Singapore Upper Air Station visited by SPARC researchers

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Singapore stratospheric zonal wind data are used by SPARC and other scientific research communities to document the Quasi-Biennial Oscillation (QBO; Baldwin *et al.*, 2001; see also a recent historical review by Hamilton, 2018). To describe the QBO, Naujokat (1986) compiled monthly mean equatorial zonal wind data based on radiosonde data from Canton Island (January 1953-August 1967), Gan Island, Maldives (September 1967-December 1975), and Singapore (January 1976-present); this data set, extended to the present using Singapore radiosonde data, is now available at Freie Universität Berlin's website (**www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/index.html**)[1]. During the past few years, various SPARC researchers have visited the Singapore Upper Air Station, and were surprised to find that the station staff were largely unaware of the extensive use of their radiosonde data for scientific research. In turn, the SPARC researchers are unaware of the history and current operational issues of the Singapore Upper Air Station. The purpose of this article is to provide some of this background information and to foster closer collaboration between the SPARC community and Singapore Upper Air Station to ensure that this world-class measurement time series is maintained and to ensure that its scientific value can be maximized. The rest of the article is organized as follows. Sections 1 and 2 present a brief history and current operational challenges, respectively, of the Singapore Upper Air Station. Section 3 presents experiences of various SPARC researchers with the station. Finally, section 4 presents a brief history and production procedures of the Freie Universität Berlin's QBO data set.

Figure 23: *A photograph of the Tai Seng site in Singapore (taken from MSS, 1995). An observer is releasing a weather balloon with attached Vaisala RS80-15N radiosonde (winds from OMEGA global navigation system).*

1. A brief history of the Singapore Upper Air Station

The Malayan meteorological annual reports published in 1952, 1953, and 1956 (MMS, 1946–1957) explain how an upper air observatory was established in Singapore. These reports provide the following detail:

- "Under a Colonial Development and Welfare grant an upper air observatory for combining radar wind and radio sonde ascents was established at the new International Airport at Paya Lebar. This project was designed to assess the value of the establishment of a permanent upper air observatory in Singapore. Regular radar wind ascents, twice daily[2], were commenced in July (1953)."

- Funds for this observatory were actually available from mid-1952 but difficulties in obtaining the equipment and stores from the United Kingdom[3] delayed the commencement of this trial, which aimed to perform research into the upper atmosphere in low latitudes for 3 years. The trial concluded in June 1956.

[1] Note that NOAA/NCEP Climate Prediction Center (CPC) and NOAA Earth System Research Laboratory (ESRL) also provide QBO indices, but they are both based on NCEP/NCAR R-1 reanalysis data. See **www.cpc.ncep.noaa.gov/data/indices/** and **www.esrl.noaa.gov/psd/data/climateindices/list/**

[2] This refers to rawinsonde ascents. Twice daily radiosonde sounding started in October 1983.

[3] Singapore, together with Cocos-Keeling and Christmas islands, was a British Crown Colony from 1946 to 1963.

- In July 1956, the station was established as a permanent feature of the Malayan Meteorological Service and finances were borne entirely by the Malaya territories. Upper air winds were determined twice daily; pressures, temperatures and humidities once daily by using radar techniques for tracking hydrogen filled balloons carrying meteorological instruments.

Radiosonde sounding actually began on 1 August 1954 at 03 UTC (Hassim *et al.*, 2019) at Paya Lebar. It is most probable that this site is identical to the Tai Seng site (1.340° N, 103.888° E; Figure 23) which was used until December 2011 when the station was moved to the current site just across the road due to land developments in the area. The observatory is now co-located with the Centre for Climate Research Singapore (CCRS) at 36 Kim Chuan Road. The current station (Figure 24; 1.34041° N, 103.888° E, 21 m altitude) is located on the top floor of the modern CCRS building. Table 1 summarizes the radiosonde instrument models used since the beginning of the upper air sounding program (see Gaffen, 1993; MO, 1961; BOM, 1976; Nash and Schmidlin, 1987; Nash *et al.*, 2011; Jeannet *et al.*, 2008; and references therein for information on most of these radiosonde models). For radiosonde wind measurements, the radar tracking technique was used up to 1983. The OMEGA global navigation system, using very low frequency (VLF) radio signals, was used between 1984 and September 1997. The Global Positioning System (GPS) has been used since October 1997. In April 1957, the launch time was changed to 00 UTC, and in October 1983, twice daily sounding at 00 UTC and 11 UTC (1040 UTC to be exact) was started (we also referred to the IGRA2 database which will be explained in the next paragraph). Around 2008, helium gas started to be used rather than hydrogen. See also Fong (2012) for some photographs of the Singapore upper air measurements around 2012 or before.

