TROPOSPHERIC AND EQUATORIAL INFLUENCES ON PLANETARY-WAVE AMPLITUDE IN THE STRATOSPHERE

Yongyun Hu and Ka-Kit Tung

Department of Applied Mathematics

University of Washington

P.O. Box 352420

Seattle, WA 98195-2420

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Abstract. Using 49-year NCEP/NCAR reanalysis data we examine two possible factors affecting the amplitudes of extratropical planetary waves in the stratosphere: tropospheric influence and the equatorial QBO modulation. Our results show that the modulation of the equatorial QBO on wave amplitude is statistically significant only for wavenumber-1 in early winter. The variability of wavenumber-2 amplitude is mainly determined by tropospheric forcing. The effect of the solar cycle on planetary-wave amplitude is also discussed.

Introduction

It has long been thought that the equatorial Quasi-Biennial Oscillation (QBO) might have a significant influence on extratropical circulation in the stratosphere. Based on the theoretical speculation that the zero-wind line (critical layer) may act as a reflector for stationary planetary waves [*Tung and Lindzen*, 1979, *Tung,* 1979] (also see [*Killworth and McIntyre,* 1985]), *Holton and Tan* [1980] (hereafter HT80) and *Holton and Tan* [1982] suggested that the equatorial QBO alters the extratropical stratospheric circulation through planetary waves. Their basic idea is: stationary planetary waves propagate from the extratropical troposphere to the extratropical stratosphere through a wave-guide of westerly zonal winds. During the easterly QBO phase the zero-wind line moves to the subtropics of the winter hemisphere and narrows the width of the planetary-wave guide in the extratropical lower stratosphere, while the westerly QBO phase tends to widen the wave guide. The narrower wave guide during the easterly QBO phase leads to planetary waves "focusing" toward the polar region and consequently causes larger wave amplitudes near the polar region. When such wave events with larger amplitudes break or dissipate, the resulting additional wave drag slows the polar night jet and warms the polar stratosphere, possibly leading to major sudden warmings [*McIntyre,* 1982]. This mechanism was supported by the results by HT80 who found that in early winter (November-December) wavenumber-1 amplitude in the extratropics was larger, and zonal wind was weaker, in the easterly phase of the QBO, as compared to those in the westerly QBO phase. *Dunkerton et al.* [1988] also showed that major sudden warmings almost never occurred when the equatorial winds were "deep westerly", although the easterly QBO phase did not consistently lead to major sudden warmings.

Using 37-year (1957/58-1993/94) National Meteorological Center (NMC) data, Naito and Hirota [1997] obtained different results depending on whether the HT80 period (1962/63-1977/78) or the period after it (1978/79-1993/94) was considered. Specifically, HT80's results failed to hold in the second period. They found that such a difference is due to the effect of the 11-year solar cycle because HT80's period happens to contain two solar minima and one maximum, while the second period covers one solar minimum and two maxima. They thought that HT80's result is more typical of solar minima. Therefore, they proposed that solar cycle effect should be considered. Given Naito and Hirota's data encompassed only three solar cycles, it would be interesting to see if their result continue to hold for longer data series.

The purpose of the present paper is to re-examine HT80's findings using longer-time data, and to attempt to include other major factors which affect planetary waves. In addition to studying the QBO modulation, we are particularly interested in the influence of tropospheric forcing on planetary-wave amplitudes in the stratosphere, and the possible effect of the solar cycle. The data used here are 49-year (November 1952- March 2001) monthly-mean geopotential heights from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) in the Northern Hemisphere. The QBO winds are the monthly-mean Singapore winds from B. Naujokat [*Naujokat,* 1986]. The solar flux data is based on the plot in Naito and Hirota [1997].

QBO composites

HT80 divided the winter season into “early winter” (November-December) and “late winter” (January-March). Using 16-year NMC data, they composited amplitudes of wavenumber 1 and 2 in the two categories according to the phase of the equatorial QBO, as measured by the sign of the mean zonal wind at 50 mb at Balboa, Canal zone (9°N). They found that in early winter, wavenumber 1 amplitude at 50 mb is about 40% greater in the easterly category than in the westerly category, with statistical significance of 99% in a student t-test. After adding up 6 more years, they found that the difference of wavenumber 1 amplitude between the two categories increased to 50%, with significance of 99.9%.

