Report on the 5th SPARC General Assembly
12-17 January 2014, Queenstown, New Zealand

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Beautiful Queenstown, New Zealand, was host to the nearly 300 scientists from around the globe that came together to participate in the 5th SPARC General Assembly from 12-17 January 2014. Usually held every four years, the six-year gap since the last General Assembly in 2008 meant that a lot has happened since SPARC had its last 'family reunion' in Bologna, Italy. SPARC's evolution has continued and its reach has extended to include aspects of the troposphere which have links with the stratosphere. This expanded focus was well reflected in the choice of the assembly themes and the science presented during the conference.

SPARC General Assemblies provide a platform to share research results, scientific ideas, and our passion for what we do. General Assemblies are also opportunities for SPARC to take stock of what has been achieved, where gaps in SPARC's research portfolio lie, and to define which areas SPARC needs to be moving into in order to remain responsive to the needs of both its members and the users of SPARC research products. All oral presentations were held in plenary, *i.e.* without parallel sessions, and were divided into six themes, namely: 'Emerging and outstanding research of relevance to SPARC'; 'Atmospheric chemistry, aerosols, and climate'; 'Stratosphere-troposphere-ocean dynamics and predictability of regional climate'; 'Coupling to the mesosphere and upper atmosphere'; 'Observational datasets, reanalyses, and attribution studies'; and 'Tropical Processes'. Each of the latter five themes had a dedicated poster session and, as is SPARC tradition, particular emphasis was placed on these sessions since they provide an unparalleled opportunity for in-depth discussions and scientific exchange at all levels. As a novelty, 45 minutes were allocated for poster presenters to give a one-minute overview of the main highlights of their work. This solicited a great response with some very creative performances and was very well received by all.

Most of the oral presentations and all abstracts are available online and can be downloaded from: **http://www.sparc-climate.org/meetings/general-assembly-2014/#c1122**. A selection of photos taken during the assembly can be viewed on the same website. The following report is a summary of some of the highlights from each of the six themes.

Emerging and Outstanding Research of Relevance to SPARC

The opening session on Sunday 12 January focused on emerging and outstanding research of relevance to SPARC's new mandate encompassing stratospheric and related tropospheric processes of importance to climate science.

The General Assembly began with an opening lecture by **Jerry Meehl** who presented an overview of the projections and predictions in the IPCC 5th Assessment Report (AR5), highlighting progress since the **4th** Assessment Report (AR4). He emphasized that the models have improved with respect to their simulation capabilities. Of the more than 40 models that participated in CMIP5 (Coupled Model Intercomparison Project Phase 5), around 14 were 'high top'

Figure 1: Participants of the 5th SPARC General Assembly held in Queenstown, New Zealand.

models with a resolved stratosphere and several were Earth System Models (ESMs) including aerosols and interactive tropospheric and/or stratospheric chemistry. Time-varying stratospheric ozone was used, constituting a substantial improvement since AR4 where half of the models prescribed a constant climatology. As a result, AR5 concluded that there is robust evidence that the representation of climate forcing by stratospheric ozone has improved since AR4. Jerry finished his talk with an outlook on the CMIP6 (Coupled Model Intercomparison Project Phase 6) experimental design (Meehl *et al.*, 2014) that is open for discussion until September 2014. The specific experimental design would be focused on three broad scientific questions on (1) systematic biases; (2) response to forcings; and (3) variability, predictability, and future scenarios. With an invited talk on recent advances in understanding cloud feedbacks, **Steven Sherwood** linked to the new SPARC focus on including tropospheric processes. He showed that many aspects of the cloud response in GCMs are consequences of relatively well-understood changes in general circulation patterns, with the deepening of the troposphere and the poleward shift of storm tracks particularly of relevance to SPARC. Models still have problems in simulating low-cloud cover but he showed new results that offer a likely explanation for the observed inconsistency among models. He finished his talk by providing recommendations for how SPARC could contribute to help answering questions in this research area, highlighting in particular the role of dynamics, the stratosphere, and the Tropical Tropopause Layer (TTL) in cloud control and cirrus cloud feedbacks.

WCRP and WWRP have recently initiated research and prediction projects on polar climate. One of these, the Polar Climate Predictability Initiative is co-led by **Ted Shepherd**, who gave an invited talk on this topic. Ted pointed out that the polar amplification of climate change and rapid melting of Arctic sea-ice contrasts with the Antarctic where sea-ice has slowly increased in area. The maximum Arctic melting in autumn gives rise to a seasonality in the rate of change, with a corresponding maximum in Arctic warming rates. The consequences of this for coastal impacts, including ecosystems, are just beginning to be understood as impacts emerge. Arctic amplification of anthropogenic warming due to the albedo feedback and other effects has long been seen in climate models and gives rise to great consistency between models compared to changes in many other regions of the globe. However, there is still uncertainty, particularly around Antarctic changes, and Ted noted that the ozone hole and associated circulation changes may be involved in the hemispheric asymmetry in recent trends. He also noted that internal variability is high at the poles and that stratosphere-troposphere interaction is a key element of this variability, acting through the North Atlantic Oscillation/Arctic Oscillation and Southern Annular Mode (SAM). Some of these processes are well reproduced in models, for example, the response of surface climate to sudden stratospheric warmings is simulated in several models. This link may also be involved in prominent long-term variability of polar climate on decadal timescales and a few studies are now suggesting it has a role in climate change. Ted noted that ultimately, it is improvement in the Arctic process modelling such as in the Arctic boundary layer that will resolve current uncertainty and provide better predictions.

Continuing the theme of interaction between the SPARC community and tropospheric climate science, **Christian Jakob** gave his insights in an invited talk on 'Long Standing Errors in Climate Models'. After pointing out that both climate and weather predictions are based on the same core models, he presented the great progress made in improving accuracy of weather forecasts and the significant increase in complexity of climate models over recent decades. He also showed evidence that surface climate is reproduced with greater fidelity in the latest CMIP5 models compared to earlier generations of models. However, in stark contrast to these improvements, the hydrological aspects of models connected to cloud radiative properties in particular have shown little progress and still represent a great source of model spread. He highlighted a recent intercomparison of aqua planet simulations where even the response to warming was not qualitatively similar across models due to different mean model biases. All of this also projects onto atmospheric circulation and regional model biases. He advocated application-, phenomenon-, and process-based analyses of models to reduce model error and urged the community to put more effort into this important underpinning task.

Dian Seidel returned to the stratosphere, but with an eye on the troposphere, to discuss temperature trends in an invited talk. She gave a historical perspective of work over the last few decades, starting with seminal works using 1D models on the radiative-convective effects of increasing greenhouse gases and then continuing to demonstrate the importance of the radiosonde network in identifying sources of stratospheric temperature variability from the Quasi-biennial Oscillation (QBO), El Niño-Southern Oscillation (ENSO), and volcanoes, for example. Dian highlighted the uncertainties in trends from both sondes and satellite datasets and the difficulties of stitching together records from different instruments, including the recent uncertainty over satellite data processing methods, which is now being revisited. She also discussed other sources of observations and pointed out that reanalysis datasets are not necessarily the answer as they contain very different stratospheric temperature trends. Intriguingly, the expected cooling of the stratosphere is not linear in time and may even occur stepwise in relation to volcanic eruptions, however, all of this occurs on a background of complex instrument errors that are not stationary in time.

