The Quasi-Biennial Oscillation:
A historical look at the Stratosphere

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Prepared for Professor Morss, 26 September 1994

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THE QUASI-BIENNIAL OSCILLATION: A HISTORICAL LOOK AT THE STRATOSPHERE

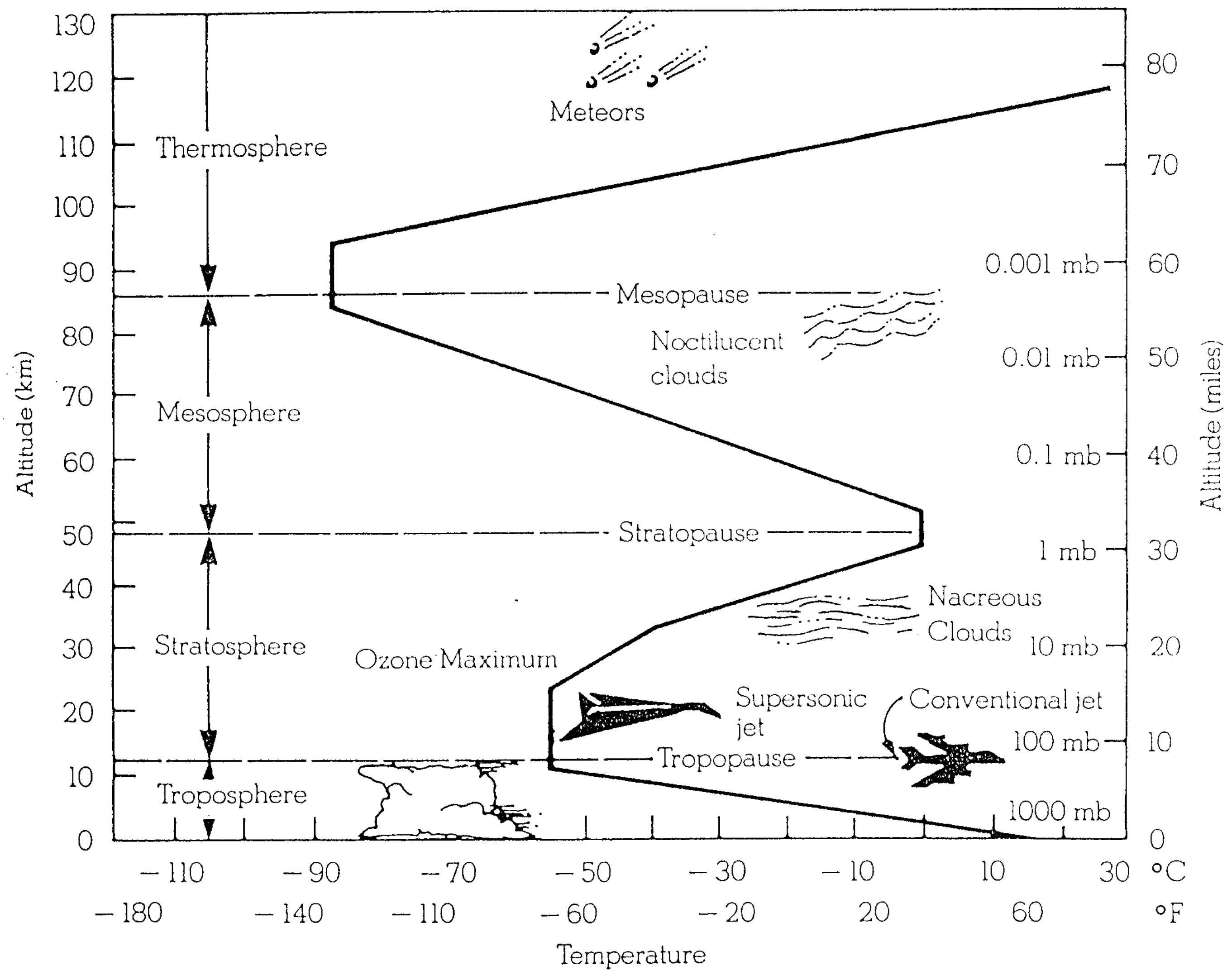
I. INTRODUCTION AND BACKGROUND

The study of the atmosphere has only recently (in the broadest sense) expanded into the upper atmosphere. As man continues his exploration of this planet, he continues to discover new properties of the atmosphere. From photochemical reactions, electromagnetic wave propagation, and thermodynamic processes all contributing to the confusion, we have been chagrined and elated at the secrets held by the "air up there".

