Chapter 4 Results

4.1 The Area-Averaged Zonal Wind Time Series

The zonal wind pattern in the lower stratosphere above the Malaysian region obtained from the NCEP/NCAR Reanalysis Monthly Mean data shows the well-known QBO feature (see Figure 4.1(a)). This zonal wind pattern develops into a more complex feature extending downwards into the troposphere. The QBO feature disappears below the 100-hPa level, instead of it, the annual feature becomes more and more prominent towards the lower troposphere, and becomes especially distinct below the 500-hPa level. After filtering out those oscillations with periods greater than 55 months and smaller than 16 months by using a binomial band pass filter having a frequency response function as shown in Figure 3.2, the QBO feature becomes more distinguishable throughout the whole troposphere and stratosphere (See Figure 4.1(b)). Nevertheless, the amplitude of the QBO-like feature in the troposphere is much smaller than that of the actual QBO in the lower stratosphere. The magnitude of the amplitude of the QBO-like feature in the troposphere is less than 5 m/s in both the westerly and easterly wind regimes. The argument of the QBO-like feature in the troposphere being an artifact of filtering doesn't arise as power spectral analyses of unfiltered zonal wind time series shown in section 4.2.4 indicate that this QBO-like feature is significant at the 90% confident level.

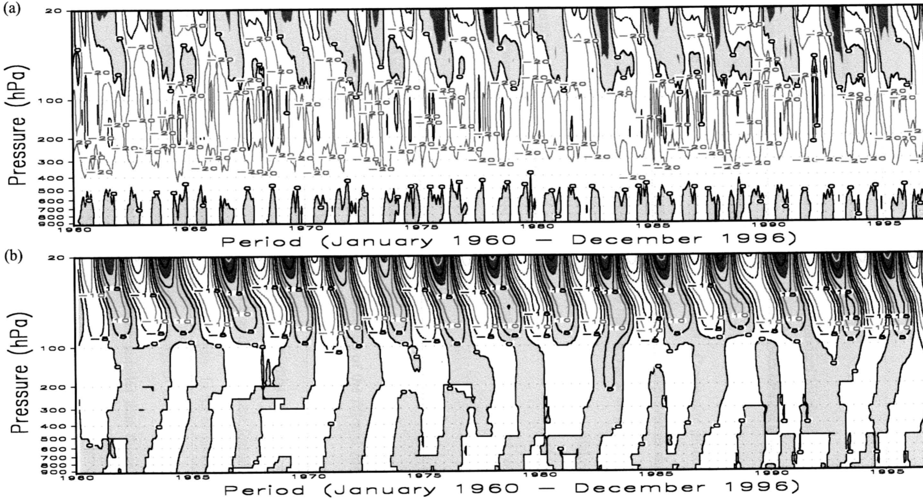


Figure 4.1 Vertical time section of (a) actual and (b) band-pass filtered monthly mean zonal winds above the Malaysian region. The westerlies are shaded. Contours are drawn at 20 m/s (actual) and 5 m/s (filtered) respectively. Tick marks of years indicate Januaries.

4.2 Zonal Wind Time Series at Standard Levels

4.2.1 Data

The zonal wind time series of all the 10 standard levels above the Malaysian region at 20, 50, 100, 200, 250, 300, 500, 700, 850 and 925 hPa are shown in Figures 4.2 and 4.3. Superimposed on each of the raw zonal wind time series in Figure 4.2 is the respective band-pass filtered zonal wind time series. Composite plots of the filtered zonal wind time series of four adjacent levels are each redisplayed as shown in Figure 4.3. It can be clearly seen that these zonal wind time series at all the 10 standard levels oscillate almost coherently. A closer examination reveals that they make around 15-17 complete oscillations in a period of 440 months from March 1960 to October 1996. In another words, the average period of these oscillations is 27.5 months, which is within the period of the QBO.

4.2.2 Autocorrelation Function

Figure 4.4 shows the autocorrelation functions of the filtered zonal wind time series with maximum lags of 30 months. The autocorrelations of the 20 and 50-hPa lower stratospheric zonal winds are significantly positive with coefficients approximately 0.83 at lags of 28 months. This clearly shows that the dominant feature in the lower stratosphere is the QBO with a mean period of 28 months. In the troposphere from 100 to 925-hPa levels, the autocorrelations are within a range of 0.17-0.41 at lags of 25-27 months. Although these autocorrelations are much smaller than those in the lower stratosphere are, it is still statistically significant at the 95% confident level to conclude that there is QBO-like feature having a mean period of 25-27 months at these levels. From the broad humps shown in the autocorrelation functions, these QBO-like

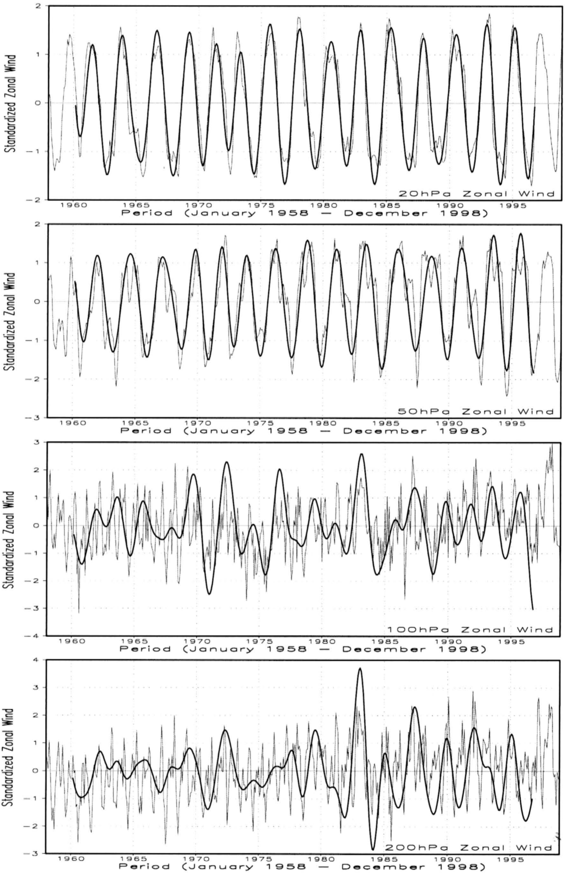


Figure 4.2 Standardized actual (thin lines) and band-pass filtered (thick lines) monthly mean zonal winds above the Malaysian region for a period of 41 years from January 1958 to December 1998. Tick marks of years indicate Januaries.

