Supplement Materials to C-RITE Final Report: Detailed Science Summaries and References

More detailed session summaries of the science sub-section break out discussions from each of the four main C-RITE Workshop science themes are contained in this section. The scientific references related to each section are also included a the end of each main section.

1. Boundary Layer flow and turbulence

After a brief plenary introduction (Petra Klein), the Boundary Layers and Turbulence session included three invited presentations focusing on Stable Boundary Layers (SBL, speaker: Gunilla Svensson, contributors: Larry Mahrt, Jielun Sun and Michael Tjernström), Convective Boundary Layers (CBL, speaker: Wayne Angevine), and Influence of Topography and Landuse (TopoLU, speaker: Julie Lundquist). The presentations were followed by a plenary discussion and three breakout sessions moderated by Jielun Sun (SBL, rapporteur: Andrey Grachev), Jordi Vila (CBL, rapporteur: Tim Wagner), and Petra Klein (TopoLU, rapporteur: Dan Li). A summary of the scientific frontiers identified by the speakers and discussions is presented thereafter. The identified needs for observing capabilities were very similar across all three subtopics and are thus presented at the end covering all boundary layer and turbulence aspects discussed.

The plenary introduction provided the rationale for organizing the session around the 3 subtopics SBL, CBL and TopoLU, with the first two talks focusing on current scientific gaps in the more traditional types of boundary-layer flow and turbulence phenomena, and the third talk highlighting the challenges of applying existing concepts to real-world scenarios where the terrain is naturally complex or the landscape has been altered by human activities or natural disasters. Over such landscapes, the structure of the atmospheric boundary layer (ABL) is distinct from the one over homogeneous terrain, and the flow and turbulence patterns are particularly complex (Fernando, 2010). It also highlighted previously discussed instrumentation needs related to boundary-layer flows and turbulence. As an example, the NRC report “Observing Weather and Climate from the Ground Up: A Nationwide Network of Networks” (2009) identified measurements of the planetary boundary-layer height, soil moisture and temperature profiles, high resolution profiles of atmospheric humidity, and profile measurements of the chemical composition as highest priorities. Similar needs were also identified in a report summarizing a workshop funded by the National Science Foundation and the National Weather Service but the report included more specific recommendations concerning the required accuracy and resolution of measurements (Hardesty and Hoff, 2012).

1.1 Stable Boundary Layers

The invited speaker Gunilla Svensson discussed unique features of SBLs: they are rather shallow O(m-100m); non-local in space and non-stationary; mixing is weak and can be very intermittent; and larger-scale features such as gravity waves, low-level jets, and slope flows affect and interact with the SBL. In the literature, SBLs are often classified into weakly stable, strongly-stable and long lived (Banta et al. 2007, Mahrt 2014). A recent paper by Steeneveld et al. (2015) summarizes the multitude of physical processes that play a role in the SBL. Different processes often have non-linear interactions with positive and negative feedbacks, which makes modeling of SBL flow and turbulence challenging. Most numerical weather predication (NWP) and climate models use rather simple, first-order turbulence closure schemes in which the stability dependence of the eddy diffusivities for heat and momentum are described by stability functions. Processes in the SBL are best described by so-called short-tail stability functions, that predict a sharp decrease in the eddy diffusivities as the Richardson number reaches values of 0.2 and the ABL becomes strongly stable. However, to assure numerical stability and adequate predictions of synoptic scale processes, NWP and climate models typically use long-tail functions with sustained mixing even under strongly stable conditions, which leads to an overprediction of near-surface temperatures by up to 10o C (Holtslag et al. 2013) and also affects the prediction of near surface winds (Sandu et al. 2013). The speaker concluded that improving SBL parameterizations for NWP and climate models remains an important challenge that impacts forecasts for all seasons and at all latitudes. The SBL presentation also stressed that the ABL is always in transition. Thus, an important science objective is finding new approaches for modeling the spatial (both vertical and horizontal) heterogeneity and non-stationary nature of boundary-layer flow and turbulence processes. More detailed observations that better capture the entire ABL structure are needed to improve the understanding of important processes and ultimately also parameterization schemes. Another important science objective is to find new approaches for accounting for the flux divergence near the surface. Important fluxes may be systematically missing in the turbulence budgets since the currently applied Monin-Obukhov theory assumes a constant flux layer near the surface. Open questions also remain about the coupling between the land surface and the SBL.

1.2 Convective Boundary Layers

The CBL presentation, given by invited speaker Wayne Angevine, highlighted how infrequently classic textbook (clear-air) CBLs are observed; the global average over land accounts for only ~ 20% (Harvey et al. 2013). Clouds often play an important role, advection is rarely negligible, and as already noted in the SBL discussion, the ABL over land frequently undergoes transitions. These effects are particularly prominent in areas where most of the people live, such as e.g. near coasts. More detailed information about the timing and shape of boundary-layer transitions are critical for improving predictions of nocturnal low-level jets and the transport and dispersion of pollutants. As an example, radar wind profile observations from the 1995 Flatland boundary layer campaign showed that turbulence decrease starts well before sunset and happens first near the boundary-layer top and not near the surface (Grimsdell and Angevine, 2002; Angevine 2008). Investigating the turbulence decay during the afternoon transition was the main objective of the Boundary Layer Late Afternoon and Sunset Turbulence (BLLAST) campaign (Lothon et al. 2014). This campaign was a large collaborative effort which allowed pooling of instrumentation to observe the ABL structure in detail. The study confirmed that while broad similarities exist in the decay of turbulence in the surface and residual layer, dissipation rate decreases first near the CBL top and opposite trends can be noted in the turbulence integral scale. It decreases near the surface but increases near the top of the CBL in the late afternoon. Large eddy simulations supported the observational findings that in a second phase, turbulence characteristics and spectra rapidly change in an upper weakly turbulent layer – a layer then referred to as pre-residual layer (Darbieu et al. 2015). The BLLAST study further showed that information about the large-scale forcing is critical for modeling the CBL evolution. Boundary layer height predictions with mixed layer models agreed much better with observation when subsidence was specified (Pietersen et al. 2015). Measuring subsidence is however extremely challenging if not impossible. The BLLAST study serves as an example of a well-designed observation campaign that was supported by numerical studies and improved the understanding of processes during the afternoon ABL processes: the ABL fades away rather than it collapses, thermals become less energetic as the surface fluxes decrease, and shear-driven entrainment stabilizes the upper CBL which explains why turbulence decays first in this region. The CBL presentation further highlighted that entrainment processes are key during the morning transition of the ABL and that the classic picture of the inversion eroding from the surface does not hold. The layer of air below 50 m often shows a warming trend before heat fluxes become positive which indicates that advection plays an important role. Numerical models often prescribe entrainment fluxes as a fixed ratio of the surface flux. Observations from BLLAST show that a constant ratio between the entrainment and surface fluxes only applies when the CBL is developed (starting midday) but not during the time periods when surface fluxes are small. In addition to surface fluxes, entrainment, and advection, aerosols can also have significant contributions to heating of the ABL. In the case of deep (> 3km) afternoon mixed layer, stratospheric ozone is entrained into the ABL causing an increase in near-surface ozone concentrations (Langford et al. 2017).

1.3 Influence of Topography and Land Use

Julie Lundquist, the third invited speaker, focused on four broad scientific frontiers in her presentation: Flow in complex terrain, urban boundary layers, impacts of geoengineering and energy extraction on ABL flows, and wildfires. About 70% of the Earth's land surface can be described as complex terrain with hills, slopes, valleys, or canyons affecting the flow, and roughly 20% can be described as mountainous. Thermally driven flows often develop when pressure gradient forcing is weak. Gradients of thermodynamic surface properties and roughness can have a strong influence on the near surface structure of the ABL but they can also influence the dynamics of vortices developing as a result of flow separation near ridges. The latter flow phenomena are also strongly dependent on the synoptic and regional scale forcing, and atmospheric stability throughout the ABL. These complex interactions between mesoscale and microscale flow challenge the simulation capabilities (Fernando 2010) and require comprehensive observation networks that can capture the high spatial and temporal variability of flow and turbulence. NWP models also have difficulties in dealing with the complexity of flow and turbulence in urban areas. More than half of the worlds' population already lives in cities and the urbanization trend is expected to continue. Yet, a recent paper concluded that " a general theoretical basis for the urban boundary layer (UBL) is still lacking" (Barlow 2014). Due to deficiencies in simulating UBLs models also fail to accurately predict urban heat stress and air quality; factors which are both critical for assessing public health impacts. The understanding of urban flow scenarios and related regional impacts is still rather schematic often characterizing the flow into dome versus plume scenarios, respectively, depending on weather the large scale dynamic forcing is rather weak or strong. The conceptual pictures are however poorly supported by observations largely due to the fact that detailed datasets are lacking that capture the 3-dimensional nature and evolution of UBL flows.

Similar to urbanization, changes in land use that is related to agricultural activities and energy extraction changes the surface roughness and thermodynamic properties of the surface which can drive local-scale circulations. In the case of wind farms turbine wake effects on transport and mixing away from the surface also become important (Aitken et al. 2014). While some progress has been made in documenting the turbine wakes (Ratjewski et al. 2016) open questions remain about the 3-dimensional nature of turbine wakes, wake interactions and their impacts on ABL structure and dynamics. Fossil fuel extraction often results in increased fugitive emissions of trace gases (Kort et al. 2014), which can alter the radiation budget of the atmosphere and also lead to secondary pollutants.

With the increased frequency of wildfires and related often catastrophic economic and human losses that can be noted worldwide, better prediction tools for wild fire spread are also critically important. Such predictions require accurate information about ABL winds and temperature but observations that document the dynamic interactions between wildfires and ABL are sparse (Hanley et al. 2013). For all four science frontiers discussed it is critical to have observation platforms that can document the dynamic and thermodynamic properties of the ABL and also its chemical composition.

References:

Aitken, M. L., B. Kosovic, J. D. Mirocha, and J. K. Lundquist, 2014: Large eddy simulation of wind turbine wake dynamics in the stable boundary layer using the Weather Research and Forecasting Model. Journal of Renewable and Sustainable Energy, 6, 033137, doi:10.1063/1.4885111.

Angevine, W. M., 2008: Transitional, entraining, cloudy, and coastal boundary layers. Acta Geophysica, 56, 2-20 doi:10.2478/s11600-11007-10035-11601.

Banta RM, Mahrt L, Vickers D, Sun J, Balsley BB, Pichugina YL, Williams EJ (2007) The very stable boundary layer on nights with weak low-level jets. J Atmos Sci 64:3068–3090.

Barlow J.F. (2014) Progress in observing and modelling the urban boundary layer, Urban Climate, 10, 216-240, ISSN 2212-0955, http://dx.doi.org/10.1016/j.uclim.2014.03.011.

Darbieu, C., et al., 2015: Turbulence vertical structure of the boundary layer during the afternoon transition. Atmos. Chem. Phys., 15, 10071-10086.

Fernando, H.J.S. (2010) Fluid Dynamics of Urban Atmospheres in Complex Terrain. Annual Review of Fluid Mechanics, 42:1, 365-389

Grimsdell, A. W., and W. M. Angevine, 2002: Observations of the afternoon transition of the convective boundary layer. Journal of Applied Meteorology, 41, 3-11.

Hanley D.E., Cunningham P., Goodrick S.L. (2013) Interaction between a Wildfire and the Sea-Breeze Front. In: Qu J.J., Sommers W.T., Yang R., Riebau A.R. (eds) Remote Sensing and Modeling Applications to Wildland Fires. Springer, Berlin, Heidelberg

Hardesty R.M, R.M. Hoff (2012) Thermodynamic Profiling Technologies Workshop Report to the National Science Foundation and the National Weather Service, NCAR/TN-488+STR NCAR Technical Note, National Center or Atmospheric Research, P.O. Box 3000, Boulder, Colorado 80307-3000.

Harvey, N. J., Hogan, R. J. and Dacre, H. F. (2013), A method to diagnose boundary-layer type using Doppler lidar. Q.J.R. Meteorol. Soc., 139: 1681–1693. doi:10.1002/qj.2068

Holtslag, A.A., G. Svensson, P. Baas, S. Basu, B. Beare, A.C. Beljaars, F.C. Bosveld, J. Cuxart, J. Lindvall, G.J. Steeneveld, M. Tjernström, and B.J. Van De Wiel, 2013:Stable Atmospheric Boundary Layers and Diurnal Cycles: Challenges for Weather and Climate Models. Bull. Amer. Meteor. Soc., 94, 1691–1706,https://doi.org/10.1175/BAMS-D-11-00187.1

Kort, E. A., C. Frankenberg, K. R. Costigan, R. Lindenmaier, M. K. Dubey, and D. Wunch (2014), Four corners: The largest US methane anomaly viewed from space, Geophys. Res. Lett., 41, 6898–6903, Langford, A. O., et al. (2017), Entrainment of stratospheric air and Asian pollution by the convective boundary layer in the southwestern U.S, J. Geophys. Res., 122(2), 1312-1337, doi:10.1002/2016JD025987.