In the final invited talk of the day, **Robert Sausen** provided an overview of the impact of aviation on atmospheric composition and climate. He showed that the non-CO_2 climate effects from aviation are large in comparison to the CO_2 effect, in particular as a result of the triggering of new clouds or modification of existing clouds, as well as the emission of nitrogen oxides that produce tropospheric ozone and reduce methane. He also emphasized that emissions from aviation are increasing particularly fast, and faster than the sum of all anthropogenic impacts. Research is underway to study whether aviation impacts can be reduced by changing the location and time of emissions, *i.e.* by climate optimized flight trajectories.

Atmospheric Chemistry, Aerosols, and Climate

Atmospheric composition is an area where SPARC has been very active in its efforts to emphasize stratospheric links to the troposphere. Together with the International Global Atmospheric Chemistry (IGAC) programme, SPARC has sponsored both the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) (Lamarque *et al.*, 2013) and, more recently, the Chemistry-Climate Model Initiative (CCMI) (Eyring *et al.*, 2013). The IGAC/SPARC CCMI is a merge of ACCMIP and the SPARC Chemistry-Climate Model Validation (CCMVal) activity, expanding the goals and deliverables of CCMVal to include tropospheric chemistry-climate. CCMI not only brings together the tropospheric and stratospheric modelling communities, but also entrains scientists working on atmospheric composition measurements and data analysis. Many presentations in the 'Atmospheric Chemistry, Aerosols, and Climate' session emphasized the bringing together of observations and models in new ways.

Combining theory and observations was a theme of **John Pyle**'s SPARC lecture. Bringing together a mixture of measurements, climate model simulations, and trajectory model calculations, John showed the progress that has been made in narrowing the emissions estimates of very short-lived species (VSLS; *e.g.* bromoform), and understanding their impact on the atmosphere, while highlighting the need for a greater spatial coverage of observations to make more progress.

Using the best estimates for VSLS emissions, model calculations suggest that VSLS contribute about 25% (5pptv) of total stratospheric bromine, contributing a 20% reduction in lower stratospheric ozone in the Southern Hemisphere. With the caveat that little is known about how VSLS emissions might evolve, a future increase in their emissions could slow, but not prevent, ozone recovery.

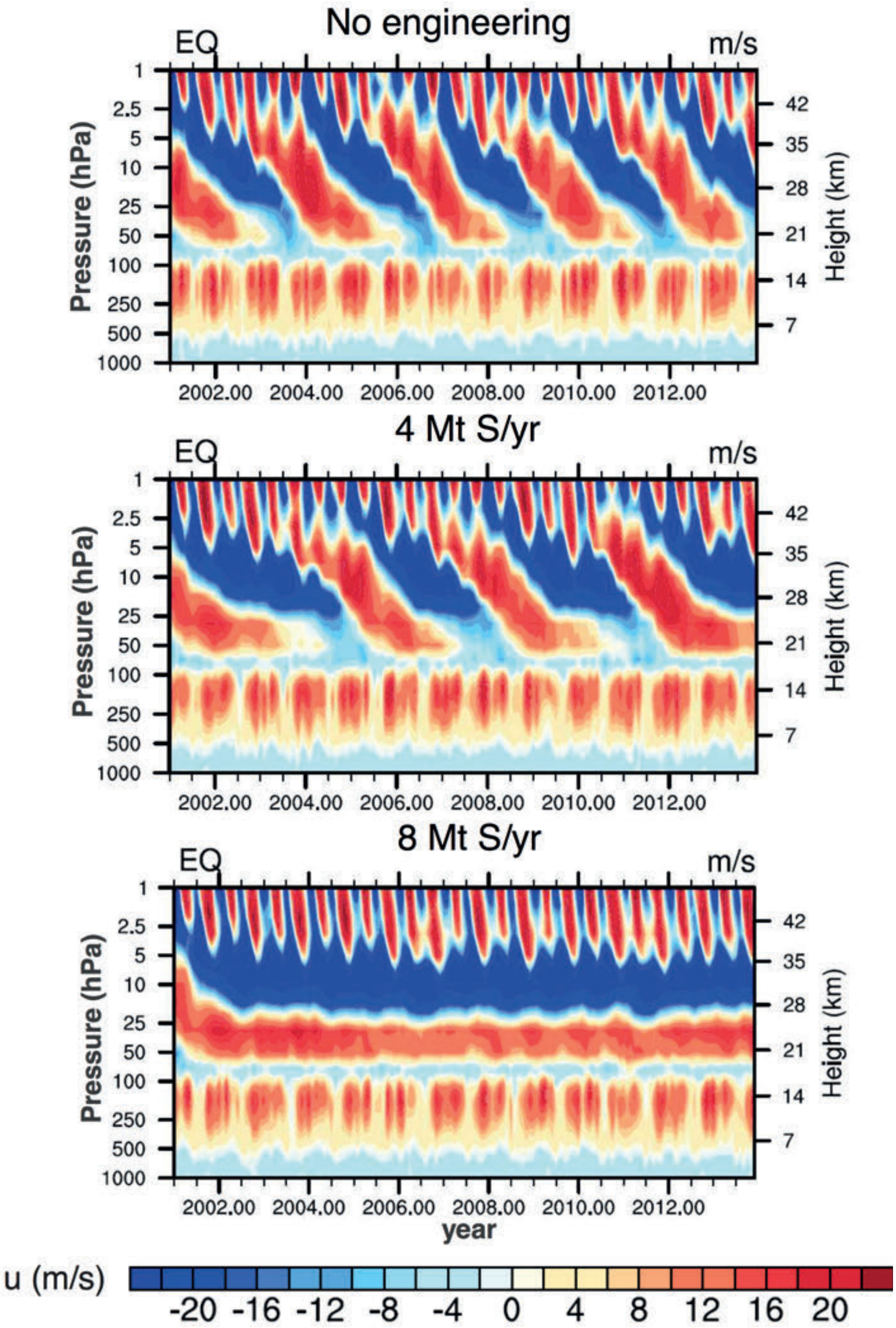
Changing tack, John also presented some chemistry-climate model (CCM) calculations probing the individual effects of the drivers of climate and composition change. The results support the conclusions drawn from recent studies (*e.g.* ACCMIP): through the expected ozone recovery and changes in stratospheric circulation, stratospheric changes will significantly impact tropospheric changes. On this theme, **Jessica Neu** presented a new way to use natural variability in stratospheric and tropospheric ozone arising from the QBO/ENSO to validate stratosphere-troposphere exchange in CCMs. Using several years of satellite observations, Jessica showed that the stratospheric ozone column variability associated with QBO and ENSO explains 16% of the variance in northern hemisphere mid-latitude ozone at 500hPa, and that a 25% increase in stratospheric ozone is associated with a 2% increase in tropospheric ozone. This analysis will be applied to an ensemble of CCMs in the CCMI activity.