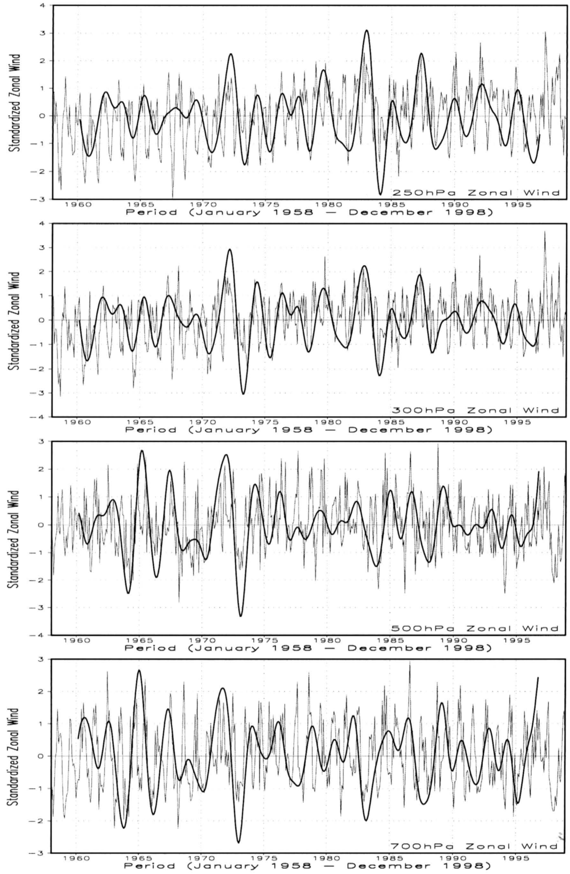
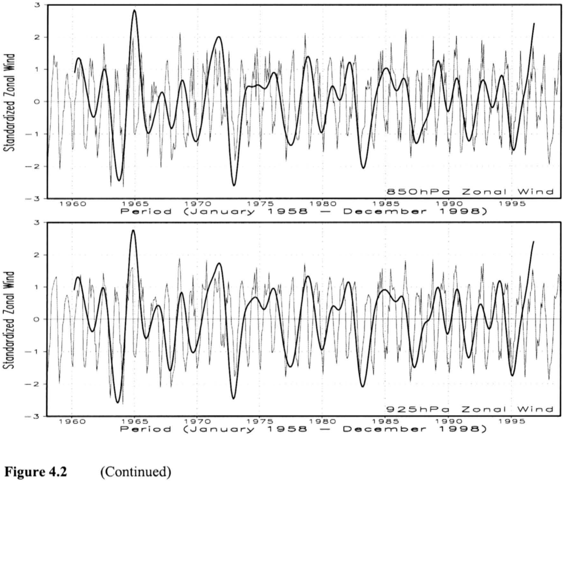


Figure 4.2 (Continued)



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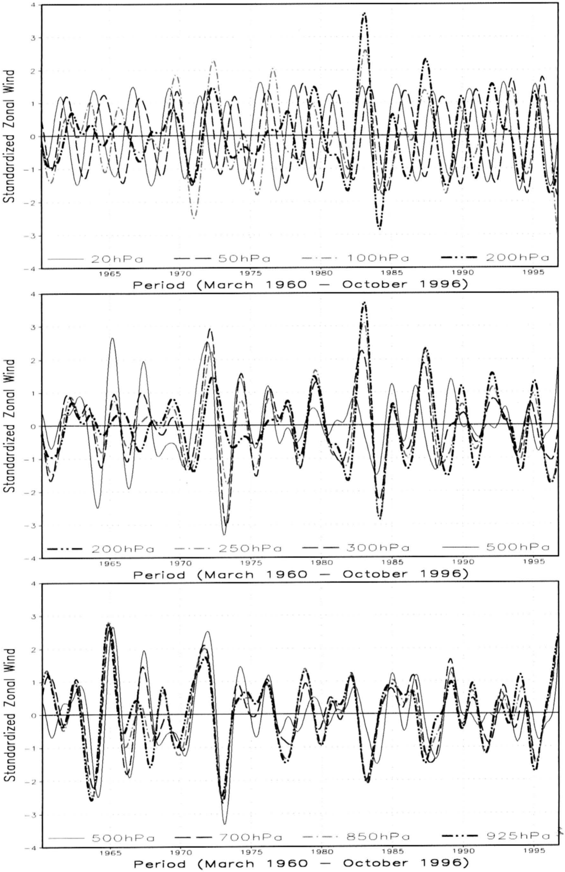


Figure 4.3 Composites of standardized band-pass filtered monthly mean zonal winds above the Malaysian region for a period of 440 months from March 1960 to October 1996. Tick marks of years indicate Januaries.

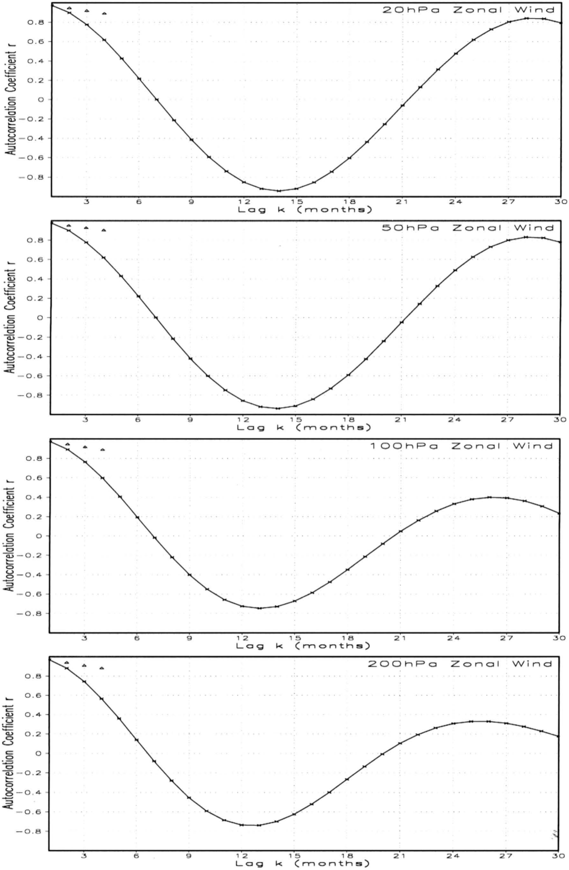
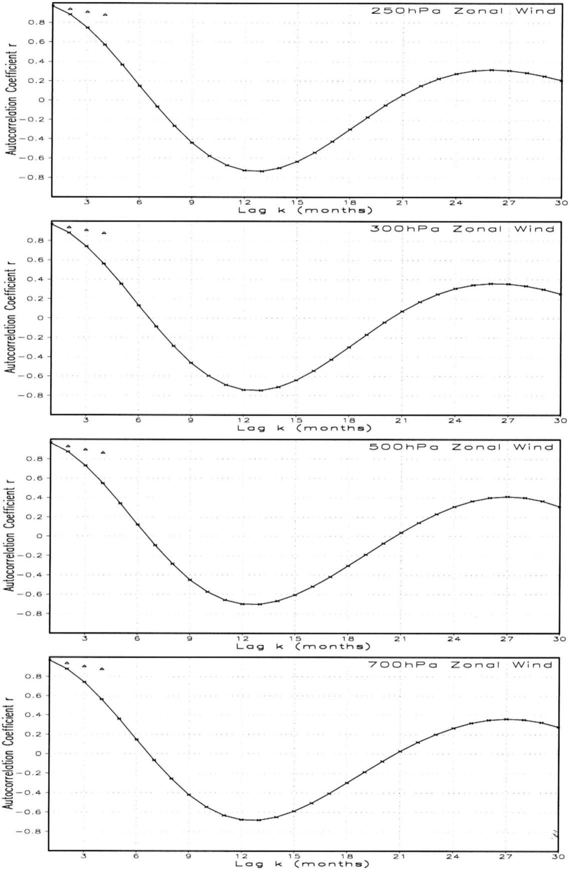


Figure 4.4 Autocorrelation functions of zonal winds above the Malaysian region with maximum lags of 30 months. The three triangles in each graph show the values of r_1^2, r_1^3 and r_1^4 respectively from left to right.



