relative cold. The Milankovitch theory of orbital variations of the Earth's orbit (Hays 1976), and the Antarctic ice surge theory (Wilson 1964). The orbital theory relies on variations in the Sun's input to the Earth's atmosphere through changes in orbital parameters.

The cause of the ice ages has been the subject of much work, for example Thomas (1979), Wilson (1964), and more recently Aharon (1980) all postulated that the ice ages are intimately related with the collapse of the Antarctic ice shelves. Continental drift is thought to have played a significant role in the long term climate history of the Earth through the accident of placing a large land mass, the Antarctic, over the South pole. With this in mind people have studied the change in sea-ice extent over many years to ascertain whether such a change is actually occurring, and numerical models have been developed to determine if the current ice shelves are stable. In the Antarctic ice surge theory a large area of sea-ice from the

Antarctic 'surges' into the southern oceans. The western Antarctic ice sheet is known to be inherently unstable and it is the disintegration of this ice sheet that is thought to lead to an ice age. (Hughes (1975) puts forward a mechanism to explain the events leading up to an ice age and the following interglacial period). When the western Antarctic ice sheet collapses it raises sea level and disrupts the Weddell and Ross sea gyre causing more pack ice to be cleared from this area and reduction of bottom water production. A complex series of mechanisms follow that eventually lead to a large part of the Northern Hemisphere being covered in glaciers. Communication of the Antarctic events is made through deep currents in the Atlantic. Whether the current ice sheet is stable however is not an easy thing to ascertain as the simple model of ice sheet flow by Bindshadler (1982) shows.

To discover the way ice ages work, study of past events is helpful. However direct observations of the weather over the world go back only about 100 to 200 years, and much less in the Southern Hemisphere. To study climate, observations need to go back much further (of the order of thousands of years). For this reason techniques have been used to study the state of the atmosphere in past ages. Indirect methods are employed, methods which infer climate parameters such as air temperature, humidity, or sea temperature by studying some ancient remains which were influenced by the weather at the time in question. This presents two problems, 1) determining from the sample conditions climate state, 2) determining the age of the sample. This may be measurement of tree ring sizes in old trees (dendroclimatology), which can go back several thousand years, or the measurements of lakebed sediments. These local measurements cannot give general information about the state of the world weather. In Antarctica and Greenland, where there are relatively old ice sheets deep ice cores can reveal much about past climates. (Very deep cores (older climates) are hampered by inadequate drilling technology.

(Allison 1983)). Cores are useful because the pressure of the ancient climate can be calculated by looking at the radius of the bubbles left behind in snow that has since become ice. Temperatures can be calculated by comparing relative amounts of two oxygen isotopes oxygen 16 and 18. Because these two isotopes have different evaporation rate temperature dependencies their ratio in ice cores gives information on ice climate at the time of formation.

There are other methods; geological, methods involving carbon dating, and observation of minute ancient skeletons for determining past climate. These methods are good for establishing events on the timescale of thousands of years. The literature is generally agreed that past climate has seen many catastrophic changes, associated with ice ages and other 'less catastrophic' such as the little ice age. However almost all researchers in the field are agreed that the Antarctic and the Antarctic ice sheets play a major role in the climate of the Earth as a whole.

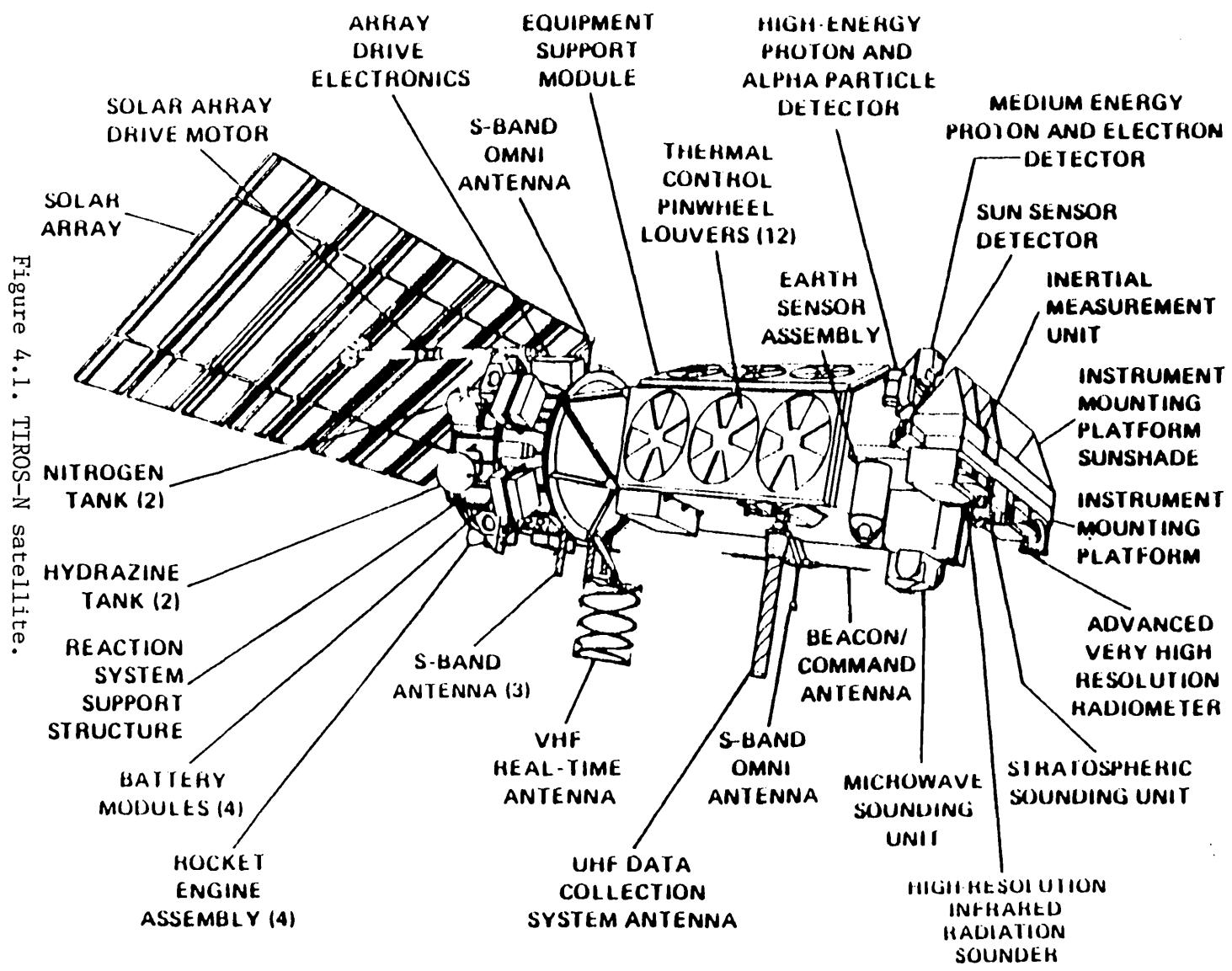
CHAPTER 4

SATELLITES AND DATA

4.1 SATELLITE METEOROLOGY

Meteorological satellites are instrument packages orbiting the planet Earth taking measurements of the radiation field. Some early satellites had small TV cameras (Vidicon cameras), for observation of weather systems. (See table below 4.1). Modern satellites however have complex instrumental loads, for observation in many wavebands. Observations are made of Earth weather systems, magnetic and electric fields as well as Solar emissions. (See figure 4.1). The reason for these expensive spacecraft is the enhanced coverage of the Earth, its oceans and its meteorology. Logistically speaking satellites are more desirable than numerous ground observations, because they provide a single source of information over a large scale (temporal and spatial), from one set of instruments, and one set of calibration coefficients. This is more desirable than hundreds of individually calibrated heliometers, for example. Over the oceans the logistical problems are more pronounced (since measurements must rely on ships). Ground observations are

sometimes more suitable for certain tasks (soil moisture, humidity, surface temperature), which are local in nature and are difficult to ascertain from any satellite platform. However some effort is being put into improving retrieval techniques for these parameters (Eyre 1982, Chesters 1981).



Satellites can be divided into two main categories, those that are in a geostationary orbit, and those which are in polar orbit. (Soon there will be a third category - a drifter - which is somewhere between the two). Geostationary satellites orbit the Earth at an altitude of 36000 km above the equator and thus have an orbital period of 24 hours. They therefore have the same sub-satellite point (nadir point) at all times (although there are small variations of a few degrees over twenty four hours). There are nominally five of these satellites, (METEOSAT-2, GOES-E, GOES-W, GMS) providing global coverage, with the exception of the poles. These satellites provide excellent temporal resolution, (they are limited only by the rate at which the instruments sample - METEOSAT-2 for example produces images in three wave bands every half hour). However they have only moderate spatial resolution, about 5 km. Because of their good temporal resolution they are used primarily for weather forecasting and research of a various kinds. (Radiation budget and cloud detection studies (England 1983), crop studies etc). However due to their fixed position over the equator they cannot view all places on the Earth, and due to foreshortening effect their spatial resolution is reduced towards the limb (8km over the British latitudes - See figure 4.2), making them unsuitable for studies of high latitudes.

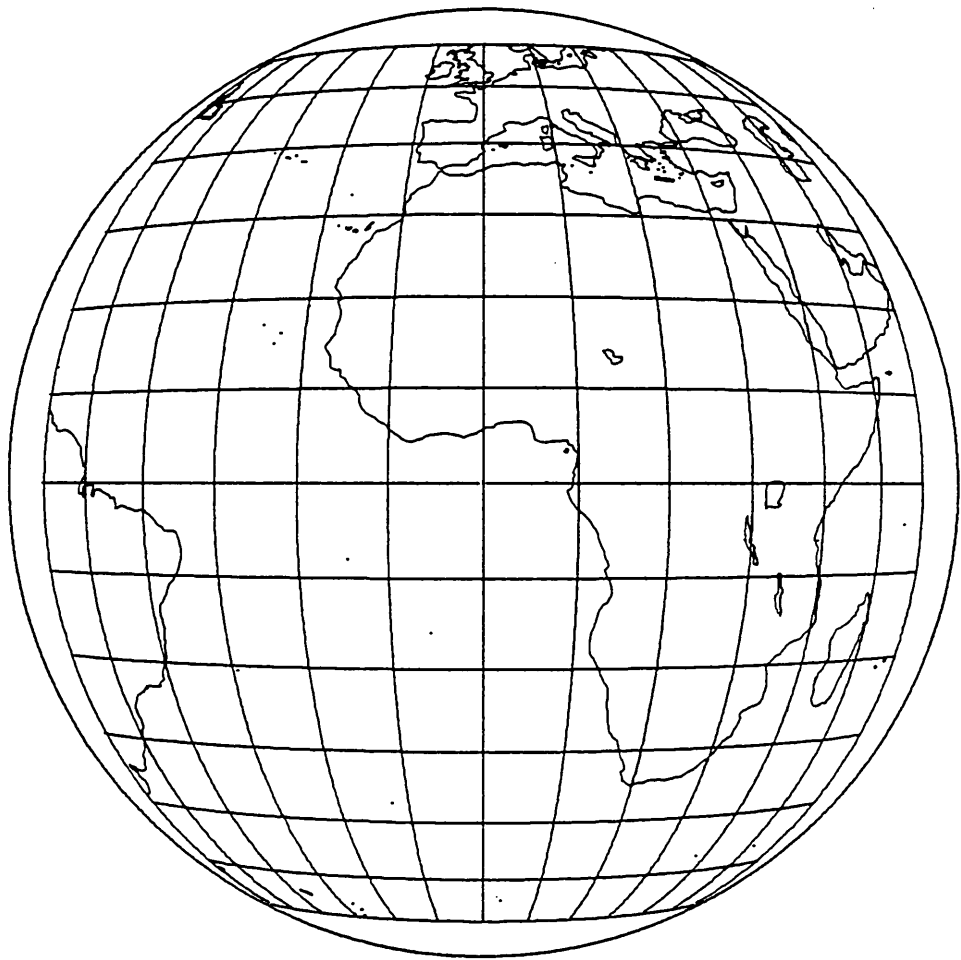


Figure 4.2. METEOSAT-2's view of the world.

Polar orbiters pass roughly over the poles of the Earth in low orbit (about 800 km). The orbits are inclined at the same angle to the Sun throughout the satellites orbit and this means that they cross a given latitude at a fixed Local Solar Time (LST). These satellites have very good spatial resolution (~1.1km in the infra-red, full resolution, and 4km in the visible for TIROS-N), because they are in low Earth orbit. In this orbit they move relative to the ground beneath them and are able to view all parts of the Earth's surface during the course of a day. Polar orbiters have disadvantages because of their short orbital period, typically ~100 minutes (Compare with METEOSAT-2 which sees the same Earth disk all the time). The short "over the horizon" time means that the large amount of data (high spatial resolution), must be disseminated very quickly (when the ground station is in view), and to ensure this, ground stations need to track the satellite as it moves in the sky. This is economically undesirable. Steerable dishes, for spacecraft command, are expensive, and duplication of ground facilities and personnel is also expensive. When the spacecraft is out of contact with all the ground stations, it must store its data on board, thus taking up valuable space and weight in the payload (METEOSAT-2 simply transmits its data after every scan line, hence it requires no data buffering).

Finally it is fair to say that geostationary and polar orbiters are complementary systems, each achieving some of the things that the other cannot. There are many polar orbiter spacecraft in operation. NIMBUS-6 for example, which measures radiation budget directly, may be considered a better instrument for the purpose of climate monitoring than the NOAA spacecraft. However the NOAA spacecraft have a longer time span of data.

4.2 THE NOAA SATELLITES

The NOAA series was a follow up to the TIROS series of satellites which ended with TIROS IX. The NOAA satellite programme was set up to meet a number of specific objectives. These include day-to-day monitoring of the environment, meteorological prediction and warning, oceanographic and hydrological services, space environment monitoring and prediction, and global research (Schwalb 1978). Recently priority has also been given to research and climate monitoring constraints (indicating that a standardised observation time should be utilised) (Gruber 1984). The programme is a joint venture by the United States, the United Kingdom and France. The US (through NASA and NOAA), supplied the space craft, the launch vehicle, and the ground station, France supplied the Data Collection System (DCS See footnote (1)) and ground facilities for 'blind orbits' and the UK (through the Meteorological office), supplied the SSU (Stratospheric Sounding Unit). NOAA based their spacecraft design philosophy on the use of proven space hardware to meet operational requirements. Some instruments flown on TIROS-N for example were modifications of instruments flown on the experimental NIMBUS craft. However in redesigning these packages for the TIROS-N satellite, care was taken to improve instrument reliability, without changing the previously proven concepts. The second generation of satellites (NOAA-1 to NOAA-5) were improved and updated when the third generation began. NASA funded the the first experimental third generation satellite, TIROS-N, which was the first to carry the full complement of instruments (with some small differences) now flown aboard the NOAA spacecraft. Each new craft over the years

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Footnote (1) - The Centre National d'Etudes Spatiales supplied the DCS, and the Centre National d'Etudes de la Meteorologie constructed and maintain the ground station - In Lannion France.

has received small modifications, such as radiometer filter changes (thus necessitating the modification of the retrieval algorithms for physical parameters), or replacement of the window channel radiometer (on TIROS-N and NOAA-6). Currently NOAA-C (NOAA-7), is in flight and supplying data. NOAA-F is scheduled for launch in September 1984. (If it is placed in orbit successfully it will be renamed NOAA-8). A summary of the TIROS and NOAA spacecraft characteristics is given in the table below. Much of the information for this table, which can be found in Kidwell (1983) and Liou (1980) is useful when analysing the data because significant systematic errors can be hidden in data when new satellites are launched due to significantly different sensitivity of instrumentation and equator crossing times.

Table 4.1. Summary of NOAA satellite data.

Launch date	PLN NOAA	Instrument	Op.name	NBC	SBC	EOP
01-04-60		TV-WA,TV-NA.(3)	TIROS-I			
23-11-60		As TIROS-I+IR scan	TIROS-II			
12-07-61		2TV-WA,HB,IR,IRP	TIROS-III			
08-02-62		TV-WA,IR,IRP,HB	TIROS-IV			
19-06-62		TV-WA,TV-MA	TIROS-V			
18-09-62		TV-WA,TV-MA	TIROS-VI			
19-06-63		2TV-WA,IR,HB,IP	TIROS-VII			
21-12-63		APT,TV-MA	TIROS-VIII			
02-07-65		2TV-WA	TIROS-X			
22-07-65		2TV-WA	TIROS-IX			
11-12-70		2APT,2AVCS	NOAA-1			
15-10-72		2VHRR,2VTPR,2SR,SPM	NOAA-2			30-01-75
06-11-73		2VHRR,2VTPR,2SR,SPM	NOAA-3			17-12-74
(1)			NOAA-4	2100	0900	15-09-76
(2)			NOAA-5	2100	0900	01-03-79
13-10-78			TIROS-N	1530	0330	20-01-80
27-06-79	A		NOAA-6	1930	0730	
29-05-80	B		(failed)			
	C		NOAA-7	0230	1430	
(4)	F			0230	1430	

Key to symbols used:

IP :Ion probe

SPM :Solar proton monitor

VTR :Vertical Temperature radiometer

AVCS :Advanced vidicon camera system

HB :Heat budget instrument

IRP :Infra-red passive

IR :Infra-red five channel scanning radiometer

PLN :Pre-launch name
SBC :South-bound equator crossing time
NBC :North-bound equator crossing time
EOP :End of operational life time
SR :Scanning radiometer

4.2.1 Orbit

Unlike the geostationary orbit, the satellites maintained by NOAA are in a near polar orbit, with a period of roughly 103 minutes (see figure 4.3).

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Footnote (1) - Systematic error developed in December 1975 until January 1976. Launched on 15 November 1974.

Footnote (2) - Launched on 29 July 1976, operational in September 1976.

Footnote (3) - TV is a one half inch vidicon camera. WA is 104 degrees and NA is 12 degrees.

Footnote (4) - Due for launch on the 6th of September 1984.

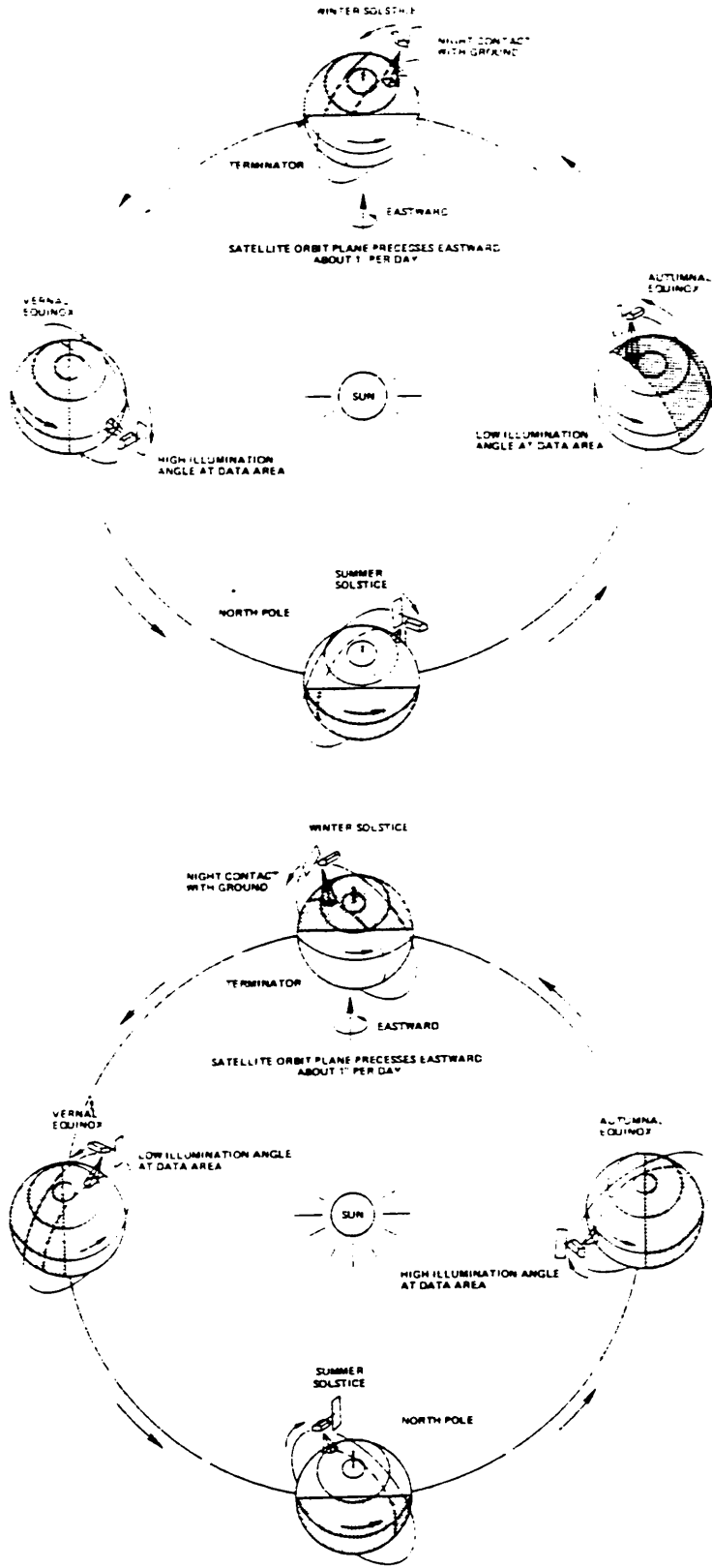


Figure 4.3. Satellite orbit precession with season.

Because of the relatively low altitude of the satellite the data accumulated during an orbit may have to be recorded on board on digital tape recorders, and then distributed to ground stations when these are available. The platforms have been designed to fly at 833 ± 90 km, two altitudes are chosen (Schwalb 1978), for a pair of operational satellites so that they do not view the same point on Earth at the same time each day. At 870 km a satellite is over the horizon for 16 minutes while one at 833 km only 15.5 minutes. Each satellite completes about 14.1 orbits/day. Because the number of orbits/day is not an integer number, the satellite sub-spacecraft tracks do not repeat, although the Local Solar Time (LST) for passing any latitude is unchanged. For this reason the equator crossing longitudes will vary from day-to-day. If required the swath (the area the satellite view sweeps out), and path of a satellite may be calculated using a spinner, (as described in Kidwell (1981)). The Sun synchronicity is not perfectly maintained during the spacecraft's lifetime, due to orbital variations. These variations will initially be caused by imperfect operation of the booster and second stage rockets that place the satellite into orbit. Subsequent orbital variations will be caused by gravitational effects and Solar forces. (Whether the LST will be earlier or later will depend on the sign of these errors). The equator crossings times are chosen using the criteria below.

1. Time that they are needed to input data to synoptic studies.
2. Visible channel, sub-point zenith angle to the Sun.
3. Orbital separation from the second satellite.

There are a number of ground stations for receiving and controlling the satellite in the USA. These Command and Data Acquisition centres (CDA's) are situated in Virginia and Alaska.

There are other centres around the world which are capable of receiving the transmissions, but not of commanding the spacecraft. With these centres for data reception the orbiter is never out of contact with the ground for more than one orbit per day.

4.2.2 Instrumentation

Descriptions of the instrumentation given here are mostly based on the experimental TIROS-N spacecraft, (Lauritson 1979, Schwalb 1978). Some modifications are obviously being made to the satellites following this but they are small and not significant for this study.

There are three main instrument packages on board the NOAA satellites, the TIROS Operational Vertical Sounder, (TOVS), the Advanced Very High Resolution Radiometer, (AVHRR), and the Space Environment Monitor, (SEM).

The TOVS is comprised of three independent instruments, the High resolution Infra-red Radiation Sounder 2, (HIRS/2), and the Stratospheric and Microwave Sounding Units (SSU and MSU). These three instruments in conjunction are designed to obtain temperature profiles from the ground to the 10 mb pressure level, water vapour concentration at three levels in the atmosphere, and total ozone concentration. The HIRS/2 instrument (which was tested on NIMBUS-6), is a 20 channel radiation sounder. It senses in the infra-red region of the spectrum from 15 micron to 4.3 micron. The Earth disk is scanned with a mirror across the satellite track, and is calibrated on board using two black bodies and space. (More details are given in Schwalb (1978), and Kidwell (1981)).

The SSU measures carbon-dioxide infra-red emission in the height range 25-50 km. This instrument is used in conjunction with HIRS/2 and the MSU to determine temperature down to the ground.

Solar activity and its influence on Earth can be studied using measurements of high energy particles caught in the Earth's magnetic field. The SEM does this by measuring protons, electrons and alpha particles emitted from the Sun using three instruments. The TED detects particles of energy 0.3 keV to 20 keV. The MEPED detects particles (electrons and protons), with energy 30 keV to 60 MeV, while the HEPAD captures alpha particles and electrons in the energy range 370 MeV to 850 MeV.

4.2.2.1 The Scanning Radiometer

NOAA-2 was the first satellite to have a scanning radiometer instead of the vidicon camera (and the first operational VTPR). Scanning radiometers are an improvement over vidicon tubes because of the relative ease with which data is extracted from these, rather than vidicon tubes, which have dark current effects and non-linear calibration functions. The AVHRR instrument (a scanning radiometer), is an improvement of an instrument flown on the ITOS series of spacecraft (the last of which was NOAA-5), but is modified to have five channels instead of two (See table 4.2). Only four are used on TIROS-N and the data in the slot for channel 5 is a repeat of the channel 4 slot. Later satellites in the NOAA series are to have all five channels operational. Data from this instrument is transmitted in High Resolution Picture Transmission format, (HRPT), LAC or GAC format (TIROS-VIII in 1963 was the first to test APT). GAC is degraded to 4km resolution and 10 bits. During blind orbits some of this data

must be stored on one of the five digital tape recorders. Usually the data is transmitted continually - direct readout mode - but in cases where the data must be stored capacity is limited. 55 ft of tape are equivalent to 100 minutes of GAC, 10 minutes of HRPT and 250 minutes TIP. This gives some idea of the relative information densities of the various formats. Basically HRPT is the full resolution data of a satellite pass that is disseminated in direct readout mode (it does not have to be stored on the digital tape recorders) while LAC is HRPT recorded on board and transmitted. Three HRPT's can be received (sometimes only two) at any particular station. The data for the heat budget tapes is ultimately derived from the HRPT information.

The radiometers are sensitive in the microwave, visible, near infra-red and thermal infra-red. The visible channel is centred on 0.5 micron, (see table 4.2), and the near infra-red at 0.9 micron. These two channels in conjunction are designed to distinguish between clouds/land water boundaries, and the extent of snow and ice. The microwave channel is centred at 3.7 micron and is used for discrimination of ice and clouds.

Table 4.2.
Table of TIROS-N channels.

	wavelength/microns	
1	0.55 - 0.90	
2	0.725 - 1.10	
3	3.55 - 3.93	
4	10.50 - 11.50	

The infra-red detector, sensitive in the region 10.5 - 11.5 micron, (filters changed on later satellites), is cooled to 105 K. This ensured a random noise from the detector equivalent to 0.12 K for a 300 K scene. (Schwalb 1978). The IFOV of this instrument is 1.3 milliradians (which gives the 1.1 km resolution). The instrument is calibrated during flight using space as a cold body and an internal body kept at 290 K.

Calculation of the AVHRR detector radiance is made using some simple assumptions. First of all, the response of the detector is assumed to be linear, (it is not quite linear - but the non-linear effects are taken out at calibration time), after every scan line. Assuming this linearity we can write:

$$R_w = G * C + I \quad (4.1)$$

where

R_w is the radiance in the window region which is a function of filter in use. (In $W/m^2/sr/m$).

G is the gain of the detector. (In $W/m^2/sr/count$).

C is the number of counts measured by the instrument. (No units).

I is the offset of the detector. (In $W/m^2/sr$).

By using Planck's equation the equivalent brightness temperature can be calculated directly from R_w .

$$E_f = c_1 * f^{**3} / [\exp (c_2 * f/T) - 1] \quad (4.2)$$

where

E_f is the spectral radiance. (In $W/m^{**2}/sr/m$).

$c_1 = 8 \pi h / c^{**3} = 1.19 \times 10^{**-5} \text{ mW}/m^{**2}/sr/cm^{**4}$

$c_2 = 1.44 \text{ cm K}$

f is the frequency.

T is the black body temperature.

by inverting equation 4.2 we obtain

$$T = c_2 * f / [\ln (c_2 * f^{**3}/E + 1)] \quad (4.3)$$

where $\ln$ represents the natural logarithm, and T is now a function of the radiance E , and is the window brightness temperature. f is taken from the central frequency of the window, and E is calculated using equation 4.1. Examples of the use of equation 4.3 are given in Kidwell (1981). Owing to the effects of limb darkening this temperature will be a function of the viewing angle which must be corrected for θ to obtain the scene brightness temperature.

The operational algorithms use the on-board black bodies for calibration. The black bodies performance is tested during the pre-launch calibration programme. During this period the radiometer instrument performance is also evaluated. These tests include measurements in a thermal vacuum, to simulate space conditions and at a range of operational temperatures, to evaluate the stability of the instrument.

To reduce the problem of radiometer degradation during operation, in-flight calibration is carried out. The gain and offset of the instrument to radiant energy falling on it are calculated from:

$$G = (R_s - R_b) / (C_s - C_b) \quad (4.4)$$

where

R_s is the equivalent radiance for the Platinum Resistance Thermometer's (PRT) measurement of space's temperature. (In $W/m^2/sr$).

R_b is the equivalent radiance for the PRT's measurement of the black bodies temperature. (In $W/m^2/sr$).

C_s is the radiometer's counts for space.

C_b is the radiometer's counts for the black body.

and

$$I = R_s - G * C_s \quad (4.5)$$

This calibration procedure depends on platinum resistance thermometers (PRT's) determining the temperature of the test bodies accurately. Ten PRT'S are used and the mean temperature of these is calculated using a weighting function (not all the PRT's necessarily have the same response). To make adjustments for the fact that the response of the radiometer is not quite linear these temperatures are modified so that the smallest error (< 0.5 K) is in the range 225 - 310 K (Schwalb 1978). Once the temperatures are determined the equivalent radiance over the filter in question is calculated using the Planck function and the filter function. These radiance values are the ones used in equation 4.4 and 4.5 to calculate the gain and intercept. The radiometer window radiance values are the raw input to the regression algorithm discussed below. The visible channel has no on-board calibration but the instrument stability has been verified from Earth (eg. Jacobowitz (1975)).

4.3 THE REGRESSION RELATIONSHIPS

The method used to calculate the total outgoing flux from the window brightness temperatures has changed from time to time. The OLR values in the set of data that have been used in this study are based on only one algorithm and emphasis will be placed on this. Details of the procedure for conversion of R_w to OLR are given in Abel (1979). The method is based on an improvement of a linear algorithm used prior to October 1979 (the data used here was however recalculated using the improved algorithm).

In brief an 'exact' radiative transfer scheme is used to calculate the total upwelling radiation for a large number of atmospheric situations, which are considered representative (about 100). Once this has been calculated the 'observed' window radiance can also be calculated by convolving the filter function with the flux distribution. The regression technique fits a curve (initially a line) to the points. The total upwelling radiation is calculated from the window radiance (from the satellite) using these empirical regression coefficients. The new method introduced by Abel (1979) also included some other improvements, namely:

1. New information was included about the atmospheric transmittance.
2. A non-linear model for radiance to flux calculation. (The linear fit led to large errors at high and low flux values).
3. A method to calculate the nadir radiance from the limb darkened radiance.

This model had 40 levels and calculated the monochromatic

transmittance at various levels in the atmosphere. These were then convolved with the filter transmittance function to obtain the 'observed radiance'. The model is 'exact' because all absorption lines are included in the spectral intervals of interest. At high pressures a Lorentz profile was used while at pressures below 100 mb a Voigtian was used. Water vapour absorption is one of the largest factors in the atmospheric absorption to be considered. In previous calculations the water vapour continuum was modelled by a constant value. In the modified procedure new improved data was used for this factor. (This may have been the single largest error in the previous model). Comparison of old with new calculations showed that there was a 4% reduction in values. In the new model a regression between flux and radiance was abandoned in favour of a flux equivalent brightness temperature and radiance equivalent temperature regression. Both techniques required the regression curve to pass through the origin as this was a physical constraint. The equation used was:

$$T_f = T_w (a + b * T_w) \quad (4.6)$$

where

T_f is the flux equivalent brightness temperature. (In K).

T_w is the window flux equivalent brightness temperature.
(In K).

a and b are the regression coefficients derived from the analysis using theoretical calculations.

The coefficients of this equation were calculated for the test atmospheres and the standard deviation of the fit was found to be 1.7K. In determining the window radiance however some account must be taken of the limb darkening effect. The radiance for observations away from nadir ($\Theta = 0$ at nadir) must be corrected so that they represent nadir radiance. This is done

using the equation:

$$R_w(0) = R_w(t) + [a_1 + a_2 * R_w(t)] (\sec(t) - 1) \\ + [b_1 + b_2 * R_w(t)] (\sec(t) - 1)^{**2} \quad (4.7)$$

where

$R_w(0)$ is the window radiance at an angle zero (nadir).
 $R_w(t)$ is the window radiance at an angle t from nadir.
 a_1, a_2, b_1, b_2 are empirically derived coefficients for the effect.

Use of this equation has shown that larger errors in radiance are found for larger angles away from zenith. (The limb darkening effect gets stronger). It was also found that the limb darkening had more effect for larger values of the window radiance. This was because in situations where high flux were to be expected (equatorial regions) high water vapour content was also to be expected (water vapour content is a major factor in limb darkening effects). Also in low flux regions (Antarctica for example) the water vapour content is low. For an angle of 64 degrees it was found that the errors in not using equation 4.7 were $1mW/m^{**2}/sr/cm$, which is equivalent to less than 0.5K. Comparison of the models also gave some indication that the linear fit was inadequate for low and high flux values. The largest errors were over the subtropical deserts, cloud-free ocean and Antarctica, where regional differences were as large as 20 W/m^{**2} . The full recalculation using the non-linear regression technique, of the data set was not carried out on the old data however. This was because it was shown that a simplified technique could be used on the mapped data already archived and that this resulted in errors (between the exact and simplified calculation) of less than 2 W/m^{**2} . The simplified correction was applied to the entire record (June 1974 - February

1978). From that time the new algorithm was used.

Once the nadir radiance (R_w) has been calculated the inverse frequency averaged Planck function for the filter is determined and used to evaluate the equivalent brightness temperature of the window.

$$T_w = B^{-1} R_w(0) \quad (4.8)$$

B has been calculated by integration over all frequencies of the Planck function with the filter function, thus obtaining the filter average function. T_w then yields the value T_f from equation 4.6 and this temperature is used to evaluate the flux from:

$$F = s T_f^4 \quad (4.9)$$

where

F is the required flux. (In W/m^2).

s is the Stephan-Boltzmann constant. (In $W/m^2/K^4$).

In summary given any window radiance (see section on the scanning radiometer), the nadir window radiance is calculated. With this value the equivalent window temperature is found by using the inverse frequency averaged Planck function for the filter, and then equation 4.6 is used to evaluate the matching equivalent flux brightness temperature. This is used to derive flux using equation 4.9.

4.3.1 Error Estimates

The archived heat budget data set (for the period June 1974 - February 1983) suffers from two main sources of systematic error. Firstly the changes in the satellite equator crossing times are known to affect the estimates of the daily mean values of OLR from empirical and theoretical studies (Short 1980, England 1984) and secondly there have been changes in the algorithms used to determine the heat budget parameters from the flux counts measured by the instruments in flight (Gruber 1984).

The first of these errors, inadequate sampling of the diurnal cycle, is known to have some effect in changes from satellite to satellite (Gruber 1984). The differences for example between NOAA-5 and TIROS-N are about 2 W/m^2 . Studies of the radiation budget (such as Stephens (1981)) must take this into account when analysing their data. However a study by Gruber (1984), has shown that the differences from this effect are smaller over the Southern hemisphere.

The heat budget data is known to be biased by about 10 W/m^2 (Gruber 1977, Gruber 1978, Jacobowitz 1978, Gruber 1984). Recent improvements have been made to the algorithm (in March 1983) but these do not affect the results here. Further improvements have been suggested to the regression calculations by Ellingson (1983) and Ohring (1984). The extent of the effects of the new algorithm are as yet not clear, but improvements have quite clearly been made and better agreement has been achieved between NOAA measurements and ERB measurements on NIMBUS. The improvements are brought about by including corrections for partially cloudy scenes. This method has been used on an operational basis since August 1983. (Gruber 1983).

The heat budget data is derived from HRPT and then mapped and averaged over a 16 by 16 pixel grid. Any 16 by 16 area with less than half the pixels present was considered as absent data. This procedure reduced random errors in the data set. (Gruber 1977). To obtain the polar stereographic projection used extensively in this study the data was projected onto the NMC grid on a 125 by 125 square array for each hemisphere. (For more details of the heat budget tape format see Section 5.1 and 5.3).

The averaging technique used to generate the NMC gridded data creates problems over the Antarctic continent (represented on a 50 X 50 pixel array) because of the satellites orbit. This is a consequence of the Sun synchronous orbit (See figure 4.2). Over the poles this averaging technique suffers from aliasing problems. The satellite does not view the whole Earth in one orbit; it takes approximately 14 orbits. On the polar stereographic projection this means that 14 sectors must be joined to produce the full hemisphere (which is circular on the projection). During winter part of a sector near the pole is in darkness, and because the satellite does not fly parallel to the terminator the dark-side measurements appear further along a swath on one side than on another. When the 14 sectors are merged a 'star' shaped pattern is produced.



Figure 4.4. Example of absorbed image.

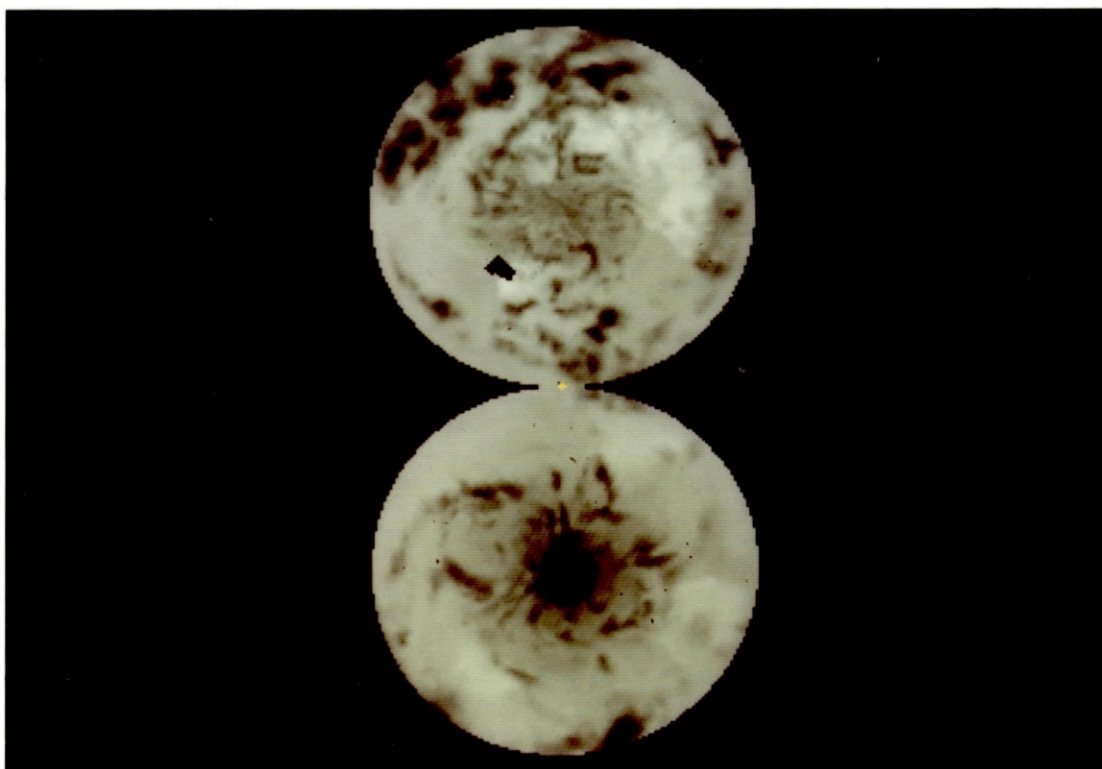


Figure 4.5. OLR image. Day time pass.

The other data shortfall is due to breakdown of the satellite which results in absent data, (for example the areas missing on figure 4.6 are due to this).

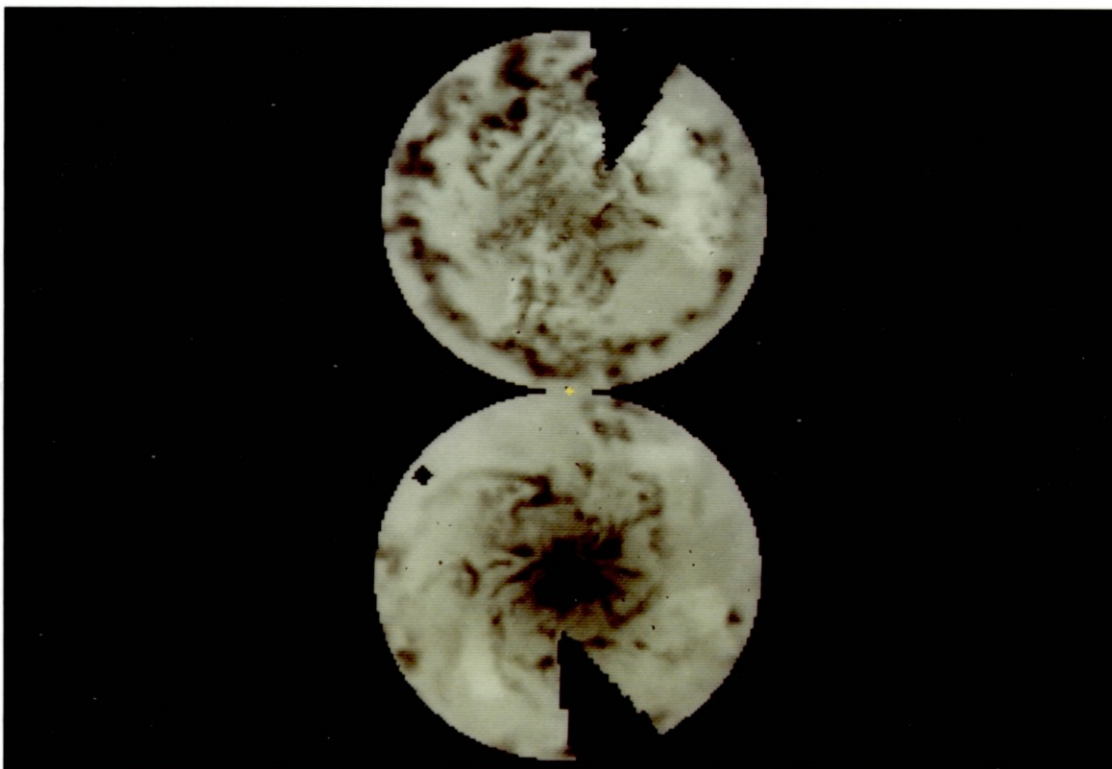


Figure 4.6. Image with example dropouts.

CHAPTER 5

DATA PROCESSING

5.1 THE HEAT BUDGET ARCHIVE TAPES

This thesis uses a number of data sources. Cloud cover information from Halley Bay and South Georgia have been supplied by the BAS, METEOSAT-2 information and data has been both received by the IPIPS system directly and read from tapes obtained from ESA. However the major data source has been the NOAA/NESS organisation in Washington which supplied the heat budget archive tapes.

