Sereno Bishop, Rollo Russell, Bishop's Ring and the Discovery of the "Krakatoa Easterlies"

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[Original manuscript received 1 February 2011; accepted 3 May 2011]

ABSTRACT *The 1883 eruption of Krakatau was a seminal event in the study of several atmospheric phenomena. This paper reviews the work that led to the first determination of the wind in the tropical stratosphere and provides some biographical background on two quite remarkable amateur scientists whose observations and analyses in the aftermath of the eruption contributed greatly to our knowledge of the stratospheric circulation. This paper will trace the path from their work in the 1880s to the mid-twentieth century when it provided the background to the surprising discovery of the stratospheric Quasibiennial Oscillation.*

RÉSUMÉ *[Traduit par la redaction] L'éruption du Krakatoa, en 1883, a été un événement fécond pour l'étude de plusieurs phénomènes atmosphériques. Le présent article examine le travail ayant mené à la première détermination du vent dans la stratosphère tropicale et fournit des renseignements biographiques sur deux scientifiques amateurs fort remarquables dont les observations et les analyses suite à l'éruption ont grandement contribué à notre connaissance de la circulation stratosphérique. Cet article retrace le chemin séparant leur travail dans les années 1880 et le milieu du vingtième siècle, moment où il a servi de toile de fond à la surprenante découverte de l'oscillation stratosphérique quasi-biennale.*

KEYWORDS stratosphere; general circulation; quasibiennial oscillation; volcanic effects

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1 Introduction

It is a pleasure to contribute to the Lawrence Mysak special issue of *Atmosphere-Ocean* with this brief article on the history of a unique scientific discovery in tropical climate variability. Lawrence is well known for his work in many areas, of course, but his influence on me was perhaps most direct during the early 1980s when we were faculty colleagues at the University of British Columbia (UBC) and he was taking the lead in explaining the importance of the interannual variability of the tropical atmosphere and ocean not only to the global climate system but also to the climate of Canada. What Lawrence was advocating at the time was new and exciting for me and others but has now become common wisdom in the climate research community. With time, it has become clear that the circulation even in the tropical stratosphere can have important effects on global surface climate variability (e.g., Baldwin et al., 2001; Coughlin and Tung, 2001; Boer and Hamilton, 2008). This article examines the early history of the observation of the tropical stratospheric circulation.

Today we know that the prevailing winds in the tropical stratosphere are predominantly zonal and undergo a quasi-regular oscillation between strong easterlies and strong westerlies, with a period that varies from cycle to cycle, but that averages about 27–28 months (e.g., Naujokat, 1986; Baldwin et al., 2001). As an example, Fig. 1 shows the height-time section of observed monthly-mean zonal winds at Singapore (1.3°N, 104.0°E) determined from regular balloon observations and plotted between the tropopause (approximately 17 km) and about 31 km for 24 years. The oscillation is fairly weak in the lowermost stratosphere, but by the 25 km level the monthly mean winds vary between westerly extremes exceeding 10 m s^{-1} and very strong easterlies of 30 m s^{-1} or more. The discovery of this phenomenon—initially thought to be a two-year oscillation, but soon renamed the Quasibiennial Oscillation (QBO)—is attributed to work conducted in the United States and the United Kingdom in 1960. However, the story of our observation of the winds in the tropical stratosphere dates back to the late nineteenth century and begins with the aftermath of one of that century's most spectacular geophysical events.

The 1883 eruption of Krakatau was a human disaster of major proportions causing approximately 40,000 deaths, mainly from the tsunami generated by the final cataclysmic explosion on the morning of 27 August. (Tragically, this history seems to have been forgotten by authorities in the Indian Ocean region who should have been much better