Lothon, M., F. Lohou, D. Pino, F. Couvreux, E. R. Pardyjak, J. Reuder, J. Vilà-Guerau de Arellano, P. Durand, O. Hartogensis, D. Legain, P. Augustin, B. Gioli, I. Faloona, C. Yagüe et al. (2014) The BLLAST field experiment: Boundary-Layer Late Afternoon and Sunset Turbulence. Atmos. Chem. Phys., 14, 10931-10960, 2014. doi:10.5194/acp-14-10931-2014.

Mahrt L (2014) Stably stratified atmospheric boundary layers. Annu Rev Fluid Mech 46:23–45.

National Research Council. Observing Weather and Climate from the Ground Up: A Nationwide Network of Networks. Washington, DC: The National Academies Press, 2009.

Pietersen, H. P., Vilà-Guerau de Arellano, J., Augustin, P., van de Boer, A., de Coster, O., Delbarre, H., Durand, P., Fourmentin, M., Gioli, B., Hartogensis, O., Lohou, F., Lothon, M., Ouwersloot, H. G., Pino, D., and Reuder, J.: Study of a prototypical convective boundary layer observed during BLLAST: contributions by large-scale forcings, Atmos. Chem. Phys., 15, 4241-4257, https://doi.org/10.5194/acp-15-4241-2015, 2015.

Rajewski, D. A., E. S. Takle, J. H. Prueger, and R. K. Doorenbos (2016), Toward understanding the physical link between turbines and microclimate impacts from in situ measurements in a large wind farm, J. Geophys. Res. Atmos., 121, 13,392–13,414, doi:10.1002/2016JD025297.

Sandu, I., A. Beljaars, P. Bechtold, T. Mauritsen, and G. Balsamo, Why is it so difficult to represent stably stratified conditions in numerical weather prediction (NWP) models?, J. Adv. Model. Earth Syst., 5, 117–133, doi:10.1002/jame.20013.

Steeneveld G-J (2014) Current challenges in understanding and forecasting stable boundary layers over land and ice. Front. Environ. Sci. 2:41. doi: 10.3389/fenvs.2014.00041

2. Dynamics and Thermodynamics of Convection

2.1 Shallow Convection

2.1.1 Fundamental Issues

The breakout speaker for shallow convection, Dr. Paquita Zuidema, focused on the role of shallow convection, particularly over the ocean, on the global water and energy cycle. Several areas of science focus include: (1) shallow cloud mesoscale organization, (2) evolution of boundary-layer flow into the ITCZ, and (3) high-latitude mixed-phased clouds. Distribution and evolution of global albedo critically linked to shallow clouds. These shallow convection over the ocean covers an extensive portion of the earth surface and comprehensive observations are difficult to obtain.

Dr. Zuidema argued that answering the above science questions requires complementary model simulations. However, large uncertainties exist in coupled atmosphere/ocean climate models in depicting low clouds that ultimately affects the cloud radiation effect. Models continue to struggle with the atmosphere/earth surface interface, internal processes in the boundary layer and microphysics, and the environment. The fundamental question is how to properly constrain these climate models with observations. To advance our understanding requires a good characterization of the four-dimensional structure of cloud fundamentals, water vapor, radiation, and fluxes.

Dr. Zuidema mentioned that we need to pay better attention to existing measurements by encouraging strong instrument mentorship and ownership of retrieval programs.

The breakout session spent some time discussing the definition and what should be included in the category of "shallow convection". The participants seemed to focus more on shallow clouds having their roots in the boundary layer over the ocean. However, other types of shallow convection such as congestus and cirrus in the hurricane outflow, and differences between land and ocean are little known.
The science frontiers include (1) the transition from shallow to deep convection over both ocean and land, (2) transitions between different types of boundary layer convection (e.g., convective rolls, open vs. closed cells), (3) controlling factors of mesoscale structures of shallow convection (e.g., environment, shear, surface fluxes, microphysics, aerosols), (4) difficult to forecast dissipation of post frontal shallow clouds and whether shallow clouds will transit into deep clouds, and (5) what controls the phase partition especially in high latitude?
The sections below summarize the key points raised in Dr. Zuidema's presentation, as well as the discussion in the breakout session moderated by Dr. Tammy Weckwerth and the rapporteur was Adele Igel.

2.1.2 Measurement philosophy

Satellite measurements (e.g., cloudSat and GOES) covering the globe are the primary data source for the cloud type and coverage. Targeted field campaigns using airborne and ground-based instruments including scanning and vertical pointing cloud and precipitation radars, lidar, microwave radiometer, dropsonde, insitu microphysical probes, etc. have provided snapshots of shallow convections in several regions around the world. These instruments provide cloud coverage and vertical structures, coarse vertical profiles of thermodynamics and moisture, samples of microphysical characteristics, vertical velocities, and aerosols. Advanced retrievals of moisture profiles, liquid water content, and microphysical properties can be achieved via multiple-frequency retrievals between S-Ka (e.g., S-Polka) and/or W-lidar (e.g., HCR and HSRL).

Airborne and satellite-based instruments are able to cover a large area but lacking temporal resolution and continuity. Ground-based scanning radars have good temporal continuity but with limited horizontal extent near the coastal region.

Although the workshop's focus was instrumentation, these observations have been mainly used to constrain and validate numerical models.

2.1.3 Measurements needed

- Comprehensive observations across scales (micro-meso-large scales)
- Surface fluxes should be known at km scale or even sub-km scale
- More ways to sense water vapor and temperature profiles in the boundary layer – DIAL, AERI
- High vertical resolution observations of wind, temperature and moisture near the inversion (< 25 m vertical resolution)
- High horizontal resolution observations of wind, temperature and moisture near the cloud edges
- Aerosol size spectrum and mixed-phase clouds
- Insitu and/or remote sensing for microphysics

2.1.4 Measurement gaps

- High-latitude mixed-phase clouds
- Moisture and its horizontal and vertical structure – needs active remote sensing instruments like DIAL and raman lidar
- Microphysical measurements to improve microphysical schemes in numerical models
- Diurnal cycles over the ocean away from the coast line

2.2 Maritime Convection

2.2.1 Fundamental issues

The breakout speaker for maritime convection, Dr. Larissa Back, focused on those aspects of convection having to do with its two-way interactions with the large-scale environment. This focus reflects a societal need to understand better how to treat convection in global weather and climate models. In terms of weather, the tropics exhibits better potential predictability on monthly time scales than do middle latitudes, due to the existence of the Madden-Julian oscillation (Ding et al., 2010).

However, this predictability is largely unrealized at this point due primarily to deficiencies in the treatment of convection in large-scale models (Jiang et al., 2015). Convection is the primary rainfall producer over the tropical oceans and is the biggest unknown in controlling the distribution of moisture in the atmosphere. This moisture and the resulting distribution of clouds play a zeroth order role in the Earth's radiation budget, with large consequences for climate change.

Dr. Back stressed the importance of understanding the lateral imports and exports of mass, moisture, and moist static energy (or moist entropy) to and from convective systems (Masunaga and l'Ecuyer, 2014; Inoue and Back, 2015). Not stressed by Dr. Back, but also of potential importance according to some investigators is the import and export of momentum (Majda and Stechmann, 2009). The mesoscale radiation budget forms an important part of the moist static energy budget and may be largely responsible for the phenomenon of convective aggregation (Muller and Held, 2012; Wing and Emanuel, 2013; Muller and Bony, 2015; Sessions et al., 2016).

Equally important are the factors that control the amount and form of convection occurring in any given area and time interval. As convection is an inherently chaotic phenomenon, only the statistical properties of convection can potentially be predicted from the variables available in a typical large-scale model (Ooyama, 1982; Xu et al., 1992; Raymond et al., 2015). This has important observational consequences as well. Observations of a single convective cell or system, though interesting, are essentially useless for answering the above questions. Enough observations need to be made in an unbiased fashion to develop a valid characterization of the statistics of convection in a given environment. Convection in strong tropical cyclones is a special case. As a tropical cyclone intensifies, it eventually reaches a point where the convection is so tightly coupled to the larger system that the two together must be treated as a single entity (Ooyama, 1982).

It should finally be mentioned that the emphasis on the ensemble aspects of convection, which hitherto have been focused on tropical oceanic regions, needs to be extended to higher latitude oceanic convection as well as convection over land, as these regions are a part of the global weather and climate system as well.

2.2.2 Measurement philosophy

Satellite measurements cover the globe but are deficient in some aspects. Winds are not well constrained in the tropics and passive microwave measurements of temperature and humidity typically exhibit low vertical resolution. (Resolution may be increased by use of GPS occultation measurements.) Routine in situ measurements over the oceans are sparse. Episodic process studies involving in situ observations provide accurate measurements but are very small in spatial and temporal coverage.

Process studies are useful in sorting out how various mechanisms work, thus providing a basis for improvements in operational modeling. However, for convection in particular, they must be designed and executed in a manner that provides a statistically significant sample of the needed measurements. Where possible, this implies repeated execution of pre-specified patterns so as to reduce sampling bias. If conditional sampling is needed to capture the phenomenon of interest, then the imposed sampling bias must be well understood for the results to be useful.

Process studies often work best when satellite observations are integrated into the study. Process studies can be used to understand biases and other problems with satellite measurements. Modeling results can also be useful, but only when the model biases and uncertainties are well understood.

Process studies are the primary focus of this document.

2.2.3 Measurements needed

The needed measurements fall into two categories:

i. Budget measurements

Grids of temperature, humidity, pressure, and wind profiles need to be made with mesoscale horizontal resolution and high enough vertical resolution to provide reliable budgets. Strong vertical gradients of these quantities are found in and just above the boundary layer. Ideally, the measurements should extend to above the tops of the deepest convection, though if this is not possible, estimates of fluxes through the tops of the measurement boxes can be made if the maximum measurement altitude is not too far below cloud tops.

Making pressure measurements to the accuracy required to understand momentum budgets in the tropics is particularly difficult, as the pressure gradients are typically weak. The accuracy of humidity measurements is also a potential problem area. Budget measurements must be “all weather”. Gaps in these measurements can cause important contributions to budgets to be missed. If, for instance, clouds or a lack of clouds result in a loss of data (think respectively Doppler lidar and Doppler radar) then this is serious problem. Multiple instruments working together may help address this issue.

ii. Direct measurements of convection

At times it may be necessary to make detailed measurements on convection in order to understand better its fundamental physics or to test cloud-resolving models. A wide variety of tools can be used to make these measurements, from scanning and profiling radars to direct penetration measurements of temperature, humidity, winds, as well as hydrometeor, aerosol, and electrical properties.

Measurements of this type are very subject to sampling bias, caused, for instance, by eagerness to look at only the most spectacular convection or by the inability to penetrate strong convection safely. Again, a well thought-out plan is needed to account for such bias.

2.2.4 Measurement tools

i. Platforms

Direct and budget measurements of convection over oceans require either aircraft or ships as platforms. Aircraft have the advantage that they can cover a large area and make in situ measurements above the surface. Ships move much more slowly, but unlike aircraft, they can remain in a fixed position for days to weeks. NSF maintains a fleet of oceanographic research vessels which could in principle be used for atmospheric measurements. NOAA ships have also been made available for these purposes.

The following is a list of aircraft platforms currently available in the NSF arsenal:

- Gulfstream-V: This aircraft has very long range, high speed, and can ascend to near the tropical tropopause. It can carry a moderate load of equipment, but suffers some performance degradation when large external pods are employed.
- C-130: This aircraft has long range and heavy load carrying capacity, but cannot ascend to the upper troposphere.
- Wyoming King Air: The King Air has moderate range and load carrying capacity but is also limited to the middle troposphere and below.