Figure 24: *The current Upper Air Station within the 4-story building sharing with the Centre for Climate Research Singapore (CCRS) located at 36 Kim Chuan Road in the central-to-eastern part of Singapore. Top left: The front view of the building; on the top right of this photo, we see the "Launch Platform" where the radiosonde preparation and balloon inflation and launch are conducted. Top right: The inside of the "Launch Platform." (The radiosonde instrument is prepared at the lower level. See Figure 26.) Bottom left: Just before balloon launch, the ceiling is being opened. Bottom middle and right: Just after a balloon launch.*

Period	Radiosonde model
Aug 1954 – Oct 1954; Aug 1956 – Mar 1957	Kew Mark 2B[4]
Apr 1957 – 1970	Kew Mark 2B
1971 – Apr 1972	Astor 403, introduced; Kew Mark 2B, still in use
May 1972 – 1975	Astor 403
1976	Astor RS4[5], introduced; Astor 403, still in use
1977	Astor RS4
1978 – 1980	Vaisala RS21-12C, introduced; Astor RS4, still in use
1981 – 1983	Vaisala RS21-12C
1984 – Sep 1997	Vaisala RS80-15N (winds from OMEGA)
Oct 1997 – 2008	Vaisala RS80 (winds from GPS)
2009 – Dec 2011	Vaisala RS92
Dec 2011 – 2015	Graw DFM-09
2015 – present	Vaisala RS41SG

Table 1: *Radiosonde models used at Singapore Upper Air Station. Updated from Hassim et al., 2019. (We also referred to Gaffen (1993)).*

Figure 25 shows a history of balloon burst pressures and associated altitudes at Singapore, using the minimum pressure point of each temperature profile as extracted from the Integrated Global Radiosonde Archive (IGRA) Version 2 (IGRA2) database (**https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00975**), with the ID "SNM00048698" for the Singapore station.

[4] Based on Gaffen (1993).

[5] This is most probably the one usually called as the "Philips RS4" (Nash and Schmidlin, 1987; Gaffen, 1993).

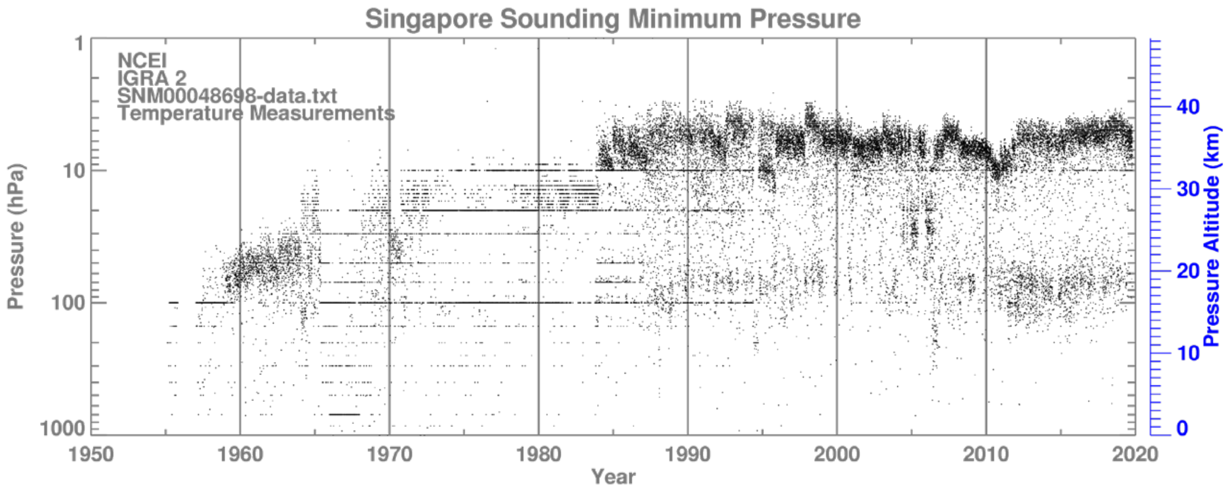

Figure 25: *The minimum pressure reached by each radiosonde flight (i.e., temperature profile), showing the approximate balloon burst point, based on historical flight data extracted from the IGRA2 database. See text for the details.*

Temperature data are used to filter out lower tropospheric wind measurements that were conducted not at the Upper Air Station but at the Changi Airport meteorological station using pilot balloons with a theodolite and using a wind profiler (the latter was in operation after October 2013). The horizontal "lines of points" correspond to the mandatory (or standard) pressure levels; they are probably due to the fact that the reporting through the Global Telecommunication System (GTS) of the World Meteorological Organization (WMO) was made only at these levels. An alternative version of Figure 25, with the maximum "height" point of each "wind" profile based on the same IGRA2 data, can be found in Figure 2 of Hassim *et al.* (2019).

