Quadrennial Ozone Symposium 2021 in Seoul, South Korea

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27-29 September 2021

Meeting venue:
Online

Organizing Committee:
International Ozone commission (IO3C) and **Yonsei University in Seoul, South Korea**

Number Of Participants: 341

Website:
http://qos2021.yonsei.ac.kr/program.php

Introduction

The Quadrennial Ozone Symposium was organized by the International Ozone commission (IO3C), supported by the local organizing committee from Yonsei University in Seoul, South Korea. Originally, the gathering of researchers studying atmospheric ozone and related processes was planned in 2020, but had to be postponed to 2021 due to the COVID epidemic. However, even in 2021 travel was not possible due to pandemic-induced travel and quarantine restrictions. Therefore, the symposium was held remotely. Keynote talks, oral, and lightning poster presentations were organized in 6 three-hour sessions from October 3rd to 9th, 2021. Nearly all presentations were discussed very lively in the simultaneous chat. After each oral session, a short Q&A period summarized main results and allowed for a brief discussion of open questions. A special Q&A online board for all session allowed to post written questions to the authors for offline discussions. The large participation of 56 early career scientists and 22 researchers from developing countries of the symposium shows continuing interest in the excellent science of the QOS community. The symposium program and presentations given can be found on the symposium Website. Links to the lists of the presentations are provided at the end of the article.

A. Stratospheric ozone science

Session A of the Quadrennial Ozone Symposium was focused on stratospheric ozone science. **Ulrike Langematz** (FU Berlin, Germany) opened the session with her keynote "Polar Stratospheric Ozone: Recent Observations, Current Understanding, and Future Evolution". She discussed ten important research questions, from how volcanic eruptions affect polar ozone, to how polar ozone is expected to develop in the

Sponsors:

National Institute of Environmental Research

National Institute of Meteorological Sciences

IUGG IAMAS International Association of Meteorology and Atmospheric Sciences

NASA

SPARC Stratosphere-troposphere Processes And their Role in Climate

WORLD METEOROLOGICAL ORGANIZATION

KOPRI Korea Polar Research Institute

future. The second keynote by **Neil Harris** (Cranfield University, UK) was titled: "Understanding Changes in Tropical and Mid-latitude Stratospheric Ozone". Using the long-term total column ozone record collected at Arosa in Switzerland as the underlying thread, he summarised a wide spread of ozone research topics, starting from health studies in the 1920s to our current understanding of the processes. The presentation covered findings related to ozone changes and variability, with a special focus on scientific achievements from the recent decades. In addition to the keynote presentations, 90 abstracts were submitted to Session A. Nineteen presentations were 5-minute talks separated into three oral sessions. 71 abstracts were summarized in 2-minute eLightning talks and were available for online viewing as posters. The presentations covered a wide range of topics, including descriptions and analysis of ground-based and satellite-based measurements in different regions of the world, modelling studies, trend analyses, studies of specific polar vortex years or events, intercomparisons of different observations and model simulations, and introduction of new and improved methodologies of ozone observations.

Several presentations (**D.H. Ahn et al; A. Lecouffe et al.; H. Lee et al.; G. Liu et al.; A. Pazmino et al.; R. Roy et al.,; M.J. Schwartz et al.; Zuev et al.**) dealt with the exceptional Antarctic winter of 2019, when a stratospheric warming caused smaller ozone hole over Antarctica compared to other years since 2000. Shortly thereafter, the Arctic experienced a very cold winter in 2020 with a strong and long-lasting polar vortex, resulting in record spring ozone loss. This exceptional event, its impacts on the Northern Hemisphere mid-latitudes, and retrospective simulations of ozone changes under the "world avoided" scenarios (i.e. due to enactment of the 1987 Montreal Protocol, **C. Wilka et al.**), were discussed in several presentations (**W. Feng et al., J.-U- Grooß et al., U. Raffalski et al., I. Tristcher et al.; P. Vargin et al.; I. Wohltmann et al**.). Many presentations were dedicated to observational record updates and comparisons of different datasets: ozone depleting substances (e.g. BrO, OClO) (e.g. **R. Querel et al.**); Very Short Lived Halogens (**E. Bednarz et al.; L. McBride et al.; R. Salawitch et al.**), ground-based measurements from Antarctica (**L. Gomez-Martin et al.; S. Kim et al.; H. Lee et al.**); ground-based and satellite-based measurement comparisons from Southern Brazil (**G. Carbajal-Benitez; L. Vaz Peres et al.**), analyses of Brewer and Pandora measurements from Canada (**X. Zhao et al.**), analyses of ozone profiles from different observing systems in Korea (**S. Eun-Ji.; D. Shin et al.**), or the Southern Hemisphere Additional Ozonesondes (SHADOZ) network in the tropics (**M. da Silva Ferreira et al.; A. Thomposn et al.**). One study investigated the stability and homogeneity of satellite- and ground-based measurement systems (**D. Hubert et al.**).