Other platforms available or potentially available to the broader research community are remotely piloted vehicles (RPVs) and balloons. NASA has a number of research aircraft with high altitude and long range capabilities, such as the DC-8, the ER-2, and 3 WB-57 aircraft. Balloons can deploy dropsondes from the stratosphere but go where the wind carries them. Many RPV platforms are in the works or in limited use, but the most notable for over-ocean atmospheric research is the Global Hawk. NASA demonstrated that this RPV can operate over a vast area near 20 km elevation with 26 hr endurance, while carrying an array of remote sensing equipment as well as dropsondes. An A-10 storm penetration aircraft is under consideration by NSF, but due to its short range it would be of limited value for maritime convection.

ii. Budget measurements

- Dropsondes: The premier tool for budget measurements of all kinds is the dropsonde. With various airborne platforms, especially the Gulfstream-V as well as NASA's DC-8, ER-2, WB-57, and Global Hawk, they can be deployed from high altitude over virtually any part of the globe. NCAR's AVAPS system has been refined to have automatic deployment and high reliability. The Yankee dropsonde is promising but in an earlier stage of development. The disadvantage of dropsondes is a relatively high cost per sonde. However, use of dropsondes is often the only way to make budget measurements on convective systems. Sonde deployment in regions of heavy commercial air traffic or over many land areas is also difficult.

- Wind lidars: NASA has developed a near-infrared Doppler wind lidar (DAWN) based on aerosol scattering. This lidar samples points on a conical scan about nadir and is able to reconstruct the three-dimensional wind. Recent experience (NASA CPEX project, June 2017) shows that profiles in the boundary layer are obtainable from 13 km, and with sufficient averaging, winds can sometimes be measured in the mid-troposphere. Ramping up the power and/or sampling rate could improve its performance further. Thin clouds can be penetrated at some loss of sensitivity, though thicker clouds are opaque, limiting its use in cloudy regions.
- Passive microwave sensing: The microwave temperature profiler (MTP) is available on NCAR aircraft. This JPL instrument has a relatively slow scan rate (complete profiles every 17 s) and unspecified vertical resolution. NASA’s HAMSR is a crosstrack-scanning passive microwave sounder that measures temperature, humidity, and liquid water profiles with vertical resolution of approximately 2 km. It has been used on a number of NASA aircraft over the years. The instrument’s coarse vertical resolution means that it cannot replace dropsondes. However, it works in both clear and cloudy conditions unless there is heavy precipitation.
- In situ measurements: High altitude radiative flux measurements can be made with existing instrumentation while deploying dropsondes. Simultaneous measurements at other altitudes would require an additional aircraft so as not to interfere with dropsonde and profiler measurements.

Direct measurements of convection

- Profiling Doppler radars: The NSF Hiaper Cloud Radar (HCR) is a W band Doppler radar mounted in a wing pod on the Gulfstream-V. HCR can stare in the nadir or zenith positions or it can scan in the crosstrack direction. Mean Doppler particle velocities, reflectivity, and depolarization measurements can be made. If needed, the full Doppler spectrum can be saved and utilized. The short wavelength of this radar means that its beam is rapidly attenuated in moderate to heavy precipitation. The University of Wyoming has a similar radar available for use on the Wyoming King Air and the NCAR C-130. NASA’s APR-3 radar has similar capabilities, but operates at 3 wavelengths, Ka band, Ku band, and W band. It has been used on the NASA DC-8. The High Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP) is a Ka/Ku band Doppler radar that operates with a conical scan to provide reflectivity and three-dimensional winds. It was designed to operate on NASA’s Global Hawk RPV. Ships may provide a suitable platform for profiling radars.
- Scanning Doppler radars: This type of radar differs from the profiling radar in that it is designed to produce input for dual Doppler analysis of precipitating regions. These radars are the only way of measuring three-dimensional flow patterns within precipitating clouds. Inclusion of polarization diversity allows inferences to be made about the form of hydrometeors. The ELDORA radar is an X band system designed originally to mount on the tail of the now-decommissioned

NCAR Electra aircraft. A Naval Research Laboratory P-3 aircraft was subsequently modified to carry ELDORA, but this aircraft was also decommissioned and ELDORA is now sitting on a shelf with no suitable aircraft platform in sight. NOAA has two X band scanning radars mounted on their WP-3 hurricane research aircraft. However, access to these aircraft for NSF-funded investigators is very limited. In order to fill this gap, NCAR has proposed to build an airborne phased array radar (APAR) to be mounted on the NCAR C-130. This would be a C band radar with dual polarization capability. Operation in the C band would reduce attenuation compared to X band radars. The development of this radar would fill a critical gap in our ability to characterize convection. Ship-based scanning radars have also been used extensively for observations of convection. These radars can be deployed together to produce dual Doppler observations, though this is rarely done, due to the expense. Single radars can produce divergence profiles in regions of high convective coverage using ship and airborne EVAD techniques (Matejka and Srivastava, 1991).

- In situ measurements: Aircraft penetrations of convection yield high spatial resolution measurements of winds, thermodynamic quantities, cloud and precipitation particle characteristics, and radiative fluxes. (The Radiometric Air Temperature instrument is needed to provide accurate in-cloud air temperatures.) A disadvantage is that measurements are made only along the aircraft path. In addition, convection with high radar reflectivity or lightning activity must generally be avoided, due to the associated risks. Maritime convection is generally less of a problem in this respect than continental convection. Discussion of cloud and precipitation particle measurements is deferred to the cloud physics section of this document.

2.2.5 Summary for maritime convection

In order to make progress on understanding maritime convection, two types of measurements are needed, (1) mesoscale grids of wind, temperature, humidity, and pressure through the depths of the troposphere, surface fluxes of heat, moisture, and momentum, surface and tropopause radiative fluxes, and (2) detailed measurements on the components of convective systems, i.e., vertical and horizontal velocity fields, temperature and humidity structure, estimates of radiative flux divergence in and around clouds, and precipitation characteristics. Facilities needed to make these measurements are:

- Mesoscale grids
  – Grids of dropsonde measurements deployed from near or above cloud tops.
  – Scanning wind lidar systems (aerosol Doppler lidar is promising but other technologies should be explored as well).
  – Passive microwave sensing of temperature and humidity profiles.
  – In situ measurement of radiative fluxes.
- Detailed convective measurements
  – Profiling Doppler radars at various wavelengths (mainly W and K band).
  – Scanning Doppler radars usable for making dual Doppler syntheses of airflow (X or preferably C band; polarization diversity would be helpful for cloud physics).

These radars could be used in profiling mode in strong convection where W and K band radars suffer attenuation.

- In situ measurements of wind (gust probe), temperature (radiometer inside clouds), humidity, and cloud physical properties.
- In situ radiative fluxes at various levels.

An aircraft with high altitude and long range capability such as the NSF/NCAR Gulfstream-V is needed for the mesoscale grids over remote oceanic regions in the tropics. Surface fluxes can be estimated from dropsonde and possibly profiler data. Upper level in situ radiative fluxes can be obtained with this aircraft.

The Gulfstream-V is capable of some cloud penetration at high altitudes in maritime convection, but is not the ideal tool for this job where there is strong turbulence or high reflectivity. The NCAR C-130 is better suited to cloud penetrations and would be able to carry the planned APAR Doppler radar and much other convective instrumentation. However, high reflectivity and lighting are out of bounds for the C-130 as well. Furthermore, this aircraft can reach only the middle troposphere. There is a need for a convective penetration aircraft (manned or unmanned) that can study convective cores inaccessible to existing platforms. Maritime convection places less demand on such an aircraft (less hail, weaker turbulence) than does severe continental convection. However, longer range capabilities would be needed than for land-based observations.

Ships can carry lidars and radars, deploy radiosondes, and make continuous in situ measurements over periods of days to weeks.

2.3 Continental Convection

2.3.1 Fundamental issues

The breakout speaker for continental (deep) convection, Dr. Matthew D. Parker, focused on the observations needed to advance our understanding of continental storms, particularly those at midlatitudes that have a high societal impact, such as severe thunderstorms that produce tornadoes, large hail, flash floods, and damaging straightline winds.

Dr. Parker argued that most of the "first-order" dynamical processes governing convective storms have been reasonably well articulated. However, we still have a rather limited understanding of how the complexities of real world storms coincide with and differ from our first-order conceptual models.

Some of the "hot topics" currently being pursued in the midlatitude convective storms community include the following: (1) lower tropospheric processes that produce (or fail to produce) tornadoes and intense mesovortices; (2) precipitation processes in storms, including the impacts of aerosols, processes in the mixed-phase region, and subsequent dynamical impacts; (3) storms in non-classical

environments (e.g., at night, during the cold season); (4) the impacts of mesoscale variability on convective storms (e.g., terrain, land-cover, etc.).
The sections below summarize the key points raised in Dr. Parker's presentation, as well as the discussion in the breakout session moderated by Dr. Stephen Nesbitt.

2.3.2 Measurement philosophy

There was broad sentiment that pooled resources (LAOF) are preferable to distributed resources (each university having its own instrument). The former fosters uniformity in data quality and data access, and allows proposal competitions to emphasize science merits, as opposed to "who will bring what."

Although the workshop's focus was instrumentation, instrumentation is only the first step. For data to be fully exploited, the community also needs advances in analysis and assimilation tools. The tools ideally should be open source, supported, widely adoptable, and written in a modern language.

2.3.3 Measurements needed

Even though the workshop's primary goal was to gather community input on the subject of future observing capabilities, it was stressed repeatedly at the workshop, by many participants in the audience, that several existing systems have an excellent track record, provide great "bang for the buck," and must continue to serve as the backbone of almost all continental deep convection projects. These core instruments are surface-based mobile radars, surface-based mobile sounding systems, mobile surface stations ("mesonets"), and disdrometers. These systems are relative inexpensive (especially compared to airborne systems), user-friendly (high measurement quality, straightforward QC), easily redeployed, and not especially fragile. These should continue to be supported as a community resource.

As for the future—the frontiers of understanding and predicting continental deep convection and its attendant hazards—advances in our understanding will require a more complete depiction of the 4D fields both inside and outside of storms. Measurements of winds, thermodynamic fields (temperature, humidity, pressure), aerosols, and precipitation particles, both at the surface and above ground, on spatial scales of a kilometer or less in the horizontal, no more than ~250 m in the vertical, and on time scales of no more than a few minutes, are critical. There remain many gaps in our ability to sample such fields to such a degree, especially when it comes to thermodynamic observations and aerosols.

The remainder of this section is organized in terms of observing needs outside of storms and observing needs inside of storms.

i. Observing needs outside of storms

We need to improve our ability to map the mesoscale lower troposphere outside of storms. Water vapor concentrations and heterogeneity has major impacts on convective predictability. Temperature fluctuations in near-ground lapse rates (linked to cloudiness, land cover, etc.) potentially influence storms in important ways, as do mesoscale (or even smaller scale) variations in the wind field owing to boundary-layer circulations, storm-induced wind perturbations, and other sources of heterogeneity. One challenge with observations that are limited to quasi-instantaneous, quasi-vertical columns (e.g., soundings, wind profilers) is that it is exceedingly difficult to separate the local state from the horizontal and temporal variability.

Upsondes. Pros: Cheap; user-friendly; easily relocatable; proven technology. Cons: Many systems and operators are needed to map temporal and spatial variability; upsondes have a potentially large downstream drift.
Dropsondes. Pros: Produce profiles that are more nearly instantaneous vertical profiles than upsondes; can quickly cover a large footprint. Cons: Cost of flight hours; unable to drop over land except in limited circumstances.
Ground-based lidars/profilers/sounders/etc. Pros: Produce a true vertical column of observations, in many cases nearly instantaneously; capture continuous evolution. Cons: Shallow sampling depth (some cases); inoperable in precipitation; attenuation by cloud (some cases); thermodynamic profiles can be poorly constrained.
Airborne lidars. Pros: Instantaneous vertical column; can quickly cover a large footprint. Cons: Cost of flight hours; inoperability in precipitation; attenuation by cloud; thermodynamic profiles can be poorly constrained; no wind information.
UAVs. Pros: Cheaper way for a single observing system to cover a somewhat large footprint. Cons: Unclear what kinds of vertical profiling payloads are possible; FAA restrictions.

