for CMIP6 (v3.1). *Geosci. Model Dev. Discuss.*, doi:10.5194/gmd-2016-91.

Meehl, *et al.*, 2007: THE WCRP CMIP3 Multimodel Dataset: A New Era in Climate Change Research. *Bull. Amer. Met. Soc.*, **88**, 1383-1394.

O'Neill, *et al.*, 2016: The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci. Model Dev.*, **9**, 3461-3482.

Phillips, A.S., C. Deser, and J. Fasullo, 2014: Evaluating Modes of Variability in Climate Models. *Eos Trans. AGU*, **95**, 453-455.

Riahi, K., *et al.*, 2016: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An Overview. *Global Environmental Change*, http://dx.doi.org/10.1016/j.gloenvcha.2016.05.009.

Ruane, A.C., *et al.*, 2016: The Vulnerability, Impacts, Adaptation and Climate Services Advisory Board (VIACS AB v1.0) contribution to CMIP6. *Geosci. Model Dev.*, **9**, 3493-3515.

Schulz, M., *et al.*, 2006: Radiative forcing by aerosols as derived from the AeroCom present-day and pre-industrial simulations. *Atmos. Chem. Phys.*, **6**, 5225-5246.

Taylor, K.E., R.J. Stouffer, G.A. and Meehl, 2012: An Overview of CMIP5 and the Experiment Design. *Bull. Amer. Met. Soc.*, **93**, 485-498.

Teixeira, J., *et al.*, 2014: Satellite Observations for CMIP5: The Genesis of Obs4MIPs. *Bull. Amer. Met. Soc.*, **95**, 1329-1334.

Zanchettin, D., *et al.*, 2016. The Model Intercomparison Project on the climatic response to Volcanic forcing (VolMIP): experimental design and forcing input data for CMIP6. *Geosci. Model Dev.*, **9**, 2701-2719.

Report on the International Workshop on Stratosphere-Troposphere Dynamical Coupling in the Tropics 22-24 October 2015, Kyoto, Japan

Marvin Geller[1], Peter Haynes[2], Seok-Woo Son[3], and Shigeo Yoden[4]

[1]Stony Brook University, New York, USA, **marvin.geller@stonybrook.edu**, [2]University of Cambridge, Cambridge, UK, [3]Seoul National University, Seoul, Korea, [4]Kyoto University, Kyoto, Japan

From 22-24 October 2015, a group of 18 researchers from seven different countries met at the Graduate School of Science Seminar House of Kyoto University (**Figure 5**). The organiser of the workshop was Professor Shigeo Yoden of Kyoto University. One of the SPARC science themes for almost a decade was "Stratosphere-troposphere dynamical coupling", but to date this was concentrated almost exclusively on coupling in mid- and high-latitudes, where the standard paradigms for interpreting and explaining troposphere-stratosphere coupling have been based on balanced dynamics, the distribution of potential vorticity (PV) on isentropic surfaces (or quasi-geostrophic PV on pressure surfaces), the material conservation of PV under adiabatic conditions, and the inversion of the PV field to recover all other dynamic and thermodynamic quantities. Great advances in understanding have occurred using these paradigms directly or paradigms related to the dynamics that arises from them, including Rossby wave propagation, baroclinic instability, wave mean-flow interaction, and so on.

On the other hand, the dynamic regime in the tropics is very different from that at higher latitudes; weather systems in the tropics involve multi-scale interactions with moist convection, for which no comparable interpretive paradigm exists. Mesoscale moist convection is the predominant source driving atmospheric motion in the tropics, whereas it is synoptic-scale baroclinic instability in the extra-tropics. Nonetheless, there is observational evidence that stratospheric variations do influence tropospheric variability in the form of moist convection or its large-scale organisation into meso- to planetary-scale systems. Furthermore, there have been some modelling studies, with both global general circulation models and regional cloud-resolving models, which show similarities to these observations, but such modelling studies have not yet reached a mature state.

This workshop was organised to discuss recent observational and modelling research in the area of stratospheric influences on tropical weather and climate, with a goal of proposing SPARC activities in this area. Topics covered during the workshop included the Quasi-Biennial Oscillation (QBO) influence on seasonal-mean tropical deep convection; QBO influence on tropical cyclones; QBO influence on the Madden-Julian Oscillation (MJO) and monsoon circulation; the influence of stratospheric sudden warmings (SSWs) on the tropical troposphere; influence of the 11-year solar cycle and stratospheric cooling trends on convection and its organisation; moist convection and multi-scale interactions in the tropics; wave-mean flow interactions and induced circulation in the tropics; and how our proposed activity might link with WCRP and other international activities.