To test whether the result in HT80 continues to hold for longer time series, we repeat their calculation using 49-year NCEP/NCAR reanalysis data. The phase of the equatorial QBO is defined in the same way according to the zonal wind at 50 mb, but using Singapore winds [*Naujokat*, 1986]. Figure 1a and b show the results for wavenumber 1. Consistent with the finding of HT80, the composite amplitude of wavenumber 1 at 50 mb is larger, by about 20%, in early winter (Figure 1a) when the QBO phase is easterly, at significance level of about 97%. In late winter, the difference of wavenumber-1 amplitudes between the two QBO phases is not statistically significant (Figure 1b), which is also consistent with HT80.

HT80 found that in later winter wavenumber-2 composite amplitude was about

60% stronger during the westerly phase of the equatorial QBO, with significance of 96%. However, when 4 additional years were added to the sample, they found that the significance dropped to about 90%. They suspected that the wavenumber-2 signal might be a result of sampling fluctuations, and suggested that a substantially longer time series may be required for a definite answer.

Our result for wavenumber 2 using the 49-year data is presented in Figure 1c and d. In both early and late winter, the differences of wavenumber-2 amplitude at 50 mb between the two QBO phases are too small to be statistically significant, consistent with HT80's conjecture. We have plotted the time series of wavenumber-2 amplitudes at 50 mb for the 49 years (figure not shown). It is found that for the 16-year data used by HT80, 3 of the 8 years in their easterly category (1966, 1971, 1977) had anomalously small amplitudes of wavenumber 2 in late winter. It is these extremely small amplitudes that lead to much smaller composite wavenumber-2 amplitude of the easterly category than that of the westerly category. Such occurrences are rare in our 49-year time series.

Naito and Hirota [1997] argued that the equatorial QBO modulation on wavenumber-2 amplitude could be uncovered when the solar cycle effect was considered. They found that for their MIN solar flux group (solar 10.7-cm radio flux less than 120×10^{-22} $Wm^{-2}Hz^{-1}$) wavenumber-2 amplitude is significantly larger in early winter when the QBO wind is easterly, while in late winter the amplitude is larger when the QBO wind is westerly (see their Table 1). The latter can be reproduced using NCEP/NCAR data for the same 37 years as theirs (Figure 2a). However, the difference of wavenumber-2 amplitude is not significant when longer-time data (January 1953-

March 2001) is used (Figure 2b). It is probably because their 37-year data series is not sufficiently long. According to Naito and Hirota's classification, each of their four groups includes very few years. For example, there were only 4 of their 37-years that belong to the group of "early winter, minimum solar flux, and easterly QBO phase".

Tropospheric influence

The composites in the previous section were done without regard to tropospheric forcing. To identify the influence from tropospheric forcing, we evaluate the vertical correlation of amplitudes of wavenumber 1 and 2 between 150 and 50 mb.

Figure 3a shows wavenumber-1 amplitudes at 150 and 50 mb at 60°N, averaged over November-December, as a function of years. The amplitude at 150 mb is multiplied by 1.5 to facilitate comparison. The correlation coefficient of the time series between the two levels is about 0.47, at 99.9% significance level. Though the vertical correlation is statistically significant, it still leaves room for other factors, such as the equatorial QBO, to modify its amplitude during its upward propagation from the tropopause to 50 mb.

One may inquire whether the significant difference of the composite wavenumber-1 amplitudes at 50 mb in early winter arises from such amplitude difference at 150 mb. To clarify this, we have calculated composite wavenumber-1 amplitudes at 60°N at 150 mb, which are 136 and 129 meters for the easterly and westerly categories, respectively. The difference between them is not significant (at 43% significance level). Therefore, the significant difference of wavenumber-1 amplitude at 50 mb is not due to tropospheric forcing or the QBO modulation on tropospheric forcing. Moreover, we have also calculated the ratio of wavenumber-1 amplitudes between 50 and 150 mb. The ratio is $221/136 \approx 1.63$ and $187/129 \approx 1.45$ for the easterly and westerly categories, respectively. This means that during upward propagation from 150 mb to 50 mb wavenumber-1 amplitude grows faster when the QBO wind is easterly.

