Chapter 5

Observed atmospheric structures

Supplemental reading:

Lorenz (1967)

Palmén and Newton (1967)

Charney (1973)

5.1 General remarks

Our introduction to the observed state of motion and temperature in the atmosphere will be restricted (for the most part) to fairly gross features. Almost no mention will be made of the numerous features most closely associated with the most common perceptions of weather: hurricanes, fronts, thunderstorms, tornadoes, and clear air turbulence, to name a few. While there is something perhaps paradoxical and certainly regrettable about these omissions, the amount of detail required to cover them would far exceed both our time and our capacity for absorption of information. There is an additional reason for restricting ourselves to larger (synoptic) scales: namely, the conventional upper air data network does not resolve the smaller scales.

The question of resolution is not a simple one and before proceeding, a few remarks on the nature of meteorological data are in order. Data, in the sense used by experimental sciences (namely, single measurements of an

isolated system), are inappropriate to meteorology. Temporal and spatial
variability are such inextricable features of meteorological phenomena that
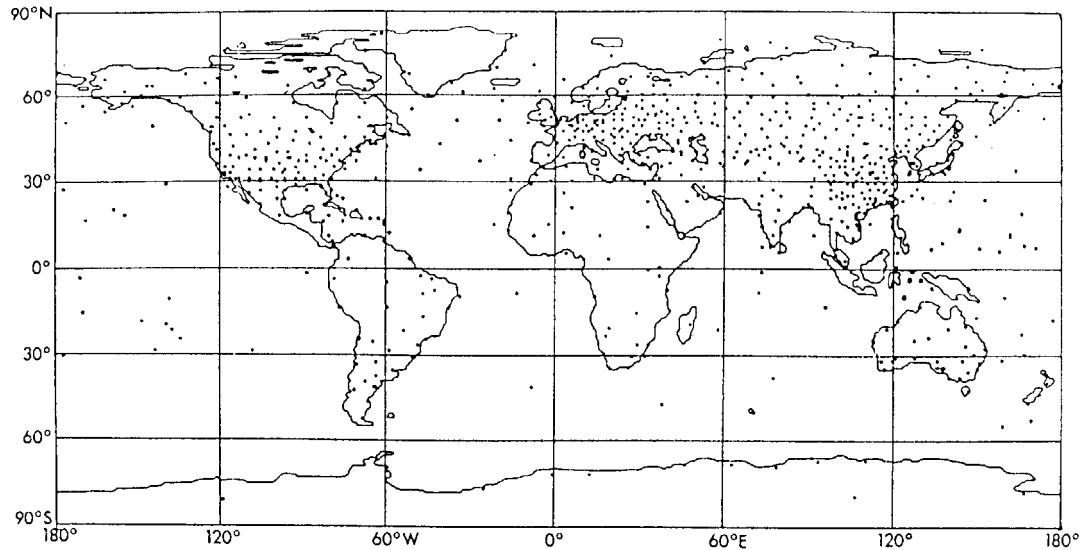isolated measurements at a single location are at best inadequate – and

Figure 5.1: Radiosonde station distribution (from Oort, 1978).

usually useless. Figure 5.1 shows the distribution of radiosonde stations
at which conventional meteorological balloon soundings are taken at least
once daily (and frequently twice daily at $0000Z$ and $1200Z$). These sound-
ings consist in pressure, temperature, and humidity measurements transmit-
ted by small radio transmitters to the ground. In addition, the balloons are
tracked by radar in order to obtain profiles of horizontal wind. In princi-
ple, such data are available with fairly high vertical resolution ($O(1\,\mathrm{km})$),
but usually the archived data sets list data only for a subset of the stan-
dard levels (surface, 1000mb, 850mb, 700mb, 500mb, 400mb, 300mb, 250mb,
200mb, 150mb, 100mb, 50mb, 30mb, 20mb, 10mb)[1]. From Figure 5.1 we see
that the horizontal distribution of stations – especially over the oceans and
in the Southern Hemisphere – is inadequate to resolve any but the coarsest
of features. The coverage, however, is extremely nonuniform, and over the

---

[1]These are supposed to be standard levels. In addition levels at which extrema occur
are supposed to be recorded as *significant levels*. Unfortunately data sets frequently omit
some of these levels.

Northern Hemisphere continents there is often fairly dense coverage. Temporal coverage is barely adequate to resolve five-day periods (one usually needs 4–6 points to resolve a period or wavelength), and height resolution, while adequate for some purposes, is usually inadequate for the resolution of boundary layers commonly observed (in more detailed measurements) below 700mb.

The limitations imposed by the crude nature of our meteorological measurements are substantial – and real. Moreover, the 'raw' data in tabular form (or any digital form) is peculiarly uninformative. Indeed, if each station produced an independent uncorrelated time series, it would be difficult to know where to begin any theoretical description (to be sure, we could then begin to formulate statistics, and attempt to explain these statistics), but, fortunately, when the data are presented in the form of global or regional maps, we see that patterns emerge which seem to evolve in a traceable manner[2]. It is, in the form of these maps, that we usually study the data. Such maps are the basis of much of this chapter. A quick glance at these maps shows representations which are continuous over the whole globe (or at least a hemisphere), while the 'raw' data come from a relatively few isolated stations. Clearly, the maps are not exactly data; they include a very substantial amount of interpolation – and this interpolation is rarely as straightforward as simple linear interpolation. Such maps are referred to as *analyzed* data. When the analysis is performed by hand by a synoptic meteorologist, it is referred to as 'subjective' analysis. The contours drawn in data-free regions probably contain useful information – especially when prepared by an experienced meteorologist – since much is known about the expected time and space evolution of disturbances. However, there is no getting away from the fact that what is drawn is *not* data. This becomes particularly disturbing when the contours show substantial detail in data-free regions. In general, these details will differ in different analyses.

When the analysis is performed according to fixed rules and algorithms, the analysis is referred to as 'objective'. The advantage of 'objective' analyses is their reproducibility, but there is no other *a priori* guaranty of greater accuracy than that found in subjective analyses. Recently, it has become common to analyze data with the aid of numerical weather prediction mod-

---

[2]As far as I can tell, this was first noted by Benjamin Franklin. He compared newspaper weather reports from various cities from the east coast to the Ohio basin, and observed that weather systems travelled east although the storms were associated with northeasterly winds.

els. Iterative use of predictions over short periods allows one to interpolate the raw data in a manner which is somehow consistent with the model physics. Moreover, such schemes allow the 'assimilation' of data other than the standard radiosonde data obtained from the stations in Figure 5.1. Of primary importance in this regard is the satellite obtained infrared radiance (from which coarse vertical temperature structure may be inferred)[3], and winds obtained from jumbo jets with accurate inertial guidance systems. Such model based analysis-assimilation schemes are impressive. Tests show that the interpolations are frequently surprisingly accurate. There is a general consensus that these new objective analyses are consideraby better than older subjective analyses – especially over the oceans. However, even these analyses are limited by (among other things) the model physics and resolution. In general, such models have only primitive parameterizations of cumulus convection, turbulence, radiative transfer, and sub-grid transfers by gravity waves. The forecast skill of such models is frequently poor in the tropics. Analysis-assimilation schemes which emphasize compatibility with the model physics often throw away actual data in order to produce a compatible analysis. Moreover, analyses based on different models frequently differ substantially (Lau and Oort, 1981).

The above description may be unduly critical. Nevertheless, there can be no doubt that the comparison of theory and data is a more difficult proposition in meteorology than in the traditional sciences. Science consists in a creative tension between theory and data: theory explaining data — data testing theory. In each case, the data consists in numbers with error bars estimating the likely uncertainty of the data. Such error bars can be attached to the results of individual soundings, but no similar methodology is readily attached to analyzed data where whole weather systems may be missed while occasionally systems are drawn which in reality didn't exist. The situation becomes even more questionable when higher levels of analysis are introduced: that is, spectral decompositions, correlations, etc. While such analyses might be applied, in principle, to the raw data, the methods are far better suited to regularly spaced data. In general, such regularly spaced,

---

[3]The global coverage afforded by satellite radiance measurements would seem likely to greatly improve global forecasts and analyses. This, in fact, has proven to be the case in the Southern Hemisphere, where there is almost no other data. However, in the Northern Hemisphere little or no improvement has been obtained. Apparently, inaccuracies and poor vertical resolution have limited the impact of satellite data when other data are available.

'gridded' data are obtained from analyzed maps. In this chapter, we will avoid such products of higher level analyses – though the results can often be informative and suggestive.

At this point it might appear that analyzed data is completely uncertain. This is certainly untrue — even though the quantitative measures of uncertainty have not been adequately developed. Certain important features on maps appear regularly and clearly (high signal–to–noise ratio) and are readily related to our tangible experience of weather. Analyzed data do, in fact, help us to isolate and quantify such features. However, 'data' as used in meteorology are not quite so concrete as carefully obtained laboratory data – and may, on occasion, even be wrong!

In describing the large–scale structure of the atmosphere, I will assume that the reader is already familiar with the variation of the horizontally averaged temperature with height. Similarly, the reader should be familiar with the typical heights at which various pressures occur. Finally, more detailed examination of the data for specific phenomena will be made in some later chapters.

5.2   Daily and monthly maps

We begin our study with eight figures, each of which consists of a set of four hemispheric maps: one for January 15, 1983, one for July 16, 1983, one for the average over January 1983, and one for the average over July 1983. The maps are all from the European Centre for Medium Range Weather Forecasting (ECMWF). Figures 5.2 and 5.6 show pressure contours at sea level (corrected for topography) for the Northern and Southern Hemispheres, respectively. Figures 5.3–5.5 show height fields for 500mb, 300mb, and 50mb in the Northern Hemisphere while Figures 5.7–5.9 show the same for the Southern Hemisphere.