Figure 5: Workshop attendees. Standing left to right: Harry Hendon, Tieh-Yong Koh, Marvin Geller, Kunihiko Kodera, Ji-Eun Kim, Toshitaka Tsuda, Kaoru Sato, Matthew Hitchman, Peter Haynes. Kneeling left to right: Keiichi Ishioka, Shigeo Yoden, Satoshi Noda, Eriko Nishimoto, Kohei Yoshida, Tri Wahyu Hadi, Seok-Woo Son, Masakazu Taguchi. Absent on this occasion: Masato Shiotani.

Discussions

Discussions took place on published results such as works on the QBO influence on tropical convection (Collimore *et al.*, 2003; Liess and Geller, 2012). These were observational studies that found statistically significant, but rather small, QBO influences on tropical deep convection using Outgoing Long-wave Radiation (OLR) data, Highly Reflecting Clouds (HRC) data, and International Satellite Cloud Climatology Project (ISCCP) data. They found that QBO easterly conditions favoured tropical deep convection, especially in regions where deep convection frequently occurs, but that the regions of enhanced convection were also accompanied by regions of suppressed convection. These papers suggested possible mechanisms to account for their results through vertical coupling (shown as Route 1 in **Figure 6**), such as QBO influences on Upper Troposphere/Lower Stratosphere (UTLS) temperatures and stability as well as QBO influences on the vertical shear of mean zonal wind in the UTLS. Another mechanism discussed at the workshop was QBO modulation of the tropics via the subtropical jets (Route 2 in **Figure 6**), which are possibly directly affected by the QBO (*e.g.*, Inoue *et al.*, 2011; Garfinkel and Hartmann, 2011a,b) perhaps through the Plumb-Bell meridional circulation (Plumb and Bell, 1982) or some generalization thereof.

Little progress has been made on modelling these effects, although the work by Giorgetta *et al.* (1999) did find a QBO effect on convective systems in a full general circulation model, where QBO nudging was applied. Of course, since most climate models can now self-consistently simulate the QBO, this could be re-examined. There have also been two very recent studies using cloud-resolving models to examine QBO influences on convection. One is the recent paper by Nie and Sobel (2015), which used the weak temperature gradient approximation as a simplified representation of the effect of large-scale circulation, and the other is the recent PhD dissertation by Yuan (2015). While both of these investigations point to the importance of convection interacting with the large-scale circulation, this was most apparent in the latter work that compared results with and without such interactions.

Published results have also indicated significant influence of the QBO on the number of Atlantic Hurricanes (*e.g.*, Gray, 1984) and on typhoon tracks in the Western Pacific (Ho *et al.*, 2009). It is interesting that early Atlantic Hurricane forecasts included the influence of the QBO but later ones did not. This is consistent with a recent paper by Camargo and Sobel (2010), which noted a significant correlation between the QBO and Atlantic Hurricanes before the 1980s, which seemed to disappear after that. Interestingly, Garfinkel and Hartmann (2007) pointed out that the correlations between the ENSO and QBO indices changed sign from negative to positive in the 1980s. It was pointed out that the Ho *et al.* (2009) paper is consistent with a QBO modulation of tropical rainfall in the western tropical Pacific, as suggested by Collimore *et al.* (2003), and Liess and Geller (2012), leading to a changed wave train in the tropospheric circulation, and in turn to a change in the steering circulation for typhoons.

A very exciting new result presented at the workshop was the data analysis by Yoo and Son (2016) which showed that the QBO has a significant influence on the MJO in the Northern Hemisphere (NH) winter. Their work shows that the MJO amplitude is substantially greater under QBO-easterly (E-QBO) conditions. **Figure 7** illustrates the standard deviation of MJO-filtered OLR for all NH winters (top), and the anomalies of this standard deviation for QBO westerly (W-QBO) phase (middle), and those for E-QBO phase (bottom). Note that the E-QBO anomalies are positive and the W-QBO anomalies are negative, and the QBO-related MJO anomalies range roughly ±10% of the climatology. Correlations between the OLR MJO Index (OMI) and mean zonal winds in the lower stratosphere are largest during NH winter months (-0.56 at 70hPa, and -0.59 at 50hPa), which are much larger than the ENSO/OMI correlations. Perhaps these new results are consistent with the QBO enhancing organised convection systems, as is suggested by Liess and Geller (2012), and recent cloud-resolving modelling results. However, more work is needed in this latter area.