The situation for wavenumber 2 is different. Figure 3b shows that November-December mean wavenumber-2 amplitude at 150 and 50 mb are strongly correlated, with a correlation coefficient of about 0.75 (wavenumber 2 amplitudes at 150 mb are multiplied by a factor of 1.1 for comparison). This means that wavenumber 2 is mainly determined by tropospheric forcing. The composite amplitudes at 150 mb are 134 and 119 meters for the two QBO categories. The difference is not significant (at 93% significance level). The amplitude ratio of wavenumber-2 between 50 and 150 mb is $147/134 \approx 1.10$ and $133/119 \approx 1.12$ for the easterly and westerly categories, respectively. This means that the growth of wavenumber-2 amplitude is not affected by the QBO phases during its upward propagation from the troposphere to stratosphere.

It can be seen from Figure 3 that the November-December mean amplitude of wavenumber 2 does not grow as much as wavenumber 1 as it propagates upward from 150 mb to 50 mb. In fact, the factor 1.1 used in Figure 3b is less than that (1.5) in Figure 3a. Therefore, it appears that, at least for the two-month mean, wavenumber 2 is trapped more than wavenumber 1 vertically. This may explain why wavenumber 2 is not modulated by the equatorial QBO in a significant way. It may also explain why wavenumber 2 is so vertically coherent. Nevertheless, it is known that in winter seasons wavenumber-2 stationary waves are occasionally propagating in the lower stratosphere.

Figure 4 shows amplitudes of wavenumber 1 and 2 at the 50 and 150 mb for late winter (JFM). The vertical correlation for wavenumber-1 amplitude (Figure 4a) is about 0.29, at 97.5% significance level. This correlation coefficient is smaller than that in early winter. Note that this weaker vertical correlation is not because the QBO modulation is stronger in late winter. As we shall point out later, it is probably because the planetary-wave guide becomes more complicated in late winter. For wavenumber 2 (Figure 4b), the vertical correlation is about 0.94, which is larger than that in early winter. This again means that wavenumber-2 amplitude in the stratosphere is determined by tropospheric forcing, and that the equatorial QBO has little modulation on wavenumber-2 amplitude. Indeed, the two lines in Figure 4b nearly overlap each other.

Conclusions

We have re-examined the influences of the QBO and troposphere on the extratropical planetary-wave amplitudes in the lower stratosphere using 49-year NCEP/NCAR reanalysis data. Our findings are:

(1) For both early and late winter, wavenumber-2 amplitude in the stratosphere is mainly determined by tropospheric forcing, and is little affected by the equatorial QBO. The solar cycle effect on wavenumber-2 amplitude was also found to be not significant.

(2) The equatorial QBO has statistically significant modulation on stratospheric wavenumber-1 amplitude in early winter, and the amplitude is generally about 20% larger when the QBO wind is easterly. In late winter, the QBO modulation is not

significant. This is consistent with HT80's results.

It appears likely that HT80's mechanism should only be looked for in early winter. In late winter, the westerly wave-guide configuration is altered drastically by the occurrence of major sudden warmings, which may overwhelm the QBO influence. As a result, the difference of wavenumber-1 amplitude becomes not significant.

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Y. Hu, K-K, Tung, Department of Applied Mathematics, University of Washington, Seattle, WA 98195. (e-mail: yongyun@amath.washington.edu; tung@amath.washington.edu)

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Figure captions

Figure 1: Meridional profiles of wavenumber-1 and 2 amplitudes at 50 mb. W (solid-line) and E (dotted-line) indicate HT80's westerly and easterly categories, respectively. Significance (%) of student's t-test, marked by $\star$, is scaled on the right-hand-side vertical axis. (a) November-December (ND) mean, wavenumber 1, (b) January-March (JFM) mean, wavenumber 1, (c) ND mean, wavenumber 2, and (d) JFM mean, wavenumber 2.

Figure 2: JFM mean meridional profiles of wavenumber-2 amplitudes at 50 mb for Naito and Hirota's MIN solar flux group. (a) Naito and Hirota's period (1958-1994), (b) 1953-2001.