One idea that emerged as a means to map the wind fields in the environments of convective storms is by way of inexpensive, low-power, single-chip receivers that could potentially be used to create a network of passive (parasitic) multi-static wind profiling radars. Another idea that emerged was small, lightweight (slow fallspeed), biodegrable probes that could be dropped by the 100s or 1000s by an aircraft. Such a system is known to be in development with at least one private-sector company. These observations could, in principle, yield the sort of thermodynamic mapping of the environment of convective storms that is needed (the wind field would be measured as well).

ii. Observing needs within storms

The focus of the discussion of the observations needed within storms to advance our understanding of storms dealt with observations above the ground, particularly thermodynamic and microphysical observations. Reliable, above-ground, thermodynamic observations in convective storms have been conspicuously missing throughout the history of severe storms research. These missing observations, and the errors in the thermodynamic fields of simulated storms, are routinely cited as being among the most important hurdles to furthering our understanding of vorticity generation in supercell storms, as well as addressing many key aspects of mesoscale convective systems, such as their maintenance and production of damaging winds. Of greatest interest are observations within the cold pools of storms, where gradients are large and substantial amounts of vorticity can be generated. With respect to observing the microphysical properties of storms, many aerosol impacts on storm properties have been hypothesized, and considerable uncertainty also still surrounds the formation of large hail and other mixed-phase processes. Hydrometeor retrievals from polarimetric radar observations are in wide use, and microphysics parameterizations in numerical models continually become increasingly sophisticated; however, the community possesses a dearth of in situ microphysical observations in storms. Hydrometeor retrievals desperately need validation, as do the microphysics parameterizations in today's state-of-the-art cloud models.

Upsondes. Pros: Inexpensive; user-friendly; easily relocatable; proven technology. Cons: Highly erratic trajectories within storms; no aerosol or precipitation information.

Dropsondes. Pros: Produce profiles that are more nearly instantaneous vertical profiles than upsondes; can quickly cover a large footprint. Cons: Cost of flight hours; unable to drop over land except in limited circumstances.

Radars (fixed, truck-borne, airborne). Pros: Three-dimensional depictions from one sensor; somewhat easily relocatable. Cons: Wind and bulk precipitation information only; assumptions needed for dual-Doppler; short wavelengths lead to attenuation and issues with hydrometeor retrievals (in the case of polarimetric radars).

Airborne in-situ sensors. Pros: Perform horizontal transects; characterize aerosols/precipitation. Cons: Cost of flight hours; information only along flight track

UAVs. Pros: Perform horizontal transects more cheaply than manned aircraft and closer to the ground. Cons: Unclear what kinds of payloads are possible; FAA restrictions (in addition to being limited to certain geographical locations, there also are somewhat restrictive ceiling limitations and a visual contact requirement); information only along flight track; may not be able to sample the most scientifically interesting parts of severe storms owing to large hail, low visibility, severe turbulence and downdrafts, and requirement that visual contact be maintained.
Lidars/profilers/sounders/etc. Pros: True vertical column, in many cases nearly instantaneously. Cons: Inoperability in precipitation, fragility of sensors often precludes operation in severe storms.

Concerning radars, dish-scanning radars in traditional scan strategies provide limited detail on fine-scale processes. The update times exceed the timescale on which many fine-scale convective features evolve. Reconstructed RHIs and dual-Doppler syntheses smear cores and do not resolve turbulent and microphysical processes. RHIs are more detailed, but only in a single slice. Improvements in, and increasing availability of, phased-array/imaging radars will greatly improve our ability to observe rapid evolution in convective storms, as well as compute more accurate trajectories from dual/multi-Doppler wind syntheses.

One not-yet-in-existence observing system in which workshop attendees exhibited a recurring interest was a swarm of 100s or 1000s of small, lightweight (slow fallspeed), biodegrable probes that could be dropped from a manned or unmanned aircraft, or perhaps even a large balloon. These observations could, in principle, yield the sort of thermodynamic mapping of the environment of convective storms that is needed (the wind field would be measured as well). There was interest in exploring other "drifter" capabilities as well. In summary, there is a considerable interest in pushing the development of technologies that can map the 4D thermodynamic fields within storms via in-situ methods, given the limitations of remote sensing within storms (e.g., attenuation by cloud and/or precipitation, slow updates/insufficient resolution in time). An airborne profiling instrument that works within clouds/precipitation would be transformative.

References

Ding, R., J. Li, K.-H. Seo, 2010: Predictability of the Madden-Julian oscillation estimated using observational data. Mon. Wea. Rev., 138, 1004-1013.

Inoue, K., and L. Back, 2015: Column-integrated moist static energy budget analysis on various time scales during TOGA COARE. J. Atmos. Sci., 72, 1856-1871.

Jiang, X. and Co-Authors, 2015: Vertical structure and physical processes of the Madden-Julian oscillation: Exploring key model physics in climate simulations. J. Geophys. Res., 120, 4718-4748.

Majda, A. J., and S. N. Stechmann, 2009: A simple dynamical model with features of convective momentum transport. J. Atmos. Sci., 66, 373-392.

Matejka, T., and R. C. Srivastava, 1991: An improved version of the extended velocity-azimuth display analysis of single-Doppler radar data. J. Ocean. Atmos. Tech., 8, 453-466.

Masunaga, H., and T. S. L'Ecuyer, 2014: A mechanism of tropical convection inferred from observed variability in the moist static energy budget. J. Atmos. Sci., 71, 3747-3766.

Muller, C., and S. Bony, 2015: What favors convective aggregation and why? Geophys. Res. Letters, 42, 5626-5634.

Muller, C. J., and I. M. Held, 2012: Detailed investigation of the self-aggregation of convection in cloud-resolving simulations. J. Atmos. Sci., 69, 2551-2565.

Ooyama, K., 1982: Conceptual evolution of the theory and modeling of the tropical cyclone. J. Meteor. Soc. Japan, 60, 369-379.

Raymond, D. J., Z. Fuchs, S. Gjorgjievska, and S. L. Sessions, 2015: Balanced dynamics and convection in the tropical troposphere. J. Adv. Model. Earth Syst., 7, doi:10.1002/2015MS000467.

Sessions, S. L., S. Sentic, and M. J. Herman, 2016: The role of radiation in organizing convection in weak temperature gradient simulations. J. Adv. Model. Earth Syst., 8, doi:10.1002/2015MS000587.

Wing, A. A., and K. A. Emanuel, 2013: Physical mechanisms controlling self-aggregation of convection in idealized numerical modeling simulations. J. Adv. Model. Earth Syst., 5, doi:10.1002/2013MS000269.

Xu, K.-M., A. Arakawa, and S. K. Krueger, 1992: The macroscopic behavior of cumulus ensembles simulated by a cumulus ensemble model. J. Atmos. Sci., 49, 2402-2420.

3. Free Tropospheric Flows and Turbulence

3.1 Terrain-Driven Flows and Turbulence

3.1.1 Background

Stratified airflow that passes over a topographic barrier generates atmospheric gravity waves or mountain waves and turbulence (e.g., Doyle et al. 2016) and has a profound influence on the atmosphere on a variety of spatial and temporal scales. These impacts range from turbulence scales, associated with downslope windstorms, rotors, internal hydraulic jumps, mountain wave overturning or breaking, to the aggregate effects of mountain wave drag and vertical flux of horizontal momentum, which contributes to the momentum balance of the atmospheric general circulation and climate [see reviews by Smith (1989), Fritts and Alexander (2003), and Durran (1990). Vertically propagating mountain waves often increase in amplitude with height because of decreasing air density and/or environmental conditions such as reverse (or negative) vertical wind shear layers, leading to wave steepening, overturning, and subsequent turbulent breakdown. Mountain waves may overturn and break as they approach a critical level, i.e. a level at which the wave phase speed is equivalent to the wind component projected along the horizontal wave vector. An increase in the atmospheric stability, such as across the tropopause, can reduce the vertical wavelength and increase the potential for wave breaking and turbulence. Wave breaking characterized by overturning of isentropic surfaces often involves nonlinear interactions and buoyant exchanges that occur in the transition to turbulence. The lee side of prominent terrain barriers are well-known for highly turbulent topographically-forced phenomena such as downslope windstorms, trapped lee waves, and rotors. Severe downslope winds, occasionally in excess of 50 m s-1 near the surface, may decelerate rapidly in the lee and give way to an unsteady return flow back toward the mountain crest that is the lower branch of a highly turbulent and intense horizontal circulation, referred to as a rotor.

3.1.2 Observing and Research Challenges and Frontiers

An improved understanding and modeling of mountain waves, winds, breaking are needed, particularly bridging the gap between theory and the real world. The theory builds on simple flows and simple terrain with simple boundary layers, and only a basic consideration of turbulence. Model parameterizations for gravity wave drag are known to be deficient and highly tuned, and observationally based advancements are needed. Specific observing and research challenges and frontiers include:

- Turbulent flow over relatively low terrain and hills; the key challenges include i) complex terrain, ii) boundary layer complexities arising from varying land surface characteristics, and iii) upstream flow sensitivity
- The role of turbulence and upwind PBL stability and depth on: i) wave launching, ii) lee waves (Smith et al. 2007; Jiang and Doyle 2008)
- The influence of varying land surface characteristics and the diurnal cycle on gravity wave launching
- The characterization of low-level turbulence in rotors and wave breaking (Doyle and Durran 2002; Grubišić et al. 2008; Strauss et al. 2015)
- The dynamical continuum of wave response from highly-turbulent internal hydraulic jumps and wave breaking, rotors, to more laminar lee waves (Armi and Meyer 2011; Durran 1986; Strauss et al. 2016)
- The turbulent characteristics of sub-rotor scale eddies (Doyle et al. 2009; Strauss et al. 2016)
- The nature of turbulent flow in downslope windstorms and within the "shooting" flow (Strauss et al. 2016)
- Topographically generated wind flow and turbulence around islands and coastal promontories under a range of surface fluxes and stabilities (Pullen et al. 2011)
- Gravity wave breaking, both in the troposphere and at higher altitudes, and its impact on mixing of chemical constituents and water vapor (Heller et al. 2017)
- Gravity wave momentum flux and energy flux diagnostics including under temporally varying environmental conditions (Smith et al. 2016; Chen et al. 2005)
- Observations of upper-atmosphere (mesosphere-lower thermosphere) wave breaking (Smith et al. 2012)

- Turbulence generated by terrain-induced blocking and microphysical processes (Rotunno and Houze 2007; Seity 2003)
- Mechanical convection over small scale terrain, and generation of clear air turbulence (Smith et al. 2012)

3.1.3 Discussion

One question asked following the plenary presentation by James Doyle concerned the trade-off between finer-scale measurements and higher absolute accuracy. The speaker favored higher spatial resolution. Another concerned the impact of moisture in cross-mountain flow on the intensity of downslope windstorms. The speaker agreed that the intensity is very sensitive to moisture. The upwind latent heating profile can determine whether or not a downslope windstorm develops an which type it is.

The breakout session focused on instrumentation capabilities needed to address these challenges. Instrumentation and capabilities discussed for the study of coupling of waves and boundary layer flows included ceilometers, wind profiler networks, and temperature and moisture profilers. It is desirable to characterize upstream conditions, as well as conditions over and downwind of complex terrain.

For characterizing low-level turbulence in regions with rotors and low-level wave breaking the following were discussed: airborne laser motion systems (LAMS) such as those currently under development at the NCAR Earth Observing Laboratory, surface–based profilers with a resolution of 25 m able to complete new profiles at 2 min intervals, a high-density network of surface-based instrumented towers, aircraft able to withstand severe turbulence, Doppler lidars, narrow-beam high-resolution radars, and rapid-scanning (phased-array) radars. Measurements are needed both in clear conditions, and in conditions with a mix of clouds and clear air. Most suitable instruments are experimental, and placing them at the right location is challenging. Also desirable are continuous measurements for extended periods of time to sample a range of conditions.

For studying mountain waves and free tropospheric fluxes associated with mountain waves a key question is the temporal variability of the fluxes and the impact of wave breaking on them. Airborne momentum and heat flux measurements are required. Specially designed up- and downsondes, and constant-level balloon packages possibly including fast temperature sensors, accelerometers, and/or optical turbulence sensors, were also proposed.

Gravity-wave drag parameterizations can possibly be improved using a combination of focused field programs over major mountain ranges and global satellite remote-sensing observations.

The final topic of the breakout session was the influence of orographic turbulence near the surface or in the free troposphere on precipitation. Observational needs include detailed microphysical observations at the surface combined with airborne in situ and profiling mm-wave radar measurements along with scanning ground-based radars covering the entire weather system from upstream, over the barrier, to downstream. Improved remote sensing of precipitation near the mountain top needs particular attention. It is difficult to get accurate in situ observations there. The role of complex terrain and gravity waves in initiating deep convection also needs study.