Many studies reported trends in ozone analysing different ground-based and satellite-based measurements with different results depending on the period and the region analysed (**H. Bencherif et al.; L. Bernet et al.; S. Davis et al.; J. Kryscin et al.; E. Maillard-Barras et al.; V. Sofieva et al.; C. Vigouroux et al.; C. Wespes et al.**) A key focus in these studies was to update our knowledge of regions in the atmosphere where ozone recovery is now detectable (**N. Azouz et al.; M. Weber et al.**). New longitudinally resolved ozone datasets, for example, provide a better picture of regional ozone changes (**M. Koledewy-Egbers et al.; V. Sofieva et al.**). A number of presentations (**K. Bognar et al.; M. Chipperfield et al.; S. Dietmüller et al.; A. Inness et al.; A. Karagodin et al.; J. Y. Li et al.; H. Nakamura et al.; M. Weimer et al.**) discussed global ozone modelling in different model simulations, especially from the WCRP Coupled Model Intercomparison Project (CMIP6, CCMI , **Keeble et al.**). Other studies looked into the impacts on the ozone distribution coming from stratospheric dynamics (**A. Chrysantou et al.; F. Hasebe et al.; M. MDiallo et al.**) from the. Quasi-biannual Oscillation (QBO, **L. Oman et al.; J. Seo et al.; Y. Yamashita et al**.) , the Asian Summer Monsoon (**L. Pan et al; M. Santee et al**.), the extreme 2020 Australian wildfires (**S. Strahan et al**.), or from varations in the lowermost stratosphere (**W. Ball et al.; L. Millan et al.; H. Ryu et al.**).

B. Ozone Depleting Substances, Sources, Sinks, and Budgets

Session B on ozone depleting substances and their replacements started with a keynote presentation by **Sunyoung Park**, who highlighted the importance of regional emission estimates derived from measurements made at the Gosan station, Jeju Island, South Korea. Data from this station have been important for understanding unexpected changes in emissions of a range of ozone depleting substances (ODSs) and hydroflurocarbons (HFCs) in recent years, such as trichlorofluoromethane (CFC-11) and trifluoromethane (HFC-23). **Professor Park** highlighted these results and demonstrated that a substantial portion of the recent unexpected global emission changes can be attributed to eastern China. Results for related gases were also highlighted as they provide insights into the causes of the unexpected emission changes on regional and global scales.

The oral presentations continued the discussion of the magnitude and distribution of unexpected emission changes for CFC-11 (**M. Lickley et al.; S. Montzka et al.; L. Hu et al.**), other chlorofluorocarbons (CFCs, **M. Lickley et al.**), and methyl bromide (CH_3Br, **H. Choi et al.**). The two final oral presentations of that session discussed recent trends

for atmospheric abundances of HFCs relative to previous projections (**G. Velders et al.**), and a new metric for assessing ozone recovery based on cumulative ozone depletion (**J. Pyle et al.**).

Presentations during the poster session expanded the discussion of themes touched on in the oral presentations. **L. Westerm** discussed global atmospheric abundance trends of the ODSs 1,1-dichloro-1-fluoroethane (HCFC-141b), and **M. Nicewonger** discussed the causes of atmospheric abundance variability measured for CH3Br. Furthermore, recent advances in spectroscopic measurements that have enabled atmospheric abundances of HFC-23 and chlorodifluoromethane (HCFC-22) to be determined over long periods were presented by **H. Nakajima**. Oceanic influences on lifetimes and inferred emissions of CFCs and HFCs were discussed by **P. Wang.** A new index was proposed by **S. Reimann** for communicating HFC atmospheric changes and climate impacts, and revisions to calculating ozone depletion potentials for short-lived gases were discussed by **D. Wuebble**s. Presentations by **M. Jesswein**, **M. Rotermund** and **I. Murata** focused on shorter-term variability in inorganic chlorine, inorganic bromine, hydrochloric acid (HCl) and hydrogen fluoride (HF) related to different atmospheric conditions in recent years. Other presentations by **G. Dreyfus, G. Wetzel, J. Jia** and **T. Brown** included a suggested a method for offsetting the adverse environmental impacts of unexpected production of ozone-depleting gases; the determination of UTLS abundances of hydrocarbons, HCOOH, and peroxyacetyl nitrate; modelled and measured ozone depletion in the Arctic induced by solar proton events; and the quantification of current and near-future impacts of rocket launches on the stratosphere.