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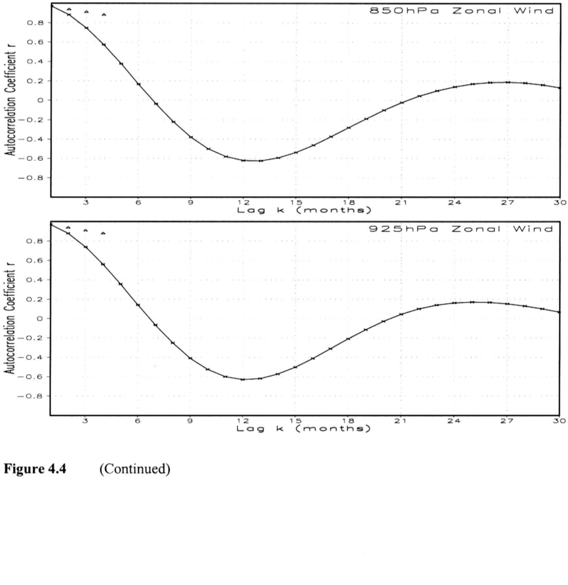


Figure 4.4 (Continued)

oscillations have periods ranging from 22 to 30 months. In fact, if the maximum lags of the autocorrelation functions are increased, it can be shown that the longest significant period of the QBO is 35 months. At lags of 12-14 months as shown in Figure 4.4, the zonal winds at all the ten levels are significantly negatively correlated with coefficients smaller than –0.6. This means that maximum easterly takes place 12-14 months after the occurrence of the maximum westerly or vice versa further implying that the zonal winds at all ten levels oscillate with periods ranging from 24 to 28 months.

Within each graph of the autocorrelation function, the first three values of the exponential function $r_k = r_1^k$ for $k = \mathbf{2,3}$ and $\mathbf{4}$, are also plotted. Comparing the values of r_k with the corresponding autocorrelations, these values are always larger, showing that simple Markov persistence is not only the dominant form of non-randomness in the series as explained in Section 3.3.3.4. Hence, r_1 overestimates the value of ρ, the lag-one correlation coefficient for the population. A better estimate of ρ is then the ratio r_2/r_1. This ratio is being used to calculate the 90% confident level later in the power spectral analysis.

4.2.3 Pearson Cross Correlation Function

Similarly the Pearson cross correlation functions of the zonal winds with maximum lags of ± 15 months are shown in Figure 4.5. The Pearson cross correlation coefficients at a particular level are computed with respect to its adjacent level higher than itself except at the 20-hPa level where calculation of the coefficients are with respect to itself acting as a control. Needless to say, at the 20-hPa level, the Pearson correlation function resembles the autocorrelation function at this level. At the 50-hPa level, the Pearson cross correlation is about 0.96 at a lag of 7 months. This shows that the westerly

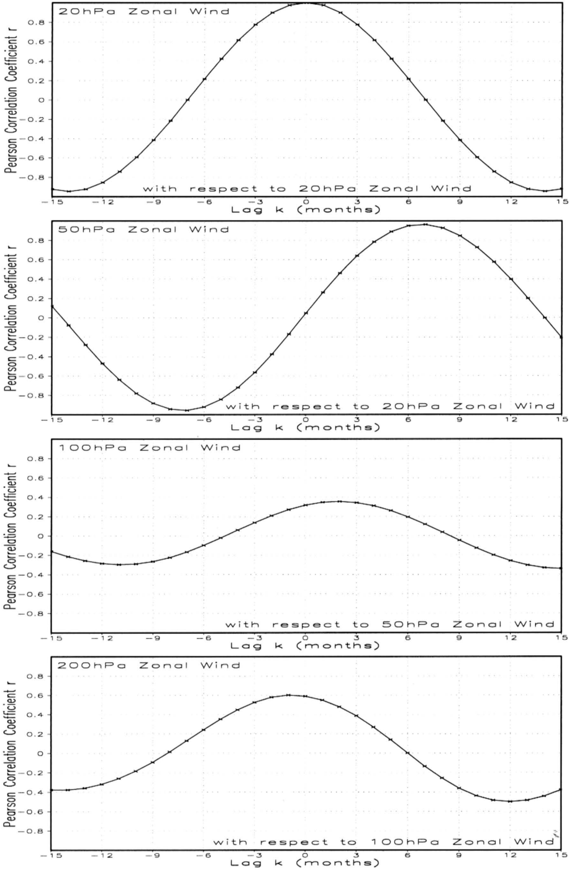
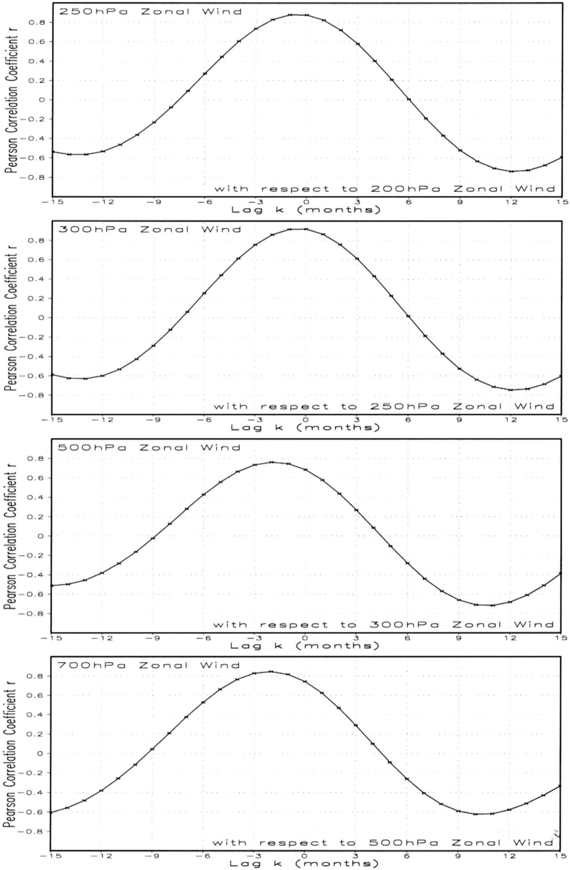


Figure 4.5 Pearson cross correlation functions of zonal winds with respect to zonal wind one level higher, except for the 20-hPa level zonal wind with respect to itself, above the Malaysian region with maximum lags of ± 15 months.



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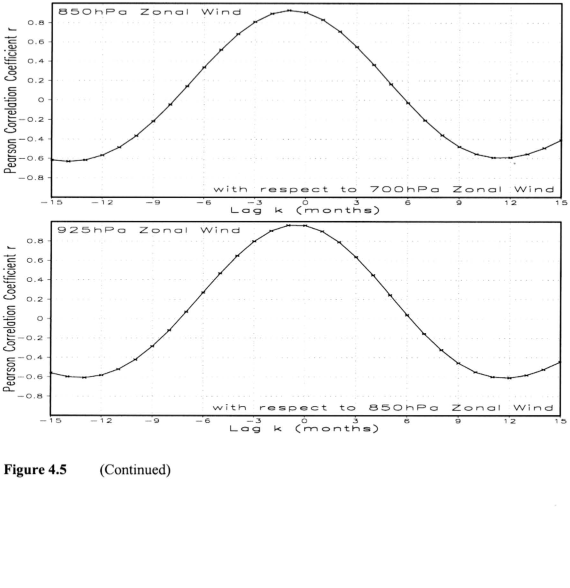