This data supplied by NOAA to Imperial College of Science and Technology (ICST) is on Computer Compatible Tapes, (CCT's). These tapes need to be read onto the local computer system and processed to allow meaningful analysis to be done. All the tape reading, archiving, processing, data reduction and analysis was done using IPIPS (Interactive Planetary Image Processing System), which is part of the CRS (Centre for Remote Sensing). The data format of the original tapes (which were written on an IBM computer) was incompatible with the needs of the research;

immediate access to individual days of data from any particular year. Many of the processing aspects of this thesis assume some knowledge of the IPIPS system, so a short description of this is given in section 2 of this chapter. The size of the image database is indicated when one considers that there are currently approximately 60, 1600 BPI, 9 track tapes comprising the original NOAA data set. The tapes contain both Polar Stereographically Projected (PSP) images and Mercator Projected (MP) images of different sizes. (For details of the heat budget data format see section 3). The size of this data set is indicated by a simple calculation to approximate the amount of data in all the tapes:

$$\begin{aligned} & 9 \text{ years} \times 365 \text{ days} \\ & \quad \times (4 \text{ PSP images} \times 125 \text{ lines} \times 250 \text{ samples} \\ & \quad \quad + 3 \text{ MP images} \times 72 \text{ lines} \times 144 \text{ samples}) \\ & \quad \times 2 \text{ bytes} \\ & = 1 \times 10^{**9} \text{ bytes} = 1 \text{ Gby} \end{aligned}$$

This is an unmanageable data base with which to work. A number of steps were taken to ensure that the size of the working data base was reduced. These are described in section 6 of this chapter.

5.2 IPIPS

The Interactive Planetary Image Processing System, (IPIPS) based at Imperial College of Science and Technology, (ICST) is a flexible multipurpose image processing/remote sensing facility, and is also part of the ICST's Centre for Remote Sensing, (CRS). The IPIPS system was used exclusively for all the analysis, data reduction and hardcopy production (including this thesis), because it has a number of advantages over other systems. It is a relatively small, friendly, accessible system (unlike mainframes, which are none of these), and most importantly is interactive, and quick to use. Its other important feature is its image display capability which was essential to this thesis. The hardware of IPIPS comprises a powerful minicomputer, (a VAX 11/780), with associated peripherals and about 1.5 Gigabytes of backup storage. The major image processing components of the system are two International Imaging Systems (IIS) image processing computers. These allow interactive processing of image data which can be viewed on colour monitors. The essential

nature of this interactive component is the rate at which large arrays of numbers (images) can be displayed and analysed. Images as large as 512 by 512 pixels with 256 shades of grey or 256 colours can be displayed (larger images can also be displayed by subsampling or minifying or using a special program IROAM which places a window over an image that can be interactively tracked across the data). Simple commands are available to carry out very complex analysis in a short time. For example, a commonly used command called ISTRETCH interactively changes the brightness and contrast of an image displayed on the colour monitor. This is useful if, for example a particular area needs close examination. There are over 100 VICAR commands which cover the operation of graphics, image manipulation (Fourier analysis, convolution, histogram equalisation and generalised 2 image linear and non-linear combinations) and image measurements (bi-spectral histogram construction, pixel-by-pixel measurements etc). Some of these commands are also very useful for presentation of results, and have been extensively used in this thesis.

Hardcopy which is essential in any analysis was obtained using the graph plotter (for graphs, maps, and contour plots), and the TV hardcopy unit attached to one of the I2S computer colour monitors (for photographic output, colour or B/W). Both graphical and image output can be obtained more rapidly on the lineprinter - although at reduced quality. A crucial component of the system is a demountable disk pack which is capable of storing a large percentage of the total NOAA data set (this disk pack's capacity is 250 Mby). This is available to users on a booking sheet system for consecutive periods of up to a day. A fuller description of this powerful and versatile system is given in Hunt (1982).

Further to ensure that this image processing system is usable a software package has been developed to make images compatible with the needs of other users. This is a set of standard routines for image Input/Output (I/O) that can be accessed for software development. A number of programs that have been written specially for this analysis have used the latest image I/O routines that allow interactive entry of parameters and generally provide a user friendly environment together with on-line documentation. This package called BISHOP (Better Image Software with Help On-line for Programs) is an improvement of the NASA funded VICAR (Video Image Communication And Retrieval) System. (BISHOP is far superior to VICAR in running under a menu driven system called TAE (Transportable Applications Executive) developed by the Goddard Space Flight Centre). A brief description of each of the programs written and the nature of the algorithms used is given in appendix A.

5.3 TAPE READING

The first stage of the data processing is to transfer data from tape to disk and into a useable form. The first stage of this operation, reading the tape, is by no means a trivial matter.

The data obtained from NOAA, written on an IBM computer, was found to be in a format called VBS. Variable Block Spanning block boundaries (VBS) is designed to save magnetic tape in that logical units of information, such as images or records, begin or end anywhere inside a physical block on tape. Since the tapes supplied did not conform consistently to the documented format the tape reading was a far greater problem than anticipated. VBS makes it extremely difficult to access any particular day, as it may start anywhere inside a block. An examples of one of the

images from the tapes can be seen in figure 5.1.

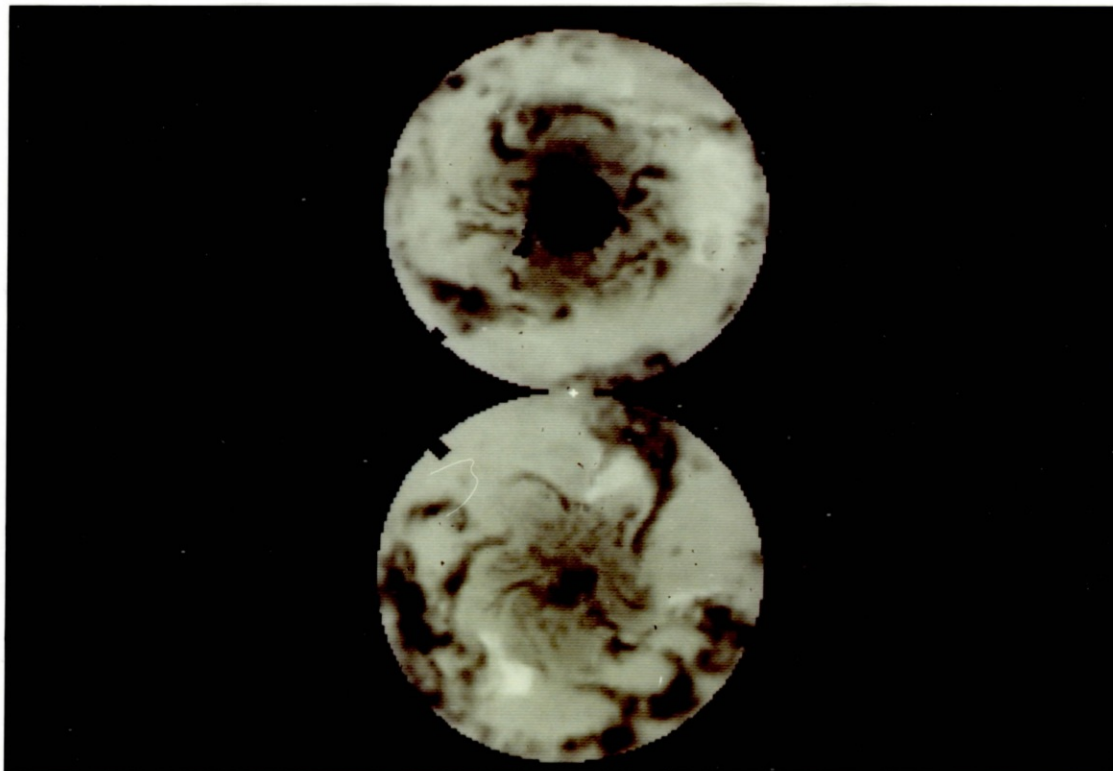


Figure 5.1. Example of OLRd image.

The heat budget archive data set comes in monthly sets one month per file with eleven data sets per day. Each day consists of:

- 1) Total outgoing flux nighttime pass N. Hemisphere.
- 2) Total outgoing flux nighttime pass S. Hemisphere.
- 3) Both 1) and 2) projected onto a Mercator globe.
- 4) Total outgoing flux daytime pass N. Hemisphere.
- 5) Total outgoing flux daytime pass S. Hemisphere.
- 6) As 5) and 6) projected onto a Mercator globe.
- 7) Available solar energy for the day N. Hemisphere.
- 8) Available solar energy for the day S. Hemisphere.
- 9) Absorbed solar energy for the day N. Hemisphere.
- 10) Absorbed solar energy for the day S. Hemisphere.
- 11) As 9) and 10) projected onto a Mercator globe.

Files 1,2,4,5,9,10 are all projected onto a polar stereographic grid. The grid is 125 by 125 pixels and all values are multiplied by 10 and coded as ten bit numbers in two eight bit bytes. During processing at IPIPS however the separate PSP images of the Northern Hemisphere and Southern Hemisphere pairs (eg. 1 and 2), were concatenated to produce one image for both the Northern and Southern Hemispheres. This reduced the number of files to 7 and also the possibility of losing one of the files of a matching pair. The PSP images are orientated by NOAA so that longitude 100 degrees East is at the top for the Northern Hemisphere, and at the bottom for the Southern Hemisphere. The meeting point of the two hemispheres is 80 degrees West on the projection (see figure 5.2).

The mercator arrays were 144 samples by 72 lines and comprised data for the whole globe. The prime meridian is vertical and runs along sample position 1. Each pixel represents an area 2.5 degrees square, (so that the top row is the data for latitudes 87.5 - 90 North). A fuller description of the data format and header information is given in Kidwell (1981). However the above list of images applies to a subset of the tapes supplied. Earlier tapes had different formats (for the physical and logical layout). In the earliest tapes from June 1974 to

January 1978 for example polar chips were also supplied after every hemisphere of PSP data, which consisted of 45 by 45 arrays of subsections of the areas over the poles. These were ignored as they were not supplied in the later tapes, and in any case they could be generated from the normal PSP data. In regions where data was missing data has been interpolated (using a 2 dimensional interpolation technique) and inserted into the MP data. These values in the MP data were flagged with minus signs (for example an interpolated value of 210.5 W/m^2 would be inserted as -2105). This interpolated data was not entered in the PSP data. The programs used to read the tapes (both major formats) are described in appendix A.

5.4 POLAR STEREOGRAPHIC PROJECTION

A polar stereographic projection is defined by the equations 5.1 to 5.3 below. The projection of a point on a sphere onto a polar stereographic map is obtained by drawing a line from the pole of the globe through the point of interest onto a plane normal to the opposite pole.

Consequently it is only sensible to draw the Northern Hemisphere and the Southern Hemisphere separately in this projection if the whole Earth is to be represented (Castleman 1979).

Since a large number of the figures assume some knowledge of the geography in the PSP an orientation around a particular image may be useful. Refer to figure 5.3. In this image a number of geographical and meteorological features are visible. The Antarctic continent is visible due to its low temperature and appears dark (low OLR flux) on the image (bottom hemisphere dark central region).

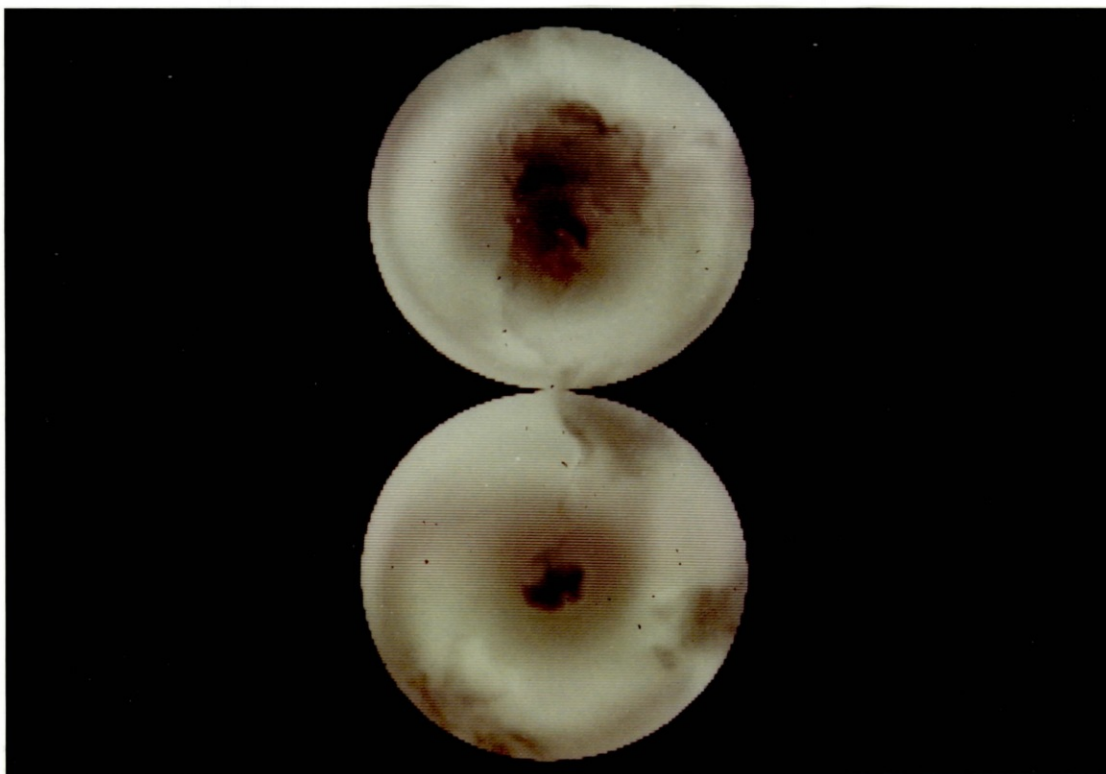


Figure 5.3. SH and NH flux image.

The Antarctic plateau (East Antarctica), is quite clearly the coldest place on the continent (on these images North is approximately to the right). Regions not directly connected with the South Pole that are of interest on a global scale are indicated below. The Himalayan region is marked with a large area of low flux in Asia, and Greenland in the Northern Hemisphere, the only other significant ice sheet in the world.

In the equatorial regions the ITCZ (The Inter-Tropical Convergence Zone) rings the equator.

There are a number of reasons why this projection was used almost to the exclusion of the Mercator one. First of all this projection is polar centred and thus ideal for the polar regions, and since this study focuses attention on the Antarctic the MP would have been of limited use. Secondly, the MP arrays had missing data added by means of interpolation and these values were flagged as interpolated by minus signs. The PSP data however did not have this interpolated data added, and as interpolated data was not used in this analysis this was another advantage of the use of PSP data. However this data set was not ideal because it took more storage space and time to process than the MP data. The Earth coordinate/line-sample transformations are also much easier to calculate on a MP because the latitude, longitude to line and sample calculations are independent of one another. Finally the PSP is not ideal for equatorial studies because these latitudes are split up into two very distinct regions on the projection, making interhemispheric relations difficult to ascertain.

5.4.1 Calculation Of Earth Coordinates

The data used in this thesis is polar stereographically projected onto a square National Meteorological Centre (NMC) grid. The polar stereographic projection is defined by the equations:

$$r = \text{TAN} [(\text{pi}/2 - | \text{latitude} |) / 2] \quad (5.1)$$

and

$$x = r * \cos (\text{longitude}); y = r * \sin (\text{longitude}) \quad (5.2)$$

for the Northern Hemisphere and

$$x = r * \cos (\text{longitude}); y = -r * \sin (\text{longitude}) \quad (5.3)$$

for the Southern Hemisphere. r is the radius of the projection and $|\text{latitude}|$ is the absolute value of the latitude. (The change in sign in equation 5.3 is due to the change in direction of longitude if the Southern Hemisphere is projected, instead of the Northern Hemisphere). Using these equations (and the appropriate scaling factors) the line and sample for any point on the Earth could be calculated. The inverse is also possible (evaluation of the latitude and longitude for any line and sample). (More details of routines used by NOAA for the coordinate transformations are given in Kidwell (1981)). Extensive use of these equations was made in evaluating the area of NMC pixels projected on to the Earth so that accurate evaluation of the areas could be made. It should be noted that the pixels on this projection are not equal in area. To evaluate the area of the pixels as projected onto the surface of the Earth, use of spherical trigonometry was made (trigonometry on the surface of a sphere). The square, projected on to a spherical surface, was split up into two triangles and the area calculated using the 'spherical excess' formula that relates the sum of the angles of a triangle on a sphere to the area of the triangle.

$$A_s = (a_n1 + a_n2 + a_n3 - \pi) * r^2 \quad (5.4)$$

where

A_s is the area of the spherical triangle

a_n1 is the first spherical angle of the triangle

a_n2 is the second spherical angle of the triangle

an3 is the third spherical angle of the triangle
r is the radius of the sphere

Using the above formula, (equation 5.4, all pixel areas could be calculated in association with the coordinate transformations mentioned (Equations 5.1 - 5.3).

The resolution of the pixel on the projection varies from 101 km (at the equator) to 202 km (at the pole).

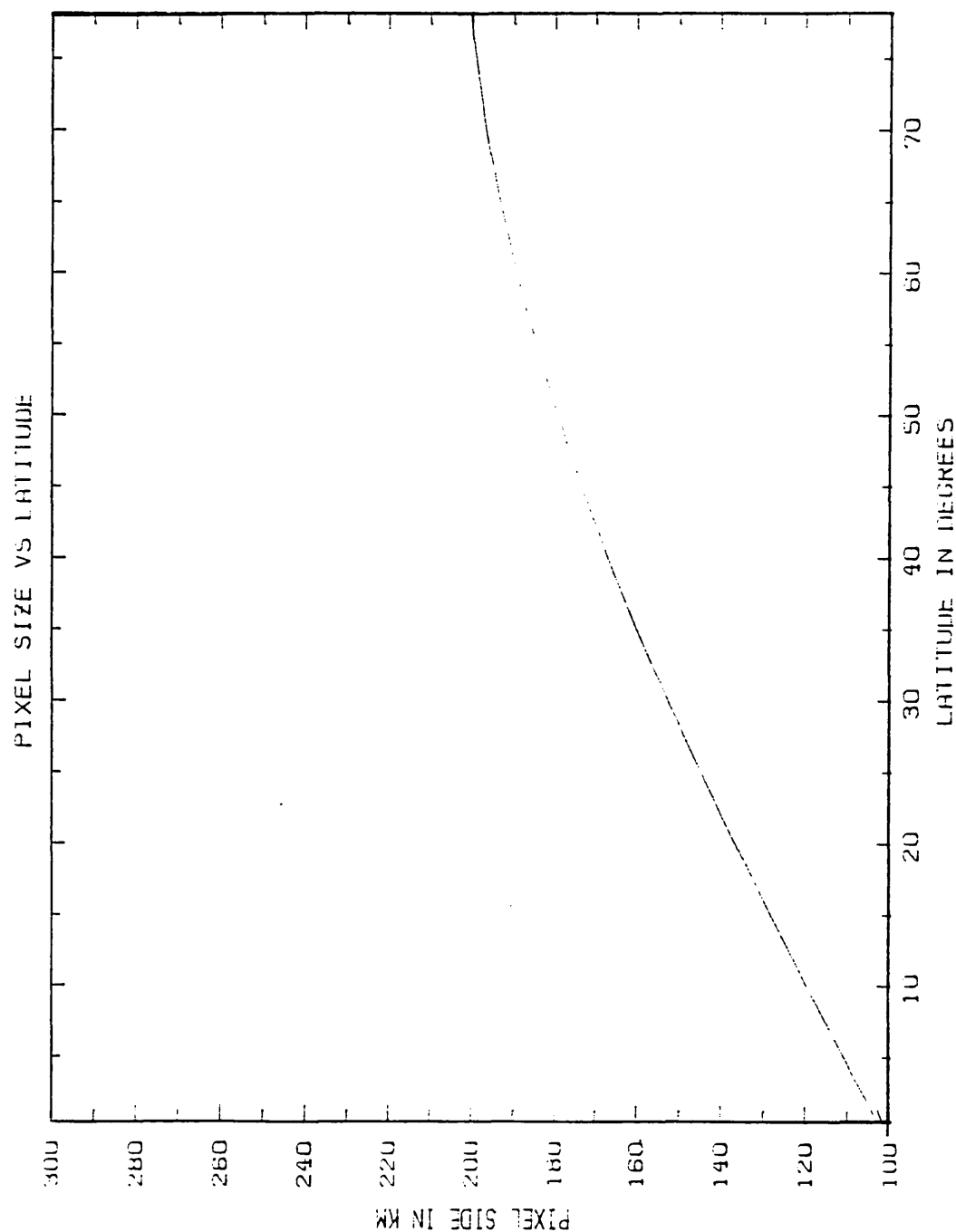


Figure 5.4 Graph of scale versus latitude.

This is a measure of the resolution of an image at that latitude. Map data obtained from the Meteorological office was used with a specially written map projection program (written under VICAR) to obtain coincident maps for overlays on both the MP and PSP data arrays.

5.5 DATA VALIDATION.

This is a very important aspect of the analysis, because of the narrow band sensors on board the NOAA spacecraft used to derive these tapes. The regression relationship involved in calculating outgoing longwave radiance (OLR) is adequate for most situations with acceptable relative accuracy (see Chapter 4 section 3). A great deal of work was done to ensure that data reduction gave meaningful and representative results.

Comparisons of flux data from this data set and those published in Stephens (1981) (values in brackets), are given below. These values have a systematic differences of about 12 W/m² compared with other published data (see Chapter 4 for details).

Table 5.1. Comparisons of fluxes.

Table of measured fluxes $OLR(W/m^2)$ at Local Solar Time,
(LST) 1530hrs

	N.Hemisphere	S.Hemisphere	Earth
SPRING 79 (Mar-Apr-May)	250 (237)	244 (237)	246 (237)
SUMMER 79 (Jun-Jul-Aug)	258 (242)	245 (232)	251 (237)
AUTUMN 79 (Sep-Oct-Nov)	251 (230)	244 (230)	247 (230)
WINTER 79 (Dec-Jan-Feb)	231 (222)	246 (238)	236 (230)

Comparisons of these seasonal means published by Stephens (1981) using the NIMBUS satellite show good agreement.

More detailed comparisons have been made between METEOSAT-2 and the NOAA satellite, on a subset of all the data and a positive bias for NOAA derived values has been found of about $10 Wm^{-2}$. This was done by taking an infra-red full disk image (supplied by ESA) for a particular day and calculating the OLR in 3 by 3 degree bins in a band of longitudes that corresponded to the local time of the polar satellite pass. Then the equivalent area on the Earth was calculated and 3 by 3 degree bins for OLR were calculated and plotted. Results indicated a linear relationship between the two sets of data from 200 to $350 W/m^2$ (the range of values of both data sets) but there was an offset of approximately $10 W/m^2$. This was in agreement with other estimates of the NOAA data bias.

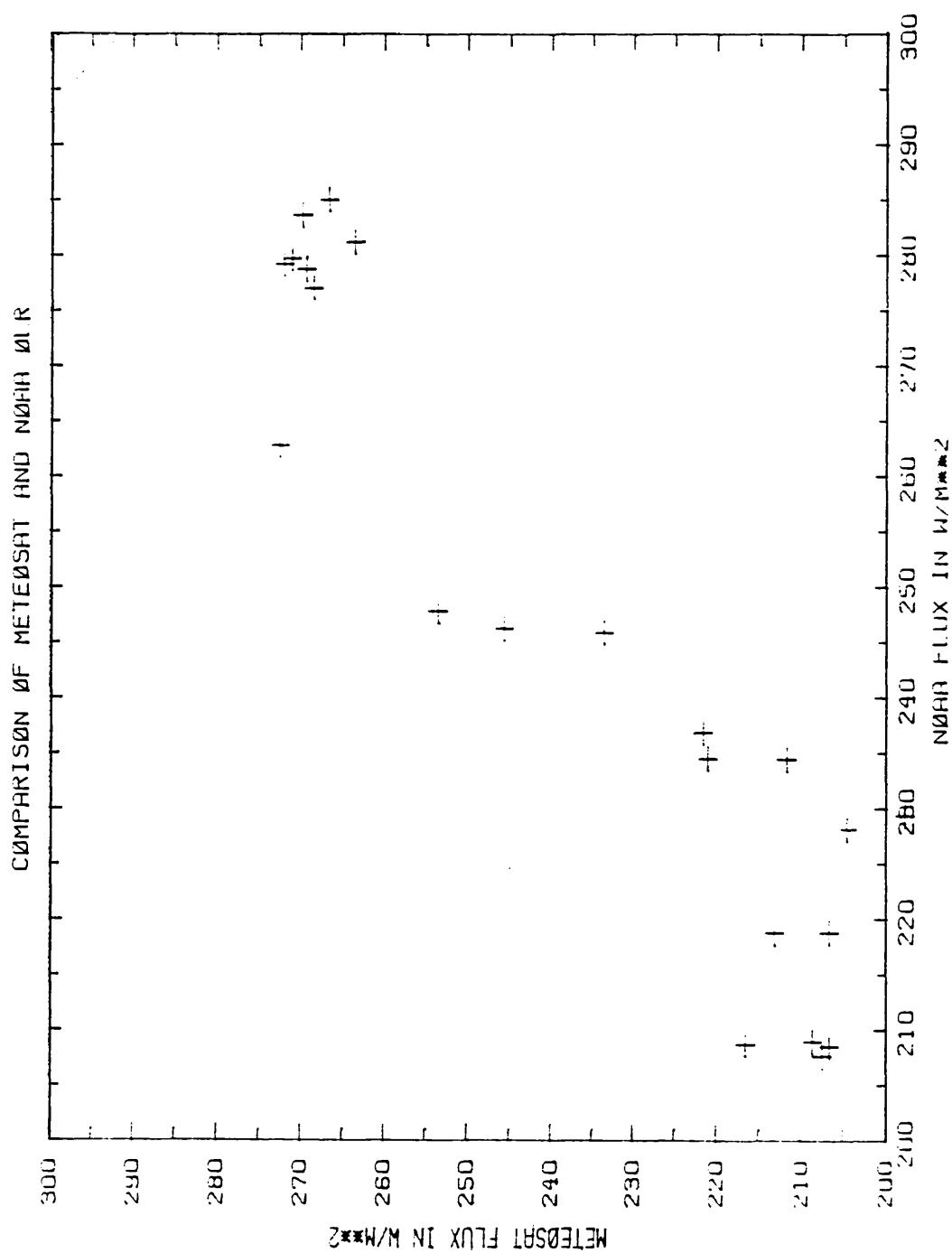


Figure 5.5. Comparison of NOAA and METEOSAT fluxes in August 1979.

5.6 DATA REDUCTION

Data reduction needs to be performed due to the otherwise prohibitive amount of computation that would have to be carried out to analyse 93 months of information. There are over 20 thousand images in the data set in all. Data reduction was carried out to produce a subset of the whole data without necessarily losing any of the informational content. The MP images were mostly unused, this resulted in a large reduction in the amount of data that had to be analysed. Time and space averages were both considered but only time averages were employed because the spatial resolution of the images was considered low anyway. Temporal averages were used most extensively to reduce the calculation burden. However time averages can also be a problem because they 'smear' all details of the data especially where mobile features such as clouds are concerned. Eventually only very broad scale climatological images remain. This technique was used with a number of integration periods. The lowest was ten days while the largest was a ten yearly average of each of the seasons. A reduction in the data burden was also achieved to some extent by finding the mean of the daylight (OLR_d) and night-time (OLR_n) data to produce a daily mean OLR value. This technique has also been used by NOAA (Gruber 1984) and it has been shown that the systematic error from satellite equator crossing times is also reduced by this method. However even with a large number of operations to reduce the size of the working data set an increase was also to be expected at some stage because of the coincident calculations of standard deviations maxima and minima (See Chapter 6). Extensive use of the absorbed image data sets was not made nor of the available flux images except in cloud calculations so these could often be kept in backup storage. Again for the teleconnection analysis only the OLR data was necessary. Finally the working data set is at present about 300 Mbytes (and growing

month by month).

When the data has been reduced to a more manageable form then the analysis can begin. There are a number of techniques used to display the data in a useful and concise form.

- o Image display, which is the most common and most useful technique displays a large array of numbers, an image, in a concise and compact form. In this form it is also easy to interpret and several images can be coincidentally displayed (or flicked between).
- o Zonal mean plots are useful for giving the global gradients of parameters, but are not so useful for analysis of local effects. However in special cases, where the poles are included, zonal plots are regional plots, For example a zonal plot from ninety degrees South to eighty degrees South. Using this method and plotting many zonal means of standard-deviations over a year the position and strength of the ITCZ could be observed.

The zonal standard deviation represents the statistical deviation of the measured mean over the shorter ten day period. See figure 5.6.

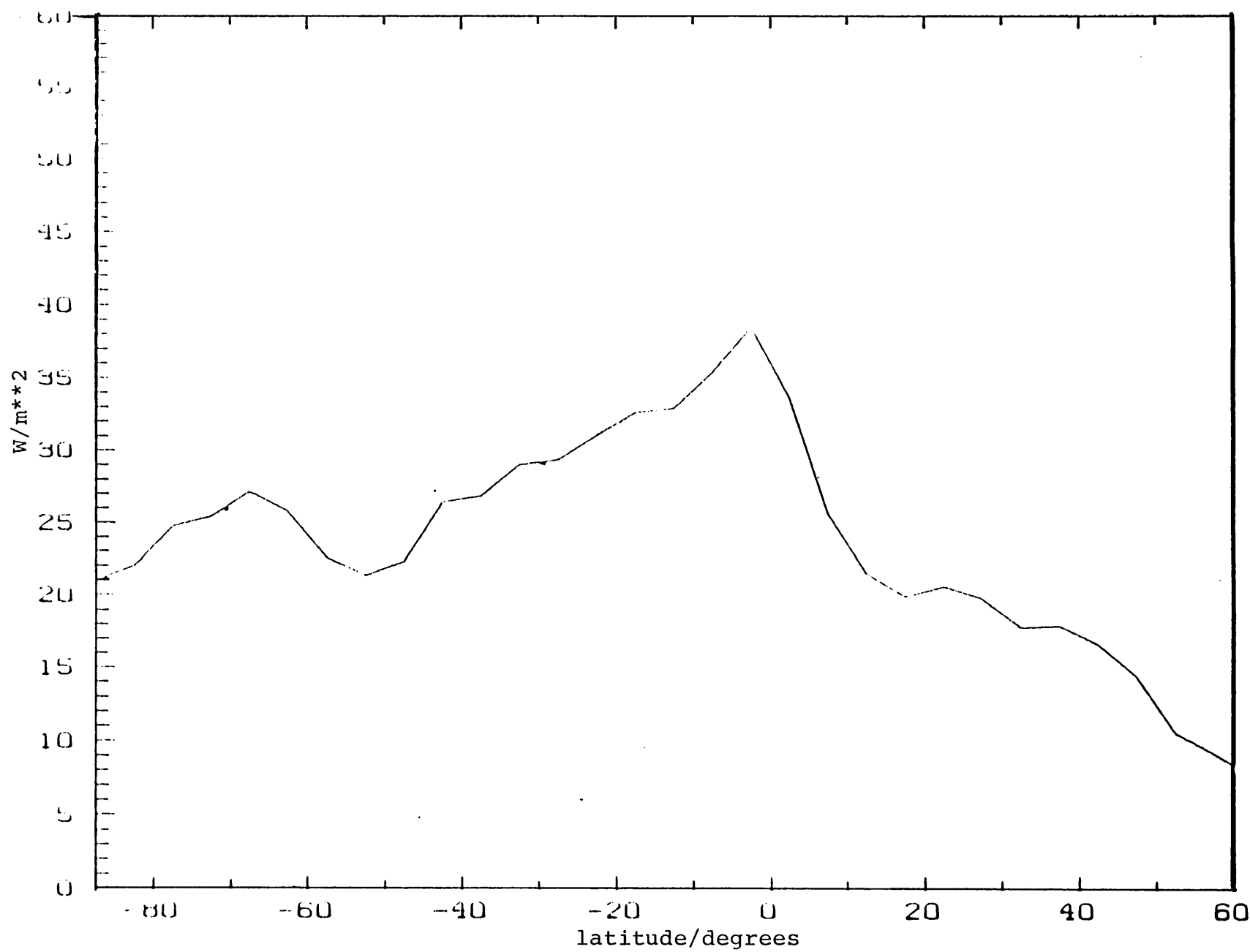
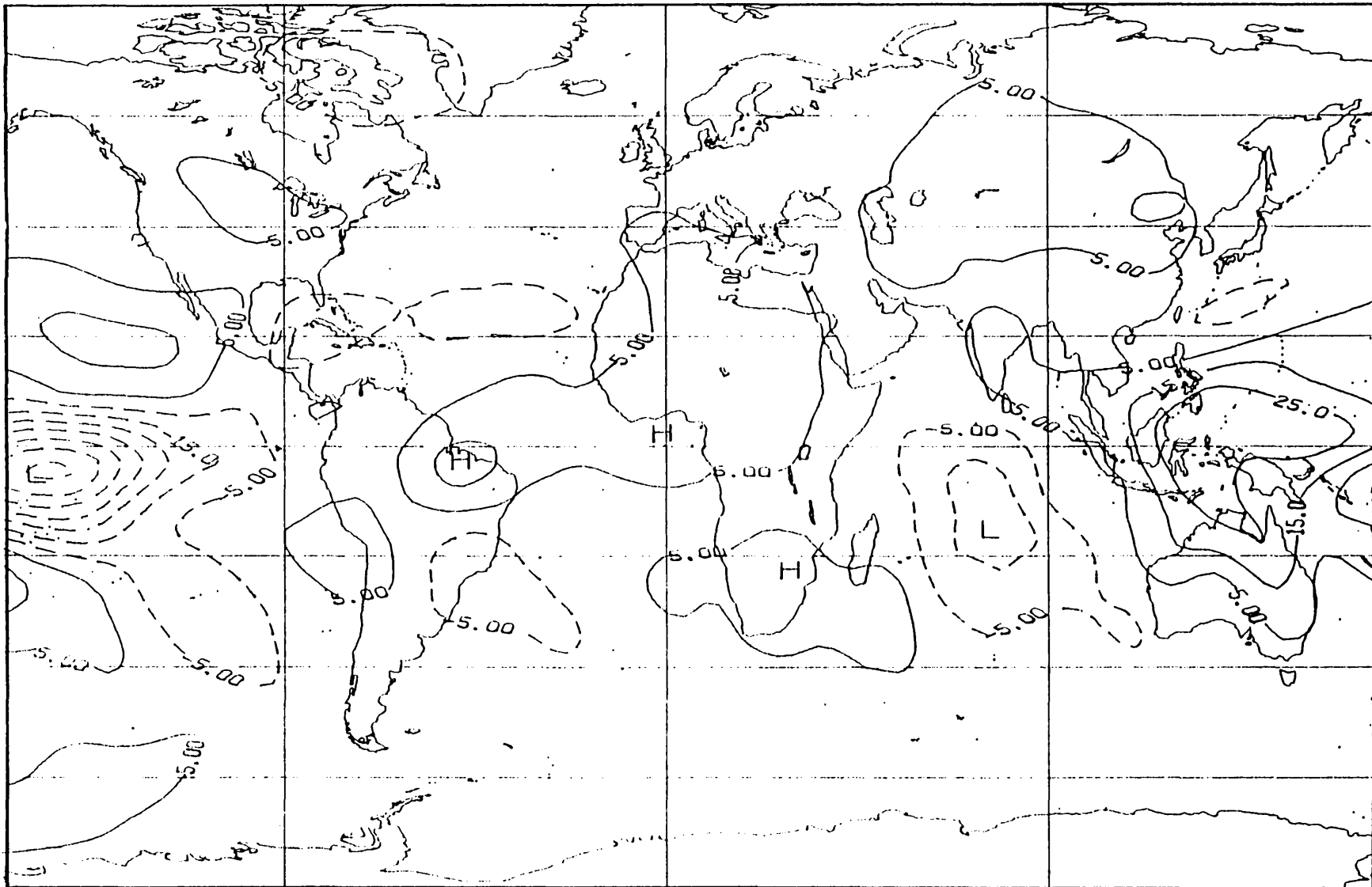


Figure 5.6. An example zonal standard deviation plot.

This error line is mostly due to atmospheric variability and attempts have been made to remove any random or systematic errors. The line is a measure of the variability of the atmosphere over the period. The peak near the equator represents the constantly rising warm air which form cumulo-nimbus towers. This atmospheric behaviour is bounded by the ITCZ but individual cumulo-nimbus towers form randomly within its borders. The randomness causes the standard deviation over a ten day period to be larger than any other area, zonally, and regionally. In other regions where the atmosphere is more stable, such as over the Southern oceans the variability is much lower.

- o Contour plots, which are useful for local measurements of the radiation parameters, but represent data in a less condensed form. For this reason less data can be viewed in this format.
- o The difference contour shows the areas on a regional basis that stand out as either colder or warmer. Figure 5.7 is a good example.

OUTGOING LONGWAVE RADIATION ANOMALY IN WINTER 1983 (W/m^2)



DATA PROCESSING

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Figure 5.7. An example contour plot.

- o Fourier analysis extracts the components of a periodic wave from any wave-form and gives the amplitudes of these and the phases of each component. The results are usually difficult to interpret. (See the discussion on Fourier analysis).

5.6.1 Image Display

Image display is the most commonly used technique for displaying the arrays of data numbers (DN). This technique used one of the image display devices available at IPIPS. Because of the limited number of grey scale values that can be displayed on the image devices (0 to 255) the data sets had to be suitably scaled for viewing. The scaling factors used depended on the maximum flux or standard deviation flux values to be displayed. The largest values in the available flux data set, which in themselves represent data with the highest possible values, had values in the order of 500 Watts per metre squared. This gives a scaling factor of about 1/20. ($500 \times 10 / 255 = 19.8$). Other appropriate scaling factors were used for the standard deviation images. For obvious reasons the anomaly maps, which could result in both positive and negative values could be displayed only by using suitable scaling and offsets to avoid negatively valued pixels (which cannot be displayed).

5.6.2 Time Averaging

The primary data reduction technique involves the averaging together of ten consecutive one day image data sets. (For more details on why a ten day mean was chosen see below). However it is of course possible at any stage to go back to the original tapes and read data at daily intervals. This was achieved using a suite of specially written programs and command procedures (See appendix A). Calculations of the mean value of a number of pixels from different images required intermediate real data sets to ensure that rounding errors did not occur. The data sets could not be read in and averaged because of problems with the number of input data sets that VICAR could handle - BISHOP has so far coped with 127 input data sets with no problems. Account had also to be taken of absent data, in both the calculation of the means and standard deviations. Ten day means were calculated using ten days of data (or twenty days if the result intended was OLR). During periods of absent data (say day 6 is missing of ten) a ten day mean is calculated so that day 11 is included. The second period ten day mean will also include day 11 as its first day. Each mean begins on the 1st 2nd or 3rd period of a month. The first period is day 1 to 10 of the month, period 2 is day 11 to 20 and period 3 is day 21 to 30 of the month. In months with more than 30 days of data (this does not happen very often due to missing data) the last day is ignored. In periods where there are not enough days for the last third the first day of the mean is moved back until there are enough days in the mean. For example suppose in February all the data for all the days are present. Then period 1 will begin on day one and end on day 10, period 2 will begin on day 11 and end on day 20 and period three will begin on day 19 and end on day 28. Similar procedures are adopted for the seasonal means. This technique was adopted to make sure that the ten day means all started approximately in the same period of the month throughout the data

set. This allows ten day means and seasonal means to be averaged together from different years.

The ten day mean is generally accepted as a climatological period just long enough to filter out the synoptic scale effects of the atmosphere. To test the applicability of this with the data chosen a number of tests were carried out from locations on the globe likely to be representative of a large number of different synoptic situations.

Table 5.2. Tested regions.

Region	Line	Sample	Latitude	Longitude
Greenland	72	70	70	-40
Mid. Atlantic	100	107	5	-30
Mid. Pacific	144	26	-5	-120
South Pole	189	63	-90	0
Oversea	183	53	-70	-140
East of S America	199	91	-40	30

The largest flux variability was found for the period of August 1979 in the Mid Atlantic region (See figure 5.8).

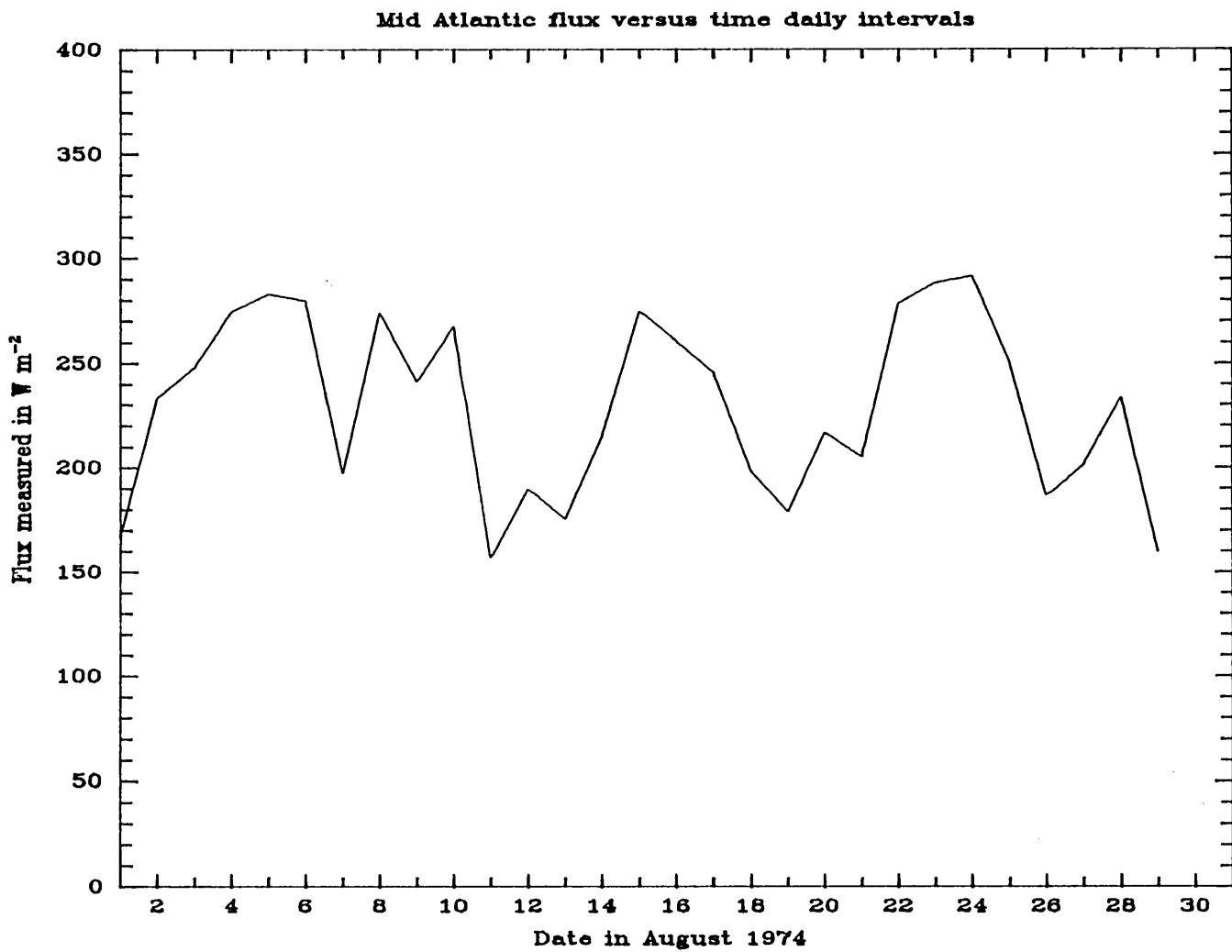


Figure 5.8. Mid-Atlantic flux versus time.