Such maps display many phenomena – though the maps presented here are insufficient to adequately isolate and quantitatively delineate such phenomena. Nevertheless, the maps warrant close and thoughtful scrutiny. In these notes, we will focus on the Northern Hemisphere maps – and even that will be done briefly, simply indicating the kinds of things one might look for. The reader should carefully study the Southern Hemisphere maps in order to see in what ways the meteorology of the Southern Hemisphere resembles and differs from that in the Northern Hemisphere.
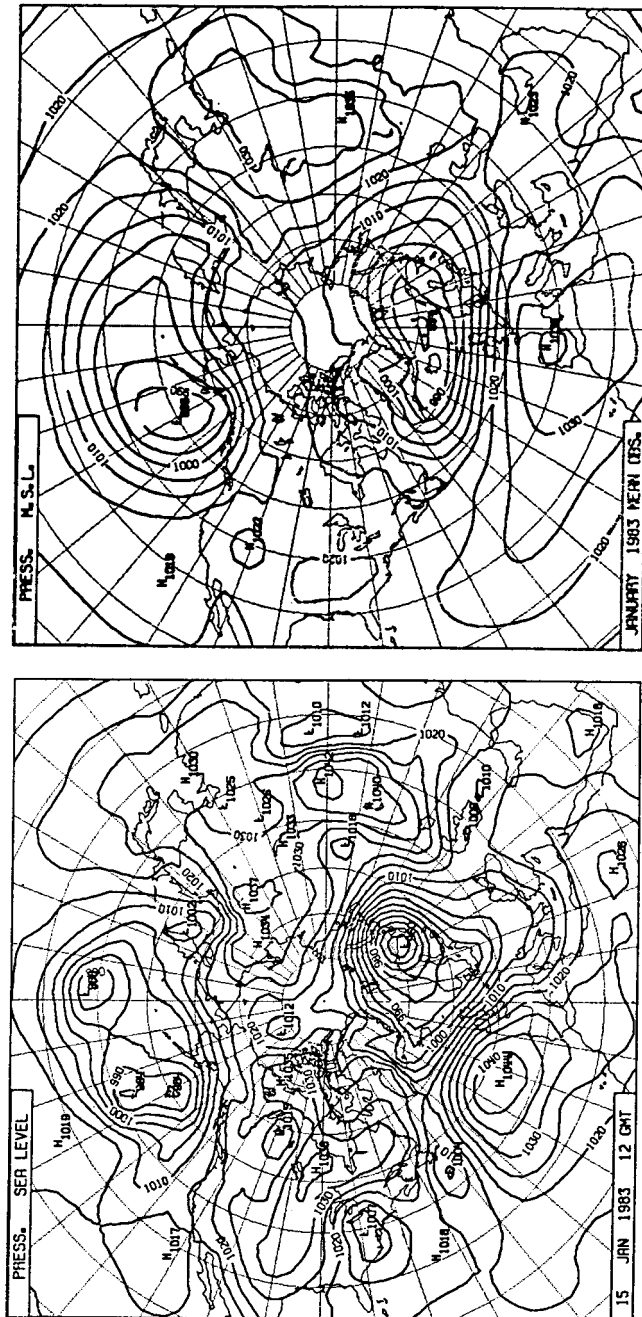
Figure 5.2: Northern Hemisphere maps of sea level pressure contours (corrected for topography) for January 15, 1983 and July 16, 1983 and monthly mean maps for January and July of 1983. Units are mb or hPa
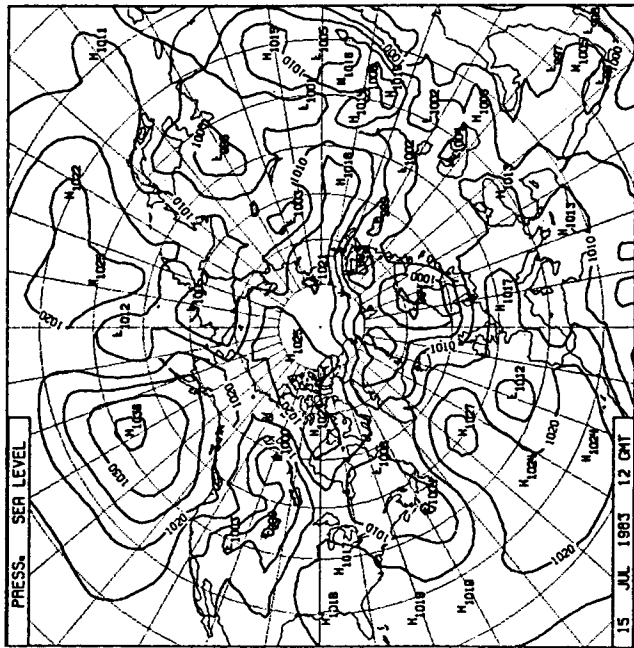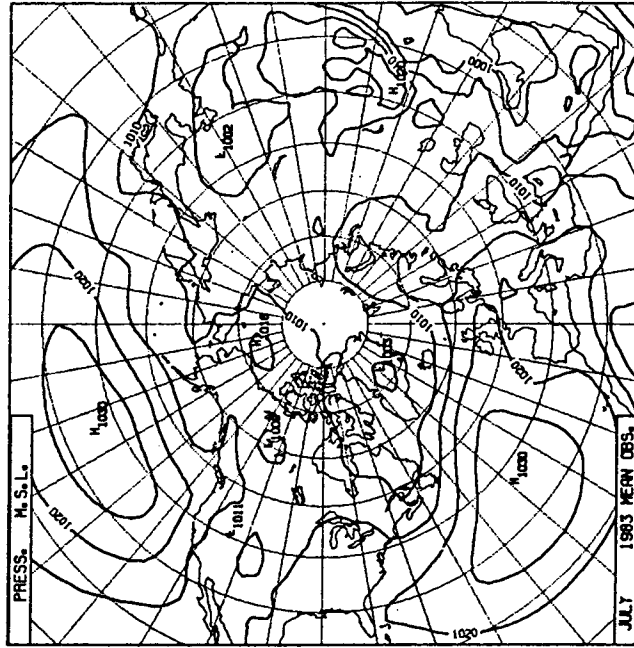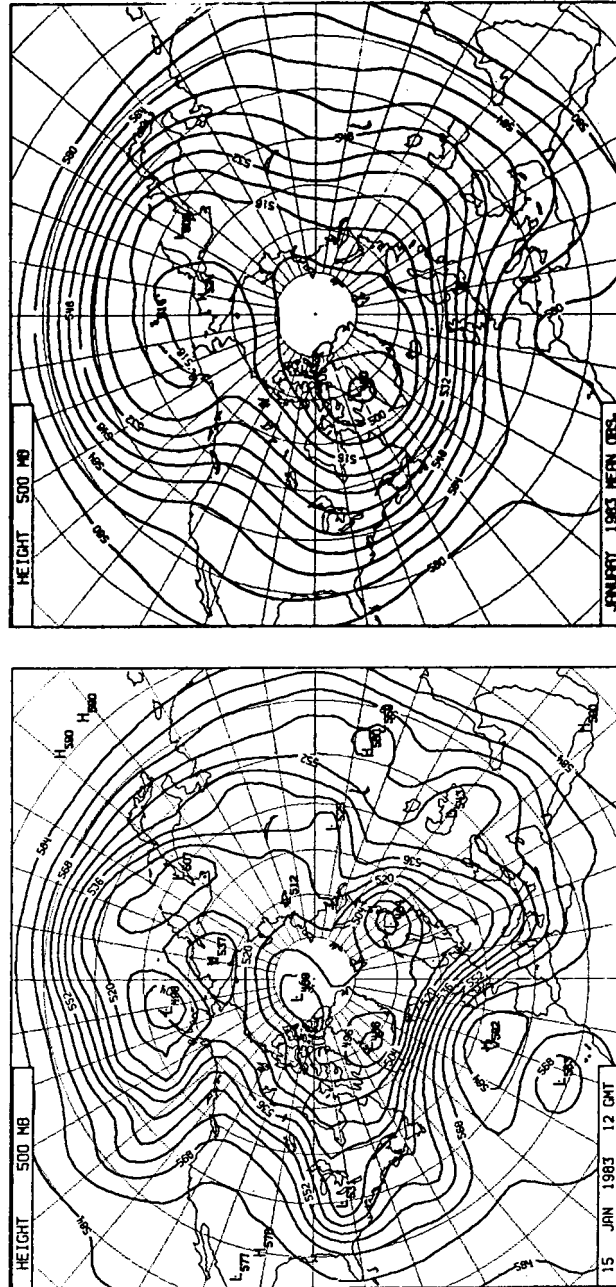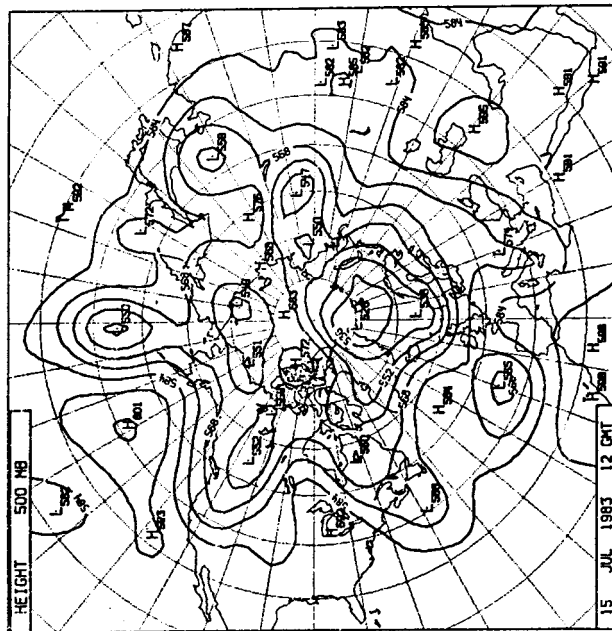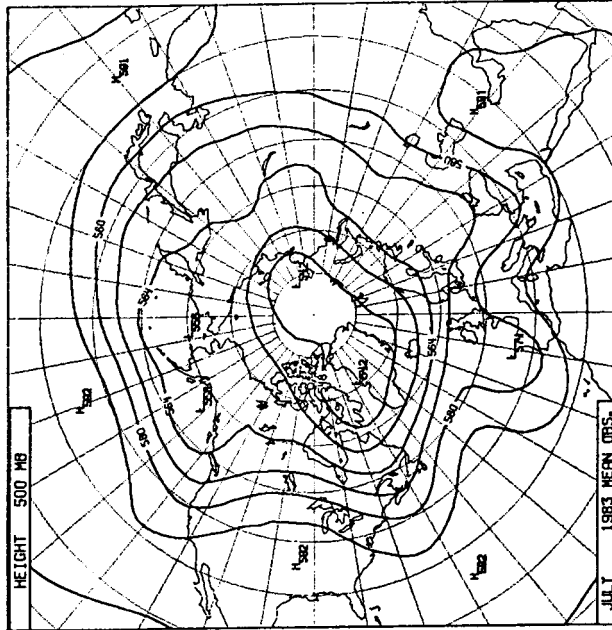
Figure 5.3: Same as Figure 5.2, but for contours of height at 500mb. Units are decameters.
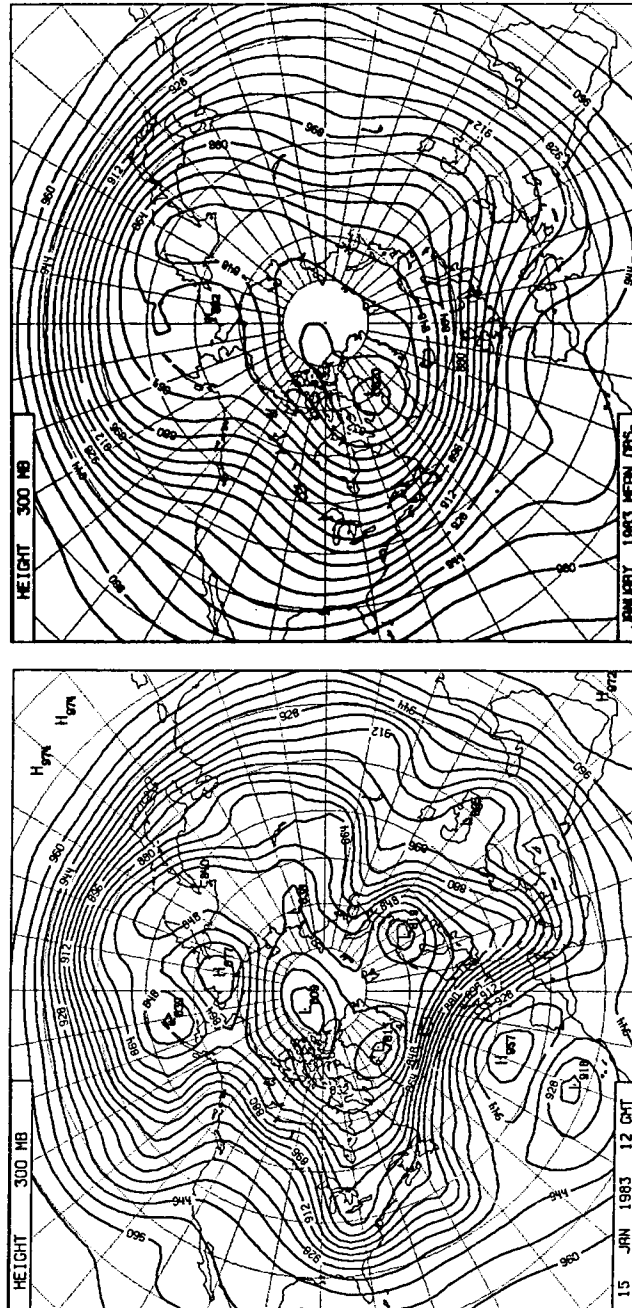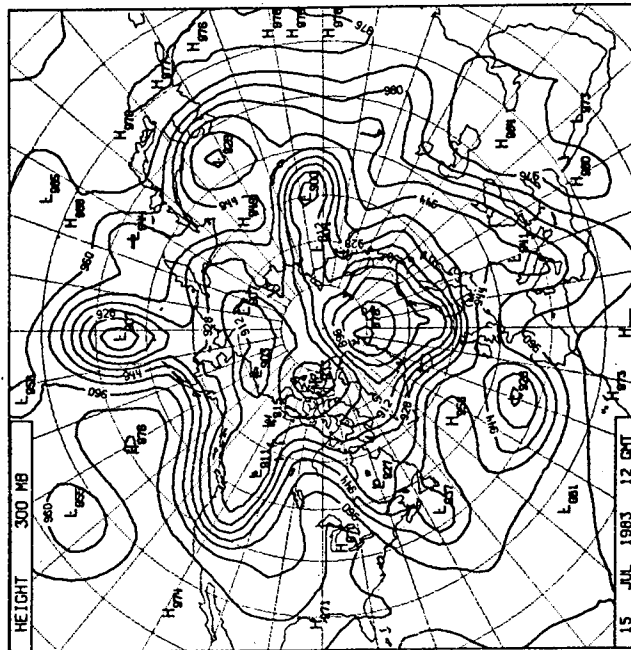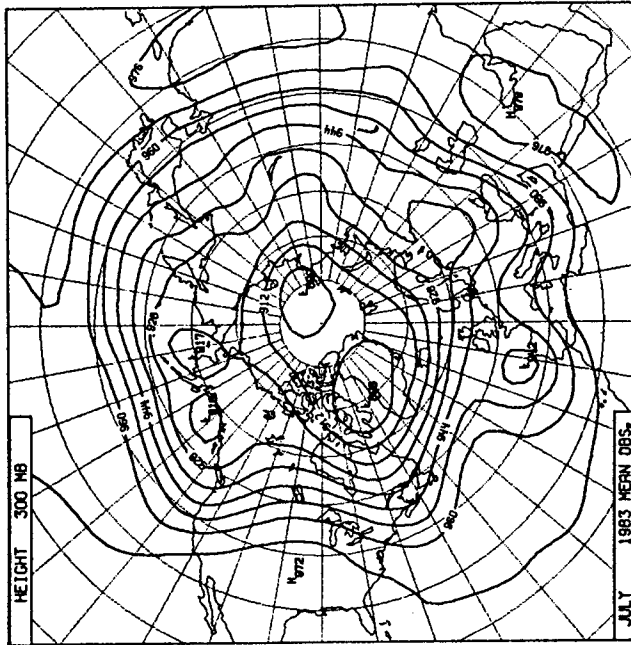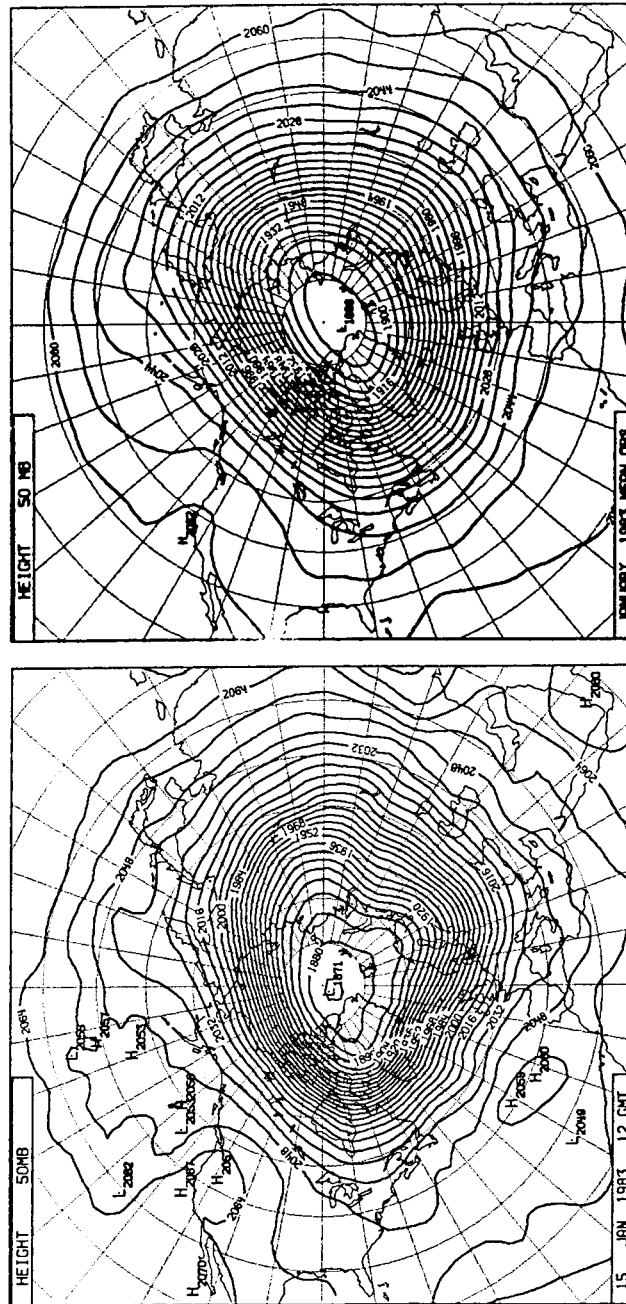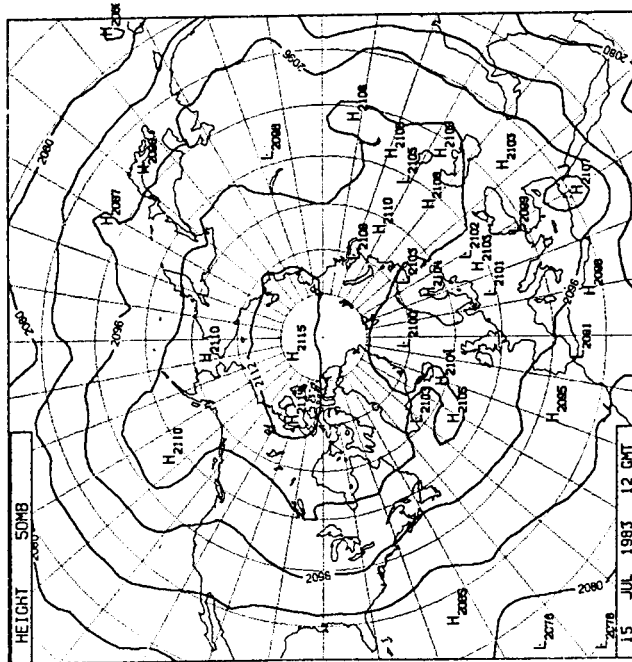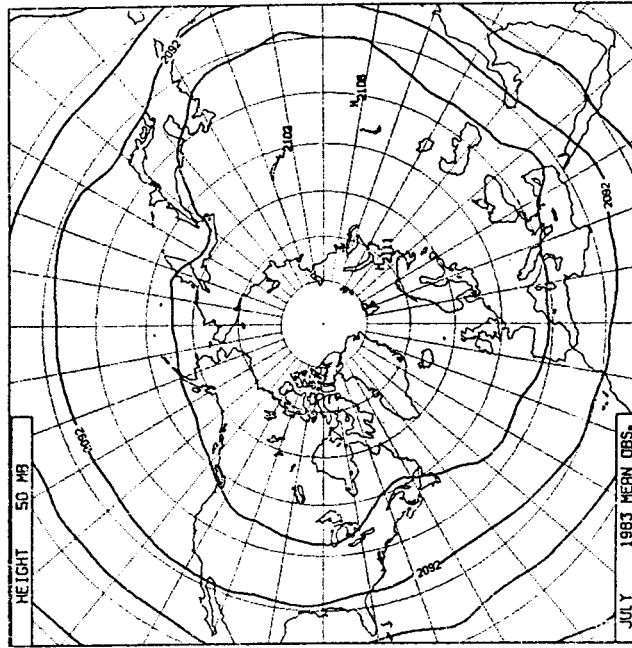
Figure 5.4: Same as Figure 5.2, but for contours of height at 300mb. Units are decameters.