Figure 4.5 (Continued)

or the easterly wind regime of the QBO propagates downwards from the 20-hPa level and reaches the 50-hPa level 7 months later. The Pearson cross correlation of around 0.35 at the 100-hPa level at a lag of 2 months shows that it takes another two more months for these wind regimes continue to propagate downwards to reach the 100-hPa level. But from the 200 up to the 925-hPa levels, the Pearson cross correlation coefficients are roughly 0.6-0.96 at a lead of 0-2 months between adjacent levels. Accumulating the leading and lagging months separately, there is a total lead of 9 months from the 100 to the 925-hPa levels as compared to a total lag of 9 months from the 20 to the 100-hPa levels. This means that the lower stratospheric wind at the 20-hPa level propagates downwards while the near-surface lower tropospheric wind at the 925-hPa level propagates upwards simultaneously and they meet each other at around the 100-hPa level after 9 months. Figure 4.6 shows the Pearson cross correlation functions of the zonal winds at different levels with respect to the 20-hPa level zonal wind. It can be seen that the zonal winds above the 300-hPa level are significantly and positively correlated. Conversely, the zonal winds below the 300-hPa level are significantly and negatively correlated. The correlation at the 300-hPa level is insignificant. Therefore, the near-surface easterlies/westerlies propagate upwards, become westerlies/easterlies after the 300-hPa level and continue their upward motion until they merge with those downward propagating westerlies/easterlies at around the 100-hPa level. The negative correlation at the 925-hPa level at a lead of 3 months means that the maximum 925-hPa easterly/westerly leads the maximum 20-hPa westerly/easterly by 3 months. Taking into consideration of a fluctuation of ± 2 months, it can be concluded that maximum easterly/westerly anomaly at the 925-hPa appears 1-2 months before maximum westerly/easterly anomaly exists at the 20-hPa level. This relationship of the lower stratospheric and the near-surface tropospheric zonal winds is illustrated in Figure 4.7.

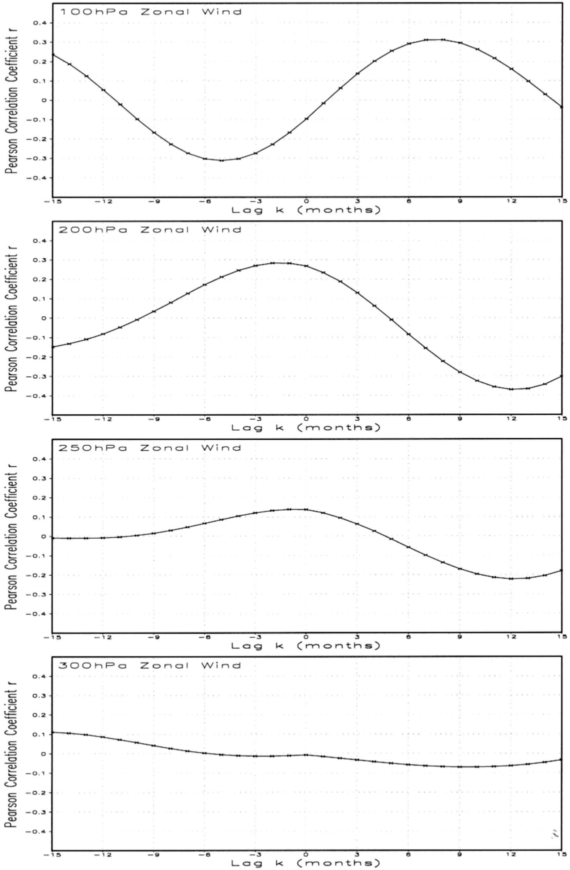

Figure 4.6 Pearson cross correlation functions of zonal winds with respect to 20-hPa zonal winds above the Malaysian region with maximum lags of ± 15 months.

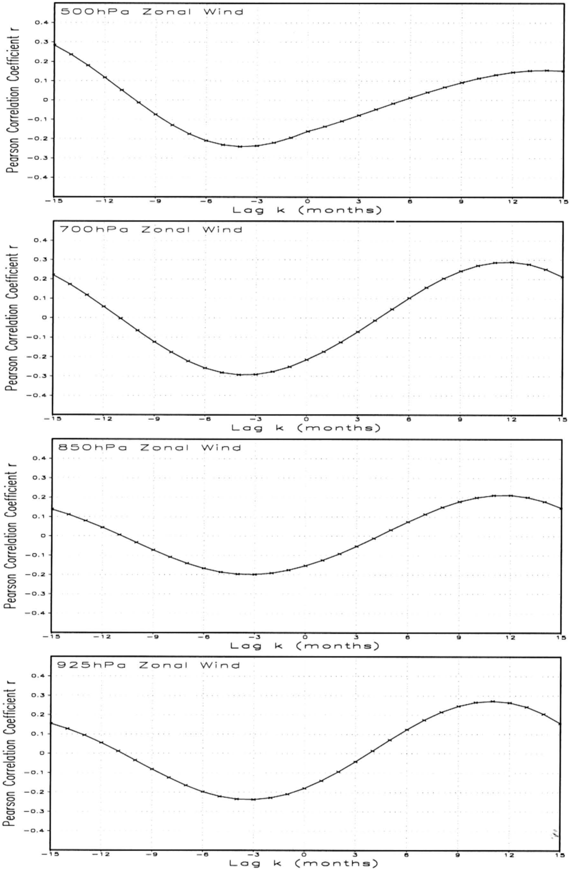

Figure 4.6 (Continued)

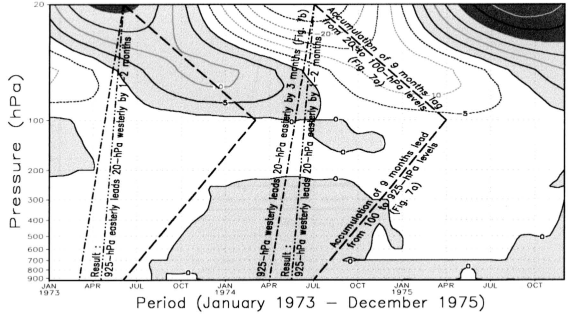

Figure 4.7 Part of the plot extracted from Figure 4.1(b) showing results deduced from Pearson cross correlation functions of the zonal winds above the Malaysian region. Dashed lines starting from July 1974 show that the 925-hPa westerly propagated upwards up to the 300-hPa level, became easterly and continued to propagate upwards until it merged with the downward propagating 20-hPa easterly in April 1975 at the 100-hPa level. Dot-dashed line starting from April 1974 shows that the maximum 925-hPa westerly leads the maximum 20-hPa easterly by 3 months. The double-dot-dashed line is the deduced result showing that the maximum 925-hPa westerly leads the maximum 20-hPa easterly by only 1-2 months, taking into consideration of a fluctuation of $\pm$ **2** months.

A similar result is deduced during the westerly phase of the QBO in June 1973, except that this time the upward propagating easterly did not change to westerly at the 300-hPa level, but propagated continuously upwards until it merged with the downward propagating 20-hPa westerly at around the 100-hPa level 9 months later.

4.2.4 The Power Spectrum

The smoothed power spectrums of the deseasonalized and detrended zonal winds with maximum lags of 240 months are shown in Figure 4.8a. From this figure, it can be seen that at the 20 and 50-hPa levels, both the spectrums have a single spectral peak each at a period of 28.2 months. This definitely shows that QBO is the only dominant feature in these two levels. Furthermore, these two peaks are broadband with periods ranging from 34.3 to 22.9 months, showing the quasi nature of the oscillation. The 100-hPa spectrum has two significant spectral peaks at periods of 43.6 and 25.3 months. The

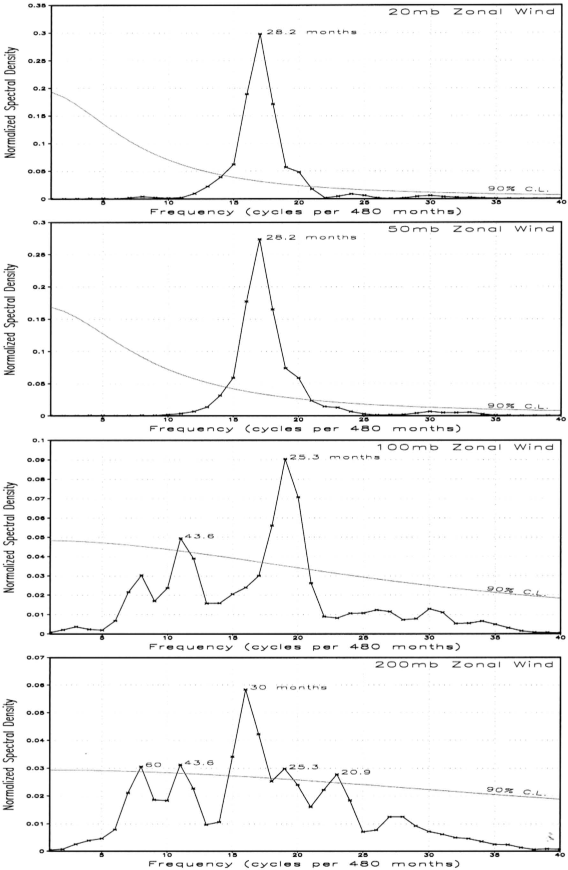

Figure 4.8a Smoothed power spectrums of deseasonalized and detrended zonal winds above the Malaysian region with maximum lags of 240 months. Lighter curve in each graph shows the corresponding 90% confident level.