Marshall *et al.* (2016) showed that the predictability of the MJO is enhanced under E-QBO phase, not only because forecasts initialised with stronger MJO events have greater skill, but also because the MJO events during E-QBO phases are more persistent compared to those of similar initial amplitude during W-QBO phases. This result has implications for global sub-seasonal to seasonal predictions. Multi-week forecast outputs from the Sub-seasonal to Seasonal (S2S) Prediction Project (**www.s2sprediction.net**) could be used for the application of extended-range predictability studies of the stratosphere-troposphere coupled system in the tropics regulated by the QBO.

There are other stratospheric influences on the tropics for which these QBO results have implications. One is the influence of stratospheric cooling trends on Atlantic hurricane activity (Emanuel *et al.*, 2013). Another is the influence of SSWs, since decreasing stratospheric temperatures in the tropical lower stratosphere have been shown to accompany warming at higher latitudes. Thus, as far as the tropical UTLS is concerned, its response to an SSW is similar to its response during the E-QBO phase (*e.g.*, Eguchi and Kodera, 2010; Kodera *et al.*, 2015).

Other topics presented at the workshop included new SMILES (Superconducting Submillimeter-Wave Limb Emission Sounder) observations (Sakazaki *et al.*, 2013), modulation of gravity wave characteristics as observed by the AIRS (Atmospheric Infrared Sounder) instrument (Sato *et al.*, 2016; Tsuchiya *et al.*, 2016); high vertical resolution temperature profiles from COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) full-spectrum inversion (Noersomadi and Tsuda, 2016); and vertical profiles of moisture, cirrus clouds, and chemical composition (Jensen *et al.*, 2015) from the NASA ATTREX (Airborne Tropical Tropopause Experiment) campaign.

There were discussions of the theoretical background of the results discussed (*e.g.*, Haynes *et al.*, 1991; Holton *et al.*, 1995), as well as some studies using a new formulation of 3-D diagnostics for wave-mean flow interactions

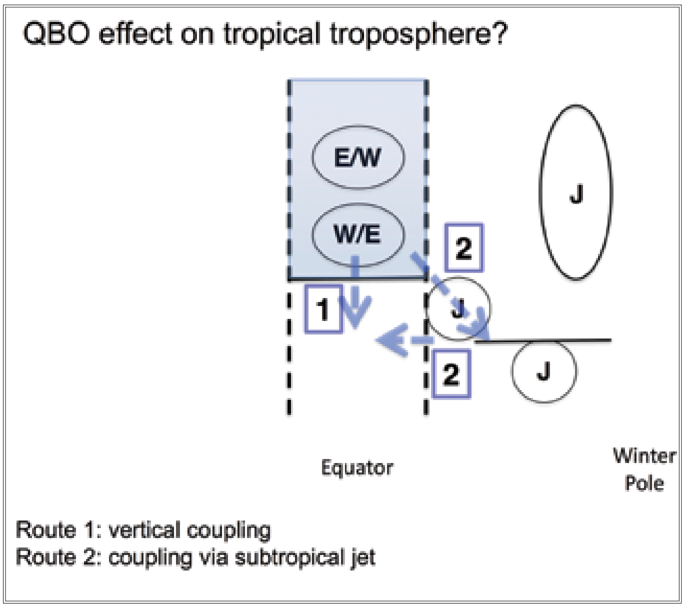

Figure 6: Illustration of two routes through which the equatorial QBO could influence the tropical troposphere. (Figure courtesy Haynes, 2016; *unpublished*).