This search for knowledge has led us to a basic overview of the vertical structure of the atmosphere. The basic vertical composition of the atmosphere can be summarized in the depiction in figure 1. The atmosphere is held, currently, to be comprised of several layers, each with different chemical and physical properties. Among these layers include the Troposphere, Stratosphere, Mesosphere, and Thermosphere. The intent of this paper is to describe a phenomenon in the stratosphere referred to as the Quasi-Biennial Oscillation, or QBO. This phenomenon occurs in the equatorial stratosphere from roughly 18 to 30 km in altitude. While the occurrence is complicated, we will begin to describe this phenomenon in simple terms. The winds in the stratosphere are basically zonal year round. At a given time they may be easterly. The main feature of the QBO is that these easterly winds will reverse, becoming westerly. This reversal occurs every 24 to 30 months (every 26 months on the average). This paper will provide a more complete discussion of this effect. This will be accomplished by giving the reader an appreciation for the early stratospheric work that lead, ultimately, to the discovery and description of the QBO, and then a discussion of several hypotheses concerning QBO origins and mechanics. Finally, a discussion of the possible impact(s) that the QBO has on the troposphere will be discussed.

II. DISCUSSION

Here, the primary intent is to provide the background history of stratospheric exploration in the last century. The period from 1880 to 1950 will be treated in a brief overview, then each following decade will be treated in a separate summary.



Meteors
Thermosphere
Mesopause
Noctilucent clouds
Mesosphere
Stratopause
Nacreous Clouds
Stratosphere
Ozone Maximum
Supersonic jet
Conventional jet
Tropopause
Troposphere
0.001 mb
0.01 mb
0.1 mb
1 mb
10 mb
100 mb
1000 mb
Altitude (km)
0 10 20 30 40 50 60 70 80 90 100 110 120 130
Altitude (miles)
0 10 20 30 40 50 60 70 80
– 110 – 90 – 70 – 50 – 30 – 10 10 30 °C
– 180 – 140 – 110 – 60 – 20 20 60 °F
Temperature

Figure 1

A. EARLY ATTEMPTS TO UNDERSTAND THE STRATOSPHERE: RESEARCH BEFORE 1950.

> "The Greeks were also the first to advance theories of meteorological phenomena, and their philosophers had much to say on such matters. A great many speculations were set forth, and by the time of Socrates meteorology was held in low esteem. A new word was coined - { meteorolexis } - to designate a mean babbling about sublime things." [McAdie, 1917]

Up until the 1880's, it was believed that there was only the troposphere, which was characterized by decreasing temperature with increasing height. Winds aloft in the midlatitudes were known to be westerly, and thus many thought that all upper atmospheric winds were similar. The 1883 eruption of Krakatau changed this view when dust from the volcano were observed travelling from east to west along the equator. This debris was around the world in 15 days. "The red sunsets and sunrises appeared progressively later from west to east and indicated an average movement of 113 kilometers per hour, 31 m/s." [McAdie, 1917]

This revelation was then followed by crude balloon soundings by Teisserenc de Bort in 1899, which reported a cessation of the temperature lapse rate. This layer, characterized by a zero lapse rate, was dubbed an isothermal layer, and later named by de Bort as the "Stratosphere" [McAdie, 1917]. This layer started at 11 km in the atmosphere, varying from 10-12.5 km. Further research revealed that the height of the initial stratospheric boundary [the tropopause] was actually even higher. The altitude of the tropopause was found to vary with season, latitude, radiation, and in the presence of a surface low or high pressure system, among other factors.