Stratospheric changes and links to climate trends and variability was a theme of several presentations. Motivated by the huge Arctic ozone loss in 2011, **Ulrike Langematz** presented model calculations examining projections of future Arctic ozone. The results show that an increased volume of polar stratospheric clouds (PSCs) in early winter, driven by stratospheric cooling, is countered by late spring increases in dynamically driven heating. While individual depletion events could not be ruled out, the calculations suggest no tendency towards more Arctic ozone holes in the future. **Thomas Reichler** discussed temperature-composition feedbacks in an Antarctic context, presenting model calculations showing that Antarctic climate variability has increased by 80% in the stratosphere and 5% in the troposphere due to ozone depletion and the associated photochemical, dynamical, and climatic feedbacks. **James Keeble** isolated the role of Antarctic ozone depletion by "switching off" halogen activation on PSCs in his model. As well as highlighting well-established stratospheric and tropospheric climate signals, the simulations suggest that Antarctic ozone depletion drives more polar downwelling in austral summer, highlighting the potential role for ozone depletion in seasonal trends in the Brewer-Dobson circulation.

Untangling the complexity of composition-climate feedbacks further, **Fiona Tummon** talked through determining the lifetimes of ozone depleting substances (ODSs) in a changing atmosphere, important for quantifying their ozone depletion potential and climate impact. The net effect of changes in climate and ODS emissions is to shorten CFC and HCFC lifetimes by 1-4%, although the climate and emission impacts are of opposite sign for each group of compounds. The lifetimes and properties of shorter-lived compounds (*e.g.* ozone, methane, aerosols) are of particular interest for climate as they are earmarked for near-term climate change mitigation, and near-term climate forcers (NTCFs) was the subject of the invited talk by **Bill Collins**. Due to their short lifetime and decadal-scale climate impacts, NTCFs impact the climate in a spatially non-uniform manner, and there are significant challenges in relating the regional climate response to the regional forcing.

Several talks discussed the impacts of aerosols on climate. Using an array of satellite data, **Graeme Stephens** used his invited talk to describe how a cloud's albedo responds to aerosol through several buffering processes, with the net effect being described by the changes in the cloud's water budget. Perhaps counter intuitively, higher model resolution will not guarantee improved representation of these aerosol effects. **Jason English** showed that describing the aerosol size distribution with a sectional model (as opposed to modal) improves the representation of aerosol evolution after volcanic eruptions. Due to particle size growth, it seems that very large eruptions have self-limiting radiative forcing. For example, despite injecting 100 times more sulfur than Pinatubo, the Toba eruption only had 20 times the effect on aerosol optical depth. Using the same model, **Ryan Neely** demonstrated the major contribution of recent smaller volcanic eruptions to stratospheric aerosol variability, dwarfing the more localized impact of increased Chinese and Indian emissions. In a similar vein, **Chao Li**'s climate model analysis suggested that the recent upward trend in stratospheric aerosol does not help explain the "hiatus" in the global mean surface temperature trend, pointing instead to a negative phase of the Arctic Oscillation. Stratospheric aerosols are often mooted as a mechanism for climate geoengineering,

Figure 2: Does the QBO disappear following geoengineering? Profile time series of zonal mean wind showing lengthened periods of QBO stalling associated with an increased rate of sulfur injection. Results taken from the ECHAM5/HAM chemistry-climate model presented by Hauke Schmidt (from Niemeier *et al.*, in prep.), confirming the results of Aquila *et al.*, 2014).



including in **Hauke Scmidt**'s invited presentation summarizing GeoMIP (the geoengineering model intercomparison project; Kravitz *et al.*, 2013), as a potential method of solar radiation management (SRM). Particular attention was given to the hydrological cycle, and it was shown that SRM overcompensates for the precipitation increase due to higher CO_2. In addition, early results from one model suggest the possibility of destroying the QBO through SRM by increasing stratospheric sulfate aerosols (**Figure 2**).

Stratosphere-troposphere-ocean Dynamics and Predictability of Regional Climate

Dynamics and predictability go hand in hand, and, with SPARC's recent extension into the troposphere, now more than ever. Accordingly, the dynamics session encompassed a broad array of topics, touching on the whole coupled atmosphere-ocean-ice system.

Doug Smith opened the session with an enlightening SPARC lecture on the role of the stratosphere in seasonal to decadal prediction, an area of active and vibrant research. He first outlined the potential sources of skill, including stratospheric warmings, solar variability, and the QBO, as well as traditional tropospheric and surface sources with which the stratosphere is interconnected. After discussing the difficulties inherent in making predictions, he highlighted the promising skill in monthly predictions of the North Atlantic Oscillation and five-year predictions of North Atlantic surface temperatures and storms. With the latest forecasts suggesting cooling in the Atlantic, wet winters and dry summers could be ahead for Europe. Continuing the prediction theme, **Seok-Woo Son** discussed the role of the stratosphere in regional surface prediction in the Southern Hemisphere, asking the question of whether interannual Antarctic ozone variability leads to any significant surface impacts. After removing the slowly varying component of ozone changes, which are primarily due to ODSs, a significant impact of Antarctic stratospheric ozone concentrations in September was found on the Southern Hemisphere surface climate in October. Low ozone years correspond to cooler temperatures over the Antarctic Peninsula, southern South America, and Australia, as well as increased rainfall over Australia (**Figure 3**).

