Report on the Joint SPARC Dynamics and Observations Workshop: SATIO-TCS, FISAPS and QBOi, Kyoto, Japan

James Anstey[1], Shigeo Yoden[2], Marvin Geller[3], Scott Osprey[4], Kevin Hamilton[5], Neal Butchart[6]

[1]Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada, Victoria, Canada, (**james.anstey@canada.ca**) , [2]Division of Earth and Planetary Sciences, Graduate School of Science, Kyoto University, Kyoto, Japan, (**yoden@kugi.kyoto-u.ac.jp**), [3]Stony Brook University, New York, USA, (**marvin.geller@stonybrook.edu**), [4]National Centre for Atmospheric Science, University of Oxford, UK, [5]International Pacific Research Center, University of Hawaii, USA, [6]Met Office Hadley Centre, UK.

Dates:
9 - 14 October 2017

Organisers:
James Anstey (Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada). Neal Butchart (Met Office Hadley Centre, UK), Marv Geller (Stony Brook University, New York, USA), Kevin Hamilton (University of Hawaii, USA), Scott Osprey (University of Oxford, UK), Shigeo Yoden (Kyoto University, Kyoto, Japan)

Host Institution:
Kyoto university, Kyoto, japan

Number Of Participants: **74**

Sponsors:

Workshop Website:
www-mete.kugi.kyoto-u.ac.jp/SPARCjws2017/index.html

Activity Websites:
www.sparc-climate.org/activities/emerging-activities/
http://www.sparc-climate.org/activities/fine-scale-processes/
http://users.ox.ac.uk/~astr0092/QBOi.html

Tropical weather, including organized large-scale phenomena such as the Madden-Julian Oscillation (MJO), is largely governed by interactions with moist convection acting across a range of spatial scales. The large-scale circulation of the overlying stratosphere, including the quasi-biennial oscillation (QBO), is largely driven by interactions with vertically propagating waves forced by tropospheric convection. Evidence from observations and models has increasingly indicated a significant downward dynamical coupling from the tropical stratosphere, including the recently discovered substantial influence of the QBO on the MJO. Phenomena with fine vertical scales likely play an important role in aspects of tropical stratosphere-troposphere coupling, and better use of observations to characterize such small scale variability may both improve our understanding and help to better constrain models.

To examine these and related phenomena, the Joint SPARC Dynamics and Observations Workshop was organized by three SPARC activities: Stratospheric And Tropospheric Influences On Tropical Convective Systems (SATIO-TCS), Fine-Scale Atmospheric Processes and Structures (FISAPS), and the Quasi-Biennial Oscillation Initiative (QBOi), and was held in Kyoto, Japan, 9-14 October 2017. Given the partial overlap of scientific interests among these SPARC activities, one goal of the joint workshop was to foster increased collaboration across their boundaries, and accordingly the week was centred on two days of plenary talks combining all three activities and spanning topics of mutual interest. The rest of the week was organized into more focussed sessions for the individual activities, and an effort was made to schedule as few parallel sessions as possible so as to encourage participants in one activity to attend sessions of the other activities. The workshop was hosted by Professor Shigeo Yoden of Kyoto University, and attended by 74 scientists from 13 countries. The workshop agenda, including the abstracts of all oral and poster presentations, is available online at the workshop website (**http://www-mete.kugi.kyoto-u.ac.jp/SPARCjws2017/index.html**).

Broadly, the workshop themes included: influences on organized tropical convection (such as the aforementioned QBO-MJO link), vertical propagation of tropical waves, fine-scale processes and structures, QBO dynamics (including the early-2016 QBO disrup-