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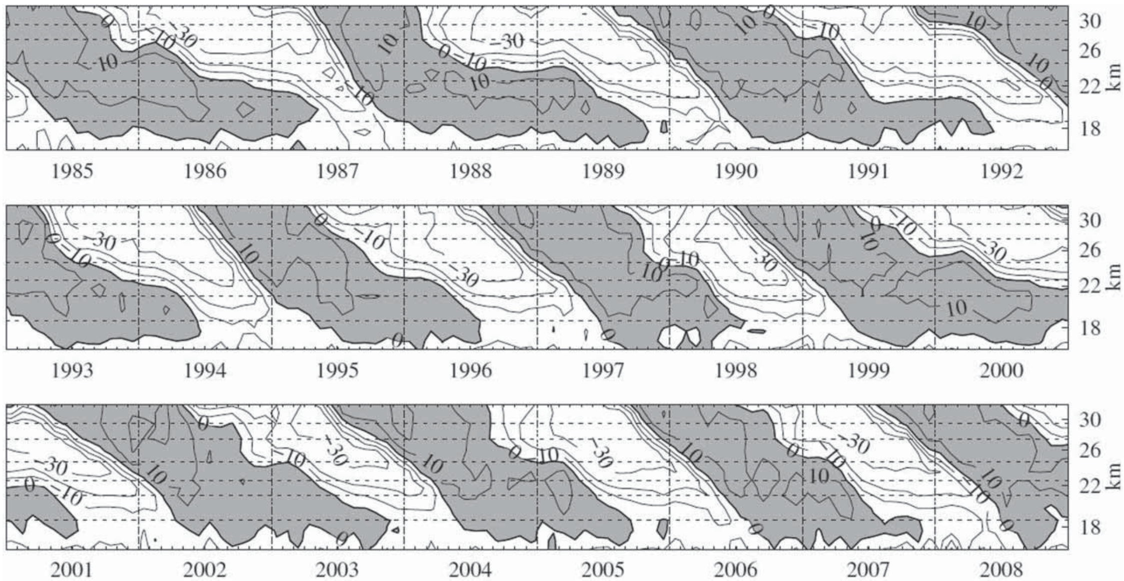

Fig. 1 Time-height section of monthly-mean zonal wind near the equator based on balloon-borne radiosonde observations. The contour interval is 10 m s^{-1} and westerly winds are denoted by shading. This is an updated version of Fig. 1 in Naujokat (1986; reproduced by permission of the American Meteorological Society).

prepared for the major tsunami generated off Sumatra on 26 December 2004). The Krakatau eruption also turned out to be a major event in the history of the study of atmospheric dynamics. In contrast to earlier major eruptions (such as that of Mt. Tambora in 1815), the existence in 1883 of an intercontinental telegraph network and a large and active international scientific community meant that the events related to the eruption of Krakatau were followed throughout much of the world in near-real time and that scientific investigations were undertaken immediately (Winchester, 2003). The initial investigations of the eruption and its effects were summarized in a report prepared under the auspices of the Royal Society of London and published in 1888. As a side note, the rapid pace of information flow contributed to the corrupt rendering of the name “Krakatau” as “Krakatoa” in the wider world, resulting in a confusion that persists today (Winchester, 2003).

Krakatau (6.1°S, 105.4°E) was a small island in the Sunda Strait between Java and Sumatra. Signs of unusual volcanic activity were observed as early as April 1883, but the main eruption began on 26 August with the final destruction of the island occurring about 10:00 am local time 27 August. The final explosion was audible 3000 km away and it produced an infrasonic pressure pulse that was recorded by barographs throughout the world. The barograph records allowed the path of the wavefront to be tracked in its passage around the world at least three times, appearing at any station at 33 hour intervals, implying a horizontal phase speed of about 330 m s^{-1}. In a classic paper Taylor (1929) demonstrated that the observations are consistent with propagation of an external gravity wave (Lamb wave) and that the observed phase speed showed that the equivalent depth of the atmosphere for free oscillations is about 10 km. Taylor’s paper greatly influenced the work on global atmospheric waves and tides in subsequent decades (e.g., Chapman and Lindzen, 1970).