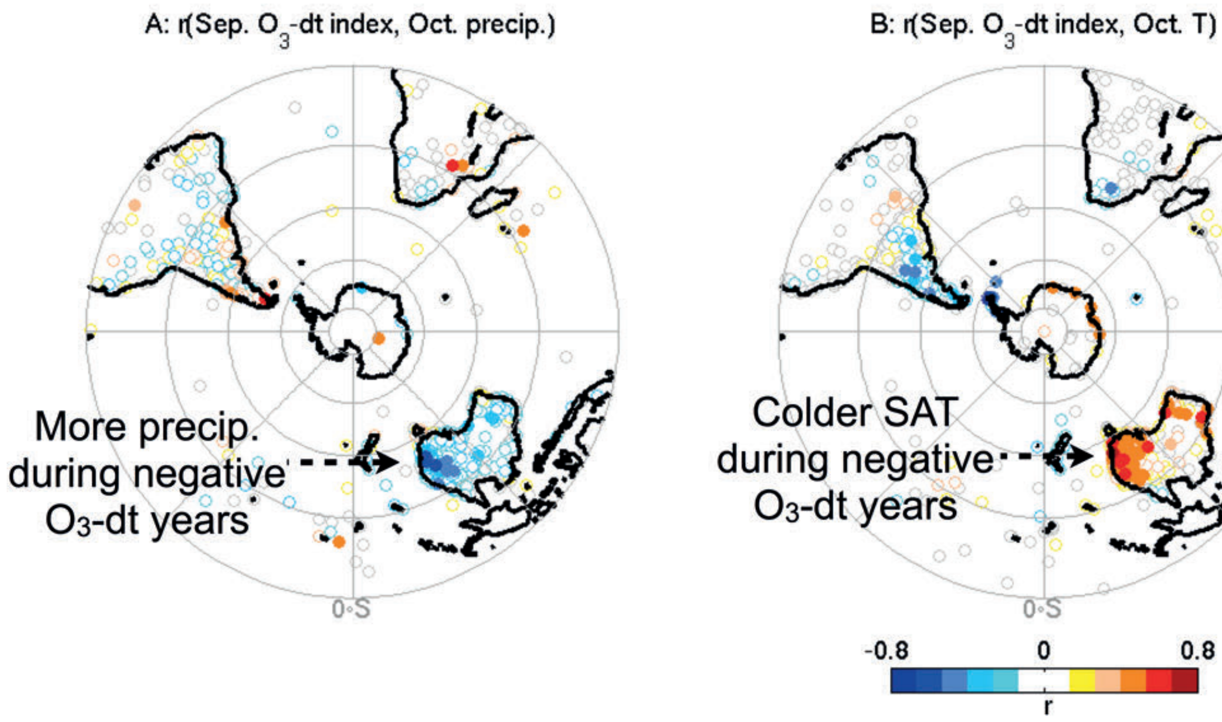


Figure 3: Lag correlation maps between the September O3-dt index and October CRU (A) precipitation, and (B) daily mean temperature. Only stations with data availability of at least 75% of the analysis period are used. The correlation coefficients that are statistically significant at the 95% confidence level are shown by filled circles. A two-tailed t-test is used to test significance. (Figure from: Son *et al*., 2013).

These impacts are comparable in magnitude to those linked with ENSO, suggesting potential for improvement in seasonal prediction for these regions during austral spring. Also focusing on the Southern Hemisphere, **Damian Murphy**, evaluated inertial gravity waves over the polar stratosphere in radiosonde observations at Davis station, Antarctica. Both up- and down-going waves were found in approximately equal number, which cannot be easily explained by a tropospheric source. This suggests that inertial gravity waves over Antarctica are formed from a source process distributed throughout the stratosphere, a source not currently included in models.

Stratosphere-troposphere intraseasonal dynamical coupling was the focus of the next three presentations. **Tiffany Shaw** gave an invited talk on the myriad of possibilities through which tropospheric and stratospheric dynamical variability couple on intraseasonal timescales. She highlighted the importance of both planetary- and synoptic-scale waves, and of both wave absorption and reflection. She then discussed the role of Atlantic sector variability in the generation of sub-polar extreme heat flux events in reanalysis data. Comprehensive general circulation models with biased representations of North Atlantic tropospheric circulation also have biased representations of extreme sub-polar heat flux events. As these events can then subsequently impact the North Atlantic circulation, it can be very difficult to isolate causality without carefully constructed model experiments. **Mark Baldwin** discussed mechanisms for the downward coupling of stratospheric variability to the troposphere. Motivated by the linearity of the tropospheric response to opposite phases of stratospheric variability and by the large surface polar response to stratospheric anomalies, he discussed the ability of stratospheric potential vorticity (PV) anomalies to modulate tropopause height. Specifically, the stratospheric polar column can expand downwards and physically compress the tropospheric polar column, and hence directly modulate winds and temperatures in the polar troposphere. The eventual surface response is stronger than can be explained by this mechanism, but this mechanism may be responsible for the initial downward coupling. Finally, **Amy Butler** discussed the definition of stratospheric sudden warmings (SSWs). After noting the lack of consensus in early literature regarding the definition, and mentioning the nearly ten different classes of definitions of SSWs that exist in the recent literature, she highlighted the importance of an accepted definition in order to robustly assess, for example, whether SSW frequency will change in future or whether decadal variability of SSW frequency occurs. She finished her talk by discussing ongoing efforts towards formulating a new, robust definition that can easily be applied to a wide range of models in both the current and future climate (see more about this in a separate article on page 23).

Ed Gerber gave an invited talk on the Brewer Dobson Circulation (BDC). After demonstrating the importance of waves for the conservation of momentum associated with the BDC, he noted that comprehensive CCMs disagree on the type of wave that is most important for this momentum conservation. Specifically, the wave sources are traditionally broken down into resolved waves, orographic gravity waves, and non-orographic gravity waves, but models agree better on the overall strength of the wave-driving than on the contribution from each of these three sources. In order to resolve this conundrum, he presented idealized general circulation model experiments in which nearly identical total BDCs are maintained by vastly different balances between gravity waves and resolved waves in a controlled environment in which gravity waves are modulated. These nearly identical BDCs occur because of compensation between the waves' sources, which is necessary in order to maintain a stable potential vorticity profile in the stratospheric surf zone. Hence inter-model differences in the waves responsible for the BDC likely do not reflect gaps in our understanding of the BDC, but rather model tuning differences.

After breaking for posters, the session continued its theme of extending from the stratosphere into the troposphere and ocean with two talks on the impacts of Antarctic ozone depletion on the climate system. In an invited lecture, **Cecilia Bitz** provided compelling arguments for why ozone depletion cannot be causing the recent observed increase in Antarctic sea-ice extent. Though there is a clear positive correlation on interannual timescales between the position and strength of the mid-latitude westerlies and sea-ice extent, modelling evidence suggests that the multi-decadal strengthening of these winds due to ozone depletion leads to a decrease in sea-ice extent. She outlined the different mechanisms controlling these fast and slow responses to the wind changes, with the slow response being dominated by enhanced upwelling of warmer waters from below, which increase sea surface temperatures and melt sea-ice. Her talk ended with a cautionary note suggesting that debate on this topic is still continuing. Turning to the impact of these strengthening winds on the ocean, **Darryn Waugh** presented observational evidence for an increase in subtropical ocean ventilation in the Southern Ocean over recent decades. Using measurements of CFC-12, he found an increase in the age of subtropical mode waters and a decrease in the age of circumpolar deep mode waters at similar depths. The changes observed are consistent with theoretical expectations and can be reproduced by models driven with increases in surface westerlies. Open questions remain though, such as what impact these changes may have on oceanic uptake of heat, freshwater, carbon, and nutrients.

The response of the surface westerlies, and in particular of the SAM, to volcanic eruptions was explored by **Kristin Kruger**. Theory suggests that volcanic eruptions in winter should lead to a positive phase of the SAM (increased mid-latitude and decreased polar cap sea level pressures) in the following winter/spring. However, observations and model simulations of recent eruptions show little signal in the SAM and, if anything, the opposite response. Through a variety of sensitivity studies, it was suggested that an injection of >190 mega tonnes of SO_2 was required to show a significant response in the surface SAM, more than ten times larger than that injected by Mt Pinatubo.