3.1.4 References

Armi, L., and G. J. Mayr, 2011: The descending stratified flow and internal hydraulic jump in the lee of the Sierras. J. Appl. Meteor. Climatol., 50, 1995–2011, doi:10.1175/JAMC-D-10-05005.1.

Chen, C.-C., D. R. Durran, and G. J. Hakim, 2005: Mountain-wave momentum flux in an evolving synoptic-scale flow. J. Atmos. Sci., 62, 3213–3231, doi:10.1175/JAS3543.1.

Doyle, J.D., Q. Jiang, P. Alex Reinecke, 2016: Numerical Modeling and Predictability of Mountain Wave-Induced Turbulence and Rotors. Aviation Turbulence: Processes, Measurement, Prediction, Springer, R. Sharman and T.P. Lane (eds.), 357-384.

Doyle, J.D., and D.R. Durran, 2002. The Dynamics of Mountain-Wave Induced Rotors. J. Atmos. Sci., 59, 186-201.

Doyle, J.D., V. Grubišić, W.O.J. Brown, S.F.J. De Wekker, A. Dörnbrack, Q. Jiang, S.D. Mayor, M. Weissmann, 2009: Observations and numerical simulations of subrotor vortices during T-REX. J. Atmos. Sci., 66, 1229-1249.

Durran, D.R.: Another look at downslope windstorms, 1986: Part I: The development of ana-logs to supercritical flow in an infinitely deep, continuously stratified fluid. J. Atmos. Sci. 43, 2527-2543.

Durran, D. R., 1990: Mountain waves and downslope winds. Atmospheric Process over Complex Terrain. AMS Monograph, 23, 59-81.

Fritts, D.C., and Alexander, M.J., 2003: Gravity wave dynamics and effects in the middle atmosphere. Rev. Geophys. 41(1), 1003. doi:10.1029/2001RG000106.

Grubišić, V., J.D. Doyle, J. Kuettner, S. Mobbs, R.B. Smith, C.D. Whiteman, R. Dirks, S. Czyzyk, S.A. Cohn, S. Vosper, M. Weissman, S. Haimov, S. De Wekker, L. Pan, F.K. Chow, 2008: The Terrain-Induced Rotor Experiment: An overview of the field campaign and some highlights of special observations. Bull. Amer. Meteor. Soc., 89, 1513-1533.

Heller, R., C. Voigt, S. Beaton, A. Dörnbrack, S. Kaufmann, H. Schlager, J. Wagner, K. Young, M. Rapp, 2017. Mountain waves modulate the water vapor distribution in the UTLS. Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2017-334.

Jiang, Q., and J.D. Doyle, 2008: Impact of the atmosphere boundary layer on mountain waves. J. Atmos. Sci., 65, 592-608.

Pullen, J., A.L. Gordon, J. Sprintall, C. Lee, J.D. Doyle, P. May, 2011: Winds, eddies and flow through straits. Oceanography, 24, 112-121.

Rotunno, R. and Houze, R. A., 2007: Lessons on orographic precipitation from the Mesoscale Alpine Programme. Q.J.R. Meteorol. Soc., 133: 811–830. doi:10.1002/qj.67

Seity, Y., S. Soula, P. Tabary, and G. Scialom (2003), The convective storm system during IOP 2a of MAP: Cloud-to-ground lightning flash production in relation to dynamics and microphysics, Q. J. R. Meteorol. Soc., 129, 523–542, doi:10.1256/qj.02.03.

Smith, R.B., J.D. Doyle, Q. Jiang, S.A. Smith, 2007: Alpine wave breaking: Lessons learned from MAP regarding mountain wave generation and breaking. Q. J. Roy. Meteor. Soc., 133, 917-936. DOI: 10.1002/qj.103.

Smith RB, Nugent A, Minder J, Kirshbaum DJ, Warren R, Lareau N, Palany P, James A, French J. 2012. Orographic precipitation in the tropics: The Dominica experiment. Bull. Am. Meteorol. Soc. 93: 1567–1579.

Smith, R.B, A.D. Nugent, C.G. Kruse, D.C. Fritts, J.D. Doyle, S.D Eckermann, M.J. Taylor, A. Dörnbrack, M. Uddstrom, W. Cooper, P. Romashkin, J. Jensen, S. Beaton, 2016: Stratospheric gravity wave fluxes and scales during DEEPWAVE. J. Atmos. Sci., 73, 2851-2869.

Smith, R.B.: Hydrostatic flow over mountains, 1989. Adv. Geophys. 31, Academic Press, New York, 1-41.

Strauss, L., Serafin, S., Haimov, S. and Grubišić, V. (2015), Turbulence in breaking mountain waves and atmospheric rotors estimated from airborne in situ and Doppler radar measurements. Q.J.R. Meteorol. Soc., 141: 3207–3225. doi:10.1002/qj.2604.

Strauss, L., S. Serafin, and V. Grubišić, 2016: Atmospheric rotors and severe turbulence in a long deep valley. J. Atmos. Sci., 73, 1481–1506, doi:10.1175/JAS-D-15-0192.1.

3.2 Turbulence in Clouds and Precipitation

3.2.1 Background

Turbulence plays a critical role in the formation, lifetime and dissipation of cloud systems. In warm clouds, the influence of turbulence on cloud microphysics and mixing with the environment has been explored for decades (Baker et al., 1984; Blyth, 1993; Shaw 2003, Kumar et al., 2013). The turbulence-driven broadening of the droplet spectrum and warm-rain initiation is one of these topics and several mechanisms have been proposed for explaining the large tail in the droplet size distribution (e.g., Cooper, 1989, Pinsky et al., 2013, Korolev et al., 2013). Recent findings from high resolution observations suggest that turbulence can generate large supersaturation variability and subsequently affect the width and the size of particle size distributions and lead to precipitation formation (Seibert and Shaw, 2017, Chandrakar et al., 2016). High spatial resolution microphysical and turbulence measurements combined with information on the cloud lifetime stage are required to extend our understanding. Similar observations are indispensable to address the influence of turbulence on particle collision/coalescence (e.g., Khain et al., 2007). Turbulence may enhance collision frequencies in areas of enhanced concentration of particles, and enhance coalescence through the hydrodynamic interaction and the transport mechanism (e.g., Pinsky et al., 2008).

Entrainment and detrainment processes greatly control the growth, evolution and decay of cumuli of all depths, ranging from shallow Cu to cumulonimbus clouds, and also of stratocumulus, including the Sc clouds commonly found in upper boundary layer over subtropical oceans with relatively low SST. Despite its importance, the question whether entrainment occurs through the cloud top via penetrative downdrafts (e.g., Squires 1958, Paluch 1979) or along the cloud edges (Heus et al., 2008) remains a topic of scientific debate. These two mechanisms can be active in clouds at the same time, although their relative importance depends on the cloud lifetime stage. Cloud-top entrainment is mainly supported by mixing diagram analysis (Paluch 1979). However, a few studies (Taylor and Baker 1991 and Siebesma 1998) have cast doubt on the validity of the Paluch analysis. Without the knowledge of where entrainment occurs or how much environmental air is involved in the process, a proper understanding of shallow cumulus clouds cannot be achieved (Blyth et al. 1988). The presence of a subsiding shell around the cumulus edges (Heus and Jonker 2008; Wang et al. 2009) and the presence of vortex-ring circulations in towering cumulus clouds (Blyth et al., 2005; Damiani et al., 2006, Damiani and Vali, 2007) has implications for the microphysical composition of clouds via entrainment and recirculation of hydrometeors because of the toroidal flow.

In mixed-phased clouds the coexistence of supercooled liquid and ice crystals is thermodynamically unstable (Korolev, 2007; Morrison et al., 2012; Field et al., 2014). Turbulence generated by cloud top radiative cooling in mixed-phase boundary-layer clouds is responsible for maintain a well-mixed boundary layer, maintain the vertical transport of water vapor and generates supersaturation with respect to liquid, thus sustaining the liquid water. In deeper stratiform cloud tops, radiative cooling may result in rather small [O(1 km)] buoyantly driven circulations, so-called generating cells, since the strong updrafts may result in sufficient supersaturations to initiate ice crystals (Plummer et al. 2014; Rauber et al. 2015; Keeler et al. 2016a,b; Keeler et al. 2017). These generating cells may explain variations in ice/snow particle concentrations and liquid water content lower down in the cloud, as well as precipitation intensity on the ground. In the upper troposphere, turbulence and gravity waves activity determines the temperature and cooling rates, thus, affects cirrus macrophysical and microphysical properties (Kärcher and Ström, 2003; Comstock et al., 2008).

3.2.2 Observing and Research Challenges and Frontiers

Further understanding of interactions between turbulence, clouds and precipitation require very high range resolution measurements (2 - 5 m) from active remote sensors (narrow-beam mm-wavelength radars, Doppler lidars) and high-frequency in-situ measurements from airborne platforms (e.g. 10 Hz or ~10 m for an aircraft travelling at 100 m/s). A combination of airborne in situ microphysics, thermodynamics, and winds, along with airborne profiling radar/lidar observations is needed. Radiosonde data and surface-based remote observations with profilers, scanning radars, and passive radiometers/interferometers also are needed for studies of these clouds.

3.2.3 Discussion

Discussion in the breakout session included the need for aerosol measurements within and above the cloud layer, precision humidity observations covering the range from sub-saturation to 40% ice supersaturation, high-resolution 3-D wind measurements (both in situ and remote, e.g. the Laser Air Motion System being developed at NCAR), and detailed cloud microphysical observations, including the distribution of spacings between droplets and ice crystals and the distinction between liquid and ice. The discussion also addressed the need to link remotely sensed velocity data (turbulence and small-scale circulations at a resolution [O(10 m)]) to cloud processes such as spectral broadening, collision-coalescence, accretion, and aggregation.

Although the speaker (Pavlos Kollias) only briefly mentioned Arctic clouds in his presentation, there was an extensive discussion of such clouds in the breakout session, because cloud top cooling and buoyantly-driven turbulence may be important in the maintenance of these mixed-phase clouds. This cloud type is important to understanding polar climate, but there are many poorly understood aspects of the processes determining their optical thickness and longevity. The needs for remote and in situ air motion, cloud microphysical, and aerosol observations of these clouds were discussed.

The main focus in Kollias's presentation was on warm boundary-layer clouds and on turbulence and circulations from the cloud-scale to the micro-scale. He emphasized the need for high-resolution kinematic and cloud observations near the cloud/clear-air interface. Small-scale entrainment across this interface is an important determinant of cloud evolution (e.g., Gerber et al. 2008) Boundary layer cloud circulations transport heat and moisture through the boundary layer and also influence regional radiative flux divergence profiles.

Not covered by Kollias, but discussed in the breakout session, is the influence of cloud turbulence on electric charge separation in storms and the lightning that can result. Charge separation is thought to occur during collisions between ice hydrometeors. Turbulence may be a key factor in understanding the conditions that lead high collision rates and electrification.

The key overall observational challenges summarized by Kollias include improved ability to sample the cloudy-clear air interface at high ([O(10 m)] or better) resolution, using narrow-beam Doppler lidar and radars and high-frequency microphysical and thermodynamic probes, coordination between slow-moving airborne platforms and ground-based observations, the need for 3-D turbulence measurements, and improved observations of aerosol properties from the surface to the cloud layer. Additional challenges discussed in the breakout session include the highly variable and intermittent nature of turbulence in otherwise stratified flow, the need for in-cloud turbulent flux estimation, the need to resolve finer scales of turbulence, and physical and legal limitations on minimum flight levels and in-cloud flight operations for manned and unmanned platforms.

References

Baker M.B., Breidenthal R.E., Choularton T.W., Latham J.: The effects of turbulent mixing in clouds. J. Atmos. Sci. 41, 299–304 (1984)

Blyth, A. M., W. A. Cooper, and J. B. Jensen, 1988: A study of the source of entrained air in Montana cumuli. J. Atmos. Sci., 45, 3944– 3964.

Blyth A.M.: Entrainment in cumulus clouds. J. Appl. Meteorol. 32, 626–640 (1993)

Blyth, A. M., S. G. Lasher-Trapp, and W. A. Cooper, 2005: A study of thermals in cumulus clouds. Quart. J. Roy. Meteor. Soc., 131, 1171–1190

Chandrakar, K. K., W. Cantrell, K. Chang, D. Ciochetto, D. Niedermeier, M. Ovchinnikov, R. A. Shaw, and F. Yang (2016): Aerosol indirect effect from turbulence-induced broadening of cloud-droplet size distributions PNAS 113: 14243-14248.