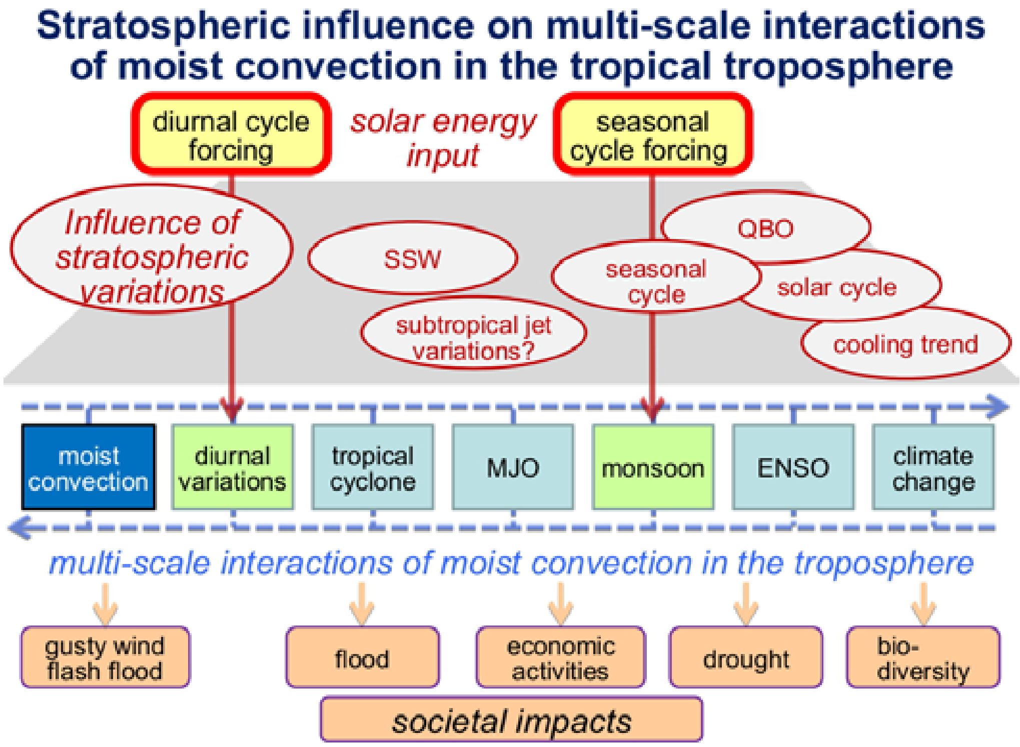

Figure 7: *Schematic overview of stratospheric influence on the tropical troposphere. Figure credit: Shigeo Yoden.*

tion), and stratosphere-troposphere coupling in the extratropics (including QBO influence at high latitudes).

While extratropical stratosphere-troposphere coupling has been a prominent SPARC focus for well over a decade, stratospheric influence on the tropical troposphere is only recently receiving more attention, and is the prime focus of the SATIO-TCS activity (Figure 7). Fully exploiting any potential predictability of tropical weather systems that originates from the stratosphere will likely require improving our understanding of, and ability to model, the QBO and its impacts, which is the focus of the QBOi activity. Relevant phenomena may include those exhibiting fine vertical scales, such as vertical mixing near the base of the QBO, cirrus formation near the tropical tropopause, or the fine-scale structure of the tropopause inversion layer (TIL) across which tropical stratosphere-troposphere coupling occurs. The main focus of the FISAPS activity is the use of high vertical-resolution radiosonde data (HVRRD) to characterize fine-scale processes that have systematic effects on the large-scale circulation, with the anticipated benefit of reducing model uncertainty (which is large in the case of the QBO). Thus there is substantial overlap between the research foci of all three of these SPARC activities, and complementarity between activities that have an emphasis on modelling (QBOi), observations (FISAPS), and a mix of the two (SATIO-TCS). The rest of this article will summarize the workshop proceedings, organized according to the aforementioned themes.

Influences on organized tropical convection

It has been known for some time that the QBO may influence tropical convection, and historical overviews were given by **Matt Hitchman** and **Marvin Geller**. The mechanisms for this influence are uncertain, but idealized models are being used to assess causality (**Tieh Yong Koh, Zane Martin, Adam Sobel, Shigeo Yoden**). In particular, **Adam Sobel** noted that the tropical precipitation response to a QBO-induced tropopause-level temperature perturbation may be non-monotonic. If tropical tropopause layer (TTL) temperature variability is the main driver leading to changes in tropical deep convection, it is important to understand the relative roles of radiative and wave-induced forcing in driving that variability (**Peter Haynes**). Mechanisms should also address why the QBO would influence the organization of convection (**Marvin Geller**). The organization of mesoscale convective clusters over tropical oceans as diagnosed with a new theoretical framework of self-organized criticality was discussed by **Chee-Kiat Teo**.