Figure 3: ND mean amplitudes at 60°N vs. years at 50 and 150 mb. (a) Wavenumber 1, (b) wavenumber 2. C_r is the correlation coefficient of amplitudes between the two levels. Amplitudes of wavenumber 1 and 2 at 150 mb are multiplied by 1.5 and 1.1, respectively, for ease of comparison.

Figure 4: Same as Figure 3, except for late winter (JFM).

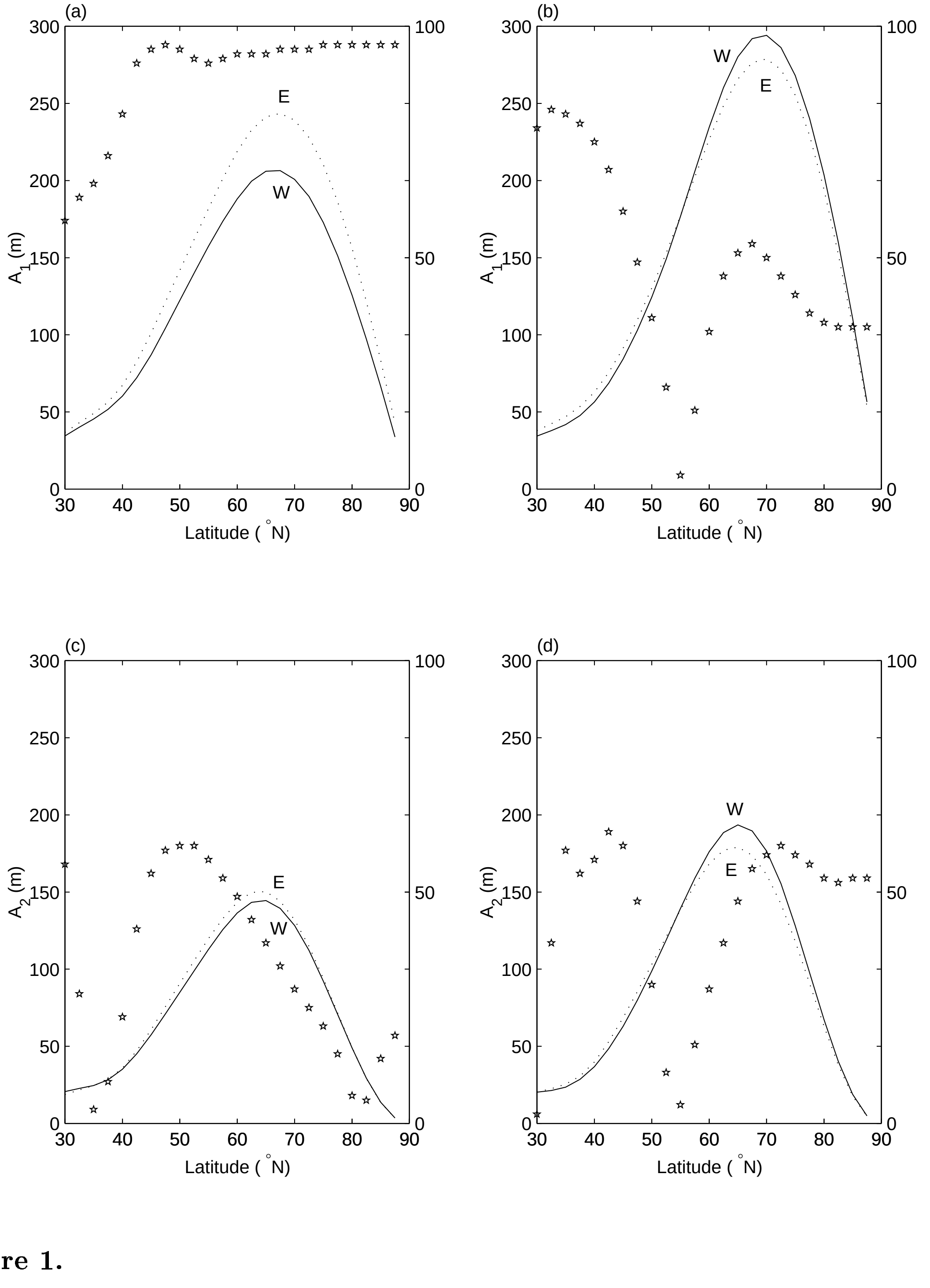

(a)
(b)
(c)
(d)
A_1 (m)
A_2 (m)
0
50
100
150
200
250
300
Latitude (°N)
30
40
50
60
70
80
90
E
W

Figure 1.

