MEETING SUMMARIES

RESEARCH COLLABORATIONS FOR BETTER PREDICTIONS OF AVIATION WEATHER HAZARDS

Hye-Yeong Chun, Jung-Hoon Kim, Dan-Bi Lee, Soo-Hyun Kim, Matt Strahan, Brian Pettegrew, Philip Gill, Paul D. Williams, Ulrich Schumann, Joel Tenenbaum, Young-Gon Lee, Hee-Wook Choi, In-Sul Song, Ye-Ji Park, and Robert D. Sharman

More than 50 participants consisting of research scientists, federal agencies, and operational forecasters from South Korea, the United States, the United Kingdom, and Germany met in Jeju Island, Korea, during 2–4 November 2016 at the Fifth Workshop on Aviation Meteorology (http://atmosdyn.yonsei.ac.kr/program_2016) to share their research results and forecasting experiences for improving the prediction of aviation weather hazards.

THE FIFTH WORKSHOP ON AVAIATION METEOROLOGY

What: Research scientists, federal agencies, and operational forecasters from Korea, the United States, the United Kingdom, and Germany discussed the development of better forecasting models and verification techniques for aviation weather hazards such as turbulence, convection, and low-level wind shear.
When: 2–4 November 2016
Where: Jeju Island, South Korea

As the volume of global air transportation has increased and continues to increase rapidly, improvement in the prediction of aviation weather hazards is greatly needed for the safety and efficiency of aircraft operations. At cruising altitudes (about $z = 5–12$ km), accurate forecasts for turbulence, icing, and convection are critical for reducing extra costs due to in-flight injuries, structural damage, and flight delays by encountering those hazards (e.g., Sharman et al. 2012; Sharman and Lane 2016). Reliable predictions of upper-level jet and wind variations can also have a significant impact on optimal flight-routing planning (Kim et al. 2015; 2016). Near airports, rapidly updated nowcasts from observing and modeling systems are crucial to identify possible low-level wind shear and downburst events, which can cause serious safety issues for departing and landing airplanes (e.g., Wong et al. 2013). From a long-term perspective, a better understanding of the two-way interaction between climate change and aviation may help establish a better strategy for green aviation in the future (Williams 2016).

AFFILIATIONS: Chun, D.-B. Lee, and S.-H. Kim—Yonsei University, Seoul, South Korea; J.-H. Kim and Pettegrew—Colorado State University, Fort Collins, Colorado, and NOAA/Aviation Weather Center, Kansas City, Missouri; Strahan—NOAA/Aviation Weather Center, Kansas City, Missouri; Gill—Met Office, Exeter, United Kingdom; Williams—University of Reading, Reading, United Kingdom; Schumann—Deutsches Zentrum für Luft- und Raumfahrt, Oberpfaffenhofen, Germany; Tenenbaum—University at Purchase, State University of New York, Purchase, New York; Y.-G. Lee and Choi—National Institute of Meteorological Sciences, Jeju, South Korea; Song and Park—Aviation Meteorological Office, Incheon, South Korea; Sharman—National Center for Atmospheric Research, Boulder, Colorado;
CORRESPONDING AUTHOR: Jung-Hoon Kim, jung-hoon.kim@noaa.gov

DOI:10.1175/BAMS-D-17-0010.1

In final form 9 January 2017

Despite the importance of research to aviation meteorology, only a few scientific groups internationally are currently studying these topics. To collaborate and promote research activities in aviation meteorology, the *Workshop on Aviation Meteorology* has been hosted biennially by Yonsei University (YSU) since 2008. The fundamental goal of this workshop is to find pathways to strengthen collaborations among the active research groups, operational weather forecast centers, and stakeholders, which can improve operational forecasting models and observing techniques to better predict and analyze aviation weather hazards and can eventually mitigate the adverse weather impact on aviation.

The participants presented and discussed on-going research results on four main themes: 1) development of global aviation turbulence forecasting systems, 2) improvements in modeling and observing systems of aviation meteorology, 3) local weather forecasts and low-level wind shear, and 4) interaction between aviation and climate change.

DEVELOPMENT OF GLOBAL AVIATION TURBULENCE FORECASTING SYSTEMS. At the requests of the International Civil Aviation Organization (ICAO) and World Meteorological Organization (WMO), two World Area Forecast Centers (WAFCs) in Washington, United States, and London, United Kingdom, have developed the World Area Forecast System (WAFS), which provides automated and consistent gridded forecasts for global aviation users (Gill 2012). In accordance with ICAO's Aviation System Block Upgrades (ASBU), ICAO/WMO required the update of the current WAFS grids especially to include severity instead of potentials and to provide probability of all hazards with increases in spatial and temporal resolution. Blending these hazard forecasts with output from third-party providers in addition to the two WAFCs will be considered at a later date.