The observational record indicates that the QBO influence on seasonal-mean tropical convection is relatively weak but that its influence on MJO is somewhat stronger (Figure 8). **Seok-Woo Son** showed that a stronger MJO amplitude occurs under 50 hPa easterly QBO (QBO-E) than westerly QBO (QBO-W), and proposed that cirrus-induced radiative heating of the TTL, enhanced by the colder tropopause

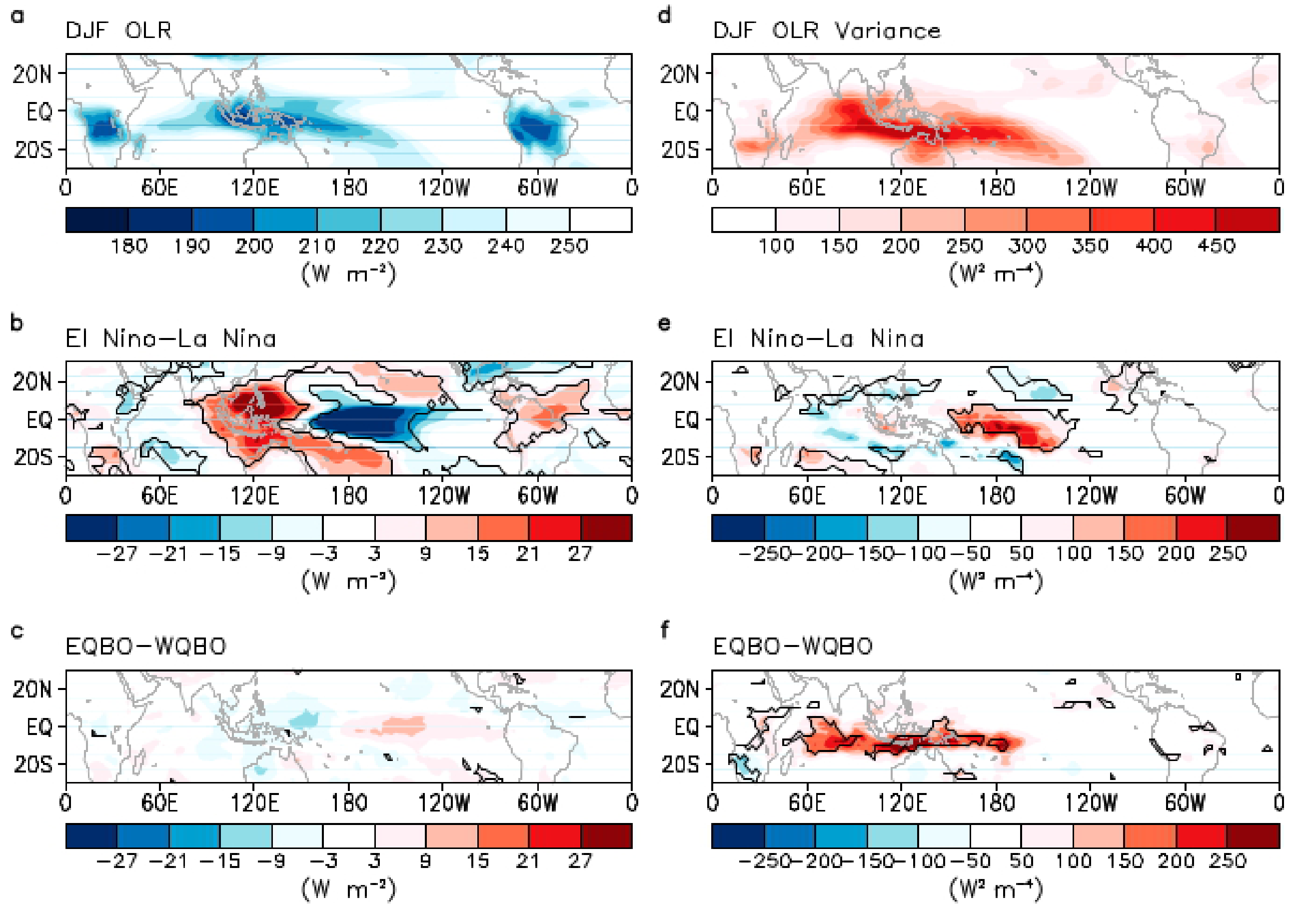

***Figure 8**: Comparison of seasonal-mean OLR and bandpass-filtered (20-100 days) OLR during December-February, for (a,d) climatology, (b,e) differences between El Niño and La Niña, (c,f) differences between easterly (EQBO) and westerly (WQBO) 50 hPa QBO. Black lines denote 95% statistical significance. From Son et al. (2017).*

that occurs during QBO-E, may act to destabilize the TTL, thereby enhancing deep convection. The MJO is more predictable, by about one week, during QBO-E (**Harry Hendon**). An ensemble of 10 models from the Subseasonal-to-Seasonal (S2S) prediction project (**http://s2sprediction.net/**) shows the same effect, with the multi-model mean increase in predictability being about 5 days, and all models showing the same sign of the effect (**Seok-Woo Son**). A note of caution, however, was indicated by the running correlation between QBO and MJO reconstructions spanning the whole 20th century, which showed a strong QBO-MJO correlation emerging only in the most recent 30 years of the record (**Harry Hendon**).

Global outgoing longwave radiation (OLR) data were analysed to show that convectively coupled waves also can respond to the QBO, with more uniform wave amplitudes observed during QBO-W (**Tri Wahyu Hadi**). The amplitude of the Boreal Summer Intra-Seasonal Oscillation (BSISO) was suggested to respond to the QBO, although the connection is stronger to the QBO winds at 20 hPa than to 50 hPa (where the winds correlate most strongly with the observed MJO; **Yayoi Harada**). On the other hand, the tropical easterly jet, which affects Indian