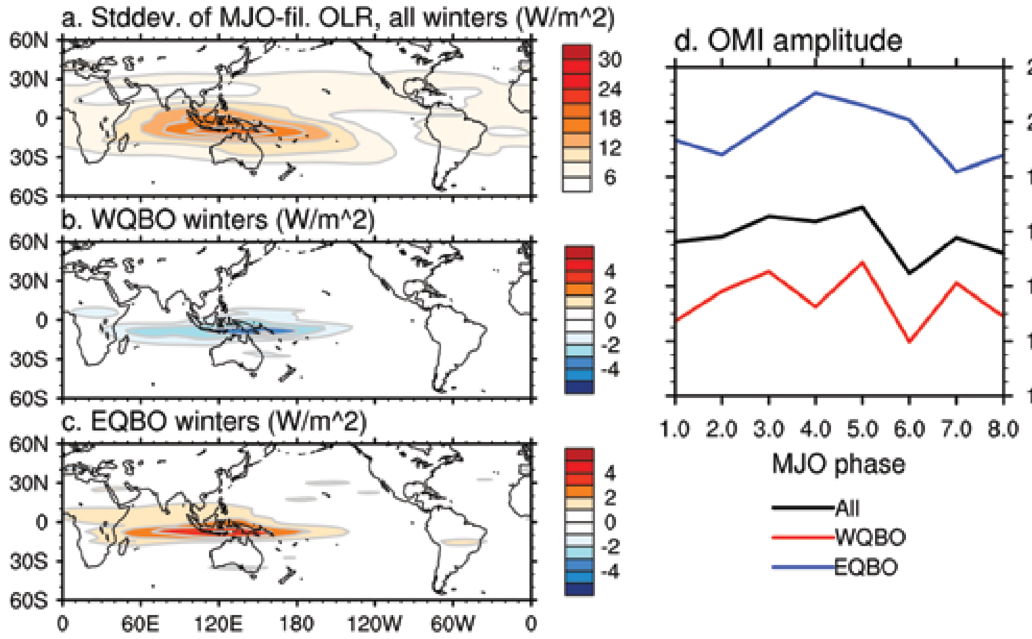

Figure 7: (a) The standard deviation of wintertime MJO-filtered OLR for all NH winters, where the MJO filtering retrieves eastward propagating wave numbers 1–5 and periods of 20–100 days. (b, c) As in (a) but for anomalies of the W-, and E-QBO winters, respectively. (d) OMI amplitude composites taken for eight MJO phases of all (black), W-QBO (red), and E-QBO (blue) winters with active MJOs. (Figure from Yoo and Son, 2016).

(*e.g.*, Kinoshita and Sato, 2014). There was also discussion about using a simplified model of the stratosphere-troposphere coupled system in the tropics (Nishimoto *et al.*, 2016), in which a QBO-like oscillation exists throughout the stratosphere and troposphere as a result of convective and gravity-wave momentum transports.

Finally, there was discussion about how the new activity might fit together with the FISAPS (Fine Scale Atmospheric Processes and Structures) activity (**www.sparc-climate.org/activities/fine-scale-processes**), as well as with the proposed new Equatorial MU Radar (**www.rish.kyoto-u.ac.jp/ear/index-e.html**) and the Years of the Maritime Continent for 2017-19 (**YMC; www.bmkg.go.id/ymc**).

Deliverables

The group envisioned that the new SPARC activity on Stratospheric and Tropospheric Influences On Tropical Convective Systems (SATIO-TCS) would have the following near-term deliverables:

1. A review paper on stratosphere-troposphere dynamical coupling in the tropics (based on this workshop) will be submitted to the Journal of the Meteorological society of Japan or the Bulletin of the American Meteorological Society;
2. Workshops and/or conferences on stratosphere-troposphere dynamical coupling in the tropics will be held in Kyoto in 2017 and 2020, with a report article or a special journal issue or section;
3. Results stemming from the collaborative research could lead to improved tropical predictions, and contribute to the WCRP Grand Challenge on near-term predictions;
4. Capacity building through the South-East Asian School on Tropical Atmospheric Science (SEASTAS) in association with the YMC project.

The proposal has been revised and approved as a SPARC emerging activity in the 24th Scientific Steering Group meeting. Anyone interested in getting involved is more than welcome to do so. Please visit the SPARC website for more details and contact the activity leaders: **www.sparc-climate.org/activities/emerging-activities/#c1880.**

References

Camargo, S.J., and A.H. Sobel, 2010: Revisiting the influence of the quasi-biennial oscillation on tropical cyclone activity. *J. Climate,* **23**, 5810-5825.

Collimore, C.C., *et al.*, 2003: On the relationship between the QBO and tropical deep convection. *J. Climate*, **16**, 2552-2568.

Eguchi, N., and K. Kodera, 2010: Impacts of stratospheric sudden warming event on tropical clouds and moisture fields in the TTL: A case study. *SOLA*, **6**, doi: 10.2151/sola.2010-035.

Emanuel, K., *et al.*, 2013: Influence of tropical tropopause layer cooling on Atlantic hurricane activity. *J. Climate*, **26**, 2288–2301.

Garfinkel, C.I., and D.L. Hartmann, 2007: Effects of the El Niño–Southern Oscillation and the Quasi-Biennial Oscillation on polar temperatures in the stratosphere. *J. Geophys. Res.*, **112**, D19112, doi:10.1029/2007JD008481.

Garfinkel, C.I., and D.L. Hartmann, 2011a: The influence of the quasi-biennial oscillation on the troposphere in winter in a hierarchy of models. Part I: Simplified dry GCMs. *J. Atmos. Sci.*, **68**, 1273-1289.

Garfinkel, C.I., and D.L. Hartmann, 2011b: The influence of the quasi-biennial oscillation on the troposphere in winter in a hierarchy of models. Part II: Perpetual winter WACCM runs. *J. Atmos. Sci.*, **68**, 2026-2041.