Hye-Yeong Chun from YSU presented the current status of the Korean Aviation Turbulence Guidance (KTG; Kim and Chun 2012) product, which forecasts aviation turbulence over East Asia, and outlined future plans to extend it as a global forecasting system, Global-KTG (G-KTG), to be based on the Global Data Assimilation and Prediction System (GDAPS) developed by the Korean Meteorological Administration (KMA). Evaluation over East Asia shows that the KTG performance depends on the season, higher in winter and fall and lower in summer. This is likely because of the lack of proper turbulence diagnostics to capture convectively induced turbulence (CIT) and a seasonal bias in the underlying GDAPS model. In addition, estimation of atmospheric turbulence in the free atmosphere using high vertical resolution radiosonde data (HVRRD), in conjunction with the project of finescale atmospheric processes (FISAPS) from Stratosphere–Troposphere Processes and their Role in Climate (SPARC; Geller et al. 2016), and its application to the aviation meteorology was suggested.

Philip Gill from the Met Office in the United Kingdom (WAFC London) presented their efforts on ensemble-based global aviation hazard forecasts. Current global forecasts from the two WAFCs are produced from deterministic model output. To communicate forecast uncertainty, the Met Office Global and Regional Ensemble Prediction System (MOGREPS) is used for probabilistic aviation weather forecasts (Gill and Buchanan 2014). Here, a multimodel ensemble combining MOGREPS and the European Centre for Medium-Range Weather Forecasts (ECMWF) ensemble is used and evaluated using the observed derived equivalent vertical gust (DEVG) from commercial aircraft for verification.

Matt Strahan from the National Oceanic and Atmospheric Administration/Aviation Weather Center (NOAA/AWC; WAFC Washington) introduced the missions and roles of the NOAA/AWC for the WAFS upgrades. Jung-Hoon Kim from NOAA/AWC also presented joint efforts with the National Center for Atmospheric Research (NCAR) for the development of the Global Graphical Turbulence Guidance (G-GTG) for WAFS upgrades. The current WAFS turbulence grid is based on a single turbulence diagnostic, the Ellrod index (Ellrod and Knapp 1992), which does not directly provide turbulence severity and does not directly consider sources of turbulence other than clear-air turbulence (CAT). In contrast, a recent version of GTG (Sharman and Pearson 2016) provides the energy dissipation rate (EDR; $m^{2/3}\ s^{-1}$), a measure of atmospheric turbulence intensity, which is calculated by optimally combining multiple component diagnostics based on various turbulence sources: CAT, mountain wave–induced turbulence (MWT), and possibly CIT. Using NOAA's Global Forecast System (GFS) and global EDR observational data (Sharman et al. 2014) for one month (October 2015), it was shown that the new global EDR forecast from the G-GTG has better performance skill than the current WAFS turbulence forecast.

IMPROVEMENTS IN MODELING AND OBSERVING SYSTEMS OF AVIATION METEOROLOGY. Improvements in forecast performance can be achieved by contributions from careful tunings and evaluations of current algorithms, better observations, development of new diagnostics, upgrades to underlying numerical weather prediction (NWP) models, and better observation-derived products.

Dan-Bi Lee from YSU presented the development of the G-KTG system that combines 10 CAT diagnostics and 2 MWT diagnostics using the GDAPS data. Individual diagnostics are mapped into an EDR scale, based on in situ flight observations (Sharman and Pearson 2016) and GDAPS calculations of each diagnostics. The performance of the G-KTG system is evaluated against global in situ EDR observations from October 2016, and the skill score was shown to be quite good.

Joel Tenenbaum from the State University of New York (SUNY) discussed the Global Aircraft Dataset (GADS) experiment, which was initiated by contributions from multiple international airlines for verification of winter jets. This has been updated and extended to provide automated DEVG measurements from a European-based airline and is now used for verification of current WAFS turbulence forecasts.

Soo-Hyun Kim from YSU suggested new near-cloud turbulence (NCT) diagnostics based on the convective gravity wave drag (CGWD) parameterization by Chun and Baik (1998). This is intended to detect NCT above convective clouds. The minimum Richardson number Ri_{min} that includes a convective GW effect, CGWD, and turbulence kinetic energy calculated using eddy viscosity from Ri_{min} and CGWD is suggested as possible NCT diagnostics. The case study shows that this approach is feasible to predict the NCT encounters (Trier et al. 2012) above the shallow convection in cold season.

