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Stratospheric Influences on Tropical Cyclones

By

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Prepared for Professor Morss, 28 October 1994

Creighton University

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(1).	Rudolph, D., 1991: AOR forecasters handbook for Guam, U.S. Naval Oceanography Command Center/Joint Typhoon Warning Center, Guam. PSC 489 Box 12, FPO AP 96536-0051.
(2), (3), and (4).	Williams, J., 1992:The Weather Book. Vintage books, Random House, New York, NY pp 131-149.
(5), (7), and (10).	Gray, W., 1989: Background Information for assessment of the expected Atlantic Hurricane activity.Colorado State University, Fort Collins, CO, 80523.
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STRATOSPHERIC INFLUENCES ON TROPICAL CYCLONES

ABSTRACT

The conventional notion of tropical cyclone forecasting generally includes a look at the surface through 200 mb winds, with little thought of the potential for influences above 150 mb. In particular, stratospheric influences are ignored. While connections between the stratosphere and the troposphere are not well understood, recent evidence indicates that there are striking connections, both direct and indirect, between these layers. These connections are already being applied, in a statistical manner, to the genesis and movement of tropical cyclones.

I. INTRODUCTION

Identifying the influences of the stratosphere on tropical cyclones will be difficult at best. All of the accepted conditions for tropical cyclogenesis are stated for phenomena in the troposphere. Similarly, the forces for tropical cyclone motion are also held to be in the troposphere. The author will provide a brief overview of pertinent factors affecting tropical cyclogenesis and motion. Afterwards, the synoptic flow in the stratosphere will be examined briefly. All focus will be on the Equatorial Stratospheric Quasi-biennial Oscillation (QBO). The impact of the QBO on the development and motion of tropical cyclones will follow. Please note that, since most arguments are made for Atlantic Hurricanes,

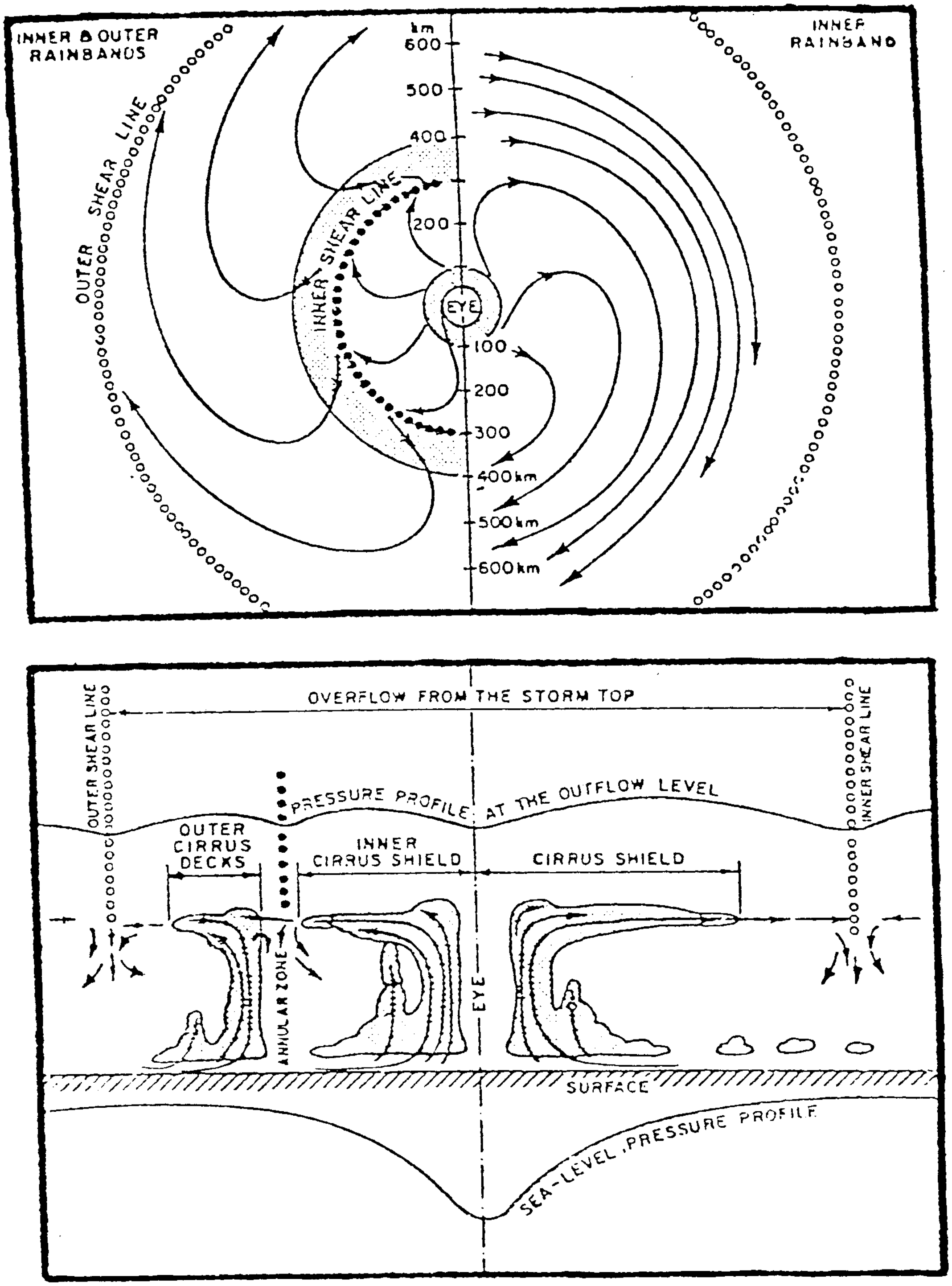


Figure 1 *Model of typhoons with outer and/or inner concentric rainbands. TOP: Upper-tropospheric outflow winds for typhoon with inner rainband only (right half) and both inner and outer rainbands (left half). Rainbands are indicated by stippling. A shear line circling the inner cirrus shield is seen when typhoon has distinct inner and outer rainbands. BOTTOM: Schematic cross-section of vertical motion, clouds, and pressure for model typhoons shown at top. The pressure along both the outer and inner shear lines is slightly low, creating convergent outflow winds which subside to a certain depth. (After Fujita et al. (215)). (from AWSTR 240)*

the author will restrict discussion to the Atlantic basin. A brief mention of the other basins will be provided.

A. Conditions favorable for Tropical Cyclogenesis.

The first effort will concentrate around the tropical cyclone itself, identifying the structure of the system, and accepted ingredients necessary for cyclogenesis.

Tropical Cyclone Structure

The structure of a tropical cyclone is viewed in figure 1. This demonstrates a cross-section of the system, indicating cyclonic inflow at the surface. Air is converging and rising (primarily) at the inner wall cloud surrouding the "eye", and under the outer rain bands. Aloft, the winds diverge and descend some distance away. Pielke [1990] stated the stratosphere acts as an inhibitor, preventing transport of air into the upper levels, causing a horizontal flow under the tropopause. While this is generally true, other work has indicated that the upper level structure can and does penetrate the tropopause. Analysis of photos from the Skylab missions of the 1970's have indicated that convective cloud tops do overshoot significantly.