The session ended with two talks focused on the Northern Hemisphere. **Kazuaki Nishii** described the relationship between blocking highs and planetary waves, finding a geographical dependence in their interaction. Blocking over North America, the Atlantic, and Europe tends to enhance upward planetary activity, warming the polar stratosphere, while blocking over Asia and the western Pacific tends to suppress planetary activity and cools the stratosphere. Finally, **Alexey Karpechko**, discussed the impact of the large 2011 Arctic ozone loss on tropospheric circulation patterns. While a strong positive phase of the Northern Annular Mode was found, as might be expected from the ozone changes, their experiments suggest that this large dynamical signal occurred primarily through pre-conditioning from sea surface temperatures rather than being driven by the ozone loss itself. A special mention is given here to the session's poster prize winner, **Masashi Kohma**, whose clear and comprehensive analysis of satellite data determined that the frequently simultaneous occurrence of polar stratospheric clouds and upper tropospheric clouds in the Southern Hemisphere is caused by blocking highs.

Coupling to the mesosphere and upper atmosphere

This session was dedicated to coupling processes between the stratosphere-troposphere (ST) and the mesosphere-lower thermosphere (MLT). An example of such coupling occurs through solar variability, which influences both systems in upward and downward directions. Total solar variability has significant impacts on regional climate, and ultraviolet variability changes ozone heating and chemistry in the middle atmosphere. Such changes modify the generation and upward propagation of atmospheric waves, including gravity waves, planetary waves, and tides. Energetic particle precipitation (EPP) from the solar wind and Earth's magnetosphere is another indication of solar influence on the climate. EPP affects ozone chemistry in the stratosphere through the production of NO_x.

In an invited lecture, **Bernd Funke** reviewed current knowledge and future issues for such solar influences on the climate. He introduced recent progress in observations of the change in spectral solar irradiance and in possible EPP estimates through observations of NO_y and OH. He also emphasized the usefulness of ESMs that offer the opportunity to perform sensitivity experiments studying interactions between solar variability and other forcing factors such as the solar-QBO relation, North Atlantic air/sea coupling, the tropical Pacific signal, and ENSO aliasing. **Anne Smith** (invited talk) also discussed coupling processes between the ST and MLT in addition to solar impacts. SSWs and the elevated stratopause events that sometimes occur subsequent to SSWs seem to enhance downward NO_x transport from the MLT. Non-migrating tides dominant in the MLT are excited by tropospheric convection, but in turn, wave propagation and dissipation can be modified by changes in MLT dynamical fields. She also discussed the predictability of the MLT by various nudging experiments using the WACCM model. She showed that the MLT system is not completely deterministic, although ST impacts on the MLT are large. Potential sources of error include expressions of wave generation from instability, gravity waves, and stratospheric variability. This means that continuous observations of the MLT region are needed.

The important role that small-scale gravity waves play in middle atmosphere coupling has been well recognised. As gravity waves are generally too small to be resolved in general circulation models, their effects need to be parameterized. However, global observations of gravity waves are required to improve these parameterizations. **Robert Vincent** characterised gravity wave properties such as momentum flux and phase speeds in the lower stratosphere using super-pressure balloon measurements at high southern latitudes. It was emphasized that in the zonal mean non-orographic gravity waves are as important as orographic gravity waves. **Charles McLandress** quantified gravity wave drag in the CMAM model and compared these results to MLS satellite observations. Results indicated the important role of orographic gravity wave drag prior to major mid-winter SSWs in the Arctic. Continuing the focus on Arctic SSWs in her invited talk, **Gloria Manney** used satellite observations of recent Arctic SSWs to clearly indicate the coupling between atmospheric regions. In particular, the impact of these events on dynamics and trace gas transport throughout the middle atmosphere was elucidated. The interannual and decadal variability of SSW dynamics and minor constituents were also presented.

Wednesday afternoon being free, the theme on coupling to the mesosphere and upper atmosphere had slightly fewer oral presentations but a wide variety of very interesting posters. Some highlights include the following. **Manfred Ern** illustrated that critical-level filtering is the main QBO-related dissipation process for gravity waves, and that enhanced gravity wave drag is observed directly above decaying summer-time mesospheric westward jet instabilities. **Takenari Kinoshita** reported on the tidal periodicity of gravity waves in the mesosphere above Alaska, suggesting that the observed 12-hour phase agreement between the zonal wind and gravity wave kinetic energy is a result of gravity wave dissipation on the tidal field. To look at gravity waves more closely, **Ronald Smith** presented an upcoming experimental project to examine gravity wave generation and propagation above New Zealand. Gravity-wave resolving, high-resolution GCMs also provide a useful tool to examine the dynamics of the middle atmosphere. Using such data, **Takatoshi Sakazaki** showed that dominant non-migrating diurnal tides, DE3 and DW5, are interpreted as inertia-gravity waves excited by convection distributed over the African and American continents (**Figure 4**). The structure and time variation of phases were consistent with satellite observations which cover limited height ranges.

Dieter Peters showed long-term variability of the extra-tropical mesosphere where a strong correlation with the stratospheric QBO was found. **Peter Hitchcock** showed that under a doubling of