Jung-Hoon Kim from the NOAA/AWC presented results of improvements to the current MWT forecasts by reducing unphysical small-scale energy in the model topography in the initialization of the NWP model (Park et al. 2016). The NWP model uses high-resolution digital elevation data interpolated to the model domain, which results in unphysical energy at scales smaller than 6 times the horizontal grid spacing (i.e., $6\Delta x$), and this needs to be properly eliminated in the model initialization. It was found that the current regional NWP model skips this procedure, which results in an adverse high false alarm ratio for MWT prediction in the western United States. After applying smoothing functions in the NWP model, the unphysical mode in the model topography was damped and has fewer spurious, trapped mountain waves, which gives better MWT forecast skill.

Brian Pettergrew from NOAA/AWC pointed out that improvements in the lightning data allow for better decision support with newly derived products. A lightning-based echo-top product was developed based on correlations between lightning density within a 5-km grid box and the height of maximum radar echo top. This allows a 2-min update cycle, which is higher than the 5-min current radar frequency. This can give better decision support especially for rapidly developing and decaying convection.

LOCAL WEATHER FORECASTS AND LOW-LEVEL WIND SHEAR.

High-resolution modeling techniques with data assimilation can provide detailed structures of the local wind shear near airports. And the analysis of observed signal patterns can allow better decision support for wind shear alerts and microbursts.

Young-Gon Lee from KMA/National Institute of Meteorological Sciences (NIMS) developed a 300-m weather prediction model that is downscaled from 17-km GDAPS to the Incheon International Airport (IIA). Data assimilation approaches using variational methods are additionally suggested by Hee-Wook Choi from KMA/NIMS to ingest observed wind data from automatic weather stations (AWSs) and the low-level wind shear alert system (LLWAS) around IIA in a cost-effective way. Better representation of model topography in a high-resolution domain with assimilated local wind data showed potential benefits to capture detailed wind forecasts and low-level wind shear (LLWS) near the airport.

In-Sul Song from KMA/Aviation Meteorological Office (AMO) demonstrated rule-of-thumb signals from observation data to predict local wind shear and downbursts in rapidly changing weather conditions. A 5-yr period of Terminal Doppler Weather Radar (TDWR) and LLWAS data was analyzed to find better patterns for foreseeing LLWS and microbursts at IIA. Results showed that there are four distinct patterns from TDWR: horizontally sheared type, low-level jet type, cyclonic rotation, and divergent–convergent type. Ye-Ji Park from KMA/AMO examined turbulence cases issued with AMO's local significant weather forecast (SIGWX) based on a regionally tuned KTG system and introduced their ongoing efforts for sharing more aircraft report (AIREP) data in Korea for better situational awareness and prediction.

Brian Pettegrew from NOAA/AWC additionally discussed the challenges and potential of new approaches for LLWS guidance and wind compression using high-resolution wind forecasts and available observational data around airports, which will be beneficial for aviation operations.

INTERACTION BETWEEN AVIATION AND CLIMATE CHANGE. Better understandings of both the impact of climate change on aviation operations and the adverse impact of aircraft emissions and contrails on climate are important to establish a long-term strategy for green aviation in the future.

Paul D. Williams from the University of Reading emphasized that the impacts of climate change on aviation have only recently begun to emerge (e.g., Williams and Joshi 2013). Here, the influence of climate change on flight routes and journey times is investigated (Williams 2016), which showed that a strengthening of the prevailing winds in future climate change scenarios causes eastbound flights to shorten and westbound flights to lengthen. From a conceptual model for journey times, the eastbound shortening does not cancel out the westbound lengthening, causing an increase of the total round-trip flight time. Even assuming no future growth in aviation, this results in 2,000 h of extra journey time per year for all transatlantic flights, with an extra 7.2 million gallons of jet fuel burnt and an extra emission of 70 million kilograms of carbon dioxide.

Ulrich Schumann from the German Aerospace Center (DLR) explained how contrails from aircraft can contribute to the global warming effect. Contrails are visible aircraft tracers and indicators for aviation climate impact, which are formed when water vapor is condensed and frozen on aerosols from the exhaust of aircraft engines when the ambient air temperature is below typically −40°C (Schumann 2012). Contrails also form prototype cirrus, offering insight into cirrus formation, which impacts the energy budget of the atmosphere because of a net change in radiative flux at the top of the atmosphere by reflecting incoming shortwave and trapping outgoing longwave radiation. Reduction of the climate impact of contrails is technically feasible by using biofuel, optimizing aircraft design, and developing climate-optimal flight routes. Operationally, changing a flight route to avoid areas that cause warm (cold) effects of contrails could minimize the total climate impact of aviation.

ACKNOWLEDGMENTS. We especially thank the following sponsors for making this workshop possible: Yonsei University, National Institute of Meteorological Sciences (NIMS) in Korea, Korea Meteorological Industry Promotion Agency (KMIPA), Aviation Meteorological Office (AMO), and Korean Meteorological Administration (KMA). This workshop was supported by the Korea Meteorological Administration Research and Development Program under Grant KMIPA2015-1080 and by Research and Development for KMA Weather, Climate, and Earth System Services (NIMS-2016-3100). Recipient of KMIPA2015-1080 is Yonsei University, and Recipient of NIMS-2016-3100 is NIMS.