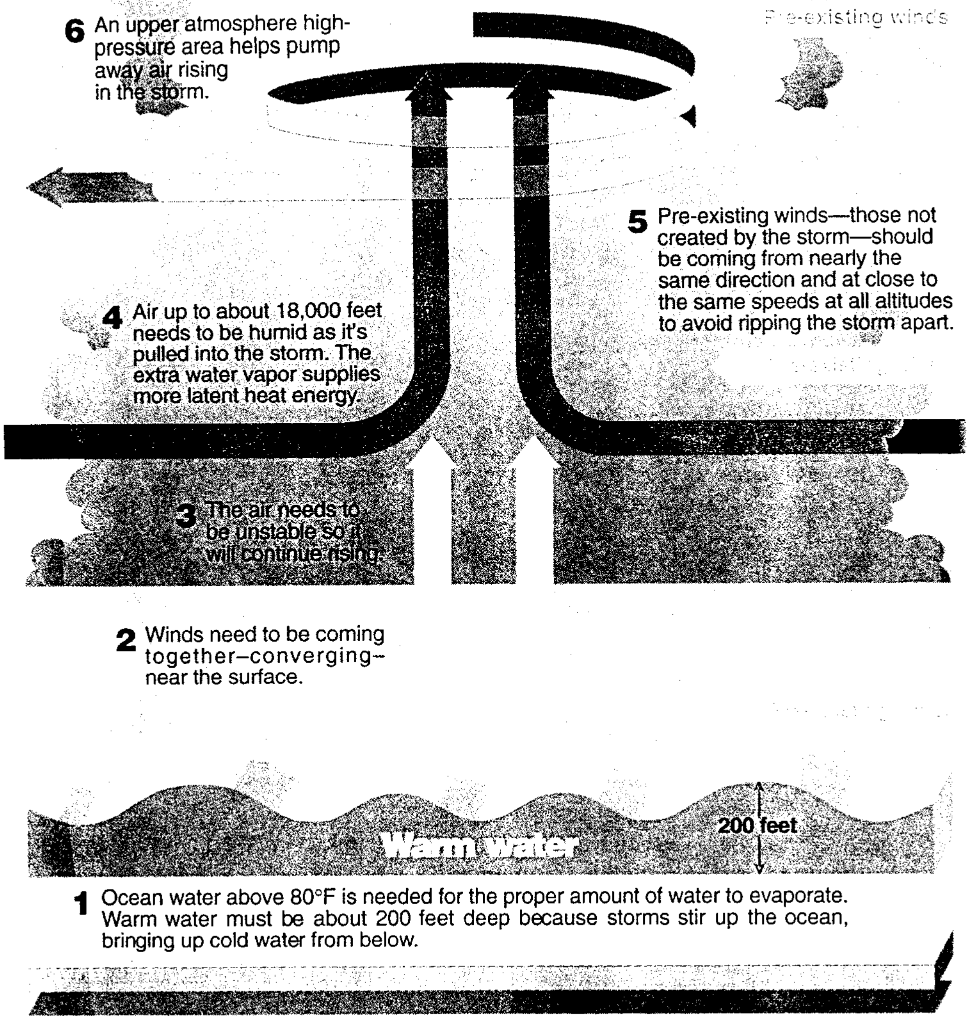
sp

> " The most surprising result...is the determination that the circular cloud [associated with Tropical Storm Ellen,1973] is a large dome protruding into the stratosphere. .....the dome is protruding nearly 3 km above the undisturbed height [tropopause] with smaller scale convective turrets protruding another 1.0 to 1.5 km higher." [Black, 1977]

More recent work by *Pfister et al* [1989] indicates that significant mass transfer is taking place between the upper troposphere and lower stratosphere in a tropical cyclone. Their data showed "evidence of injection of tropospheric

The ingredients a hurricane needs

Fewer than 10 percent of tropical weather disturbances grow into tropical storms because the right ingredients are relatively rare.



6 An upper atmosphere high-pressure area helps pump away air rising in the storm.

5 Pre-existing winds—those not created by the storm—should be coming from nearly the same direction and at close to the same speeds at all altitudes to avoid ripping the storm apart.

4 Air up to about 18,000 feet needs to be humid as it's pulled into the storm. The extra water vapor supplies more latent heat energy.

3 The air needs to be unstable so it will continue rising.

2 Winds need to be coming together–converging–near the surface.

1 Ocean water above 80°F is needed for the proper amount of water to evaporate. Warm water must be about 200 feet deep because storms stir up the ocean, bringing up cold water from below.

Figure 2

air , even at these altitudes above the nominal top of the transition zone above 17.5 km" [Pfister et al, 1989]. Their conclusions were also interesting:

> "...we have shown that :(1) there is a subadiabatic transition zone above the tropospheric anvil containing both stratospheric and tropospheric air; (2) the presence of this zone appears to depend on differences between the surface and anvil winds; and (3) there is evidence of overshooting turret detrainment and gravity wave induced turbulence, both of which may contibute to generating the transition zone" [Pfister et al. 1989]

Thus, the structure of a tropical cyclone clearly can and does have a reflection in the stratosphere. While the implications of this are not obvious, suffice to say that we will need to at least consider stratospheric influences on a cyclone.

Tropical Cyclogenesis

The general conditions necessary for cyclone formation are as follows (also see figure 2):

(1) Ocean Temperature must be high enough relative to air temperature. Usually, 26-27 °C is considered a threshold value in the deep tropics. [Riehl, 1979]. This must be coupled with a relatively deep oceanic mixed layer.

(2) A pre-existing concentration of cyclonic vorticity must be present in the lower through middle troposphere. This may serve as the "initial disturbance".

Note that, along with this condition goes the idea that the atmosphere must be capable of permitting deep convection to occur. The atmosphere should be warm and moist throughout the vertical column, and conducive to overturning when the air becomes saturated. [Pielke, 1990]

(3) Weak vertical wind shear (i.e. "less than about 15 knots between the upper and lower troposphere..." [Pielke, 1990]) is necessary to permit vertical development of the cyclone. Strong shear can displace the deep convection and the associated

warm column away from the low-level circulation, resulting in weakening or dissipation of the system [Rudolph, 1991]

(4) A cyclone will generally form within a latitude band of 5 to 25 degrees (although some special cases have formed around 2-5 degrees latitude). No storms form on the equator. This is due to a minimum value of the "coriolis parameter " (the component of the earth's rotation) needed to provide sufficient angular momentum to actually induce air rotation [Riehl,1979]

(5) The development of a synoptic scale anti-cyclone in the upper troposphere over the surface cyclone. This will permit air mass to be evacuated from the region of the cyclone, and permit surface pressures to fall.

It is valuable to remember that the primary contributor of energy to a tropical cyclone is the release of the latent heat of condensation. As a parcel of moist air is lifted, it is cooled (in the troposphere) in accordance with the lapse rate, until the parcel is cooled sufficiently to change phase. As the water vapor turns to liquid, the water releases latent heat. This heat is added to the atmosphere, thus warming the environment. This creates a dynamically unstable situation, enhancing upward vertical motion (see figure 3).

While the above list is accepted for most conventional forecasting uses, recent work by Gray [1988] indicates that there may be other influences afoot. He stated:

> " The reasons for season to season variations in Atlantic hurricane activity are becoming better understood. These variations are closely associated with seasonal differences in the stratospheric wind or the Quasi-biennial Oscillation (QBO), the presence or absence of El Nino [El Nino / Southern Oscillation (ENSO)] events, the western tropical Atlantic Sea Level Pressure Anomaly (SLPA), and the lower Caribbean Basin 200 mb (12 km) Zonal Wind Anomaly (ZWA)". [Gray, 1989]

How water powers hurricanes

Heat released when water vapor condenses into water drops or turns directly into ice high in the air supplies most of the energy for hurricanes. The amounts of energy are huge: In one day a hurricane can release enough energy to supply all of the nation's electrical needs for about six months.