Figure 5.5: Same as Figure 5.2, but for contours of height at 50mb. Units are decameters.
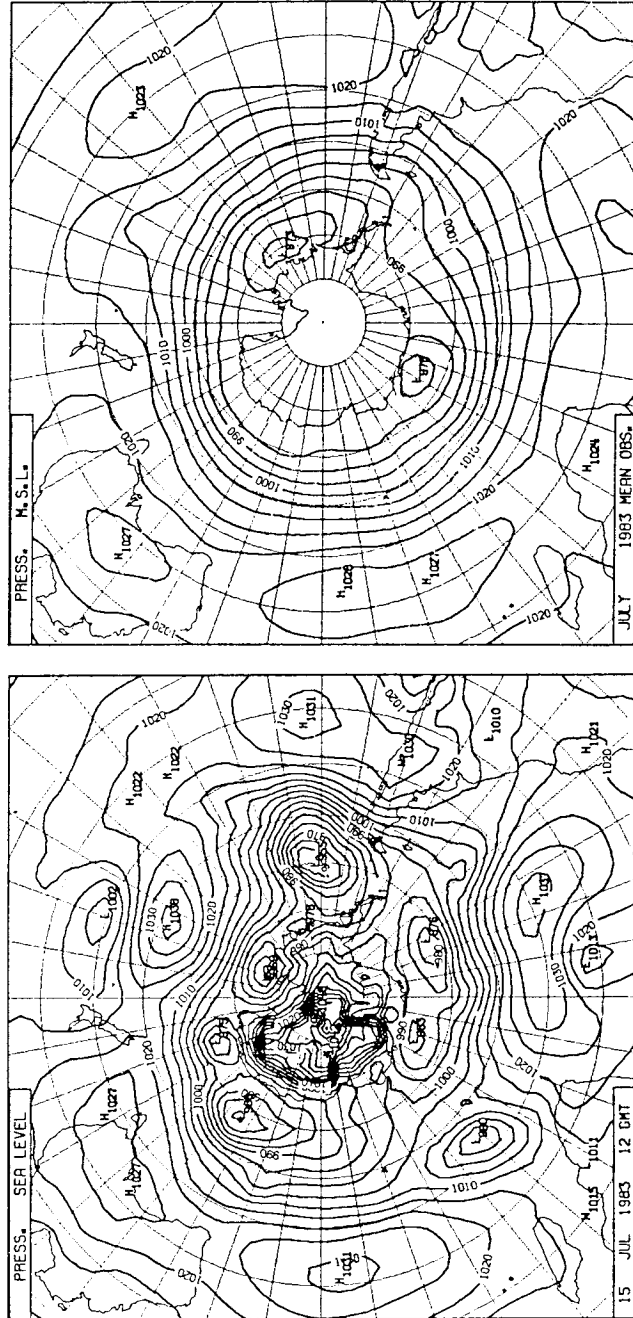
Figure 5.6: Same as Figure 5.2, but for Southern Hemisphere.
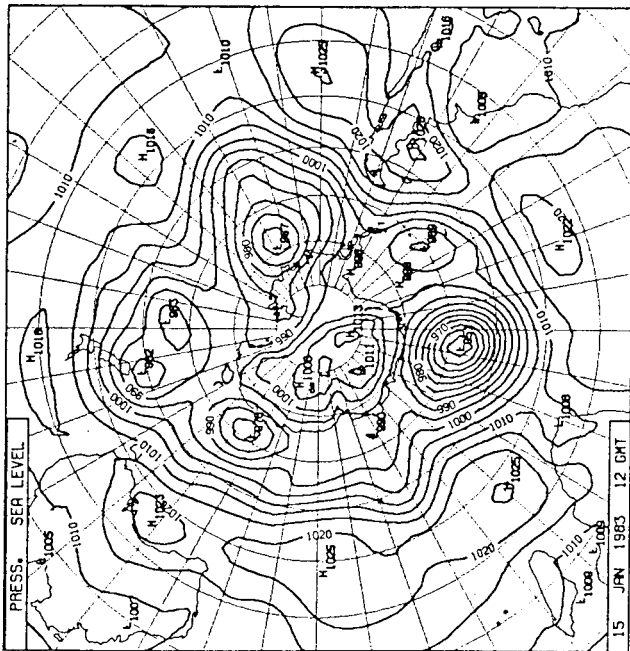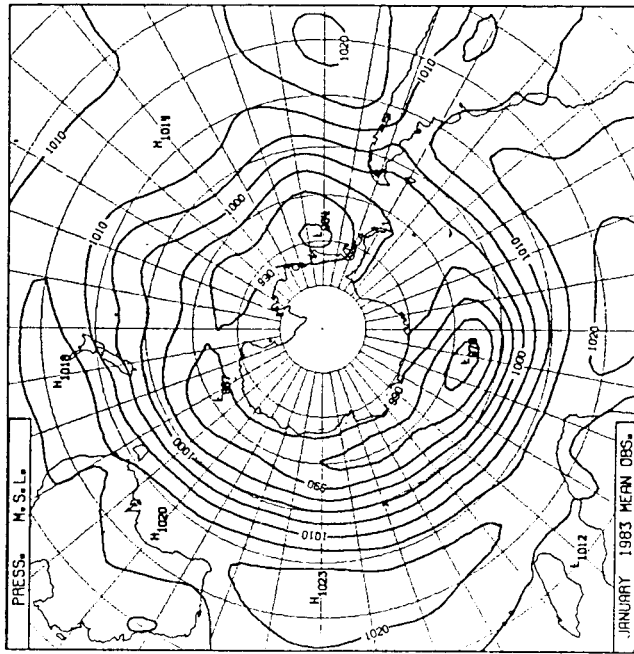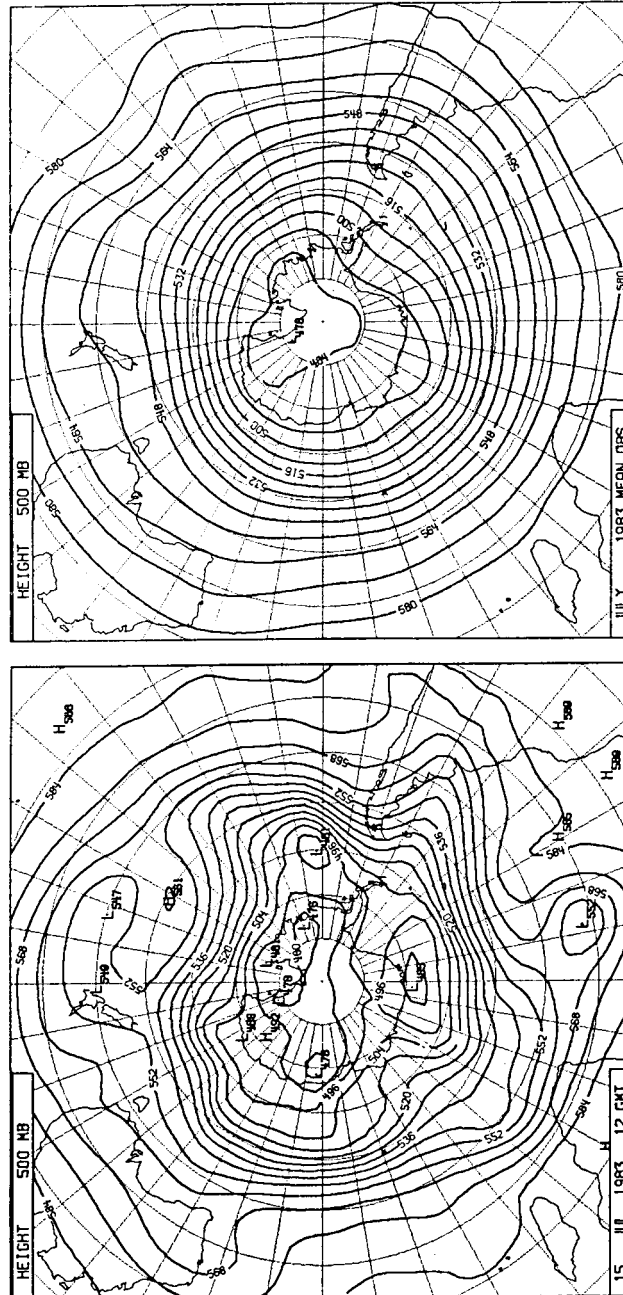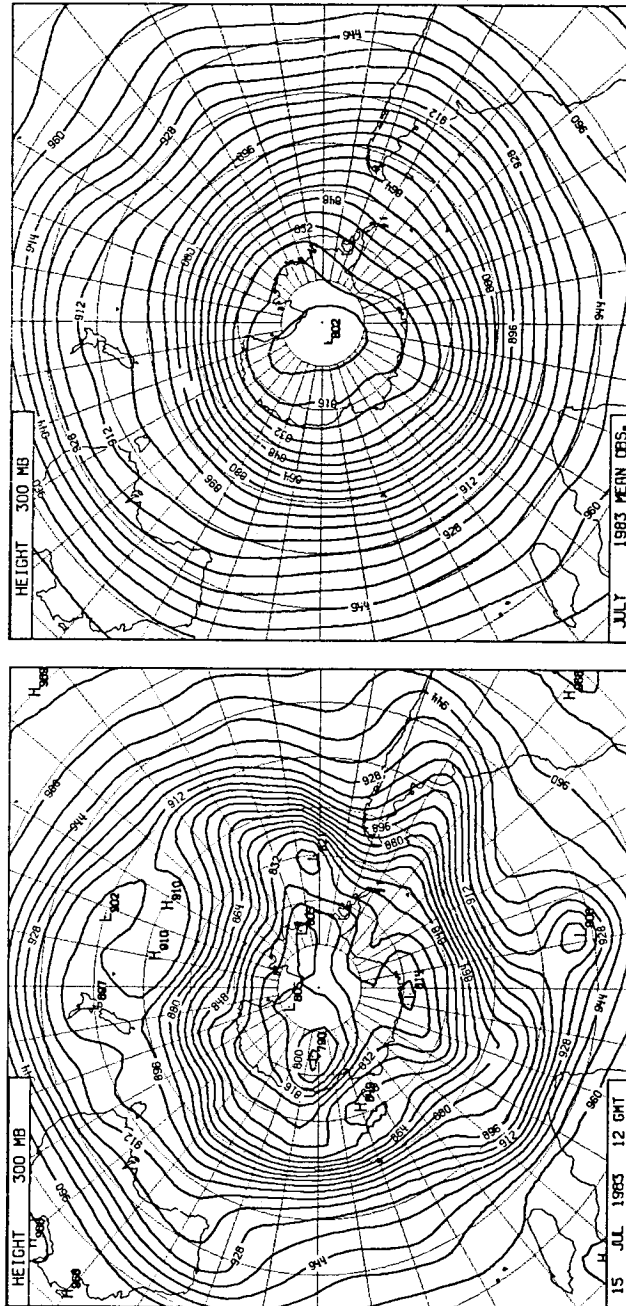
Figure 5.7: Same as Figure 5.3, but for Southern Hemisphere.
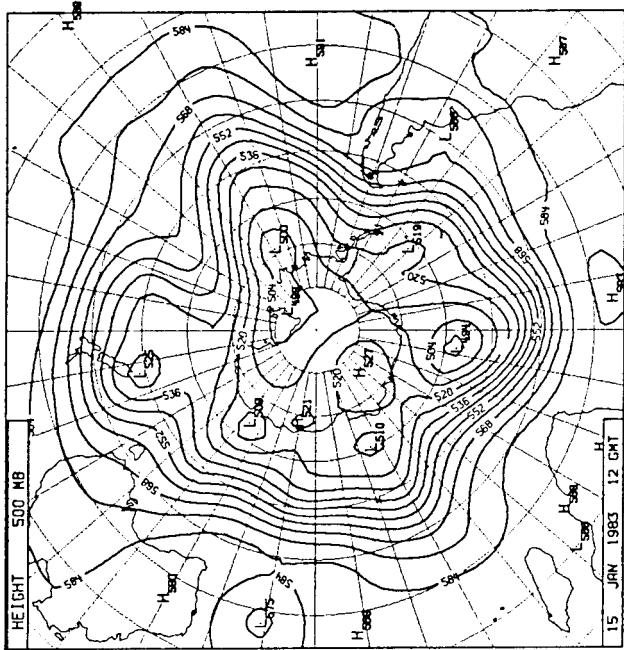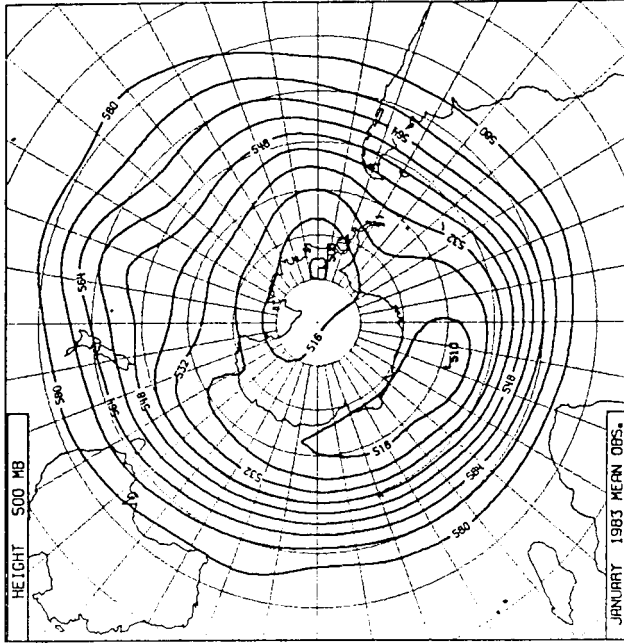
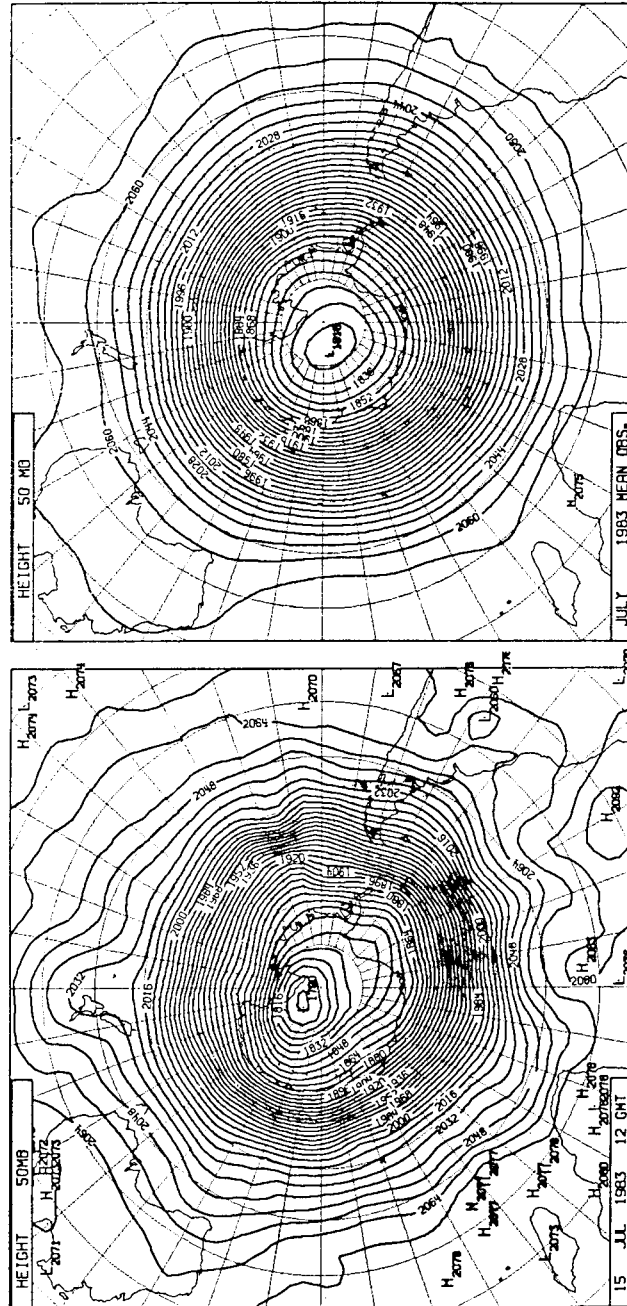Figure 5.8: Same as Figure 5.4, but for Southern Hemisphere.