Giorgetta, M.A., L. Bengtsson, and K. Arpe, 1999: An investigation of QBO signals in the east Asian and Indian monsoon in GCM experiments. *Clim. Dyn.*, **15**, 435-450.

Gray, W.M., 1984: Atlantic seasonal hurricane frequency. Part I: El Niño and 30 mb quasi-biennial oscillation influences. *Mon. Wea. Rev.*, **112**, 1649-1668.

Haynes, P.H., *et al.*, 1991: On the 'downward control' of extratropical diabatic circulations by eddy-induced mean zonal forces. *J. Atmos. Sci.*, **48-4**, 651-678.

Ho, C.-H., *et al.*, 2009: Influence of stratospheric quasi-biennial oscillation on tropical cyclone tracks in the western North Pacific. *Geophys. Res. Lett.*, **36**, L06702, doi: 10.1029/2009GL037163.

Holton, J.R., *et al.*, 1995: Stratosphere-troposphere exchange. *Rev. Geophys.*, **33-4**, 403-439.

Inoue, M., M. Takahashi, and H. Naoe, 2011: Relationship between the stratospheric quasi-biennial oscillation and tropospheric circulation in northern autumn. *J. Geophys. Res.*, **116**, D24115, doi:10.1029/2011JD016040.

Jensen, E.J., *et al.*, 2015: The NASA Airborne Tropical TRopopause EXperiment (ATTREX): High-altitude aircraft measurements in the tropical western Pacific. *Bull. Amer. Meteor. Soc.*, doi:10.1175/BAMS-D-14-00263.1.

Kinoshita, T., and K. Sato, 2014: A formulation of three-dimensional residual mean flow and wave activity flux applicable to equatorial waves. *J. Atmos. Sci.*, **71**, 3427-3438.

Kodera, K., *et al.*, 2015: The role of convective overshooting clouds in tropical stratosphere-troposphere dynamical coupling. *Atmos. Chem. Phys.*, **15**, 6767-6774.

Liess, S., and M.A. Geller, 2012: On the relationship between QBO and distribution of tropical deep convection. *J. Geophys. Res.*, **117**, D03108, doi: 10.1029/2011JD016317.

Marshall, A.G., *et al.*, 2016: Impact of the Quasi-Biennial Oscillation on predictability of the Madden-Julian Oscillation. *Clim. Dyn.*, doi:10.1007/s00382-016-3392-0.

Nie, J., and A.H. Sobel, 2015: Responses of tropical deep convection to the QBO: Cloud-resolving simulations. *J. Atmos. Sci.*, **72**, 3625-3638.

Nishimoto, E., S. Yoden, and H.-H. Bui, 2016: Vertical momentum transports associated with moist convection and gravity waves in a minimal model of QBO-like oscillation. *J. Atmos. Sci.*, **73**, 2935-2957.

Noersomadi, and T. Tsuda, 2016: Global distribution of vertical wavenumber spectra in the lower stratosphere observed using high-vertical-resolution temperature profiles from COSMIC GPS radio occultation. *Ann. Geophys.*, **34,** 203-213.

Plumb, R.A., and R.C. Bell, 1982: A model of the quasi-biennial oscillation on an equatorial beta-plane. *Quart. J. Roy. Meteor. Soc.*, **108**, 335-352.

Sakazaki, T., *et al.*, 2013: Diurnal ozone variations in the stratosphere revealed in observations from the Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) on board the International Space Station (ISS). *J. Geophys. Res. Atmos.*, **118**, 2991–3006, doi:10.1002/jgrd.50220.

Sato, K., *et al.*, 2016: Climatology and ENSO-related interannual variability of gravity waves in the Southern Hemisphere subtropical stratosphere revealed by high-resolution AIRS observations. *J. Geophys. Res.*, **121**, 7622-7640.

Tsuchiya, C., *et al.*, 2016: MJO-related intraseasonal variation of gravity waves in the Southern Hemisphere tropical stratosphere revealed by high-resolution AIRS observations. *J. Geophys. Res.*, **121**, 7641-7651, doi:10.1002/2015 JD024463.

Yoo, C., and S.-W. Son, 2016: Modulation of the boreal wintertime Madden-Julian oscillation by the stratospheric quasi-biennial oscillation. *Geophys. Res. Lett.*, **43-3**, 1392-1398.

Yuan, W., 2015: ENSO modulation of the QBO, and QBO influence on tropical convection. Ph.D. thesis, Stony Brook University, 149pp.