The advances in stratospheric research were limited by technological issues. The typical method of observation was a crude sounding balloon. As technology improved, however, researchers were able to launch balloons with significant sensors onboard. One early example of this was the joint expeditions of the U.S. Army Air Corps/National Geographic Society "Explorer" manned stratospheric balloon missions of the Mid 1930's. The first of these missions, the Explorer I, was launched in 1934. This first experience with manned missions to the atmosphere was trouble-laden, when,

> "... at an altitude of 60,000 feet, ...flight personnel discovered that the bottom of the bag was torn in several places, the descent was begun. At 18,000 ft, ... [the flight crew] climbed out on top [of the pressurized gondola], with their parachutes. The tears had increased in size . . . as the descent continued... At about 3,000 ft an explosion occurred and the entire top of the balloon was torn away. The men were fortunately able to take safely to their parachutes and from the air saw the gondola crash below them. Fortunately, also, it was found possible to salvage a large part of the scientific records made during the flight." [Briggs,1935]

The lessons of Explorer I were taken to heart, and the same brave team tried again one year later. Explorer II of 1935 was a success, reaching a then record altitude of 72,395 feet (approximately 21.5 km). Explorer II took an tremendous amount of data while in the stratosphere, including Cosmic Ray Observations, Neutron (and other heavy particles) studies, Vertical Distribution of Ozone, Electrical Conductivity, Chemical Composition studies, wind information, and even collection of micro-organisms. While the data from these expeditions did not resolve all the main questions of the day, some positive results followed. More detailed knowledge of ozone variations led a significant alteration in the model in the accepted ozone distribution structure. Better knowledge of the upper atmospheric chemistry was of great value. Also, experiments in long range radio communications were received with great praise and wonder.

With this foundation of information on the stratosphere, meteorologists were able to begin a deeper probe into the upper atmosphere. Significant research began after the second world war. During 1940's, upper air data was collected and stored. As technology improved, balloons were able to attain altitudes of 35 km+. Temperatures were noted to rise at these altitudes, and this rise was attributed to ozone concentrations [Humpreys,1941]. Also, numerous expeditions were undertaken to obtain upper air soundings from remote locations. The Tropical Atlantic Expedition of 1948 [Vuorela,1948] discovered a broad easterly current extending well into the stratosphere. Another analysis of the stratosphere included the work of Colon, 1948, in which he took all soundings that penetrated the stratosphere. He was able to identify the winds 7 km above the tropopause. He found that, just above the tropopause, the winds were easterly, with a maximum wind at 3 km above the tropopause. He also noted some westerly winds at different times, but they were weak. Colon dubbed the easterly stratospheric winds the "Krakatoa Current", after the aforementioned volcanic dust event of 1883.

B. MODERN STRATOSPHERIC RESEARCH: SIGNIFICANT DEVELOPMENTS

During the Explorer missions, the community of meteorologists were still under the impression that the atmosphere consisted of the troposphere and stratosphere. Knowledge of the mesosphere and thermosphere came later. Here, a discussion of each decade, with associated research and discoveries, follows.

1. Research from 1950-1960

In the early 1950's, soundings up to 35 km were becoming more common. Also, researchers had a new tool: the computer. While all these early systems were cumbersome at best, the availability of such systems enabled scientists the ability the produce models of the stratosphere.

Early work in the decade by von Berson (Reed, 1961) indicated a narrow channel of westerlies in the same location as the so-called Krakatoa Current. This channel was restricted between 20 degrees North and 20 degrees South, and between altitudes of 20 and 30 km. The Krakatoa Current and the von Berson westerlies comprised the known knowledge of the stratosphere.

Continued work in the stratosphere revealed more discernible patterns, and relationships to the tropospheric flow were observed. Radiosondes were able to rise to the 50 mb level, providing a better look at the atmosphere. Work by Austin and Krawitz, 1955, demonstrated cases where tropospheric cyclones developed as a result of the inductive 50 mb height falls in the strattosphere. In addition to this, research by Jordan, 1955, demonstrated a relationship between the stratospheric winds and tropopause height, where a maximum in the strotospheric wind field would result in a minimum in the tropopause height.