The other major meteorological contribution of the observations after the Krakatau eruption involved tracking the stratospheric aerosol cloud. Colourful twilight phenomena are produced by the solar illumination of stratospheric aerosol, and the periods after major eruptions are often notable for widespread reports of spectacular sunsets and extended twilight duration. Today we understand that a major explosive eruption ejects hot gases and solid aerosol material that can rise to heights well into the stratosphere (e.g., DeFoor et al., 1992). While solid aerosol material mostly falls out over the first few weeks after the eruption, a long-lasting effect is provided by increased sulphur content caused by the stratospheric injection of sulphur-dioxide. The sulphur-dioxide reacts with the water vapour in the stratosphere to produce a thin layer of very small (typically <0.5 μm diameter) sulphuric acid droplets (e.g., Thomason, 1992). These droplets can remain in the stratosphere until they are flushed back to the lower atmosphere by the large-scale circulation (a process with a time scale of about 2 years).

In the months after the 1883 eruption, the “Krakatoa sunsets” became quite notable. The British artist William Ascroft made many vivid watercolour sketches of the skies at Chelsea in 1883, several of which were printed by colour lithography as the frontispiece for the Royal Society report (Ashcroft, 2008). The publication of this frontispiece represented a noteworthy pioneering effort in sophisticated colour printing. Recently Olson et al. (2004) speculated that the disturbingly red skies in Edvard Munch’s famous 1893 painting *The Scream* may have been inspired by Munch’s own viewing of the vivid Krakatau sunsets in the previous decade.

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2 Sereno Bishop

Rev. Sereno Bishop (1827–1909) of Honolulu made one of the first reports of unusual optical phenomena following the Krakatau eruption. By mid-September 1883 Bishop had made the speculative leap that the optical phenomena he had seen in Honolulu were caused by the eruption of Krakatau in August. Bishop later put together what may be the first comprehensive account of the spread of the aerosol cloud in the immediate aftermath of the eruption. Bishop also described the halo-like display around the sun in the period after the Krakatau eruption, and this phenomenon is still referred to as "Bishop's Ring." These accomplishments surely represent the first significant contributions to the atmospheric sciences from Hawaii, but this was only a small part of the colourful and important career of Rev. Bishop. Bishop's biography was written by his friend Lorrain Thurston, himself a major figure in the history of Hawaii. The following information comes from Thurston (1916).

Sereno Edward Bishop (Fig. 2) was born in Hawaii to Artemas and Elizabeth Bishop, one of six protestant missionary couples that had left New Haven in 1822 to settle in the Kingdom of Hawaii. Sereno grew up on the island of Maui but was sent to the United States for his advanced education, receiving degrees from Amherst College in 1846 and Auburn Theological Seminary in 1851. Bishop accepted a position as a "seamen's chaplain" at Lahaina on Maui and arrived back in Hawaii in 1853. The port of Lahaina was then the crossroads of shipping in the Pacific with over 300 American ships calling each year. The seamen were a notoriously rough group of men and the job of "seamen's chaplain" must have been a challenge. Mission houses at Lahaina were even reported to have been bombarded on occasion by artillery on boats during this period! Bishop served for nine years in this position and then as a missionary in Hana on Maui, returning to Lahaina in 1865 to serve as principal of a high school. In 1877 Bishop moved to Honolulu, where he joined the government's department of surveying and participated in real estate development. From 1887 to 1902 Sereno was editor of *The Friend*, a monthly journal originally devoted to promoting temperance, but during that period was "the official mouthpiece of the Protestant religious life and progress in the Islands" (Thurston, 1916). Sereno became a prominent journalist, notably becoming a correspondent for Hawaiian affairs in the *Washington Star*, then an important newspaper in the US capital.

Sereno Bishop's time as a journalist coincided with a critical period in the Kingdom of Hawaii and its relations with the United States. Hawaii had survived as an independent Kingdom ruled by a constitutional monarch and an elected legislature. However, the Hawaiian government had to

Fig. 2 The Reverand Sereno Edward Bishop in an 1888 photo (reproduced from Hawaiian Mission Children's Society (1901)).

adjust to the realities of American power and influence. From 1887 to 1898 the tensions between American and native Hawaiian interests played out in a string of key events, including the 1893 overthrow of the monarchy and establishment of a republic dominated by American businessmen, culminating in 1898 with the annexation of Hawaii by the United States. Bishop was a strong voice for the aggressive pursuit of American interests, notably arguing for annexation in his *Washington Star* reports and in correspondence printed in the *New York Evening Post*.