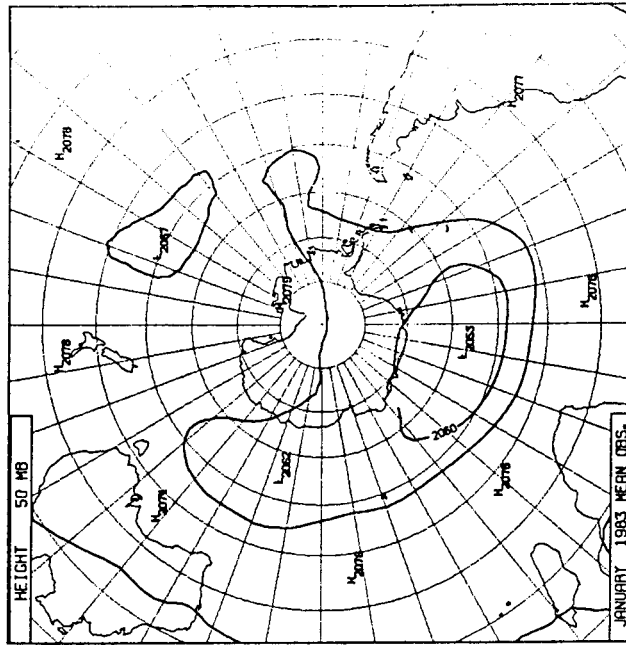Figure 5.9: Same as Figure 5.5, but for Southern Hemisphere.

Figure 5.2 shows maps of Northern Hemisphere sea level pressure. Note, for example, the following:

1. Daily maps show more fine-scale structure than do monthly means implying that fine-scale structure is associated with shorter time scales than a month.

2. The intensity of structures is greater in winter than in summer.

3. Note the large-scale lows over the oceans and highs over land in the January mean. Note the reversal of this pattern in the July mean.

In Figure 5.3, which shows height contours at 500mb, note the following:

1. Again note the loss of fine-scale structure in the monthly means.

2. Fine-scale structure (especially for January 15) tends to be less associated with closed contours than in Figure 5.2. This is *not* because these features are weaker at 500mb; rather, it is due to the stronger mean zonal[4] flow at 500mb[5].

3. Again features are less intense in summer than in winter.

4. Notice that in contrast to the results at the surface, the phase of the waves in the monthly mean maps is much the same in both January and July.

Turning to Figure 5.4, which shows height contours at 300mb, we see a rather substantial similarity to Figure 5.3 except for a general intensification of the zonal mean flow and the eddies (deviations from the zonal mean).

In moving to Figure 5.5, which shows height contours at 50mb, from Figure 5.4, we are moving across the tropopause. We now see a close similarity between the daily maps and the monthly means indicating a relative absence of short-period features. We also see an increase in the dominant spatial scale. In the summer we see a pronounced reduction in both eddies and the zonal mean.

The reader can confirm from Figures 5.6-5.9 the presence of most of the above features in the Southern Hemisphere. However, the monthly means

---

[4]*Zonal* refers to the west-to-east direction along a latitude circle.

[5]The reader should make sure that he understands this point. If necessary, synthesize some contours for assumed wave and mean flow magnitudes.

show much less wave structure – presumably due to the relative absence of land in the Southern Hemisphere. Nevertheless, what wave structure there is in the monthly means for the Southern Hemisphere is much the same in both amplitude and phase for both January and July. In the Northern Hemisphere, the monthly mean waves were significantly stronger in January.

5.3 Zonal means

5.3.1 Seasonal means

As is evident from the preceding figures, maps display the superposition of many phenomena and systems. As such, they are difficult to analyze unambiguously. It is usual to process the maps in such a manner as to isolate some subset of what is going on. Taking monthly means is an example of such processing. Another example, of great historical importance in meteorology, is the taking of zonal means in order to study the height and latitude variations of such means. Figures 5.10 and 5.11 show the meridional sections of zonally averaged zonal wind and temperature for each season (from Newell *et al.*, 1972).
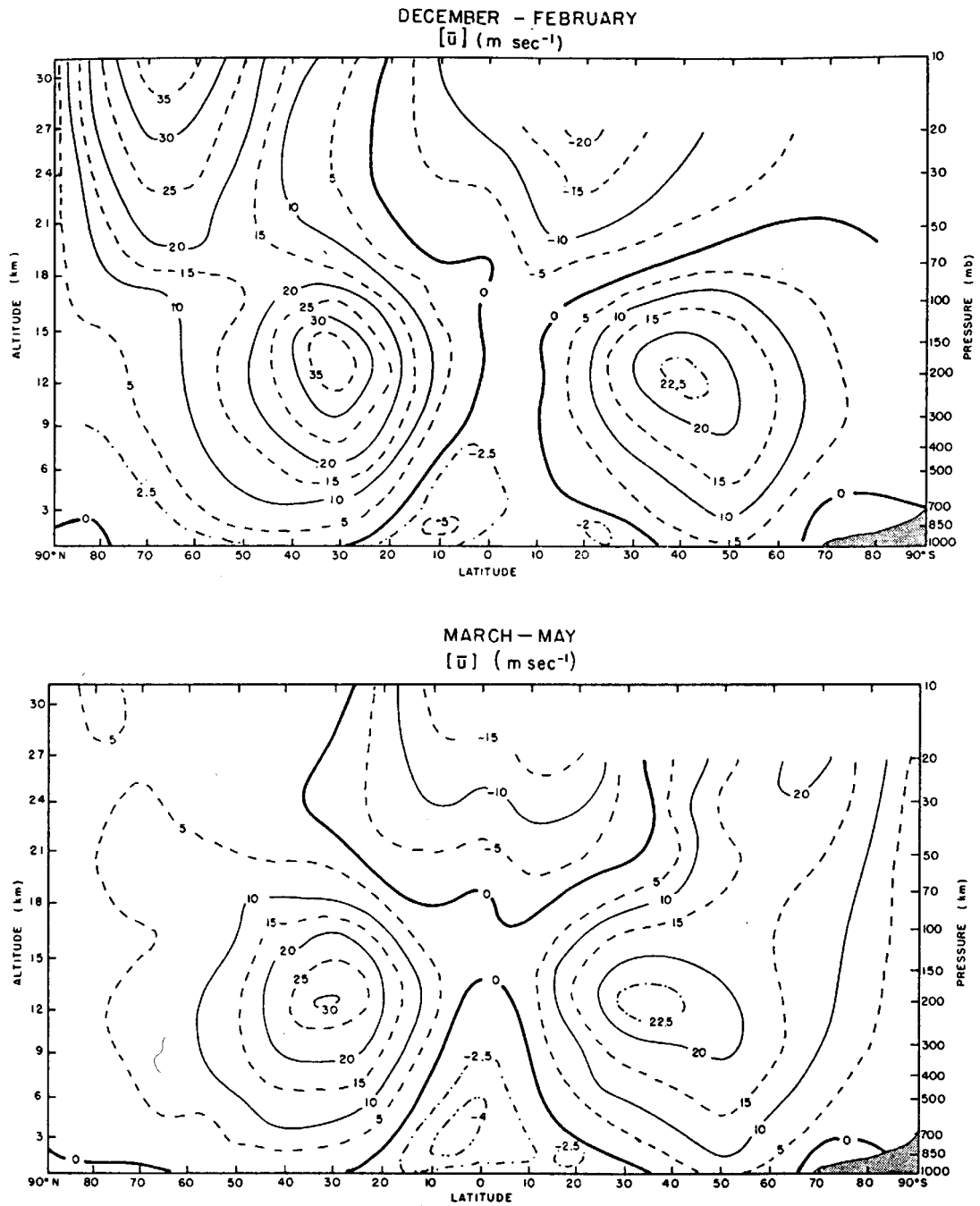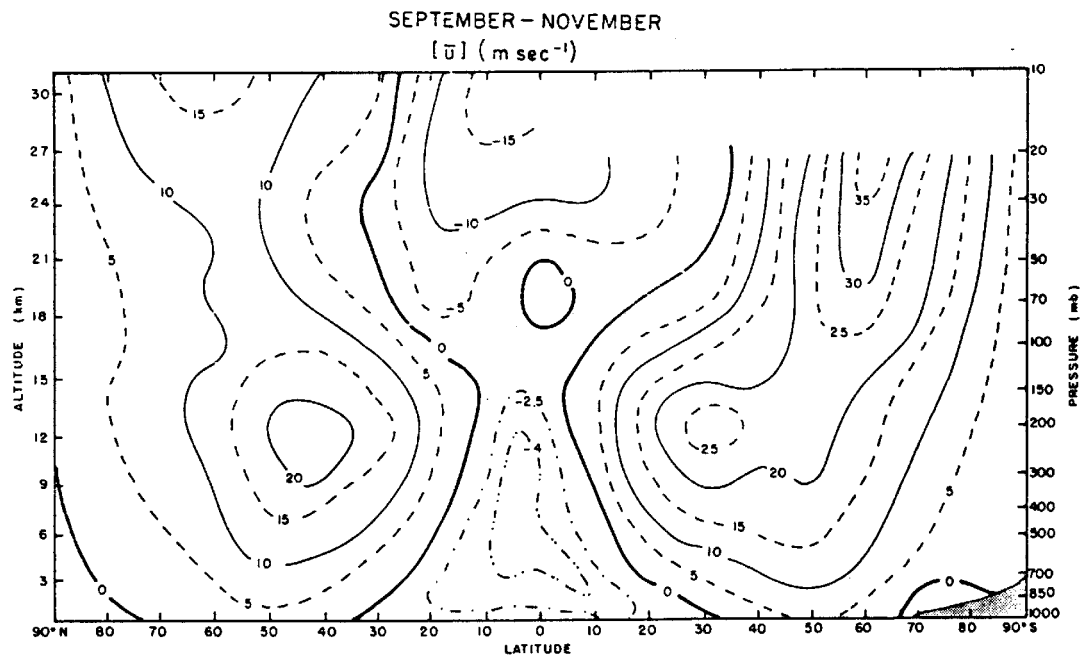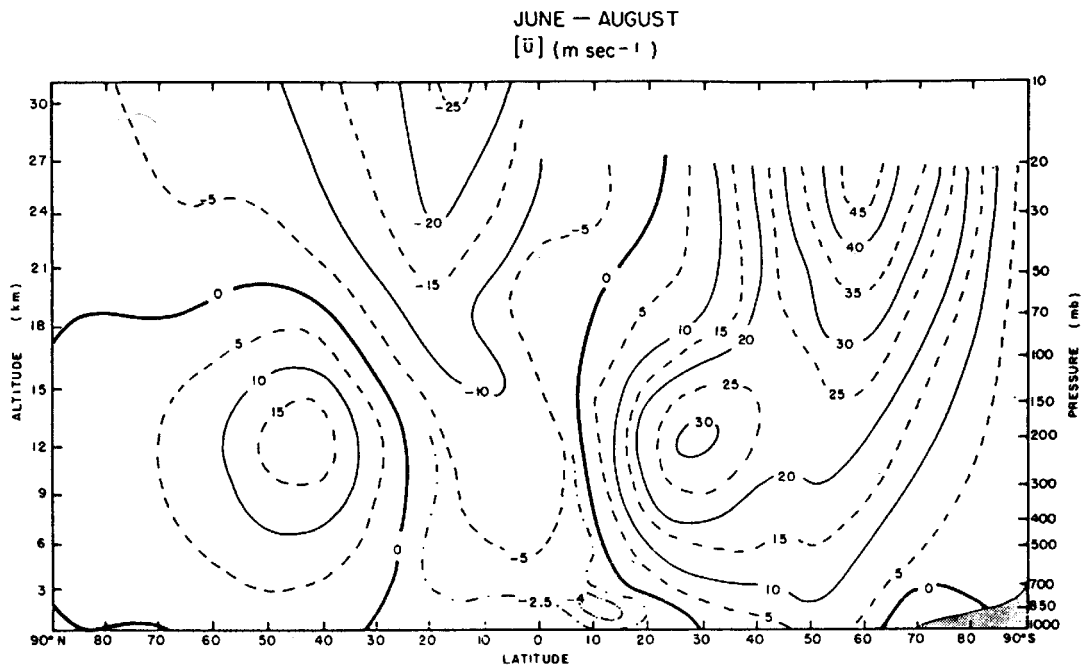
Figure 5.10: Meridional section of zonally averaged zonal wind for each of the four seasons (from Newell, *et al.*, 1972).