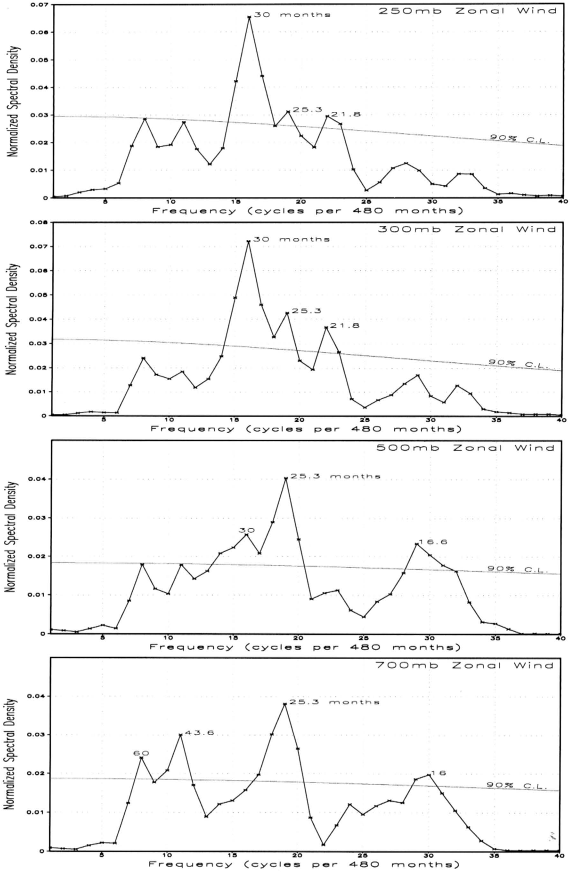

Figure 4.8a (Continued)

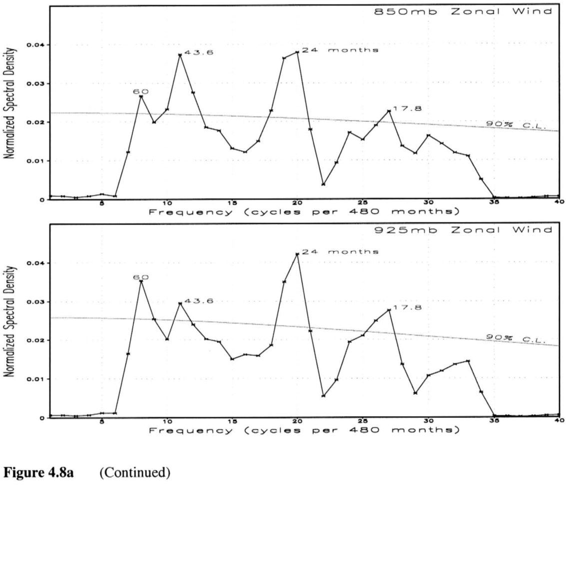

Figure 4.8a (Continued)

25.3-month peak has broadband periods ranging from 28.2 to 22.9 months that are well within the range of the QBO. This means that QBO is still one of the main features in this level. The other peak could possibly indicate the presence of oscillation that probably is related to the well-known El-Nino Southern Oscillation phenomena.

In the troposphere from 200 to 500-hPa levels, the spectrums of the deseasonalized and detrended zonal winds show two significant spectral peaks within the range of the QBO, one at a period of 30 months and the other at 25.3 months, within a significant broadband period of 32 to 24 months. Each of the spectrums of the 700 to 925-hPa levels winds show only one spectral peak within the range of the QBO at a period of either 25.3 months or 24 months. Hence, QBO-like signal is significant even in the troposphere. Again, at almost all the levels in the troposphere, there appear to have at least two more significant peaks of longer wavelength with periods of 60 and 43.6 months that could possibly indicate the presence of oscillations that probably are related to the well-known El-Nino Southern Oscillation phenomena.

To enhance the QBO features in the lower stratosphere as well as the QBO-like features in the troposphere, power spectrums of the band-pass filtered zonal winds are shown in Figure 4.8b.

4.3 500-hPa Geopotential Height

Raw and filtered area-average 500-hPa geopotential heights above the Malaysian region are shown in Figure 4.9a. The raw data series shows clearly the seasonal fluctuation as well as the long-term trend. The filtered data series shows a wave pattern that closely resembles the QBO pattern. The 500-hPa geopotential height is almost

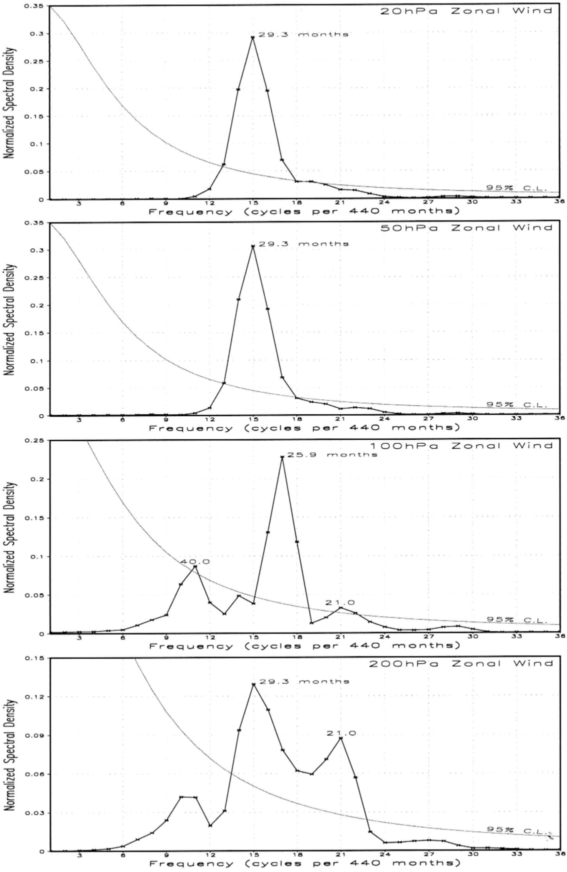

Figure 4.8b Smoothed power spectrums of band-pass filtered zonal winds above the Malaysian region with maximum lags of 220 months. Lighter curve in each graph shows the corresponding 95% confident level.