summer monsoon rainfall, was shown to be clearly modulated by ENSO but displayed no clear connection to the QBO (**Nithya K**). The Asian summer monsoon anticyclone in the upper troposphere / lower stratosphere (UTLS) may also exhibit internal variability, as indicated by **Arata Amemiya** using an idealized numerical model.

QBO influence is of interest partly because of the very high predictability of the QBO, but it is not the only stratospheric perturbation that could affect the tropical troposphere. Cooling of the eastern Pacific tropical ocean over the last decade, related to the so-called "hiatus" in global warming, occurs concurrently with a poleward shift and strengthening of the Hadley Cell. This change in the Hadley Cell, representing a shift in the location of extreme deep convection, could be influenced by the effect of lower stratospheric cooling (due to increased CO_2) on the stability of the TTL (**Kunihiko Kodera**). Case studies indicating that an abrupt northward shift of convection can occur in response to lower stratospheric cooling due to fluctuations in the Brewer-Dobson circulation were presented by **Rei Ueyama**. A remote influence of Stratospheric Sudden Warmings (SSWs) on tropical convection was shown by **R. Remya** using radar data from Cochin, India (10N, 76E). MJO convection may respond to solar cycle forcing, particularly during times when QBO and solar influences interfere constructively to affect lower stratospheric stability (**Lon Hood**). An ENSO response to Arctic ozone changes was suggested by **Jianping Li.**

The link between tropical cyclones and upper-level conditions around the tropopause was also explored, with **Tetsuya Takemi** showing the strong effect of upper level temperature on cyclone intensification, **Matt Hitchman** discussing stratosphere-troposphere coupling due to tropical cyclone PV dipoles, and **Ravindran Babu Saginela** examining stratosphere-troposphere exchange over the North Indian Ocean associated with tropical cyclones.