Comstock, J. M., R.-F. Lin, D. O'C. Starr, and P. Yang (2008), Understanding ice supersaturation, particle growth, and number concentration in cirrus clouds, J. Geophys. Res., 113, D23211, doi:10.1029/2008JD010332.

Cooper WA (1989) Effects of variable droplet growth histories on droplet size distributions. Part I: Theory. J Atmos Sci 46(10):1301–1311

Damiani, R., G. Vali, 2007: Evidence for Tilted Toroidal Circulations in Cumulus. J. Atmos. Sci., 64, 2045–2060.

Damiani, R., G. Vali, and S. Haimov, 2006: The structure of thermals in cumulus from airborne dual-Doppler radar observations. J. Atmos. Sci., 63, 1432–1450.

Field, P. R., Hill, A. A., Furtado, K. and Korolev, A. (2014), Mixed-phase clouds in a turbulent environment. Part 2: Analytic treatment. Q.J.R. Meteorol. Soc., 140: 870–880. doi:10.1002/qj.2175

Gerber, H. E., G. M. Frick, J. B. Jensen, and J. G. Hudson, 2008: Entrainment, mixing, and microphysics in trade-wind cumulus. J. Met. Soc. Jap., 86A, 87-106.

Heus, T., and H. J. J. Jonker, 2008: Subsiding shells around shallow cumulus clouds. J. Atmos. Sci., 65, 1003–1018. Link

Heus, T., G. Van Dijk, H. J. J. Jonker, and H. E. A. Van den Akker, 2008: Mixing in shallow cumulus clouds studied by Lagrangian particle tracking. J. Atmos. Sci., 65, 2581–2597, doi:10.1175/2008JAS2572.1

Kärcher, B. and Ström, J.: The roles of dynamical variability and aerosols in cirrus cloud formation, Atmos. Chem. Phys., 3, 823-838, doi:10.5194/acp-3-823-2003, 2003

Keeler, J. M., B. F. Jewett, R. M. Rauber, G. M. McFarquhar, R. M. Rasmussen, L. Xue, C. Liu, and G. Thompson, 2016: Dynamics of cloud-top generating cells in winter cyclones. Part I: Idealized simulations in the context of field observations. J. Atmos. Sci., 73, 1507–1527, doi:https://doi.org/10.1175/JAS-D-15-0126.1.

Keeler, J.M., B.F. Jewett, R.M. Rauber, G.M. McFarquhar, R.M. Rasmussen, L. Xue, C. Liu, and G. Thompson, 2016: Dynamics of Cloud-Top Generating Cells in Winter Cyclones. Part II: Radiative and Instability Forcing. J. Atmos. Sci., 73, 1529–1553, https://doi.org/10.1175/JAS-D-15-0127.1.

Keeler, J.M., R.M. Rauber, B.F. Jewett, G.M. McFarquhar, R.M. Rasmussen, L. Xue, C. Liu, and G. Thompson, 2017: Dynamics of cloud-top generating cells in winter cyclones. Part III: Shear and convective organization. J. Atmos. Sci., 0, https://doi.org/10.1175/JAS-D-16-0314.1.

Khain, A., M. Pinsky, T. Elperin, N. Kleeorin, I. Rogachevskii, and Kostinski (2007), Critical analysis of results concerning droplet collisions in turbulent clouds, Atmos. Res., 86, 1–20

Korolev, A., 2007: Limitations of the Wegener-Bergeron-Findeisen mechanism in the evolution of 441 mixed-phase clouds. J. Atmos. Sci. 64, 3372–3375

Korolev, A., M. Pinsky, and A. Khain, 2013: A new mechanism of droplet size distribution broadening during diffusional growth. J. Atmos. Sci., 70, 2051–2071, doi:10.1175/JAS-D-12-0182.1

Kumar, B., Schumacher, J. & Shaw, R.A. Theor. Comput. Fluid Dyn. (2013) 27: 361. doi:10.1007/s00162-012-0272-z

Morrison, H., G. de Boer, G. Feingold, J. Harrington, M. D. Shupe, and K. Sulia, 2012: Resilience of persistent Arctic mixed-phase clouds. Nat. Geosci., 5, 11–17.

Paluch, I. R., 1979: The entrainment mechanism in Colorado cumuli. J. Atmos. Sci., 36, 2467–2478.

Pinsky, M., A. Khain, and H. Krugliak (2008), Collisions of cloud droplets in a turbulent flow. Part 5: Application of detailed tables of turbulent collision rate enhancement to simulation of droplet spectra evolution, J. Atmos. Sci., 63, 357–374.

Pinsky M, Mazin I, Korolev A, and Khain A (2013): Supersaturation and diffusional droplet growth in liquid clouds. J Atmos Sci 70:2778–2793

Plummer, D. M., G. M. McFarquhar, R. M. Rauber, B. F. Jewett, and D. C. Leon, 2014: Structure and statistical analysis of the microphysical properties of generating cells in the comma head region of continental winter cyclones. J. Atmos. Sci., 71, 4181–4203, doi:https://doi.org/10.1175/JAS-D-14-0100.1.

Rauber, R. M., and Coauthors, 2015: The role of cloud-top generating cells and boundary layer circulations in the finescale radar structure of a winter cyclone over the Great Lakes. Mon. Wea. Rev., 143, 2291–2318, doi:https://doi.org/10.1175/MWR-D-14-00350.1.

Siebesma A. P., 1998: Shallow Cumulus Convection. Buoyant Convection in Geophysical Flows Volume 513 of the series NATO ASI Series pp 441-486.

Shaw, R. A., 2003: Particle-turbulence interactions in atmospheric clouds. Annu. Rev. Fluid Mech, 35, 183–227.

Squires, P., 1958: The microstructure and colloidal stability of warm clouds. Part I. The relation between structure and stability. Tellus, 10, 256–261

Taylor, G. R., and M. B. Baker, 1991: Entrainment and detrainment in cumulus clouds. J. Atmos. Sci., 48, 112–121, doi:10.1175/1520-0469(1991)048<0112:EADICC>2.0.CO;2.

Wang, Y., B. Geerts, and J. French, 2009: Dynamics of the Cumulus Cloud Margin: An Observational Study. J. Atmos. Sci., 66, 3660–3677, https://doi.org/10.1175/2009JAS3129.1

3.3 Clear-air Turbulence

3.3.1 Background

Clear-air turbulence (or "CAT") refers to turbulence in the free atmosphere (upper troposphere and lower stratosphere, UTLS) which is typically associated with enhanced wind shears and reduced stabilities usually found in the vicinity of jet streams, the tropopause and upper-level fronts. It is specifically defined to exclude turbulence in the vicinity of convective clouds, although in practice this exclusion is difficult to monitor. Turbulence associated with mountain waves is also sometimes reported as "CAT", since it can occur in clear air, even though it has a distinctly different source. Understanding the nature of CAT is important for identifying the thermal and dynamic structure of the free atmosphere, including the mixing of trace gases and pollutants and UTLS exchange processes. But it has received most attention through its effect on the safety and efficiency of (mainly) commercial aircraft flight, and scintillation effects on communications. From the aviation perspective, according to NTSB and FAA statistics, encounters with elevated turbulence account for 75% of all air carrier accidents in the UTLS, costing the airlines ~ $200M/yr, with ~ 14 serious and 50 minor injuries to flight attendants and crew (although not all injuries are reported). It is also the second leading factor affecting air traffic workload, due to pilots requesting route deviations.

Intensive field campaigns to study CAT were conducted in the 1960s and 1970s, mostly under sponsorship of the US Air Force (see reviews by Pao and Goldburg 1969, National Academy of Sciences 1972, and Vinnichenko et al. 1980), but since then little interest in the subject has survived and dedicated field campaigns have been practically nonexistent. However in support of aviation needs, some progress has been made with the availability of higher resolution numerical weather prediction (NWP) models, and the implementation of ground-based and airborne turbulence sensing technologies. A recent book edited by Sharman and Lane (2016) reviews current understanding, measurements, and forecast guidance of turbulence for aviation applications.

A reduction of hazardous aviation turbulence encounters requires a better fundamental understanding of the character of CAT, as well as knowledge of its genesis and life cycle. This is difficult given its small scale relative to operational observing systems, and to its relative rarity. For instance, the probability of encountering what is known as "severe" turbulence (vertical acceleration excursion > 9.81 m s-2, or 1 "g") is about 10-5 to 10-4, see Sharman et al. 2014). Better understanding of the character of CAT can be accomplished through targeted in situ plus remote observations using research aircraft. The most important scales for aviation applications turbulence observations lie in the inertial range and these scales are easily measured using a gust probe (and profiling mm-wave Doppler radar), but would require simultaneous measurements of the vertical structure of the environment (e.g., stability and shear) as well. However, since elevated CAT is a rare event, field campaigns must use forecasts of CAT to establish regions that are worth committing flight resources for "productive" penetrations.

Progress in forecasting has been made (Sharman and Pearson 2017), but the accuracy using operational NWP models is still not acceptable for useful operational implementation. There are various reasons for this, but one is the coarseness of the input NWP model, which does not allow adequate resolution of shear, stability, and K-H billows. Even convection-permitting operational models such as the HRRR (3 km) do not adequately capture convective-scale processes, and the timing and location of deep convection will remain a probabilistic forecast irrespective of model resolution. Convection is important to CAT for the effects it has on the surrounding environment and on gravity wave production by the storm and propagation of those waves into the clear-air environment (e.g., Lane et al. 2012, Trier and Sharman 2016). But even far away from cloud, turbulence forecasting based on NWP models is difficult since the nature of the energy cascade from the NWP modeled resolved scales to aircraft scales must be better understood. The nature of this cascade process has been studied e.g. by Nastrom and Gage (1985), Lindborg (1999) by using specially fitted sensors on commercial aircraft that allow collection of data over scales from large to small over many thousands of flights. Future research should resurrect these measurement strategies, in addition to performing concentrated field programs.

3.3.2 Observing and Research Challenges and Frontiers

Given our lack of fundamental understanding of CAT, it is an area ripe for scientific progress with new instruments (such as high-resolution profiling Doppler lidars and radars) deployed in carefully planned field campaigns that will enable NWP model studies including developments of better subgrid turbulence parameterizations applicable to the strongly stratified shear flow environment of the UTLS, climatological studies, and case studies involving high-resolution nested simulations.

3.3.3 Discussion

In the breakout session there was a discussion of how best to measure CAT. High-resolution (50 m or better) profiling radars and lidars can capture the release and evolution of shear instabilities (such as K-H billows) in stratified flow. High resolution rawinsondes and dropsondes offer the high vertical resolution needed to dynamically understand shear-driven turbulence in stratified flow, but they limited by spatial and temporal variability. The possibility of using driftsondes with a reel-down line of temperature and humidity sensors (but no wind) was discussed, as was the Global Hawk UAV with a combination of in situ and remote sensing instrumentation. Another potential scheme is a flying formation of networked smaller instrumented UAV's, although targeting logistics might be formidable.

Somewhat analogous to the use of a formation of UAVs would be deployment of a number of constant pressure balloons. A new development is very small drifters called eMotes. Large numbers of these could be dropped in an appropriate region from a moving aircraft to monitor air motions and thermodynamics at high resolution in a region.

The instrumenting of commercial transport vehicles with sophisticated accelerometers and air motion sensors, along with temperature and humidity sensors, was discussed. This was done in the 1970's with five B-747's flying long intercontinental routes, as part of the NASA Global Atmospheric Sampling Program (GASP) (Holdeman et al. 1980). It was done later by European scientists in the Measurement of Ozone, water vapor, carbon monoxide, and nitrogen oxides aboard Airbus In-service aircraft (MOZAIC) (Marenco et al. 1998). Commercial aircraft fly their scheduled routes, avoiding turbulence where possible, with a research payload that is only periodically serviced by research technicians. These data have been a source of data for the study of turbulence in the upper troposphere. The instrumentation is more sophisticated than that used in the routine AMDAR and TAMDAR meteorological data downlinking systems providing data for the numerical weather prediction process. A new effort of this sort can take advantage of new technology. On research aircraft forward-looking radars and lidars have been tried, but the technique suffers from lack of reflectors in the clear air. It is unlikely such equipment could be installed on in-service transport aircraft.

One theme that emerged was that progress is likely to be best when high resolution regional or global models are used to guide field campaign observations. The models can be used to help forecast regions likely to contain turbulence, as well as to physically diagnose the processes producing observed turbulence. In turn, model output can be compared to observations and results used to improve the models.