It was during the later half of the decade, data was retrieved near Canton Island and Nairbi, Kenya by a group headed by Reed, Campbell, Rasmussen, and Rogers. While their final results were not published until 1961, the data they used was collected from July 1955 and February 1960. Figure 2 shows the data collected during this study. They described their work as follows:

> "Stratospheric wind data for Canton Island (3° S) and Nairobi, Kenya (2° S), reveal that during the period July 1955 - February 1960 alternate bands of easterly and westerly winds progressed downward from the highest level of observation (30 km) at intervals of approximately 1 year, suggesting the presence of a 2-year zonal wind oscillation in the equatorial stratosphere. The bands circle the entire globe, reach their greatest strength near 25 km,are about 10 km deep at intermediate levels, move downward at about 1 km per month, and weaken and become erratic near the tropopause. On the basis of ozone measurements it is argued that the downward propagation represents a wave motion, not a mass transport. The periodic appearance of westerly momentum at the equator suggests the presence of disturbances in the tropical stratosphere which transport momentum in a preferred manner." [Reed et al,1961]

In addition to the above, they determined that "above the 50 mb level (21 km), easterlies are more frequent than westerlies and are generally of greater strength." [Reed et al, 1961].

While Reed et al did not determine the causes for this oscillation, their work acted as a landmark in the area of stratospheric research. The original concept of the von Berson westerlies and Krakatoa easterlies gave way to this near-biennial wind oscillation.