C. Tropospheric Ozone scienc

Session C was composed of 33 presentations representing the research activities from 16 countries. The session's keynote presentation "Ozone Pollution and Research Programs in China: An Overview", was given by **Prof. Yuanhang Zhang** of Peking University (China). His presentation drew attention to deteriorating surface ozone pollution over China in recent years, which is mainly caused by high loading and slow reduction of Volatile Organic Compounds (VOCs). Ozone mitigation practices in China have led to a regionally integrated multi-pollutant control strategy with short-term priority to VOCs and long-term priority to Nitrogen Oxides (NOx). The contributed presentations covered major topics of tropospheric ozone research, including trends (**Liu et al.; Zieme et al.**) and variabilities of tropospheric ozone on local, regional, and global scales (**Hubert, et al.; Soulie et al.; Mayer et al.**). Further topics highlighted the impacts of local emissions on ozone pollution (**Oak et al.**), the effects of the COVID-19 pandemic on tropospheric ozone (**Steinbrecht et al.**), the role of stratospheric transport on free tropospheric ozone (**Chouza et al.; Ma et al.**), and recent advances in ozone chemistry modelling (**Sudo and Matsuda**). The presentations showed that there is increasing availability of tropospheric ozone records, enabled by the growing list of ozone-observing satellites (including OMI, MLS, GOME, SCIAMACHY, GOME-2, OMPS and TROPOMI). Both tropospheric ozone products produced by combining nadir and limb viewing observations and the reanalysis products assimilating satellite data provide rich information for analysing tropospheric ozone behaviour including stratosphere-troposphere-exchange, and for evaluating CCMs. Discussions during the Q/A session reflect the interest in the community for these products. A wide range of analyses were presented using airborne, balloon-borne, ground-based, and research vessel-based ozone measurements, many combined with meteorological measurements. Results show that these diverse modes of observations play an important role in process studies and modelling tropospheric ozone.

D. Ozone, Climate, and Meteorology

This session covered the impacts of climate change on atmospheric ozone, evolution of large-scale circulation, radiative forcing of ozone, and the impacts of ozone changes on surface climate and meteorology. It also covered a recent hot topic, the impact of the large-scale Australian wildfire events in late 2019 to early 2020 on the composition of the lower stratosphere in the Southern Hemisphere.

In the oral session, 10 presentations, including the keynote talk by **Amanda C. Maycock**, provided an overview of the numerous impacts of tropospheric and stratospheric ozone variability and its