2. Operational Challenges at the Singapore Upper Air Station

As seen in Figure 25, the Singapore Upper Air Station faces difficulties in regularly attaining the burst pressure of 10 hPa or better, especially during the evening ascents where the typical premature balloon bursts rate is more than 30 %. In the presence of significant low cloud cover, or after widespread heavy rains, the premature bursts rate can be more than 40 %. The very cold tropopause could be one of the causes of this balloon behaviour. As the Arctic site Ny-Alesund has faced similar challenges (cold tropopause and premature bursts), and subsequently improved balloon performance by pre-heating the balloons and treating them in a bath mixture of diesel, kerosene and engine oil, it has been suggested to test similar solutions at the Singapore station. However, due to its unique location within an office building, there are concerns over smell and fire safety. The Singapore station will therefore explore alternative options, such as spraying the surface of the balloon with a thin layer of oil, and pre-heating the balloons in a water bath.

Another solution to the early balloon burst problem that has been proposed by the Global Climate Observing System (GCOS) Reference Upper Air Network (GRUAN; **https://www.gruan.org**; see also the next section) community is to use the so-called double balloon flight configuration with a larger balloon inside a smaller "sacrificial" balloon. The Singapore station did trials with double layer balloons (1000 g inner, 350 g outer) which did not result in improvement in burst heights under challenging weather conditions. The Singapore station will explore different configurations of double balloons.

Singapore is a heavily urbanized island, and air traffic over Singapore is congested. Over the last few years there have been several radiosonde landings over mainland Singapore, including the airport, which resulted in disruptions. While the conventional radiosonde releases have been a long standing arrangement, there are challenges in securing approvals for new types of soundings (such as multiple-payload soundings).

3. SPARC researchers' experiences at Singapore Upper Air Station

Greg Bodeker visited the Singapore Upper Air Station on 19 January 2015 and again on 28 July 2015.

His visit was in his capacity as co-chair of GRUAN with the goal of eventually establishing Singapore as a GRUAN site. The three main objectives of GRUAN are to provide long-term high-quality climate records of vertical profiles of selected Essential Climate Variables (ECVs), to constrain and calibrate data from more spatially comprehensive global networks, and to fully characterize the properties of the atmospheric column. GRUAN is described in more detail in Bodeker *et al.* (2016). Given the importance of the Singapore upper-air soundings, it was imperative that its long-term continuity was assured and that establishing Singapore as a GRUAN site would foster that long-term continuity. After his first visit to the Singapore station, Bodeker sent a list of 122 papers that mentioned the use of the Singapore upper-air data as a measure of the value of these data to the community researching different aspects of the QBO.

Lawrence Coy, Paul Newman, Scott Osprey, Qing Liang, Rich Eckman, and Ralf Tuomi visited the station on 8 August 2017 (Figure 26) while attending the 14th annual Asia Oceania Geosciences Society (AOGS) meeting in Singapore. During the AOGS meeting, there was a special session on "The Quasi-Biennial Oscillation and its Role in the Climate System" (**http://www.asiaoceania.org/aogs2017/public.asp?page=spec_lectures.htm**). This session (10 August 2017) featured talks by Lawrence Coy on "Quasi-Disruptions of the QBO: Tropical Wave Activity of 1987-88 and 2010-11 Compared to the 2015-16 NH Winter", Paul A. Newman on "The 2015-16 Disrupted Quasi-biennial Oscillation's Impact on Stratospheric Trace Gases", Scott Osprey on "The Representation of the QBO and its Effects in Modern Climate Models", and Seok-Woo Son on "QBO Modulation of the Interannual Variability of the Madden-Julian Oscillation". Naturally, the attendees wanted to see the station that was so prominently featured in all of these talks. Prompted by the 2015-16 disruption of the QBO (Newman *et al.*, 2016; Osprey *et al.* 2016) and by the visit, Newman and Coy developed a website to highlight a number of QBO features, including winds, phase, temperature, water vapor, and ozone from a variety of observational systems (**https://acd-ext.gsfc.nasa.gov/Data_services/met/qbo/qbo.html**). For this website, the twice daily profiles of Singapore sounding data are taken through the WMO GTS, and bad or missing data are filled with MERRA-2 reanalysis winds (Gelaro *et al.*, 2017) to create monthly means.

Masatomo Fujiwara visited the Singapore Upper Air Station on 23 May 2019 during the GRUAN 11th Implementation and Coordination Meeting (ICM-11; GCOS, 2019), as a GRUAN working group member and a co-chair of the GRUAN task team on radiosondes. The station was certified as a GRUAN site in early 2019.