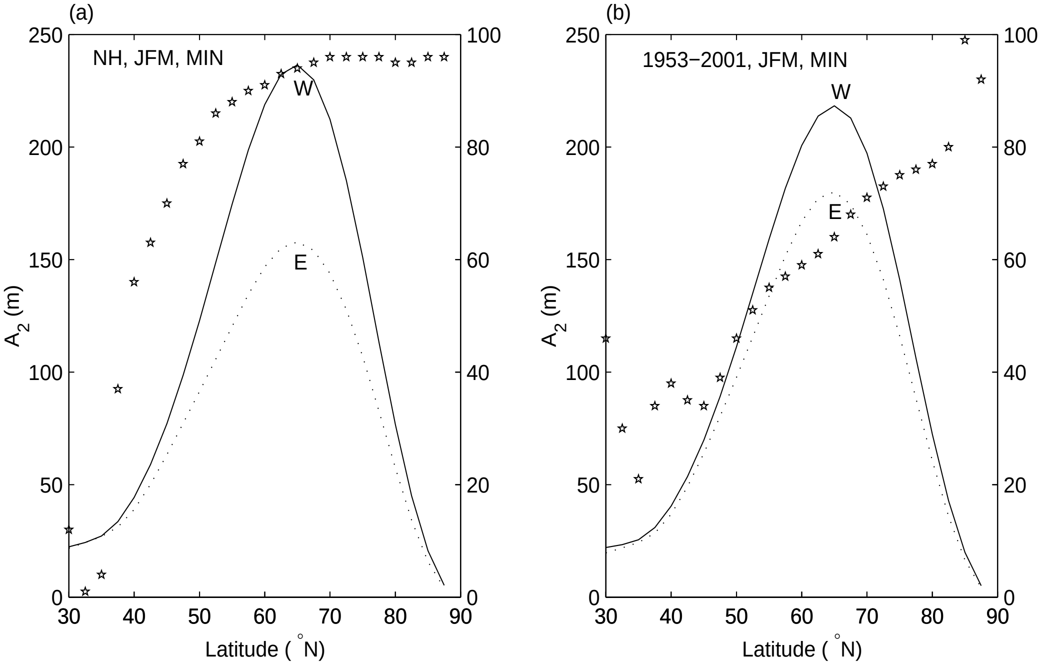

(a)
NH, JFM, MIN
W
E
A$_2$ (m)
250
200
150
100
50
0
100
80
60
40
20
0
30
40
50
60
70
80
90
Latitude (°N)
(b)
1953−2001, JFM, MIN
W
E
A$_2$ (m)
250
200
150
100
50
0
100
80
60
40
20
0
30
40
50
60
70
80
90
Latitude (°N)

Figure 2.