Periods longer than this would lose some temporal resolution in the climate variability observations, while shorter periods would give rapid non-climatological scale variations. These short time scale effects would be due to fronts passing through the field of view, (in mid latitudes) or the development of cumulo-nimbus towers, (in equatorial regions), which would affect the measured flux due to the effect of clouds. In Figure 5.9 we see an example of just such a rapid, short time scale variation over the Mid-Atlantic in August 1974. The effect of averaging this flux is plotted in Figure 5.9. The slope levels off at about 10 days with some variation thereafter due to the nature of the atmospheric fronts passing the field of view. A number of other regions were also investigated. See table above.

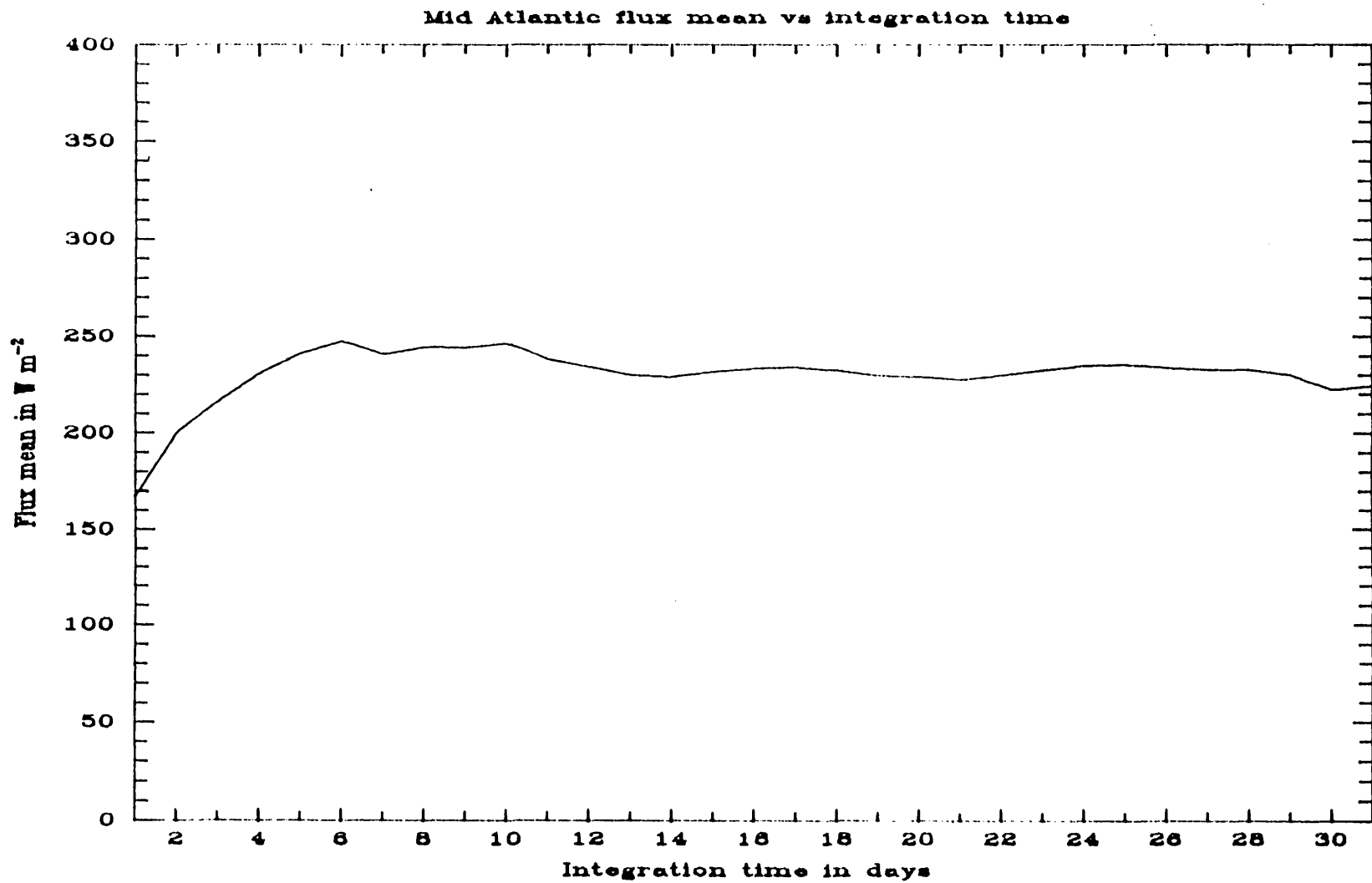


Figure 5.9. Mid-Atlantic OLR vs. averaging period.

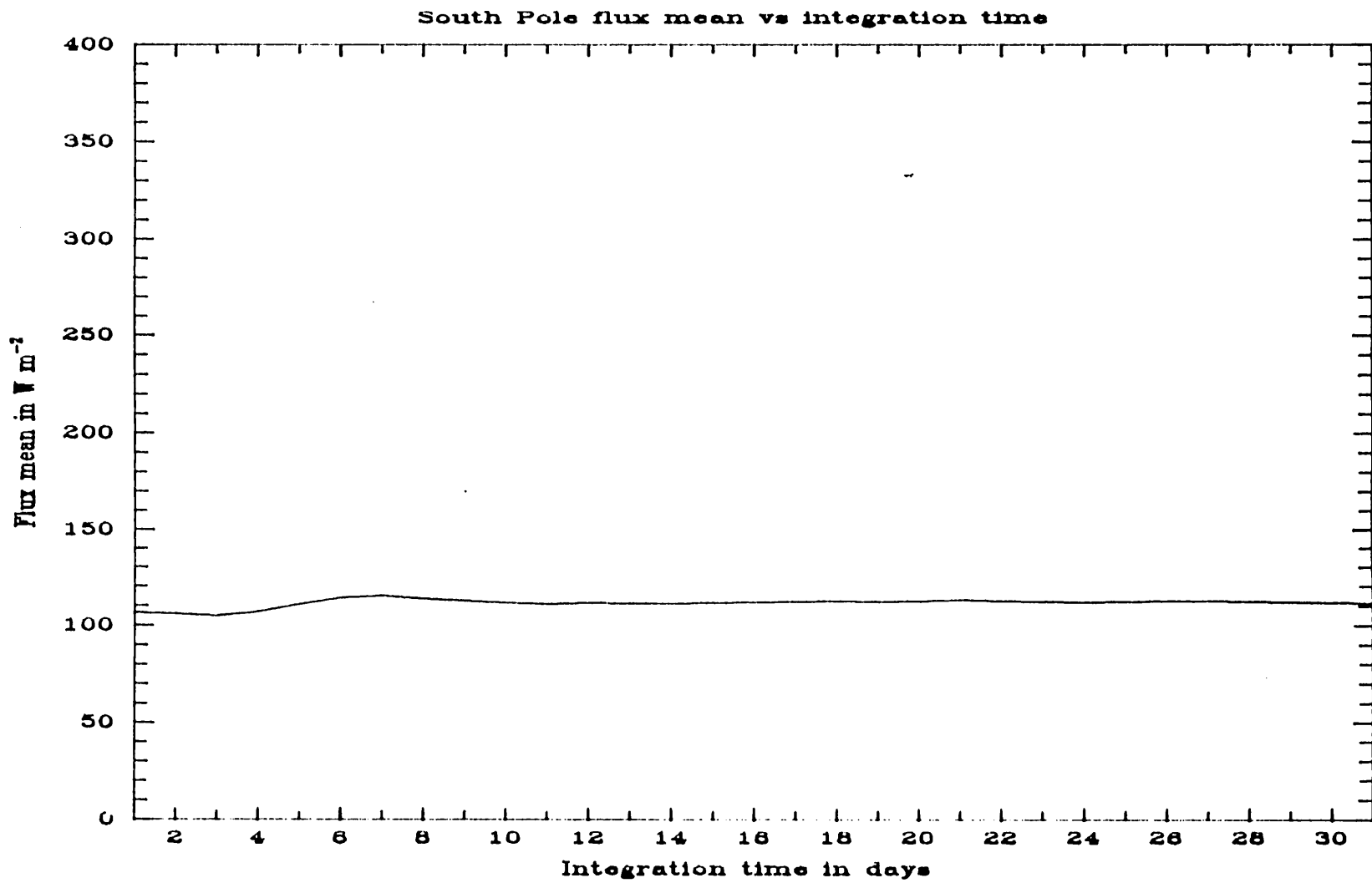


Figure 5.10. South pole flux vs integration time.

In figure 5.10 over a less synoptically active region the ten day mean is a more than adequate period over which to integrate or filter out the weather. There are variations from hemisphere to hemisphere and also with season. By taking a value of the temporal mean that is the smallest possible for excluding synoptic scale motions, it is then possible to analyse all cases by adding several means together when necessary.

5.6.3 Standard Deviations

Error images, or more properly in this context, standard deviation images, are a measure of the local variability of the radiation budget parameter being measured. These were calculated at the same time as the mean images, as this was the most cost effective method in terms of CPU time and tape to disk data transfers. Atmospheric variations are indicated by using the definition of the standard deviation.

'Error' images have been calculated for each mean, to indicate the variability within the image. The two images in combination are a powerful tool for analysis of events which appear in these ten day means. For example the change over the period of the mean at the equator is much larger than anywhere else on a zonal mean plot. This indicates the position of the ITCZ for that ten day period. Similar studies are being carried out from METEOSAT data to track the position of the ITCZ. The combination of image and matching error image over a longer period of time will indicate the expected range of flux values to be measured, and more interesting, the change in these parameters with time. Maximum and minimum observations of fluxes were also archived to give an indication of the maximum range of values to be expected. The ability remains if necessary, to calculate

means over longer periods of time, from fifteen days to a maximum of the whole period. The nature of the investigation which used the error images, involved the assumption that the variations were due to meteorological phenomena and not to random, or systematic fluctuations in the data set. The random errors cannot be detected, because of the natural variability of the atmosphere, whereas systematic errors can be detected in some cases. Satellite failures during the ten day period of the mean manifest themselves as regions of high standard deviations on the error images. However these systematic errors are easily detected simply by looking for areas of high error obviously due to a non-physical cause. These images were excluded from the data set when the purpose of the investigation was to monitor natural variability in the climate. (See example figure 5.11). Another simple technique used to exclude non physical high error images, is to look at the number of pixels that have gone into the estimate of an error point.

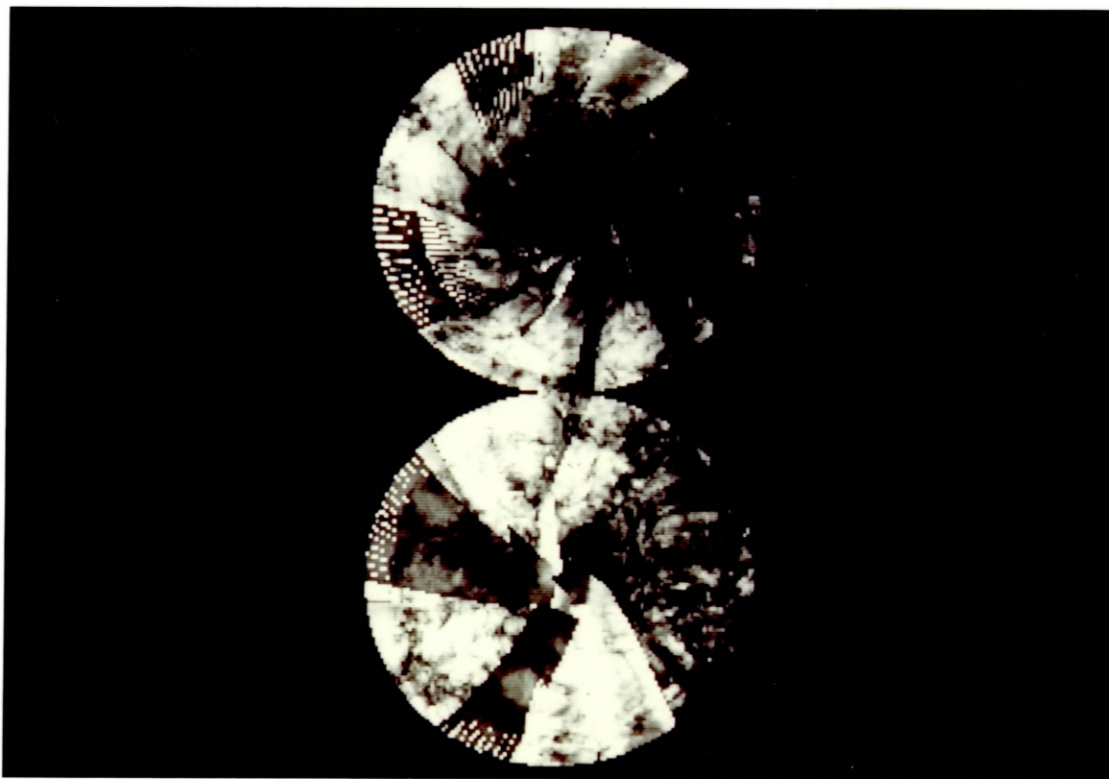


Figure 5.11. Standard deviation image with missing data.

An arbitrary lower limit of fifteen points was put on the number of pixels which must be in an error point before the mean and standard deviations could be included in the data set. The type of error which gives rise to few pixels being counted in the average error is again systematic (it is due to a large amount of missing data in the region of interest) these points were also excluded. The standard deviation values were calculated using the formula below.

$$Sd = \text{SQRT} (\text{Sum} [(x_m - x_i)^{**2}]) / (N - 1) \quad (5.5)$$

where

Sd is the standard deviation.

x_m is the mean of the measurements.

x_i is the i th measurement.

N is the number of the points in the measurements.

N the number of points in the mean will vary from position to position on the globe but this was taken into account.

CHAPTER 6

ANALYSIS OF RADIATION BUDGET STATISTICS

6.1 MEANS AND RELATED STATISTICS

In this chapter a number of radiation climate statistics of the Antarctic and the Southern Hemisphere are quantified. An attempt is made to evaluate the required accuracy of climatic means bearing in mind the natural variability. Some of these statistics for the Northern Hemisphere are also quantified. Among the statistics used are various means (ten day, seasonal and data set), first standard deviations and differences of particular periods from means (anomalies). Some interpretation of results is also attempted directly and indirectly using Fourier analysis.

When seasons are referred to in this chapter (and other chapters) they are based on the following definitions for the Southern Hemisphere.

Spring	-	September	October	November
Summer	-	December	January	February
Autumn	-	March	April	May
Winter	-	June	July	August

6.2 ANALYSIS OF MEANS AND STANDARD DEVIATIONS

The usefulness of OLR data as a diagnostic tool is primarily through the observation of clouds. Because of the high infra-red opacity of clouds these appear dark on infra-red images. Clouds are also transient features (generally over a period of say ten days). Due to these properties land surface features tend to be high-lighted in images of OLR means. To illustrate this effect in figure 6.1 we see ten images with cloud movement and a mean of these to indicate the accentuation of the land surface.

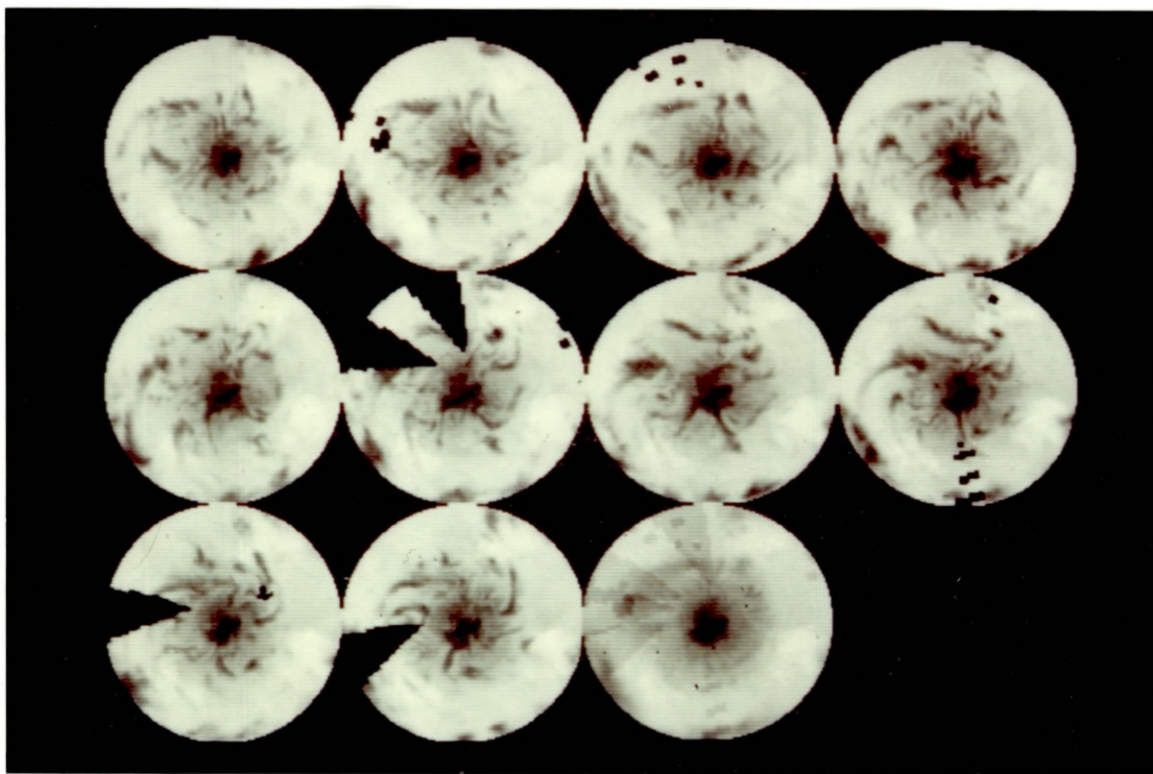


Figure 6.1. Cloud movement in an OLR image over land.

From these images an Earth-atmosphere brightness temperature can be calculated (for each pixel location) from the application of Stefan-Boltzmann law: (Also see footnote (1)).

$$F = s T^{**4} \quad (6.1)$$

where:

F is the flux. (In Watts per metre squared.)

s is Stefan's constant. (In $W/m^{**2}/K^{**4}$)

T is the Black Body temperature. (In Kelvins.)

In situations where clouds are persistent over an area for a long time they can be distinguished from the land due to the differing scene temperature. However in certain circumstances where the underlying surface is ice or snow, clouds are difficult to distinguish from the surface because the two have similar

radiometric properties in both the infra-red and visible. However they are sufficiently different in most circumstances to be distinguishable. Because of these basic properties of clouds, OLR mean images are useful for a number of purposes. (1) They give an indication (over a suitable integration time) of where the major climatological cloud bands lie. (2) In regions of sea-ice (such as in the southern ocean or in the Arctic) the sea-ice edge can be monitored. Some cloud distributions are often not representative of the 'normal' climatic circulation but these are of less interest to the climatologist. The stability of a particular situation can also be measured using coincident standard-deviation data on means. This is because clouds also have a marked effect on the evaluation of standard deviation values due to their mobility and high contrast in comparison to the warm surface features. Analysis of the meaning of some of the standard deviation maps is given in section 2.3.

6.2.1 Ten Day Means

Because ten day means cover such a short period of time an image series of these is not shown here (there would be too many images). However graphical plots of OLR for various regions are shown for the data set period.

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Footnote (1) - Surface temperatures are not retrieved from this data set because there are a number of difficult problems associated with their determination. A radiative transfer solution is possible but only in situations where the height temperature profile is available. If T_s is required it is much easier to use the vertical sounder data on the NOAA satellite which was designed for this task.

In figure 6.2 a limited regional OLR analysis for the Antarctic region for 1980 is shown. In figures 6.3 to 6.6 such plots are shown for the Antarctic, the Southern Hemisphere the Northern Hemisphere and the Arctic.

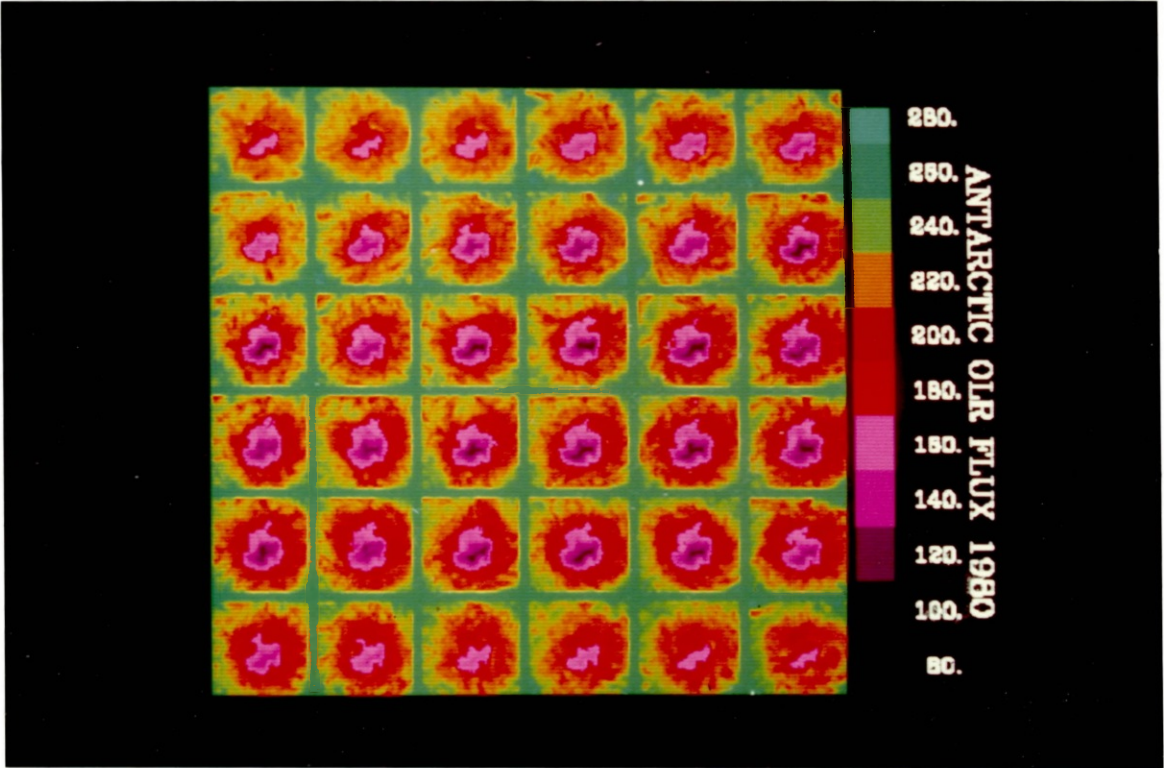


Figure 6.2. The Antarctic flux change with time (1980).

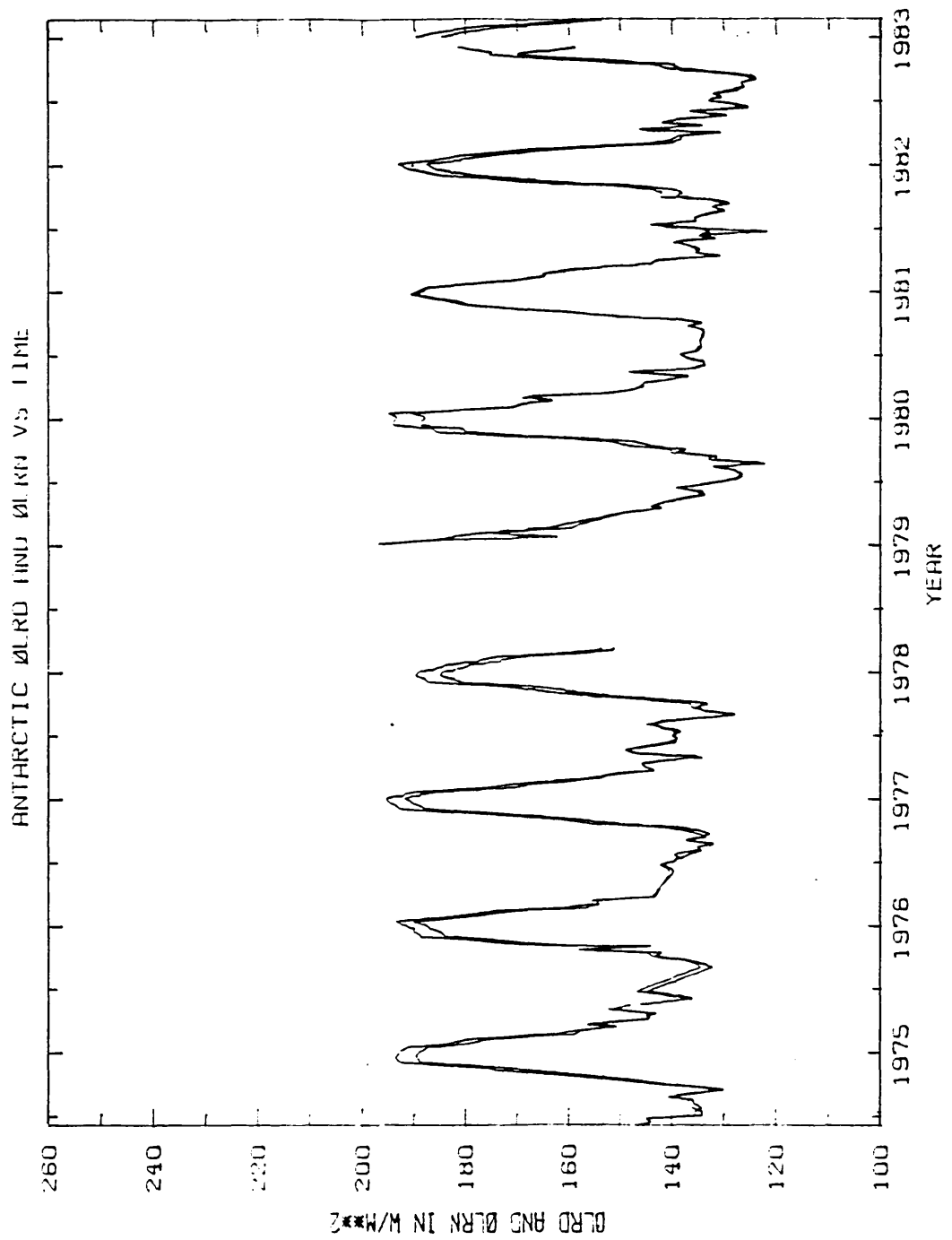


Figure 6.3. Antarctic flux versus time.

Figure 6.2 shows how the flux over Antarctica changes with time on a regional basis. In these series of images (three images per month) we see the evolution of flux from the period 1-10 January 1980 (top left) to 21-30 December 1980 (bottom right) - 1980 was a typical year in terms of OLR for the Antarctic (see figure 6.3). The first six boxes represent the end period of summer in the Southern Hemisphere (continued from the bottom right). During the summer period the OLR flux reaches a minimum of about 130 W/m^2 on the central region of the Antarctic plateau (219K, -53 degrees Celsius). (See footnote (2) about brightness temperature). During the relatively 'warm' period the land sea interface is delineated by a 200 W/m^2 contour (227K, -45 degrees Celsius). During the end of the summer season the flux values begin to drop very rapidly. By the end of February the summer minimum is exceeded only in regions near the coast, and the summer coastline flux is over the sea. The ragged appearance of this contour during the transition season autumn is due to the large number of depressions that reach this region at that time. During the end of the autumn period (April May) there is very little change in the outgoing flux near the periphery of the continent, due to the compensating effect of warm advected air from over the sea. However during this period the flux over the central plateau drops from 110 W/m^2 to 80 W/m^2 . In winter (June to August) there is very little change in flux both over the periphery and over the plateau. This is caused by the very stable conditions prevalent over most of the continent when the cold layer of air over the Antarctic is unperturbed by a strong diurnal cycle due to the lack of Solar input. The spring season

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Footnote (2) - Brightness temperatures are generally colder than surface temperatures, however in the case of the Antarctic it is possible that warmer cloud layers during an inversion can interpose themselves between the satellite and the ground causing the surface to appear warmer than it really is.

is accompanied by a rapid warming over the sea and a more modest warming over the land.

The information in these series of images is more generally condensed and presented in the form of a graph. For example in figure 6.3 we see the OLR for both the day time (OLRD) and night time (OLRN) pass of the satellite over Antarctica. (The Antarctic region in the graph is defined as a circle 30 pixels wide centred on the South Pole, the region extends to -80 degrees latitude). The first feature apart from the annual variation in flux is the obvious systematic difference between 0330 and 1530 during summer (the line above is the 1530 pass). This is because as summer approaches some heating takes place which causes a systematic difference between the two observations. The difference between the two passes is only a few W/m^2 during the transition seasons but can be as high as 6 W/m^2 in the summer. In the Antarctic winter the solar insolation is zero over these regions which means that during the dead of winter there will be little difference between day and night time fluxes. The offset of the outgoing peak of OLR is displaced about 30 days from the maximum insolation period. This effect is due to the time required for the surface to react to the long term change in Solar heating (thermal lag).

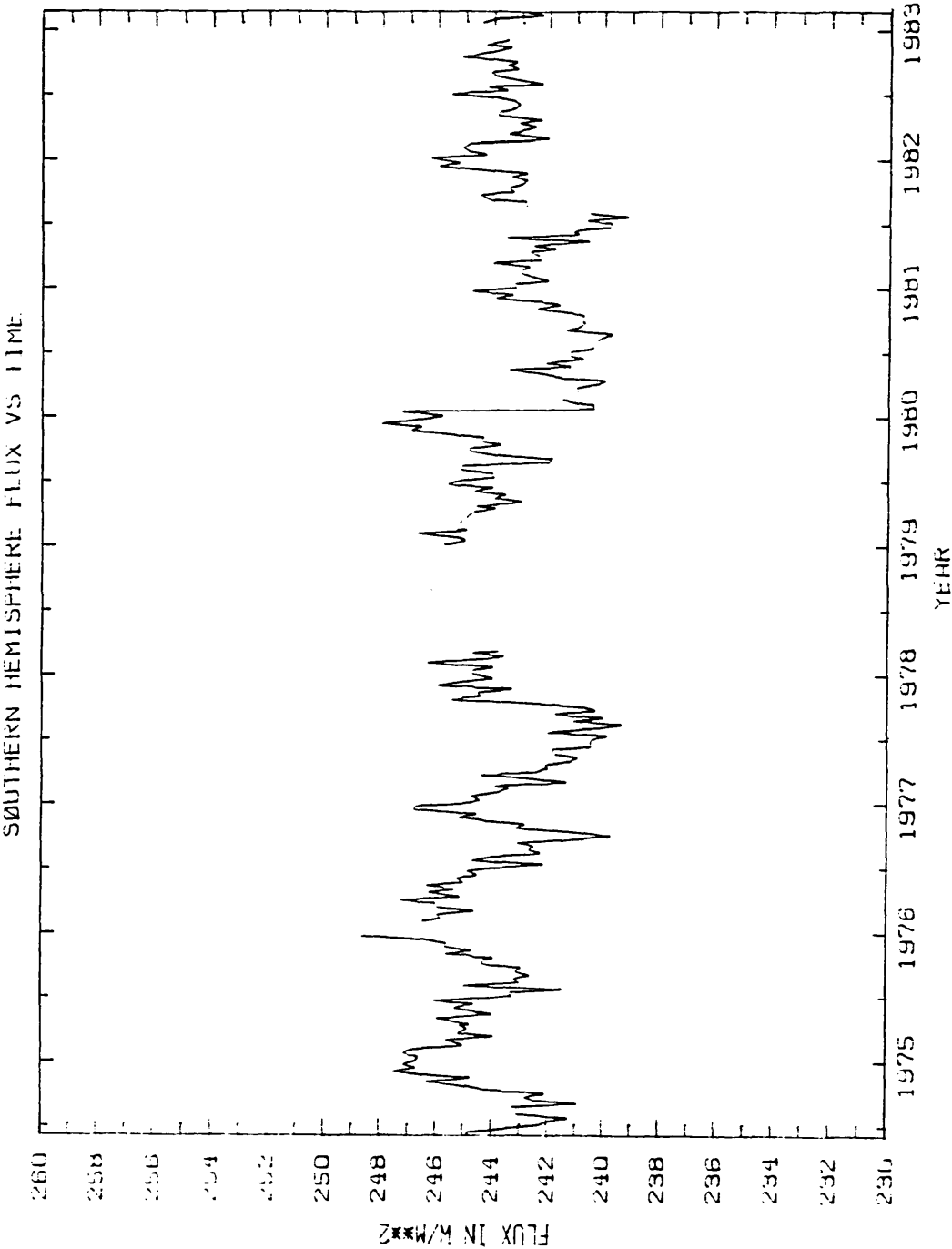


Figure 6.4. Southern Hemisphere flux vs time.

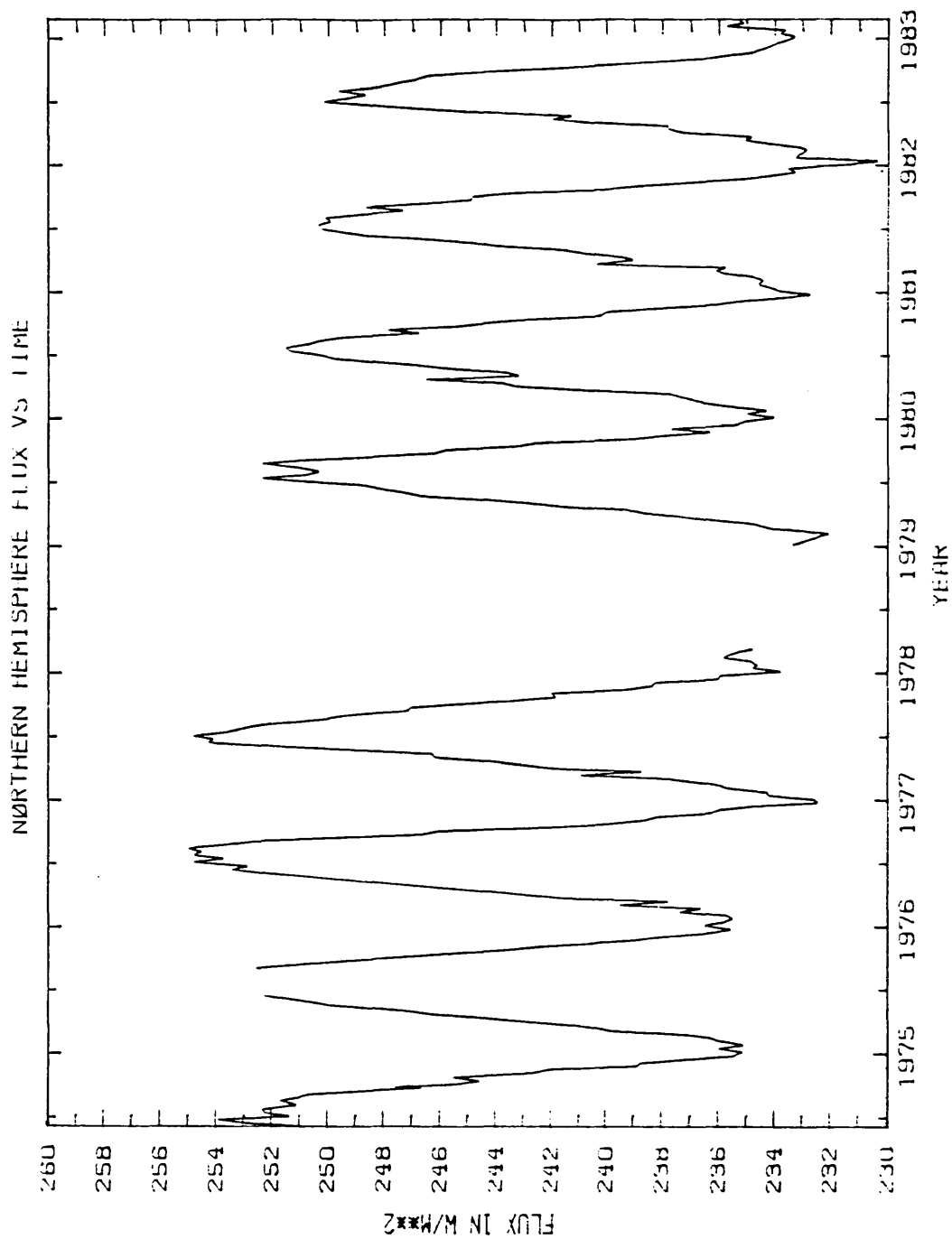


Figure 6.5. Northern Hemisphere flux vs time.

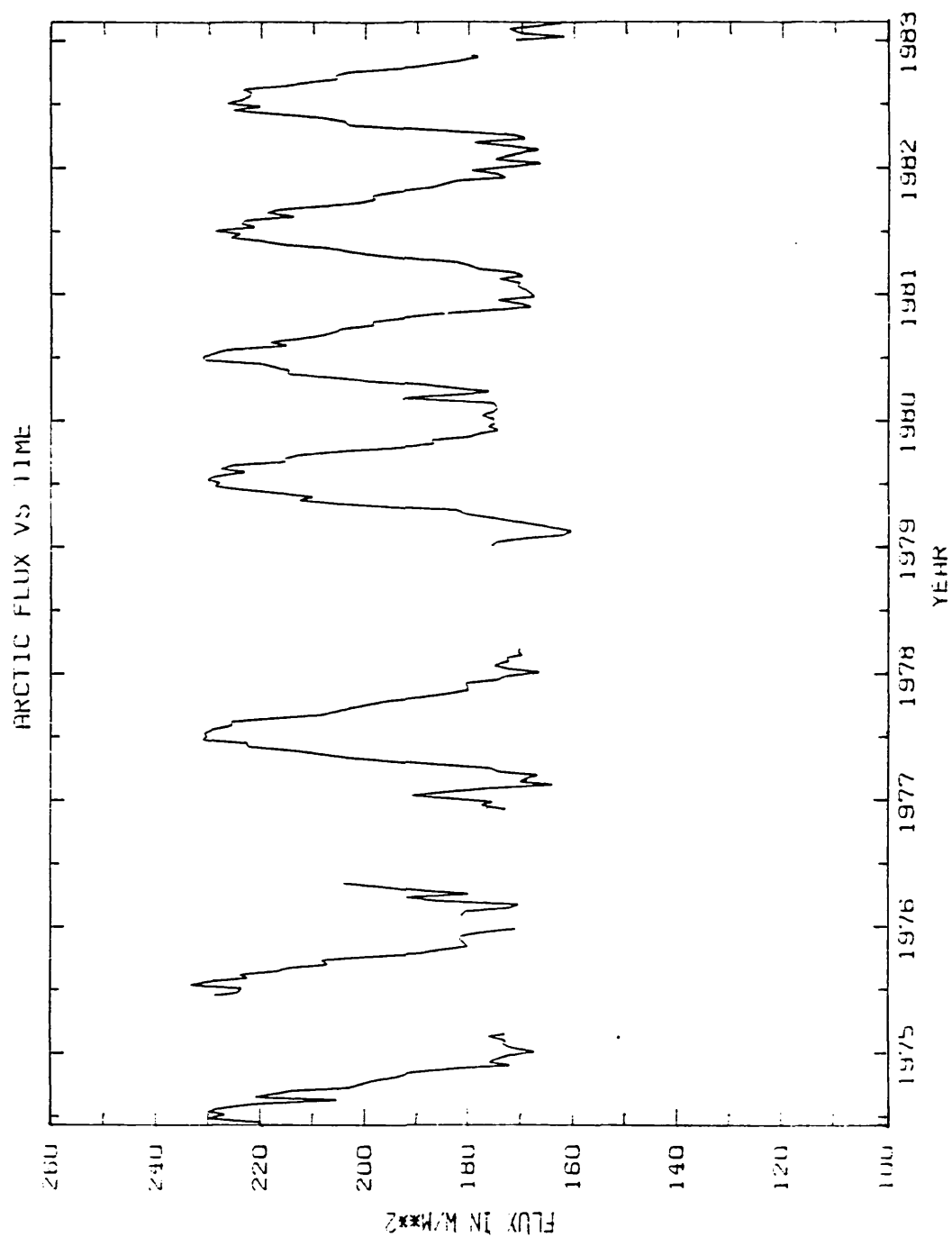


Figure 6.6. Arctic flux vs time.

Also displayed quite clearly is the 'Kernlose' winter effect. During winter the temperature trace usually has a sharp bottom; a point where the temperature trend reverses (Wexler 1958). However in the Antarctic a flat bottom is reached in temperature during which there are many reversals in the temperature trend. This is thought to be caused by the large meridional temperature gradients which occur at this time across the sea-ice/sea interface. These temperature gradients cause the atmosphere to be highly baroclinic and the instabilities thus caused produce cyclones which import 'warm' air into the Antarctic region. This effect was first determined in terms of surface temperatures but the effect on the OLR is clearly similar. The other major factor to be noted in this graph is the asymmetry of the annual cycle. The period of cooling is slow relative to the warming period. This is caused by the sea in the region of interest. During the cooling period convective currents are set up that bring warm water to the surface. During the warming period however the currents are not set up because the water is stable with warmed water at the surface. Figure 6.4 shows the average flux in the Southern Hemisphere for a number of years. Over such a large area there is very little variation in the OLR. In fact the values throughout the period lie in the range 248 to 240 W/m^2 . However since the variations are so small care must be taken in the interpretation of the results due to systematic sampling errors. (These absolute values are also in error by the amounts described in Chapter 4). There is a weak annual cycle, that is indicated by the peaks that occur at the beginning of each year. However after the period 1980 (when satellite crossing times were changed) the strength of this cycle is reduced from 8 W/m^2 (before 1980) to 6 W/m^2 in mid 1981. After this period (another satellite) the cycle seems to be further reduced. These apparent changes in amplitude of the cycle are in fact due to sampling the diurnal cycle at different times of the day. However even bearing this in mind it is quite clear that over the Southern Hemisphere the annual variation of OLR is about 8 W/m^2 .

with variations from year to year of about 2 W/m^2 .

A similar plot is shown for the equivalent Northern Hemisphere area. In figure 6.6 the Arctic area flux is shown. Comparisons with figure 6.3 are useful because of the contrasts and the similarities. The range in variation in both figures is about the same, 80 W/m^2 . While the size of the variations are similar the absolute values for these ranges are not. In the Northern Hemisphere the maximum values are about 230 W/m^2 while in the Southern Hemisphere the maximum is only about 190 W/m^2 (the lower limits are similarly different). These variations are due to the different distribution of land masses in the two polar regions. For example the variation in flux in the Northern Hemisphere has a much sharper turn round point unlike the Southern Hemisphere.

To investigate the nature of the zonal distribution of fluxes figure 6.7 was used. In this plot time is plotted as the x coordinate at monthly intervals (monthly values are included in this section for convenience). A contour plot is formed of a series of zonal means with the North pole at the bottom and the South pole at the top. This generalised view point has its advantages in describing the broad outlook. The Northern Hemisphere is obviously different from the Southern Hemisphere. The gradient of flux changes in the Northern Hemisphere indicate a very much more rapid and extensive area of change than in the Southern Hemisphere. The primary cause of this is the cold air mass that sits over the Antarctic during winter. From the slope of the line it is clear that there is little change in the flux over this region during this time. The spring warming event that is so common in the Antarctic is also indicated by the relatively large slope in the autumn season. The Northern Hemisphere in comparison gradually changes throughout the year with no period of time when the flux is stabilised. This is indicated by the 45 degree lines in the bottom part of the diagram. The ITCZ near

the centre of the diagram is indicated by a region of low flux values. From the shape of this region it is clear that the ITCZ moves north during the Northern Hemisphere summer and is more southerly during the winter season. However this figure is a zonal mean and hides many longitudinally dependant features especially with regard to the ITCZ which may be more northerly over the land than over the sea for example. The regions either side of the ITCZ are the subtropical highs in the two hemispheres.