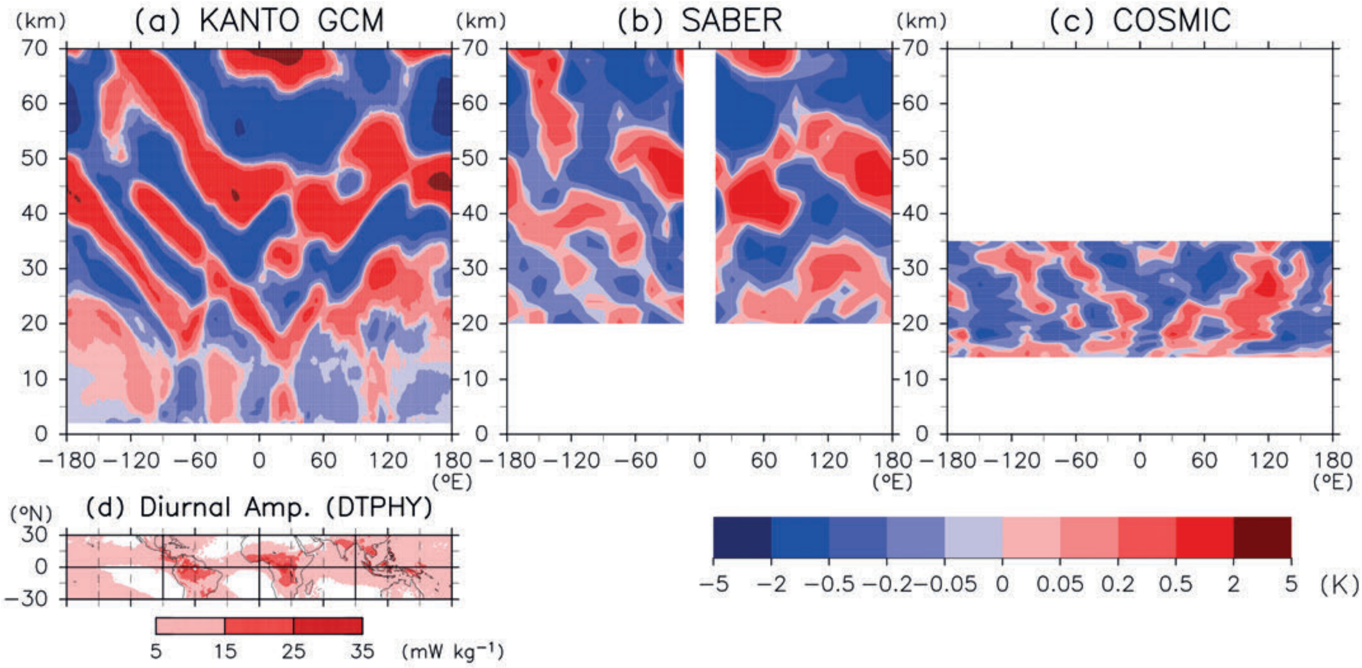


Figure 4: Longitude-altitude section of the annual-mean temperature component of non-migrating tides at 1200UTC averaged for 10°S-10°N, from (a) a high-vertical resolution GCM (KANTO) simulation, (b) SABER observations, (c) COSMIC observations, and (d) latitude-longitude section of annual-mean amplitude of the diurnal harmonic component of diabatic heating averaged for heights of 5-14km from the KANTO model. Both migrating and non-migrating components are included for (d). (Figure from: Sakazaki *et al.*, in prep.).

CO_2, radiative damping is projected to strengthen by 10-30% through most of the stratosphere, which will have an effect on large-scale stratospheric phenomena, including the waves which drive the QBO and recovery from SSWs. Radiosondes and CMIP5 models indicate that the QBO amplitude has weakened in the lower stratosphere in the second half of the 20th century (**Yoshio Kawatani**), providing support for a long-term trend of enhanced upwelling near the tropical tropopause. **Sebastian Schirber** demonstrated a realistic QBO using purely convection-based gravity wave parameterization in the ECHAM6 GCM.

Finally, **Kota Okamoto** examined barotropic/baroclinic instability in the upper mesosphere using high-resolution GCM data. The anomalous latitudinal PV gradient frequently observed in winter is attributable to the poleward shift of (resolved) gravity wave drag in association with the stratospheric jet shift. Large longitudinal dependence of the anomalous PV latitudinal gradient was also indicated.

Observational datasets, reanalyses, and attribution studies

Observations of the meteorology and composition of the atmosphere and their spatial and temporal variability are essential to advancing our understanding of Earth's climate system and its response to natural and anthropogenic changes. In particular, comprehensive long-term records underpin reliable assessment of climatological behaviour, attribution of trends, and evaluation of the risks of extreme climate anomalies and events. **Karen Rosenlof** opened the session with a SPARC lecture exemplifying this theme. Her talk illustrated how measurements of key quantities such as water vapour, ozone, and temperature can be used to study the stratospheric mean meridional circulation, commonly referred to as the BDC, which cannot be measured directly but is inferred from constituent observations. After a historical overview summarizing how measurements of trace species elucidated mass transport in the stratosphere, she highlighted the abrupt ~2°C drop in zonally averaged temperatures observed at the tropical cold point at the end of 2000. This was associated with a change in the strength of the BDC near the tropical tropopause, and she further discussed the significant impact that these changes may have had on climate. She ended the talk by noting that much is still to be learned about variability in the BDC, and that continued global observations of stratospheric trace gases and temperature are critically important if we are to accurately predict how stratospheric circulation will respond to changes induced by greenhouse gases (GHG) or solar radiation management.

Three talks examined long-term ozone datasets. **David Tarasick** presented a homogenized record of Canadian ozonesondes from 1996 to 2012 and showed that interannual variability and long-term changes in free tropospheric ozone are correlated with those in the lower stratosphere, suggesting that tropospheric ozone concentrations over mid-latitude sites in Canada are strongly influenced by stratospheric intrusions. **Richard Stolarski** analysed 36 years of Solar Backscatter UltraViolet (SBUV) satellite measurements derived from several instruments using a common data processing algorithm in which ozone amounts are retrieved in broad upper and lower stratospheric layers. In the upper stratosphere, the SBUV data showed an upward trend in ozone in addition to that attributable to ODSs, consistent with the fact that GHG-induced cooling slows ozone loss in that region. In the lower stratosphere, the data indicated decreases in ozone at all latitudes, contrary to the expectation that changes in circulation strength would lead to increases in ozone at middle and high latitudes; thus no signature of circulation speed-up was detected in the SBUV data. In an invited talk, **Mark Weber** also explored the coupling between chemical and dynamical effects on ozone and the impact of variability and trends in the BDC on detection of ozone recovery. Using satellite total ozone observations in both hemispheres from the merged GOME/SCIAMACHY/GOME-2 dataset (1995–2010), he found a compact linear relationship between the winter-mean extra-tropical 100hPa eddy heat flux (a measure of BDC strength) and the ozone spring-to-fall ratio (**Figure 5**); that a similar relationship is seen in chemistry climate models suggests that current models realistically describe stratospheric circulation variability and its effect on total ozone. Future changes in the modelled relationship indicate a shift from ODS-related ozone recovery to a regime in which GHG changes dominate in the second half of the 21st century. While positive ozone trends in the upper stratosphere (40–45km) derived from satellite limb measurements over the last decade may be indicative of recovery, negative ozone trends in the tropical middle stratosphere (30–35km)