JUNE — AUGUST
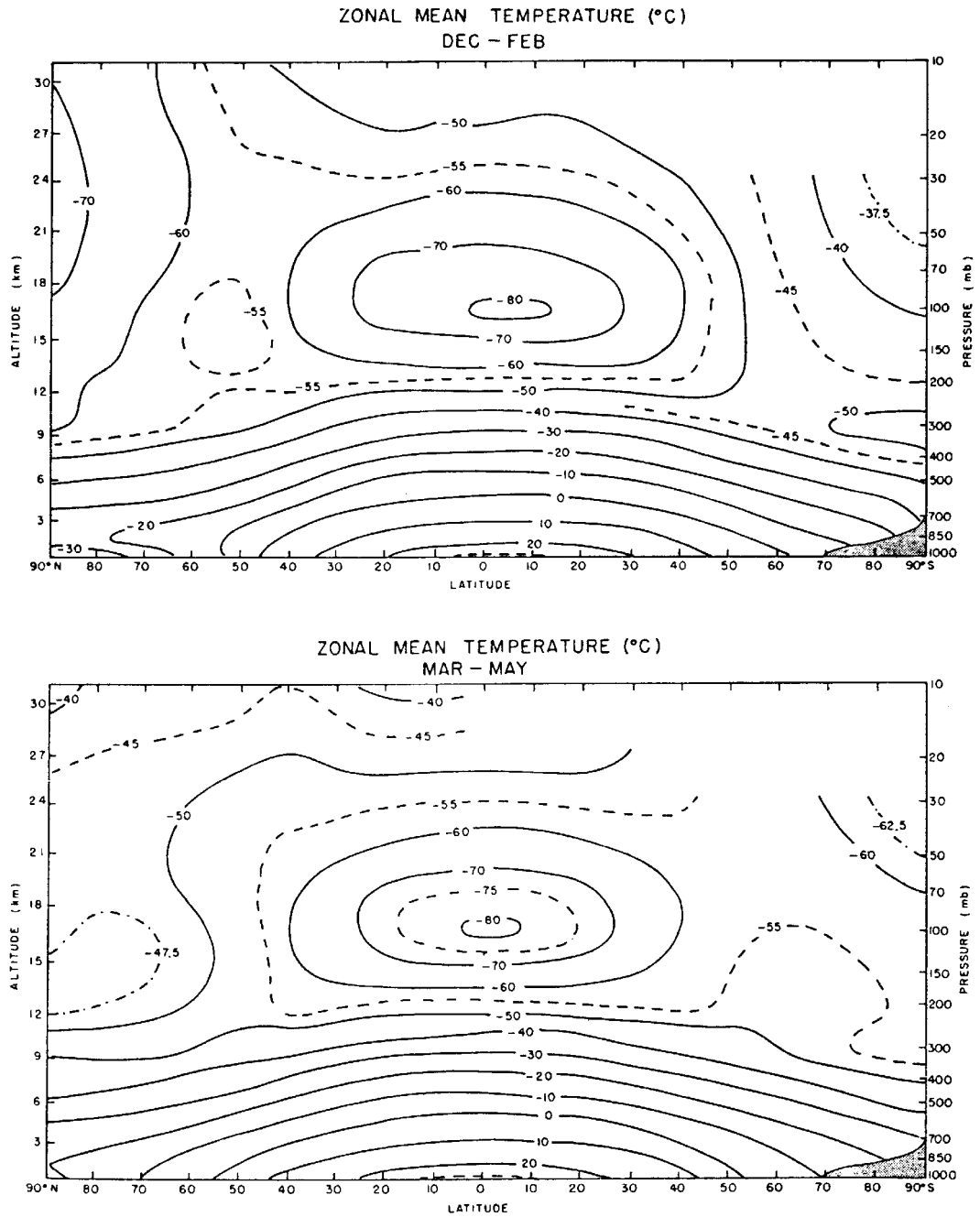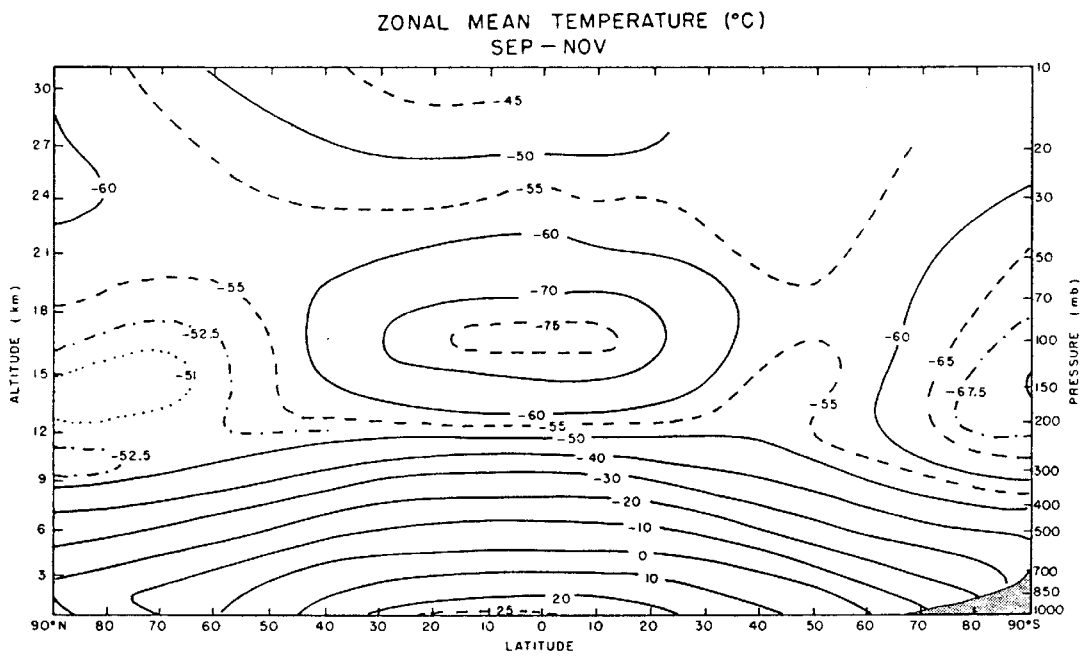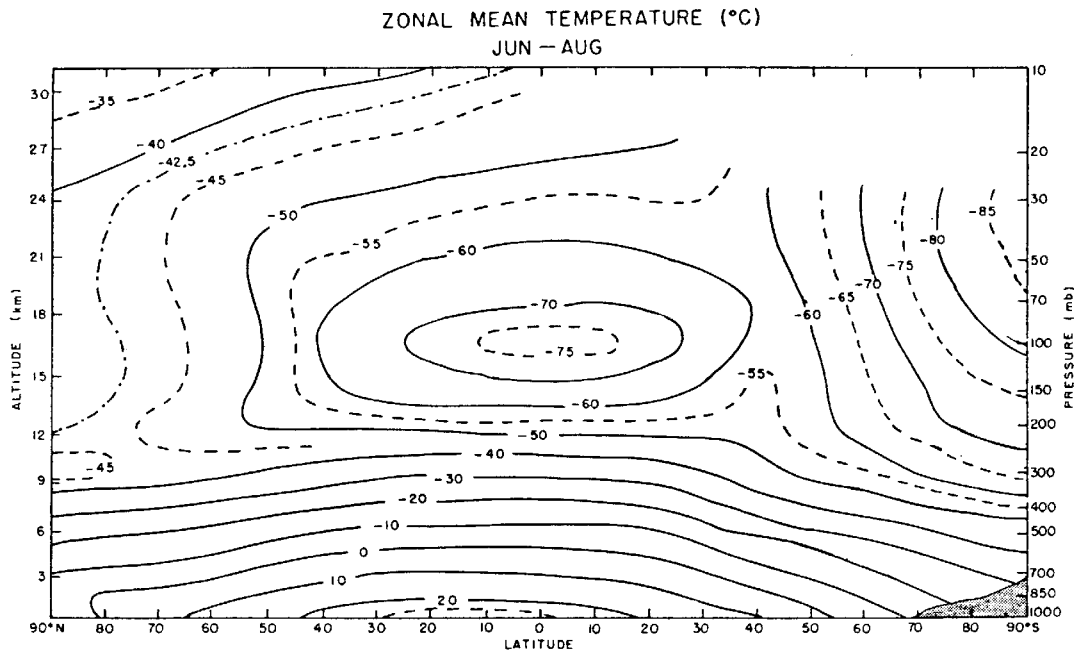[ū] (m sec⁻¹)

SEPTEMBER — NOVEMBER
[ū] (m sec⁻¹)

Figure 5.11: Same as Figure 5.10, but for zonally averaged temperature.

ZONAL MEAN TEMPERATURE (°C)
JUN — AUG

ZONAL MEAN TEMPERATURE (°C)
SEP — NOV

The following are a few of the features which may be noted in these figures:

1. Regardless of season, surface winds tend to be easterly (from the east) within 30° of the equator and westerly poleward of 30°. Surface easterlies tend to be stronger on the winter side of the equator.

2. The midlatitude troposphere is characterized by westerly jets in both hemispheres. The jet maxima occur at about 12km altitude (~ 200mb). The winter maxima are stronger ($\sim 30 - -50$m/s) and occur near 30° latitude. The summer maxima are weaker and occur further poleward ($\sim 45°$ latitude).

3. In the winter stratosphere, there is also a polar night westerly jet centered near 60°. This jet is generally stronger in the Southern Hemisphere winter. It also lasts longer there. What might be going on?

4. Zonally averaged zonal winds and temperatures are pretty nearly in thermal wind balance. Thus, below 12km, where westerly flow is increasing with altitude, temperatures are decreasing away from the equator. However, above 12km, where westerly winds are decreasing with height, we have minimum temperatures at the equator. In the summer hemisphere, temperatures increase monotonically to the pole. However, in the winter hemisphere, a temperature maximum is reached in the lower stratosphere near 50° and the temperature falls rapidly poleward of this latitude (consistent with the presence of the polar night jet).

Figure 5.12 shows the winter–summer differences in zonally averaged temperature (taken from Newell *et al.*, 1972). Not surprisingly, these differences are small in the tropics and large at high latitudes. Notice as well the differences between the Northern and Southern Hemispheres (Why?).