Vertical propagation of waves

William Randel discussed temperature observations from Global Positioning System (GPS) satellites, highlighting the rapid rise in the number of soundings in recent years and the remarkable increases in data density expected in the near future. He used GPS sounding data to examine tropical wave activity, including the small-scale waves that provide a large contribution to the forcing of the QBO, and showed that the largest tropical temperature variances occur at the smallest spatial scales (Figure 9). Reanalyses also provide valuable datasets for examination of tropical waves, as assessed by **George Kiladis** who showed a strong association of stratospheric waves with the QBO, and also that stratospheric Kelvin wave activity is related to the MJO during December-February. Reanalyses represent a mixture of observational information and model simulation, which can be difficult to disentangle. **Corwin Wright** presented comparisons of gravity waves in reanalyses with satellite observations (SABER, HIRDLS and AIRS), sampling the reanalyses in the same way that the satellites sample the real atmosphere. Results suggested that inter-reanalysis differences are related to the reanalysis models' vertical and horizontal resolution, which is a model sensitivity that can strongly affect the QBO. **Kevin Hamilton** proposed that wave propagation and dissipation in models could be diagnosed by adding an artificial wave forcing near the tropopause to generate monochromatic waves that propagate into the stratosphere, providing a novel method for model intercomparison.

The behaviour of large-scale equatorial waves in the QBOi multi-model ensemble (hereafter "QBOi models") was presented by **Laura Holt**, who showed that Kelvin and Rossby-gravity modes at 50 hPa are fairly robust across the models, but often tend to have larger amplitude than found in the ERA-Interim reanalysis. In precipitation spectra these same modes show much more inter-model variation, with roughly half of the models showing realistic Kelvin modes and fewer still showing realistic Rossby-gravity modes. Effects of smaller-scale waves on the QBO were examined by **Yoshio Kawatani**, who found that the QBO period during El Niño was about 2 months shorter than during La Niña in a model where the QBO was driven entirely by resolved waves, but a model in which small-scale waves were parameterized using fixed sources showed no such effect.

Fine-scale processes

Marvin Geller gave an overview of FISAPS, whose scientific focus is to better characterize and understand atmospheric processes occurring on fine ver-

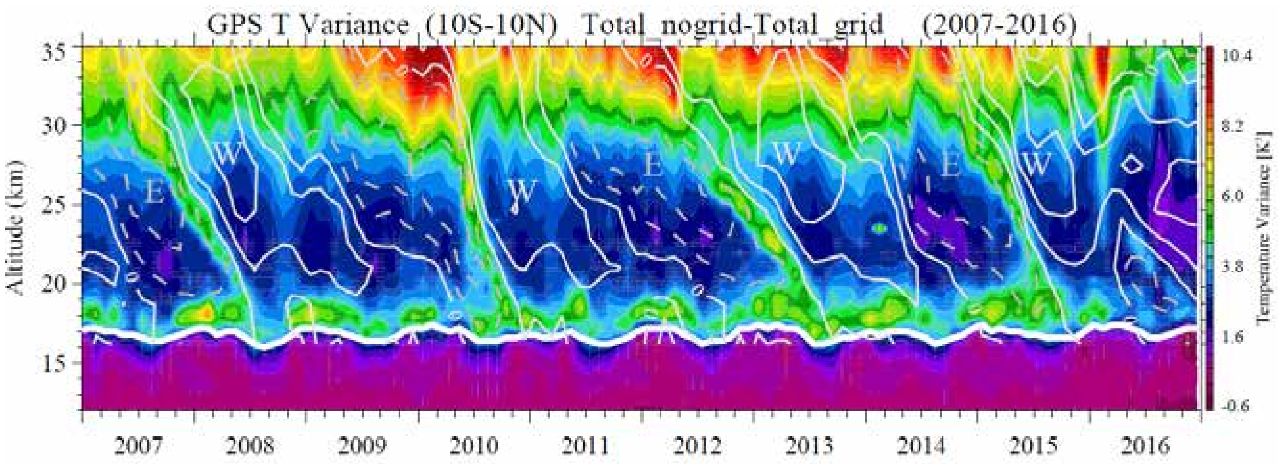

***Figure 9:** Zonal variance of GPS daily temperature observations in the tropics (10S-10N) for zonal wavenumbers larger than 10 (horizontal wavelengths < 4000 km). White solid and dashed lines show the QBO winds. Thick white line shows the tropical tropopause. Figure credit: William Randel.*