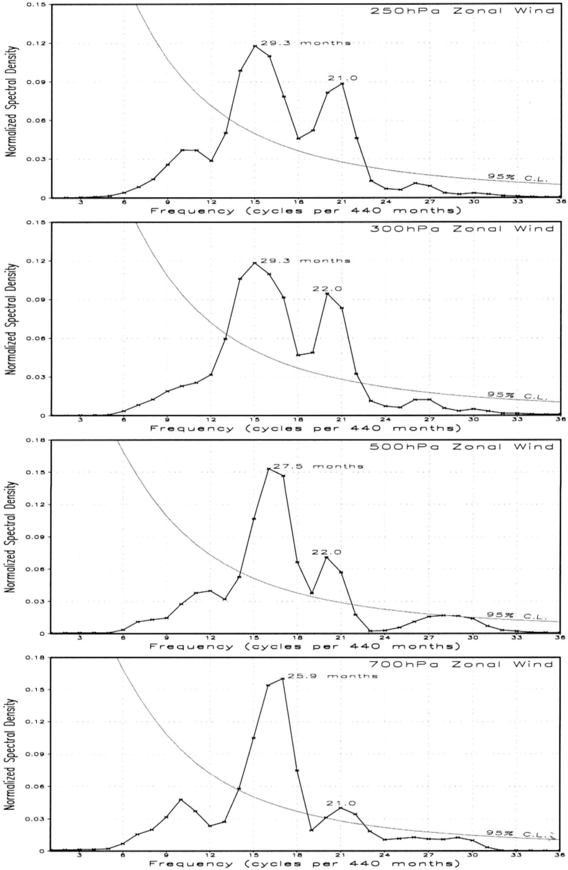

Figure 4.8b (Continued)

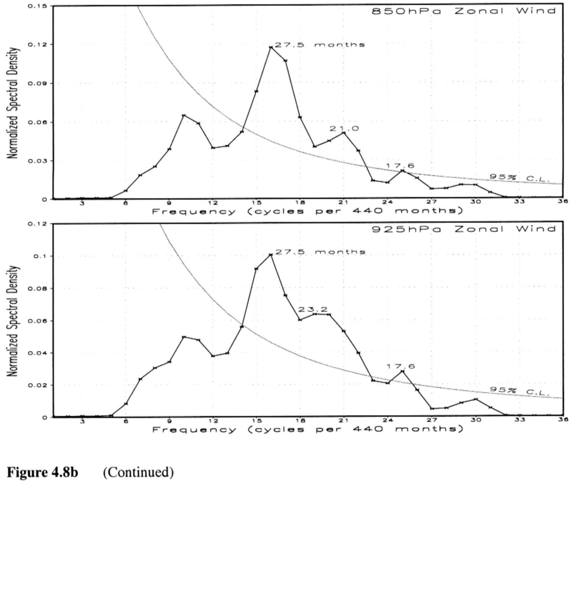

Figure 4.8b (Continued)

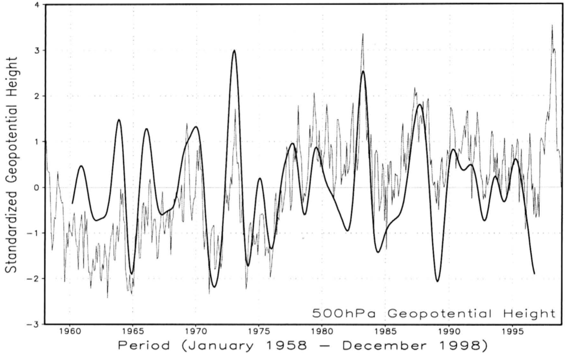

Figure 4.9a Standardized actual (thin line) and band-pass filtered (thick line) monthly mean 500-hPa geopotential height above the Malaysian region for a period of 41 years from January 1958 to December 1998. Tick marks of years indicate Januaries.

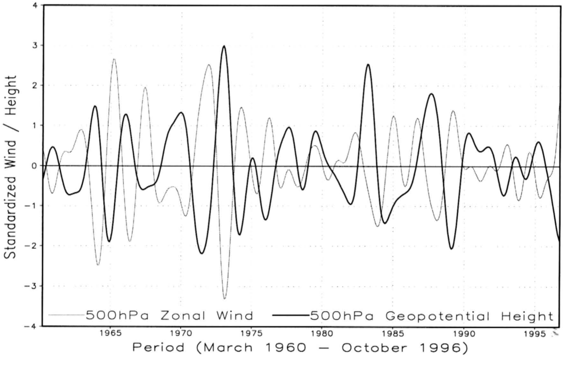

Figure 4.9b Standardized band-pass filtered monthly mean 500-hPa geopotential height (thick line) superimposed on the 500-hPa zonal wind (thin line) above the Malaysian region for a period of 440 months from March 1960 to October 1996. Tick marks of years indicate Januaries.

completely out of phase with the 500-hPa zonal wind as in Figure 4.9b. This means that the bulging of the 500-hPa geopotential height is approximately in phase with the easterly wind at this level.

These features can be proven statistically as can be seen from Figures 4.10a, b and c. The autocorrelation function of the 500-hPa geopotential height in Figure 4.10a shows that the series is negatively correlated significantly with a coefficient of -0.65 at a lag of 14 months. That is to say, the bulging of the 500-hPa geopotential height will be followed by a depression in height after 14 months and vice versa.

Figure 4.10b shows the Pearson cross correlation functions of the 500-hPa geopotential height with respect to the 20 and 500-hPa zonal winds. The 500-hPa zonal wind is significantly negatively correlated with height with a coefficient of –0.78 at a lag of –3 months and positively correlated with a coefficient of +0.6 at a lag of 11 months. This proves that the bulging of the height occurs 3 months before the occurrence of the strongest easterly and 11 months after the occurrence of the strongest westerly at this level. On the other hand, the correlation between the 500-hPa height and the 20-hPa zonal wind is very much weaker. At a coefficient of about +0.29, the bulging of height at the 500-hPa level is leading the maximum westerly at the 20-hPa level by 4 months.

From the power spectrum of the deseasonalized and detrended 500-hPa geopotential height shown in Figure 4.10c, it can be seen that the 500-hPa geopotential height has two significant peaks within the range of the QBO, one at a period of 30 months and the other at 25.3 months. There is also another significant spectral peak at a period of 43.6 months within a period ranging from 40 to 48 months. Again, this spectral peak could possibly indicate the presence of oscillation that probably is related to the well-known El-Nino Southern Oscillation phenomena.

All the graphs shown in Figures 4.10a, b and c indicate that the most prominent

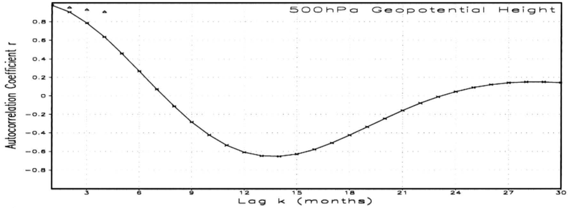

Figure 4.10a Autocorrelation function of 500-hPa geopotential height above the Malaysian region with a maximum lag of 30 months. The three triangles show the values of r_1^2, r_1^3 and r_1^4 respectively from left to right.

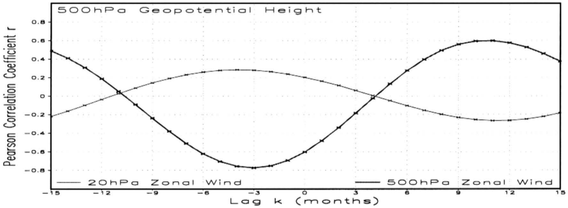

Figure 4.10b Pearson cross correlation functions of 500-hPa geopotential height with respect to the 20-hPa (thin line) and 500-hPa (thick line) zonal winds above the Malaysian region with maximum lags of ± 15 months.