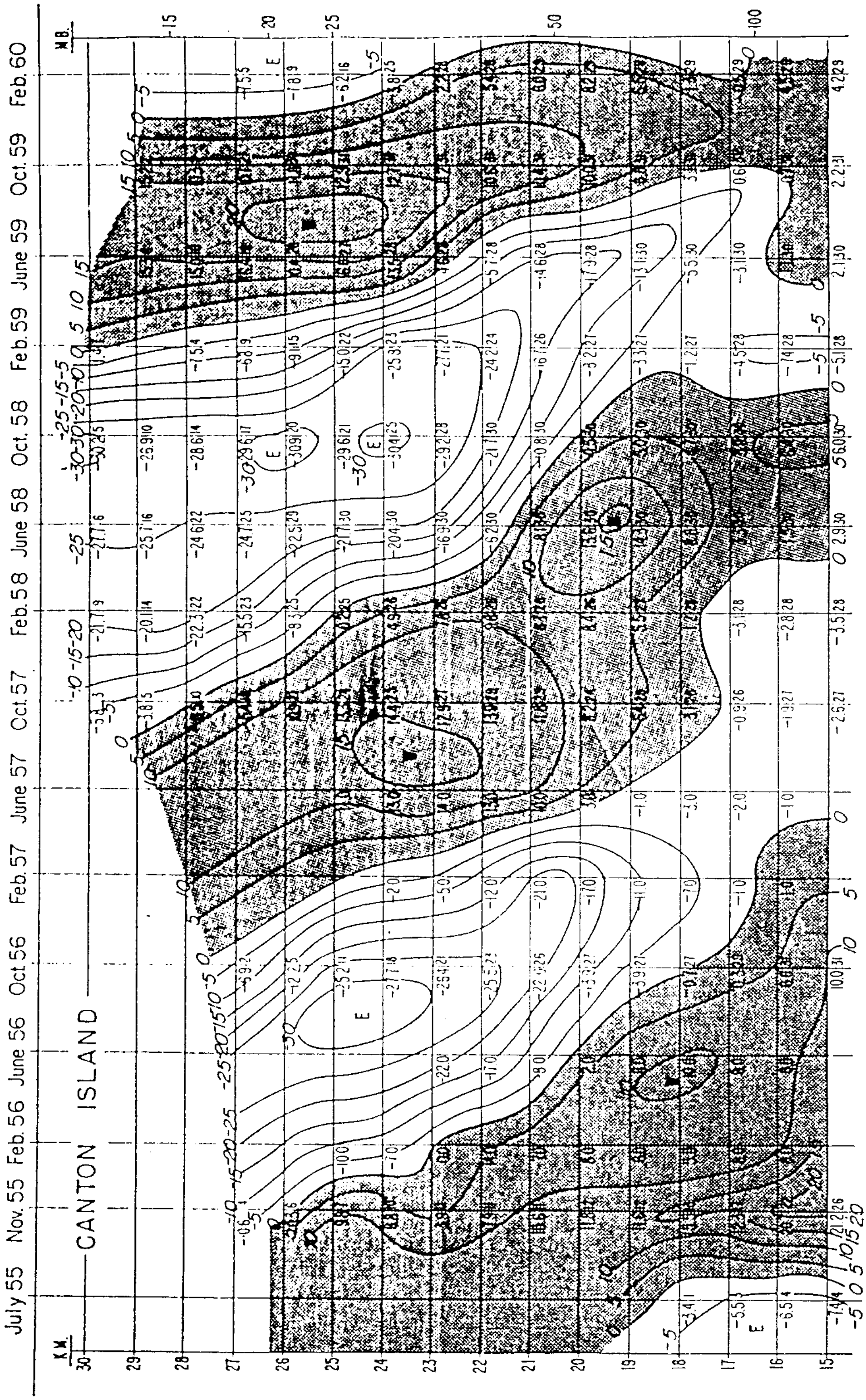

CANTON ISLAND
July 55
Nov. 55
Feb. 56
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Figure 2

2. Research from 1960 -1970

In 1961, a feature similar to Reed's 26-month wind oscillation was discovered. This was the 26 month temperature oscillation, discovered by Veryard and Ebdon in 1961. Later in the 1960's, a fluctuation in ozone concentrations was also observed, and its variation was related to the oscillation by Funk and Garnham, who noted that "at levels of warm temperature anomalies, there is above normal ozone concentration. Cold temperatures bring below normal concentration of ozone". [Mestrovich,1993] Also, it was noted that when equatorial temperatures are warm in a layer about 21km, the ozone amount is higher than normal near the equator, and less than normal in the subtropics. Work done by Rangarajan [1964] indicated that the oscillation wind fields and ozone concentrations were "exactly out of phase". His findings suggested that the variations in ozone are mutually connected with winds.

Earlier findings were further expounded upon by Reed et al [1966], where a definitive description of the Quasi-Biennial Oscillation (QBO) was made public. It has been widely accepted that the properties given by Reed et al represent the areas that must be explained by any theory regarding the cause of the QBO. The conclusions are provided below:

> "1. The period of the oscillation varies with a mean of approximately 26 months.
> 2. There is no significant variation of the period with height.
> 3. However, the phase of the oscillation changes with height, e.g. the easterlies and westerlies appear earlier at the highest levels and progress downward at an average speed of slightly greater than 1 km/month
> 4. The amplitude of the oscillation attains a maximum value of about 25 m/s near the 25 mb level (approx. 25 km.). Below this level, winds rapidly diminish in magnitude as you approach the tropopause.
> 5. Comparison of the zonal winds between 50,000 and 70,000 ft demonstrates little correlation between the oscillations within the troposphere and stratosphere.
> 6. Cycle to cycle amplitude variations of the oscillation are observed." [Thomas, 1993]

The primary features that require explanation from any theory include (1) the periodicity of the QBO, (2) the appearance of zonally symmetric westerlies at the equator, and (3) Downward propagation, without loss of amplitude, of the reversal.

Numerous theories emerged from this period as to the causes for the QBO. All theories fell into one of three categories: (1) extraterrestrial influences, (2) internal theories based on some natural cycle in the atmosphere, and (3) internal theories suggesting subharmonic response to shorter-period driving mechanisms, such as the annual heating cycle. [Mestrovich, 1993]. One example of the extraterrestrial influences was the hypothesis offered by Shapiro and Ward. They believed that a solar / electromagnetic source was behind this. Variations in Ultra-violet radiation may be causing the QBO pattern. Photochemical reactions with ozone were postulated as the primary source of energy. This did explain several features of the QBO, but, the observational data did not back up this concept statistically. In 1968, Wallace and Holton argued that radiative heating could not cause the the QBO, since the diabatic heating range would have to be 1.5C at the equator in order to produce the observed amplitude and oscillation. There is a great deal more potential energy in the stratosphere than kinetic. Conversion of potential energy to kinetic was shown to exhaust the supply of potential energy unless the strong diabatic heating was resupplying it. Their conclusion was that this (the QBO) was a dynamic effect.

Another theory was provided by Lindzen and Holton in 1968. They suggested that the QBO is the result of the interaction of long-period, vertically propagating gravity waves with the zonal wind. Absorption of momentum of these waves by the mean flow leads to a downward propagating zonal wind profile.

Theoretical efforts were extensive in the sixties, and continued into the seventies.

3. Research from 1970-1980

The theorized upward propagating equatorial planetary scale waves of Holton - Lindzen, 1968, were further explored, and in 1972, Holton and Lindzen sought to better understand the role of Yanai and Kelvin waves at critical levels and how they affected momentum flux in the stratosphere.