tical scales (less than about 1 km). One important data source for such investigations is HVRRD. While HVRRD are potentially available at all worldwide radiosonde stations that transmit data to operational weather forecasting agencies, in practice only a limited number of nations make their data easily available to the worldwide research community. **Marvin Geller** gave a summary of the present HVRRD availability as well as an overview of how the data availability to the research community is likely to increase in light of the increasing demand for these data by the operational weather forecasting agencies. **Hye-Yeong Chun** showed how turbulence estimates using HVRRD compared to aircraft measurements of turbulence, and **Muhsin Muhammed** gave evidence of diurnal variations of turbulence in the troposphere and lower stratosphere at some Indian stations.

One potential application of HVRRD is obtaining atmospheric turbulence information, but the methods for doing this depend on relating the measured Thorpe scale to the Ozmidov scale. This is one of the principal challenges for FISAPS, which requires comparison of HVRRD estimates of turbulence to those measured by dedicated research measurements of atmospheric turbulence. One such dedicated research measurement method was discussed by **Franz-Josef Lübken**, who explained how the LITOS instrument (Leibniz Institute Turbulence Observations in the Stratosphere) can resolve the Kolmogorov microscale of turbulence. In the Antarctic, the PANSY radar has been used to examine turbulent dissipation in the troposphere and lower stratosphere (**Kaoru Sato**), and can be compared against observations by balloon-borne instruments (**Yoshihiro Tomikawa**). Direct numerical simulations (DNS) of turbulence were discussed by **Ling Wang**. The comparison between DNS modelling with HVRRD, LITOS, and other measurements of turbulence is a fruitful direction for FISAPS.

Since improved observational constraints on turbulent mixing could improve the modelling of large-scale dynamical variability such as the tropical tape recorder, **Marvin Geller** discussed a recently published paper by Glanville and Birner (2017), and suggested that determination of turbulent vertical mixing in the vicinity of the tropical tropopause should be one of FISAPS's goals. Gravity waves are another small-scale process with a large imprint on the large scale (e.g., the QBO), and are also poorly constrained in models. A new method for observing them using AIRS satellite data was discussed by **Neil Hindley**. A variety of fine-scale processes in the UTLS region will be observed by the upcoming Strateole 2 campaign, as described by **Albert Hertzog**. Long-duration balloons will perform 3-month flights at altitudes of 18 and 21 km, during both QBO phases, circumnavigating the global UTLS and measuring gravity wave momentum fluxes, cirrus microphysics, dehydration, and cross-tropopause transport.

QBO dynamics and the early-2016 QBO disruption

The QBO is strongly dependent on a number of processes that operate at small vertical and/or horizontal scales – such as gravity waves, radiative damping of waves, and vertical mixing – that are unresolved in typical atmospheric general circulation models (AGCMs) and not well constrained by observations. Understanding the ramifications of the resulting model uncertainty is a goal of the QBOi activity, which has assembled a multi-model ensemble of AGCMs that simulate the QBO with varying degrees of fidelity as shown by **Andrew Bushell**. His talk documented significant inter-model variability in the QBO amplitudes, and demonstrated that those QBOi models with fixed sources for their parameterized non-orographic gravity waves underestimated the typical cycle-to-cycle QBO variability.