The contemporary world looks less favourably on imperialism. In 1993, a resolution was passed by the US Congress and signed by President Clinton, apologizing for the overthrow of the Hawaiian Kingdom. Sereno Bishop's role in these events is still controversial, and he has been taken to task for his imperialist views as recently as 2003 in the leftist magazine *Counterpunch* (Leupp, 2003).

According to Thurston (1916) Bishop had a local reputation as an amateur scientist with interests particularly in geology. Bishop's contributions as an atmospheric scientist were sufficiently prominent for his death to be mentioned in the *Monthly Weather Review* (Anonymous, 1909).[1]

Sereno Bishop's first connection to Krakatau occurred on 5 September when, along with the rest of the population of Honolulu, he observed the remarkable afterglow of the sunset. On 19 September he heard the news about the Krakatau eruption and sent a letter to his local newspaper, the *Saturday Press* 22 September 1883 edition (cited in Bishop (1884b)) to "record the date of 5 September when the first and most brilliant display was observed, being moved thereto by the arrival of news of the Java eruption, whose proximity in time seemed to lend especial importance to the phenomenon." Bishop acted to track down other anecdotal observations of the arrival of the sunset phenomena and discussed the phenomena in a series of brief letters to

[1]It may be helpful to note that, although a prominent figure in nineteenth century Hawaii, Sereno Bishop is less well known today in Hawaii than his near-contemporary, Charles Reed Bishop (1822–1915). Charles Bishop founded a major bank in Hawaii and married Hawaiian princess Bernice Pauahi Paki. The Bishop name survives today in Bishop Street in downtown Honolulu and the Bishop Museum in Honolulu, both commemorating Charles and Bernice Bishop. Sereno Bishop does not seem to have been a relation of Charles Bishop, who was born and educated on the US mainland and arrived in Hawaii in 1846.

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Nature (Bishop, 1884a; published by *Nature* each issue with other similar brief observations from other contributors under the title *The Remarkable Sunsets*). By May 1884 Bishop could publish a fairly comprehensive account of his deductions in the *Hawaiian Monthly* (Bishop, 1884b). After a brief description of the Krakatau eruption and its immediate effects Bishop writes:

> Gigantic as were these effects, they were surpassed in strangeness and extent, by those conspicuous effects which were left upon the earth's atmosphere causing remarkable sunset and sunrise glows which have set the world wondering. … Among the … problems connected with this immense atmospheric effect ... there was one phenomenon of unique and colossal character, which not coming under the personal observation of European and American savants, seems to have attracted little attention … It is the fact named in the caption to this article of a strong fling from the eruptive column of Krakata [*sic*] a vast stream of smoke due west with great precision along a narrow equatorial belt with an enormous velocity, nearly around the globe … It thus appears that while the general diffusion of the bulk of the Krakatoa vapors was tardy … reaching New York in twelve weeks, … there was at the beginning a special and exceptional stream of the same … due west along the equator striking our Honolulu skies in only ten days from its source.

This may be the first fairly complete description of the "Krakatoa easterly" phenomenon, and this paper was influential enough to be referred to in the Royal Society report of 1888. Bishop wrote a later summary (Bishop, 1886) which won an award in a contest for essays explaining the post-Krakatau optical phenomena sponsored by the Warner Observatory in Rochester, New York. Bishop was concerned that the extremely strong wind speeds implied by his work (more than 30 m s^{-1}) were found elsewhere in the atmosphere only in hurricanes (indeed the modern day threshold for a storm to be considered a hurricane is sustained near-surface winds exceeding 34 m s^{-1}). He speculated that the volcanic eruption itself may have excited the motion of the upper atmosphere in this extreme manner, a notion now rejected, but Bishop deserves credit for the basic finding of the "Krakatoa easterly" phenomenon at low latitudes.

In addition to noting the remarkable post-Krakatau twilight phenomena, Bishop also described the continuous presence during daylight of a faintly coloured halo around the sun. This phenomenon is still called "Bishop's Ring" which is defined as "An observation of a faint, broad, reddish-brown corona by the Rev. S. Bishop of Honolulu during the eruption of Krakatoa [*sic*] in 1883. He described an angular radius of the inner edge of 20° and an angular width of about 10°. Subsequent observations are rare to nonexistent" (AMS, 1959). It is now known that this halo is caused by diffraction of sunlight around the very small spherical sulphuric acid droplets.