3.3.4 References

Holdeman, and co-authors, 1980: The Global Atmospheric Sampling Program (GASP). NASA Technical report 19850071725 (available at https://ntrs.nasa.gov/search.jsp?R=19850071725)

Lane, T. P., Sharman, R. D., Trier, S. B., Fovell, R. G., Williams, J. K., 2012: Recent advances in the understanding of near-cloud turbulence. Bull. Amer. Meteor. Soc. 93(4), 499-515.

Lindborg, E., 1999: Can the atmospheric kinetic energy spectrum be explained by two-dimensional turbulence? J. Fluid Mech., 388, 259-288

Marenco, A., et al., 1998: Measurement of ozone and water vapor by Airbus in-service aircraft: The MOZAIC airborne program, an overview. J. Geophys. Res., 103(D19), 25631–25642, doi:10.1029/98JD00977.

Nastrom, G. D., and K. S. Gage, 1985: A climatology of atmospheric wavenumber spectra of wind and temperature observed by commercial aircraft. J. Atmos. Sci., 42, 950-960.

National Academy of Sciences, 1972: Plan for U. S. clear-air turbulence research in the Global Atmospheric Research Program, H. A. Panofsky (ed), 36 pp.
Pao, Y.-H., Goldburg, A., 1969: Clear Air Turbulence and Its Detection. Plenum Press, New York.

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

Sharman, R. D. and T. P. Lane (eds), 2016: Aviation Turbulence Processes, Detection, Prediction. Springer.

Sharman, R. D., 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.

Sharman, R., and J. Pearson, 2017: Prediction of energy dissipation rates for aviation turbulence: Part I. Forecasting non-convective turbulence. J. Appl. Meteor. Climatol., 56, 317-337.

Trier, S. B., and R. D. Sharman, 2016: Mechanisms influencing cirrus banding and aviation turbulence near a convectively-enhanced upper-level jet stream. Mon. Wea. Rev., 144, 3003-3027.

Vinnichenko, N. K., Pinus, N. Z., Shmeter, S. M., Shur, G. N., 1980. Turbulence in the Free Atmosphere. Plenum, New York.

4. Physical Processes in Convection

In this section we present various aspects of convective processes that are important research topics not only for reasons specific to each subdiscipline (e.g., the vertical redistribution of greenhouse gases within the atmosphere) but also because these topics help us better understand the convective dynamics (e.g., chemical tracer dilution as an indicator of updraft entrainment). There are many physical processes important for understanding convection, and it can be challenging to separate them into discrete topic areas, as the processes all interact with each other in nonlinear ways. That said, to help organize the key research needs, physical processes have been organized into three categories: 1) aerosols, cloud physics, and radiation, 2) cloud electricity and lightning, and 3) chemistry. Each of these categories is summarized below with key science questions highlighted.

4.1 Aerosols, Cloud Physics and Radiation

Cloud microphysical processes are key in understanding convection, as phase changes are one of the primary driving forces behind all convection. Aerosols act as nuclei for hydrometeors and the effects of varying nuclei concentrations are particularly significant in shallow and/or weakly forced convection, as well as in the developing stages of deep convection. However, the estimated magnitude of the impacts of aerosols on cloud characteristics are varied, as described in the literature (e.g., Rosenfeld et al. 2008, Tao et al., 2012). Further, understanding the cloud microphysical processes continues to be challenging, with the most uncertainty residing with ice physical processes. Both aerosols and cloud characteristics impact the radiation budget, especially for boundary layer stratocumulus and cirrus anvils of deep convective storms, thereby affecting weather and climate. To reduce the uncertainties associated with aerosols, clouds, and radiation processes, more targeted observations, as outlined below, are needed.

Dr. Sue van den Heever presented an overview of the current state of scientific research in aerosols, cloud physics, and radiation (https://www.eol.ucar.edu/system/files/2017-CRITE-vandenHeever-FINAL.pdf).

The most fundamental challenge in correctly representing convective processes, both theoretically and in simulations, is fully understanding the feedbacks between vertical motion and aerosol and microphysical processes. Recent studies have shown that CRMs and regional forecasting models frequently overpredict the vertical velocity of convective storms (Varble et al 2014) particularly in the stronger portion of the vertical velocity distribution (Marinescu et al 2016). These issues have been attributed to shortfalls in the microphysical parameterizations, especially ice processes, as well as the feedbacks between ice processes and dynamics (Varble et al 2014). The utilization of bin microphysics appears to assist in mitigating this problem (Fan et al 2016), but certainly not in its entirety. This misrepresentation of convective vertical velocities produces errors in convective mass fluxes, storm organization, precipitation intensity, storm longevity and the transport of water vapor, momentum, energy, aerosols and chemical species. However, addressing the over prediction of vertical velocity in deep convective storms is very challenging given the lack of in situ co-located measurements of both vertical velocity and microphysical characteristics. While radar is very useful in this regard, particularly with new advances in Doppler and dual polarization, ground-based radars are generally attenuated in deep convective storm systems, and uncertainties remain regarding both hydrometeor identification and the estimates of vertical velocity. To address this gap, in situ measurements in deep convective storm cores are needed.

A second scientific frontier is determining the role of hydrometeor size distributions in microphysical processes and cloud-radiative forcing. Correctly representing particle size distributions (PSDs) within numerical models is highly challenging, especially in bulk parameterization schemes. Convective cloud processes have been shown to be very sensitive to the manner in which the size distribution of hydrometeors is represented within these microphysical parameterizations (e.g. Gilmore et al., 2004; van den Heever and Cotton, 2004; Milbrandt and Yau, 2006; Morrison and Grabowski 2007; Ćurić et al., 2010; Igel and van den Heever, 2017)]. At least one factor describing the PSD, e.g., the distribution shape parameter, needs to be set *a priori* in 2-moment bulk schemes. Unfortunately these parameters often have to be set rather arbitrarily as there is limited observational evidence on which to base these values. And while no such *a priori* settings need to be made in bin microphysical parameterizations in which the evolution of the PSD is predicted, the validation and improvement of the representation of the PSD has been limited by the relatively infrequent and spatially limited nature of observations. Such arbitrary settings can impact numerous microphysical processes in convective storms. For example, in recent simulations with bulk microphysics schemes, it was found that evaporation rates are much more sensitive to the value of the shape parameter than are condensation rates (Igel and van den Heever, 2017). The results of Morrison and Grabowski (2007) suggest that switching from a low to a high shape parameter value results in a decrease of the effective radius and an increase in the cloud water path, droplet number concentration, and optical depth of shallow cumulus clouds. Further, observations that do exist of cloud droplet size distributions indicate a wide spread in the shape parameter (e.g., Miles et al 2000). Most observational studies examining the raindrop size distribution have been conducted at the ground, after raindrops have interacted with turbulent boundary layer air (e.g., Uijlenhoet et al., 2003; Niu et al., 2009; Friedrich et al., 2015)]. Some field campaigns have made in-cloud raindrop size distribution observations, but such observations have been limited in space and time and often to particular cloud types (e.g., Yuter and Houze, 1997; Heymsfield et al., 2015)]. Incorrect representation of the PSDs leads to errors in convective storm representation including quantitative precipitation forecasts, cold pool intensity, flash flooding, and the production of large hail at the surface, and impacts aerosol-cloud interactions. There is crucial need for improved and more frequent observations of PSDs, which would be best accomplished via in situ observations.

Graupel and hail observations are another crucial need. In spite of some excellent early work in the field, there is a general lack of information on graupel/hail characteristics for various storms and environments. Accurately representing ice processes in numerical models is the most challenging task facing microphysics modelers, partly due to our lack of understanding of ice processes themselves, as well as to our limited observations of ice species and their characteristics within deep convective storms. While some schemes represent both graupel and hail, most schemes do not allow for the representation of both species simultaneously thus forcing the user to choose *a priori*. Prior studies have demonstrated significant sensitivity to the manner in which graupel and/or hail are represented including 200 to 300% variations in the stratiform and convective rain areas (e.g., Adams-Selin et al 2013). Others have shown significant differences in the cold pool intensity, storm structure and rainfall amounts due to variations in mean hail diameter, the intercept parameter and/or the graupel/hail density (e.g., Gilmore et al 2004; van den Heever and Cotton 2004). Melting and riming have important thermodynamic and lightning implications but are poorly represented (e.g., Morrison and Grabowski 2010; Saleeby and Cotton 2008). The recent development of the P3 scheme (Morrison and Milbrandt 2015) represents an attempt to counter some of the need for some of these a priori settings. While the prediction of large hail at the surface is an important societal problem (Dennis and Kumjian 2017), representing the tail of the hail size distribution using either bulk or bin microphysics schemes remains challenging. The ability to represent hail processes correctly is particularly important in the accurate prediction of precipitation in severe storms, where the distribution of hail relative to the updraft varies significantly (Grant and van den Heever 2014). Observations of graupel and hail characteristics and size distributions are lacking both within convective storm systems and at the surface. Observations are needed of surface and in-storm number concentration, mixing ratio and size of both hail and graupel, as well as their density and fall speed. These observations are needed over the lifetime of the storm, and for a wide variety of storm types and environments. While some measurements can be done at the surface, *in situ* measurements are crucial, highlighting the need for a storm-penetrating aircraft.

Finally, the effects of the spatial distribution, both in the vertical and horizontal dimensions, of aerosols on cloud microphysical and radiative processes remain uncertain. Aerosols are lofted on scales ranging from synoptic through mesoscale and demonstrate significant variability in both vertical and horizontal directions.

The altitude of a given aerosol layer plays an important role in the manner in which radiation interacts with these layers. This in turn impacts the static stability and hence the storm development and formation (e.g., Grant and van den Heever 2014; Saide et al 2015; Fan et al. 2015). The altitudes of aerosol layers also impact the manner and amount of aerosols ingested by storm systems and hence cloud processes (e.g., Lebo 2014; Marinescu et al 2017). Field campaigns such as DC3 have demonstrated the importance of variations in the horizontal distribution of aerosols on deep convective storm characteristics (Barth et al 2015). In spite of the importance of the vertical and horizontal distribution of aerosols on cloud processes, most aerosol measurements available to cloud modelers are either point measurements at the surface, or aerosol optical depth (AOD) measurements from satellite or ground platforms. While satellites provide global measurements, AOD is not particularly useful to modelers given their need for three-dimensional fields and hygroscopicity characteristics. Thus, the evaluation of the simulated impacts of aerosols on cloud processes must rely on the measurements from field campaigns.

In summary, in order to address the gaps in knowledge regarding aerosol, cloud physics, and radiation processes of convection, the key need is to obtain frequent, high spatial and time resolution measurements of vertical velocity, cloud particle size distributions, and aerosol characteristics (e.g. concentrations, size distributions, hygroscopicity). It is highly desired to obtain the entire particle size distribution and to obtain the above parameters near the updraft core and top.These measurements are best obtained via airborne platforms, e.g. drones and aircraft. Specific measurements of hail and graupel characteristics at the surface and within storms are also needed, via storm-penetrating aircraft and targeted field campaigns. Measurements of three-dimensional spatial and temporal distributions of aerosol concentrations, moisture variables, and temperature will reduce uncertainties regarding impacts of aerosols on clouds and radiation. These observations can be collected with aircraft, aerosol lidar, and other facilities.

References

Adams-Selin, R.D., S.C. van den Heever, and R.H. Johnson, 2013: Impact of graupel parameterization schemes on idealized bow echo simulations. Mon. Wea. Rev.,141,1241-1262.

Ćurić, M., D. Janc, and K. Veljović (2010), Dependence of accumulated precipitation on cloud drop size distribution, Theor. Appl. Climatol., 102(3), 471–481, doi:10.1007/s00704-010-0332-5.

Dennis, E. J., and M.R. Kumjian, 2017: The impact of vertical wind shear on hail growth in simulated supercells. Journal of the Atmospheric Sciences, 74, 641-663.

Fan, J., Y. Liu, K. Xu, K. North, S. Collis, X. Dong, G. J. Zhang, Q. Chen, P. Kollias, and S. J. Ghan (2015), Improving representation of convective transport for scale-aware parameterization: 1. Convection and cloud properties simulated with spectral bin and bulk microphysics: CRM model evaluation, J. Geophys. Res. Atmos.,120, 3485–3509, doi:10.1002/2014JD022142.