An expected consequence of the model uncertainty is that modelled QBOs will not respond robustly to forcing, such as increased greenhouse gas concentration, or when the models are used for prediction from observed initial conditions. **Yaga Richter** showed that the QBOi models exhibit widely varying responses to climate-change forcing, including period shortening, lengthening, or the disappearance of the QBO altogether. **Tim Stockdale** and **Young-Ha Kim** assessed QBO predictability using the same models run in hindcast mode and found considerable inter-model variation in predictive skill in the lower (70 hPa) and upper (10 hPa) regions of the QBO. Investigations of particular sensitivities of individual models were also discussed. **Hiroki Kashimura** found strong sensitivity of the QBO in two AGCMs to horizontal resolution, diffusion, and numerical time step, with no indication of convergence. Inclusion of interactive ozone in a model was shown to lengthen its QBO period, suggesting that tuned gravity wave drag in models lacking interactive ozone could be unrealistically weak (**Jack Chen**, **Marvin Geller**). Representing the QBO impact on ozone, which is substantial and extends to high latitudes (**Tobias Kerzenmacher**), is an important aspect of modelling the QBO.

Figure 10: *Group photograph of the workshop participants.*

The lack of a robust response of modelled QBOs to global climate forcing is likely a symptom of over-tuning of gravity wave parameterizations. A similar weakness in model formulation may lie at the root of the failure of current seasonal forecast systems to predict the 2016 QBO disruption. **Peter Hitchcock** described the dynamics of analogous disruptions occurring in the equatorial mean wind oscillations in a very idealized AGCM and characterized them as a two-stage process involving an initial trigger followed by a sustained feedback. This suggests that the evolution of the real disruption should be predictable following the activation of the trigger, possibly sometime in Dec 2015. **Rolando Garcia** discussed analogous events that are occasionally seen in free-running AGCMs. Notably he showed that under quadrupled CO_2 concentration, the NCAR WACCM exhibited three similar events in a 30-year simulation, two of which corresponded with El Niño events (as does the observed 2016 disruption). **Nagio Hirota** found, using large ensemble experiments, that not only El Niño ocean temperatures but also Arctic sea ice concentration could be important in generating the anomalous waves that forced the disruption. Changes in minor constituents (ozone, N_2O, and HCl) related to the disruption were discussed by **Toshihiko Hirooka**.

Extratropics

Although most attention at the workshop was on the tropics, one focus of the QBOi activity is to better understand the extratropical impacts (teleconnections) of the QBO. **Lesley Gray** showed observed QBO links to surface climate diagnosed by multiple regression analysis, including evidence of influence during early and late NH winter that appears to be distinct from QBO modulation of the stratospheric polar vortex. As with QBO links to tropical deep convection, these links may represent additional pathways for tropospheric influence beyond the conventional hypothesis of QBO-vortex coupling via a stratospheric pathway, often referred to as the Holton-Tan effect.

The stratospheric QBO-vortex coupling nevertheless remains of interest due to its persistence in the observed record to date and the fact that it has not been fully explained. **Hua Lu** examined mean-flow forcing diagnostics on isentropic levels and argued that, depending on the location of the forcing in the extratropical stratosphere, linear or nonlinear processes could contribute to inducing the Holton-Tan effect. **Richard Scott** placed coupling between the vortex and tropical winds in the context of stratospheric internal variability as seen in a hierarchy of models. An alternative framework for viewing QBO-vortex coupling was suggested, based on an idealized model with prescribed PV gradients representing the vortex and different QBO phases.

For the QBOi models, **James Anstey** showed that coupling between the QBO and the NH winter stratospheric polar vortex has appreciable inter-model variation, with the multi-model ensemble exhibiting on average a link that is weaker, but consistent in sign, with the observed signal. The corresponding surface signal, which in observations resembles the NAO, varies strongly among models (and is not even consistent in sign). The lack of a coherent surface response in the models may implicate the models' ability to represent downward coupling due to stratospheric vortex variations accurately, as discussed by **Mark Baldwin**. Other mechanisms of vertical coupling may also be at play, such as downward reflection of planetary waves (**Hitoshi Mukougawa**). Observed variability also includes the imprint of other low-frequency influences besides the QBO, such as the 11-year solar cycle (**Hua Lu**).