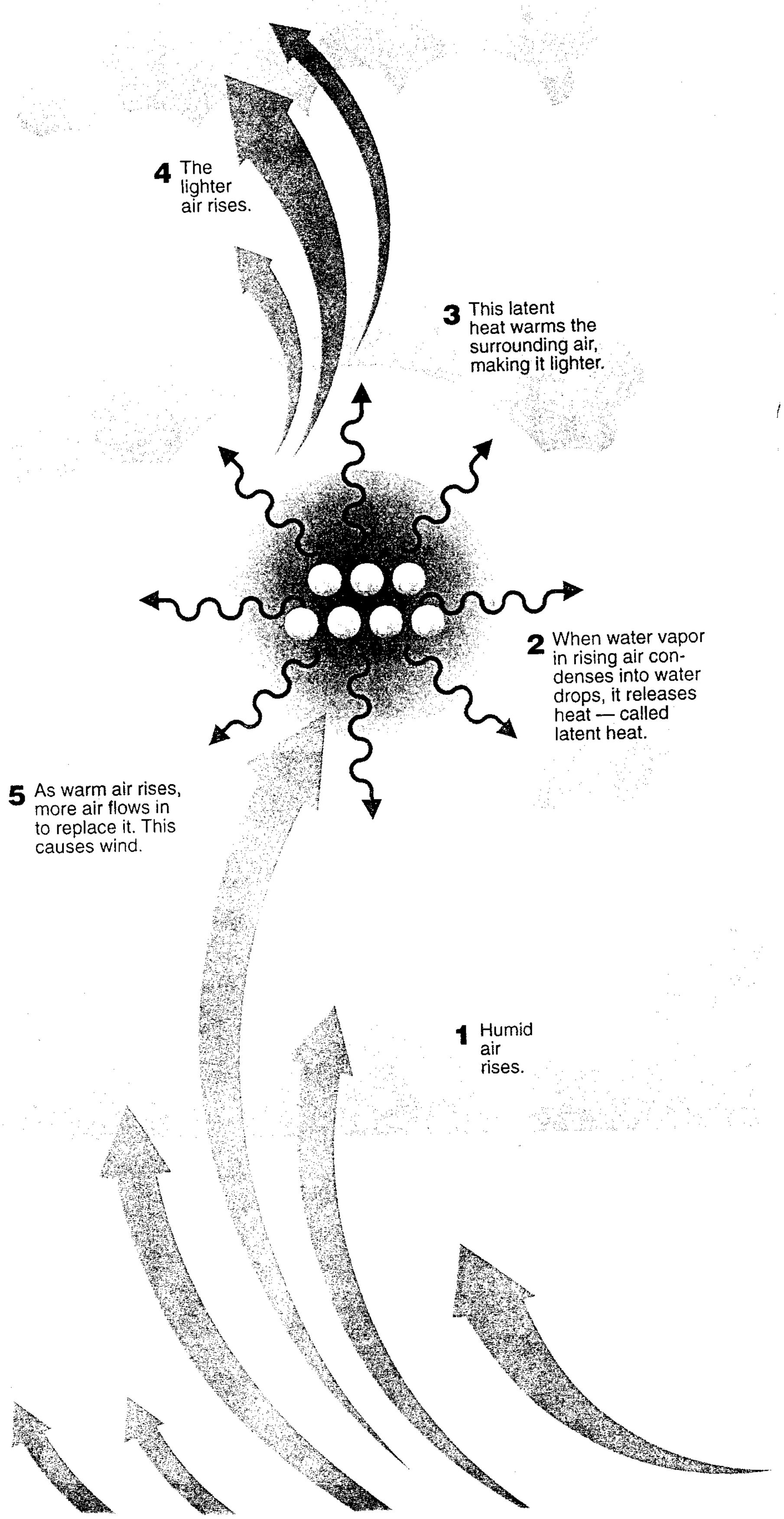
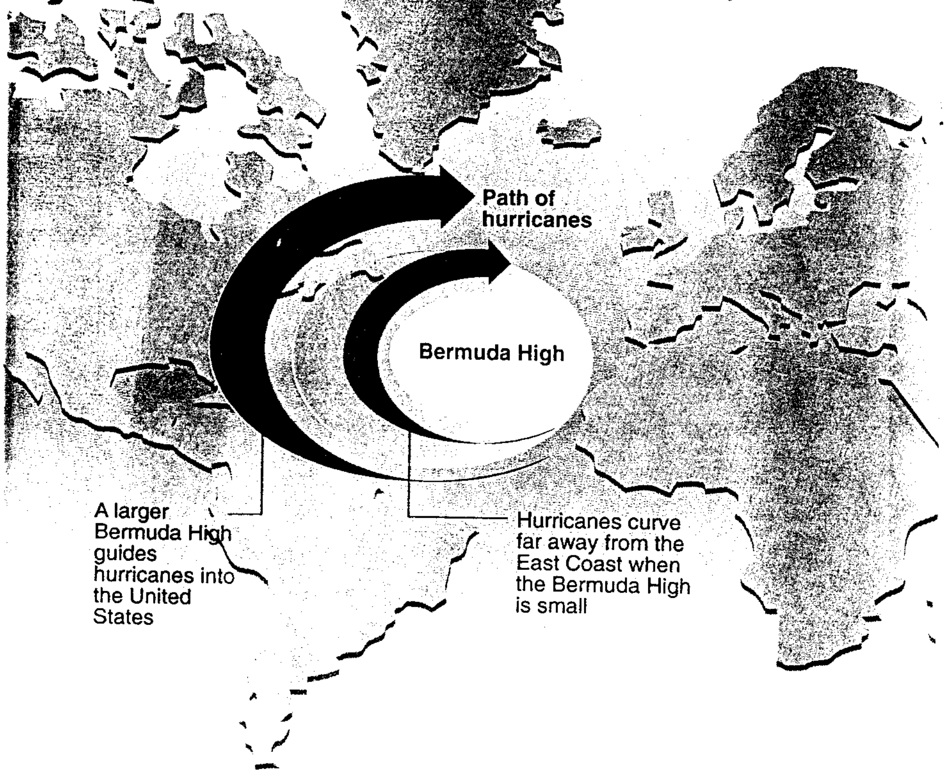


Figure 3

How the Bermuda High helps guide hurricanes

The clockwise winds around the area of high pressure that dominates the Atlantic Ocean — the Bermuda High — establish the steering currents for many hurricanes.



A larger Bermuda High guides hurricanes into the United States

Hurricanes curve far away from the East Coast when the Bermuda High is small

Figure 4

While the mechanics of these relationships are not fully understood, some theories exist as to the reasons for these interactions. In particular, we will focus on the QBO, ENSO, and SLPA effects.

B. Controls on Tropical Cyclone Movement.

"Tropical cyclone motion results because the storm is embedded in a larger scale region of moving air, referred to as the steering current, which tends to move the low-level cyclonic, upper -level anticyclonic circulation and associated deep cumulonimbus convection in the direction of that flow" [Pielke, 1990]. Chan and Gray [1982] have indicated that the mid-level of the atmosphere (from 500 to 700 mb) seems to reflect storm motion with reasonable precision. Viewing the issue on a synoptic scale, a strong extra-tropical jet stream can have a profound impact on a tropical cyclone, causing rapid accelerations. More importantly, though, is the effect of a "center of action", which is defined as a climatological high or low pressure system (e.g. the Bermuda High, Pacific High, Aleutian Low, etc.) For example, the Bermuda High is known to establish the steering currents for many Atlantic Hurricanes (Figure 4). A larger Bermuda High guides hurricanes close to the United States, where a smaller system will cause a storm to recurve away from the US [Williams, 1993]. One tale of the movement of Hurricane Betsy of 1965 paints a clear picture: "...Betsy was moving northwest around the southern rim of the Bermuda High subtropical ridge.... As the storm was moving northward off the east coast...a readjustment occurred in the hemisphere flow patterns owing to a trough in the westerlies over the central US.

This change resulted in the propagation of the subtropical ridge towards the west until it was north of [Betsy]. As a result...Betsy was blocked from continuing its climatologically expected northward movement and became stationary....." [Pielke, 1990]. Clearly, one can see that these synoptic scale features have a major impact on cyclone motion. While there are other, more complex interactions that may be considered with respect to tropical cyclone motion, this will conclude our discussion on motion.

The impact of the stratosphere may seem sadly lacking in this theory. However, the author will later attempt to demonstrate an actual link between the the stratospheric patterns and the steering flow for tropical cyclones.

redundant terms

C. Primary Stratospheric Features.

Because this paper focuses on the effects in the tropics, efforts will concentrate on stratospheric features in that regime. It has been determined that large-scale, equatorially confined waves propagate vertically and zonally through the stratosphere. " Above 35 km the seasonal variation is characterized primarily by a semiannual oscillation of the mean zonal wind. Well below 35 km... the equatorial stratospheric seasonal cycle is completely overwhelmed by a long term oscillation that is not directly linked to the march of the seasons. This oscillation, which is of somewhat irregular period (averaging 27 months), is called called the 'quasi-biennial' oscillation (QBO)" [Andrews et al, 1987]. The QBO is characterized by the following features:

redundan terms

"(1) An alternating pattern of eastward and westward wind regimes that repeat at intervals varying from about 22 to 34 months, with an average period of 27 months.