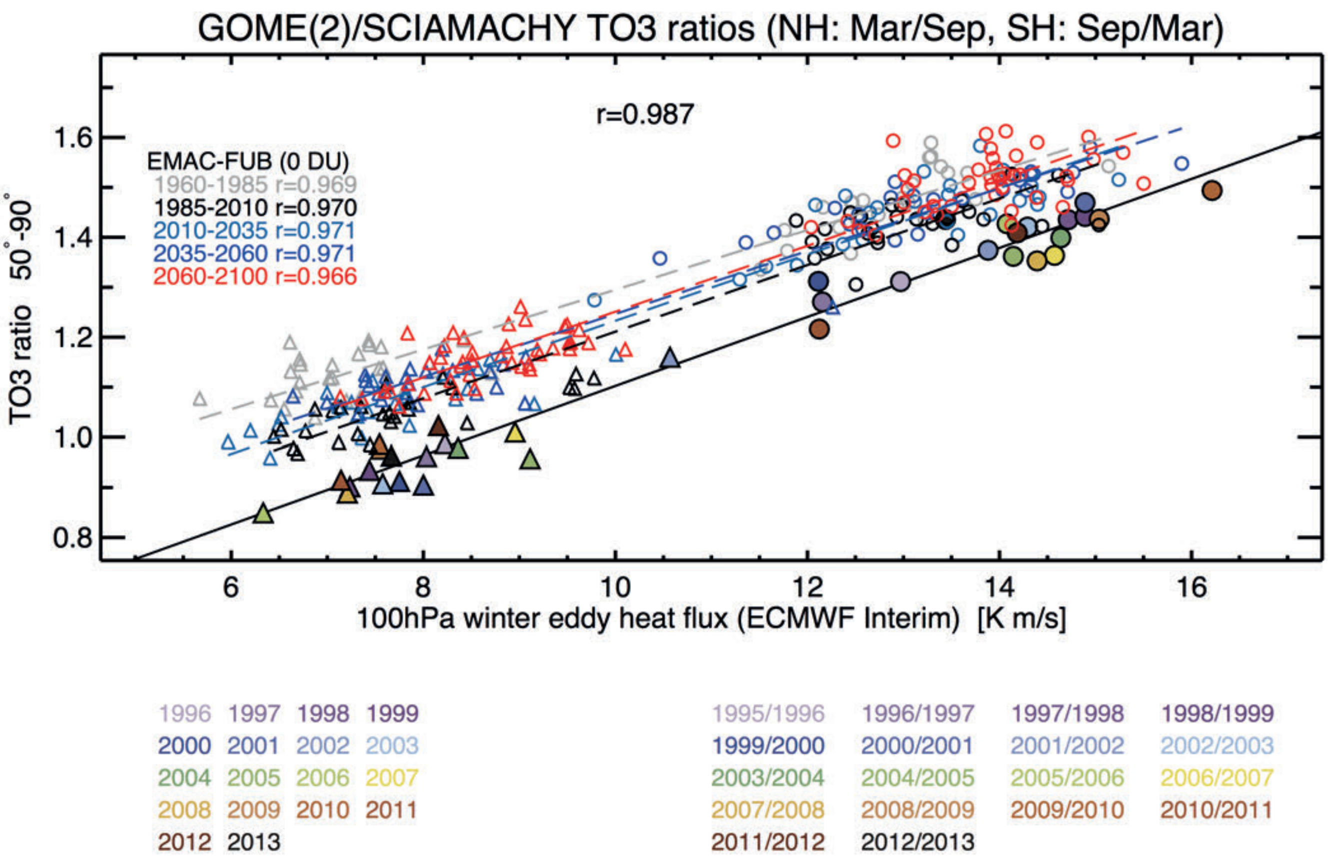


Figure 5: Spring-to-autumn ratio of polar cap total ozone as a function of absolute extra-tropical winter mean eddy heat flux for both GOME2/SCIAMACHY and the EMAC-FUB model. Southern hemisphere data is shown using triangles, the northern hemisphere with circles. The different colours correspond to different periods/years. (Figure updated from: Weber et *al*., 2011).

are possibly linked to changes in NO_x. In another talk based on satellite observations, **Gabriele Stiller** reported on the status of the SPARC Water Vapour Assessment II (WAVAS II) initiative, which will provide an intercomparison and quality assessment of satellite water vapour datasets, with the ultimate aim of producing a consistent multi-instrument data record covering the last 30 years.

Meteorological analyses were the focus of two presentations. **Gilbert Compo** gave an invited talk on developing the 20th Century Reanalysis version 3 (20CRv3); an international project to produce global states of the atmosphere, land, and ocean spanning the period from 1850-2013 using an Ensemble Kalman Filter and assimilating only surface pressure observations. The previous version of the historical reanalysis (20CRv2), which provides near-surface to tropopause, 6-hourly fields at 2-degree spatial resolution as well as estimates of the dataset's time-varying quality, is useful for a broad range of climate applications. These include validating climate models, determining storminess and storm track variations over the last 150 years, understanding historical climate variations, and estimating risks of extreme events. 20CRv3 improvements include higher spatial resolution, a better-resolved stratosphere, increased observational density, and a companion ocean reanalysis.

Masatomo Fujiwara performed multiple linear regression analysis on monthly-mean zonal-mean temperature from nine atmospheric reanalyses to investigate the global climate response to major volcanic eruptions over the 1958–2009 period. Most reanalyses showed statistically significant warming in the tropical lower stratosphere following the eruptions of both Pinatubo and El Chichón, but only the Pinatubo eruption produced significant cooling in the tropical troposphere; the response to the eruption of Mt. Agung was asymmetric about the equator, with warming in the Southern Hemisphere mid-latitude upper troposphere/lower stratosphere (UTLS).

Finally, **David Karoly** closed the session with an invited review that underscored the necessity for both high-quality long-term observational datasets and reliable climate model simulations in trend detection and attribution studies. Such studies have allowed quantification of the anthropogenic contribution to observed changes in annual global mean surface temperature. Compared with the surface and troposphere, fewer detection and attribution studies have been applied to the role of the stratosphere in recent climate changes because limitations in observational and modelling datasets and large internal variability complicate attribution of stratospheric changes. Examples shown include attribution of observed trends in lower stratospheric temperature and springtime tropospheric zonal wind in the Southern Hemisphere to Antarctic ozone depletion.

Tropical Processes

Tropical processes are an important component of UTLS studies since the tropics act as a gateway to the stratosphere. Future climate change is expected to change boundary conditions for transport and chemistry in this region and, for example, influence the Indian and Asian monsoons. The session included ten oral presentations, four of which were invited, and a number of posters. In an invited talk, **Masakazu Taguchi** examined aspects of tropical and extra-tropical connections associated with the QBO, modulation of the QBO especially by ENSO, and effects of the QBO and ENSO on the northern hemisphere winter stratosphere. He showed that frequency or probability of major stratospheric sudden warmings (MSSWs) show non-linear changes with ENSO and QBO and emphasized that understanding the mechanisms responsible for these effects will be a challenge.

Ji-Eun Kim presented a new wave scheme for trajectory modelling of stratospheric water vapour. A consequence of the exponential dependence on saturation mixing ratios with temperature is that realistic representations of temperatures in reanalysis datasets are critical to dehydration simulations. The new scheme results in enhanced wave amplitudes of those currently under-represented in reanalyses, thereby maintaining wave variability that would otherwise be absent. This has important implications for improving tropopause temperatures and saturation processes along trajectories in the tropical tropopause layer.