Workshop outcomes

The participants generally agreed that holding this joint workshop was valuable and likely led to greater participation than would have been the case for individual workshops. Also, some new research horizons resulted from interaction among the different SPARC activities. In general, we recommend that more such joint workshops of SPARC activities be considered. The SPARC QBOi, SATIO-TCS, and FISAPS activities discussed their future plans, and all activities have some plans for future meetings, some in connection with the upcoming SPARC General Assembly in October 2018. FISAPS also discussed holding a small focussed workshop in the next year or so. For SATIO-TCS, this was the kick-off workshop and activity plans for the near future were discussed, including writing a review paper summarizing our current understanding and future challenges, opening a web page for the archive of related information, and forming sub-groups for various activities. For QBOi, plans were made for the coming year to complete the set of papers analysing the initial set of QBOi experiments described in Butchart et al. (2017), as well as to hold a side meeting at the SPARC General Assembly to decide on future directions for the activity.

Acknowledgements

We thank the Japan Society for the Promotion of Science (JSPS) KAKENHI Grant Numbers 24224011, 17H01159, JSPS Core-to-Core Program, B. Asia-Africa Science Platforms, and the UK Natural Environment Research Council (NERC) grant NE/P006779/1 (GOTHAM) for financial support that made the workshop possible, and WCRP/SPARC for providing travel assistance to five of the early career scientists who attended. Special thanks go to the staff of the Integrated Earth & Planetary Science Hub (IEPS Hub) of Kyoto University for local organization. We also thank the rapporteurs who provided notes on the workshop sessions: Nawo Eguchi, Syugo Hayashi, Laura Holt, Nithya K., Yoshio Kawatani, Ryo Mizuta, Muhsin Muhammed, Shigenori Otsuka, Remya R., Ravindra Babu Saginela, Masakazu Taguchi, Tetsuya Takemi, and Kohei Yoshida. Finally, we sincerely thank Richard Scott for giving an excellent workshop summary talk on the final day of the joint workshop.

References

Anstey, J., Hamilton, K., Osprey, S., Butchart, N. and Gray, L., 2015: Report on the 1st QBO modelling and reanalyses workshop, 16–18th March 2015, Victoria, BC, Canada. SPARC Newsletter 45, 19–25.

Anstey, J., Osprey, S., Butchart, N., Hamilton, K., Gray, L. and Baldwin, M., 2017: Report on the SPARC QBO Workshop: The QBO and its Global Influence – Past, Present and Future 26–30th September 2016, Oxford, UK. SPARC Newsletter 48, 33-41.

Butchart, N., *et al.*, 2017: Overview of experiment design and comparison of models participating in phase 1 of the SPARC Quasi-Biennial Oscillation initiative (QBOi). *Geosci. Model Dev. Discuss.*, doi:10.5194/gmd-2017-187, in review.

Geller, M., Chun, H.-Y. and Love, P., 2016: FISAPS – An Emerging SPARC Activity. SPARC Newsletter 47, 8-10.

Geller, M., Haynes, P., Son, S.-W., and Yoden, S., 2017: Report on the International Workshop on Stratosphere-Troposphere Dynamical Coupling in the Tropics 22-24 October 2015, Kyoto, Japan. SPARC Newsletter 48, 17-21.

Geller, M., Chun, H.-Y. and Love, P., 2017: Fine-Scale Atmospheric Processes and Structures. SPARC Newsletter 49, 10-20.

Glanville, A.A. and Birner, T., 2017: Role of vertical and horizontal mixing in the tape recorder signal near the tropical tropopause. *Atmos. Chem. Phys.*, **17**, 4337-4353, doi:10.5194/acp-17-4337-2017.

Hamilton, K., Osprey, S., and Butchart, N., 2015: Modeling the stratosphere's "heartbeat". *EOS*, **96**, doi:10.1029/2015EO032301.

Son, S., Y. Lim, C. Yoo, H.H. Hendon, and J. Kim, 2017: Stratospheric Control of the Madden–Julian Oscillation. *J. Climate,* **30**, 1909–1922, doi:10.1175/JCLI-D-16-0620.1.