3 Rollo Russell and the motion of the Krakatau aerosol cloud

Like Bishop, Francis Albert Rollo Russell (1847–1914) collected the anecdotal reports of the first observations of the twilight phenomena following the eruption and used these to track the spread of the aerosol plume, but his study was on a large scale and was published several years later in several chapters of the Royal Society report (Russell, 1888a, 1888b, 1888c, 1888d). Rollo Russell is an interesting figure from an exceptionally distinguished family. He was the son of Lord John Russell the reformist British Prime Minister (held office 1846–52 and 1865–66). Rollo Russell was the last child born of a serving British Prime Minister until 2000 when Tony Blair's son Leo was born. Rollo Russell was also the uncle of Bertrand Russell (1872–1970), the famous mathematician, philosopher and social activist. Remarkably enough, the young Bertrand Russell's intellectual interests were inspired by his uncle's work on the Krakatau dust cloud. Eight decades later Bertrand Russell recalled (Russell, 1967):

> My uncle Rollo had some importance in my development as he frequently talked to me about scientific matters, of which he had considerable knowledge … He was a meteorologist, and did valuable investigations of the effects of the Krakatoa [*sic*] eruption of 1883, which produced in England strange sunsets, and even a blue moon. He used to talk to me about the evidence that Krakatoa had caused the sunsets, and I listened to him with profound attention. His conversation did a great deal to stimulate my scientific interests.

Rollo Russell seems to have been a gentleman scholar with no particular profession. He managed to made a mark both as an amateur scientist (with his Krakatau papers and a later book on public health; Russell, 1892) and as a poet and writer of hymns for the Unitarian Church (Russell, 1893). He also seems to have joined these interests in what may be a characteristically Victorian fashion, using "biblical meter to write modern psalms referring to atmospheric pressure, atoms and the now discredited substance, ether," according to Hromatko (2008).

Russell's papers, which were published in a Royal Society report (Russell, 1888a, 1888b, 1888c, 1888d), listed and discussed quite a remarkable number of anecdotal reports of optical phenomena in the days and months after the Krakatau eruption. Russell did a masterful job in sorting out these observations and producing a coherent picture of the aerosol transport operating in the stratosphere, concluding that the plume first travelled zonally in a band around 20°S–20°N, then over the next several months spread to mid-latitudes. Russell produced a map showing the boundary of the plume determined day-by-day for about the first two weeks based on his collected anecdotal reports (he also produced other maps showing the spread over the next several months). The boundary lines on his map are reproduced (but redrafted) in Fig. 3. The lines attempt to delineate the western and, in some cases, part of the northern and southern boundaries of the region where twilight phenomena were observed by the end of each day. There