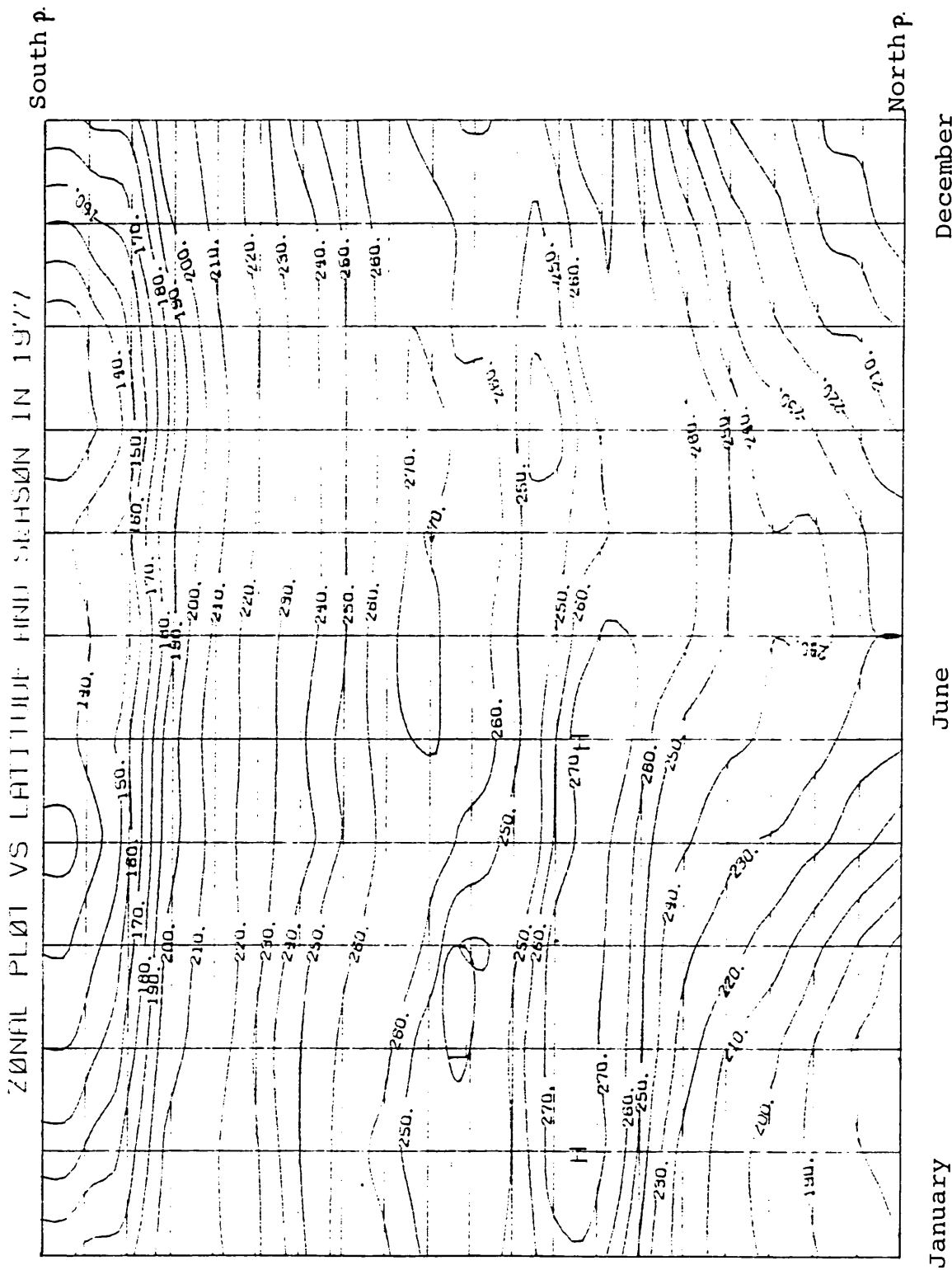


Figure 6.7. Zonal plot versus latitude and season.

6.2.2 Seasonal Means

The seasonal means defined above are repeated here for convenience. In this section Southern Hemisphere seasons are used exclusively and are defined as follows:

Spring	-	September	October	November
Summer	-	December	January	February
Autumn	-	March	April	May
Winter	-	June	July	August

(Boreal seasons are defined in the normal way where Northern Hemisphere seasons are mentioned). See footnote (3) for figure descriptions.

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Footnote (3) - Figure 6.8 to 6.15 are arranged in groups of four. Each quadrant represents the Southern Hemisphere seasonal means for one year. The top left is Spring the top right is Summer the bottom left is autumn and the bottom right is Winter. Because of the order of the seasons in the Southern Hemisphere, the correct chronology of these images is obtained if they are viewed bottom left, bottom right, top left, and top right.

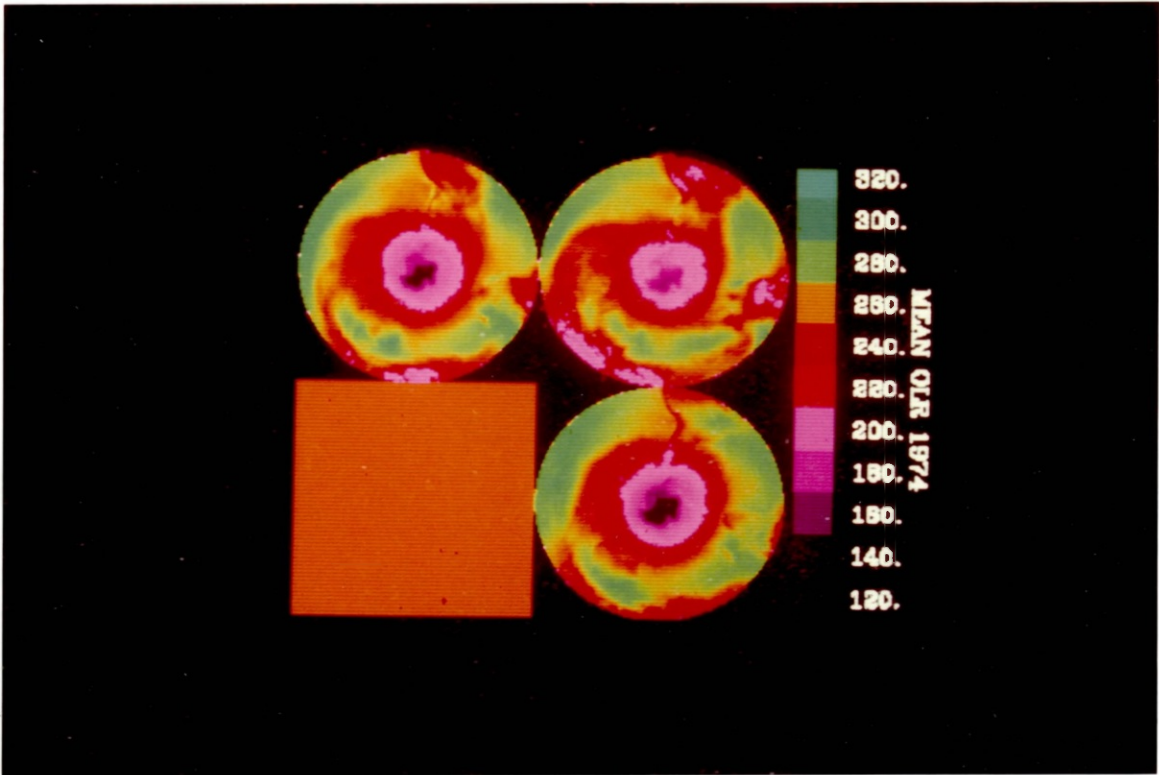


Figure 6.8. Mean flux for 1974.

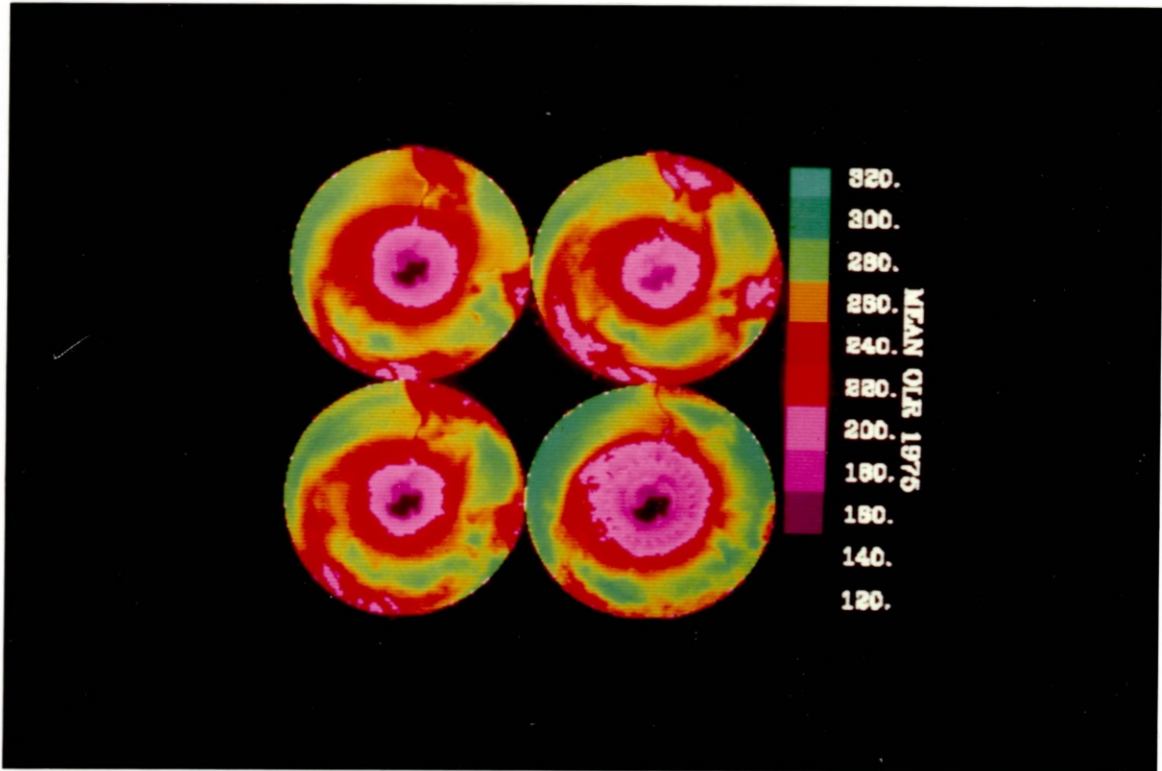


Figure 6.9. Mean flux for 1975.

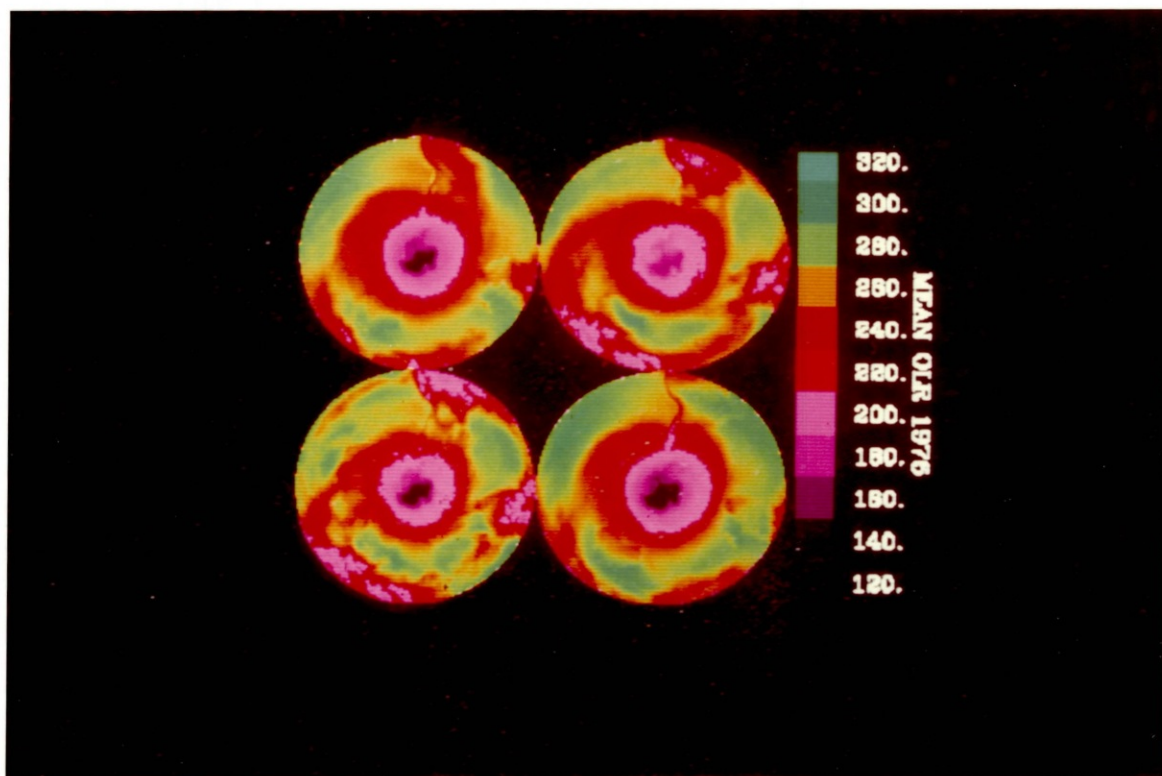


Figure 6.10. Mean flux for 1976.

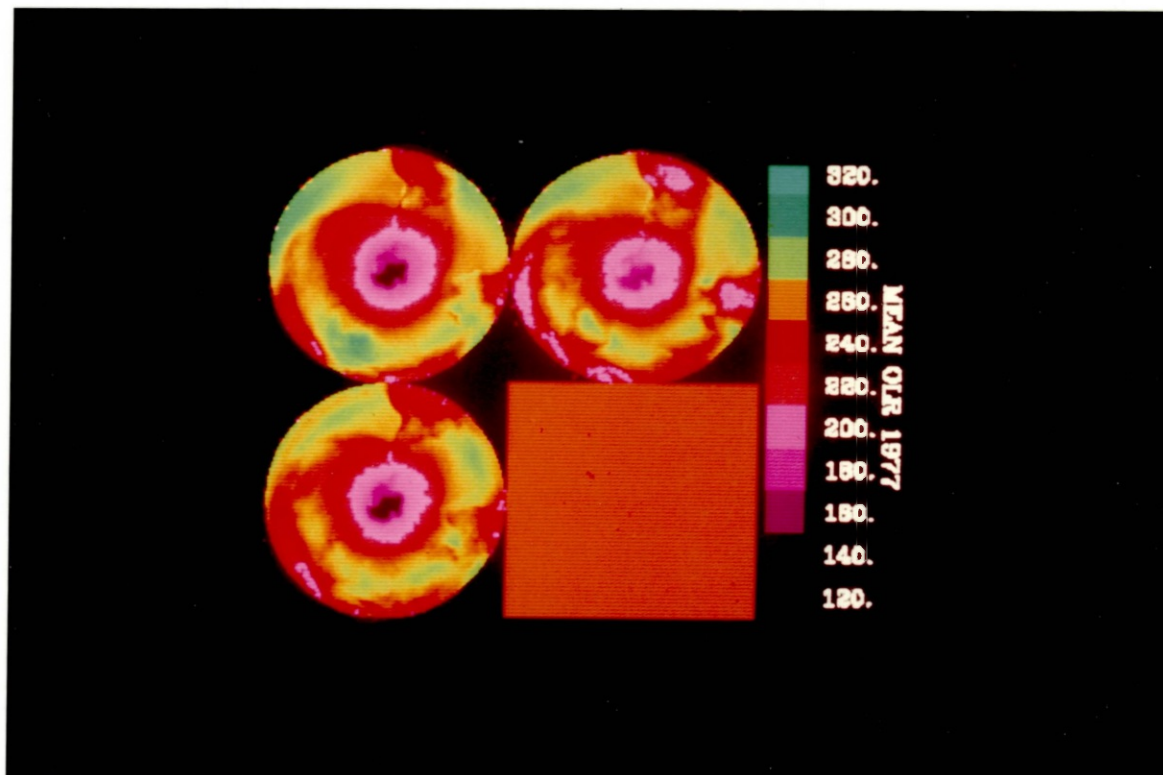


Figure 6.11. Mean flux for 1977.

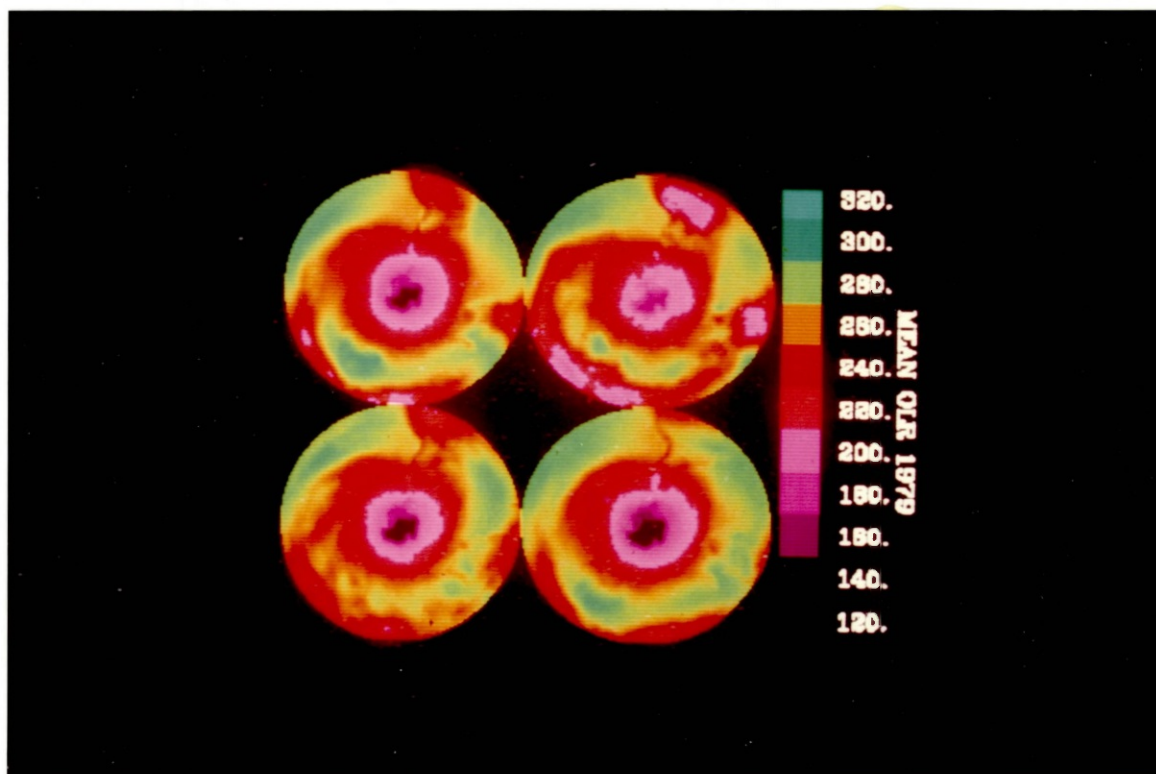


Figure 6.12. Mean flux for 1979.

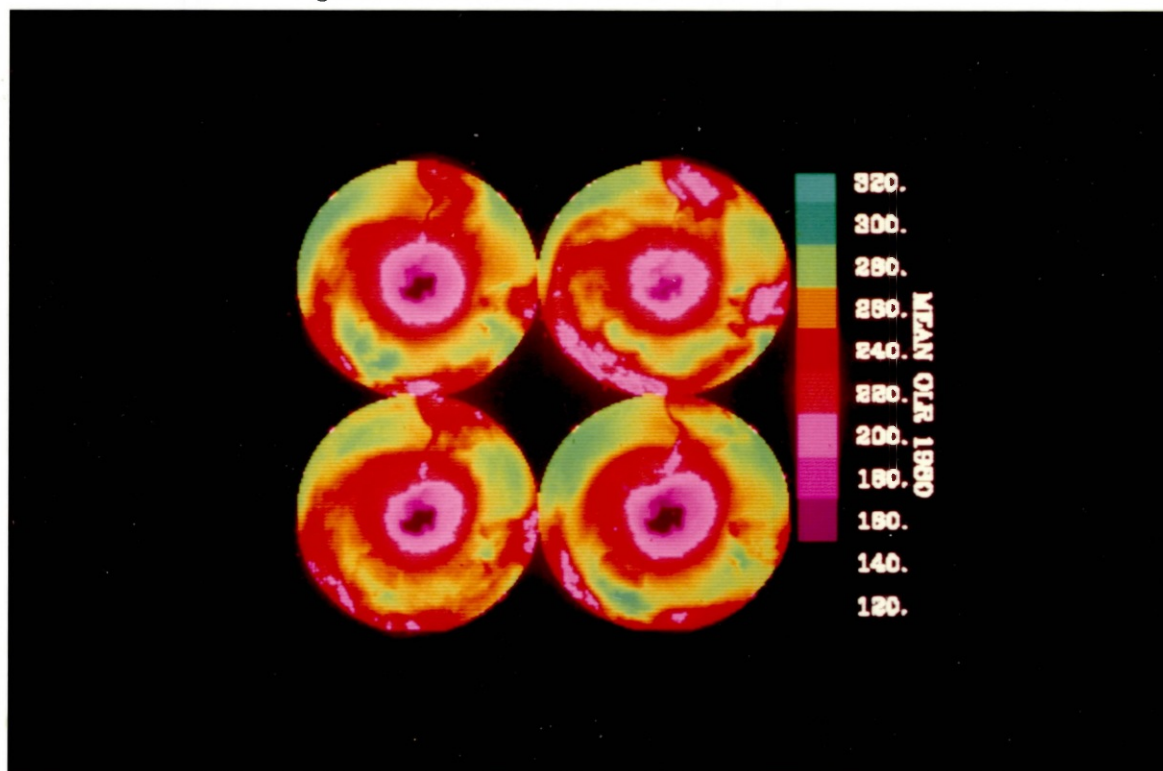


Figure 6.13. Mean flux for 1980.

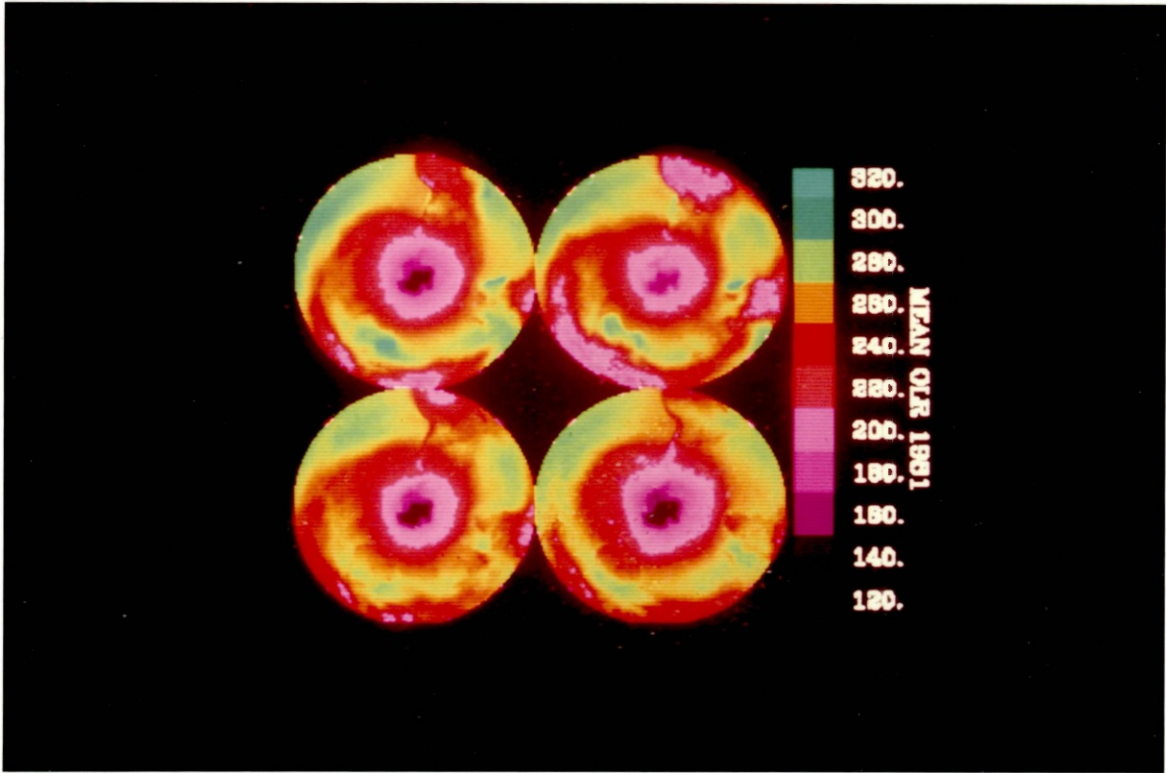


Figure 6.14. Mean flux for 1981.

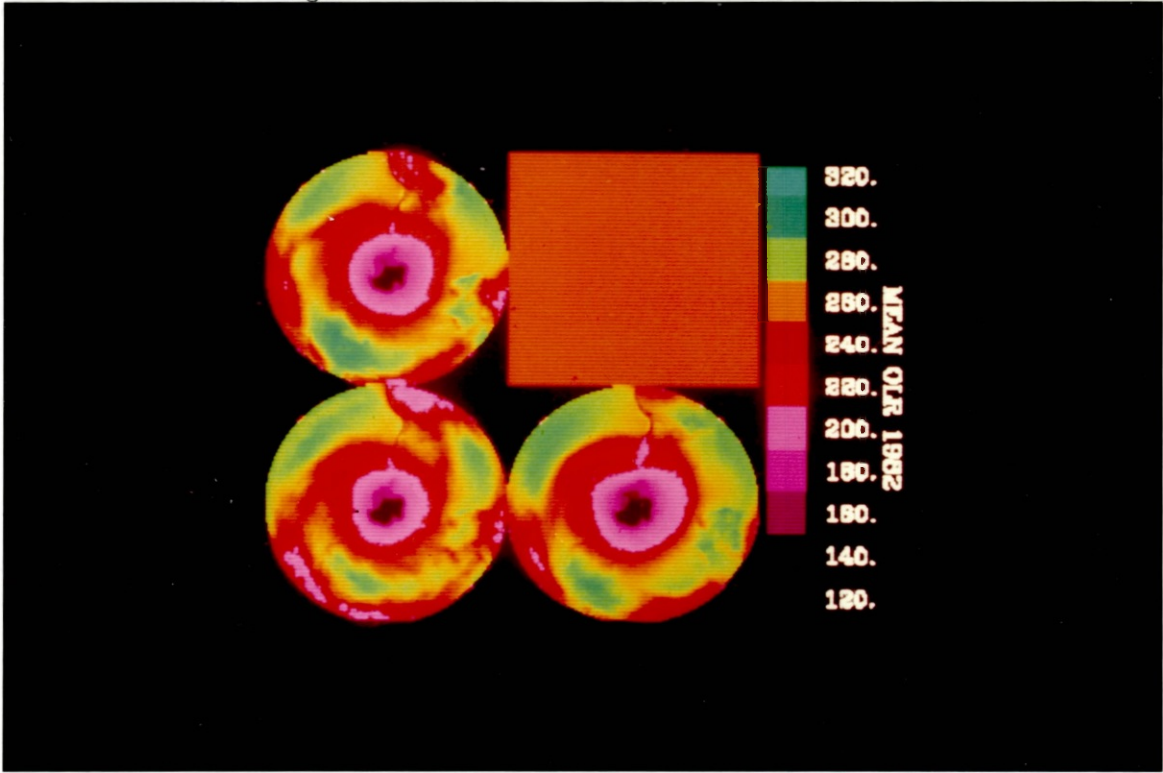


Figure 6.15. Mean flux for 1982.

Starting with winter 1974 (bottom right) the positions of the major land masses such as South America are visible (indicated by the position of the Andes mountain range which acts as a barrier to the zonal flow), South Africa (which is hardly visible on these means during winter) and Antarctica which is a region at the south pole. The ITCZ and the position of the Indonesian climatic front are just visible in the Southern Hemisphere during this period. This region from 60 degrees West to 120 degrees West is a region where there is much activity associated with the ITCZ, troughs and decaying lows, moving eastward. No other subtropical or trade wind fronts are visible during the winter period. In the South East Pacific the strong anticyclone that is quasi-stationary in this region has moved the ITCZ north.

In winter when the ice extent is greatest the position of an Antarctic front is clearly detectable. It is that region bounded to the north by flux values $>230\text{W/m}^2$ and to the south by the Antarctic continent. This fairly broad region (65 degrees south to 45 degrees south) indicates the region in which frontal frequency is highest. Also visible on all the winter images is a tongue of low flux extending from the tip of the Antarctic peninsula in a NE direction and thought to be indicative of the ice floes which are advected northward during the winter into the southern ocean. Over the Brazilian region the generally strong Atlantic anticyclone persists which causes frequent easterlies over a large portion of the South American continent. This is in contrast to the situation in summer in this region when weakened easterlies mix with warm humid air over the Amazon basins, causing considerable rainfall (compare summer and winter images of South America). The south African region in this season shows very little sign of activity. However during the other seasons much activity is seen both over the Congo basin and over the western part of the Indian ocean. During the spring, and summer seasons humid air over Africa causes activity that spreads eastwards. Activity is reduced in autumn in this region.

There are sufficient differences from year to year to be of note. The major differences between the winter circulations are to be found in the intensity and position of the south Pacific cloud band. For example in 1976 the circulation appears slightly stronger than for 1974 and 1975. Similarly 1982 appears to be more developed than the preceeding 3 years. This may be related to the El Nino but a clear connection between the two is not apparent. Similar comments apply to the Spring Summer and autumn circulation. However much of this variation is also due to either the timing or the position of events rather than to the absolute strength of a phenomenon.

In summer the south east Pacific is thought to be particularly inactive (as the images show) but that there are occasional showers in some regions. With regard to these showers it has been suggested that they are due to thin stratiform clouds which do not show on satellite pictures (Mc Donald 1938). However there is a region off the south America that shows a small reduction in flux, especially in summer and spring. Over south America the ITCZ is thought to be sufficiently far south that either the 2 hemispheric circulations flow side by side or that there is some mixing. With regard to the spring and autumn seasons these are transition periods when circulations are either decaying or establishing their new regimes. For example the south Pacific climatic cloud band first becomes a feature joined to the Antarctic convergence in spring. By summer it is a very strong feature ($<200 \text{ W/m}^2$). These differences are further discussed in section 3.0 using anomaly maps.

6.2.3 Seasonal Variability

The standard deviation maps for the data set at seasonal intervals are shown in figures 6.16 to 6.23. The lay out is similar to the means figures. Before any analysis of the standard deviation maps is attempted it will be useful to show the relationship between the mean radiation maps and the standard deviation maps. To illustrate these 1979 will be used as an example. In Northern spring the regions of high standard deviation of OLR ($> 27 \text{ W/m}^2$) are associated mostly with regions of low flux values. This is because clouds are variable features (even on ten day means) and thus give rise to regions of rapidly varying flux. Because of the nature of these calculations regions where on the average fluxes are not very low, say regions in the south east Pacific large standard deviations will appear even when there are only a few clouds because of the large change in flux that occur. In summer (Southern Hemisphere winter) the climate is sufficiently stable so that most standard deviations are below the 10 W/m^2 mark, except in regions near the equator. During autumn the situation is similar to spring with large cloud bands being associated with high standard deviations. High standard deviations over the south pole may be due to changes in the temperature structure in this region during the transition season. Finally in winter this activity disappears. Much of the activity is now associated with the major land masses (excluding Antarctica) or down wind of these.

The general features of interest in these standard deviation maps will be considered in chronological order (winter to autumn). In winter the OLR standard deviations are very small ($< 5 \text{ W/m}^2$) in the regions associated with the south eastern Pacific's quasi-stationary anticyclone, the south Atlantic's anticyclone and the Indian ocean area. The major disturbances are due to the ITCZ (since this lies further north in the

winter), and appears in the longitude region from 10 degrees East to 190 degrees East. Over the Pacific there is no sign of the ITCZ activity (which is in the Northern Hemisphere). Moving further southward towards the subtropical highs we note increased activity associated with the climatic bands and with regions over south America and to some extent over south Africa. These variations ($15-30 \text{ W/m}^2$) are also indicative of some of the moving cyclonic disturbances in this region. Some of these disturbances reach as far as the coast of Antarctica itself where they usually dissipate. This weak activity over the Antarctic is replaced by a much more vigorous change during spring (when the rapid changes in area fluxes occur). In the spring standard deviation values can get as high as 25 W/m^2 over the Antarctic. In Summer activity near the coast of Antarctica is reduced to below the 5 W/m^2 level, with small regions indicating the rare cyclones that reach this far south in summer. The autumn values again indicate increased activity (another transition season) but not as vigorous as spring.

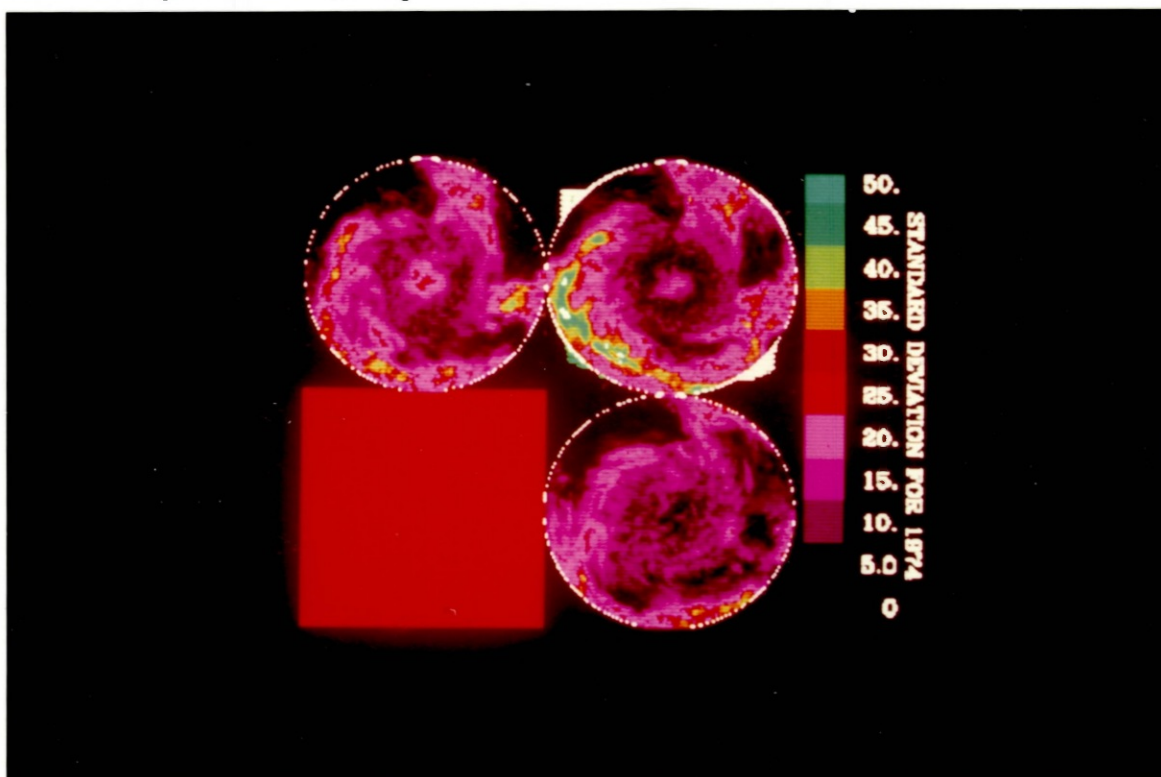


Figure 6.16. Standard deviation flux for 1974.

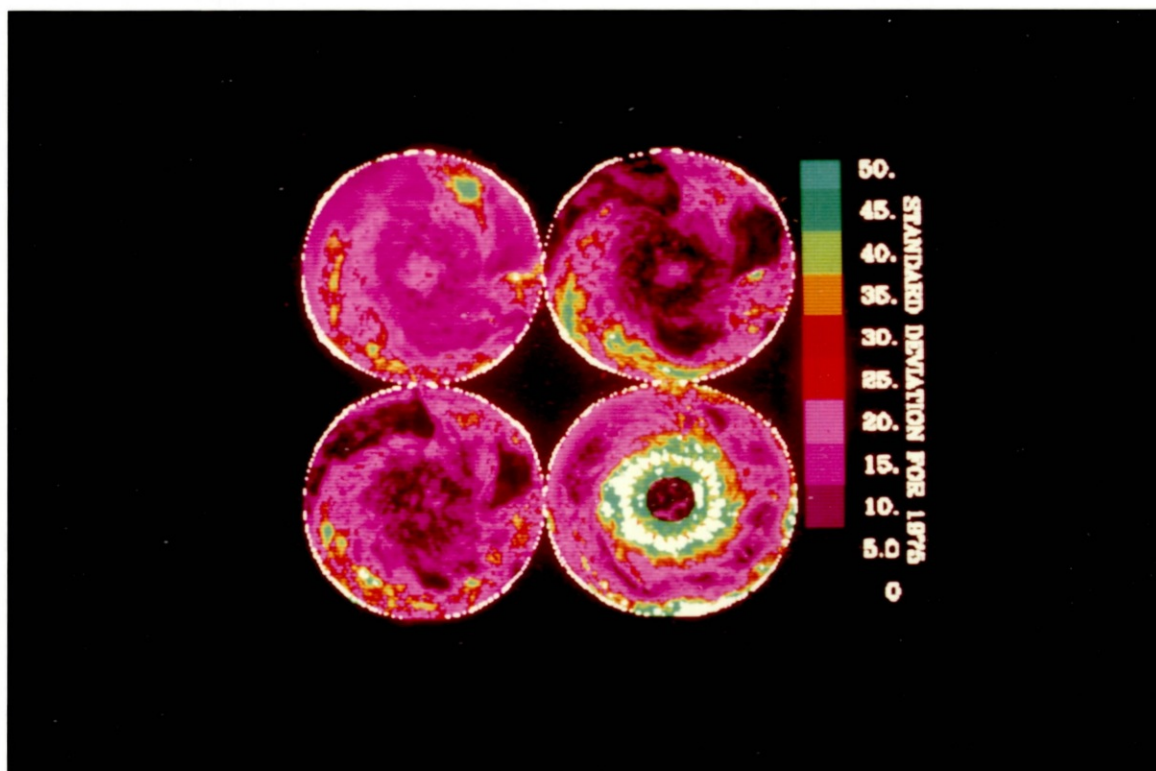


Figure 6.17. Standard deviation flux for 1975.

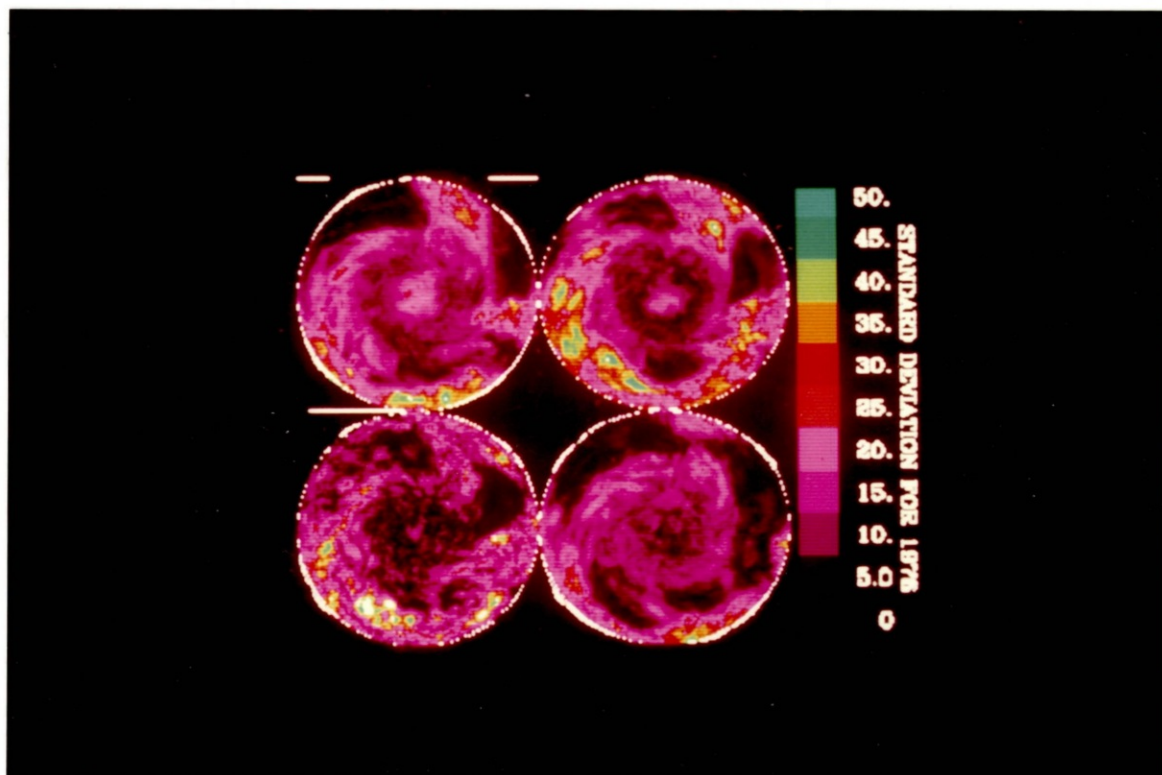


Figure 6.18. Standard deviation flux for 1976.

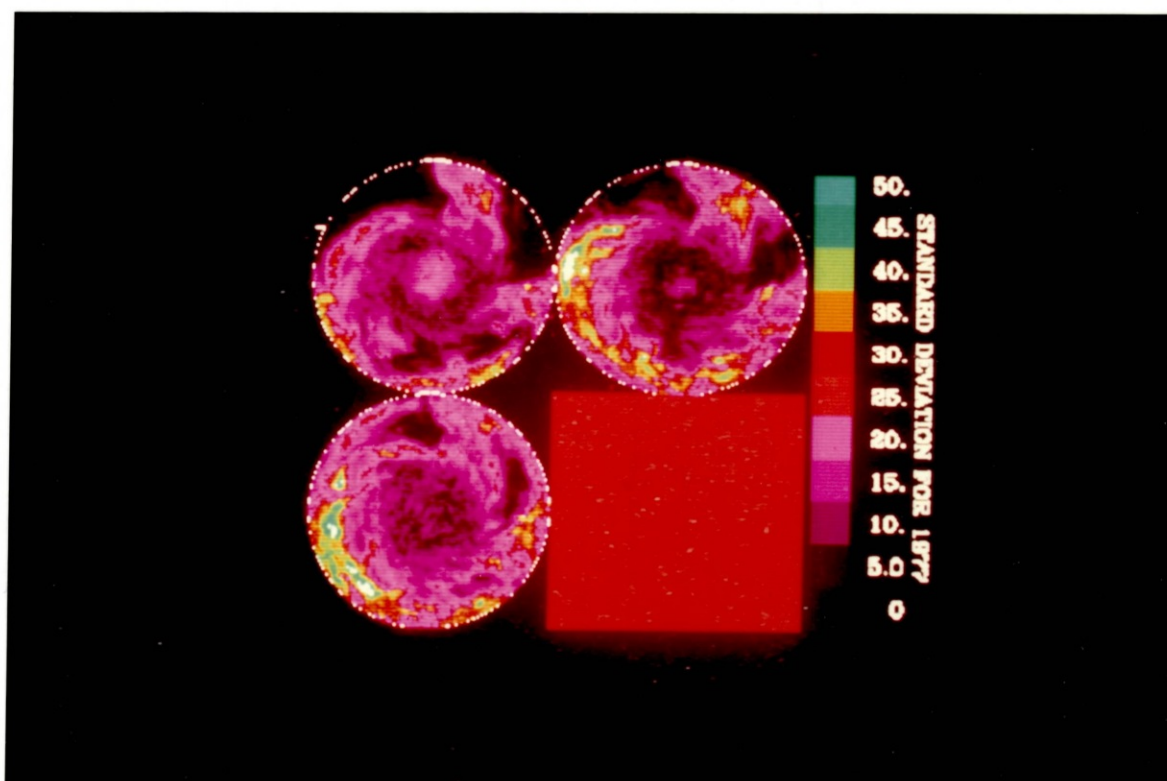


Figure 6.19. Standard deviation flux for 1977.