5.3.2   Zonal inhomogeneity and rôle of analysis

The zonal wind at any given longitude will, of course, differ from the zonal average. December–February sections for various longitudes are shown in Figure 5.13; June–August sections are shown in Figure 5.14. Inhomogeneity is greatest in the Northern Hemisphere where
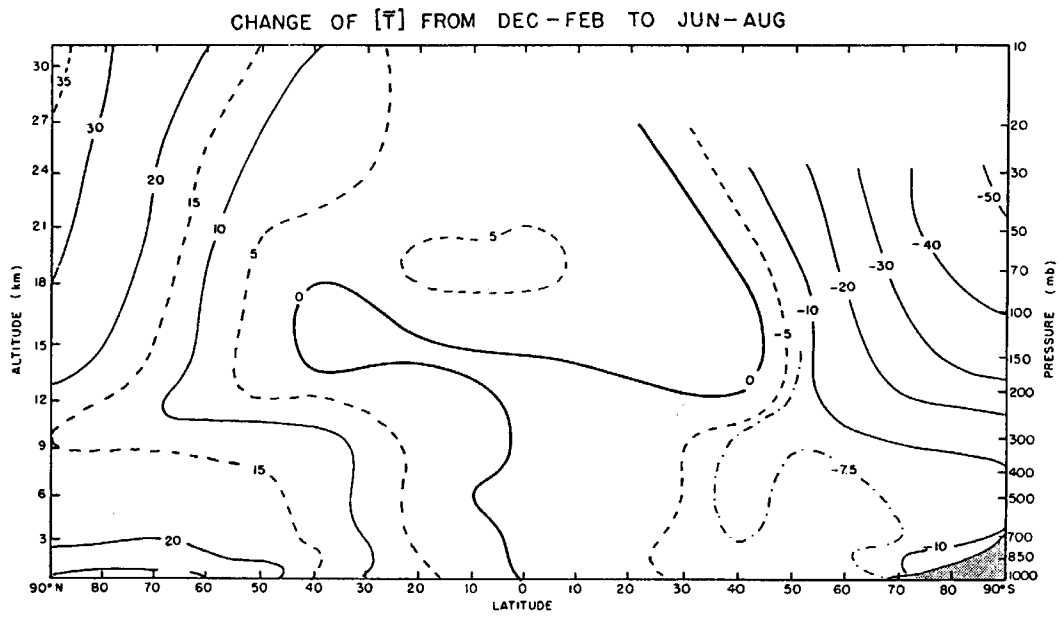
Figure 5.12: Winter–summer differences in zonally averaged temperature (from Newell *et al.*, 1972).
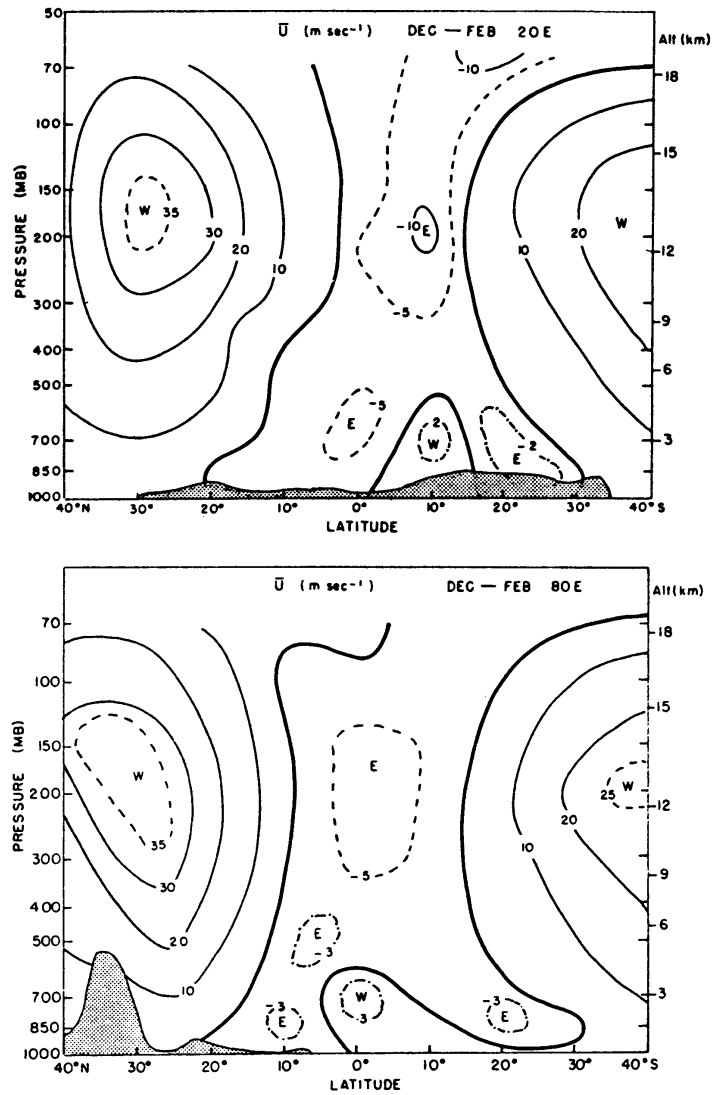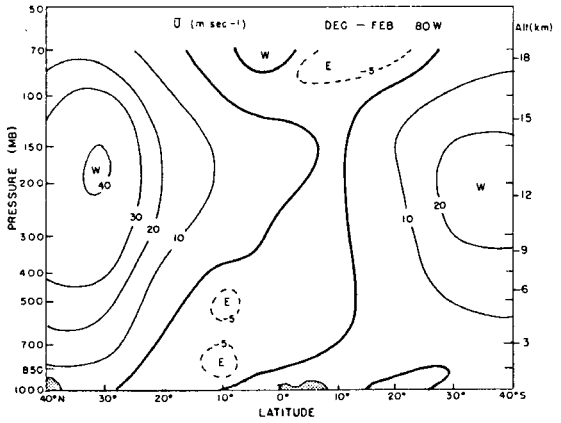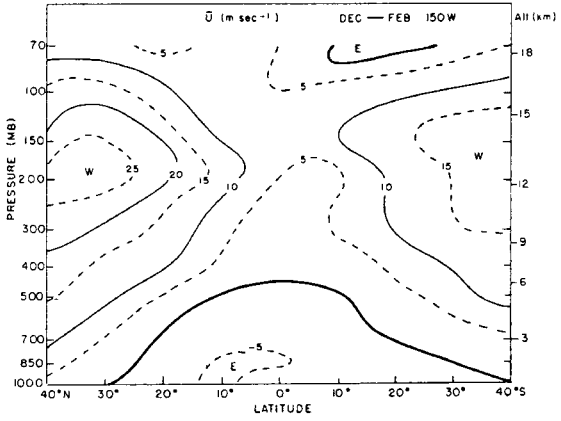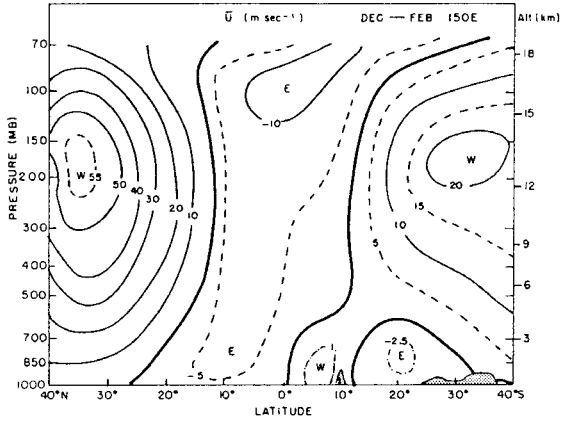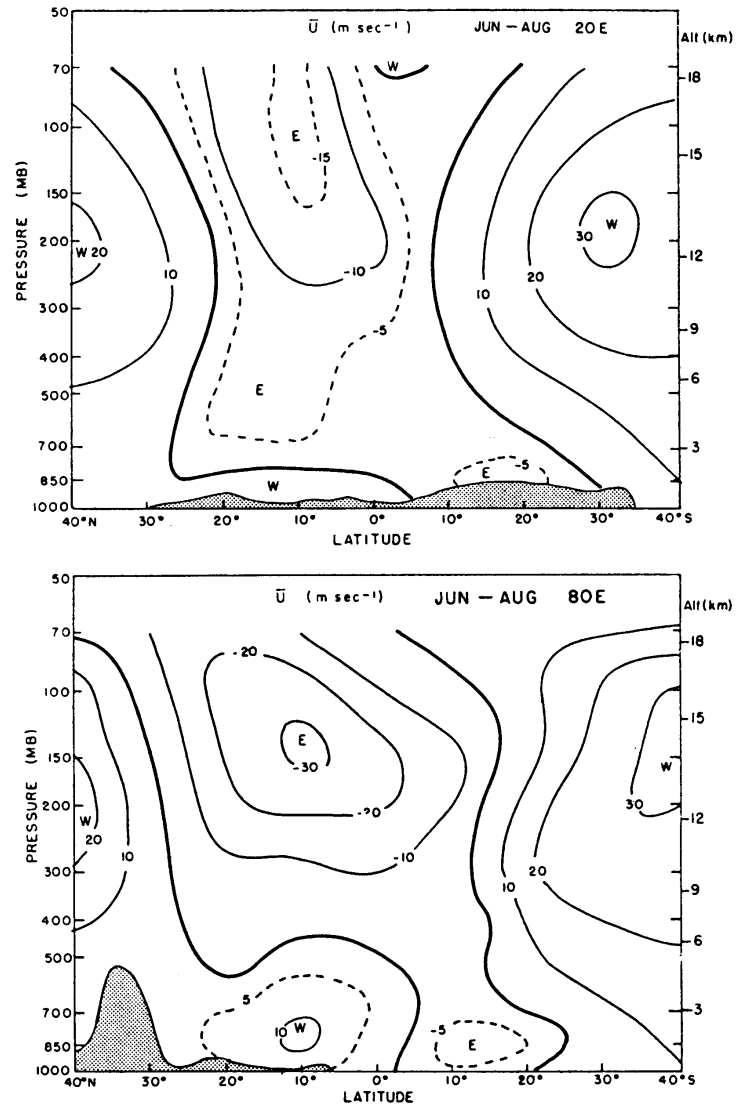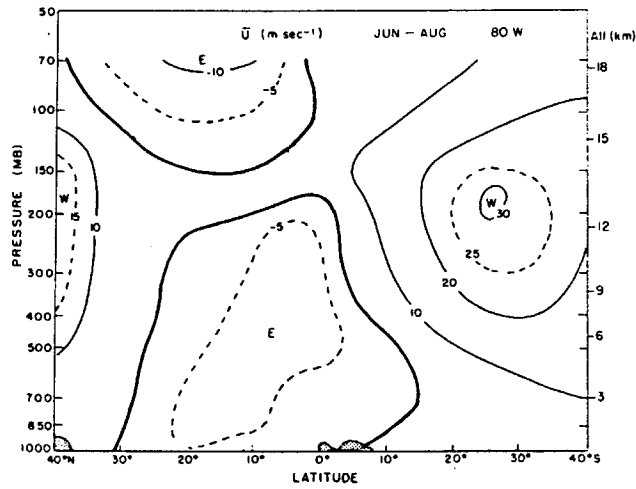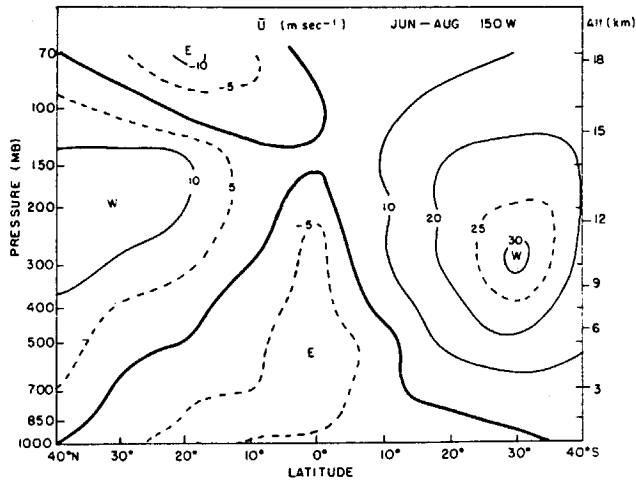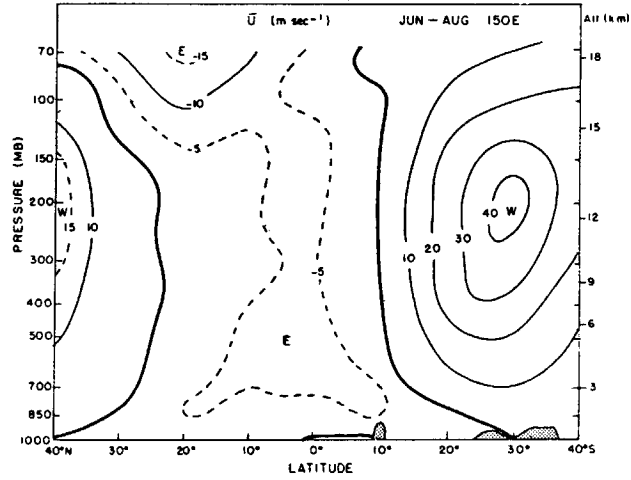
Figure 5.14: Meridional sections of June-August zonal winds at specific longitudes (from Newell *et al.*, 1972)

values about double the zonal average may be found at some longitudes. This is also seen in Figure 5.15, where Northern Hemisphere winter contours of zonal wind at 200mb are shown. Also, as already noted in the beginning of this chapter, the data we are dealing with are analyzed data. Figure 5.15 shows the results of two different analyses (GFDL and NMC) and the differences between the two analyses. The differences are on the order of 10–20%, which is a plausible measure of our uncertainty.

5.3.3   Middle atmosphere

So far we have concentrated our attention on the zonally averaged zonal wind and temperature in the troposphere and lower stratosphere. Figure 5.16 shows these quantities up to the lower thermosphere. The data is primarily Northern Hemisphere data; the right and left halves of the sections correspond to winter and summer. Note the monsoonal nature of the mesospheric winds: winter is characterized by westerlies; summer by easterlies. Note also that temperature increases monotonically from the winter pole to the summer pole at the stratopause (*ca.* 50km), but at the mesopause (*ca.* 83km) the temperature is increasing monotonically from the summer pole to the winter pole. This is again consistent with thermal wind balance.

5.3.4   Quasi-biennial and semiannual oscillations

Figure 5.16 assumes that stratospheric and mesospheric winds are dominated by an annual (12 month) cycle. Near the equator this turns out to be untrue. Figure 5.17 shows a time-height section of zonal wind at Canton Island (2°46′S) (which turns out to be characteristic of the zonal average). Note that zonal winds form a downward propagating wave-like structure with a period of about 26 months; this is referred to as the *quasi-biennial oscillation* which dominates the tropical zonal wind between 16km and 30km. The situation up to 56km is shown in Figure 5.18. Here we see that above about 32km, a *semiannual oscillation* is dominant. Figures 5.17 and 5.18 are based on monthly means. It turns out that stratospheric tropical zonal winds also sometimes display important short period oscillations. In Figure 5.19 we see an oscillation with a period of about 12 days. This has been identified as an *equatorial Kelvin wave*[6].