To better enable the reader, a few terms will be defined. First, a Yanai wave is an easterly mode wave with a maximum zonal phase speed of about 23 m/sec. It is also referred to as a mixed Rossby-gravity wave. The Kelvin wave is a westerly mode wave with a maximum zonal phase speed of approximately 10-11 m/sec. The critical level denotes the "level at which the mean horizontal flow Doppler shifts to zero" [Lindzen, 1971]. The original QBO theory developed by Holton and Lindzen expected that momentum change occur between the above mentioned waves and the mean flow was critical level momentum absorption. As a consequence, a spectrum of waves with a continuous distribution of phase speeds between maximum westerly and easterly velocities was required. Research work by Lindzen found that no evidence for these intermediate waves was evident. Lindzen developed a set of equations that eliminated the need for such waves. In 1972, Holton and Lindzen reevaluated their theory. They suggested that even the primary causative mechanism for the oscillation is associated with vertically propagating equatorial Kelvin waves and mixed Rossby-gravity waves which originate in the troposphere. While accepting that solar activity may play some interactive role, Holton and Lindzen maintained that the absorption of momentum of these large scale waves by the mean flow is sufficient to produce the zonal momentum source necessary to drive the QBO. This process of wave-mean flow interaction, coupled with the damping of wave energy by infrared radiation into space can account for the generation, downward propagation, and approximate periodicity of the QBO. This theory is the most widely accepted dynamical explanation of the oscillation, to this day.

4. Research from 1980 to the present

A number of different research paths have been travelled during the last 14 years. Recently, investigators have brought back the idea of solar activity and volcanic events to the QBO. Work has been done to correlate sunspot number to to zonal wind period. However, the correlations demonstrated thus far have not been promising. Volcanic impacts on the QBO are not clear, either.

Studies on the relationship between ozone flux and the QBO have been more promising. Recent work indicates that near-equatorial ozone is possibly associated with vertical advection and modulation of planetary scale Rossby and gravity waves. Equatorial ozone anomalies have consistently followed the transition to the west phase of the QBO. Figure 3 shows the trend between ozone anomalies and the QBO winds in the stratosphere

The remainder of this paper will provide a brief overview with respect to the relationship between the QBO and the troposphere. It is the author's intent to display the major affects the QBO may have on the forecaster.

III.SOME IMPLICATIONS OF THE QBO PHENOMENA IN THE TROPOSPHERE

First, recent work by Holton has indicated that anomalous strengthening of the polar jet tends to occur in conjunction with the west phase of the QBO at 50 mb. The centroid of the north polar vortex is displaced farther toward the Pacific Ocean at the time of the QBO's west wind maxima. In addition to this, work has been done to see if the QBO has