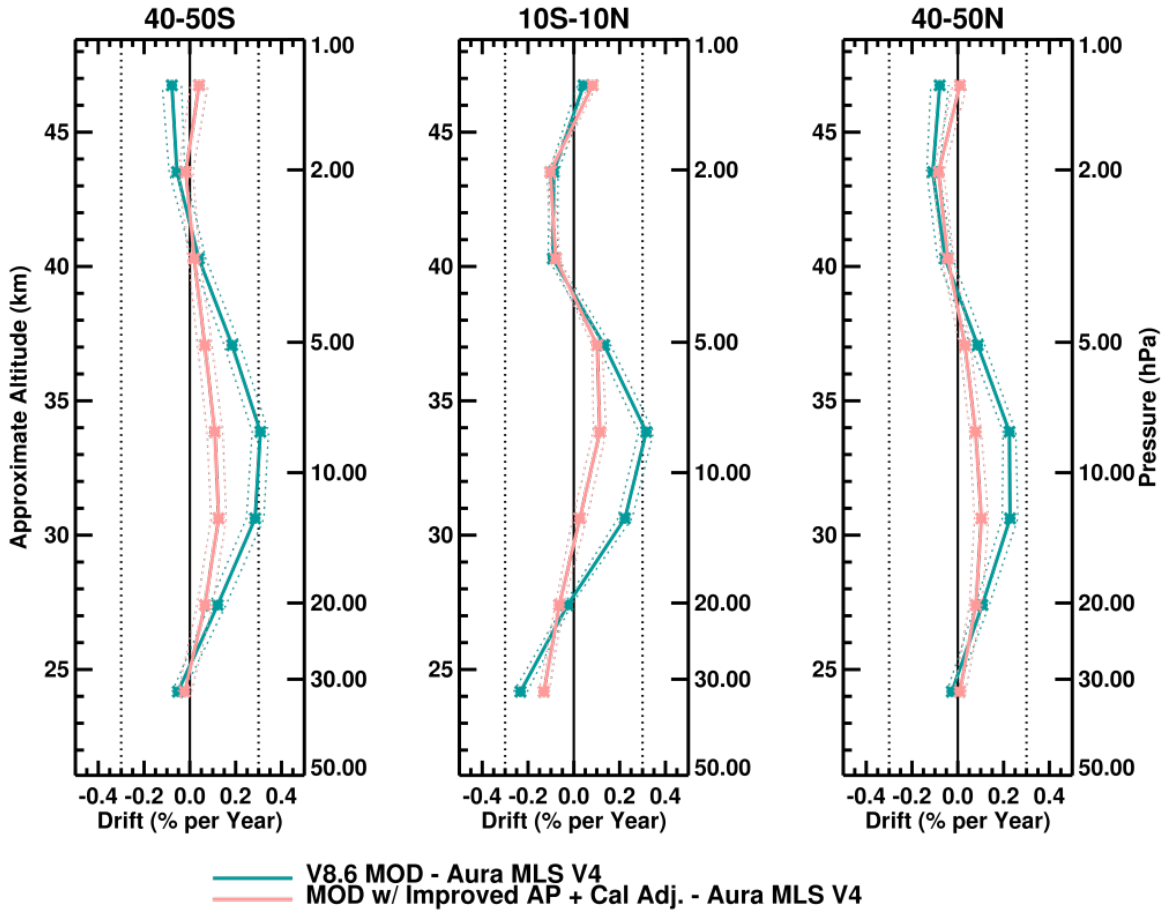

Figure 13: *Relative drift (in % per year) between the SBUV Merged Ozone Dataset (MOD) and Aura Microwave Limb Sounder for the period 2004-2018 shown for three wide latitude zones. Green lines represent relative drifts in the MOD record based on version 8.6 SBUV data. Pink lines are for the MOD with the improved climatology and updated cross-calibrations, demonstrating increased stability of the updated MOD record. The new advanced climatology (Frith et al., 2020; Ziemke et al., 2021) is used in evaluation of the relative offsets between pairs of overlapping Solar Backscattered UltraViolet (SBUV) instruments. The instrument bias corrections improve consistency of the NASA's historical merged ozone record.*

trends on global and regional climates as synthesized in the IPCC Sixth Assessment Report and the WMO/UNEP 2022 Scientific Assessment of Ozone Depletion. The need for interactive stratospheric ozone in climate models, in comparison with prescribed ozone, was shown and discussed by four presenters: **Feng Li** for Southern Hemisphere troposphere in austral spring; **Marina Friedel** for Northern Hemisphere surface climate focusing on springtime Arctic ozone depletion; **Pu Lin** for global stratospheric temperature trends in response to ozone depletion; and finally, **Olaf Morgenstern** for Southern Annular Mode using CMIP6 models with and without stratospheric chemistry. Using reanalyses for past decades, CMIP5, and CMIP6 models for 1950-2100, **Peter von der Gathen** showed a statistically significant increase in the local maxima of PSC formation potential within the Northern Hemisphere polar vortex. **Gabriel Chiodo** investigated the radiative impacts of ozone-depleting substances focusing on the period with the largest growth of atmospheric ODS abundances (1955-2000) and found their unique contributions to climate change including warming of the lowermost tropical stratosphere. The final three talks were on the impacts of the Australian wildfire events on the stratosphere: **Michelle L. Santee** showed Microwave Limb Sounder (MLS) measurements of various relevant species including biomass-burning products in the Southern Hemisphere stratosphere; **Sergey Khaykin** analyzed satellite aerosol and other data, showing a massive injection of absorbing aerosols into the stratosphere that created a self-maintained anticyclone, or smoke-charged vortex that persisted for three months and ascended to 35 km altitude, while **William J. Randel** also analyzed various satellite data, pointing out that the polar ozone depletion, temperature, and polar vortex evolution broadly resembled the effects

of the Calbuco volcanic eruption in 2015.