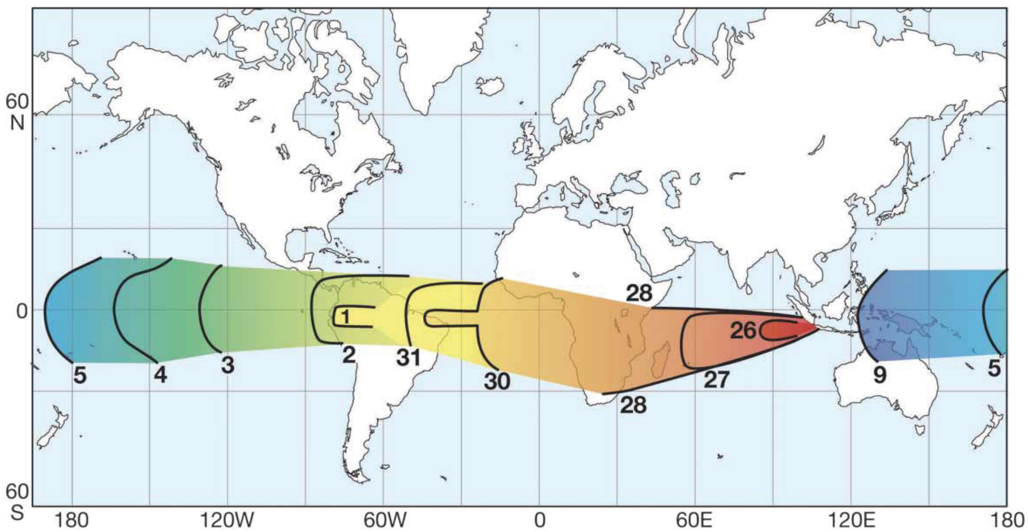

Fig. 3 Map showing the observed spread of the twilight phenomena in the two weeks following the Krakatau eruption. The black lines are redrafted from Russell (1888d) and show his determination of the westward extent of the phenomena each day. The shading was added by the present author and represents an estimate of the actual extent of the volcanic aerosol cloud each day, based on other information in Russell (1888d).

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are no lines for 29 August or 6, 7 and 8 September, and no western boundary is indicated for 28 August, deficiencies all presumably reflecting a lack of data. This map is supplemented in the Royal Society report by another map that shows Russell's estimate of the full extent of the plume by 7 September. This second map guided the present author in adding shading to Fig. 3 to suggest approximately the full extent of the plume each day. Given the scattered nature of the observations it is not clear how much credence can be given to some of the finer details in Fig. 3, such as the apparent narrowing of the western edge of the plume on 1 September.

The most striking aspect of Fig. 3 is the rapid westward spread of the plume. If one supposes that by 10 September the plume moved over Krakatau again, then the plume circled the globe in 15 days, corresponding to a mean easterly wind velocity of about 30 m s^{-1}. The results depicted in Fig. 3 show some substantial variations in the westward drift, with faster motion until about 5 September. Attempts were made to estimate the height of the aerosol from ground-based observations. These estimates were as high as 40 km for the altitude of the initial plume, a level that seems rather high compared with better-observed recent major eruptions (e.g., DeFoor et al., 1992). Certainly it seems reasonable to suppose that in August–September 1883 the equatorial stratosphere was occupied by a deep easterly phase of the QBO and that the peak easterly wind speed at some level in, say, the 22–30 km range could have been about 30 m s^{-1}.

4 Comparison with the Pinatubo eruption aftermath

The eruption of Mt. Pinatubo (15.1°N, 120.3°E) in the Philippines in June 1991 provides an interesting comparison. This eruption was even larger than that of Krakatau, at least in terms of total mass injected into the atmosphere. Apparently no one has tried to duplicate Russell's use of anecdotal evidence of twilight phenomena to track the progression of the Pinatubo aerosol cloud. Of course, for this space-age eruption the stratospheric aerosol (and gas) from the Pinatubo eruption could be monitored using satellite observations. Stowe et al. (1992) tracked the initial evolution from observations of reflected solar radiation with the Advanced Very High Resolution Radiometer onboard an operational National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellite. They concluded that the aerosol cloud circled the earth in about 21 days, corresponding to a mean zonal velocity of about −21 m s^{-1}. This is also consistent with the ground-based lidar observations of the arrival of the aerosol plume over the Mauna Loa Observatory on Hawaii (19.5°N, 155.6°W) 16 days after the main eruption (DeFoor et al., 1992). The lidar observations showed that the initial plume was mainly around 22–24 km altitude (i.e., close to 30 hPa). For comparison, the 30 hPa monthly mean zonal-mean equatorial wind determined from the European Centre for Medium-range Weather Forecasts reanalyses (ECMWF ERA-40) for June 1991 was −20.5 m s^{-1} and for July 1991 was −25.4 m s^{-1}. The zonal-mean winds at 15°N and 30 hPa in the ERA-40 data are slightly weaker −16 m s^{-1} in June and −22.9 m s^{-1} in July. It seems the simple tracking of the first arrival of the aerosol cloud can be used to estimate the prevailing zonal winds in the lower stratosphere accurately.