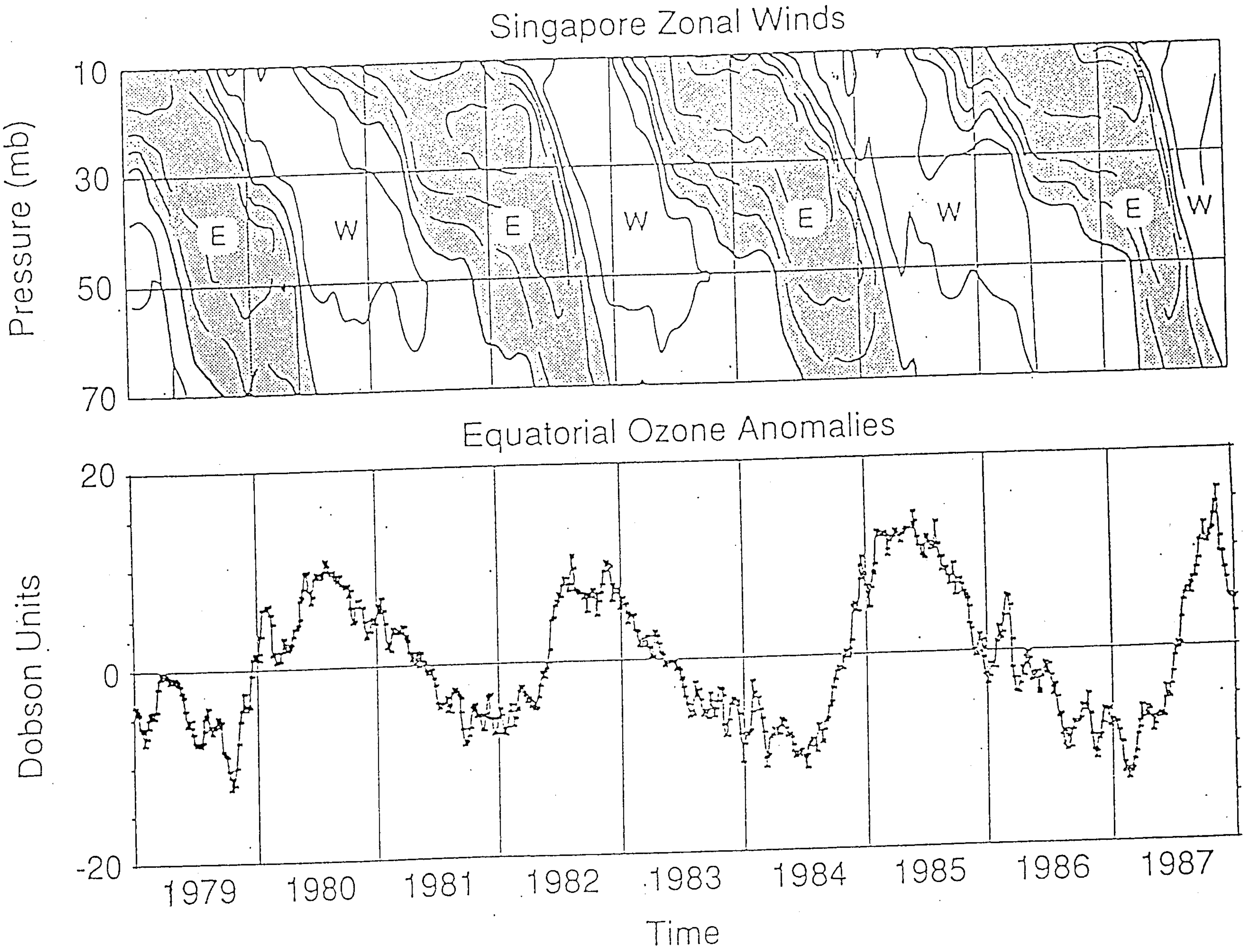

Figure 3. Zonal mean equatorial ozone anomalies, and time height section of Singapore zonal winds in m/sec. [after Bowman, 1989]

an impact on the location of synoptic "centers of action", namely,the Azores High, Pacific High, Aleutian Low, etc. Significant correlations were found between the equatorial stratospheric zonal winds and the longitude and pressure of the Azores High, and the latitude of the Pacific High. During the west phase of the QBO, the Azores High tends to be far west, and the pressure relatively low.

Much attention has been directed to studying the QBO as a climate factor, affecting the equatorial and extra-tropical stratosphere, in addition to the tropical troposphere and oceans. Specifically, the QBO has been linked to ....

- Occurence of intense Pacific and Atlantic basin tropical cyclones. Incidence is highly biased, by a factor of two to one, to the west phase of the QBO.
- The El Nino-Southern Oscillation (ENSO). The east phase of the QBO consistently precedes the sequence of events leading to the onset of warm (El Nino) sea surface temperature events in the central and eastern Pacific. The west phase tends to favor the development of La Nina (anomalously cold sea surface temperatures.
- The strength of all major monsoonal circulations is related to the phase of the QBO. During the west phase of the QBO, good correlations have been noted relating the QBO to precipitation averages at numerous stations.

IV. SUMMARY AND CONCLUSIONS

The Quasi-Biennial Oscillation is a complex interaction of oscillating winds, temperature, and ozone in the equatorial stratosphere. It is believed to be caused, dynamically, by a combination of Rossby and gravity waves, in addition to, possibly, some solar effects and photochemical interactions. While the causes are still being researched, clear relationships are being observed between the QBO and the tropospheric motion from the equator to the polar jet. The QBO has been, is, and will be an important phenomenon to analyze for for synoptic weather forecasting, in the future, when it is better understood.

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