Figure 26: *SPARC researchers discuss with the station staff at the Upper Air Station radiosonde preparation area of the CCRS building on 8 August 2017. From left to right: Ralf Tuomi (Imperial College London, UK), Paul A. Newman, operation staff Dahlan Samubari, Scott Osprey (University of Oxford, UK), and Lesley Choo.*

Before the visit, based on the information from Greg Bodeker described above, Fujiwara communicated with James Anstey and decided to bring two "gifts" for the radiosonde operators. One is the world famous textbook on meteorological dynamics, "An introduction to dynamic meteorology" written by the late Professor James R. Holton (Holton and Hakim, 2013); its Figure 12.15 (p. 433) uses historical Singapore data and shows time-height cross section of equatorial zonal wind, describing the QBO, as an update from Naujokat (1986). The other is the SPARC Newsletter No. 45 that includes an article by Anstey et al. (2015), as a showcase of recent research activities on the QBO. At the station, with these presents, Fujiwara briefly explained the QBO and its global impacts to the radiosonde operators (Figure 27), emphasizing that their daily work has significant importance on the global climate research community.

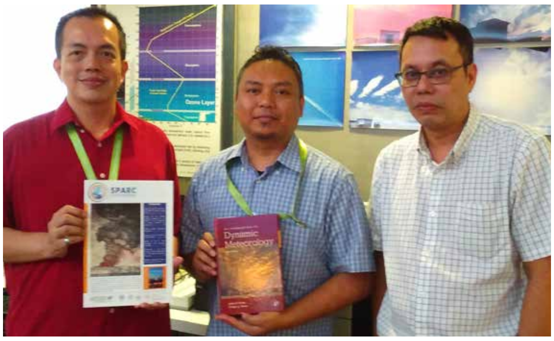

Figure 27: *Radiosonde operation staffs (from left to right: Lam Tuck Wai, Dahlan Samubari, Mohd Shahril Fuad) of the Singapore Upper Air Station holding SPARC Newsletter No. 45 and James R. Holton's textbook "Dynamical Meteorology" (5th edition) on 23 May 2019.*

4. Freie Universität Berlin's QBO data set

With the increasing number of radiosonde soundings in the framework of the International Geophysical Year (IGY) 1957/58 the Institute of Meteorology at the Freie Universität Berlin (FUB) began in 1957 to produce daily maps of the stratosphere for the Northern Hemisphere based on radiosonde soundings. In the scope of this work, Barbara Naujokat of the Stratospheric Research group started to build up the FUB QBO data set. For the early years (January 1953 – August 1967) soundings from Canton Island (3°S, 172°W) were used, followed later by soundings from Gan Island (Maldives 1°S, 73°E; September 1967 – December 1975), and finally from Singapore (1°N, 104°E; January 1976 – present) (Naujokat, 1986; Labitzke and van Loon, 1999). Until today, the FUB QBO time series is updated regularly using the technique of Naujokat (1986). The monthly QBO time series is based on the Singapore radiosonde soundings (Station ID 48698), as they are distributed via the WMO GTS. FUB receives the GTS radiosonde data via Germany's National Meteorological Service (DWD). All available soundings for 00 and 12 UTC[6] are used, decoded and error checked. The wind direction and speed for the mandatory pressure levels 100, 70, 50, 30, 20, and 10 hPa (if available) are directly taken from the sounding. In addition to these main pressure levels, significant level data for the stratosphere, encoded in part D of the GTS data, are incorporated in the FUB QBO data set. Significant levels are defined by the air pressures where the vertical temperature gradient changes sign. Using the wind direction and speed of the significant levels thus enhances the vertical resolution of the QBO. The wind direction and speed in knots are then converted to the zonal and meridional wind components. As the data on significant levels are on non-mandatory pressure levels which change from sounding to sounding, interpolation to a set of standard pressure levels is required. The interpolation to the final pressure levels 100, 90, 80, 70, 60, 50, 45, 40, 35, 30, 25, 20, 15, 12, and 10 hPa is linear in p^{R_d/c_p}, with R_d the specific gas constant for dry air, c_p the specific heat capacity of dry air at constant pressure, and $R_d/c_p = 0.286$. The interpolated data are lastly averaged over all soundings available for each month, to get the final monthly mean wind data, as published in Naujokat (1986). The FUB QBO data set is widely used for different applications, for example to specify the QBO winds in models, and can be downloaded from **https://www.geo.fu-berlin.de/met/ag/strat/produkte/qbo/index.html**.

In this article, we have presented both operational and research aspects of the Singapore upper air measurements focusing on the QBO.

[6] As explained in section 1, the latter time is actually 11 UTC, or 1040 UTC to be exact.

We strongly hope that this short article will foster and stimulate closer collaboration between research and operational communities. Such a collaboration is a key to ensure long-term continuity of climate monitoring which is sometimes at risk for various reasons in various parts of the world.

Acknowledgments

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