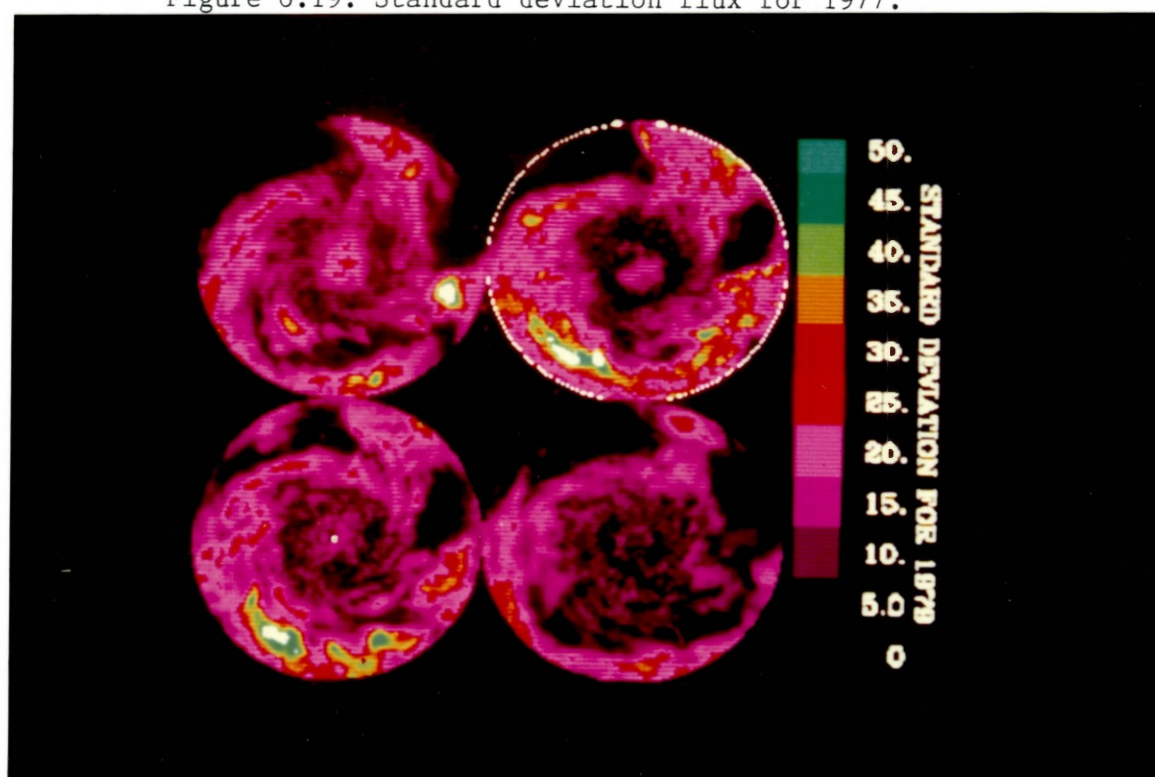


Figure 6.20. Standard deviation flux for 1979.

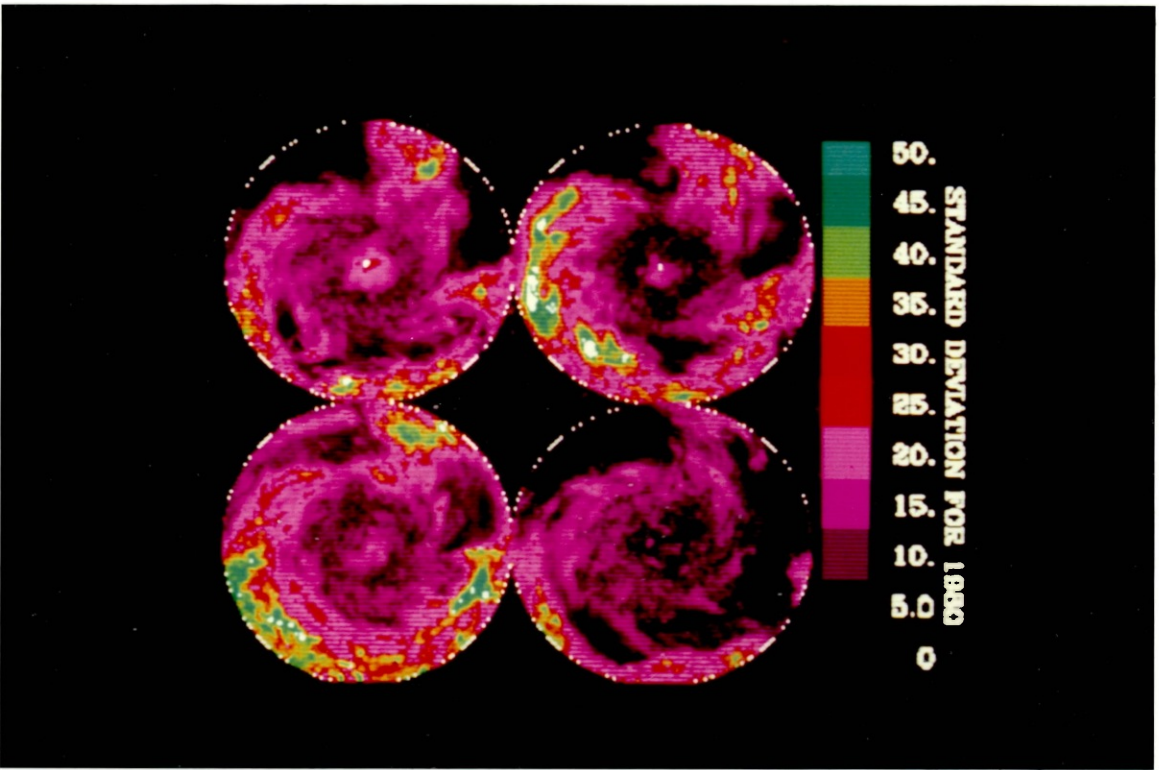


Figure 6.21. Standard deviation flux for 1980.

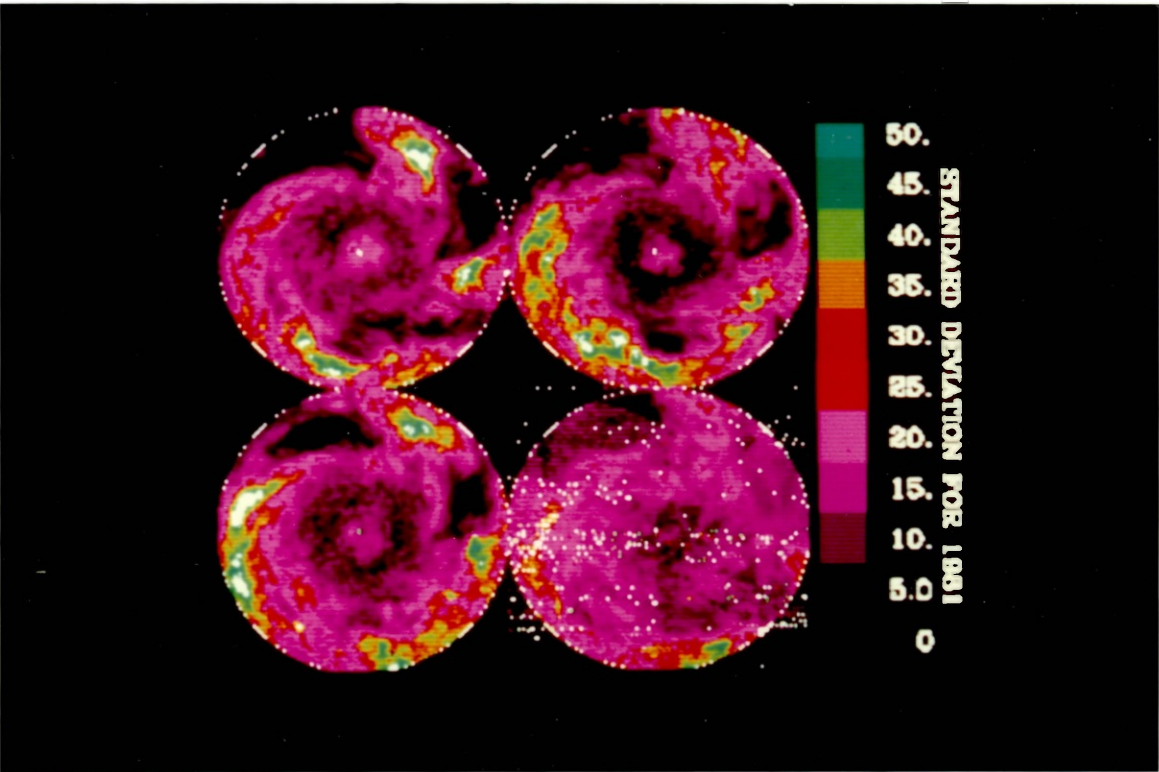


Figure 6.22. Standard deviation flux for 1981.

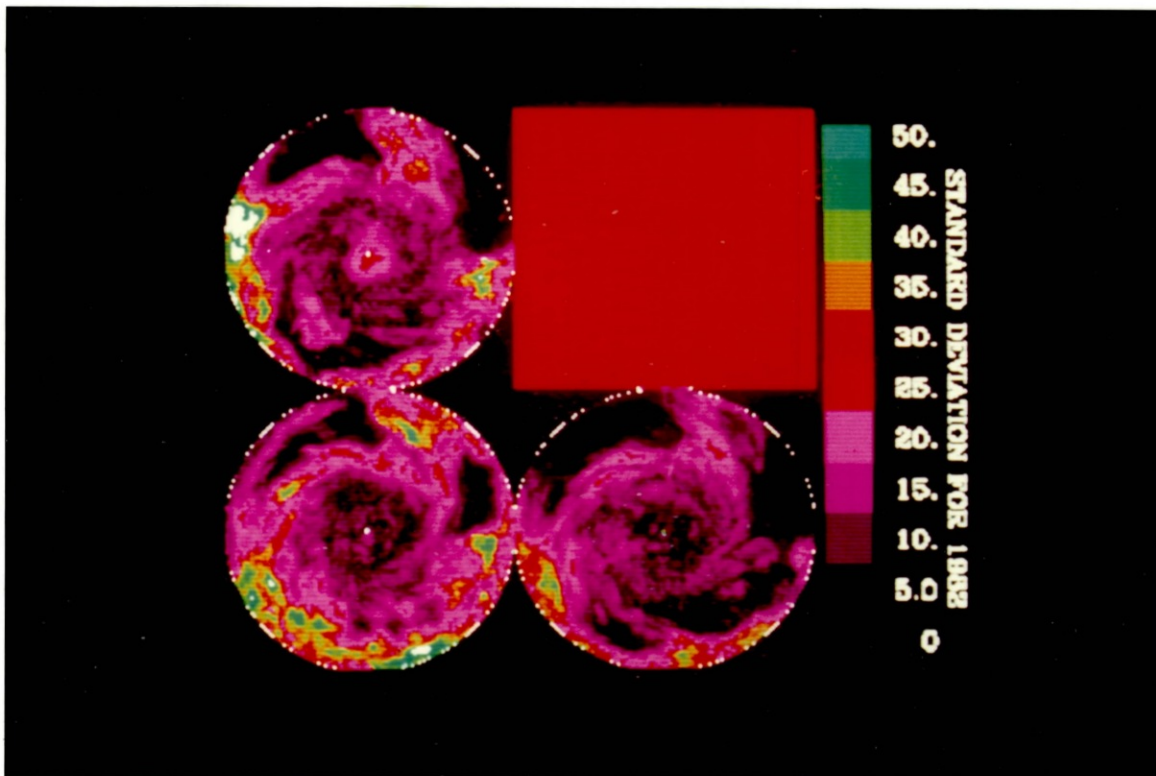


Figure 6.23. Standard deviation flux for 1982.

Most values lie in the range 0 to 20 W/m^2 . Values greater than 50 W/m^2 are shown as white regions. Some bias towards the equatorial regions is to be expected in these plots because of the higher flux values to be found here. Even bearing this in mind the Antarctic shows high standard deviations (about 20 W/m^2) at times. The highest values are to be found over the climatic cloud bands, especially during autumn and summer. The lowest values are found over many of the permanent anticyclone features, either the south east Pacific or south Atlantic any time of the year.

The standard deviation plots for the data set means show that the values for these are very much lower than the equivalent measurements for the seasonal mean. This is as expected due to the $1/n$ scaling in results due to the increase in the number of data points. The real measure of variability is made by measurement of the average size of anomalies (see section 3.0). The data set means have generally fewer features than the

seasonal means - for obvious reasons - but these are better indicators of the radiation climate. On these seasonal means the climatological cloud bands are clearly defined and their inter-seasonal variation measurable on the standard deviation maps.

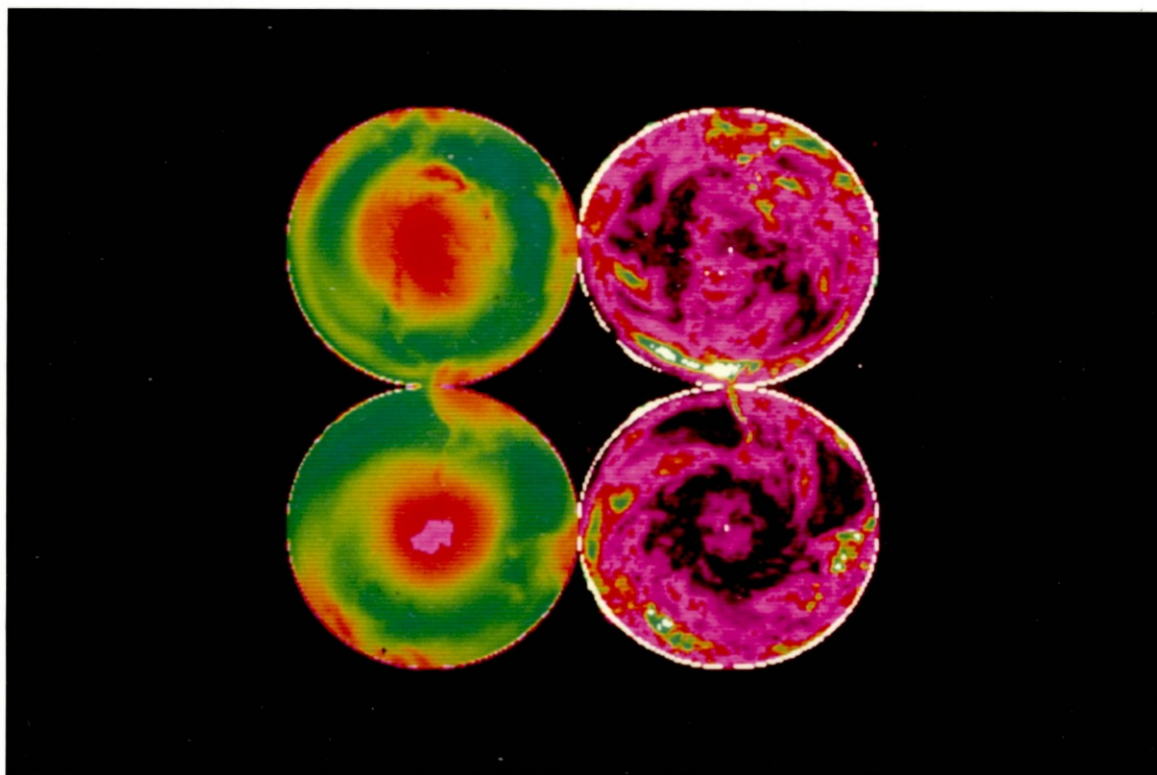


Figure 6.24. Spring mean and standard deviation.

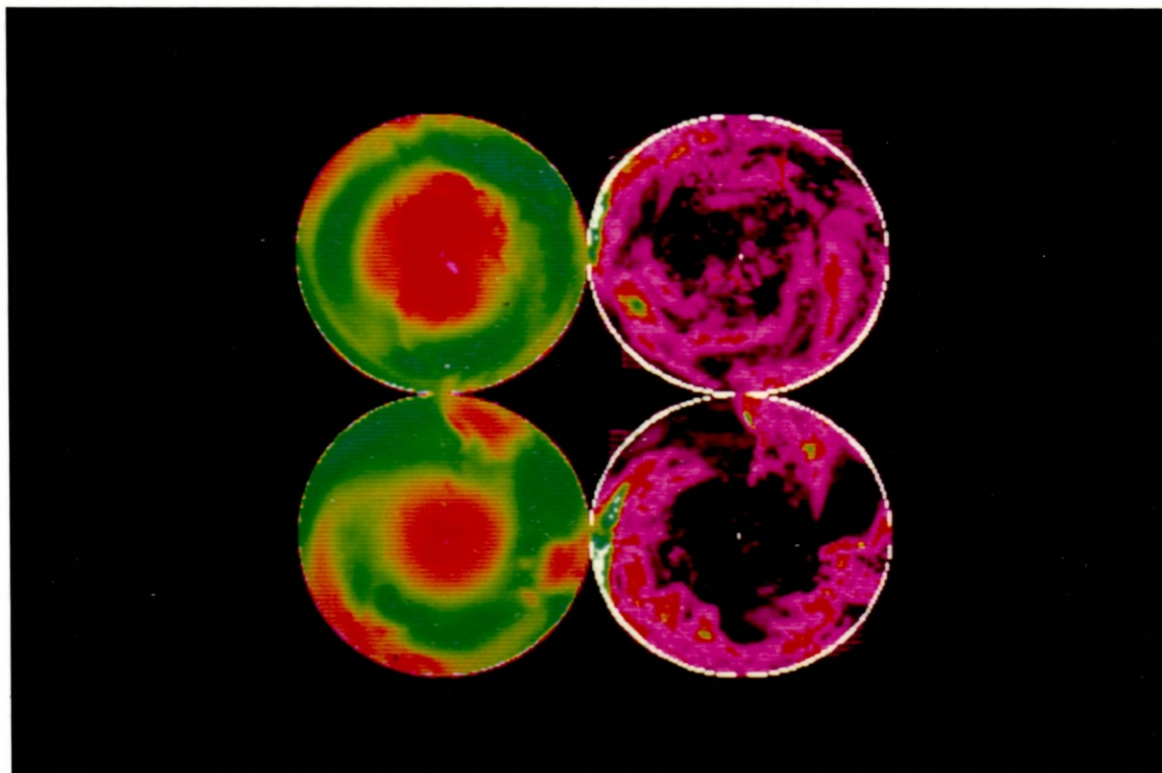


Figure 6.25. Summer mean and standard deviation.

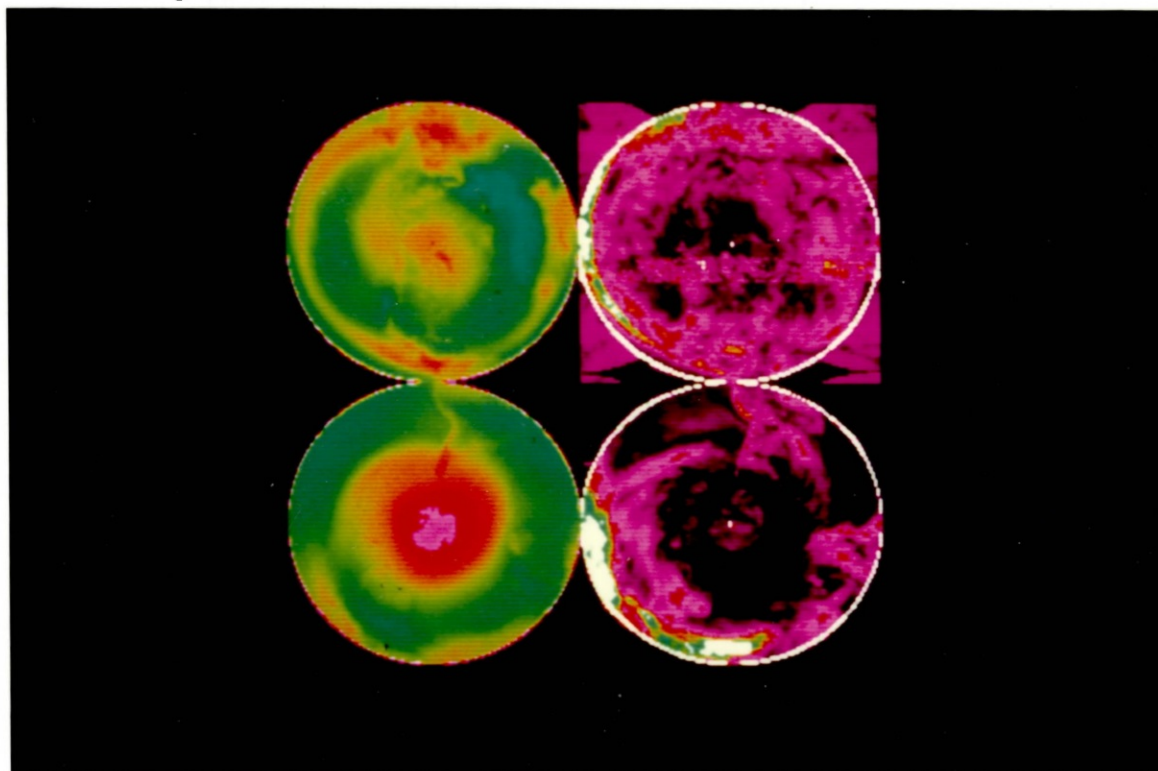


Figure 6.26. Autumn mean and standard deviation.

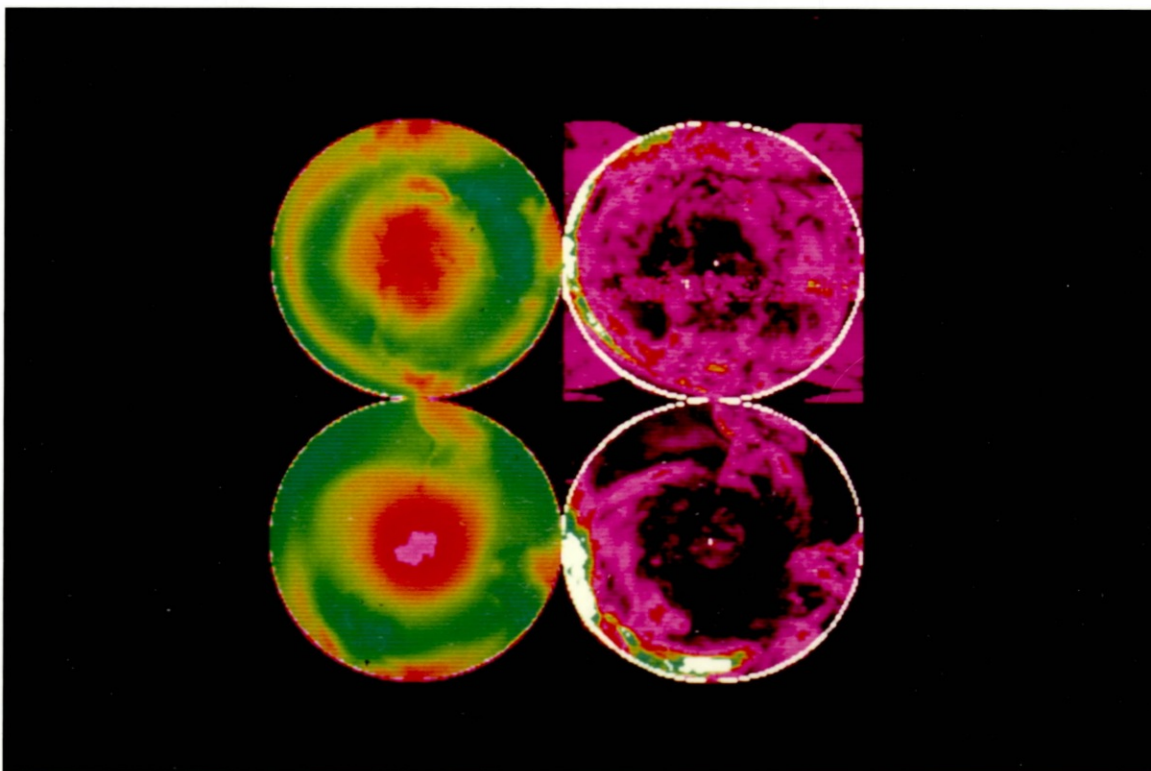


Figure 6.27. Winter mean and standard deviation.

6.3 SEASONAL ANOMALIES

Anomalies as defined in this section refer to the differences between the longer term and short term means. (See equation 6.2). For seasonal means this is the difference of the seasonal from the data set seasonal mean. For example the 1980 Spring season anomaly would be defined as:

$$\text{Ano}(\text{ Spring, 1980}) = \text{SMe}(\text{ spring, 1980 }) - \text{DSm}(\text{ spring }) \quad (6.2)$$

where

$\text{Ano}(\text{ season, year})$ is the anomaly for the season in the year specified. (In W/m^2).

$\text{Sme}(\text{ season, year})$ is the seasonal mean for year. (In W/m^2).

$\text{DSm}(\text{ season})$ is the dataset mean for the season. (In W/m^2).

On these images we see regions of both positive and negative anomalies. In most situations the negative anomalies can often be found very close to positive anomalies. Generally this will be due to the change in position of a cloud band. Examples of this can be seen in the 1975 and 1977 images. Anomalies are generally of the order of $+10 \text{ W/m}^2$ to -10 W/m^2 over a large part of the globe. This is about one standard deviation of the variability. The largest regions of anomalies are consistently associated with the south Pacific cloud band and its position. Periods of greatest anomaly occur during 1975 and 1982, both periods one year before an El Nino event.

The Antarctic has little effect on these anomaly maps except in a few situations where the surrounding areas are at normal flux values but the Antarctic is colder than normal (eg winter 1979). However in general anomaly gradients are not aligned with the continental boundary. Seasonal anomalies are also used in chapter 8 where teleconnection analysis is carried out.

In this respect anomalies may not be significant, in that they may be part of the natural variability of the climate system (although this is rather a loose definition of anomaly flux - it should more properly be called difference flux - it is the one more generally used in the current journals). Bearing this in mind it remains after an anomaly has been measured to show that it is a significant departure from the normal situation or that it is a statistically significant anomaly.

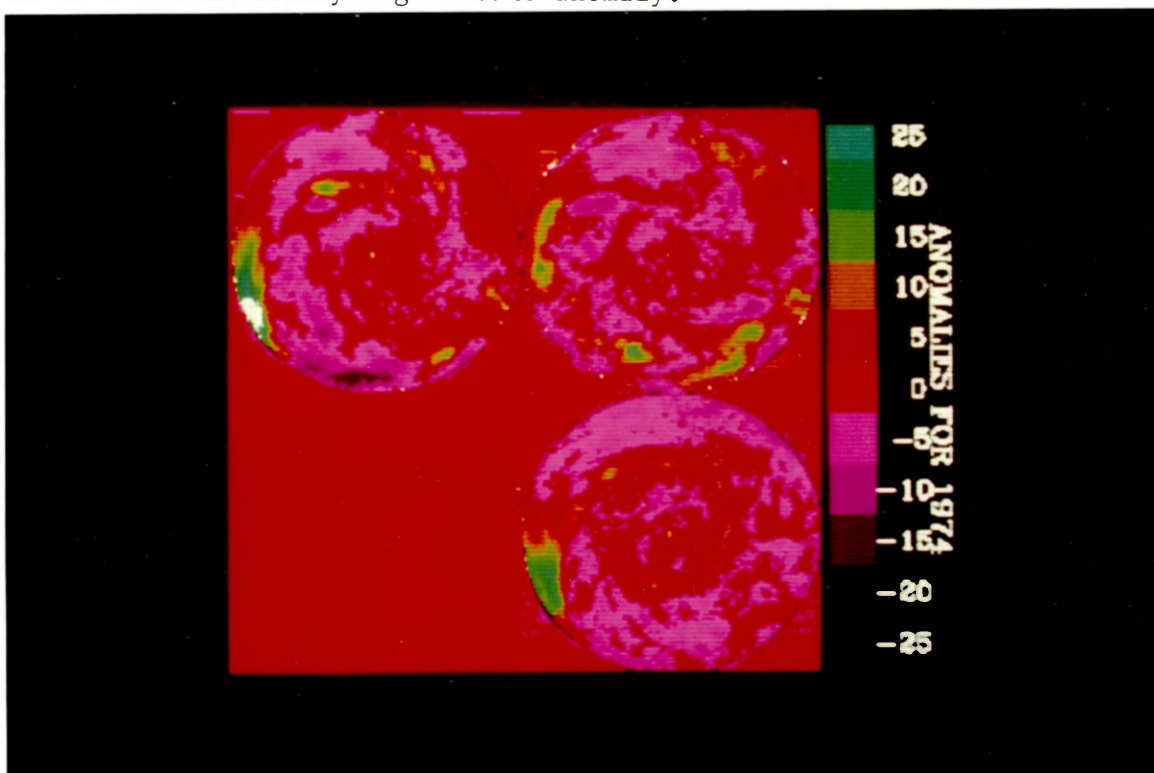


Figure 6.28. Anomaly for the Southern Hemisphere in 1974.

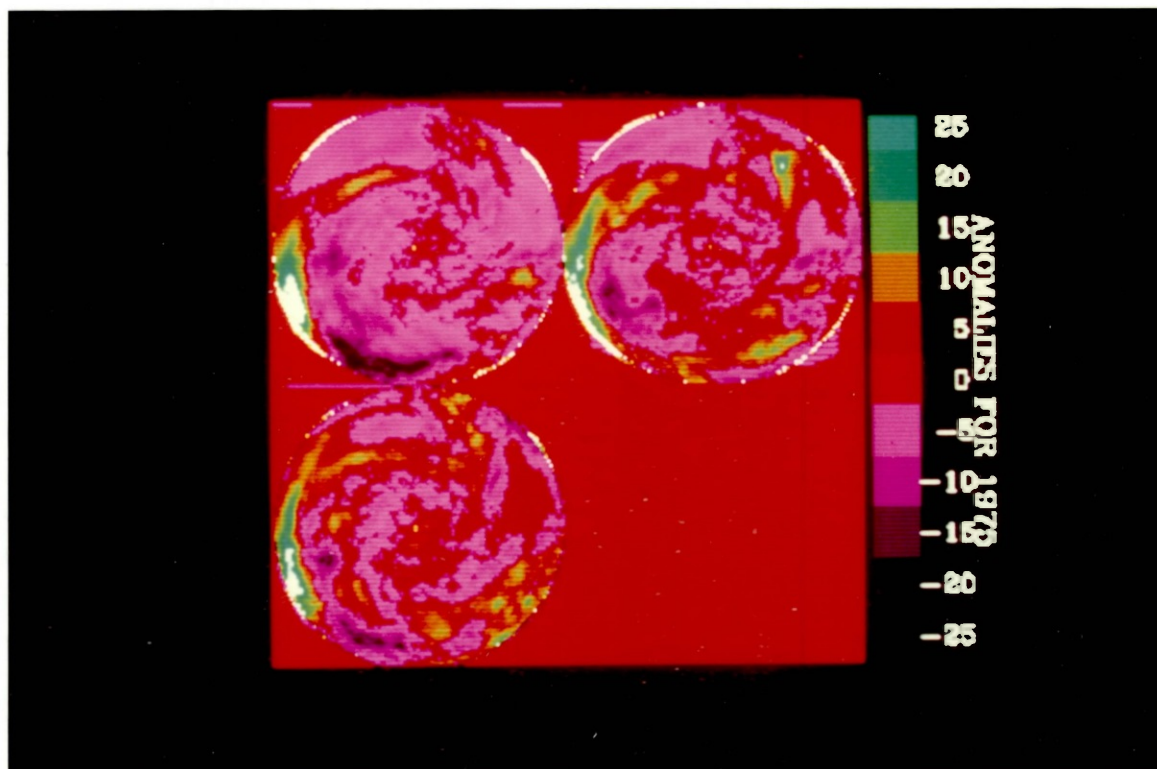


Figure 6.29. Anomaly for the Southern Hemisphere in 1975.

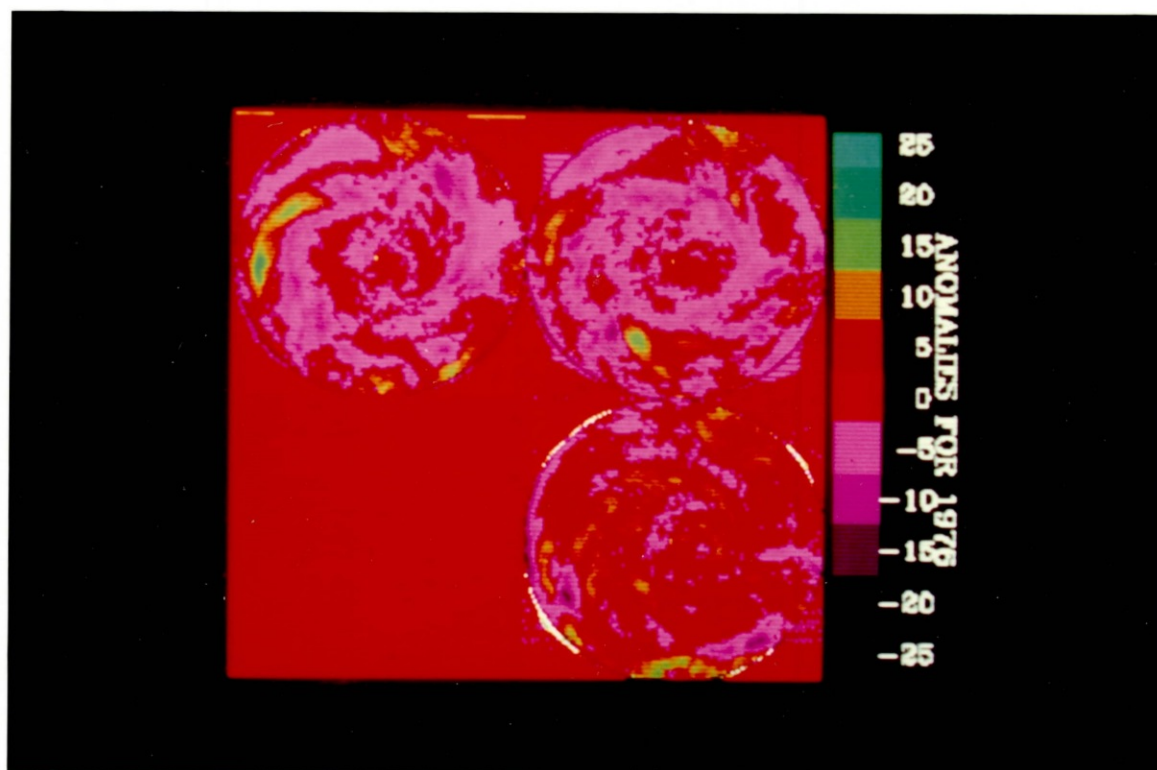


Figure 6.30. Anomaly for the Southern Hemisphere in 1976.

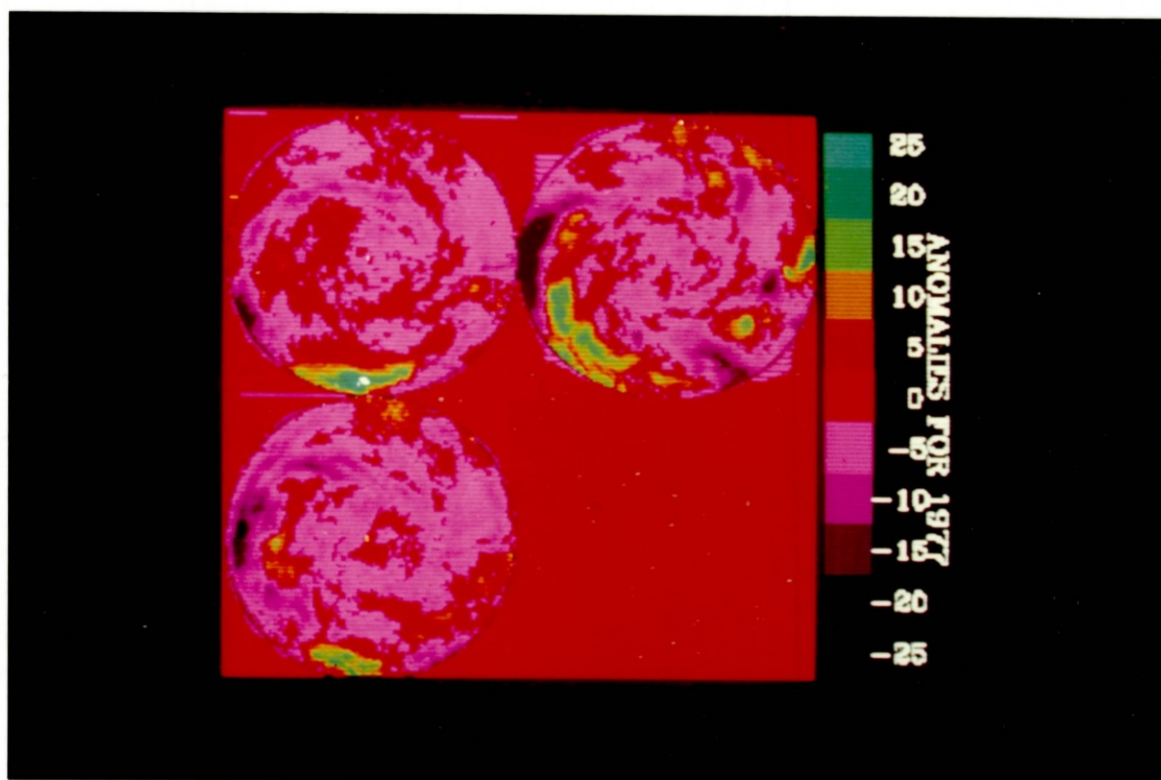


Figure 6.31. Anomaly for the Southern Hemisphere in 1977.

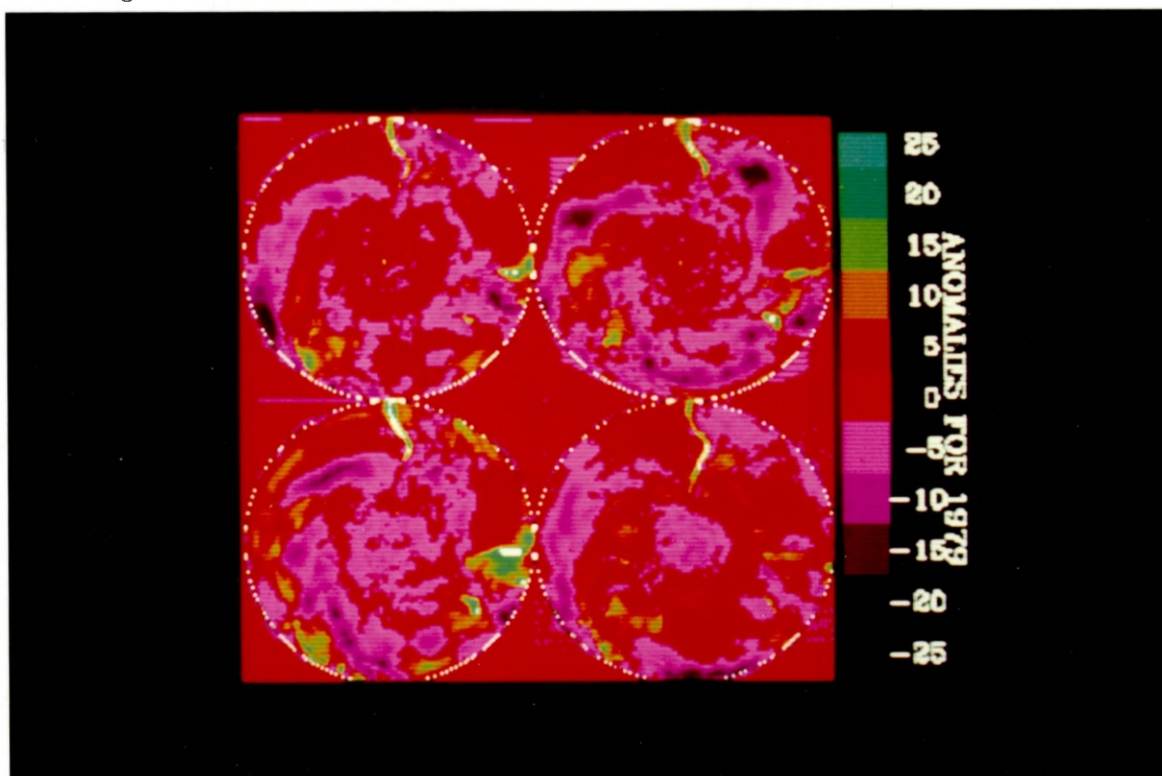


Figure 6.32. Anomaly for the Southern Hemisphere in 1979.

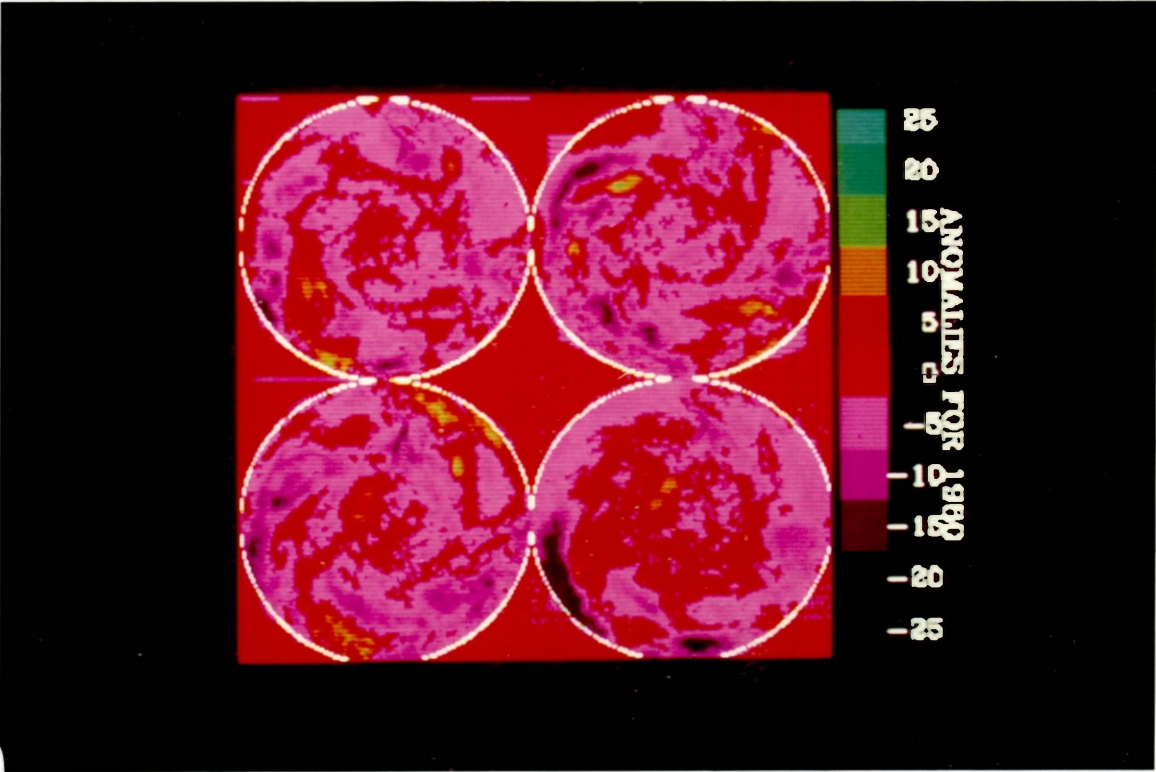


Figure 6.33. Anomaly for the Southern Hemisphere in 1980.