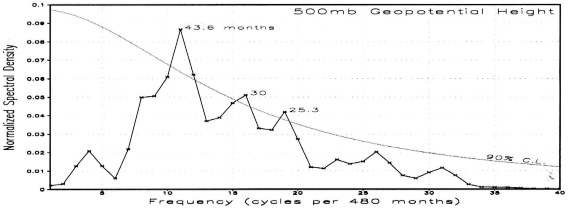

Figure 4.10c Smoothed power spectrum of deseasonalized and detrended 500-hPa geopotential height above the Malaysian region with a maximum lag of 240 months. Lighter curve shows the corresponding 90% confident level.

feature the 500-hPa geopotential height series exhibits is the QBO-like oscillation with periods of about 25 to 30 months.

4.4 Sea Surface Temperature (SST)

The raw data series of SST shows a clear annual fluctuation and a long-term trend as can be seen in Figure 4.11a. Superimposed in the same figure is the band-pass filtered SST data series. It can be seen that both the seasonal variation and trend are successfully removed, and the wave pattern looks more like the TBO pattern. Comparing with the filtered data series of the 925-hPa zonal wind, only two short periods from 1960-62 and 1967-68 show warm SST in phase with westerly and cold SST in phase with easterly as shown in Figure 4.11b. The remaining periods under survey show warm SST almost in phase with easterly and cold SST almost in phase with westerly. A detailed observation shows that often the easterly and westerly were actually leading the warm and cold SST respectively by few months.

The autocorrelation function of SST shown in Figure 4.12a infers that warm SST will be replaced by cold SST every 13 months and vice versa as indicated by the autocorrelation coefficient of -0.7 at a lag of 13 months. A positive coefficient of 0.19 at a lag of 27 months further implies that the SST data series exhibit TBO pattern with a mean period of 27 months.

Figure 4.12b shows the Pearson cross correlation functions of SST with respect to 925-hPa zonal wind and 500-hPa geopotential height. The function with respect to zonal wind shows that the warm SST lags behind the 925-hPa easterly by 4 months while the function with respect to height indicates that warm SST lags behind the 500-hPa

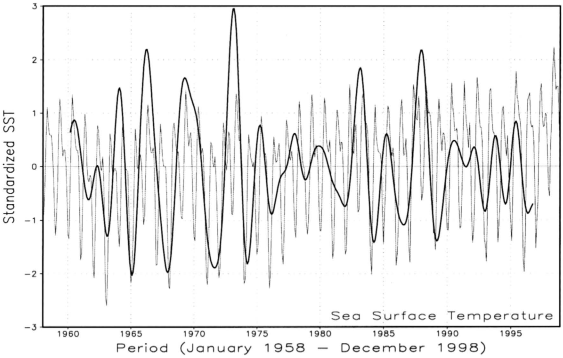

Figure 4.11a Standardized actual (thin line) and band-pass filtered (thick line) monthly mean SST in the Malaysian region for a period of 41 years from January 1958 to December 1998. Tick marks of years indicate Januaries.

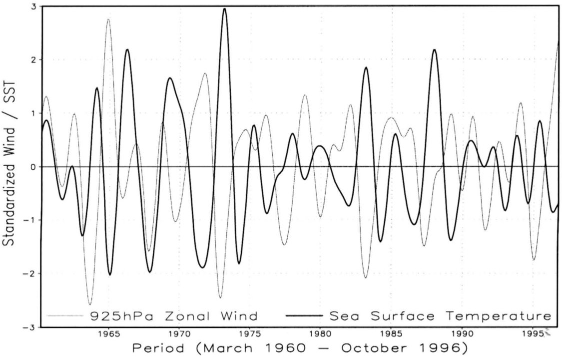

Figure 4.11b Standardized band-pass filtered monthly mean SST (thick line) superimposed on the 925-hPa zonal wind (thin line) in and above the Malaysian region for a period of 440 months from March 1960 to October 1996. Tick marks of years indicate Januaries.

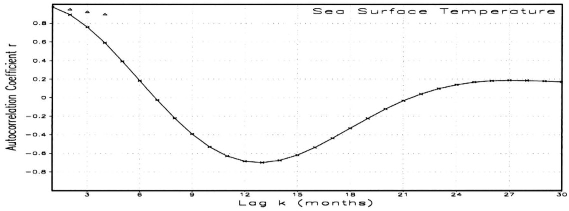

Figure 4.12a Autocorrelation function of SST in the Malaysian region with a maximum lag of 30 months. The three triangles show the values of r_1^2, r_1^3 and r_1^4 respectively from left to right.

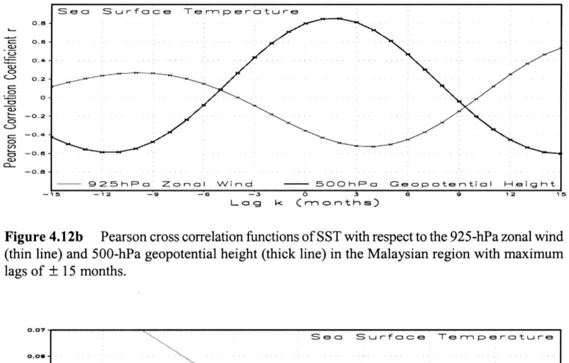

Figure 4.12b Pearson cross correlation functions of SST with respect to the 925-hPa zonal wind (thin line) and 500-hPa geopotential height (thick line) in the Malaysian region with maximum lags of ± 15 months.

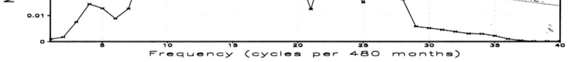

Figure 4.12c Smoothed power spectrum of deseasonalized and detrended SST in the Malaysian region with a maximum lag of 240 months. Lighter curve shows the corresponding 90% confident level.

geopotential height by 2 months.

The smoothed power spectrum of SST as shown in Figure 4.12c also has two significant spectral peaks within the range of the QBO, one with period of 30 months and the other a period of 25.3 months. This proves that the SST data series exhibits quasi TBO with periods ranging from 25 to 30 months. There are two more significant but smaller spectral peaks at period of 20.9 and 17.8 months. These two peaks could possibly represent some other oscillations in the atmosphere, or the harmonics of the El-Nino Southern Oscillations.

4.5 Tropopause Height

Figure 4.13 shows the individual raw and filtered tropopause height series of all the five Malaysian meteorological UAO stations. A composite of the filtered series is shown in Figure 4.14a with their average series superimposed on them. Visually the average filtered tropopause height series show QBO-like features. From a composite of heights, wind and SST as in Figure 4.14b, it can be seen that the bulging of the tropopause height is most of the time in phase with the bulging of the 500-hPa geopotential height. The bulging of the tropopause height is always a month or two in advance before the SST around the sea adjacent to Malaysia becomes warmest and always three to six months leading the 20-hPa zonal westerly.