Erik Johansson examined how the vertical structure in cloud radiative heating is related to Indian monsoon activity using five years of CALIPSO and CloudSat data. The heating contribution is greatest for high clouds followed by alto- and nimbostratus and then by deep convective cores. While the latter have the strongest heating, they are infrequent compared to other cloud types. Strong differences are also noted between pre- and post-monsoon periods and between

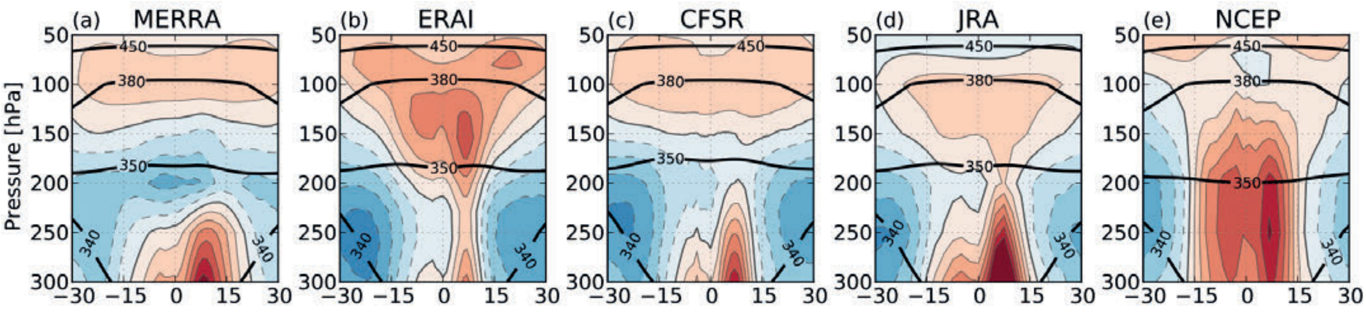


Figure 6: Zonal mean total diabatic heating averaged from 2001-2010 for (a) MERRA, (b) ERA-Interim, (c) CSFR, (d) JRA, and (e) NCEP reanalyses. This figure illustrates that the uncertainty in the total diabatic heating in the UTLS region from reanalyses is so large that it cannot be used to constrain the vertical upwelling in this region. (Figure from: Wright and Fueglistaler, 2013).

eastern and western regions of the subcontinent. **Andrew Gettelman** (invited) presented the current state of knowledge of cloud formation processes in the tropical tropopause layer (TTL) and reviewed how they are represented in CCMs, which represent the TTL structure well but cloud microphysics are a notable weakness. Ice nucleation mechanisms, while essential to represent cloudiness and dehydration, are particularly difficult to simulate. He indicated that tropical tropopause temperatures are expected to increase as a consequence of anthropogenically produced climate change. Improving models requires new and unique observations to target our knowledge gaps. In describing the relationship of the Asian Summer Monsoon to the UTLS, **Keasava Mohanakumar** (invited talk) showed how water vapour is transported to the lower stratosphere with large-scale spatial and temporal variability. The QBO seems to modulate the monsoon circulation by enhancing the monsoon low-level jet during its westerly phase. The rapid warming of the equatorial Indian Ocean and upper tropospheric cooling in the Tibetan anticyclone region causes a decrease in the strength of the tropical easterly jet stream in the upper troposphere, which in turn causes a change in the summer monsoon rainfall pattern.

Stephan Fueglistaler showed how the assumption of dehydration following the Clausius-Clapeyron relation in TTL air parcels leads to a dry bias in comparison to observations and that the Lagrangian dry point was spatially and temporally highly variable. He defined the 'residence time' effect that lowered the stratospheric entry level of water vapour as the circulation strengthened and, hence, improved agreement with observations. The net effect of dehydration can thus vary with constant cloud microphysics. **Felix Bunzel** indicated that mixing processes prevent one-to-one correspondence between stratospheric age-of-air and residual circulation transit times. He showed how the two-way mixing of air parcels between the tropics and extra-tropics increases air-parcel age-of-air values. Equilibrium climate model runs suggest a constant mixing efficiency as residual mass flux increases. However, CCMVal-2 models exhibit strongly varying efficiency that may be due to different model dynamics (*e.g.*, wave spectrum) and/or numerics (*e.g.*, advection scheme, or diffusivity).

Bernard Legras (invited talk) gave a comprehensive review of transport across the TTL and showed that the South Asia Pacific warm pool region is a main contributor to TTL air parcels throughout the year, with combined maritime convection always the dominant source. Trapping within the Asian Monsoon Anticyclone is most effective for parcels transported by convection over the Tibetan plateau and continental Asia north of 20°N. Key remaining transport issues are the need to validate reanalysed winds and heating rates (see for example **Figure 6**), the importance of sub-grid-scale high-frequency motion, and a quantitative estimate of detrainment from convection. **Robyn Schofield** discussed mass fluxes and detrainment over the maritime continent noting that the representation of convection is important for closure in many biogeochemical cycles. Convection transports a large fraction of bromine and sulfur species as well as CFC-substitute gases aloft. Comparisons of convective mass fluxes over Darwin, Australia, from the WRF model and the 3-hourly ERA-Interim archived values for mass flux and detrainment (representative of observational/coarse model convection) reveal significant differences. Correct representation of convective mass fluxes will require turbulence resolution.

The last presentation of the SPARC General Assembly was given by **Debashis Nath**, who presented an analysis showing an increase in potential vorticity intrusion (PVI) events into the tropics over the last several decades using reanalysis datasets. He proposed a mechanism that involves a shift in warm tropical sea-surface temperatures westward from the eastern Pacific, which affects the Walker circulation and increases the strength of equatorial westerlies in the central Pacific. The PVI trend enhances convective activities in the tropical Pacific sector and affects the dynamics over the tropics.

Some Final Words

Overall, the 5th SPARC General Assembly was an outstanding event and a clear reflection that SPARC is thriving. The meeting, as well as SPARC's general direction, is benefitting from the extended focus on stratosphere-troposphere processes and their role in climate. Example questions that SPARC will work on in future include: How important is interactive chemistry for surface climate prediction? How much does UV irradiance vary across the solar cycle, and what influence does this have on climate? What is the role of the stratosphere in persistent systematic model biases? What are the regional impacts of stratospheric geoengineering? Through what mechanism(s) does the extra-tropical stratospheric circulation affect the surface? What is the role of the stratosphere in the surface temperature 'hiatus'? Do changes in the cryosphere impact the stratosphere-troposphere system? The science presented at the 5th SPARC General Assembly provided a clear indication that we are making steps in the right direction to answer these questions and that SPARC as a whole is continuing to evolve in response to the challenges of a changing world.

The success of the 5th SPARC General Assembly was possible only because of the many hours dedicated by many people. Special thanks are owed to the local organising committee that was chaired by Greg Bodeker and supported by Emma Scarlet, Karin Kreher, and Stefanie Kremser for all their hard work and the huge amount of time invested. We also thank the SPARC Project Office and the WCRP Joint Planning Staff for their help in organising the event. The financial support of all the SPARC General Assembly sponsors, which helped bring a large number of young scientists and scientists from developing nations to New Zealand, is also very gratefully acknowledged. They are: WCRP, WMO, WIGOS, GAW, WWRP, NSF, APN, CSA, ARC, NIWA, ESA, SPARC Project Office, Antarctic New Zealand, COSPAR, Tofwerk, Aerodyne Research, Bodeker Scientific, Macquarie University, and the University of Otago.

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