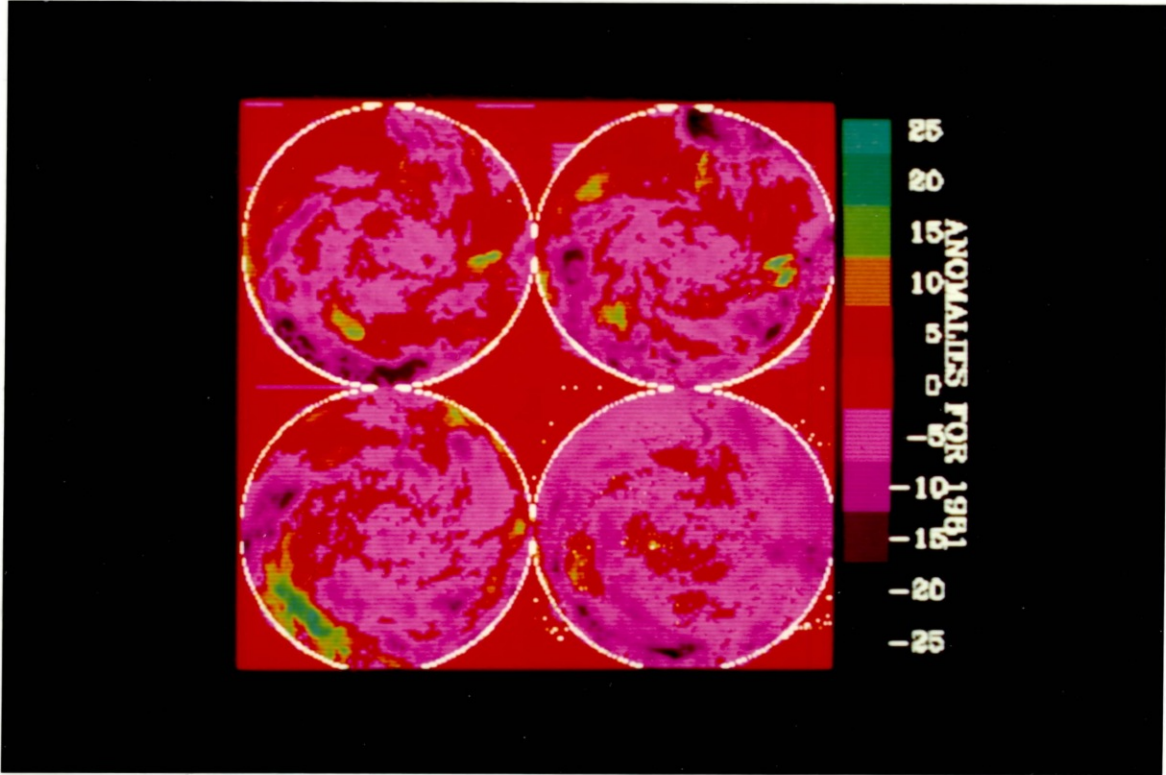


Figure 6.34. Anomaly for the Southern Hemisphere in 1981.

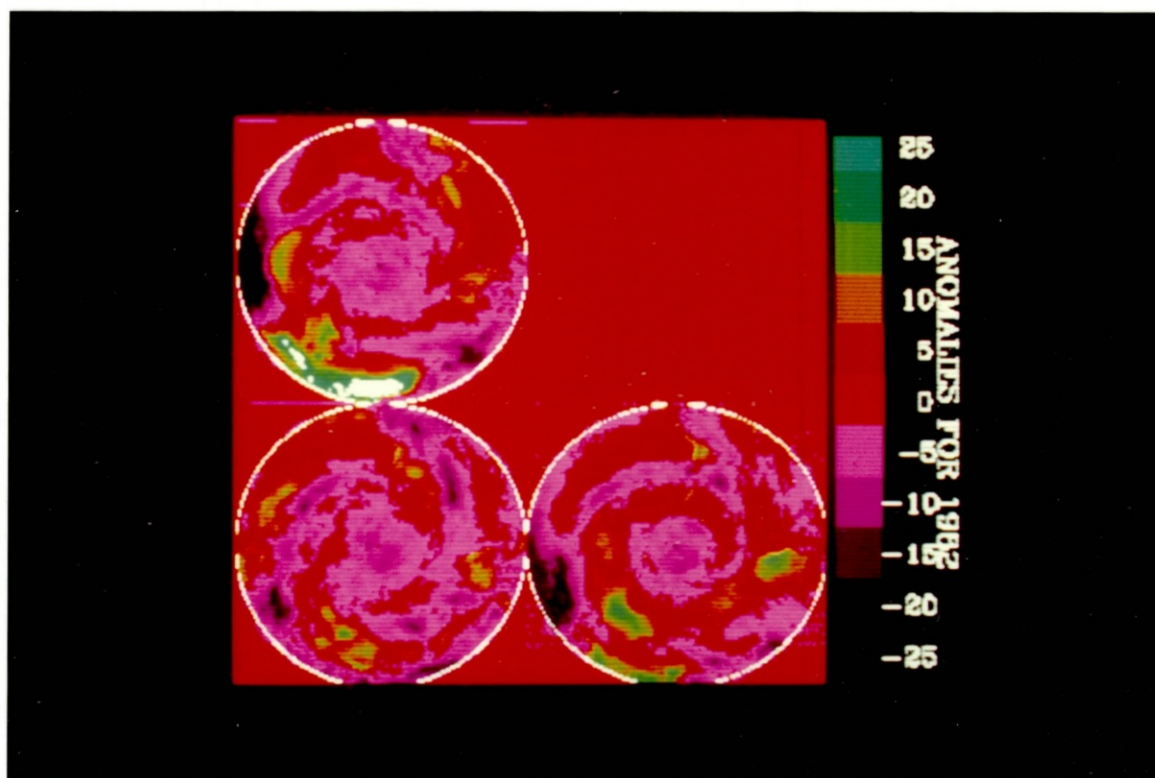


Figure 6.35. Anomaly for the Southern Hemisphere in 1982.

6.4 THE EARTH'S ALBEDO

Because of the way that NOAA/NESS calculate the available energy and absorbed Solar energy which they archive on the monthly heat-budget tapes albedo can be calculated. The terrestrial albedo can be calculated on a daily basis, using the data available, by employing a simple relationship between the absorbed and available fluxes.

$$a = ((ava - abs)/ava) = (1 - abs/ava) \quad (6.3)$$

where

a is the system albedo.

ava is the available solar energy. (In W/m^2)

abs is the absorbed solar energy. (In W/m^2)

Measurements of reflected Solar energy (in the visible part of the spectrum) at the satellite pass time, are used with the Solar input flux to calculate an instantaneous value of the albedo. Further it is assumed that this instantaneous measurement of the system albedo is representative of the daily mean albedo. The validity of this assumption depends to a great extent on the time of the satellites equator crossing (England 1984). In the worst case, estimates of the daily mean visible flux, can be in error by as much as 30 W/m^2 . Using this 'daily-mean' albedo the daily mean reflected energy is calculated using:

$$\text{refl} = a * \text{ava} \quad (6.4)$$

where

a and ava are as above.

refl is the reflected visible flux which is a daily mean value. (In W/m^2)

The daily mean absorbed flux, which is archived being calculated from:

$$\text{abs} = \text{ava} - \text{refl} \quad (6.5)$$

From the above (equation 6.3) the albedo was calculated and used to derive the Earth atmosphere system albedo on a pixel by pixel basis. This method was suitable for constructing albedo maps, where the albedo was calculated at every grid point (for which the available Solar flux and absorbed Solar flux were present).

For larger area albedo, (global, hemispherical, etc), results from these maps could not be used directly to average over the areas of interest because of the nature of albedo and the area weighting problem (the fact that all pixel do not represent an equal area of the Earth on the projection used). One would assume that:

$$am = [a'(1) + a'(2) + a'(3) + \dots + a'(n)] / Ar \quad (6.6)$$

where

am is the mean albedo (area weighted).

a'(1) is the area weighted albedo of pixel one

.

.

.

a'(n) is the albedo of the nth pixel.

Ar is the total area of interest.

and an area weighted pixel is calculated from:

$$a'(n) = a(n) * Ar(n) \quad (6.7)$$

where Ar(n) is the area of the nth pixel, however am is defined as:

$$am = \frac{[refl'(1) + \dots + refl'(n)]}{[ava'(1) + \dots + ava'(n)]} \quad (6.8)$$

but equation 6.6 above expands to:

$$am = [refl(1)/ava(1) + \dots + refl(n)/ava(n)] / Ar \quad (6.9)$$

which is not equal to expression 6.8 above.

To ensure that correct area averages of the albedo were calculated, values of the reflected and available flux were summed and averaged (after being area weighted) and the albedo evaluated in accordance with equation 6.8. Results are summarised below.

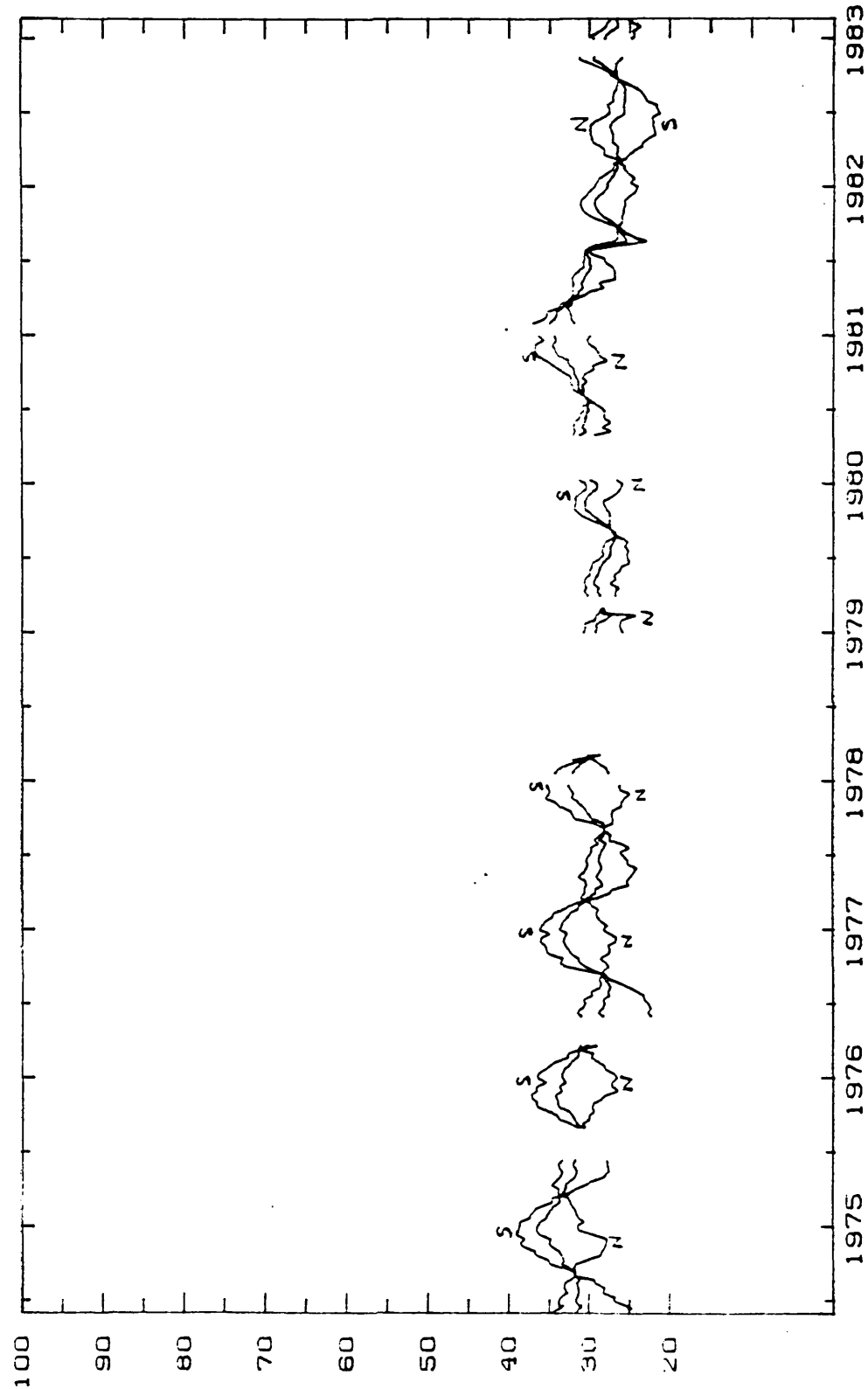


Figure 6.36. Hemispheric and global albedo.

As is seen from the figure the average global albedo is variable between 27 and 35% and is variable from year to year. Its average value for the whole period is 31%, this agrees fairly well with published data eg (Stephens 1981). Albedo was calculated for all pixels where the available Solar flux was greater than 50 W/m^2 . These areas of the globe that had available flux $< 50 \text{ W/m}^2$ were dark and were considered to contribute in only a very minor way to the global albedo. To test this assumption the level at which the albedo was calculated and included in the average was changed to 5 W/m^2 . The change in the global average albedo for the Southern Hemisphere (the only one there was any noticeable difference for) was from 30.1% to 30.2%.

This would indicate that although the albedo for the snow ice surface is very high because of the low light levels during winter in regions with low to zero Solar input ($< 50 \text{ W/m}^2$) the effect on the albedo is almost unobservable.

6.5 THE NET RADIATION BUDGET

Measurements of the other parameters of interest such as net flux can be obtained from the data set available. For example the net flux can be found using:

$$\text{net-in} = - ((\text{OLRd} + \text{OLRn}) / 2) + \text{abs} \quad (6.10)$$

where

net-in is the net ingoing flux. (In W/m^2)

OLRd is the daytime outgoing longwave flux. (In W/m^2)

OLRn is the night-time outgoing longwave flux. (In W/m^2)

abs is the absorbed flux. (In W/m^2)

and hence the heat budget for the year over a hemisphere or the whole globe can found, a climatological parameter of great importance. This parameter is plotted over the entire globe for a period of the dataset. The overriding factor to bear in mind when interpreting this plot (See figure 6.37) is that the net flux calculated at any time will be biased to the state of the diurnal cycle for the time of the satellite passage. For this reason (because polar orbiters do not integrate over one diurnal cycle) the variation in net flux during a year is actually partly a measure of the change in the diurnal cycle throughout the year. Thus from figure 6.37 we see that during summer in the Southern Hemisphere (dotted line) the diurnal cycle at the satellite pass time is on average at $+40 \text{ W/m}^2$, while in winter it is at approximately -80 W/m^2 . The seasonal variation in net flux is larger for the Southern Hemisphere than for the Northern Hemisphere. Thus the global net flux (central line) follows the Southern Hemisphere trend more closely (Northern and Southern Hemisphere fluxes are 6 months out of phase). The Southern Hemisphere variation is larger because of the relative similarity in magnitude of absorbed fluxes as opposed to the large differences in OLR fluxes (compare figures 6.4 and figure 6.5). The upward trend in fluxes is due to the changes in satellite equator crossing times.

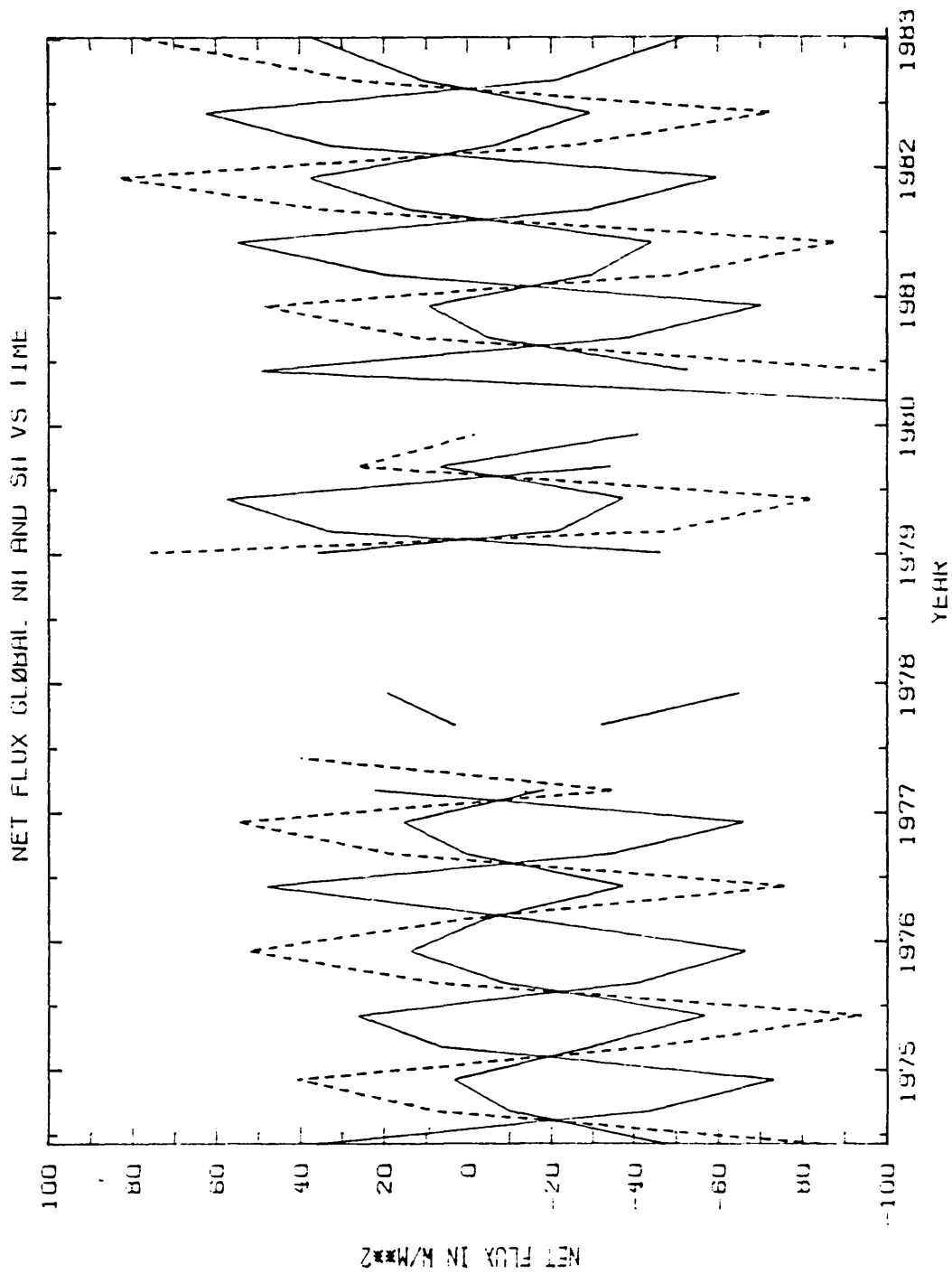


Figure 6.37. Net flux for the Northern Hemisphere Southern Hemisphere and the globe.

6.6 FOURIER ANALYSIS

Fourier analysis involves the determination of a dependant variable (in this case OLR) in terms of sines and cosines. The independent variable in this case is time. Other techniques exist which use a different basis set of orthogonal functions, but they all evaluate the coefficients of the basis set required to reconstruct the function being studied. In situations where the system forcing function is known to be sinusoidal (or cosinusoidal) such as the analysis of musical tones this technique can be extremely useful. However in a complex situation such as the one being studied here the components of the resulting time dependant functions may not resolve into identifiable sinusoidal elements, or worse may resolve into spurious frequencies which merely indicate the non-sinusoidal nature of the problem. That is the results are generally difficult to interpret unless specified peaks in the spectrum can be shown to have some physical significance. It is undoubtedly the case that a time series analysis of the data would indeed show a peak at a frequency of one year, the annual cycle, but would a peak at three weeks (one-sixteenth of a year) be meaningful?

The data used is available in quantity and of high enough quality to merit a Fourier analysis. There are enough cycles in the nine year period to indicate the dominant periods over which changes occur in the atmosphere.

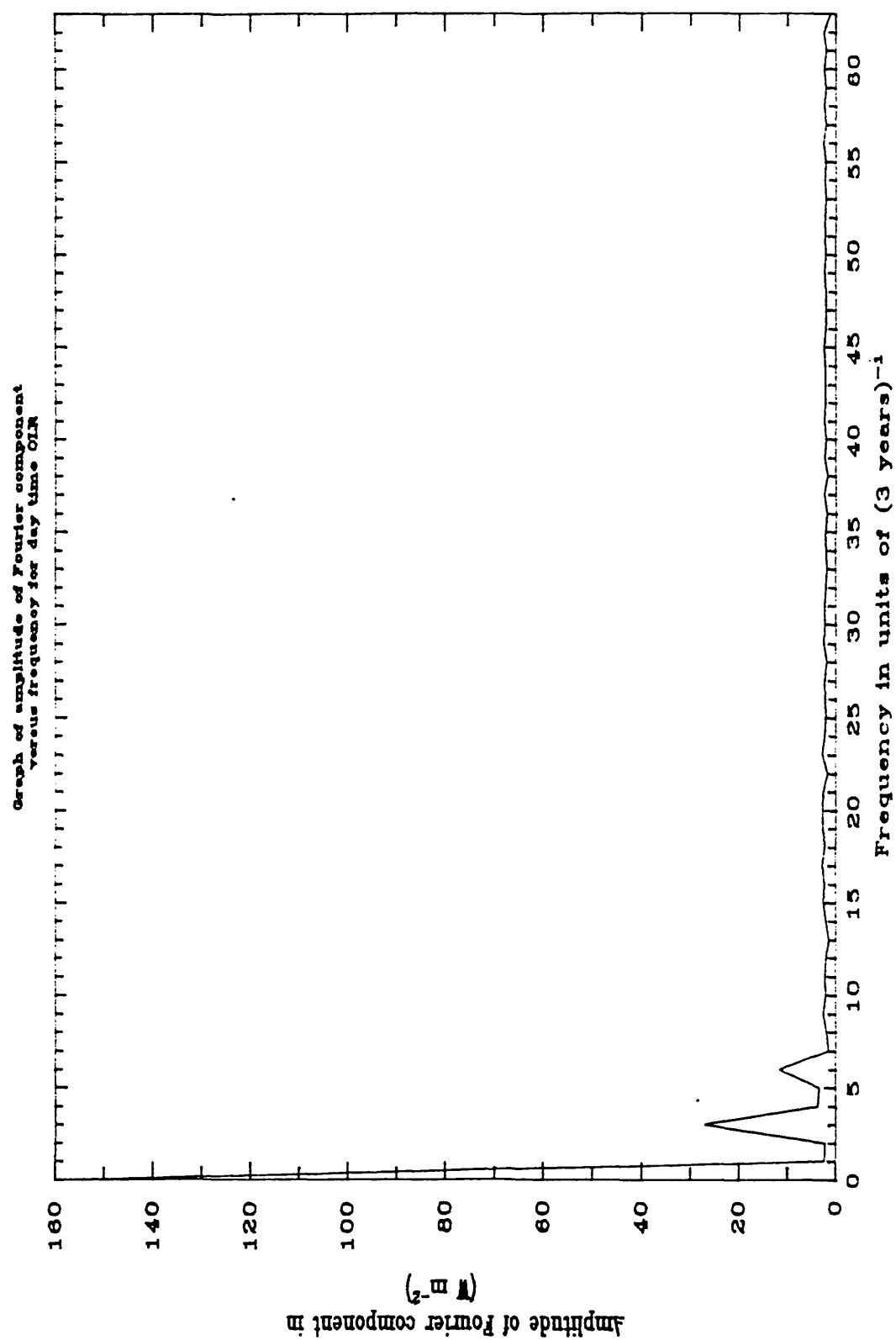


Figure 6.38. The results of a Fourier analysis.

An example analysis was carried out on a test data set (See figure 6.38) The peak at frequency zero accounts for the steady state background mean flux about which the annual cycle oscillates. It is approximately 150 Watts per metre squared in this case. Care must be taken when using this form of analysis to ensure that a whole number of yearly cycles were included. Spurious effects can also be obtained by attempting to fit Fourier spectra to data sets with large gaps if the computer program that is being used is a Fast Fourier Transform (FFT) type. Because of these two restrictions on the input data set two periods were chosen one from day 1 to 1096, a 3 year period and another three year period from day 1680 to 2776. (Day 1 is defined as the first of June 1974). The yearly cycle is shown by the peak at 3 per 3 years frequency. The only other definite peak occurs at 6 per 3 years (6 monthly) and has an amplitude of about 15 W/m**2. A reconstruction of the wave is seen in figure 6.39.

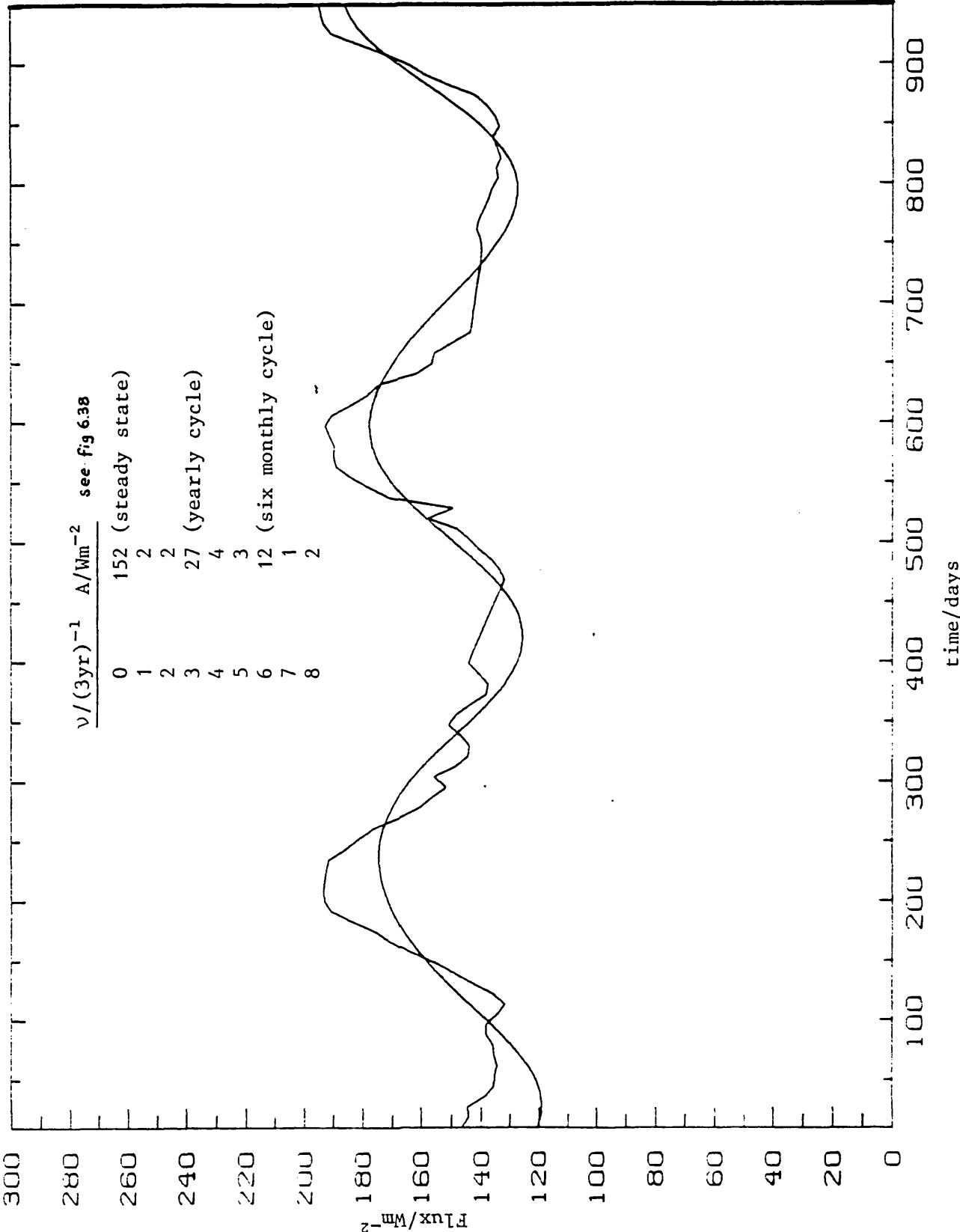


Figure 6.39. Reconstructed wave form.

It must be borne in mind that even though figure 6.38 indicates a six monthly cycle this could merely be an artefact of the Fourier analysis and have no physical significance. However the Fourier analysis carried out is by no means exhaustive. A complete study of Fourier analysis of this data would constitute a major project in itself.

CHAPTER 7

CLOUD AND ICE AREA

7.1 DETERMINATION OF CLOUD AMOUNTS

Determination of cloud cover is important because clouds are a significant element in the radiation budget regime of the Earth-atmosphere system. A major program, the International Satellite Cloud Climatology Project (ISCCP) has been set up to determine a global cloud climatology using satellite techniques. There are currently three basic cloud analysis techniques. They are threshold statistical and radiative transfer techniques (WMO, 1982).

Threshold techniques generally divide IR imagery into regions, such as low, middle and high level cloud. The value of the threshold is sometimes not fixed and depends to some extent on the shape of the histogram. This brings us on to statistical techniques which can work with histograms (as mentioned above) or use spatial frequency information derived from the image. While statistical techniques are more 'intelligent' they pay the price of increased computational overheads. With increasing

statistical complexity more calculations have to be carried out per pixel classified. Radiative transfer techniques make the assumption that the flux values associated with any measurement are uniquely associated with particular cloud amounts of the scene as long as the vertical temperature structure is known approximately. Because of the complexity of solving the radiative transfer problem this method of attack is very time consuming indeed.

Both techniques that are used here are statistical in nature and depend on the natural variability of the atmosphere over a certain period. By assuming that over a reasonably large area both fully cloud covered and cloud free pixels are viewed cloud amounts can be determined. This assumption is used in one of the techniques used here. (This is clearly a poor assumption as the graphs 7.1 and 7.2 show). This is because cloud free or cloud filled areas can cover larger areas than 5 by 5 pixels. In cases where albedo can be measured a more reliable method is used (ie when infra-red and visible fluxes are available). An albedo of 1 is assumed to represent 100% cloud cover and when the albedo is equal to the surface albedo 0% cloud cover is assumed. Cloud amounts between these cases are calculated simply on a pro rata basis.

7.1.1 Cloud Area From Infra-red Fluxes.

Assuming the simple relationship between measured flux and cloud amount for the visible and infra-red regions of the spectrum.

$$I(k) = x * A(k) + CI \quad (7.2)$$

where:

$A(k)$ is the cloud amount in region k . (No units.)

$I(k)$ is the Infra-Red flux in region k . (In W/m^{**2})

x is a constant. (In W/m^{**2})

CI is a constant for the Infra-Red channel. (In W/m^{**2})

By making further assumptions, an estimate of cloud amount from only the infra-red flux can be made (or only the visible flux). The two assumptions required are; one, that within a reasonably sized area there are representatives of both the fully cloud covered and cloud free pixels. Let M_i and M_a , be the minimum and maximum flux values in the regions of interest i and a respectively. Hence for region i , and a ,

$$I(i) = x * (M_i) + CI \quad (7.3)$$

and

$$I(a) = x * (M_a) + CI \quad (7.4)$$

Subtracting one from the other gives the result,

$$I(i) - I(a) = x * (M_i - M_a) \quad (7.5)$$

Solving for x

$$x = [I(i) - I(a)] / [M_i - M_a] \quad (7.6)$$

Solving for CI

$$CI = I(i) - M_i [(I(i) - I(a)) / (M_i - M_a)] \quad (7.7)$$

substituting for x and CI in the equation for I(k) , (7.2) and solving for A(k).

$$A(k) = \frac{[M_i (I(k) - I(a)) - M_a (I(k) - I(i))]}{(I(i) - I(a))} \quad (7.8)$$

The determination of M_a and M_i is crucial in deriving the cloud amounts from this formula. Most authors make the simplest assumption that $M_a=1$ and $M_i=0$ and thus obtain the formula:

$$A(k) = (I(i) - I(k)) / (I(i) - I(a)) \quad (7.9)$$

The data was first used on a daily temporal scale to check the difference between the daily and ten day mean calculations. Results indicated that there was very little difference in the range of cloud amounts for these periods, because the size of area covered by the pixels was so large. M_a and M_i are calculated by looking at a 5 by 5 box of pixels centred on the pixel of interest. The values of M_a and M_i are selected from the maximum and minimum from the 25 pixels. This monospectral technique was only used when both channels were not available.

7.1.2 Cloud Area From Visible And IR Fluxes.

Over a period of about a year determination of the maximum measured and minimum measured albedo was made on a seasonal timescale. A period of a year was chosen because this was assumed to be a long enough to ensure that every pixel was cloud free at some time. Having determined these conditions it is a simple matter to determine the albedo at any point and time using the absorbed and available Solar fluxes at ten day intervals. By using the assumption that for any particular surface type and illumination condition the albedo of a scene is directly

proportional to the area of the scene covered in cloud, accurate estimates of cloud cover can be made. Most cloud amounts derived here were made using the above method. (Using the formula 7.10).

$$A(k) = 100 * a(k) / [1 - Sa(k)] \quad (7.10)$$

where

$A(k)$ is the cloud amount in pixel k .

$a(k)$ is the albedo for pixel k .

$Sa(k)$ is the surface albedo for pixel k .

both a and Sa are measured from 0.0 to 1.0 but A is measured as a percentage. This method does not rely on the assumption made in section 1.1 but has a somewhat less severe restriction that over a year any region will have had at some time the surface visible from the polar orbiter.

7.1.3 Discussion Of Errors

While the above mono-spectral technique is simple to use, it must be borne in mind that the assumptions made in deriving the cloud amounts do not hold in all cases.

Among the problems that arise involve the values of Ma and Mi which are not the same for every point on the globe nor are they constant for any particular location over time. Further problems are possible because of the variation of the relationship between the outgoing flux and the cloud amount from area to area. The most serious problems arise over ice and snow. This is because over these cold surfaces the distribution of brightness temperatures is inadequate and makes the estimation of

cloud amount inaccurate. In extreme circumstances, when the surface appears colder than the cloud, as may happen in Antarctica, the cloudy pixels will be classed as cloud free and the snow-ice surface will be classed as cloud filled! This problem will arise for both methods used here over snow, ice and other cold surfaces.

For the monospectral method by choosing a 5 by 5 pixel area one is forced to use the assumption that within that area there are cloud classes distributed over the range M_a to M_i . While this may be true in a large number of cases there will clearly be some situations, perhaps when a large area is completely cloud covered, when estimates of cloud area using this technique will be seriously in error. This can be avoided to some extent by choosing larger areas for this statistical technique. However this approach comes up against two serious problems. 1) The time taken for the calculation of the central pixel cloud amount increases as the square of the size of the box in pixels containing the area. Larger than 5 by 5 boxes were not used for this reason, and that increases by a modest amount to 6 by 6 or 7 by 7 would not have significantly improved the situations where 5 by 5 boxes were completely cloud filled, because in these situations much larger areas than 8 by 8 areas are filled. (For example see figures 6.8 to 6.15). However some improvement should have been observed at the cost of much increased computer time usage. 2) By increasing the area of analysis the assumption is implicit that the physical structure of the surface and atmosphere is unchanging in nature at all the pixel locations. In some situations sea and land pixels which have very different surface radiative properties, were used together in the same box. This will cause land/cloud areas to be underestimated in cloud amount and sea/cloud areas to be overestimated. If the area of the box is increased the number of cases when overestimates/underestimates of this type occurred, would increase. In this study all 5 by 5 group pixels not showing

sufficient variation in the flux amounts were not used to estimate cloud.

In conclusion in most cases the estimates were fairly accurate but situations can occur when these will be grossly in error (by up to 50%). To make some independent assessment of the accuracy of these measurements comparisons with data supplied by the British Antarctic survey were made. Cloud amount from ground truth measurements were collected for an extended period from 1974 to 1980 at two stations Halley Bay (Latitude=-75.5 degrees, Longitude=26.7 degrees West) and South Georgia (Latitude=-54.3 degrees, Longitude= 30 degrees West). Comparisons of the Halley Bay data are made in figure 7.1 and 7.2. The BAS measurements were supplied for this study covering roughly the period June 1974 to June 1980. The original data, supplied at about 10 day intervals was binned over 11 data points. The NOAA derived values were binned over 5 data points. This was done to obtain the best fit over the dataset period (to compensate for the different areas of view of the two systems). Comparison of these data is made difficult by the inherent differences in the data sources. The one is made by ground observation in octas (scaled for this study) and represent a limited area, and to some extent the result depends on the observer (strictly for accurate comparisons the solid angles of the two observers are quite different an effect which should be considered, however in this situation there are sufficient other effects to make such an adjustment unnecessary). The satellite data is essentially a continuous distribution and is an average value over an area approximately 150 km**2 unlike the ground observer. Bearing in mind these differences it is not surprising that an exact fit is not obtained. Even so there are some striking similarities. In the period at the beginning of 1976 the curves match very well as is the case during most of the end of 1976 to the middle of 1977 and the middle of 1979. The results derived from the NOAA data here were made using both IR and visible derived data. In

regions where only IR data was used the comparisons were very much poorer.

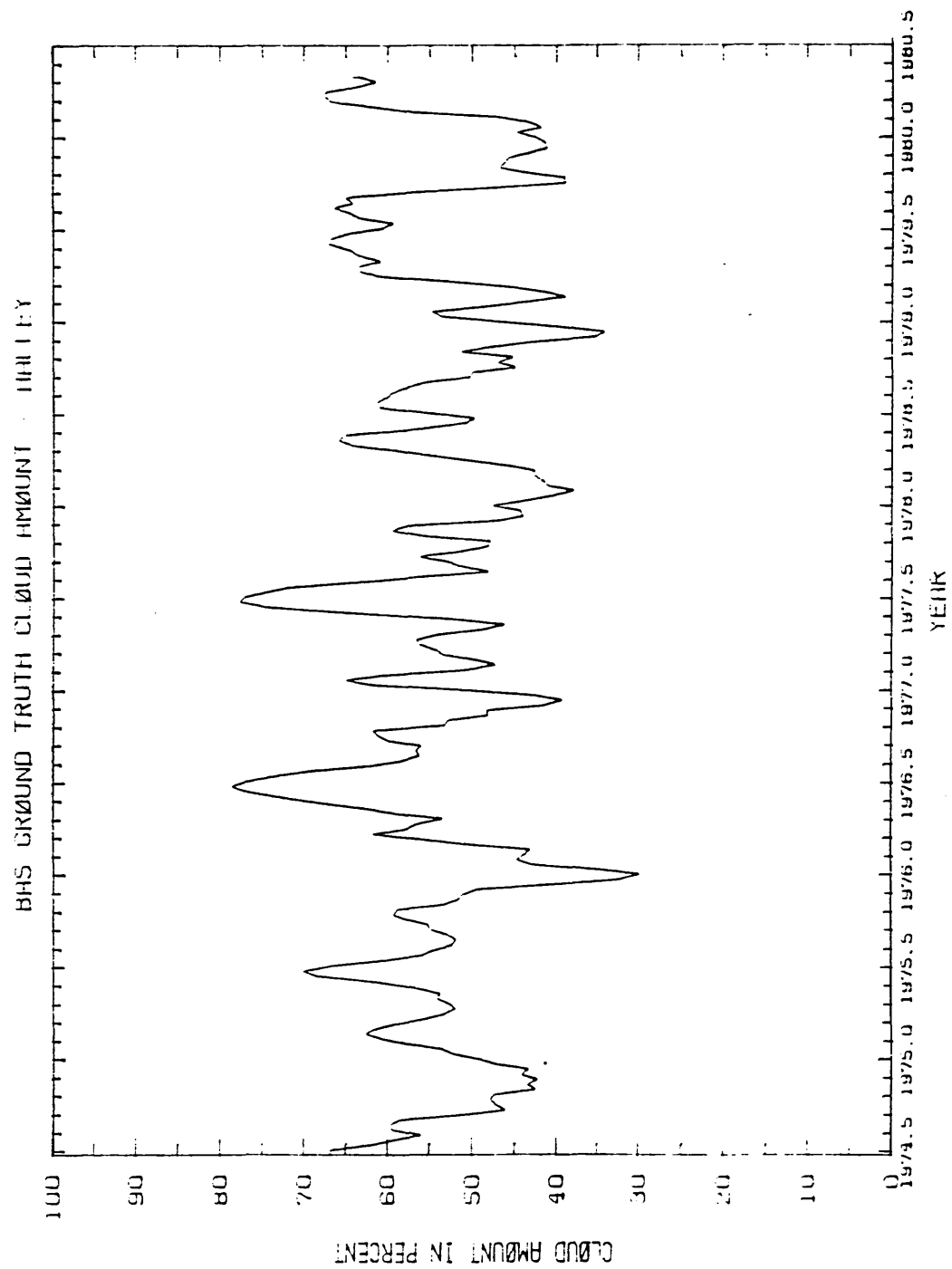


Figure 7.1. Cloud amount vs time for Halley Bay. BAS measurements.

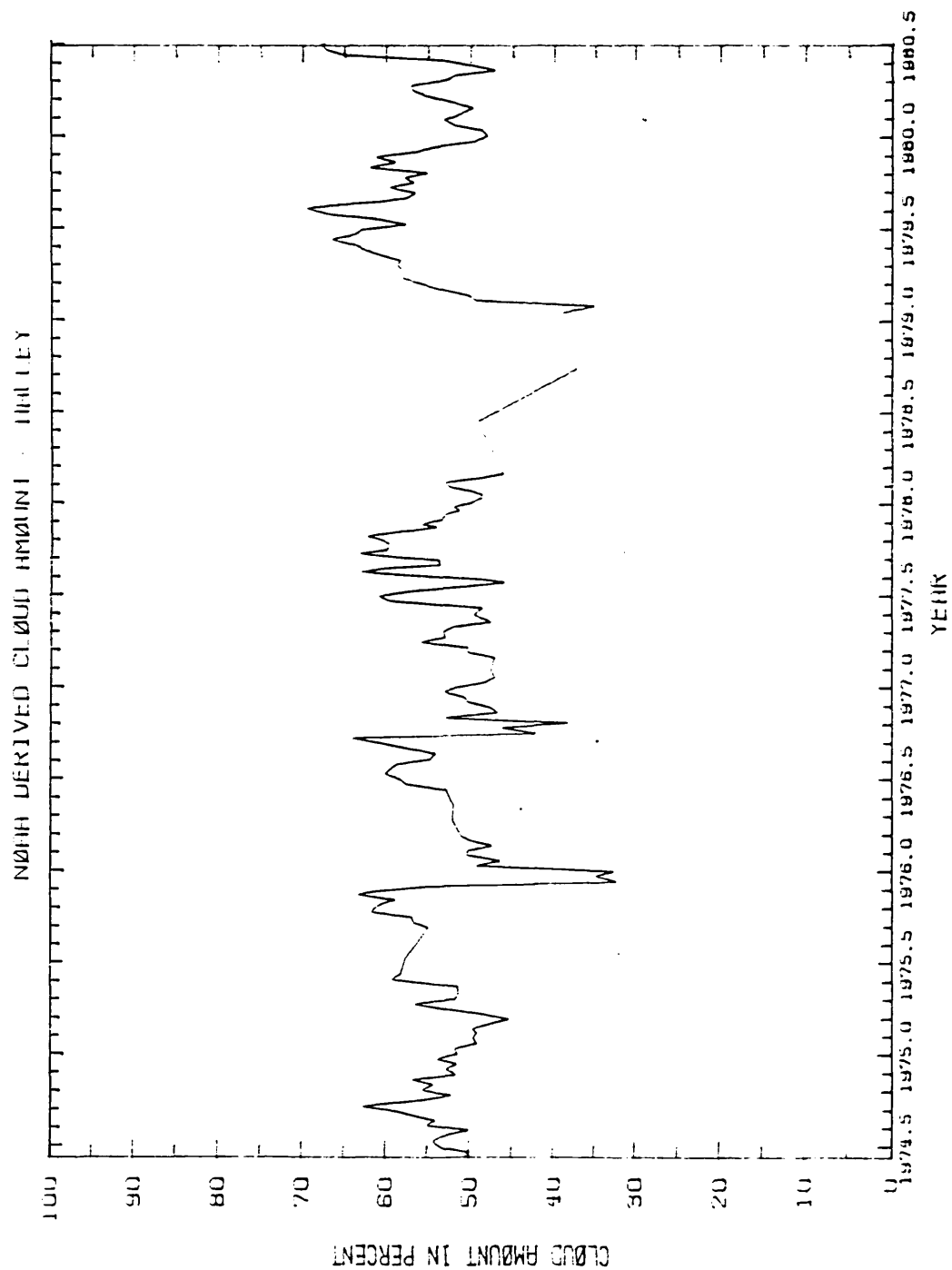


Figure 7.2. Cloud amount vs time for Halley Bay. NOAA derived.