The poster session continued and expanded the science discussion of session D's theme of ozone, climate, and meteorology using both atmospheric observations and climate models. Overall, 33 posters were presented. These summarized a broad range of science studies from the regional scale to the global scale; including observations that defined the importance of continuing long-term monitoring networks, improved sensitivity, and validation, along with the use of observations in the evaluation of model results. Modeling and observational studies tested our understanding of key chemical processes in both the troposphere and stratosphere.

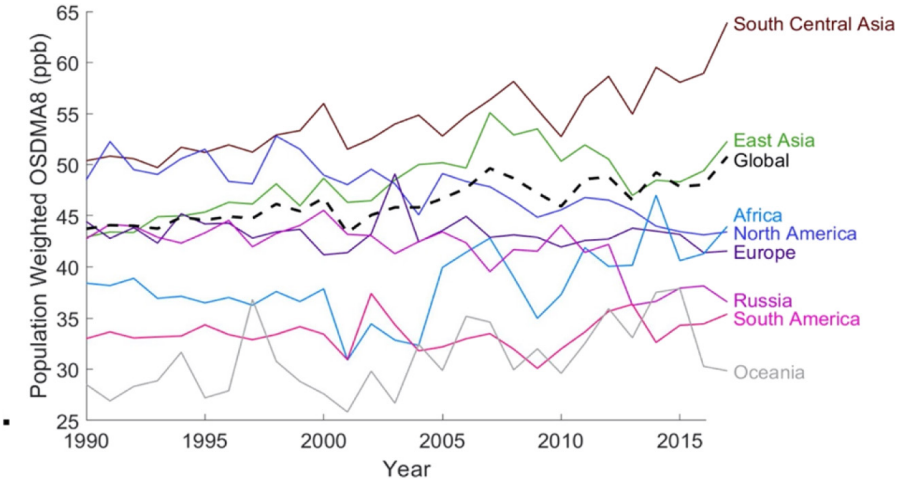

Figure 14: *Ozone trends regionally averaged for 1990-2017 period. The metric is population weighted OSDMA8 (ozone season daily maximum 8-hour mixing ratio). All trends have a p-value less than 0.05, except for Europe and South America (Fig. 5b in DeLang et al, 2021)*

E. Ozone Monitoring and Measurement Techniques

This session had the most abstract submissions and had to be split into several sessions. It started with the keynote talk by **Natalya Kramarova** (NASA Goddard) giving a historic overview of the stratospheric ozone products based on the satellite remote sensing techniques. She concentrated on the SBUV and OMPS UV instruments and discussed recent advances made in separation of instrumental artifacts and natural variability signals (see Figure 13) that are embedded in the long-term combined ozone records used for trend analyses. The topic of satellite validations using ground-based observations included discussion of the needs for NOAA's operational ozone products (presented by **L. Flynn et al.**), offered a first look at the GEMS satellite ozone products validation (by **A. Keppens et al.** and by **K. Baek et al.**), and voiced concerns with the gaps and inconsistencies between ground-based datasets (**T. Verhoelst et al.**). The session also addressed new homogenized satellite products with a focus on tropospheric ozone trends (by **A. Keppens**), enhancement in ozone profile retrievals by combining UV and IR observations (by **N. Mettig et al.**), machine learning techniques (by **D. Loyola et al.** and by **S. Dhomse et al.**), and the use of satellite records to fill in the gaps of the long-term ground-based ozone records (by **L. Zhang et al.**). The advances in stability and consistency of the ground-based and satellite-based records were demonstrated in several oral and multiple poster presentations that discussed results of homogenization of ozonesonde records (**R. Van Malderen et al.**), new version of Pandora total ozone record using climatological effective temperature (**M. Tiefengraber et al.**), coherence between the Umkehr and overpass satellite ozone records (**I. Petropavlovskikh et al.**), transition of the surface ozone networks to the new ozone cross-sections (**P. Brewer et al.**), impacts of the time response in ozonesonde cells on ozone vertical biases (**H. Vömel et al.**), and attribution of the "drop-off" in ozonesonde records to manufacturing changes (**R. Stauffer et al.**). Updated assessment of the Brewer reference triad performance (from 1999 to 2019) and the first comprehensive assessment of the Double Brewer reference triad were shown (**X. Zhao et al.**) compared to ground-based and satellite measurements. The oral session also paid a tribute to 25 years of recurrent and sustained experiments to assure data quality in ozonesonde records (**H. Smit et al.**). Several presentations introduced new satellite instrument concepts, including the Infrared Tomography Explorer (**B.-M. Sinnhuber et al.**) and the Community Microwave Limb Sounder (**N. Livesey et al.**) for continuing and expanding the capability of global observations of atmospheric composition change. Sixty poster presentations gave a detailed overview of the status and achieve-