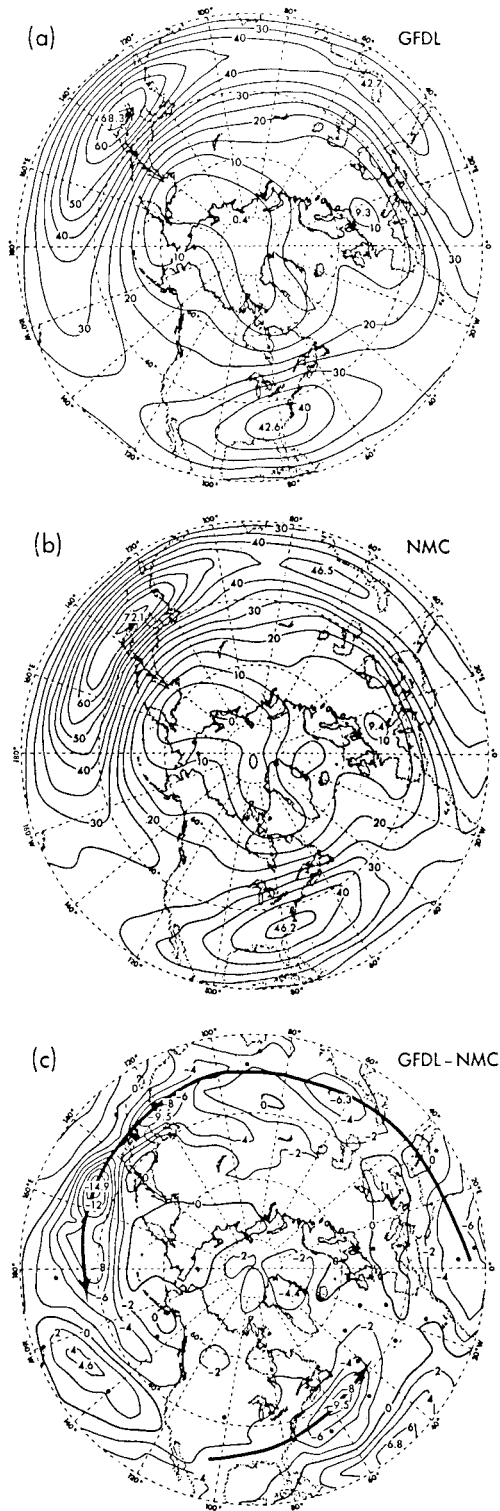[6]We will explain what this is in Chapter 11.

Figure 5.15: Northern Hemisphere contours of 200mb zonal winds for two different analyses (GFDL and NMC) as well as contours of the differences (from Lau and Oort, 1981).
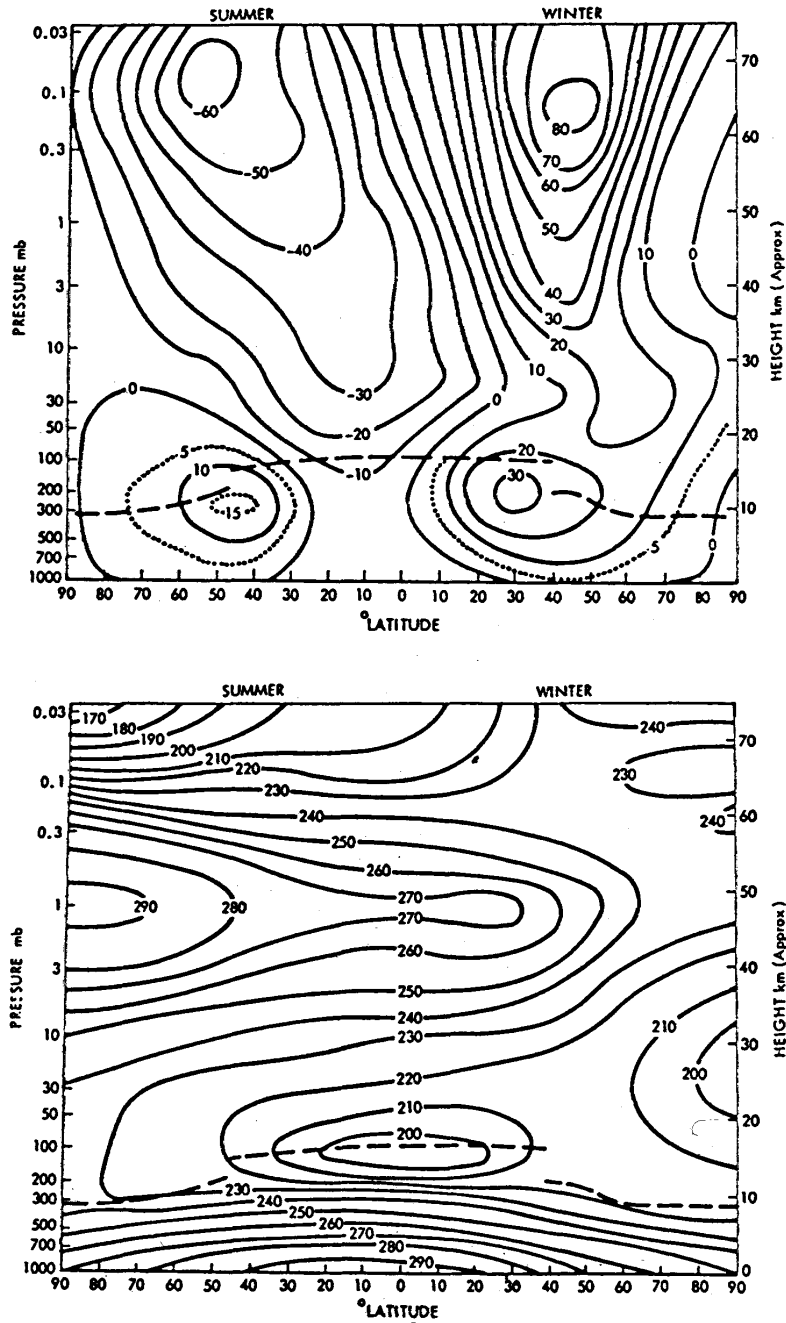
Figure 5.16: Zonally averaged zonal winds and temperatures up to the lower thermo-
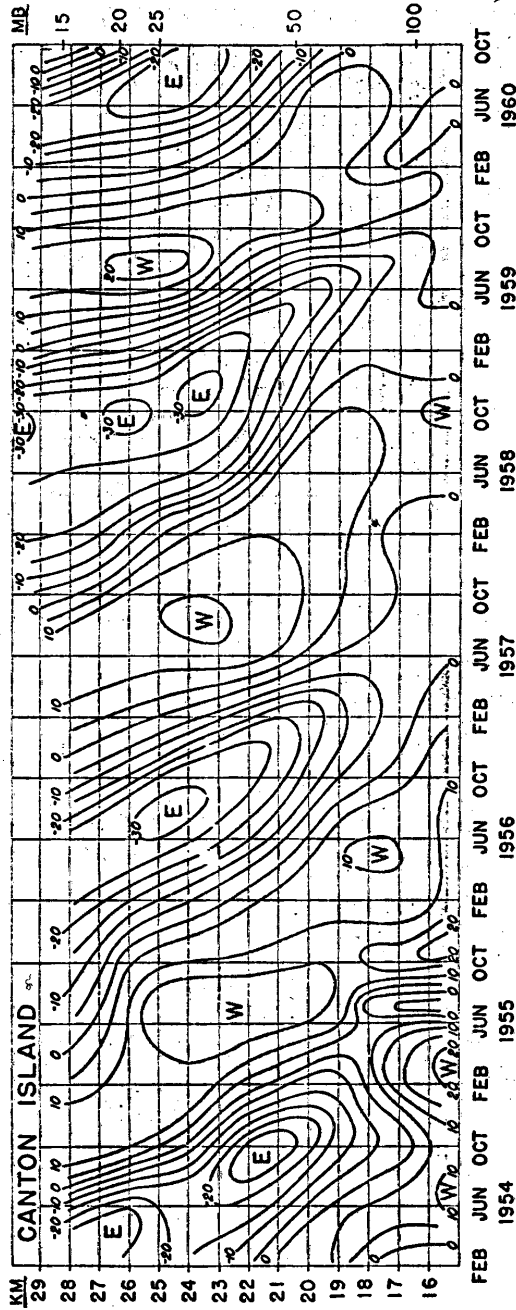sphere (from Andrews, Holton, and Leovy, 1987).

Figure 5.17: Time-height section of monthly–mean stratospheric zonal winds at Canton Island (2°46′S) (from Reed and Rogers, 1962).
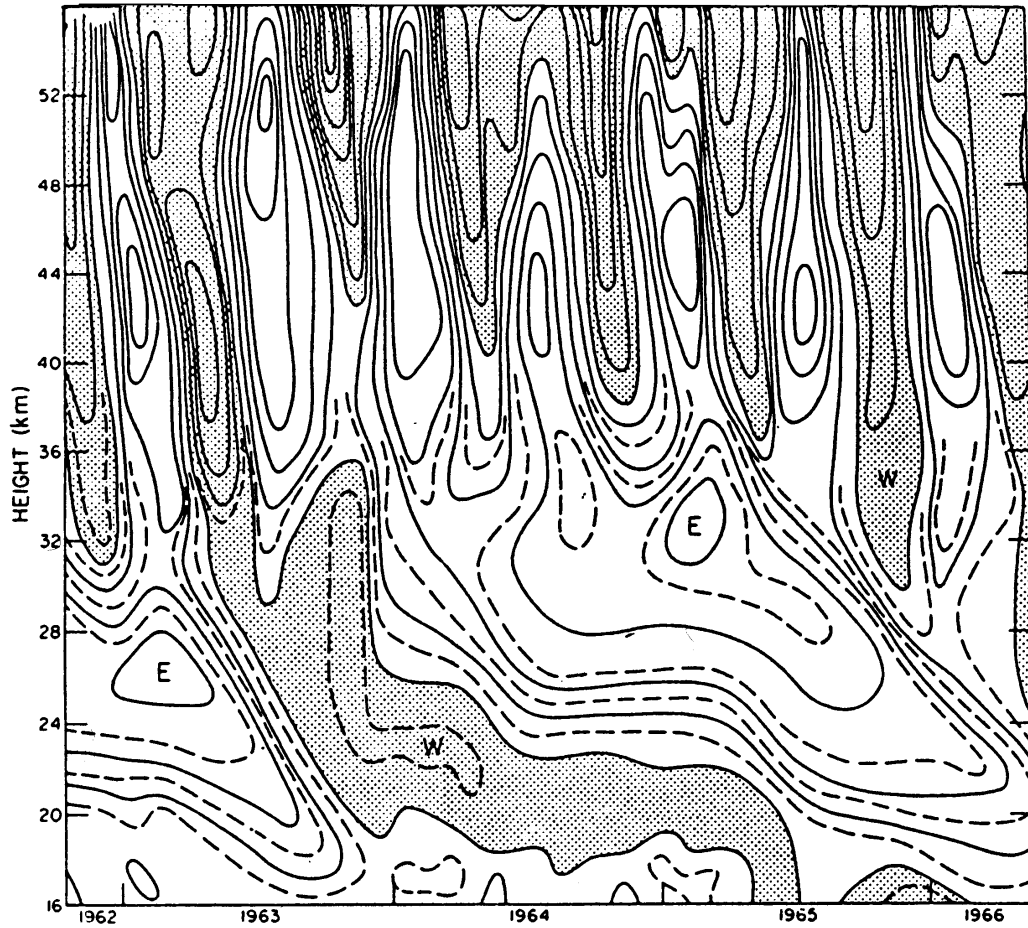
Figure 5.18: Time-height section of near-equatorial monthly mean zonal winds between 16km and 56km (from Wallace, 1973). The solid contour intervals are $10\,\mathrm{ms}^{-1}$. Shaded regions refer to westerlies and unshaded regions refer to easterlies.
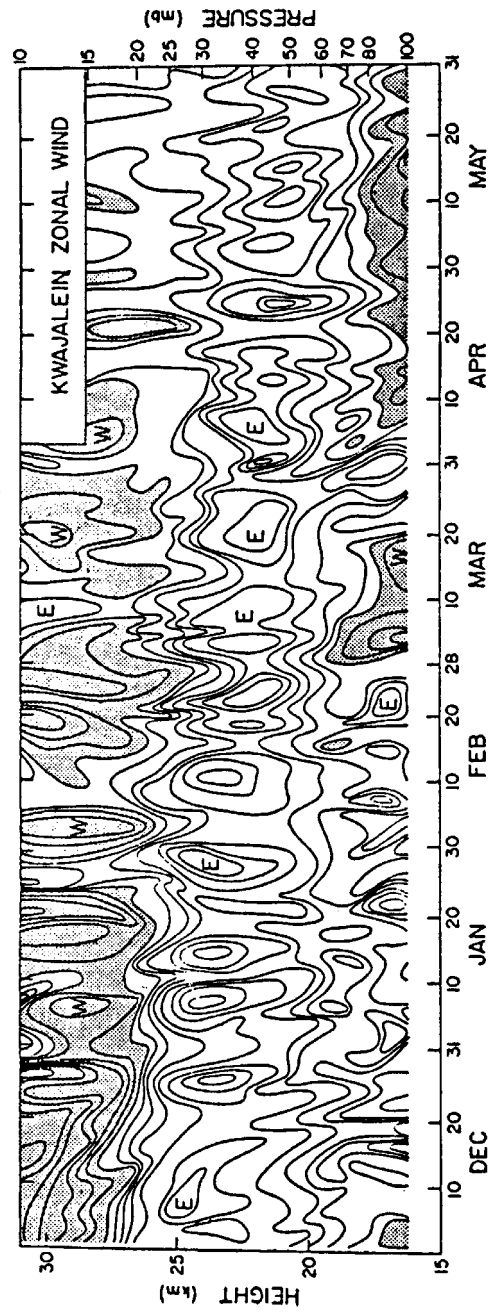
Figure 5.19: Time–height section of daily zonal winds over Kwajalein (from Wallace and Kousky, 1968). The contour intervals in Figure 5.19 are $5\,\mathrm{ms}^{-1}$.

5.3.5   Stratospheric sudden warmings

Figures 5.5 and 5.16 suggest a rather regular seasonal behaviour in the middle and high latitude stratosphere. However, occasionally (every 1–4 years or so) in the Northern Hemisphere this pattern breaks down rather spectacularly in a midwinter *stratospheric sudden warming* where the winter pattern breaks down and a summer pattern onsets – during the winter polar night. Figure 5.20 shows a Northern Hemisphere
map for January 25, 1957 – just prior to the onset of such a warming. The pattern is almost identical to that in Figure 5.5. (Note that North America is at the bottom of Figure 5.20, while it is at the left in Figure 5.5; note also that height in Figure 5.20 is in 100s of feet while in Figure 5.5 it is in tens of meters.) However, by February 4, 1957, Figure 5.21 shows a significant change: zonal wavenumber two has amplified strongly and seems to have drifted westward. This change is accompanied by a zonally averaged poleward heat flux which leads to the zonally averaged changes in zonal flow and temperature shown in Figure 5.22. Observe the change of the temperature minimum at the pole into a temperature maximum. Note also the change from Arctic westerlies to easterlies.