REFERENCES

Chun, H.-Y., and J.-J. Baik, 1998: Momentum flux by thermally induced internal gravity waves and its approximation for large-scale models. *J. Atmos. Sci.*, **55**, 3299–3310, doi:10.1175/1520-0469(1998)055<3299:MFBTII>2.0.CO;2.

Ellrod, G. P., and D. I. Knapp, 1992: An objective clear-air turbulence forecasting technique: Verification and operational use. *Wea. Forecasting*, **7**, 150–165, doi:10.1175/1520-0434(1992)007<0150:AOCATF>2.0.CO;2.

Geller, M. A., H.-Y. Chun, and P. T. Love, 2016: FISAPS—An emerging SPARC activity. *SPARC Newsletter*, No. 47, SPARC Office, Zurich, Switzerland, 8–10.

Gill, P. G., 2012: Objective verification of World Area Forecast Centre clear air turbulence forecasts. *Meteor. Appl.*, **21**, 3–11, doi:10.1002/met.1288.

——, and P. Buchanan, 2014: An ensemble based turbulence forecasting system. *Meteor. Appl.*, **21**, 12–19, doi:10.1002/met.1373.

Kim, J.-H., and H.-Y. Chun, 2012: Development of the Korean Aviation Turbulence Guidance (KTG) system using the operational Unified Model (UM) of the Korea Meteorological Administration (KMA) and pilot reports (PIREPs). *J. Korean Soc. Aviat. Aeronaut.*, **20**, 76–83, doi:10.12985/ksaa.2012.20.4.076.

——, W. N. Chan, S. Banavar, and R. D. Sharman, 2015: Combined winds and turbulence prediction system for automated air-traffic management applications. *J. Appl. Meteor. Climatol.*, **54**, 766–784, doi:10.1175/JAMC-D-14-0216.1.

——, ——, B. Sridhar, R. D. Sharman, P. D. Williams, and M. Strahan, 2016: Impact of the North Atlantic Oscillation on transatlantic flight routes and clear-air turbulence. *J. Appl. Meteor. Climatol.*, **55**, 763–771, doi:10.1175/JAMC-D-15-0261.1.

Park, S.-H., J.-H. Kim, R. D. Sharman, and J. B. Klemp, 2016: Update of upper-level turbulence forecast by reducing unphysical components of topography in the numerical weather prediction model. *Geophys. Res. Lett.*, **43**, 7718–7724, doi:10.1002/2016GL069446.

Schumann, U., Ed., 2012: *Atmospheric Physics: Background–Methods–Trends*. Springer, 877 pp., doi:10.1007/978-3-642-30183-4.

Sharman, R., and T. Lane, 2016: *Aviation Turbulence: Processes, Detection, Prediction*. Springer, 523 pp.

——, and J. M. Pearson, 2016: Prediction of energy dissipation rates for aviation turbulence. Part I: Forecasting nonconvective turbulence. *J. Appl. Meteor. Climatol.*, **56**, 317–337, doi:10.1175/JAMC-D-16-0205.1.

——, S. B. Trier, T. P. Lane, and J. D. Doyle, 2012: Sources and dynamics of turbulence in the upper troposphere and lower stratosphere: A review. *Geophys. Res. Lett.*, **39**, L12803, doi:10.1029/2012GL051996.

——, L. B. Cornman, G. Meymaris, J. Pearson, and T. Farrar, 2014: Description and derived climatologies of automated in situ eddy dissipation rate reports of atmospheric turbulence. *J. Appl. Meteor. Climatol.*, **53**, 1416–1432, doi:10.1175/JAMC-D-13-0329.1.

Trier, S. B., R. D. Sharman, and T. P. Lane, 2012: Influences of moist convection on a cold-season outbreak of clear-air turbulence (CAT). *Mon. Wea. Rev.*, **140**, 2477–2496, doi:10.1175/MWR-D-11-00353.1.

Williams, P. D., 2016: Transatlantic flight times and climate change. *Environ. Res. Lett.*, **11**, 024008, doi:10.1088/1748-9326/11/2/024008.

——, and M. M. Joshi, 2013: Intensification of winter transatlantic aviation turbulence in response to climate change. *Nat. Climate Change*, **3**, 644–648, doi:10.1038/nclimate1866.

Wong, W.-K., C.-S. Lau, and P.-W. Chan, 2013: Aviation model: A fine-scale numerical weather prediction system for aviation applications at the Hong Kong International Airport. *Adv. Meteor.*, **2013**, 532475, doi:10.1155/2013/532475.