ments of the ground-based, in-situ, aircraft and satellite networks, introduced new and enhanced calibration techniques (the Eubrewnet activities were featured in several posters). Posters also discussed reprocessing of satellite and ground-based data in order to improve the accuracy and consistency of observed ozone records across different techniques, with a significant number focussed on homogenization of ozonesonde observations. Further posters introduced improvements to old measurement approaches along with proposed new ones (e.g., SAGE IV) for tracking ozone, CFCs and atmospheric tracers needed to verify stratospheric ozone recovery and for understanding of causes of changes in tropospheric ozone. Common interest of the tropospheric and stratospheric ozone research communities was satisfied with new information in terms of monitoring and technological development.

F. Environmental and human health effects of atmospheric ozone and UV

The focus of this session was on the influence of atmospheric ozone and UV radiation on public health, agricultural crop yield, ecosystem service impacts, and material degradation. A keynote by **Prof. Jason West** provided evidence from mapping global ground-level ozone concentrations for the period between 1990 and 2017 (see Figure 14) in support of health impact assessment. Further talks covered surface UV radiation and its contribution to the increase of melanoma incidence in Europe over a period of 20 years (**A. Czerwinska et al.**), the temporal variability of solar UV radiation in Brazil (**G. Reis et al.**) and a comparison of the temporal variability of erythemal UV-B dose measurements (**S. F. Leon-Luis et al.**, presented by **A. Redondas**). A projection of total ozone and DNA weighted UV radiation changes in the future, exploring the influence of greenhouse gases in the atmosphere, was presented by **K. Eleftheratos**. **S. Falk** introduced a characterisation of subarctic biomes for land surface modelling of ozone pollution and climate risk and I. Fountoulakis highlighted findings from a satellite-based UV and visible climatology for biological and agricultural applications for Greece and Cyprus. Poster presentations covered the estimation of UV Indices and biological dose rates, as well as the application of various models to achieve this for South Korea (**H. Lee et al., J. Kim et al.**), and changes in the Aura OMI Total column and UV Index over Indonesia, linking these to regional cloud cover (**N. Komala et al.**). Discussions of the tropospheric

Figure 15: *Participantsof the Quadrennial Osone Symposium 2021*

ozone impacts on forests in Delhi, India (**P. Saxena et al.**) and the relationship between ozone and cardiorespiratory mortality for different age groups in a region in Greece (**L. Dimitriadou et al.**) were followed by an introduction of the SOUVENIR project (SOlar UV Extensive Network for Information and Reporting, DOI:10.13140/RG.2.2.18274.04802), a network for solar UV measurements (**G. Fasano et al.**). **C. Gonzalez** presented a comparison of measurement results of global UV spectral irradiance, while **K. Cizkova** focused on modelling of spectral UV radiation at the Marambio base on the Antarctic Peninsula. The variation of stratospheric ozone concentrations and genotoxic effects of solar UV radiation in southern Brazil (**B. C. Borin et al.**) and further work on the climatology of the UV index, as well the behaviour of the index during events influenced by the Antarctic Ozone Hole over southern Brazil was presented by **B. C. Lopes**.

Links to Sessions

Session A

http://qos2021.yonsei.ac.kr/download/program/1.QOS2021_Program_SUN1.pdf

http://qos2021.yonsei.ac.kr/download/program/2.QOS2021_Program_MON1.pdf

Session B

http://qos2021.yonsei.ac.kr/download/program/6.QOS2021_Program_TUE2.pdf

http://qos2021.yonsei.ac.kr/download/program/7.QOS2021_Program_TUE3.pdf

Session C

http://qos2021.yonsei.ac.kr/download/program/8.QOS2021_Program_WED1.pdf

Session D

http://qos2021.yonsei.ac.kr/download/program/9.QOS2021_Program_WED2.pdf
http://qos2021.yonsei.ac.kr/download/program/12.QOS2021_Program_THU3.pdf

Session E

http://qos2021.yonsei.ac.kr/download/program/10.QOS2021_Program_THU1.pdf

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http://qos2021.yonsei.ac.kr/download/program/17.QOS2021_Program_SAT2.pdf

Session F

http://qos2021.yonsei.ac.kr/download/program/14.QOS2021_Program_FRI2.pdf

http://qos2021.yonsei.ac.kr/download/program/18.QOS2021_Program_SAT3.pdf

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