5 Later developments

At the turn of the twentieth century there was increased exploration of the atmosphere at altitudes above 10 km using unmanned and, in some cases, even manned balloons (e.g., Labitzke and Van Loon, 1999). These studies led to the recognition that above the global troposphere lies a very stable layer we know as the stratosphere (e.g., Labitzke and Van Loon, 1999). The notion that the Krakatau observations had established that the prevailing flow in the equatorial stratosphere is easterly was apparently well ingrained by the early twentieth century, and the occasional observations of westerly winds were regarded as anomalous. The entry for “Krakatoa” in the *Encyclopedia Britannica* of 1911 reads in part:

> It was computed that the column of stones, dust and ashes projected from the volcano shot up into the air for a height of 17 m[iles] or more. The finer particles coming into the higher layers of the atmosphere were diffused over a large part of the surface of the earth, and showed their presence by the brilliant sunset glows to which they gave rise. Within the tropics they were at first borne along by air-currents at an estimated rate of about 73 m[iles] an hour from east to west … (Krakatoa, 1911).

von Hann and Suring (1914) include the following comments (translation taken from Labitzke and Van Loon, 1999):

> Surprisingly westerlies are at times embedded in the high-level easterlies and this has been observed at heights between 16 km and 20 km both in equatorial East Africa and on Java. When Semaru (3780 m) erupted on Java on 15 November 1911, a gigantic cloud consisting of ashes rose 19–24 km above sea level, where it was deformed by westerlies. There is no explanation of why westerlies should occur at these elevations.

Hamilton (1998) reviews the rather sporadic direct observations of the winds in the tropical stratosphere in the first half of the twentieth century (see also Hastenrath, 2006). The record was sufficiently sparse for the conventional wisdom to have remained that the winds in the tropical stratosphere are predominantly easterly but that on occasion anomalous westerlies are observed. It seems plausible that Russell’s beautiful and impressive map showing the consistent westward motion day after day over a broad equatorial band may have caused later researchers to assume intense and steady easterlies as the “normal” situation in the tropical stratosphere and strong evidence was needed to dispel this erroneous notion (of course, simple dynamical considerations also may have led scientists to expect easterlies on the equator as the normal situation). Wexler (1951) quotes Russell (1888d) in his review of the tropical stratospheric circulation. Palmer (1954), in what appears to have been a very influential review, quotes Wexler (1951) and this seems to have still been the orthodox view of the tropical stratospheric circulation. Remarkably (as pointed out by Hastenrath (2006)) this “classic” view was still featured in a prominent textbook published in 1963—three years after the published discovery of the QBO (Reiter, 1963)!

The late 1950s and early 1960s saw the first analysis of stratospheric wind observations from regular daily soundings at stations near the equator. The standard picture was challenged by Graystone (1959) and Ebdon (1960) who noted large and systematic interannual fluctuations of the zonal winds observed in the equatorial stratosphere. Ebdon and Veryard (1961) and Reed et al. (1961) were able to show that these variations took the form of nearly-repeatable cycles with a period near two years, thus becoming the discoverers of what we now know as the QBO.

6 Summary

The QBO of the prevailing winds in the tropical stratosphere is one of the most remarkable phenomena observed in the atmosphere. Although directly affecting a huge geographical area and a great depth of the atmosphere, the QBO was not discovered until 1960 by which time several years of regular daily in situ observations were available. The background to this discovery was provided by the earlier determinations of the tropical stratospheric winds which can be considered to have begun with the observations and deductions of the amateur scientist and citizen of the Kingdom of Hawaii, the Rev. Sereno Bishop. Bishop found that a very strong westward jet of dust near the equator was necessary to explain his collected observations. Bishop’s insights were confirmed several years later in the masterful work of the English amateur scientist Rollo Russell. Russell’s work was still regarded as definitive six decades later by the prominent American meteorologist Harry Wexler. Wexler’s and Russell’s views were adopted by C.E. Palmer in his 1954 paper that seems to have become the standard review of the tropical circulation at the time. The surprising discovery of the QBO then took place against the backdrop of Palmer’s influential paper.

Acknowledgements

This research was supported by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), by the National Aeronautics and Space Administration (NASA) through grant No. NNX07AG53G and by NOAA through grant No. NA09OAR4320075, which sponsor research at the International Pacific Research Center. The author thanks three anonymous reviewers for their comments.

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