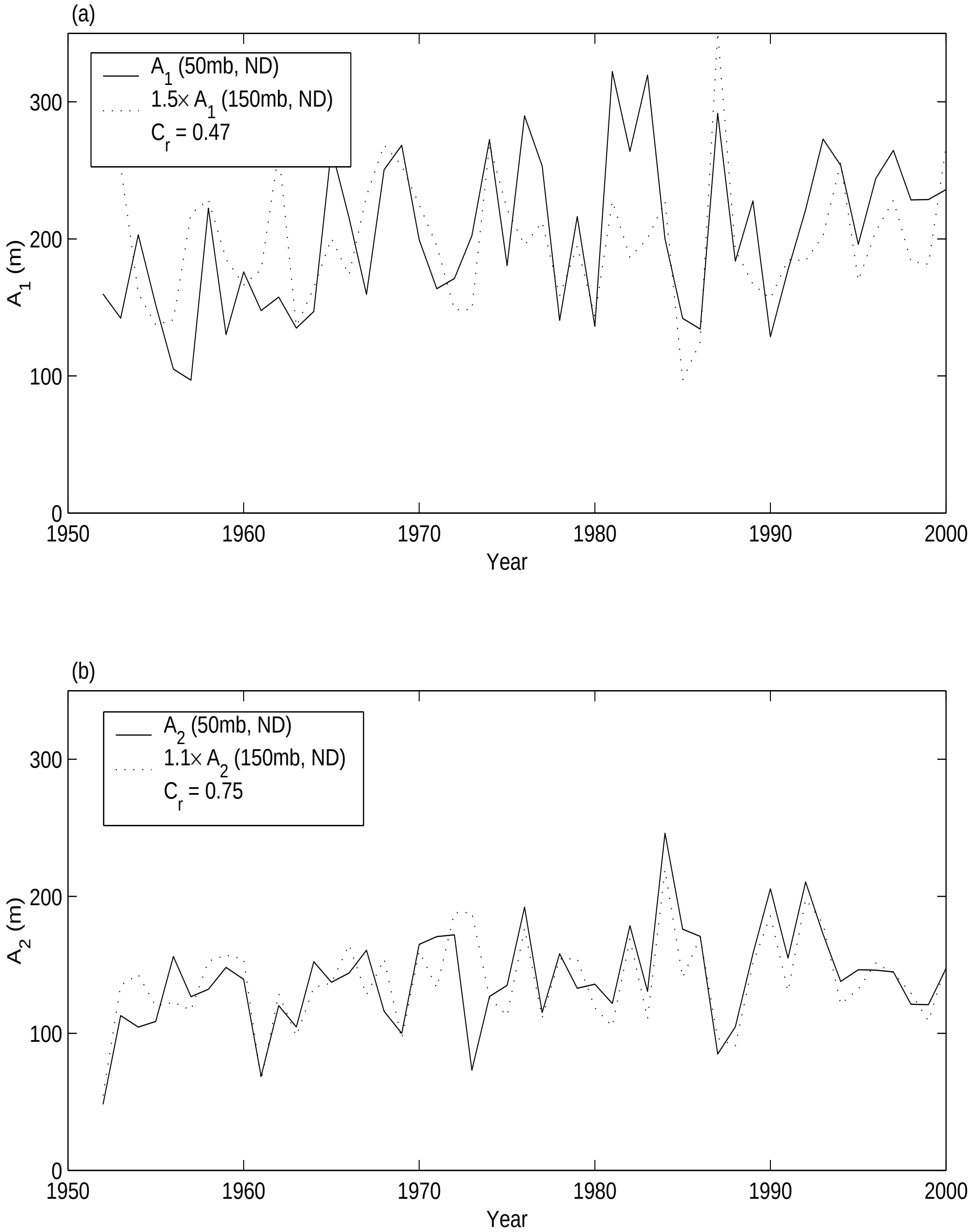
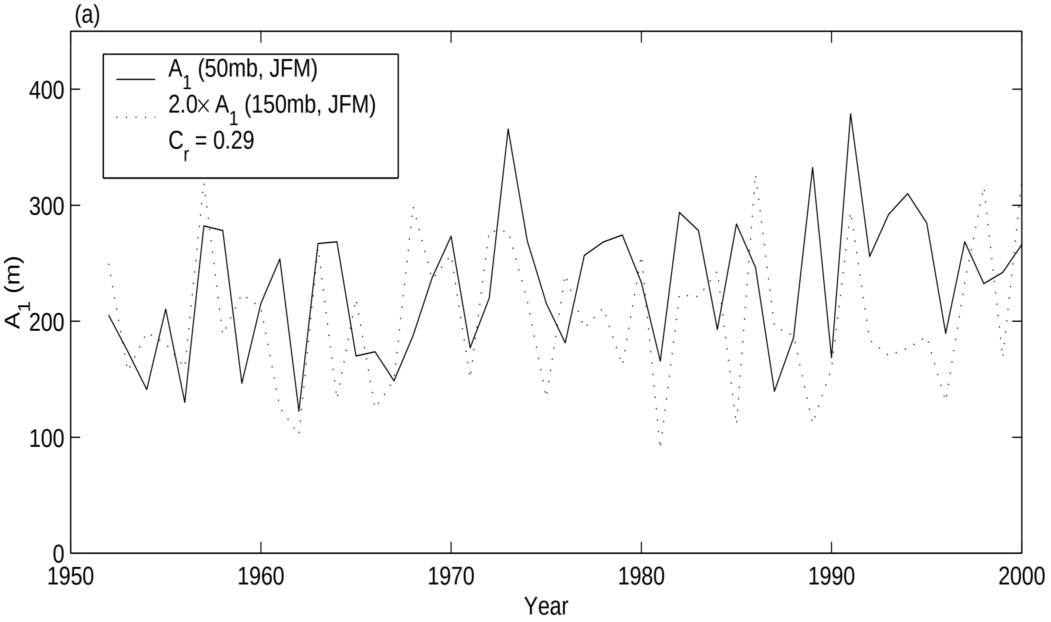