(2) Downward propagation of successive regimes at an average rate of about 1 km/month, but with westerly shear zones descending more regularly and more rapidly than easterly shear zones.

(3) Amplitude nearly constant in height between 40 and 10 mb, but decreasing rapidly as regimes descend the 50 mb level."
[Andrews et al, 1987]

The QBO is observed between 18 and 30 km in the stratosphere. Because it is possible for QBO winds to descend to levels as low as 18 km (practically at the tropopause), it makes sense to consider the impact of the QBO on tropospheric convection which extends into the stratosphere, such as that associated with tropical cyclones. As a result, the discussion regarding stratospheric influences on tropical cyclones will be directed towards the QBO exclusively. For additional information on the QBO, the reader is referred to previous work by the author [McCrone, 1994].

The remainder of this paper will be directed towards the specific influences of the QBO on Atlantic Hurricanes. First, a disussion of the direct QBO influences will be covered, then the indirect affects will follow. The indirect effects provide, for example, information on how the QBO impacts the steering flow of the middle troposphere. This effect is then related to the movement of tropical cyclones. Afterwards, a presentation of a seasonal forecasting technique will be provided to demonstrate the influence of the QBO on tropical cyclones.

II. DIRECT QBO IMPACT

The conditions that exist during the two phases of the QBO at 50 mb

(20 km) are illustrated in figure 5. On the left, the east phase conditions are present. At this time, winds at the equator are from the east, and the winds at 10°N are strongly from the east. On the right, west phase conditions are displayed. The winds on the equator are from the west, and the winds at 10°N are only light from the east.

too terse - could use some expansion - to lead reader through the diagrams better

A. Accepted Theory prior to 1984.

While the QBO was first discovered in the early 1960's, few people had any idea what impact the QBO had on any tropospheric phenomenon. The beliefs ~~of that time~~ prior to 1984 are best summmarized by Riehl, 1979:

> " The Hurricane circulation weakens and disappears toward 100 mb, and easterlies already prevail at this height. These strengthen upward considerably to 50 mb [See figure 6] and attain 25 m/s at 25 mb. Of course, there is no information within the hurricane core, but one would think that any strong perturbation there would be transmitted as far as stations on the Forida Coast. On the basis of the charts shown, the assumption of a 100 mb top appears justified."

B. Dr. Gray's 50 mb wind Theory of 1984.

In 1984, the above viewpoint changed when Gray issued a paper on the seasonal variations of Atlantic Hurricanes. According to Gray:

> "....Hurricane formation and hurricane intensity is also influenced by vertical wind shear conditions in the lower stratosphere. Hurricane formation is inhibited when lower stratospheric winds (or winds just above the tropopause [TROP]) blow too strongly from the east as shown by the upper left diagram [of figure 7]. This causes the central cloud convection and the influences of such convection to be sheared off to the west as shown by the lower left diagram of this figure. These conditions are inhibiting to hurricane activity. By contrast, when lower stratospheric zonal winds blow only lightly from the east as shown by the upper right diagram [of figure 6] , vertical wind shear conditions remain weak and hurricane inner-core deep convection

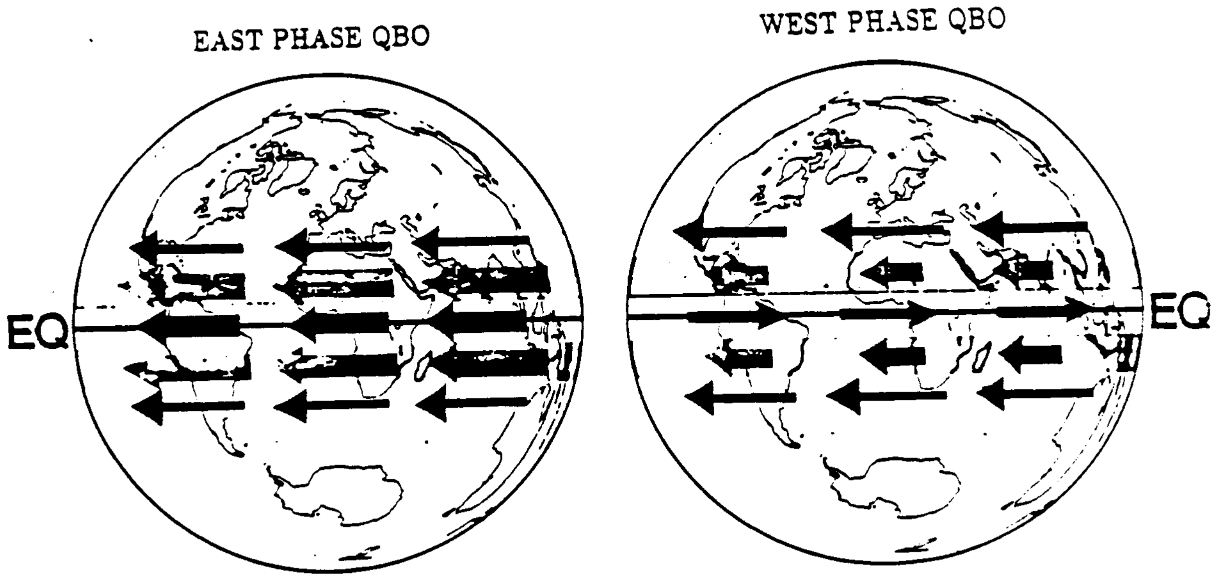


Figure 5 Illustration of the two basic stratospheric Quasi-Biennial Oscillation (QBO) wind conditions which occur over the tropics at 50 mb or 20 km altitude during the summer seasons of both hemispheres. The left diagram shows conditions during the easterly phase of the QBO when easterly winds occur on the equator and winds at 10°N are strongly from the east. The right diagram, by contrast, shows conditions during the westerly phase of the QBO when stratospheric winds on the equator are from the west and winds at 10°N (or 10°S) latitude are only weakly from the east. Hurricane activity is suppressed with conditions of the left diagram (east phase) and enhanced with conditions of the right diagram (west phase).

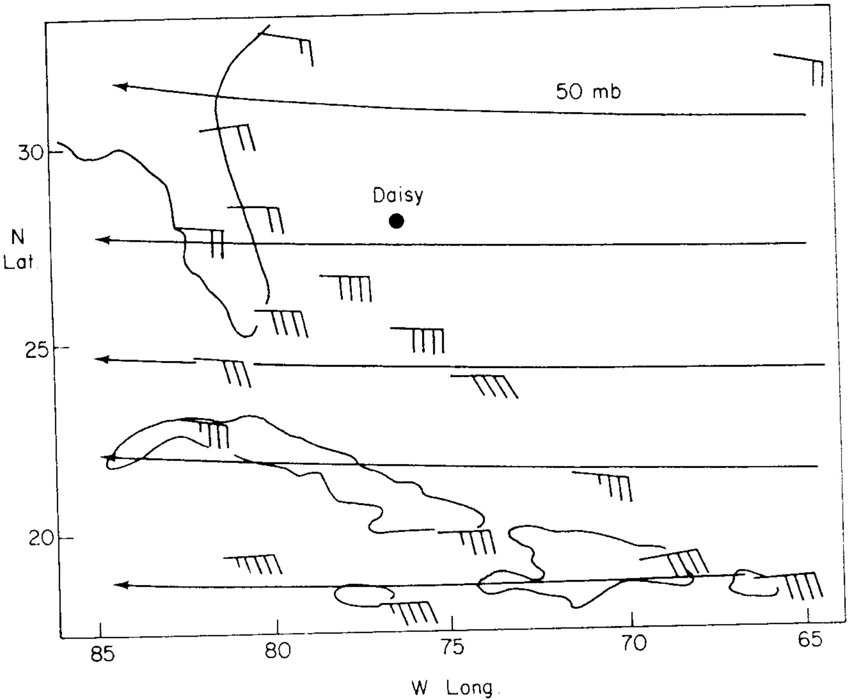


Figure 6 Winds at 50 mb over the West Atlantic-Florida region during hurricane Daisy on 26 August, 1958 (29).