The autocorrelation function of the corresponding tropopause height series shown in Figure 4.15a shows that the bulging of the tropopause height is highly and negatively correlated with coefficients roughly of –0.8 at a lag of 13 months. This indicates that similar to the 500-hPa geopotential height the bulging of the tropopause height occurs 13

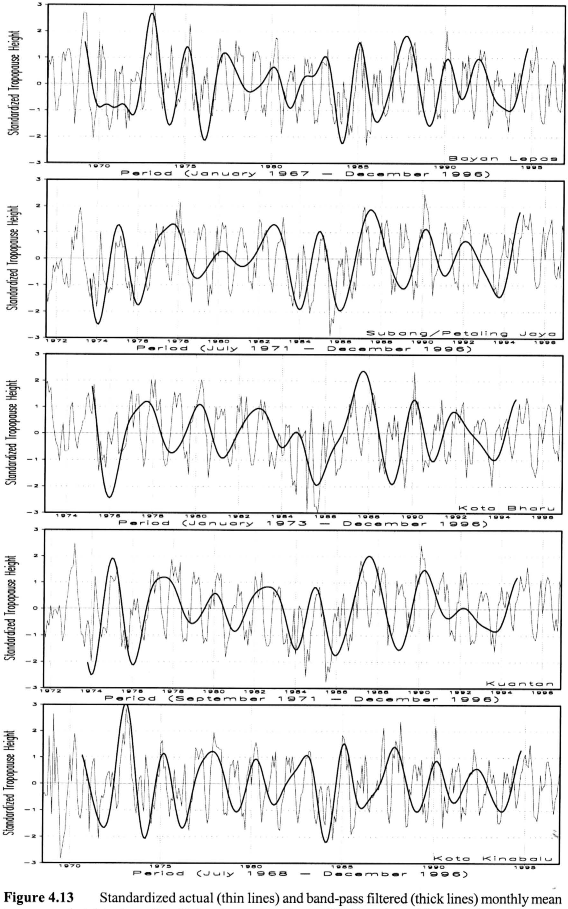

Figure 4.13 Standardized actual (thin lines) and band-pass filtered (thick lines) monthly mean tropopause heights above five Malaysian meteorological UAO stations. Note that the starting year of each station is different. Tick marks of years indicate Januaries.

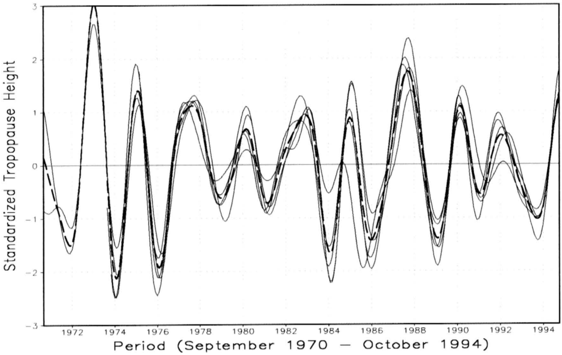

Figure 4.14a Composite of standardized band-pass filtered monthly mean tropopause heights (thin solid lines) above five Malaysian meteorological UAO stations. Thick dashed line shows the average values of the five stations used to represent the area average above the Malaysian region. Tick marks of years indicate Januaries.

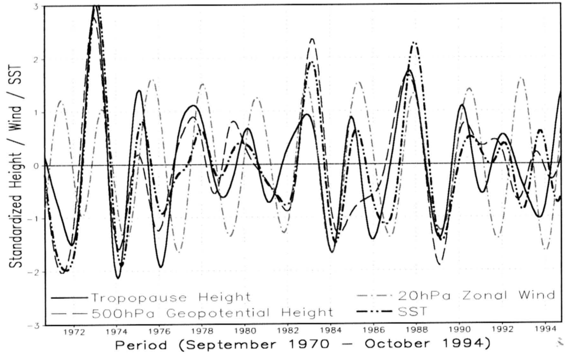

Figure 4.14b Standardized area-average band-pass filtered monthly mean tropopause height (solid line) above the Malaysian region superimposed with 500-hPa geopotential height (dashed line), 20-hPa zonal wind (dot-dashed line) and SST (double-dot-dashed line). Tick marks of years indicate Januaries.

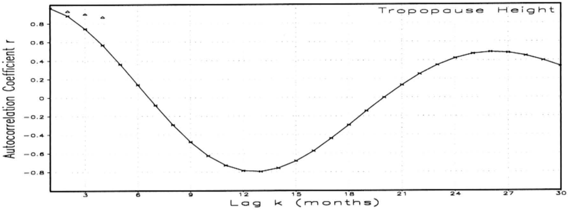

Figure 4.15a Autocorrelation function of tropopause height above the Malaysian region with a maximum lag of 30 months. The three triangles show the values of r_1^2, r_1^3 and r_1^4 respectively from left to right.

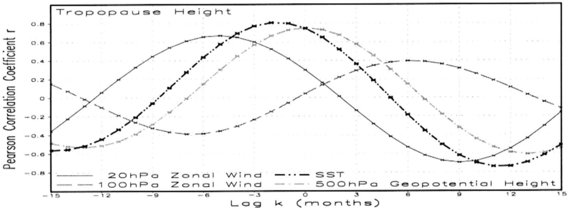

Figure 4.15b Pearson cross correlation functions of tropopause height with maximum lags of ± 15 months above the Malaysian region with respect to the 20-hPa (solid line) and 100-hPa (dashed line) zonal winds, 500-hPa geopotential height (dot-dashed line) and SST (double-dot-dashed line).

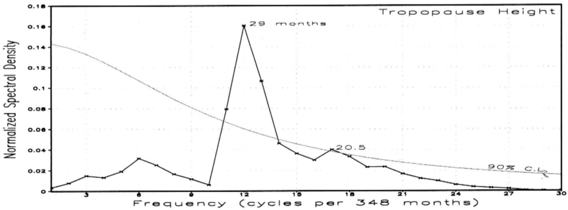

Figure 4.15c Smoothed power spectrum of deseasonalized and detrended tropopause height above the Malaysian region with a maximum lag of 174 months. Lighter curve shows the corresponding 90% confident level.

months after the depression in height and vice versa. This is consistent with the analysis, as the autocorrelation becomes significantly positive again at a lag of 26 months.

From the Pearson cross correlation functions of tropopause height shown in Figure 4.15b, the bulging of the tropopause height is exactly in phase with the bulging of the 500-hPa geopotential height and occurs 2 months in advance before the SST becomes warmest. The Pearson cross correlation functions of the tropopause height with respect to zonal winds show that the bulging of the height occur 5 months in advance of the 20-hPa westerly but 6 months after the 100-hPa westerly.

The smoothed power spectrum of deseasonalized and detrended tropopause height shows a significant spectral peak with a period of 29 months proving that the tropopause height series also exhibit a QBO-like wave pattern (see Figure 4.15c). The broad spectral band with periods ranging from 24.9 to 31.6 months indicates the quasi structure of this wave. The other significant spectral peak at a period of 20.5 months is much smaller.

4.6 Correlation of Zonal Wind over Western and Central Pacific Region with respect to the Malaysian Region

In order to construct a model applicable to the Malaysian region but with zonal winds blowing into or out of this region from the western and central Pacific near the earth's surface, an examination of the Pearson cross correlation of the 925-hPa zonal wind over the western and central Pacific bounded by 0°-7.5°N latitudinally and 120°E-180°E longitudinally with respect to the 925-hPa zonal wind over Malaysian region is necessary. From Figure 4.16, this correlation of the 925-hPa zonal winds shows that the zonal wind maximum (westerlies) and minimum (easterlies) over the western and central

Pacific lag those over Malaysian region by one month. In another words, strong westerlies or easterlies continue to strengthen over the western and central Pacific by a month after the Malaysian region has experienced the strongest westerlies or easterlies respectively.

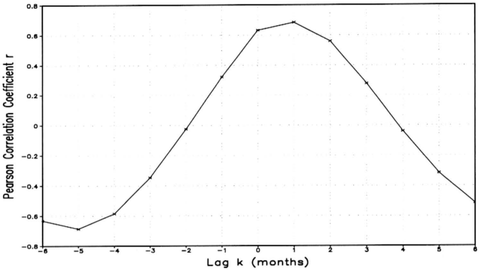

Figure 4.16 Pearson cross correlation of the 925-hPa zonal wind over the western and central Pacific bounded by 0°-7.5°N latitudinally and 120°E-180°E longitudinally with respect to the 925-hPa zonal wind over Malaysian region.