(a)
A$_1$ (50mb, ND)
1.5× A$_1$ (150mb, ND)
C$_r$ = 0.47
A$_1$ (m)
0
100
200
300
1950
1960
1970
1980
1990
2000
Year
(b)
A$_2$ (50mb, ND)
1.1× A$_2$ (150mb, ND)
C$_r$ = 0.75
A$_2$ (m)
0
100
200
300
1950
1960
1970
1980
1990
2000
Year

Figure 3.


(a)
A$_1$ (50mb, JFM)
2.0× A$_1$ (150mb, JFM)
C$_r$ = 0.29
A$_1$ (m)
0
100
200
300
400
1950
1960
1970
1980
1990
2000
Year

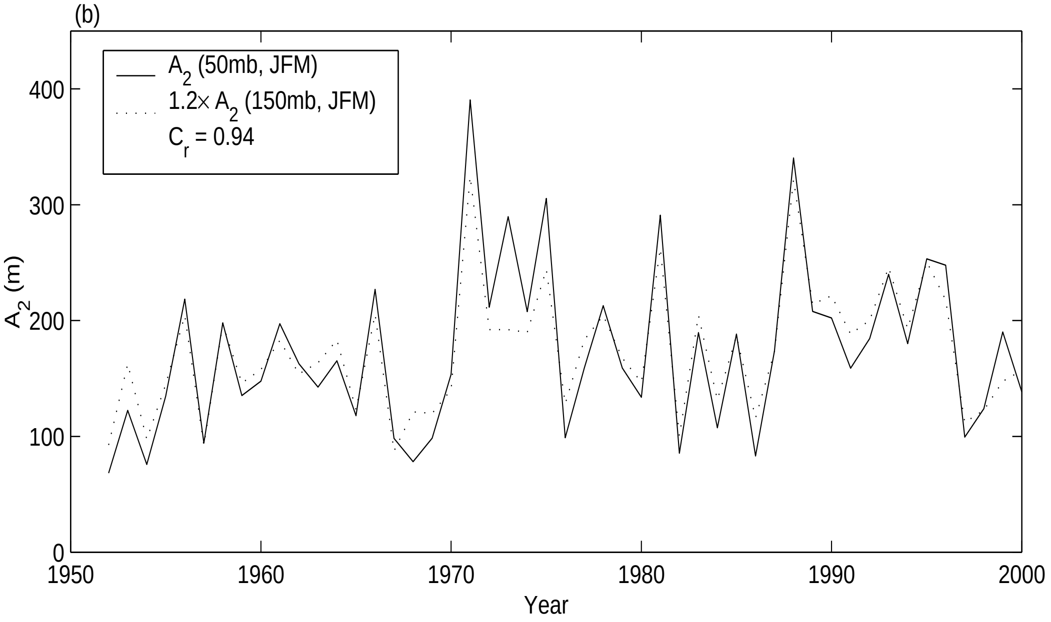

(b)
A$_2$ (50mb, JFM)
1.2× A$_2$ (150mb, JFM)
C$_r$ = 0.94
A$_2$ (m)
0
100
200
300
400
1950
1960
1970
1980
1990
2000
Year

Figure 4.