> and the influences of such convection is not sheared off to the west in the lower stratosphere. Conditions on the right diagrams [of figure 7] are more favorable for hurricane formation and the development of intense hurricanes" . [Gray, 1989]

Gray goes on to point out the fact that weak easterlies at 10°N are caused by the QBO. The primary point, though, is this: the QBO is believed to have a shearing influence on hurricanes, where the east phase of the QBO causes a high shearing environment to occur, thus inhibiting the development of a hurricane. The west phase of the QBO causes weak easterlies to prevail over 10 degrees North. This brings a low shear environment, conducive to cyclone formation. The reader will remember that low shear was one of the five main factors leading to tropical cyclone formation. Thus, this issue of stratospheric shear is potentially very significant.

To further demonstrate the QBO - shear connection, data will be provided from the work of Runk, 1993. In figure 8, we see a plot of the QBO winds with a plot of total number of tropical cyclones exhibiting a shear pattern. Also on this plot is a recounting of the percentage of tropical cyclones undergoing shear. This data was obtained by analysing numerous tropical cyclone images (between Sp January 1987 through December 1993 *from around the world.* In order to reduce the possibility of subjective overestimation, agreement was sought with historical records from tropical cyclone warning agencies, such as the National Hurricane Center in Coral Gables, FL, and the Joint Typhoon Warning Center in Guam. While the methodology may not be free from potentially high statistical errors, one can see in the data a clear, in - phase correlation between the QBO and