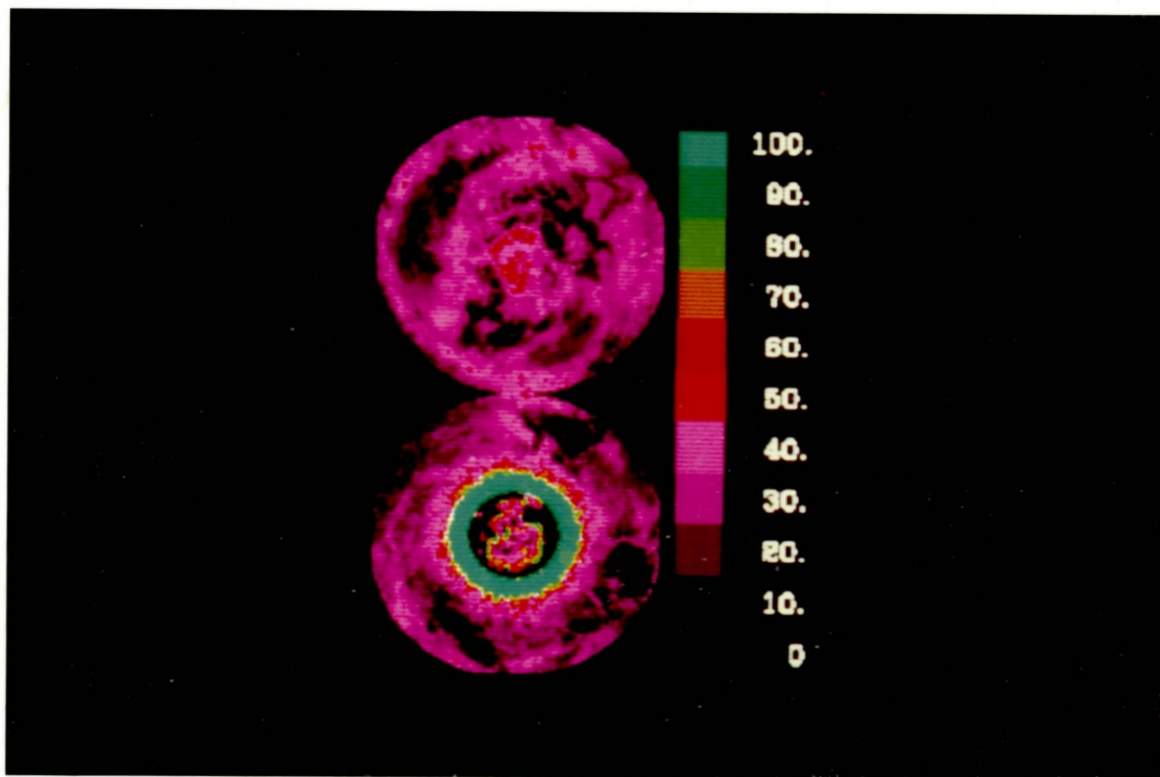


Figure 7.3. Example cloud images for 1980.

The results on a ten day mean period for the cloud image are quite instructive in describing the effects of the combination of these two algorithms. Since a 5 by 5 pixel area would be required in cases where both absorbed and OLR data are not available there is a region around the image in which cloud amounts are set to zero. Once we are within this region the bispectral technique is being used and the derived cloud areas are quite accurate. Near the south pole a large area has been designated as fully cloud covered, this is not unusual in the Southern Hemisphere. Inside this bright region however zero cloud amounts are indicated. This is because the bispectral technique cannot be used (there is insufficient solar input) and the mono-spectral method does not evaluate cloud amounts because there is insufficient variation in fluxes for a meaningful answer. Once the continental area is reached however the infra-red fluxes vary sufficiently so that the monospectral technique attempts some classification. This is why the first non-zero values appear at the coastline of Antarctica.

7.2 ICE AREA CALCULATIONS

Ice area calculations usually involve human operators who analyse high resolution images and through a combination of experience and skill deduce the position of the ice edge. In classification techniques however an automatic procedure is developed to deduce the nature of the pixel being observed. The ideal spectral interval for ice classification is in the microwave at 1.55 cm. In this region of the spectrum ice has an albedo of 0.84 to 0.95 while water at 0 degrees centigrade has an albedo of 0.4. Work done by Zwally (1981, 1983) on detecting ice edge and hence ice area was done using the electronically scanning microwave radiometer (ESMR) with a resolution of about 30 km. Comparisons with the work here were done for the period 1973 - 1976. For this study automatic image classification is carried out using an algorithm based on histogram information derived from NOAA satellite imagery. Since visible information is not available throughout the year and is especially poor during the period of maximum ice extent (August to September) the infra-red channel data was used. Using the IR channel therefore a histogram of the pixel brightness population is made for a region corresponding to the maximum ice extent. Because ice and sea have different brightness temperatures and also because sea-ice is a more permanent feature than cloud, the histogram shows definite regions corresponding to different flux populations. Because of the nature of the histogram the period over which the mean is taken can effect the histogram distribution observed. This is because a significant part of the histogram is polluted by clouds. The effect these clouds have depends on the period of the mean involved. If it is a long period mean then the clouds will appear in more pixels and will therefore make the two main distributions broader and flatter, thus bringing them closer together. In short term means however clouds will be more likely to populate their own hump in the histogram.

The colder population represents the ice and sea-ice while the much larger population corresponds to the 'warm' sea. (Refer to figure 7.4 to 7.7). Each of these figures shows the two hump structure indicating that there are two distinct regions in the images in question. Comparisons of Northern Hemisphere summer (Figure 7.5) and Northern Hemisphere winter (figure 7.7) show the variation at the lower flux range from 120 W/m^2 in summer to 150 W/m^2 in winter. By segmenting the images at the boundary of these two distributions pixels above 160 W/m^2 can be classified as not-ice pixels while those below can be classified as ice pixels. To calibrate the algorithm the threshold was adjusted until the summer ice area was 14 million square kilometres (the area of the Antarctic's permanent ice sheet). While this scheme is simple it compares well with the Zwally data. A graph of ice area against time for the South polar region is shown in figure 7.8. Values are consistently 20% overestimated during Southern Hemisphere winter and slightly underestimated during Southern Hemisphere summer.

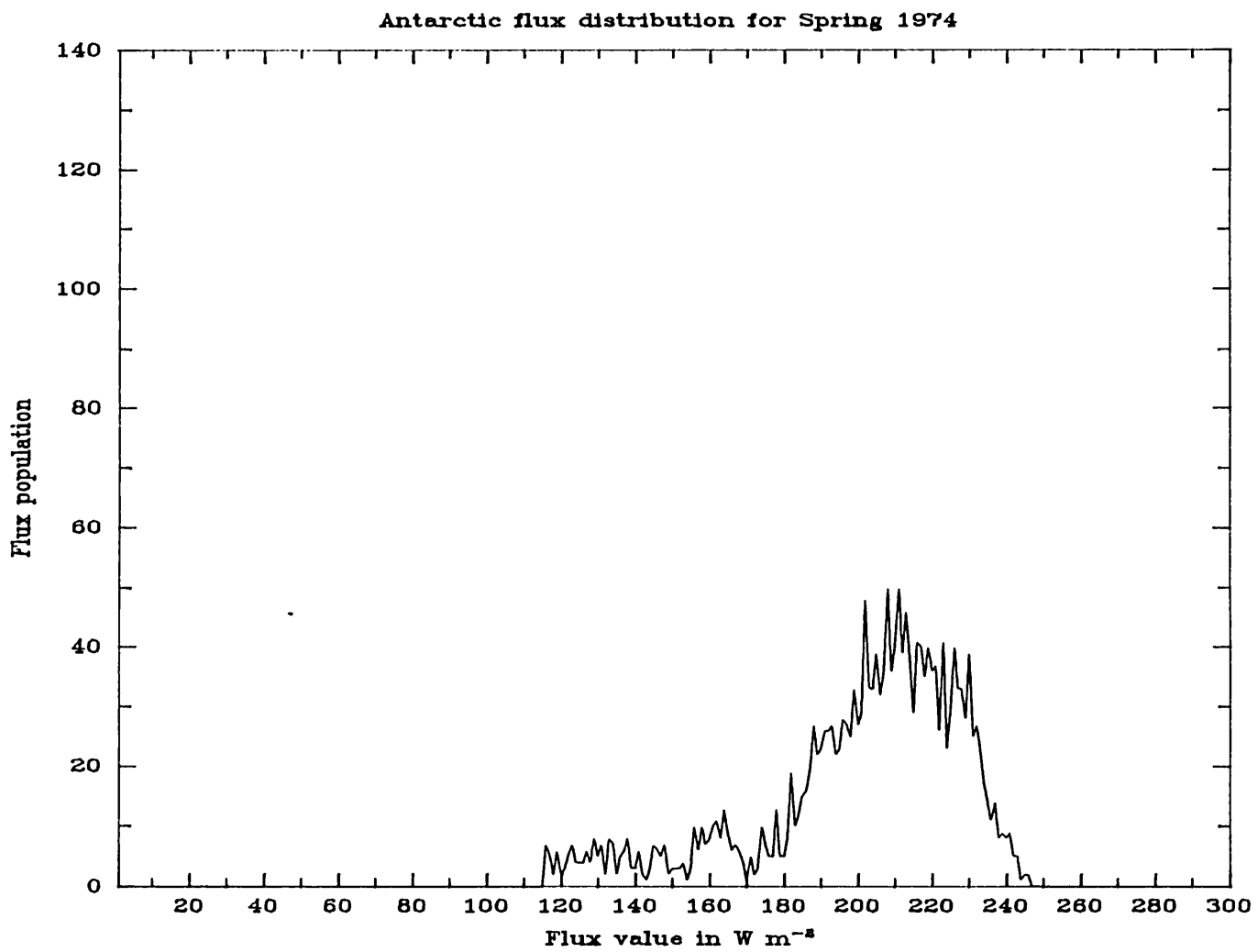


Figure 7.4. Spring histogram.

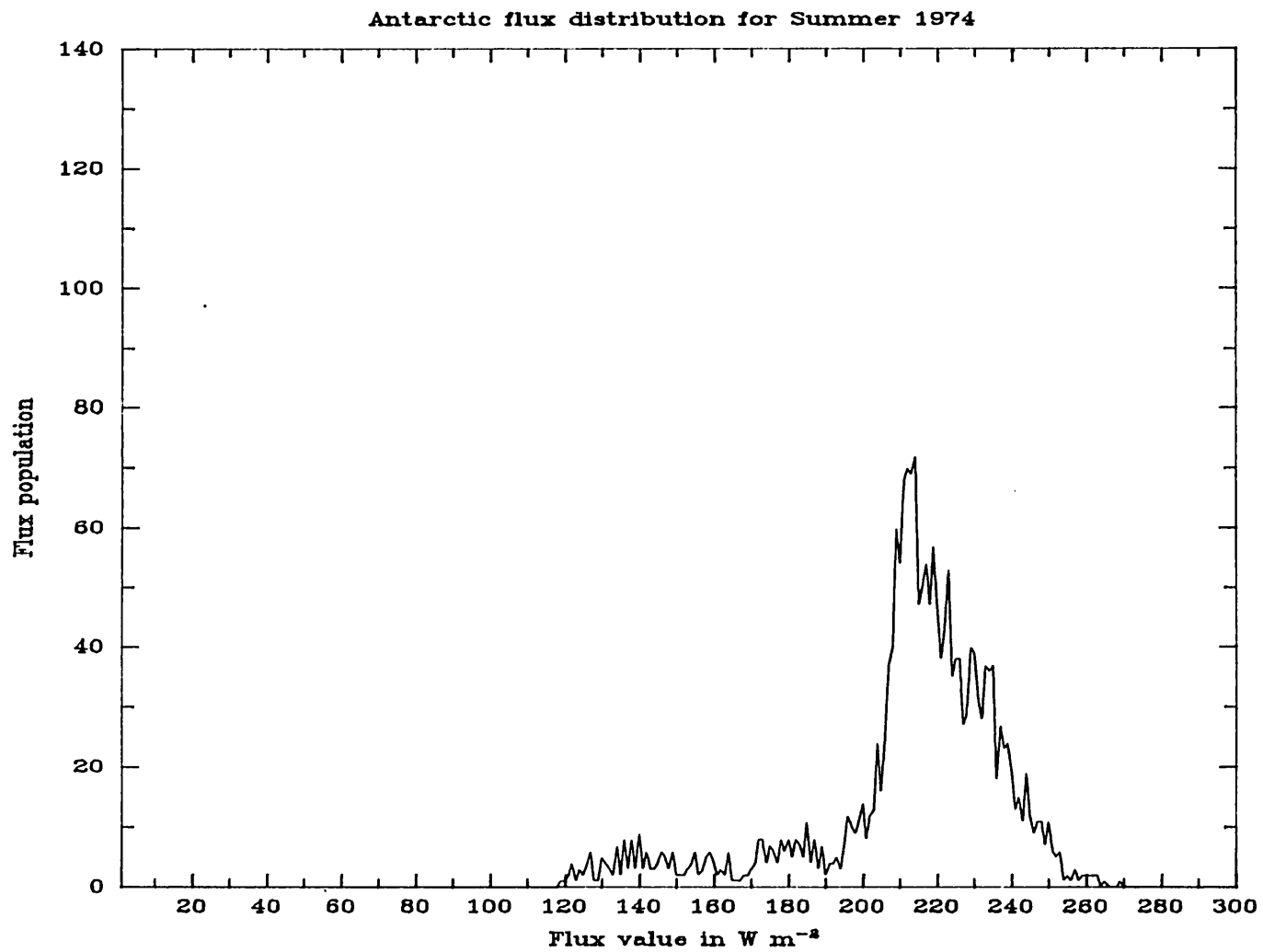


Figure 7.5. Summer histogram.

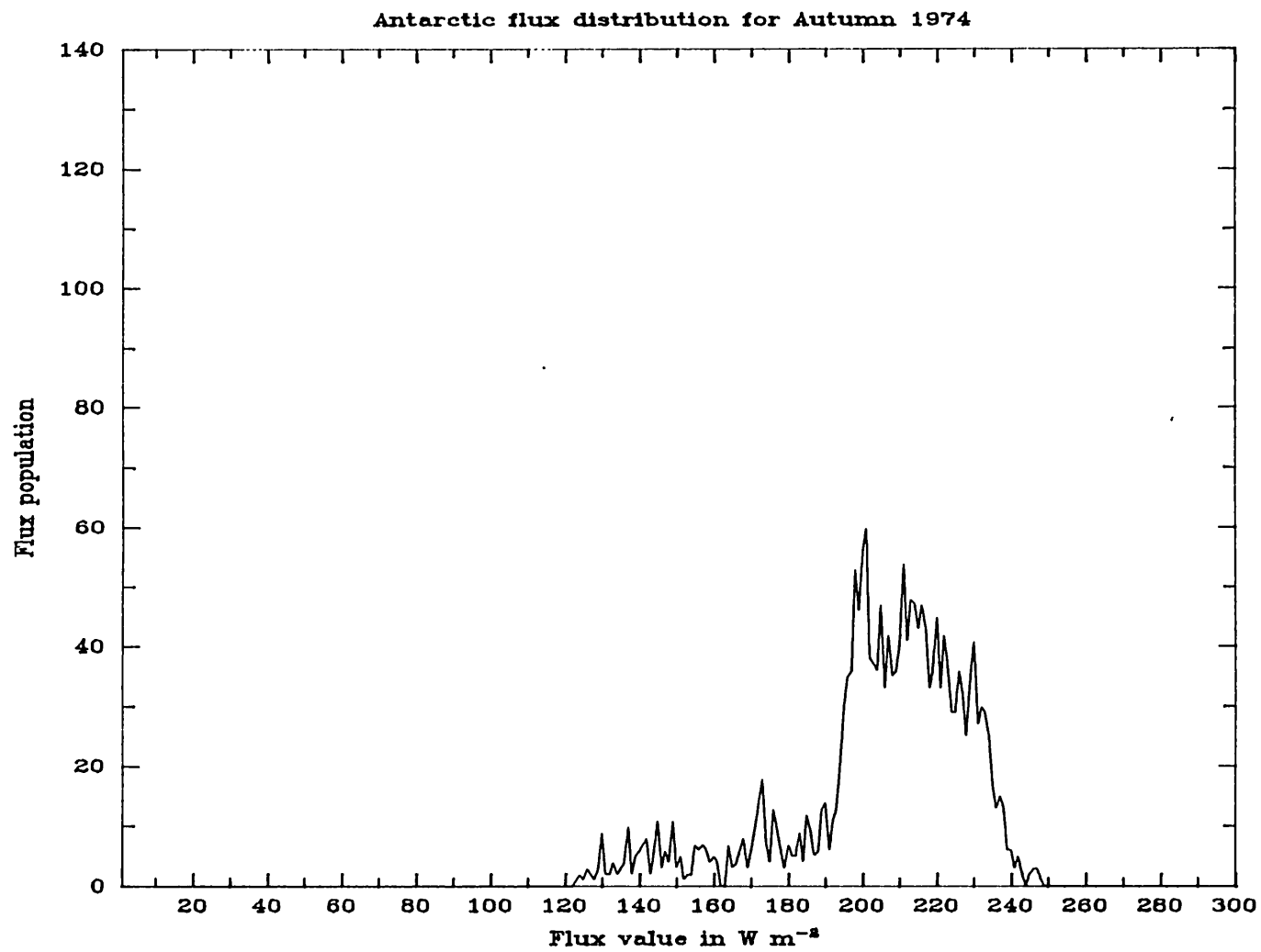


Figure 7.6. Autumn histogram.

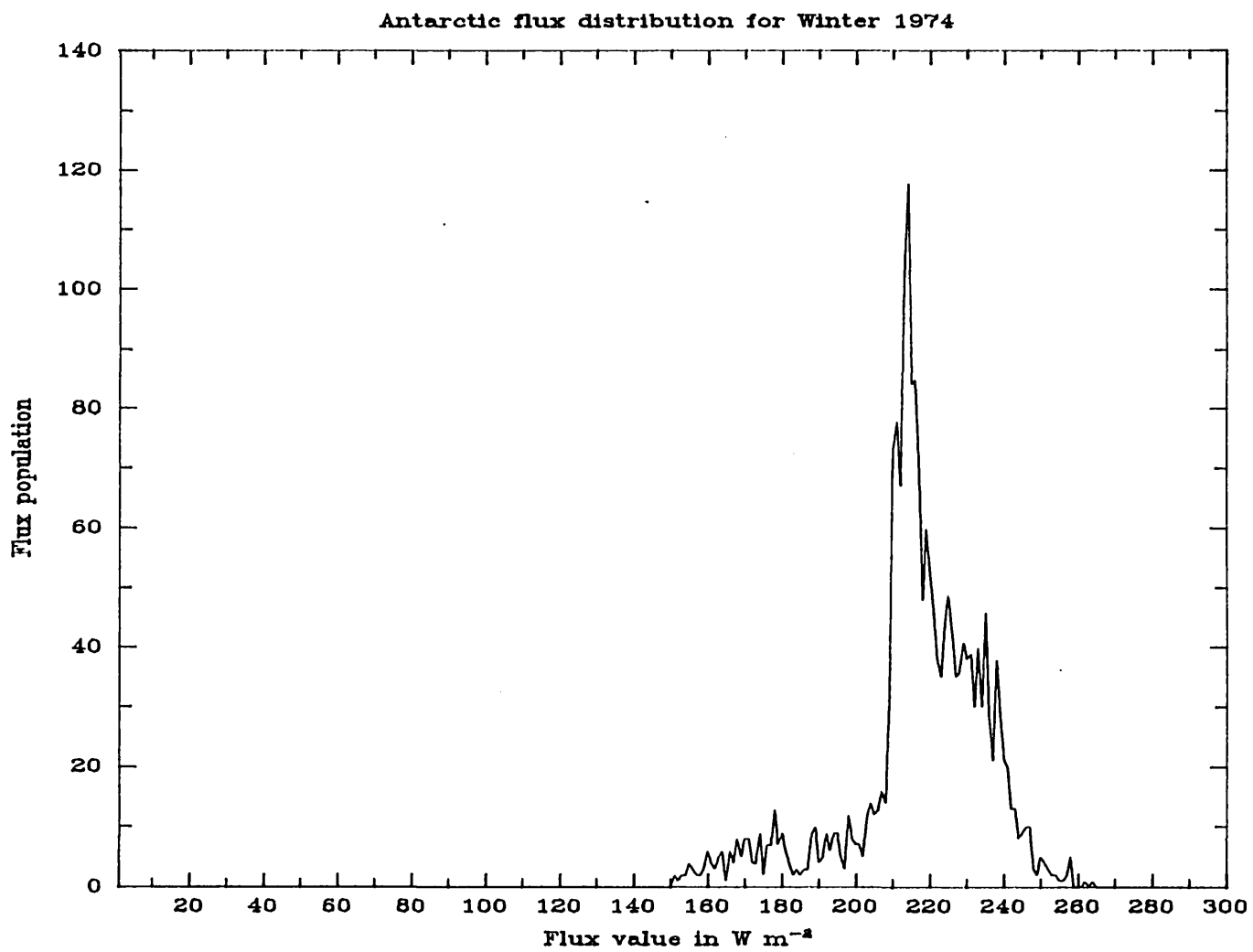


Figure 7.7. Winter histogram.

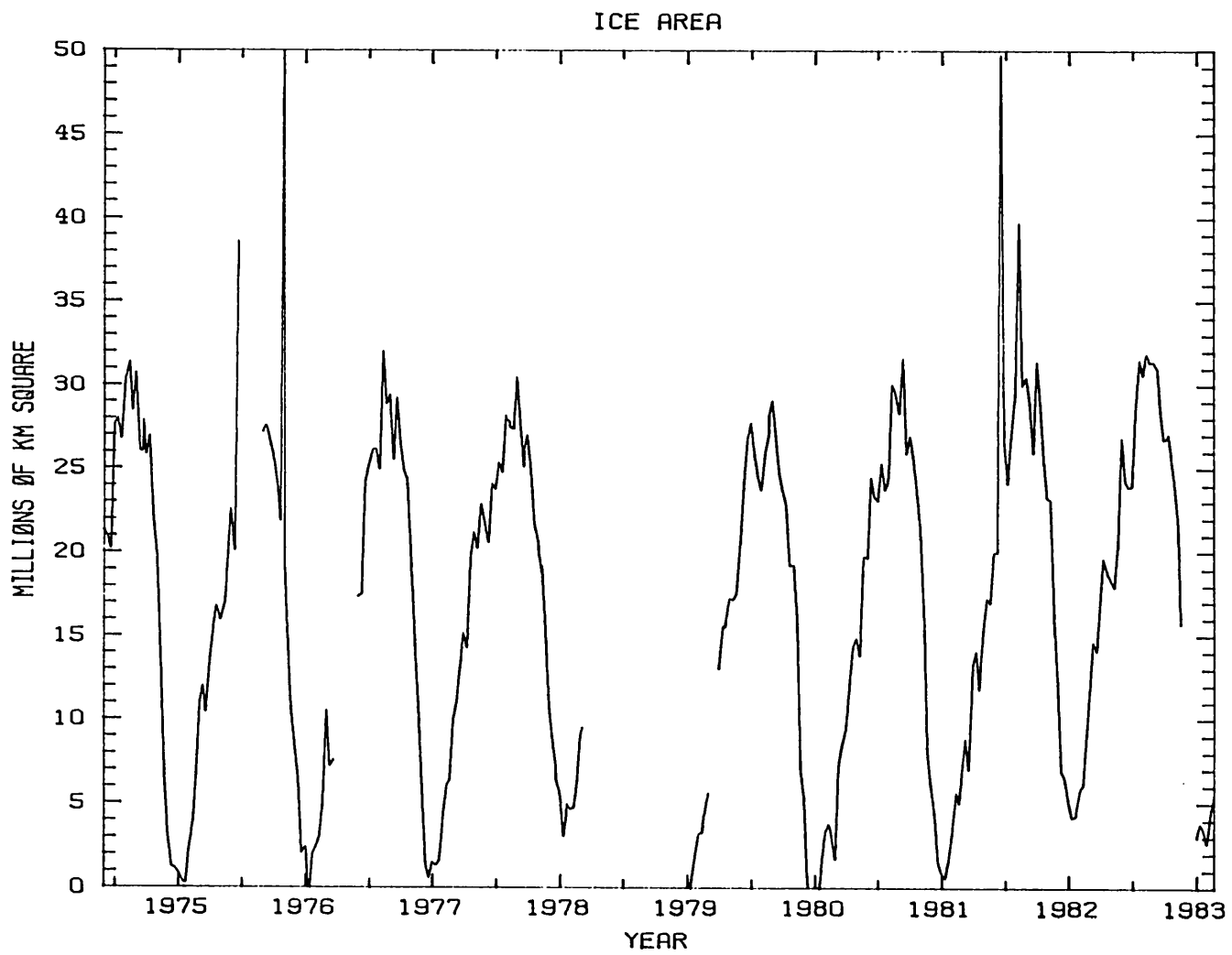


Figure 7.8. Ice area in SH vs time.

7.2.1 Discussion Of Errors

The errors associated with this threshold technique are caused by the fact that the area in question cannot be accurately described as consisting of only ice and not ice. (It is clear that the two major pixel classes will in fact almost touch in regions where ice is melting or sea ice is freezing). However to complicate matters all pixel images are large enough to contain mixtures of both these classes and the third cloud class. This will tend to smear the join between the major sea and ice classes and flatten the humps associated with these. The fixed threshold that was used for this ice classification was used because it gave superior results to techniques that had variable thresholds. While these methods were more sophisticated in that they searched for the neck between the two distinct distribution, this region of the histogram was sufficiently variable from image to image so that there was a large variation in estimated ice area in consecutive ten day periods. A fixed threshold is superior because it does not suffer from this problem but is poor because it does not adapt to the changing seasons (hence the under and overestimates mentioned earlier). It is conceivable that a more complex scheme for threshold determination will prove superior when the stability problem has been solved.

CHAPTER 8

TELECONNECTIONS

8.1 LCC ANALYSIS METHODOLOGY

The basis of lagged cross correlation analysis is the correlation coefficient between two time series. A correlation of +1 indicates a perfect correlation (the functions are identical) while a -1 indicates perfect anti-correlation. Lagging the Y time series is allowed either forward in time (positive lag) or back in time (negative lag).

The correlation factor is defined as follows: Given two time series $X_1, X_2, \dots, X_n$ and $Y_1, Y_2, \dots, Y_n$ the cross correlation is calculated between X_t and lagged values of Y_t using equation 8.1.

$$R_{xy}(1) = \frac{\sum_{t=1}^{n-1} [(X(t) - X_m) (Y(t+1) - Y_m)]}{n S_x S_y} \quad (8.1)$$

where

$R_{xy}(1)$ Is the cross-correlation value between time series x and time series y with lag 1.

$X(t)$ is the general element of the time series.

X_m is the mean value of the time series.

1 is the lag used for the cross correlation.

n is the number of time steps.

S_x, S_y are the standard deviations of the two time series.

In the totally general case the solution to the objective lagged cross correlation of the time series of image data would result in output data greater than the input data. Consider the following. For a 125 by 250 image every point must be correlated with every other point, since any other procedure would imply some presupposition. If over the nine year period we consider lags of up to one year at temporal intervals of ten days then for each analysis (there can be more than one depending on which criterion you choose for correlation), there will be $L \times S \times T$ images generated. L is the number of lines and S is the number of samples T is the number of time lags considered. If both positive and negative lags are considered over a 2 year period at 10 day intervals then for any particular time, correlations will have to be carried out 145 times. (72 forward, 72 backward and plus one). In total this must be done every time in the nine years of data, so this gives a total of $125 \times 250 \times (145)$ which

is 4.5 million images. This situation is obviously ridiculous because it generates more data to analyse than the original data set! (This figure will be somewhat reduced by excluding redundant correlation attempts).

A number of alternatives are open to reduce the amount of output from this analysis. First of all the analysis does not have to concentrate on pixels but instead may use boxals (boxes of pixels) of say 5 by 5. This would reduce the output by a factor of 25. The reasoning behind such a simplification is simple. Pixels that are close together in space are also likely to be well correlated. While this is usually the case the fine grain of the original data is being sacrificed and this approach will not detect small areas which are locally correlated. However there seems no indication that this does occur in reality. All global teleconnections that have been investigated thus far have proved to be fairly large in scale (~ 100 km) and not very well localised (Kerr May 1982, Hahn December 1976, Rogers 1982). A second option is to reduce the temporal resolution of the analysis by using seasonal time steps instead of ten day intervals. This simplification would reduce the output by a factor of $145/17 = 8.5$. Again this has the problem that resolution is given up for reduced data output, this time in the temporal domain. Another approach is to specify the area of interest before doing the analysis. (For example see Ka-Ming Lau (1983)). In this case the data output will be reduced by a factor of 125×250 . This does still retain some degree of objectivity because the regions with which the chosen region are to be correlated are not chosen subjectively. Instead each point on the globe is tested for its time sequence correlation so that the output data is only T images, where T is the factor defined above.

8.1.1 Antarctic Teleconnections

The last approach described above was used for analysing the data used in this thesis, with the spatial grid equal to the pixel size and with seasonal time steps. The predefined region was Antarctica. An accurately aligned map was laid over the image and an area averaged time sequence for the Antarctic region was calculated. Using these simplifications the number of images generated by this analysis for the Antarctic region was only 17.

The parameter to be used for correlation was also very important as this would determine how easily strong correlations could be identified. The mean OLR flux itself would be a bad choice because the correlation signal would be swamped by the seasonal signal. In fact time series lagged forward or back by one year would be very strongly correlated in such a scheme. To take out this very strong seasonal signal and in fact any other strong signals that persist from year to year the mean yearly cycle was used as the basis for the calculation of an anomaly time series. In this scheme every point on the image has associated with it a time series lasting nine years that is the difference between the current flux and the long term mean flux for that part of the year. This is different to the scheme used by Ka-Ming Lau (1983) but is simpler to implement. The results are shown in figures 8.1 to 8.5.

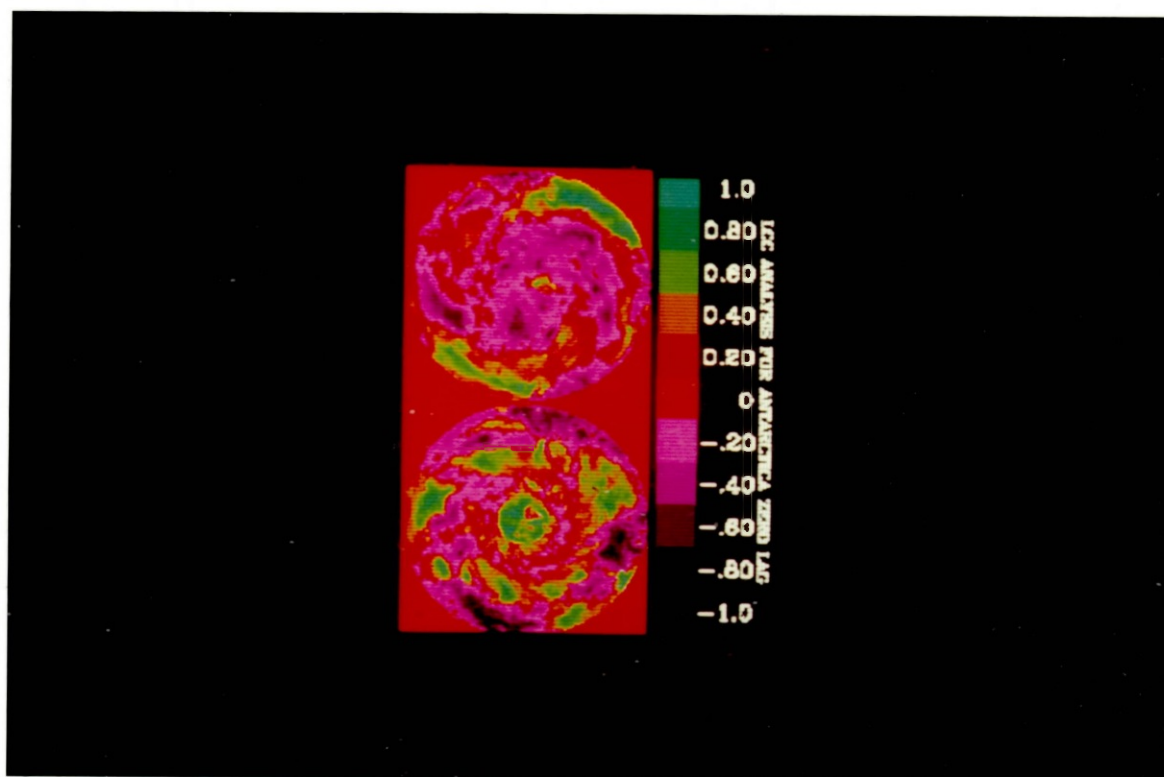


Figure 8.1. Correlation for lag zero.

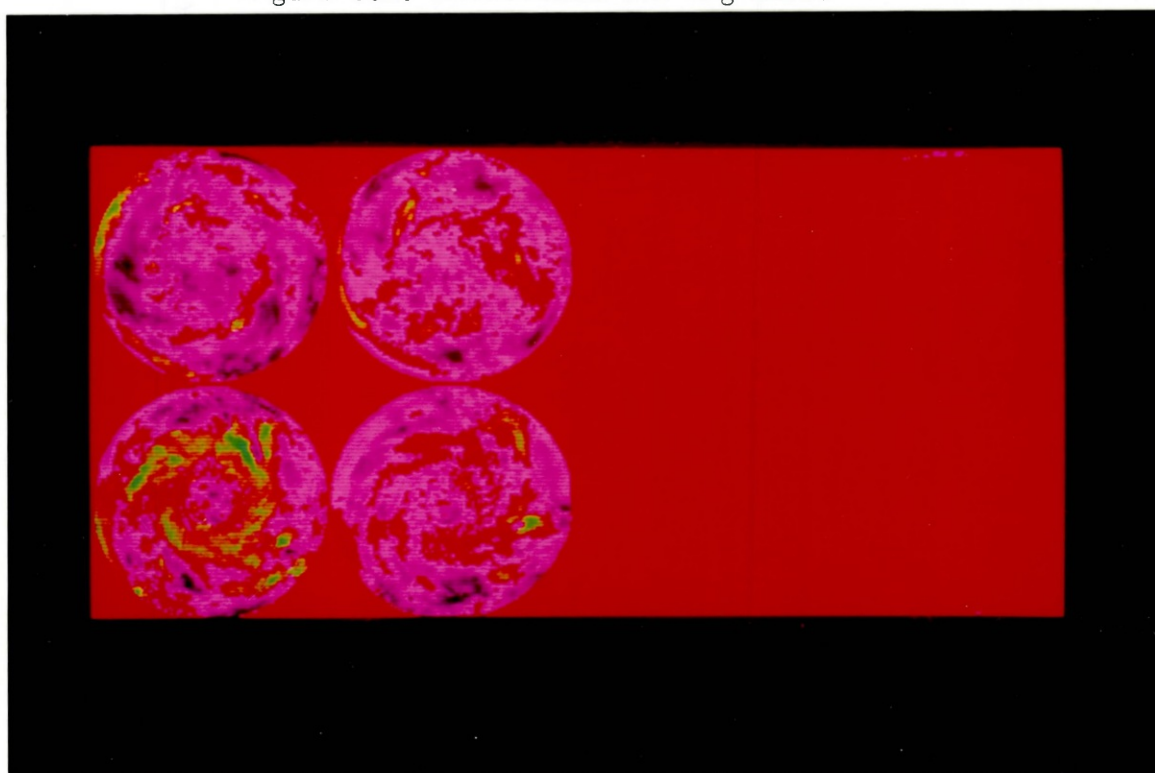


Figure 8.2. Correlation for lag plus 1 to plus 4.

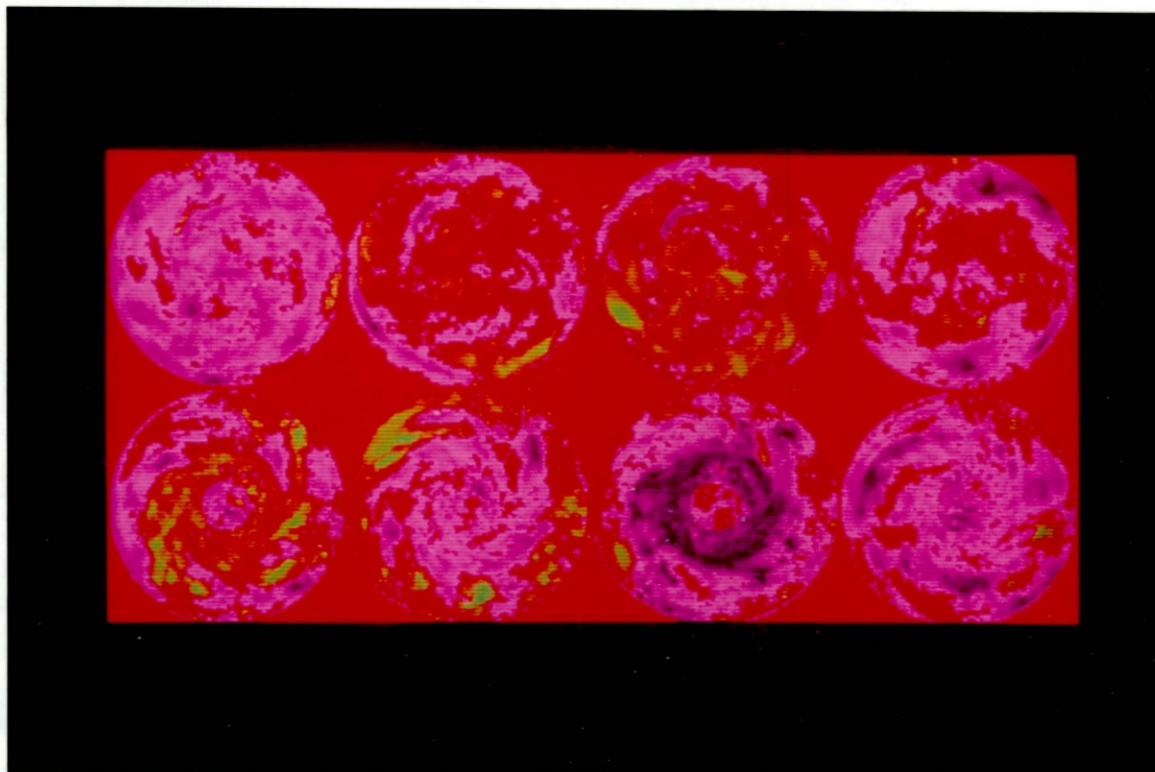


Figure 8.3. Correlation for lag minus 1 to minus 4.

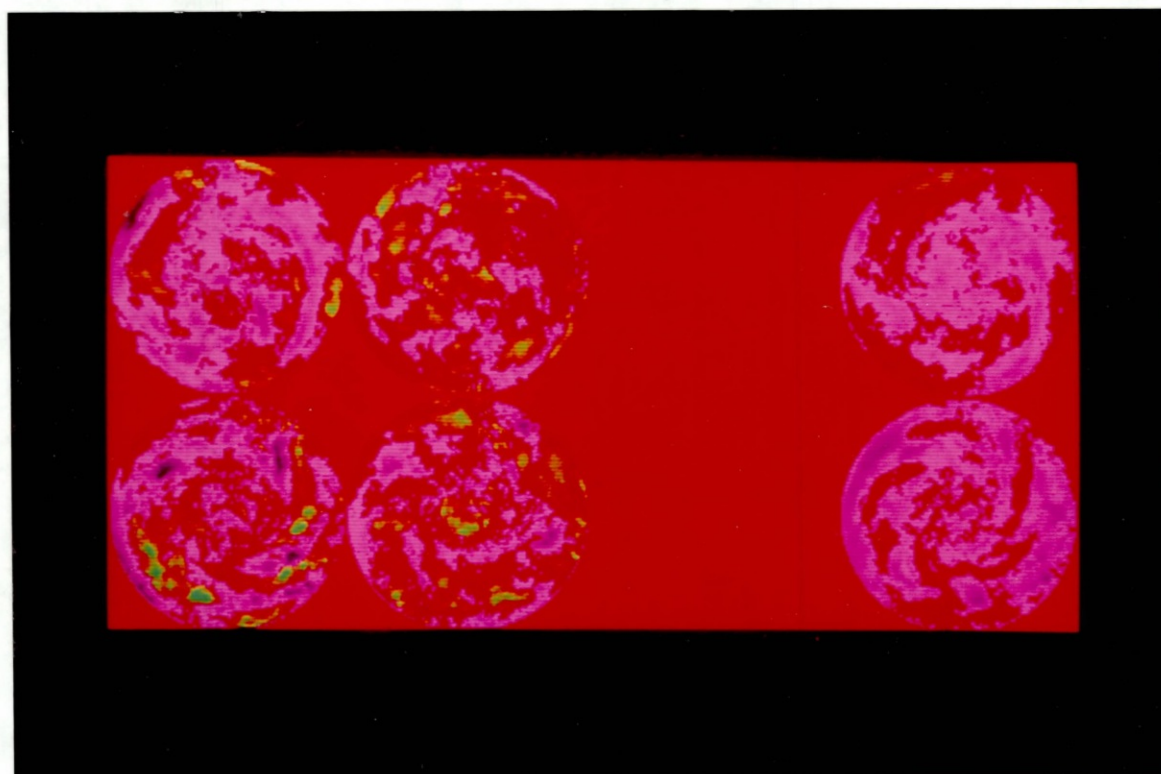


Figure 8.4. Correlation for plus 5 to plus 8.