5.4   Short period phenomena

Finally we return briefly to our initial comment on the omission of shorter scale phenomena. It is increasingly recognized that some of these phenomena, in the form of vertically propagating waves, play an essential rôle in the large scale circulation. This will be discussed in later chapters. Such waves have been long noticed in rocket data, examples of which are shown in Figure 5.23. Notice the large amplitude perturbations ($\sim 20°$C) with vertical wavelengths of from 10–15km. These perturbations tend to become obvious at lower altitudes in winter. Rocket data for day–night temperature differences are also of some interest. Examples are shown in Figure 5.24. What stands out in these figures is the very large day–night differences observed in the upper mesosphere ($O(20°$C$)$) and the fact that as often as not, the night is warmer. The reader should consider what this implies about how the atmosphere behaves – and, in particular, how the atmosphere 'knows' when it is day or night. The implications are by no means restricted to the upper atmosphere.
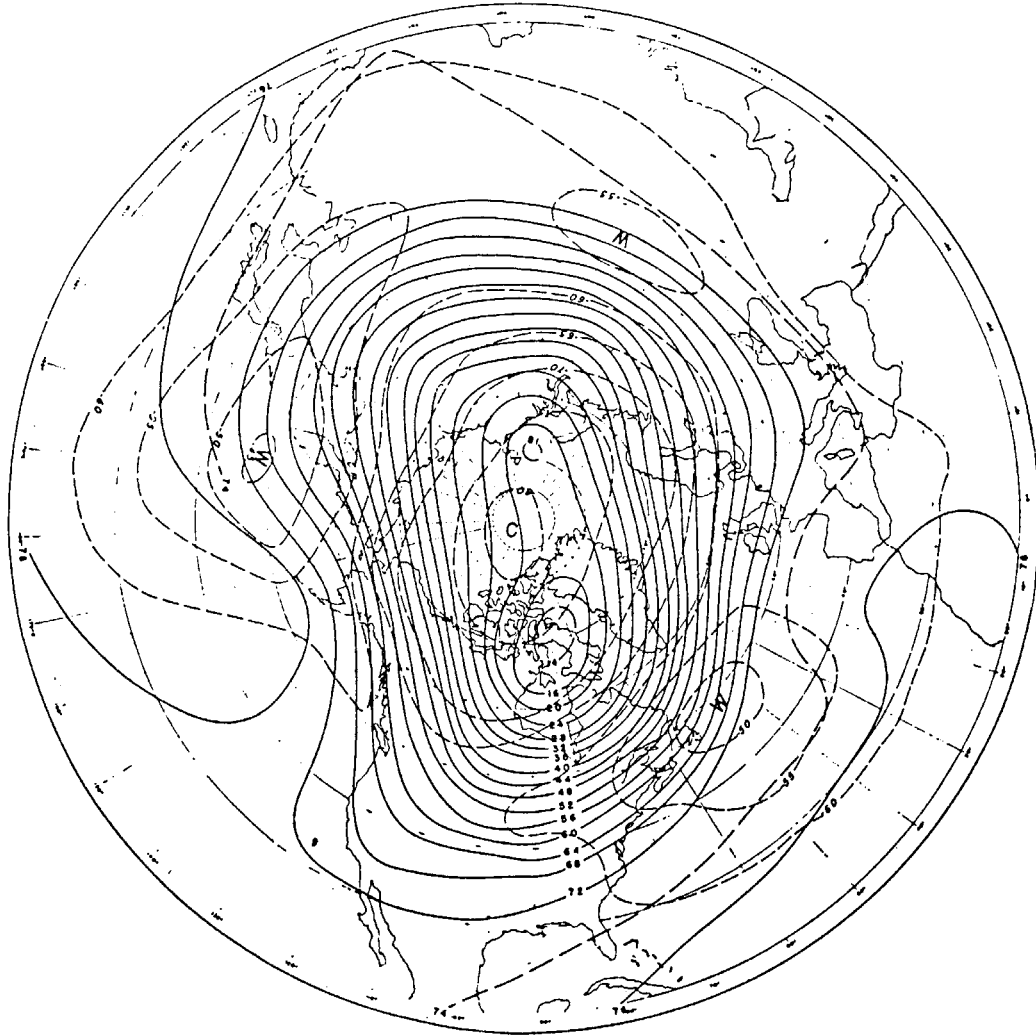
Figure 5.20: Northern Hemisphere 50mb height map for January 25, 1957 (from Reed, Wolfe, and Nishimoto, 1963). The solid contours refer to height in 100's of feet. The dashed contours refer to temperature in ^oC. The solid contours refer to height in 100's of feet. The dashed contours refer to temperature in units of $^\circ$C.

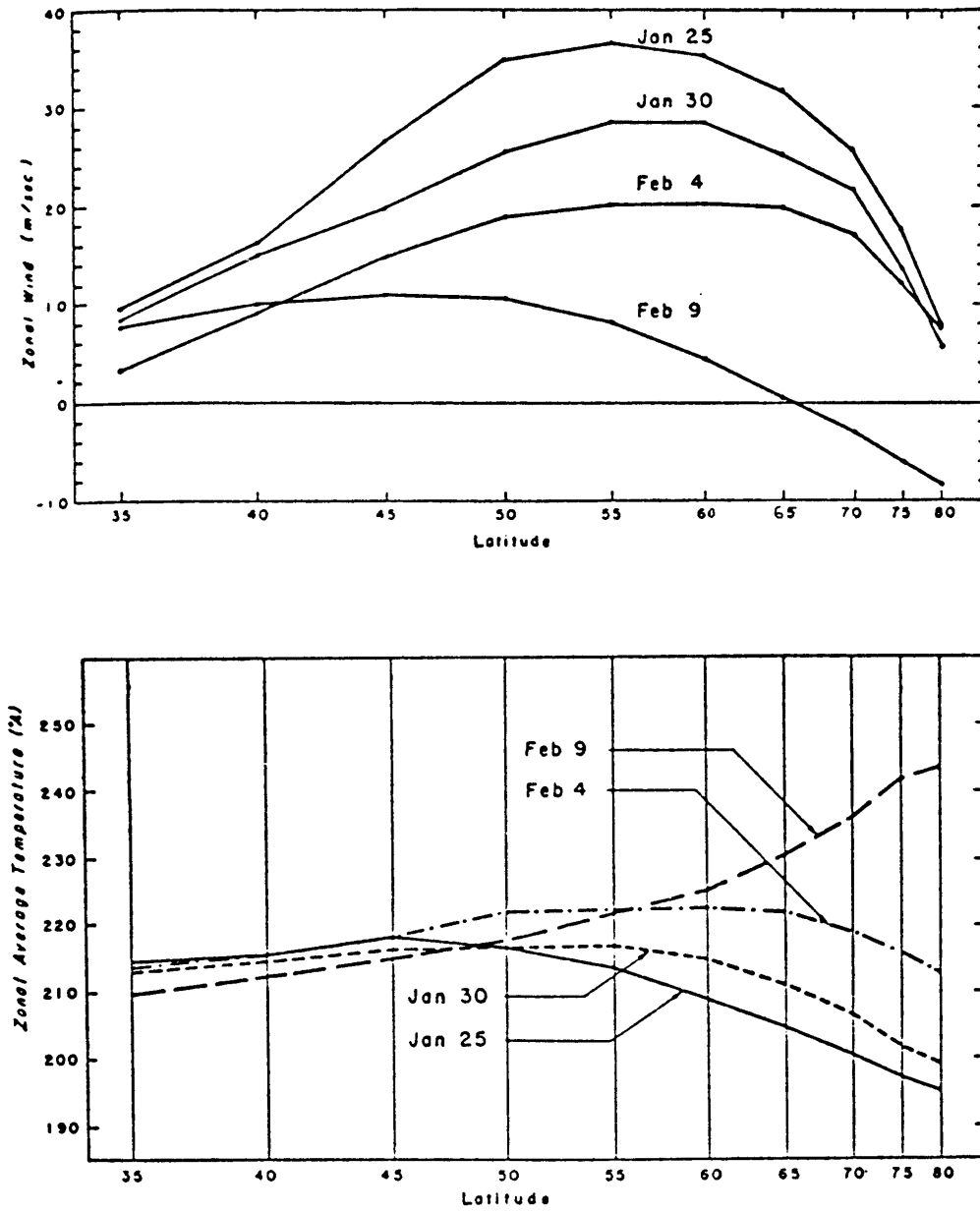Figure 5.21: Same as Figure 5.20, but for February 4, 1957.

Figure 5.22: Zonally averaged zonal winds and temperatures at 50mb as functions of latitude for various times in the course of a sudden warming (from Reed *et al.*, 1963).
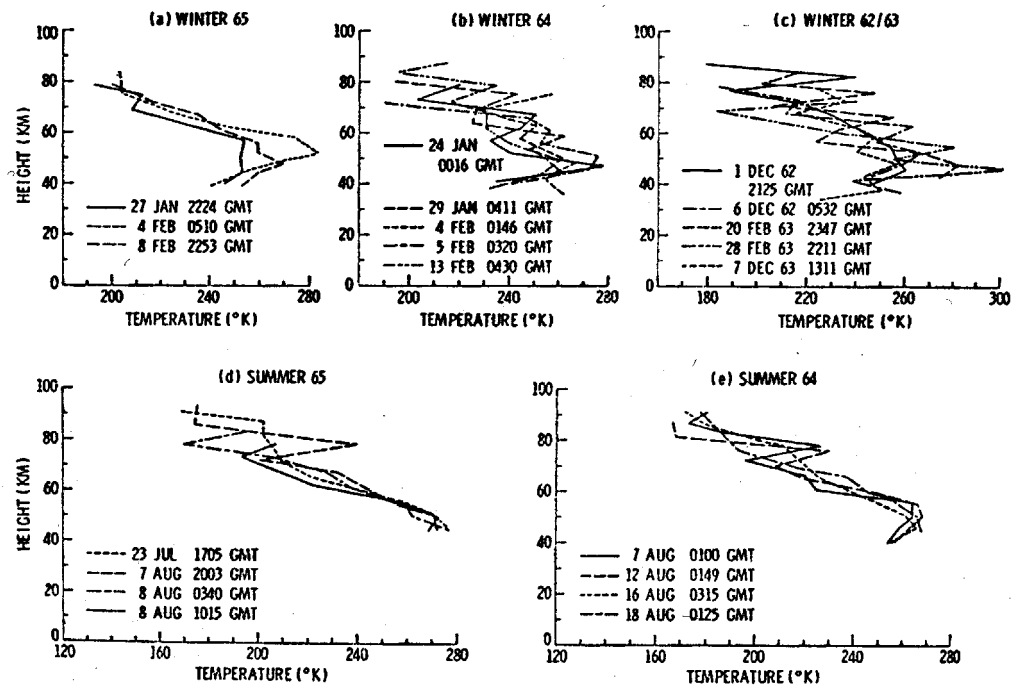
Figure 5.23: Rocket soundings of temperature over Wallops Island (38°N) (from Theon *et al.*, 1967).
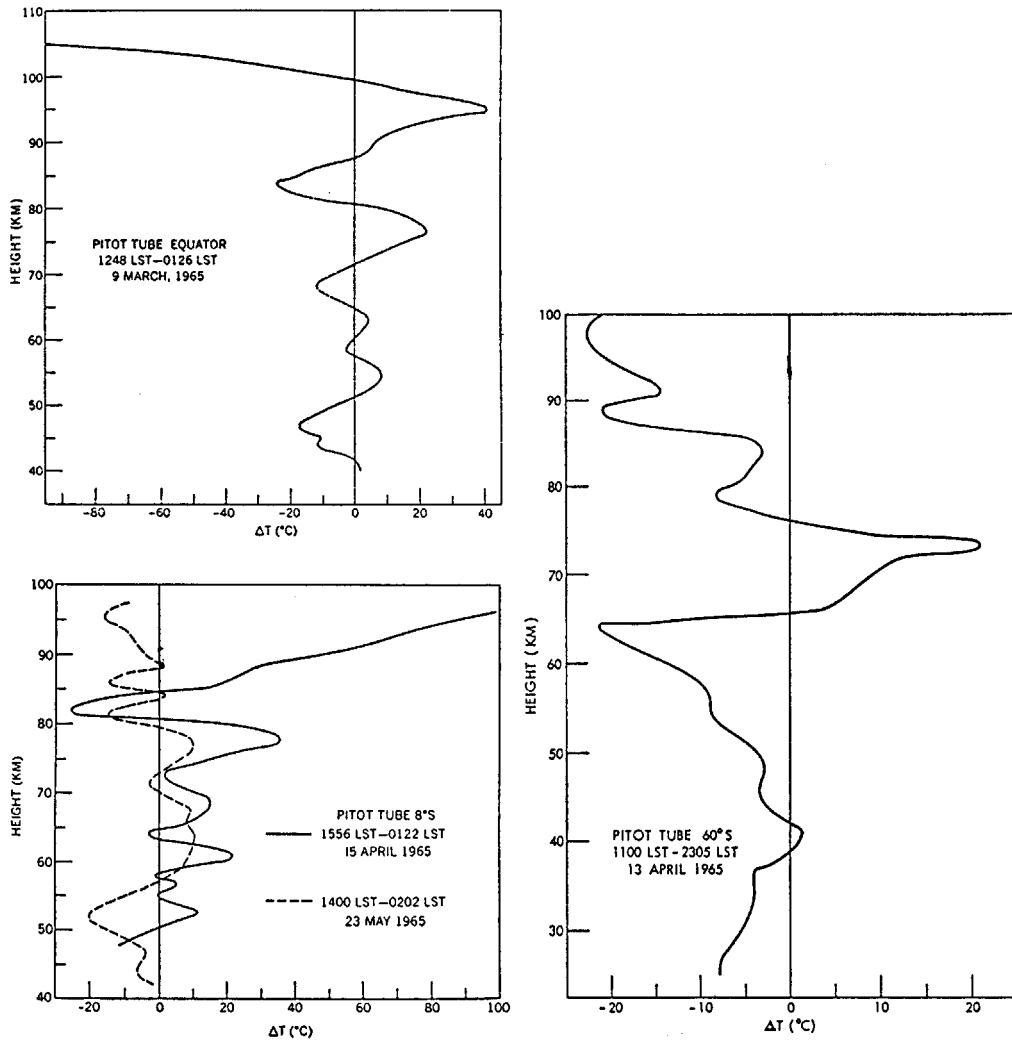
Figure 5.24: Day–night temperature difference profiles obtained from rockets (from Theon *et al.*, 1967).