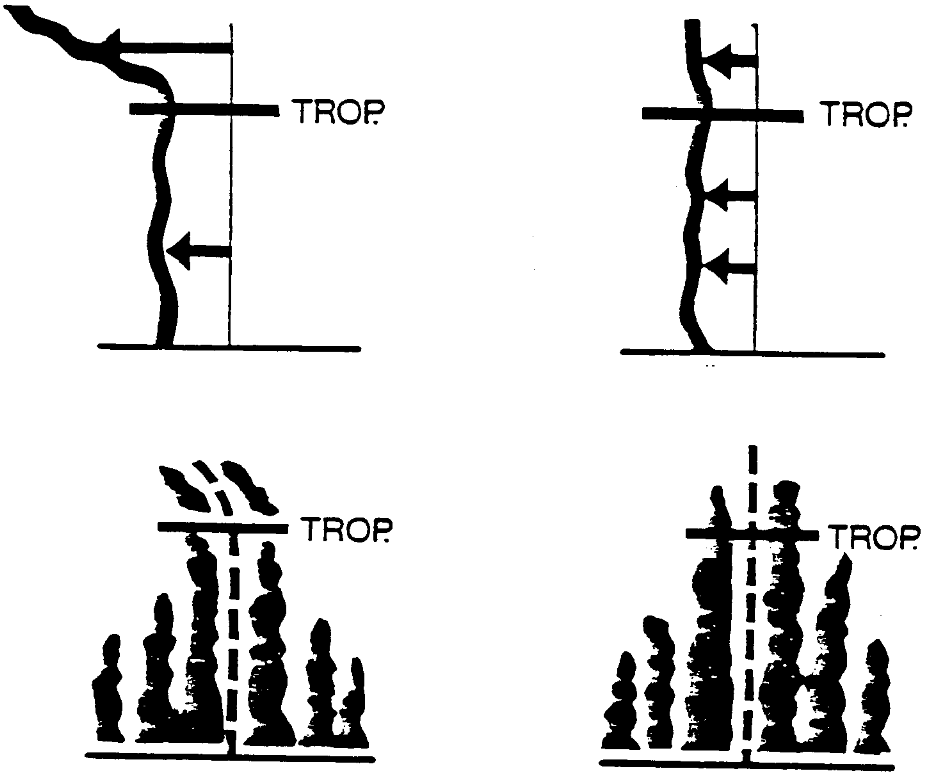


Figure 7

QBO Cross-Section, 1987-1993

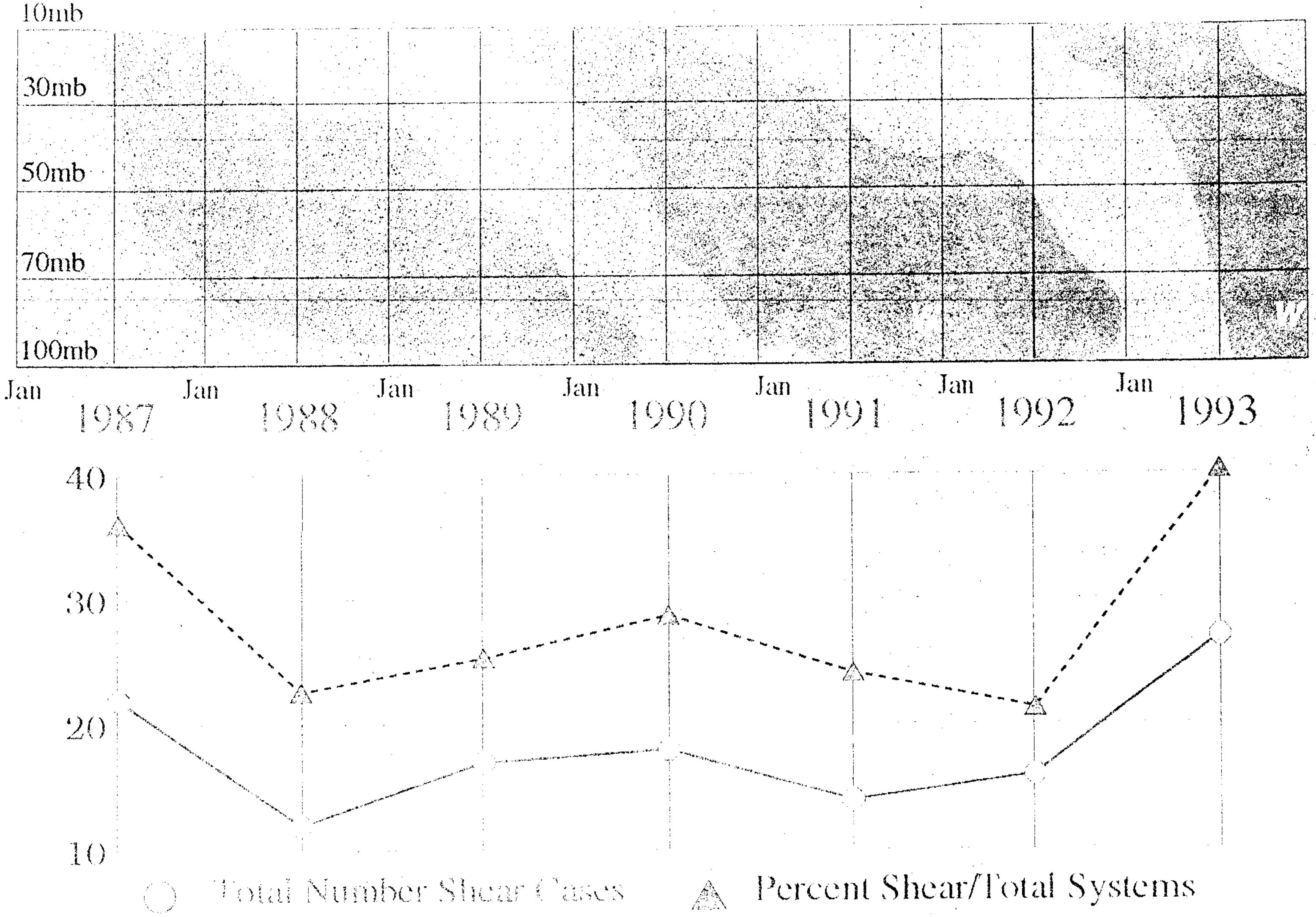


Figure 8

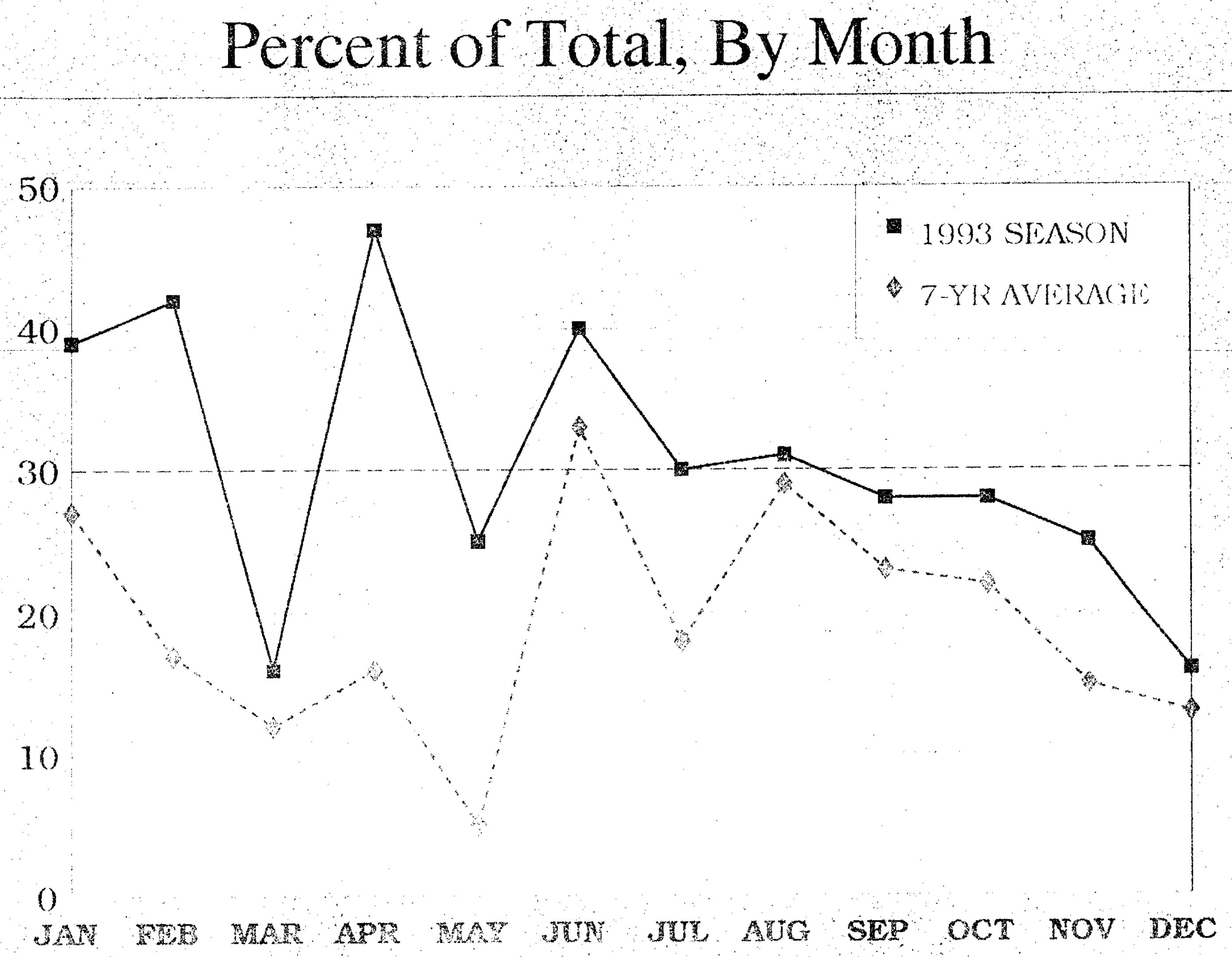

Percent of Total, By Month
1993 SEASON
7-YR AVERAGE
50
40
30
20
10
0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

Figure 9

both total number of shearing cases , and total percentage of shearing cases. Figure 9, also from Runk's work, indicates a clear relationship between the QBO wrong tense and shearing. Here, the actual number of shearing cases in the 1993 season is compared with the 7 year average, as calculated from the data used in figure 8. Note the time period: January was an east QBO phase month, then the shift to the QBO west phase occurred in the June-July time frame. The total number of shear cases was much higher than the expected 7 year average *during the QBO east phase*, as the theory by Gray would have predicted. After the months of June and July, when the west phase of the QBO sets up, the total number of shear cases is basically in good agreement with the expected 7 year average, as expected. phrasing

With this data in mind, we could probably conclude with this, and be satisfied that the QBO does indeed have an impact on tropical cyclones. However, we will briefly discuss a couple of other factors of interest. These factors will demonstrate how much additional impact the QBO has on the situation.

III. INDIRECT QBO INFLUENCES

Gray's work from 1984 stated that the Sea Level Pressure Anomaly (SLPA), the occurence of an EL-Nino/Southern Oscillation (ENSO) event, and the QBO winds had a seasonal impact on the formation of tropical cyclones. Furthermore, work has been done to show that SLPA and the ENSO are not independent of the QBO. There is a relationship between the QBO and the ENSO/SLPA effects. Each will be discussed in turn. The paper will also discuss the relationship that the QBO has on the steering currents over the tropics. Additionally, a discussion of the relationship between the QBO and precipitation will be covered.

A. QBO-ENSO Connection

During the early 1980's, it was believed that the QBO and ENSO (high Sea Surface Temperature [SST] anomaly in the eastern equatorial Pacific) were independent of each other. However, in 1989, Shapiro argued that the east phase of the QBO consistently precedes the sequence of events leading to the onset of the [ENSO] in the central and eastern Pacific. The work of Gray et al [1992] further argued this point, stating that a "stratospheric QBO - troposphere - ocean interaction influences the timing of major ENSO events in the tropical ocean-atmosphere system. For the purposes of this paper, we will stop here and state that the east phase of the QBO precedes ENSO events (in other words, if the QBO east phase onset is occurring, then an ENSO ***might*** occur, but an ENSO will not begin ***unless*** the QBO east phase is setting up).

Next, Gray [1989] stated that " Atlantic hurricane seasons during moderate or strong [ENSO] events average only about 40 percent as much hurricane activity as occurs during [non-ENSO] seasons. This difference is related to stronger upper tropospheric (200 mb or 12 km) westerly winds which typically occur over the Caribbean Basin and western Atlantic during [ENSO] seasons."