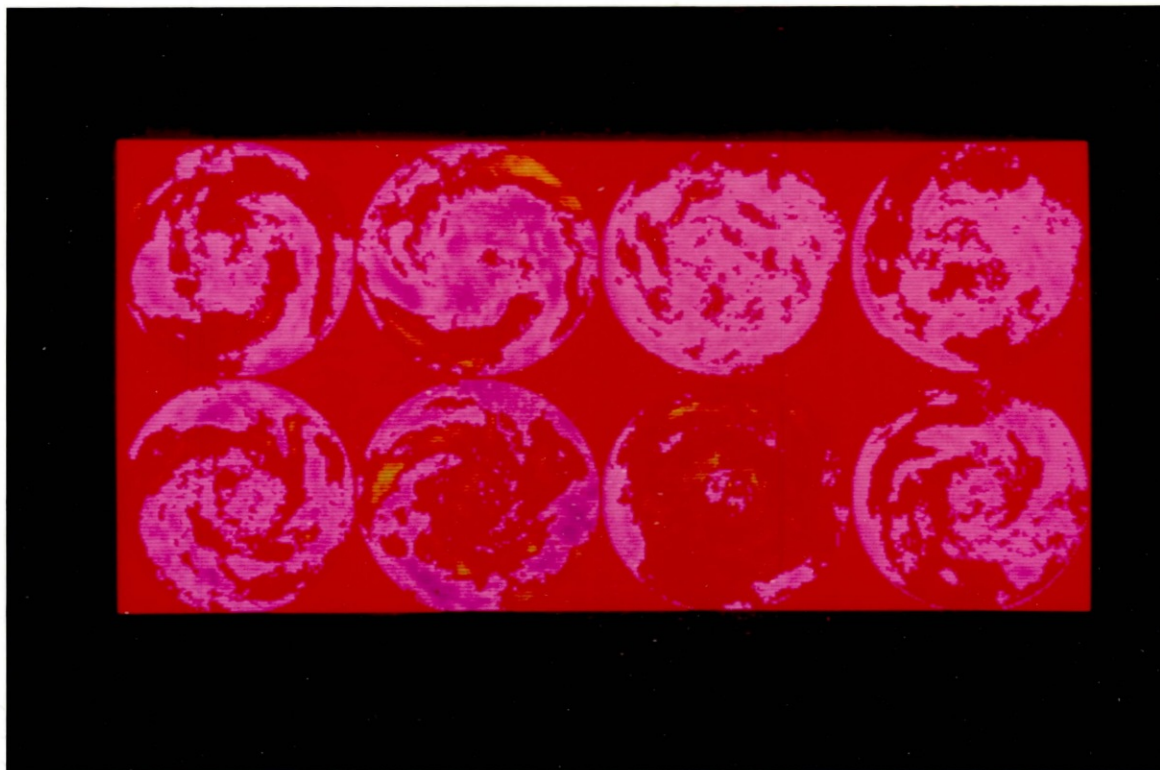


Figure 8.5. Correlation for minus 5 to minus 8.

In figure 8.1 to 8.5 we see some of the results of the LCC analysis carried out. In figure 8.1 the zero lag image is shown. This represents the regions around the world that are in unison with the Antarctic anomalies. At zero lag one is forced to interpret high correlation factors (0.8 to 1.0) as similar responses of the atmosphere to external forcing. That is one would not expect this to indicate that either the Antarctic was influencing climate elsewhere or vice versa. The regions in the Antarctic and its surrounding area are very highly correlated because the base cycle was determined using a blotch region that covered all areas on the Antarctic mainland. Regions not in the Antarctic area that are well correlated are associated with regions away from the main cloudbands while most other areas do not seem to be very well correlated at all (-0.4 to 0.4). These regions are areas where the seasonal global anomaly is unperturbed by clouds. The largest regions of significant anticorrelation are associated with either one of three main cloud bands and the ITCZ. In the positive lag images regions of green indicate areas that influence the Antarctic; that is the reference time series is displaced forward in time. The displaced time series as expected show much lower correlation. After 2 seasons it is clear that no region on the globe significantly affects the Antarctic. The negative lagged images show a similar trend. The result would seem to indicate that most if not all significant correlations to Antarctic climate occur within 1 or 2 seasons of the time being studied.

The ice area calculations made in chapter 7 were not sufficiently accurate to be used in an LCC analysis using anomalies because the errors in the calculations are in excess of the year to year anomalies

CHAPTER 9

RESULTS AND CONCLUSIONS

9.1 ATMOSPHERIC VARIABILITY AND LONG TERM TRENDS

The atmospheric variability shown in figures 6.16 to 6.23 indicate that on the time scale of this analysis there are variations in climatic parameters of the order of only 10-30 W/m**2. To investigate the long term variation of fluxes over the Antarctic figure 9.1 was constructed for analysis and from it we can see that there is a small trend towards lower fluxes from the region. While this trend is small (~ 0.87 W/m**2/year) it is substantiated by independent work done by Raper (1983) and has a correlation factor of 0.54.

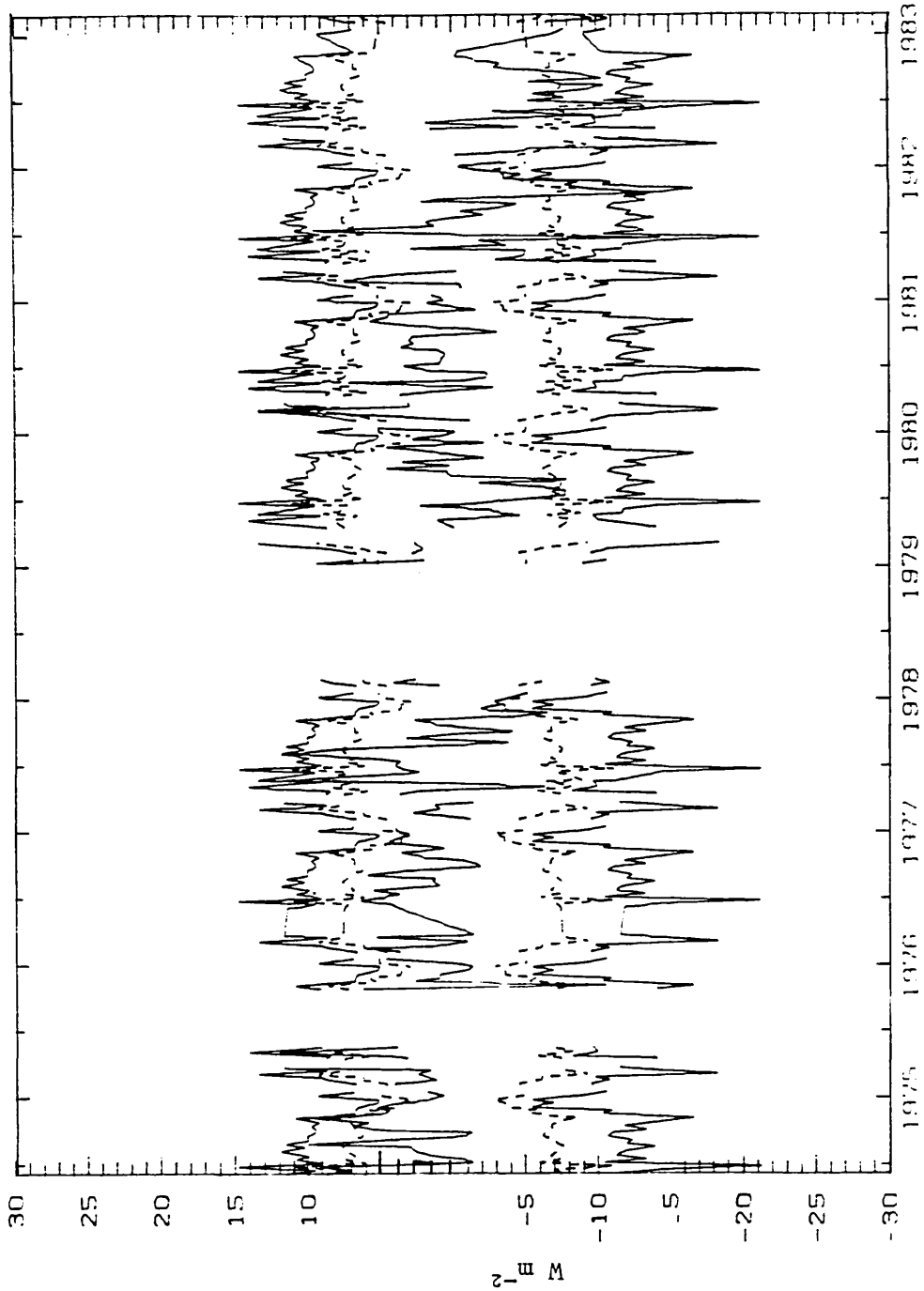


Figure 9.1. Graph of South polar anomaly flux versus time.
(see page 212)

As shown in Charalambides (1984) a change of 0.87 W/m^2 over the period of this analysis is equivalent to about 3K change in brightness temperature over the Antarctic. This suggests that the surface temperature is increasing which would then suggest an increase in the overall cloud amount and a decrease in OLR from the area.

The data presented is also useful for modellers who wish to have some point of reference for their results. The periods of uninterrupted data can be used as the starting conditions for a model to determine the suitability of the model for prediction of radiation budget. The data spans a sufficiently long period so that the results present a useful climatology, especially for the Southern Hemisphere and the Antarctic regions for which the coverage has often been poor. Improvement in the time period for the data would be an advantage for all future studies because although the data covers a considerable period it is still too short and consists of too many satellites of varying observational quality. The largest improvement in the data set used can be obtained by ensuring the same satellite equator crossing times (this is being considered) and an improvement in the regression algorithm (this has been done).

9.2 DETERMINATION OF CLOUD AMOUNTS

The cloud classification technique used in this study has been relatively successful in most areas of the globe but has some difficulty over snow or ice covered surfaces. This is because of the similar albedo and infra-red transmittance of snow and ice to cloud cover. In situations where the albedo cannot be determined accurately the cloud cover estimate is likely to have larger error bars. Since this is the situation for the Antarctic for a

large proportion of the year a different technique would be useful. The average cloud amount is shown in figure 9.2 for the period of the data set. This was calculated using the techniques discussed in chapter 7. While this graph is only an example the NOAA data with the CLD program could calculate cloud amounts over particular regions for comparison with other independant data.

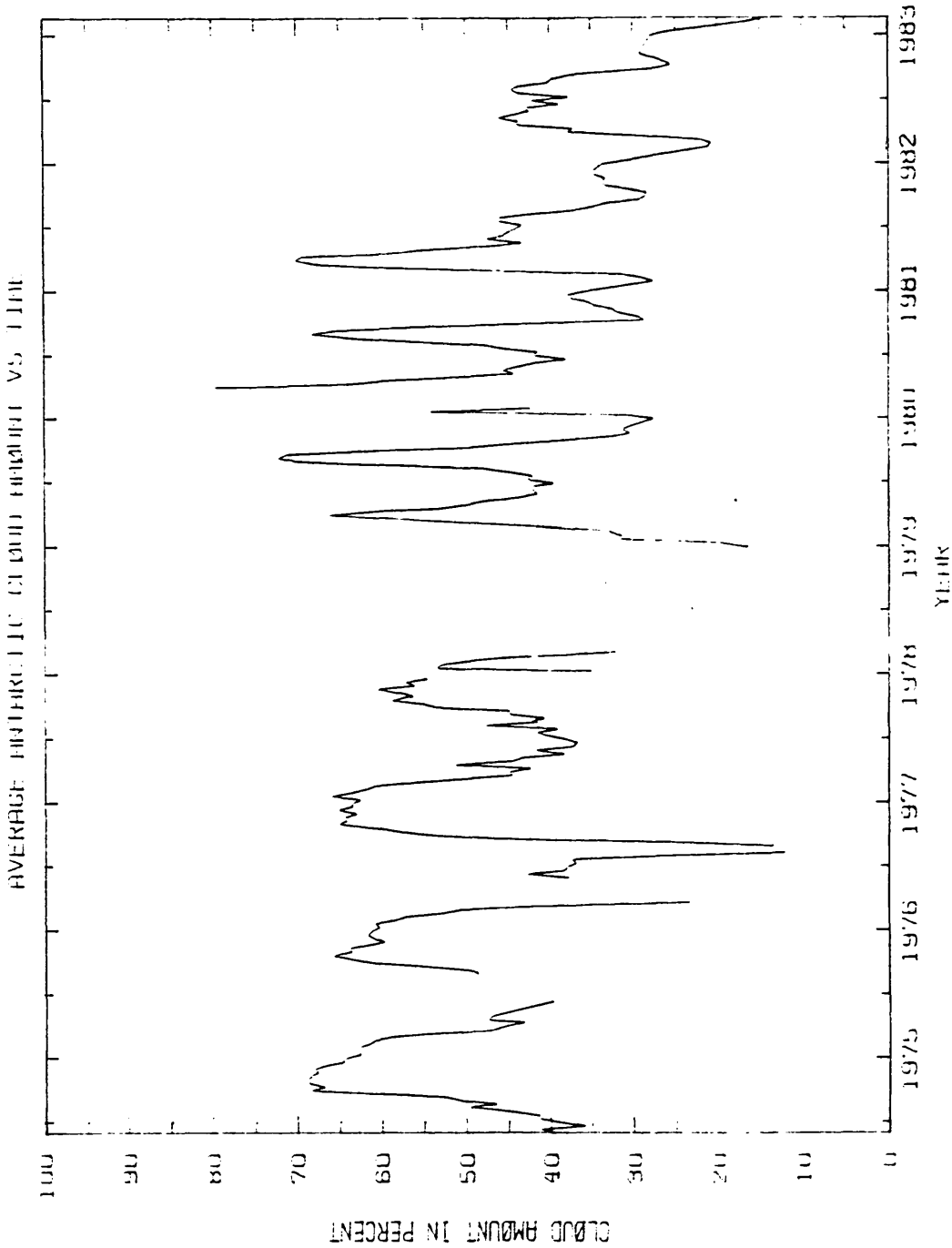


Figure 9.2. Antarctic cloud amount 1974 to 1983.

9.3 DETECTION OF THE ICE AREA

The method employed in this study to evaluate ice areas is prone to some problems of interpretation because of the effect of misclassification. This is mostly due to persistent cloud in imagery in which sea ice is to be detected. However this classification error is also due to some extent to the simplicity of the algorithm used. Even with these limitations the program ICE which determines ice areas using a segmentation procedure based on histograms is reasonably successful and compares favourably with more sophisticated work done by Zwally (1981).

There are significant prospects for a large improvement in the accurate determination of sea ice area in the Southern Hemisphere using a better classification technique based on the technique used here, perhaps using visible channel information when possible and a more sophisticated algorithm in sea/ice cloud/ice cloud misclassification situations.

9.4 TELECONNECTION ANALYSIS

While the validity of the approach used in this thesis has not been proved its results certainly indicate features that need to be explained in terms of atmospheric phenomena. The results shown using this approach indicate that the Antarctic regions responds very much like the open oceans to anomalies (see figure 8.1) rather than to regions often covered in cloud. At lags greater than ± 4 seasons the correlations imply little connection between the Antarctic and any region. The technique is certainly powerful even at seasonal increments and at a fairly coarse spatial scale. The technique could be improved in a

number of ways the most drastic being the change in the size of the time step, perhaps to monthly size. Other improvements could be refining the statistic calculated to give a measure of significance based on a random time series as Ka-Ming Lau (1984) have done.

9.5 SUMMARY

In summary the main objects of this thesis have been met namely the establishment of a useful climatology for the Antarctic and a measurement of the anomalies associated with it. While these anomalies have proved to be smaller and less frequent than expected they have proved useful with the LCC analysis that was used to objectively determine the links between different areas in the Earth's atmosphere. The same data have been used to establish the cloud amounts on a global scale and covering a considerable period of time. While the ice areas in the Southern Hemisphere have not been so accurately determined the technique used can be enhanced to provide useful data. Use of ice area data as the independant time series with the LCC analysis also holds some prospects for determination of the physical mechanisms that drive the teleconnections involving the Antarctic region.

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APPENDIX A

LIST OF ACRONYMS

APT.....Automatic Picture Transmission
AVCS.....Advanced Vidicon Camera System
AVHRR.....Advanced Very High Resolution Radiometer
BAS.....British Antarctic Survey
BP.....Before Present
BPI.....Bytes Per Inch
CAD.....Command And Data acquisition centre
CPU.....Central Processing Unit
DCP.....Data Collection Platform
DN.....Data Number
EOP.....End of Operation
ESA.....European Space Agency
ESMR.....Electrically Scanning Microwave Radiometer
FGGE.....First Global Garp Experiment
GAC.....Global Area Coverage
GARP.....Global Atmospheric Research Programme
GMS.....Geostationary Meteorological Satellite
HB.....Heat Budget instrument
HF.....High Frequency
HEPAD.....High Energy Proton and Alpha-particle Detector

HIRS/2.....High resolution Infra-red Radiation Sounder
HRPT.....High Resolution Picture Transmission
I2S.....Image International Systems
IBM.....International Business Machines
ICST.....Imperial College of Science and Technology
IFOV.....Instantaneous Field of View
IGY.....International Geophysical Year
IIS.....International Imaging Systems
IP.....Ion Probe
IPIPS.....Interactive Planetary Image Processing System
IR.....Infra-Red five channel scanner
IRP.....Infra-Red Passive
ITCZ.....Intertropical Tropical Convergence Zone
JAS.....Journal of Atmospheric Science
LAC.....Local Area Coverage
LST.....Local Solar Time
MP.....Mercator Projection
MSU.....Microwave Sounding Unit
NASA.....National Air and Space Administration
NBC.....North Bound Crossing
NMC.....National Meteorological Center
METEOSAT...METEOrological SATellite
MEPED.....Medium Energy Proton and Electron Detector
NERC.....National Environmental Research Council
NESDIS.....National Environmental Satellite Data and
 Information Service
NESS.....National Environmental Satellite Service
NOAA.....National Oceanic and Atmospheric Administration
OLR.....Outgoing Longwave Radiation
PLN.....Pre-Launch Name
PSP.....Polar Stereographic Projection
PPL.....Process Peripherals Limited
PRT.....Platinum Resistance Thermometer
SBC.....South-Bound Crossing
SEM.....Space Environment Monitor

SPM.....Solar Proton Monitor
SSU.....Stratospheric Sounding Unit
TED.....Total Energy Detector
TIP.....TIROS Information Processor
TIROS.....Television Infra-Red Operational Satellite
TOVS.....TIROS Operational Vertical Sounder
VAX.....Virtual Address eXtension
VBS.....Virtual Block Spanning block boundaries
VICAR.....Video Image Communication And Retrieval
VMS.....Virtual Memory System
VTR.....Vertical Temperature Radiometer

APPENDIX B

PROGRAMS WRITTEN

A number of analysis programs were written during the course of these studies. A description of what these programs do and their length will give some idea of the problems encountered and how these problems were solved.

- o AREAFUN: This is a subroutine that is used by most of the programs to calculate the area of pixels on the NMC grid when projected onto the Earth's surface. Extensive use of spherical trigonometry is made. It uses the IJTOLL and LLTOIJ routines supplied by NOAA to convert from latitude, longitude to line and sample and vice versa. (115 lines).
- o BARE1,BARE2: These are the two programs that between them read the NOAA HB tapes and write them according to VICAR format. Use of low level VAX routines for tape reading are made and some error checking is done on data input. (290 and 78 lines).

- o ICONT: This is a general purpose routine for contouring arrays of data. Example of the output from this program are figure 5.7 and 6.7. It may be run interactively on the I2S or run as a normal command. It has many options and may use any of the CORE compatible character sets for labelling. (404 lines).
- o CMAP: This is the map drawing program for the Earth. Figure 1.1, 4.2 are outputs from this program. The program prompts for all needed parameters not entered on the command line and has six projections to choose from. Projection 6 is a polar stereographic projection which is used extensively in this thesis. An auto-fitting option is available if regions on an image can easily be identified. (1242 lines).
- o ICE: This program calculates ice areas by an automatic classification technique based on infra-red data. It also has the option for a variable threshold if needed. It may be run with the input defined as a wild card specification for a file name so that a number of file names are analysed, the results are written into a file. (194 lines).
- o CORANTSEA: Correlates the Antarctic seasons. This program takes in a number of data files that are specified and uses these as a basis for time series that will be used for anomaly analysis. The time series is worked out on a seasonal basis for every pixel in the standard image. NAG routines are used for the correlation of the time series. (366 lines).

- o CLD: In this program cloud amounts are worked out on a pixel by pixel basis using both infra red and visible imagery where possible. The matching image pairs are calculated by the program and found on disk using the naming convention used throughout this thesis for images. (350 lines).

APPENDIX C

SUPPLEMENTARY MATERIAL

Studies of the radiation over Antarctica during
1974-1983, and their possible relationship to climatic
variation.

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ABSTRACT

We present the results of a study of the anomalies in the Earth's

radiation budget determined from the analysis of nine years of observations from the NOAA polar orbiter satellites for the period, 1974-1983. We estimate the standard deviation in the outgoing flux for this period is generally less than 12 W/m^2 . The results show that there are several areas in which the statistical variance is in excess of 20 W/m^2 which are associated regions of radiation budget anomalies in excess of the atmospheric variation. In this paper we discuss the relationship of the anomalies with climatic change in this region.

INTRODUCTION

Satellite studies of the Earth's radiation budget are an important element in the overall observation of the terrestrial climates driving forces. Observations of radiation budget parameters have been made for almost two decades by a variety of satellites. (eg. /1/ - /4/) All these previous observations have been made with sun synchronous polar orbiting satellites, which sample each point on the Earth at a fixed local time, and therefore introduce an unknown sampling error, due to the diurnal cycle, into the derived physical parameters. Investigation into the inter-annual variability of the atmosphere using these platforms such as /4/ are faced with aliasing errors due to the different satellite equator crossing times. A study has recently been made of the magnitude of the errors due to temporal and spatial sampling in the radiation budget observations /5/. Consequently, it is now possible to quantitatively estimate these errors due to the differing equator time crossings of the various spacecraft which have provided radiation budget observations during the past decade.

A long time history of radiation budget observations provides important information on the radiative driving of the atmospheric circulation, and several studies have been carried out to investigate the relationship of these variations with large scale

circulation change, particularly in the tropical atmosphere /6,7/. Anomalies in the outgoing longwave radiation have been shown to be closely related to sea surface temperature anomalies associated with the southern oscillation /7/. A further important study /8/ has shown that these radiation budget measurements may be used as basis for investigating atmospheric teleconnections.

In this paper we have used a set of observations of the Earth's radiation budget for the period 1974-1983, obtained from the NOAA satellites, to investigate the radiative properties of the atmosphere and their relationship with the circulation changes. The study derives the geographical distribution of the radiative anomalies which are statistically significant in the particular periods of this observational series.

The results presented in the paper are primarily concerned with the anomalies in the Antarctic region. It is well known that the polar regions are a key area in the changing climate of the Earth. We therefore discuss these anomalies and their possible links with other changes in the radiation budget in the Southern hemisphere through the period 1974-1983.

DATA

The data set used in this study is derived from the NOAA/NESS polar orbiting satellites. The regression technique used to calculate the broadband flux from the narrow band flux are discussed in /9/, /10/. The outgoing flux (OLR) values were used from this data set and the absolute errors in the conversion from narrow band to wide band fluxes are estimated to be 5% /10/. The aliasing errors are expected to be 6 and 30 W/m**2 in the infrared and visible channel respectively /5/. The results in this paper are primarily concerned with high latitudes in the southern hemisphere where there are regular observations from the polar

orbiter spacecraft. Consequently, the aliasing errors in this region are less than at other regions of the planet.

DATA ANALYSIS PROCEDURES

The data set used in this study extend from June 1974 to February 1983. There is a gap in the data set in 1978 where the NOAA spacecraft were not operating. However, the data provides a long record of the components of the Earth's radiation budget that may be used for investigations of the statistical properties of the atmosphere, and the variations from one year to another. With this data set the main "weather" fluctuations can be eliminated, so that any statistically significant variations determined in this study refer to possible climatic changes. To calculate the data set means the daily data was first binned and averaged at an interval of ten days. This enabled a suitably long integration time to smooth away the short term 'weather' fluctuations, but short enough to allow flexibility to choose longer term means at other stages of the analysis. In every year of the data set, the observations were arranged in 36 ten day means so that three mean data sets represented each month. These aggregated data sets were then used as the basis for the data set mean at a temporal resolution of ten days.

In the resulting data set each component of the radiation budget is established on the Earth at a resolution of 100 km, throughout each measurement year, at ten day intervals. With this set of measurements we may then establish the mean radiation budget fields, and in any month in the observation period, and derive the deviation from the mean values. We define these deviations in the radiation budget parameters as the anomalies.

RESULTS

In figure 1 we show the variation of the anomalies in the

outgoing longwave flux from June 1974 to February 1983 for the Antarctic region bounded by 80-90 degrees south. We find that the statistical variance is in the range of 3-12 W/m**2 with errors of +/- 2W/m**2 (relative) and +/- 10W/m**2 (absolute). These results suggest that 70% of the values throughout the mean year lie in the 6-7 W/m**2 range.

The results in figure 1 indicate an apparent downward trend in the outgoing longwave flux throughout this observational period. From a least squares fit to this data, we estimate the decrease in flux amounts to 0.8 W/m**2/year with a correlation coefficient of 0.54. If we assume a surface flux of 200 W/m**2 for this region, this variation is equivalent to a change of 3K in the brightness temperature. This trend in the outgoing longwave flux is also consistent with independent measurements of the south polar region /11/. They suggest that the surface temperature is increasing which would then be equivalent to an increase in the overall cloud amount and a decrease in the longwave flux as shown in figure 1.

In figure 2 we show the mean longwave flux distribution for each of the four seasons. Spring (SON), Summer (DJF), Autumn (MAM) and Winter (JJA). The maximum flux found is 320W/m**2 and the lowest values of 140W/m**2 and 100W/m**2 over the ice region of the Antarctic continent. The data show a persistent region of polar convergence marked by a ring of small flux values associated with the main cloud arcs. In spring there is a large area of low flux values in the region 50-90 degrees south. In summer, there is an apparent link between the cloud developments in Indonesia with Antarctic. While this link seems to occur at most seasons, it is strongest in the southern summer when the ice extent is also smallest. The winter distribution appears to reflect a change in the ITCZ structure which seems to have moved further south. The NE region of Brazil is apparently less affected by cloud with much higher flux values than observed over

other land areas.

The mean variance for the outgoing longwave radiance for these seasons derived from the "mean" data set is shown in figure 3. The values for NE Brazil increase steadily from summer to autumn reaching values of more than 20W/m^2 , and then decrease in magnitude as winter advances. The Indonesia/South Pacific cloud arc is most intense in the summer with values of 20W/m^2 . Over South Africa the variations in the cloud systems are probably responsible for the high values of $15\text{--}20\text{W/m}^2$ in summer and autumn. Two branches appear to develop in the South Pacific zone in autumn producing a variance of 10W/m^2 . Throughout the year, the variance over most of the eastern Pacific is less than 5W/m^2 . Over Antarctica the highest values of $2\text{--}8\text{W/m}^2$ occur in the autumn period.

In figure 4 we show the normalised mean variance data set where the values are percentages of the local mean value. This approach serves to reduce the equatorial biases in the data. The results show that the greater atmospheric activity, and largest variance, is concentrated over the circumpolar trough in autumn and spring. There are also larger anomalies in the neighbourhood of the ice edge with the greatest values occurring during the period of maximum rate of change of ice area /12,13/.

Figure 5 illustrates the behaviour in a particular year, 1980, of a strong teleconnection between the Indonesia region and the south pole. It is strongly bounded by a large negative anomaly of -128W/m^2 where cloud is absent in 1980, with a strong positive anomaly of $+100\text{W/m}^2$ where the ITCZ has shifted further south than usual. Brazil again shows regional changes. During 1980, the positive anomaly seems to move in a north easterly direction over the south American continent from spring to winter.

CONCLUSIONS

In this study we have presented some results of the behaviour of the anomalies in the outgoing longwave flux observed during the period 1974-1983. The downward trend in the flux is consistent with independent measurements of a warming of the Antarctic region. From studies of the mean data set for this period, it would appear that the Antarctic region is strongly influenced by the atmospheric circulation in distant regions of the southern hemisphere, particularly in Indonesia and the Brazil area of south America. Changes in the local cloud distributions may affect the precise locations of these "apparent teleconnections". Further studies are being conducted to investigate the inter-annual changes in the outgoing radiation fluxes, and the influence of changes in cloud and ice distributions for the Antarctic region.

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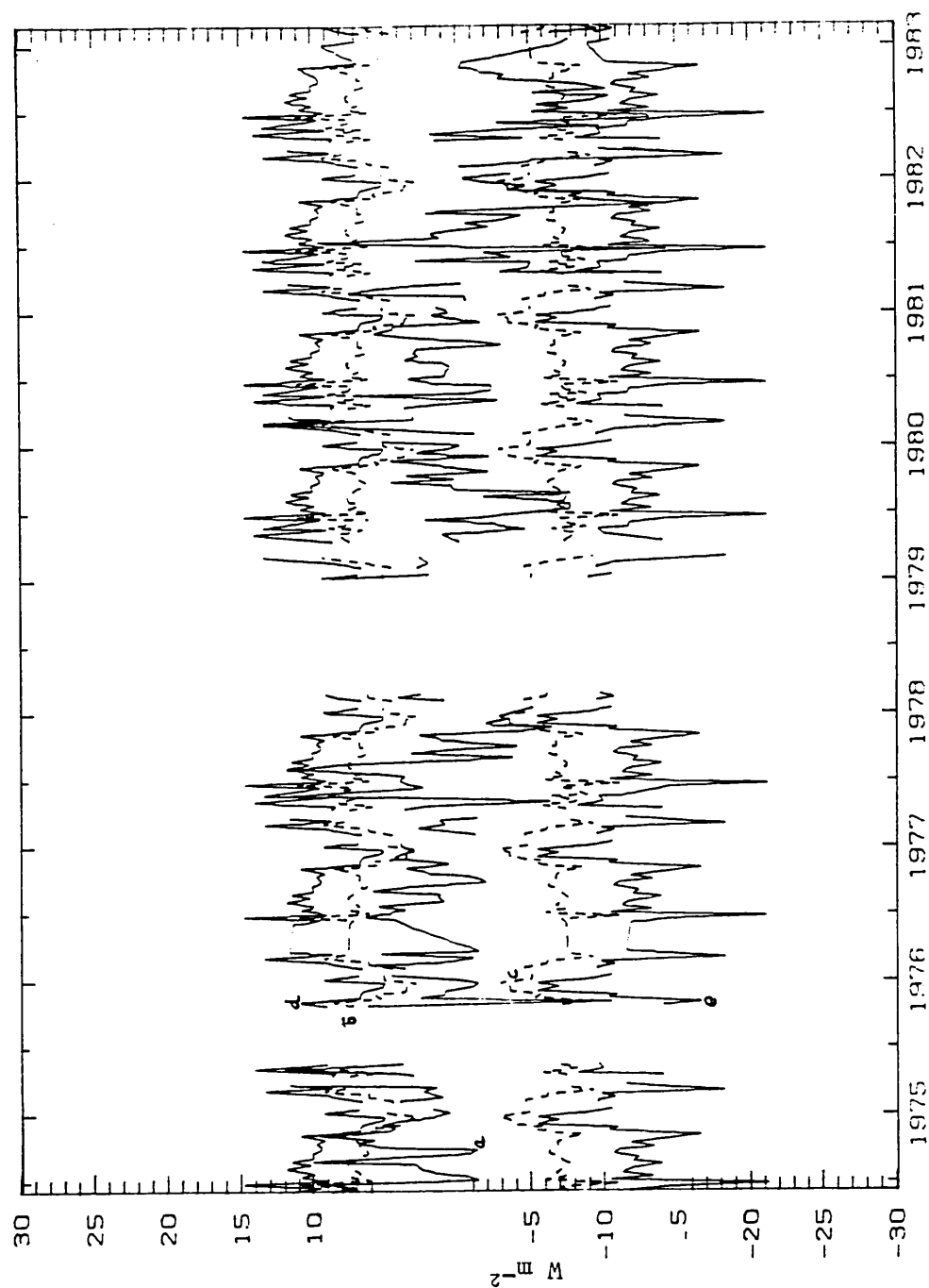


Figure 1. The variation anomaly flux over the Antarctic from June 1974 to February 1983 at ten day intervals.^(a) The first standard deviation (plus^(b) and minus^(c)) is marked with upper^(d) and lower^(e) limits on measured values marked above and below.

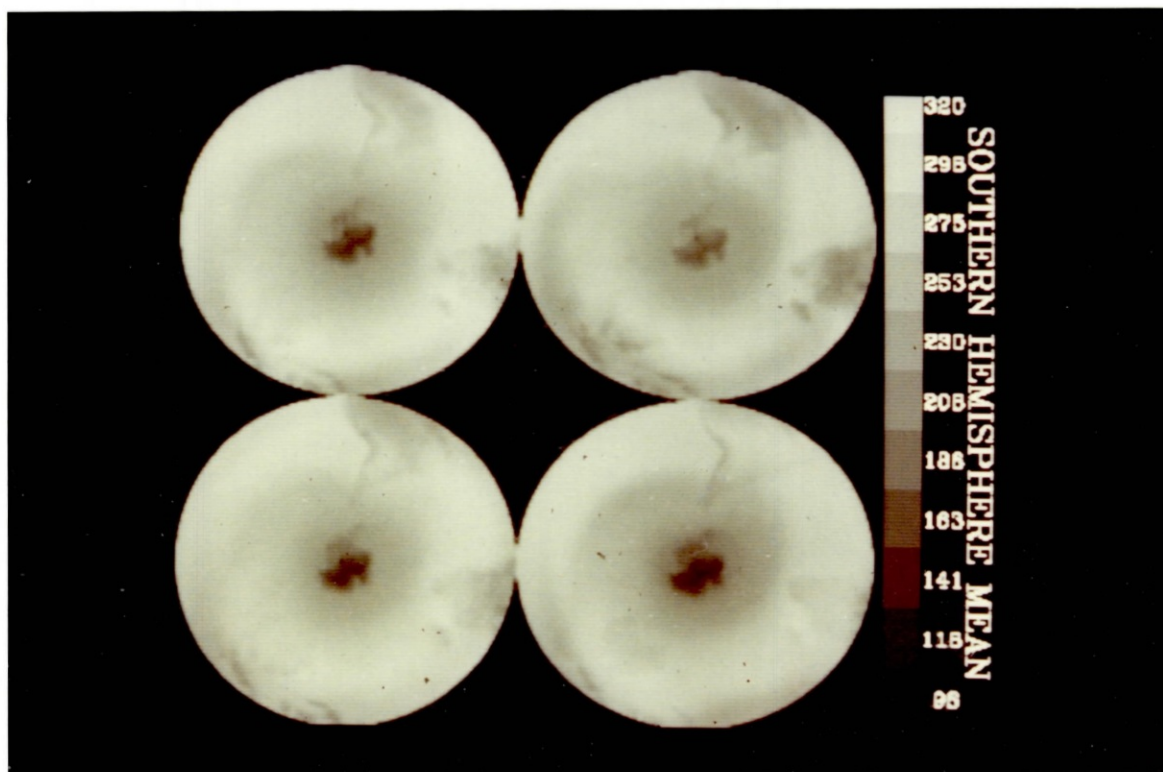


Figure 2. The mean data set for OLR (1974-1983) for the four seasons Spring(September, October, November) Summer(December, January, February) Autumn(March, April, May) Winter(June, July, August)

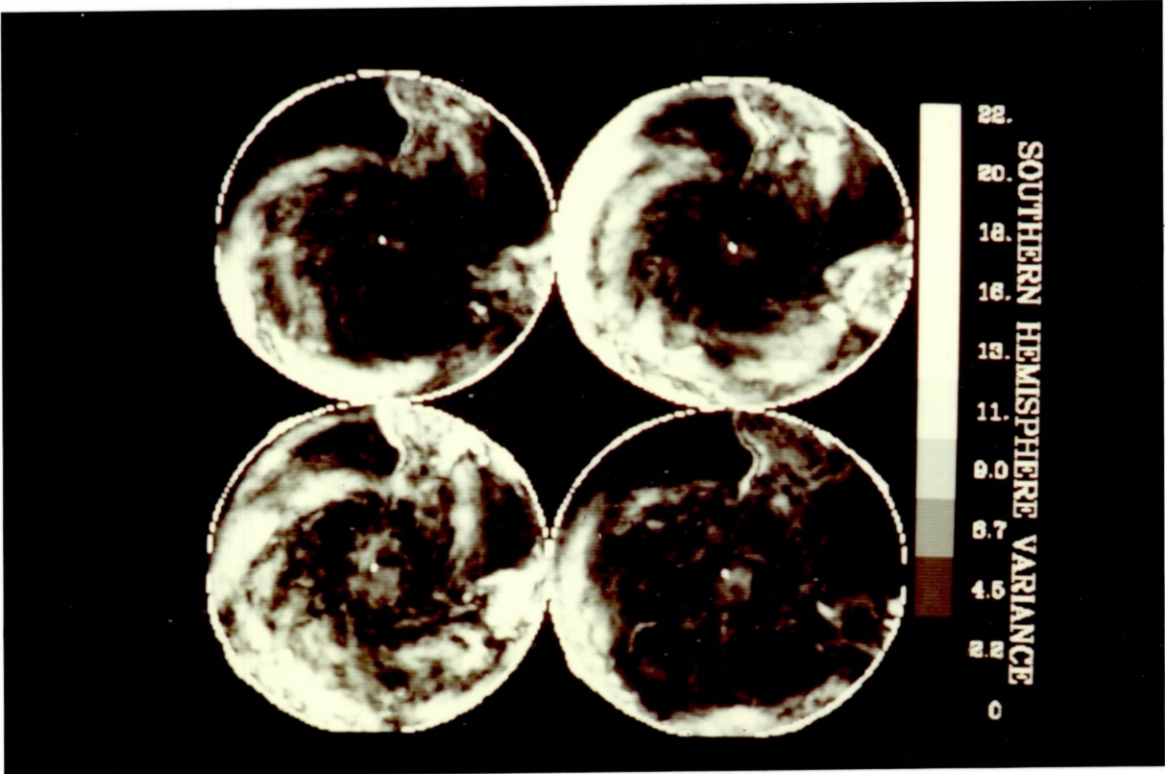


Figure 3. The mean data set variance for OLR for the four seasons illustrated in figure 2.

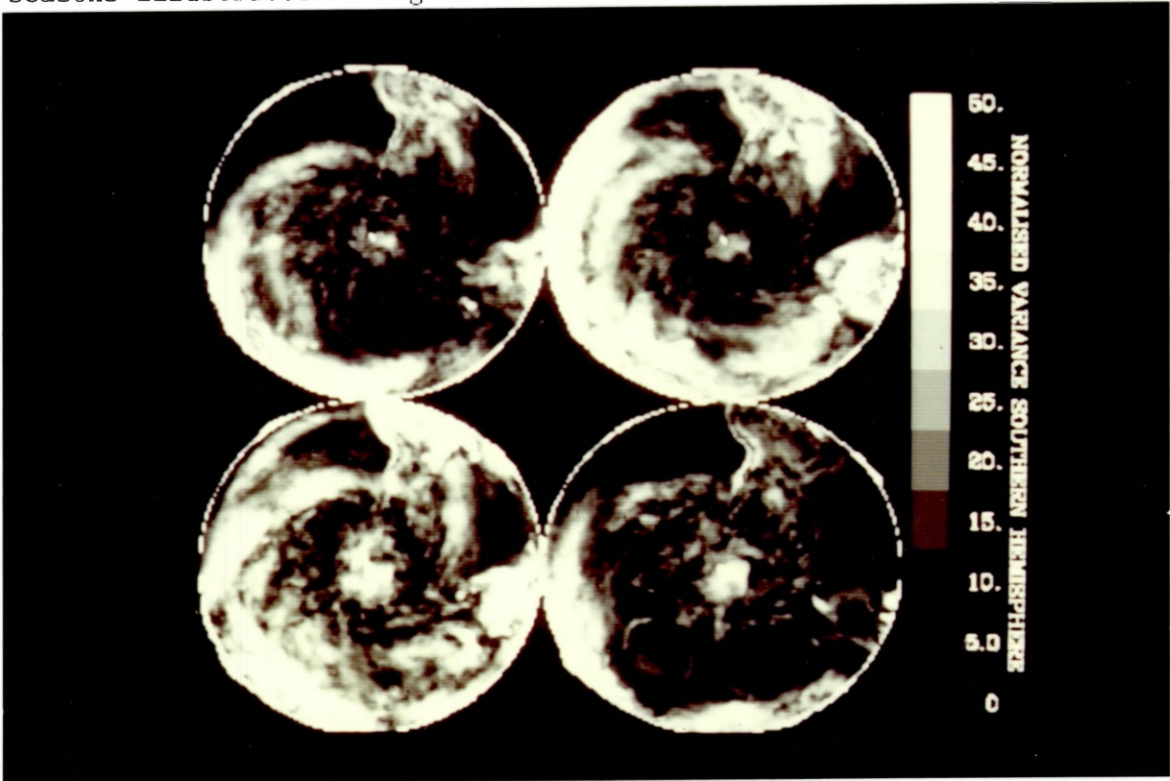


Figure 4. The normalised variance for OLR values in percentages

of the mean value for the data shown in figure 3.

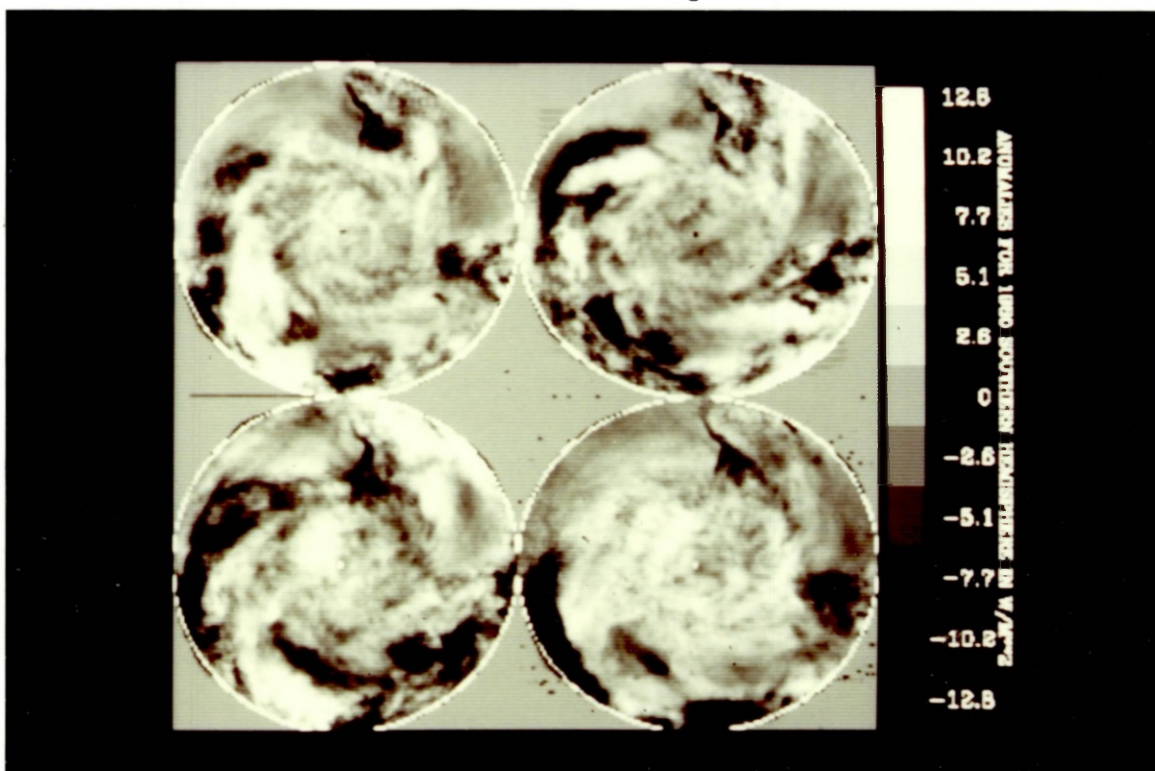


Figure 5. The anomalies in the OLR in 1980 for the southern hemisphere.