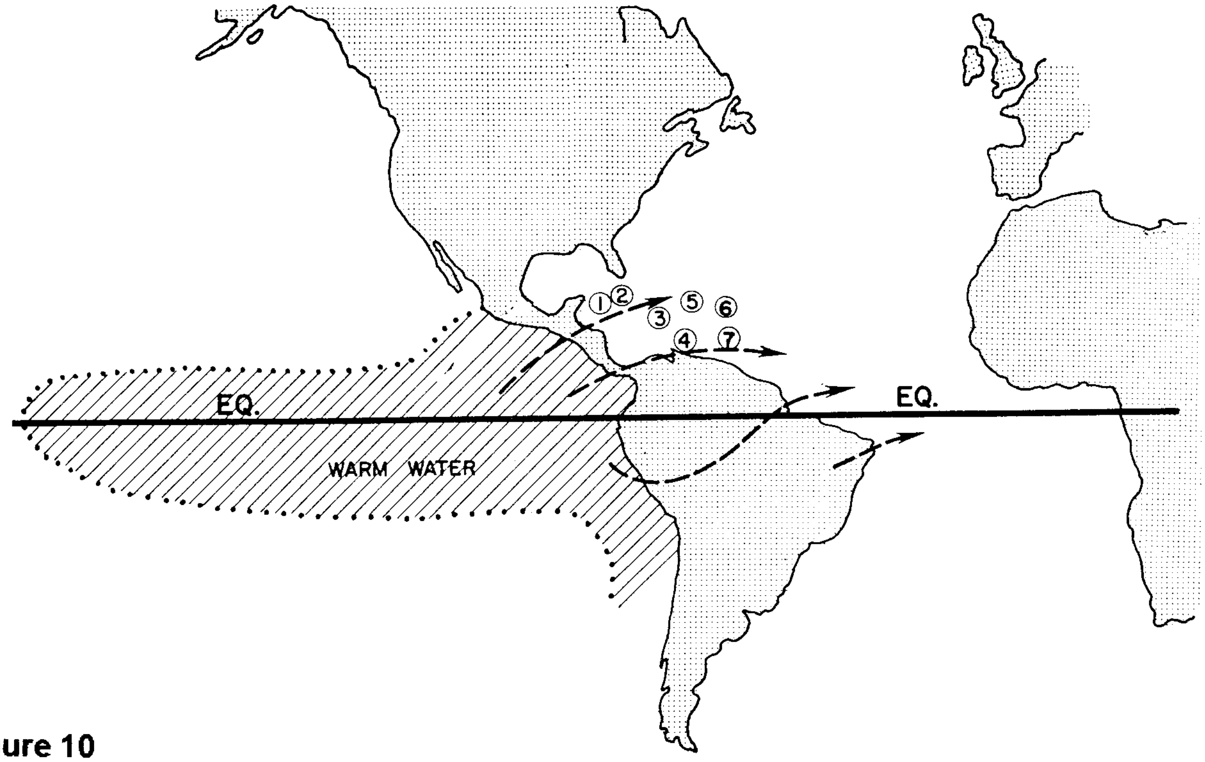


Figure 10

Deviational upper tropospheric (~200 mb) outflow wind patterns due to enhanced deep-cumulus convection in the eastern tropical Pacific in moderate and strong El Niño years. These wind patterns are hypothesized to result from anomalously warm eastern Pacific water. [Numbers indicate upper-air stations at Swan Island (1), Grand Cayman (2), Kingston, Jamaica (3), Curaçao (4), San Juan (5), St. Maarten (6) and Barbados (7)].

See figure 10 for an illustration of ENSO winds at 200 mb. Gray also remarked that "... the stronger the 200 mb zonal winds are from the west, the greater the suppression of seasonal hurricane activity and vice-versa." Note that this is exactly one of the primary factors leading to tropical cyclogenesis. Weak vertical wind shear in the upper troposphere will cause a hurricane to more readily develop, where a stronger flow aloft will cause the cyclone to weaken.

not necessarily weaken but certainly not develop

In summary, then, the QBO/ENSO/Tropical Cyclone connection can be stated this way : the QBO is a primary influence on the ENSO, the ENSO induces great upper tropospheric flow, and this increases the shear over a hurricane, thus causing the storm to weaken. or not develop at all

B. QBO- Center of Action Relationship.

The work of Angell and Korshover, in 1969, disclosed a strong indication of quasi-biennial variations in mean monthly surface pressure near the locale of the North Atlantic and North Pacific subtropical highs and subpolar lows. The most pronounced oscillation was found in the Atlantic, where the Azores-Bermuda High undergoes a 0.4 mb pressure amplitude, and the Icelandic Low experiences a 0.6 mb variation. The mean-monthly latitudes and longitudes of the centers of the subtropical highs also showed a quasi-biennial periodicity. The Bermuda High was found to oscillate in a northest/southwest direction, where the Pacific High moved in a northwest/southeast direction. In both cases, the pressure maxima occur a few months after the latitude maxima. This work also demonstrated evidence for a possible quasi-biennial variation in the frequency of

change? variation? complete the thought

Id question these results because the location of centers without solid obs becomes very subjective and probably had a bearing in their results.

Atlantic hurricanes, western Pacific typhoons, and severe storms in India. The observed tropical cyclone frequency was above average when the "centers of action" (the subtropical highs, in this case) were the most intense. Their final observations in 1969 indicated a possible correlation between the oscillation of typhoon frequency and the QBO. Regretably, their work on tropical cyclone relationships ended here.

Encouraged by the results of the 1969 study, the team (of Angell and Korshover) moved on to further work in 1974, when they published a second paper on quasi-biennial phenomena. They detailed strong correlations between the 50 mb zonal winds at Balboa, Panama and the behavior of the two previously mentioned centers of action (the Bermuda High and the Pacific High). A correlation of 0.67 was found between the Balboa winds and the longitude of the Bermuda High. A -0.50 correlation was found between the zonal winds and the central pressure of the Bermuda High. At the time of QBO west wind maximum, the Bermuda High tends to be farthest west, and lowest in pressure. [Mitchell, 1993]

As for the Pacific High, the latitude of the high was correlated to the zonal winds by a factor of -0.64. At the time of the QBO west phase maximum, the Pacific High tends to be situated close to the equator.

While the mechanics of this relationship between the QBO and the centers of action are not fully understood, there is an obvious impact on tropical cyclones. If the QBO modifies the centers of action, then the steering currents in the tropics will be modified. As discussed earlier, these steering currents are essential to understanding the movement of tropical cyclones. Understand the QBO/Center of Action forces, and you will have a QBO - tropical cyclone movement relationship. No work has been done (to the author's knowledge) to directly correlate the QBO to tropical cyclone tracks (although Shapiro [1982] alluded to such a connection), but the relationship does seem compelling.

If Gray has not done it, I doubt anyone else has - care to give it a shot?

C. QBO - Sea Level Pressure connection

As discussed in the previous section, Angell and Korshover, in 1969, found an approximate 28 month oscillation in the sea level pressure monthly means. Shapiro [1982] "...inferred that hurricane activity and regional shifts are physically related in the frequency band of the QBO. A quasi-biennial oscillation in sea level pressure and other atmospheric properties will modulate both activity and track [of Atlantic Hurricanes]." Shapiro further reasoned that the behavior of the Bermuda High also played a contributing role in this activity.

Gray [1984] found a strong relationship between the QBO and the SLPA. He described the 30 mb zonal winds as "best detected in surface pressure. A comparison of the August-September mean SLPA with different phases of the QBO .... [revealed] consistent August-September pressure anomaly differences of about 0.2 to 0.5 mb which are associated with the different ... QBO signals." Gray further commented that : " It is well known that seasonal hurricane activity is negatively correlated with seasonal SLPA. " The reader is referred to the work of Gray [1984] and Shapiro [1982] to see this relationship fully explained. However, for the purpose of this discussion, it is sufficient to note that the the QBO causes changes in SLPA, and the changes in SLPA (across the Atlantic, in this case) cause changes in hurricane activity.

D. QBO-Precipitation relationship

A study of rainfall variations in the Indian subcontinent by Mukherjee et al [1985] indicated that 15% of the precipitation variability was associated with the QBO pattern. Knaff [1991] also indicated such a relationship. He suggested that there was a physical link between the stratospheric QBO and the tropical troposphere, indicating that west QBO phases typically have higher amounts of precipitation than the QBO east periods during the Southern Hemisphere summer. Knaff further noted that :

> " The rawindsonde data shows that the upper troposphere cools as the lower stratosphere warms. But there is not complete thickness compensation. The colder upper troposphere goes with slightly lower surface pressures. Rawindsonde composites also show that during west phase QBO periods, lapse rates tend to be more unstable, producing a potentially more convectively active atmosphere." [Knaff, 1991]

Again, the reader may recall that the second general condtion for tropical cyclogenesis is the idea that "...the atmosphere must be capable of permitting deep convection". Thus, it may be concluded that the QBO has a fundamental impact on ***atmospheric stability.*** This, of course, immediately translates into one of the main factors favoring tropical cyclone formation.

IV. GRAY'S SEASONAL HURRICANE PREDICTION SCHEME

The paper by Gray in 1984, again, provided much information regarding the impact of the ~~QNO~~ QBO, ENSO, and SLPA. Gray developed an equation relating the number of Atlantic hurricanes per season with the QBO wind speed/direction, the SLPA, and the existence (or non-existence) of the ENSO intensity.

A. How to perform the objective computation.

Forecasts have been made by Dr. Gray since 1984 regarding seasonal hurricane activity. He issues the initial forecast on 1 June usually, which is (1) the beginning of the hurricane season, and (2) close enough in time to predict both the QBO and ENSO with reasonable skill. Gray stated that the number of hurricanes per season is given by

> " .... a simple formula for the hindsight prediction of the seasonal number of hurricanes:
>
> (Hindsight-predicted number of hurricanes per season)
>
> $$= 6 + (QBO_1 + QBO_2) + EN + SLPA \qquad (1)\text{"}$$

where

QBO_1 : 30 mb equatorial wind direction correction factor: if westerly, add 1. If easterly, subtract 1. Set to zero if zonal wind direction during the season is in a change-over phase from east to west or west to east.

QBO_2 : correction factor for change in 30 mb equatorial zonal wind u during the hurricane season : if uniformly increasing westerly (positive du/dt), add 1; if uniformly decreasing westerly (negative du/dt), subtract 1. Set to zero if there is a change in sign of du/dt during the season. The total QBO correction represents the sum of QBO_1 and QBO_2 and varies between +2 and -2.

EN : El Nino influence: if present, subtract 2 for a moderate El Nino event, 4 for a strong event; otherwise set to zero.

SLPA : average SLPA for April-May from the six Carribbean basin stations

> [listed here: Miami, Brownsville (TX), Merida (Mexico), San Juan (Puerto Rico), Barbados, and Curacao]. Add 1 if SLPA is < -0.4mb. Add 2 if SLPA is less than -0.8 but greater than -0.4 mb. Subtract 1 if the SLPA is +0.4 to +0.8 mb . Subtract 2 if the SLPA is greater than +0.8 mb. Set this factor to zero if the SLPA is between -0.4 and +0.4 mb. The pressure correction should lie between 2 and -2. " [Gray, 1984]

Special considerations were given to boundary conditions. First, if equation (1) should give a value less than 3 during an ENSO event, then disregard this computation and make a forecast for at least 3 hurricanes. Also, if the equation gave a value less than four during a non-ENSO year, then disregard the equation and forecast at least 4 hurricanes.

In addition to this, Gray developed an equation that also calculated the number of named tropical storms in the Atlantic. The equation is given below:

"Hindsight - predicted number of hurricanes plus tropical storms per season:

$$= 9 + QBO + EN + SLPA \qquad (2)"$$

where :

QBO : the 30 mb equatorial wind direction correction factor. Add 1.5 for a westerly wind, and subtract 1.5 for an easterly wind. During ENSO events, add 2.0 for a west wind, and subtract 2.0 for easterly winds. Set to zero for a change over situation. Make no correction for the change in QBO wind *speed* during the season.

EN : The ENSO effect is similar to equation (1) above, except that 0.7 is added during a non-ENSO period.

SLPA : This is the same as in equation (1).

In addition to the computation of projected hurricane and tropical storm development, equations were developed to predict other tropical cyclone features, such as hurricane days (a "*hurricane day*" is a 24 hour period in which a hurricane exists). For example, if a cyclone becomes a hurricane, and remains at that intensity for five days, then you have 5 hurricane days. If you have 2 cyclones that exist at hurricane intensity for the same 4 day period, then a total of 8 hurricane days are said to be observed. The author will not recount the methodology for computing the predicted number of hurricane days, etc. For more information, see the papers by Gray of 1984 and 1989.

Now that we've seen the relationships expressed, we shall briefly discuss the performance of these equations in predicting hurricane activity.

B. Performance of Gray's equations.

Tables (1) and (2) on the next page show the verification statistics for Dr. Gray's hurricane prediction scheme. Table (1) gives data from his original paper in 1984, showing the performance that his equations *would have had* if they were used 30 years ago. Table (2) shows actual forecasts and verifications from 1984 through 1988. Note in particular the climatological averages at the bottom of table (2). When comparing the climatological averages with Gray's equation results, one can see that the equations yield either similar or better results than climatology would reveal. Note the tremendous performance equation (2) exhibits in predicting the number of named tropical storms, where a significant improvement over climatology is indicated. Looking at the errors associated with Gray's equations as compared to the errors associated with straight climatology, one can see (for the period from 1984 to 1988) that the standard deviation of the errors for Gray's tropical storm equation

Table 1 Hindcast-predicted number of hurricanes plus tropical storms per year from QBO, EN and April–May SLPA correctional factors versus observed number of hurricanes and tropical storms per year.

	Correction factor					Number of hurricanes plus tropical storms		
Year	QBO	EN	Apr–May SLPA	Total QBO + EN + SLPA	Round-off of total*	Predicted	Observed	Predicted minus observed
1950	1.5	0.7	+2	4.2	+4	13	13	0
1951	1.5	0.7	+2	4.2	+2	11	10	+1
1952	−2.0	0.7	0	−1.3	−1	8	7	+1
1953EN	1.5	−2	+2	1.5	−2	11	14	−3
1954	1.5	0.7	+1	3.2	+3	12	11	1
1955	1.5	0.7	+1	3.2	+3	12	12	0
1956	−1.5	0.7	0	−0.8	−1	8	8	0
1957EN	2.0	−4	0	−2.0	−2	7	8	−1
1958	−1.5	0.7	+2	1.2	1	10	10	0
1959	1.5	0.7	−1	1.2	+1	10	11	−1
1960	−1.5	0.7	0	−0.8	−1	8	7	+1
1961	1.5	0.7	−2	0.2	0	9	11	−2
1962	−1.5	0.7	−2	−2.8	−3	6	5	+1
1963	0	0.7	−2	−1.3	−1	8	9	−1
1964	1.5	0.7	−1	1.2	+1	10	12	−2
1965EN	−2.0	−2	0	−4.0	−4	5	4	+1
1966	1.5	0.7	0	2.2	+2	11	11	0
1967	0	0.7	−1	0.3	0	9	8	1
1968	−1.5	0.7	−1	−1.8	−2	7	7	0
1969	1.5	0.7	+2	+4.2	+4	13	14	−1
1970	−1.5	0.7	0	−0.8	−1	8	10	−2
1971	1.5	0.7	0	2.2	+2	11	13	−2
1972EN	−2.0	−4	0	−6.0	−6 (−5)	4	4	0
1973	1.5	0.7	0	2.2	+2	11	7	+4
1974	−1.5	0.7	−1	−1.8	−2	7	7	0
1975	1.5	0.7	0	2.2	+2	11	8	+3
1976EN	0	−2	−1	−3.0	−3	6	8	−2
1977	−1.5	0.7	−2	−2.8	−3	6	6	0
1978	1.5	0.7	+1	3.2	+3	12	11	1
1979	−1.5	0.7	+1	0.2	0	9	8	1
1980	1.5	0.7	+1	3.2	+3	12	11	1
1981	−1.5	0.7	0	−0.8	−1	8	12	−4
1982EN	−2.0	−4	0	−6.0	−6 (−5)	4	5	−1

* Correction factor must not be less than −4 in a non-El Niño year or less than −5 in an El Niño year. Applicable correction factors in parentheses.

yields a value of ~ 1.14, whereas the standard deviation of the errors associated with climatology yields a value of ~ 2.88.

A similar analysis for hurricanes reveals a standard deviation (of errors) of 1.0 for equation (1), whereas the climatological errors are ~ 1.48.

V. CONCLUSIONS

In conclusion, the QBO has a profound impact on the genesis, development, and motion of Atlantic Hurricanes. The impact is evidenced by direct influences, such as lower stratospheric shear. Also, indirect influences are important, since there appears to be a correlation between the QBO and the ENSO, middle tropospheric steering flow, Sea Level Pressure Anomaly, and the rainfall in the tropics. Also, empirical equations have been derived that relate QBO wind velocity to the number of hurricanes/tropical storms. Specifically, equation (2) [tropical storm number] has demonstrated particular success. The errors associated with predicting storm number using climatology are nearly three times greater than the errors using equation (2). Errors associated with the prediction of hurricane numbers are also better than climatology, however, only modestly so. Such a performance over climatology would imply that the QBO/ENSO/SLPA equations will more adequately provide an indication of tropical cyclone activity. In particular, the QBO terms are the most significant in both equations (1) and (2), since the QBO will *almost always give a value,* where the ENSO and SLPA terms are much more random. Since the QBO represents the most consistent term in both equations, one may reason that the QBO does indeed have a significant impact on Atlantic Hurricane activity.

dont know that Id call it
"significant" until the tracks and
intensities, speed of development, etc were added
to the data set

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