Fan, J., D. Rosenfeld, Y. Yang, C. Zhao, L. R. Leung, and Z. Li, 2015: Substantial contribution of anthropogenic air pollution to catastrophic floods in Southwest China. Geophys. Res. Lett., 42, 6066–6075.

Friedrich, K., E. a. Kalina, J. Aikins, M. Steiner, D. Gochis, P. a. Kucera, K. Ikeda, and J. Sun (2015), Raindrop size distribution and rain characteristics during the 2013 Great Colorado Flood, J. Hydrometeorol., (2015).

Gilmore, M. S., J. M. Straka, and E. N. Rasmussen (2004), Precipitation Uncertainty Due to Variations in Precipitation Particle Parameters within a Simple Microphysics Scheme, Mon. Weather Rev., 132(11), 2610–2627, doi:10.1175/MWR2810.1.

Grant, L.D., and S.C. van den Heever, 2014: Aerosol-cloud-land surface interactions within tropical sea breeze convection. J. Geo. Res., 119, 8340-8361.

Grant, L.D., and S.C. van den Heever, 2014: Microphysical and dynamical characteristics of low-precipitation and classic supercells. J. Atmos. Sci., 71, 2604-2624.

Heymsfield, A. J., A. Bansemer, M. R. Poellot, and N. Wood (2015), Observations of Ice Microphysics through the Melting Layer, J. Atmos. Sci., 72(8), 2902–2928.

Igel, A. L., and S. C. van den Heever, 2017: The Importance of the Shape of Cloud Droplet Size Distributions in Shallow Cumulus Clouds. Part I: Bin Microphysics Simulations, J. Atmos. Sci., 74(1), 249–258, doi:10.1175/JAS-D-15-0382.1.

Lebo, Z. J., 2014: The Sensitivity of a Numerically Simulated Idealized Squall Line to the Vertical Distribution of Aerosols. J. Atmos. Sci., 71, 4581–4596.

Marinescu, P.J., S.C. van den Heever, S.M. Saleeby, S.M. Kreidenweis, and P.J. DeMott, 2017: The microphysical roles of lower and versus middle tropospheric aerosol particles on mature stage MCS precipitation. Accepted pending revision at J. Atmos. Sci.

Marinescu, P.J., S.C. van den Heever, S.M. Saleeby and S.M. Kreidenweis, 2016: The microphysical contributions to and evolution of latent heating profiles in two MC3E MCSs. J. Geo. Res., 121, 7913-7935.

Miles, N. L., J. Verlinde, and E. E. Clothiaux, 2000: Cloud droplet size distributions in low-level stratiform clouds. J. Atmos. Sci., 57, 295–311.

Milbrandt, J. A., and M. K. Yau (2006), A Multimoment Bulk Microphysics Parameterization. Part III: Control Simulation of a Hailstorm, J. Atmos. Sci., 63(12), 3114–3136, doi:10.1175/JAS3816.1.

Morrison, H., and W. W. Grabowski, 2007: Comparison of bulk and bin warm-rain microphysics models using a kinematic frame-work. J. Atmos. Sci., 64, 2839–2861, doi: 10.1175/JAS3980.

Niu, S., X. Jia, J. Sang, X. Liu, C. Lu, and Y. Liu (2009), Distributions of Raindrop Sizes and Fall Velocities in a Semiarid Plateau Climate: Convective versus Stratiform Rains, J. Appl. Meteorol. Climatol., 49(4), 632–645.

Morrison, H., and W. Grabowski, 2010: An Improved Representation of Rimed Snow and Conversion to Graupel in a Multicomponent Bin Microphysics Scheme. J. Atmos. Sci., 67, 1337-1360.

Morrison, H., and J. A. Milbrandt, 2015: Parameterization of ice microphysics based on the prediction of bulk particle properties. Part I: Scheme description and idealized tests. J. Atmos. Sci., 72, 287–311, doi:https://doi.org/10.1175/JAS-D-14-0065.1.

Rosenfeld, D., U. Lohmann, G. B. Raga, C. D. O'Dowd, M. Kulmala, S. Fuzzi, A. Reissell, M. O. Andreae, 2008: Flood or drought: How do aerosols affect precipitation?, Science, 321, 1309-1313, doi:10.1126/science.1160606.

Saide, P. E., and Coauthors, 2015: Central American biomass burning smoke can increase tornado severity in the U.S. Geo- phys. Res. Lett., 42, 956–965.

Saleeby, S.M., and W.R. Cotton, 2008: A Binned Approach to Cloud-Droplet Riming Implemented in a Bulk Microphysics Model. J. Applied Met. and Clim., 47, 694-703.

Tao, W.-K., J.-P. Chen, Z. Li, C. Wang, and C. Zhang, 2012: Impact of aerosols on convective clouds and precipitation, Rev. Geophys., 50, RG2001, doi:10.1029/2011RG000369.

Uijlenhoet, R., M. Steiner, and J. A. Smith (2003a), Variability of Raindrop Size Distributions in a Squall Line and Implications for Radar Rainfall Estimation, J. Hydrometeorol., 4(1), 43–61.

van den Heever, S. C., and W. R. Cotton (2004), The impact of hail size on simulated supercell storms, J. Atmos. Sci., 61(13), 1596–1609.

Varble, A., E. J. Zipser, A. M. Fridlind, P. Zhu, A. S. Ackerman, J. Chaboureau, S. Collis, J. Fan, A. Hill, and B. Shipway (2014), Evaluation of cloud-resolving and limited area model intercomparison simulations using TWP-ICE observations: 1. Deep convective updraft properties, J. Geophys. Res. Atmos., 119, 13,891–13,918, doi:10.1002/2013JD021371.

Yuter, S. E., and R. A. Houze (1997), Measurements of Raindrop Size Distributions over the Pacific Warm Pool and Implications for Z–R Relations, J. Appl. Meteorol., 36(7), 847–867.

4.2 Cloud Electricity and Lightning

Cloud electrification and resultant lightning are important components of the convective system. Changes in lightning flash rate have been shown to be predictive of increasing storm intensity. Lightning flash rate and extent also provide important information about the chemical impact of severe storms because of NOx (and subsequently ozone) production. However, lightning flash rate prediction and parameterization remains a major challenge for the community, hindered by uncertainty in updraft characteristics and microphysical processes for a given storm.

Dr. Larry Carey presented an overview of the current state of scientific research in cloud electricity and lightning (https://www.eol.ucar.edu/system/files/2017_CRITE_Physical_Processes_Electricity_and_Lightning_Carey_FINAL.pdf).

While current instrumentation has greatly increased our ability to observe the electrical and lightning properties of storms, many of the processes behind those properties remain poorly observed and poorly understood. Multi-link hypothesis chains often have missing links due to gaps in scale, accuracy or availability of needed observations. Additionally, without sufficient in situ observations, our ability to improve remote sensing is stunted.

One key scientific frontier is the need for a better understanding of microphysical and kinematic interactions with electrification and lightning. Specifically, how do variations in microphysics and kinematics establish charge structure and polarity, and what are the resulting lightning properties as a function of storm morphology and lifecycle? While the general linkages between graupel, charge structure and lightning are well understood, much storm-to-storm variability does not fit the accepted relationships. The hypothesis is that much of this error is due to poorly observed properties and microphysical processes which control concentrations of cloud water and cloud ice. For example, improved prediction using non-inductive charge theory is promising (e.g., Bruning et al. 2014), but the science remains speculative without the needed measurements of cloud water and its rate of conversion to ice throughout the mixed-phase region. There is an urgent need for platforms that can observe cloud hydrometeors and electrical characteristics in the storm core. These are many of the same uncertainties that plague microphysics in general.

The impact of variability in kinematics also needs further study. Convective updraft volume is well correlated to lightning flash rate. However, results that deviate from that correlation suggest that other microphysical and kinematic processes are at work (Mecikalski et al. 2015). Another kinematics-related topic needing further study is understanding the exact processes behind the "lightning jump" (e.g., Shultz et al. 2015), which has been shown to be a valuable predictor of severe weather. In and near strong updrafts, flashes tend to be smaller and more frequent, while flashes far from strong vertical drafts exhibit the opposite tendency. Bruning and MacGorman (2013) showed that the turbulent eddies in and around these strong drafts are playing an important role, resulting in small pockets of charge and frequent, small flashes. There is a critical need for high temporal (<1 minute) and high spatial (10 m) sampling to capture these convective scale processes; an example of such a platform would be rapid scan radars, such as phased array or imaging radars.

A third science area to improve is our understanding of how the environment interacts with electrification and lightning. Fuchs et al. (2015) conducted a comprehensive study of thousands of storm observations from different regions of the United States to determine what environmental conditions are responsible for various electrification characteristics, such as high flash rates and anomalous charge structures. Robust relationships were found linking high flash rates to high cloud base height and high environmental instability. The proposed mechanism suggests that decreased cloud water depletion, controlled by these environmental factors, is an important component of increased lightning activity (also proposed by Bruning et al., 2014). This motivates the need to better constrain cloud water with observations.

The final major science frontier discussed by Dr. Carey is how lightning is initiated inside storms. What is the role of local cloud electrical and microphysical properties and processes? Rison et al. (2016) showed fast positive breakdown was the cause of a high-power discharge known as narrow bipolar event (NBE). They found a wide range of strengths and that fast positive breakdown was the initiating event of numerous lightning discharges, maybe all flashes. The fast positive breakdown is purely dielectric, in contrast to runaway electron avalanches. To better understand lightning initiation and the charge transported by lightning, lightning observing platforms need expanded 'visibility' to all processes occurring along the complete lightning channel, by including other frequencies and newer techniques (e.g., VHF broadband interferometer array, high-precision, fast-sampling E-field change arrays), including continuous monitoring where it is not yet possible. Such observations will enhance our understanding of lightning energetics and channel lengths, parameters which are needed for physical models of NOx production. Further, we are limited with our current lightning mapping arrays to fixed locations. To collect data on lightning characteristics from a wider range of storms and thermodynamic environments, a portable lightning mapping array is needed. Availability of an electricity observational suite in other campaigns studying convection will ensure that advancements in cloud electricity track the state of the art in other sub-disciplines.

In summary, in order to advance our knowledge on cloud electricity and lightning, the following science gaps and needs should be addressed. Measurements of cloud water and its rate of conversion to ice throughout the mixed-phase region will improve prediction of lightning. Thus, there is an urgent need for platforms that can observe cloud hydrometeors, including their electrical charge, and electric fields and other electrical characteristics ofin the storm core environment. The in situ observations of cloud hydrometeors and electrical characteristics will provide necessary information for determining connections between cloud physics, kinematics, and environment with cloud electricity and lightning and for improving remote sensing measurements. Among the platforms for these in situ observations, a storm penetrating aircraft is a high priority. There is a critical need for high temporal (<1 minute) and high spatial (10 m) sampling to capture kinematic, microphysical, and electrical characteristics at convective scales; an example of such a platform would be rapid scan radars, such as phased array or imaging radars. To better understand the physics of the lightning process, lightning observing platforms need expanded 'visibility' to all components and locations of the flash, by including other frequencies and newer techniques (e.g., VHF broadband interferometer array, E-field change (Marx) meter array). Further, we are limited with our current lightning mapping arrays to fixed locations. A portable lightning mapping array would enable data collection of lightning characteristics from a wider range of storms and thermodynamic environments. These measurements are also needed to address issues outside of the storm core. A scientific frontier highlighted by multiple researchers in the breakout discussions is that the uncertainties of cloud water and ice, kinematic and environmental control on electrical and lightning processes within anvil clouds and stratiform precipitation are perhaps even more acute than in deep convection. Dye and Willett (2007) demonstrated that significant electric fields occurred for many tens of minutes and across tens of kilometers well downstream of convective cores. They speculated that charge separation occurred as result of ice-ice particle collisions in the absence of supercooled cloud water. Other studies have demonstrated that a local charging mechanism likely contributes to lightning initiations in supercell anvils (Kuhlman et al. 2009) and in the stratiform regions of mesoscale convective systems (Carey et al. 2005) where the presence and amount of supercooled cloud water, ice hydrometeor properties and kinematic characteristics are uncertain.

References

Bruning, E. C. and D. R. MacGorman, 2013: Theory and observations of controls on lightning flash size spectra. J. Atmos. Sci., 70, 4012–4029, doi:10.1175/JAS-D-12-0289.1.

Bruning, E., S. A. Weiss, and K. M. Calhoun, 2014: Continuous variability in thunderstorm primary electrification and an evaluation of inverted-polarity terminology. Atmos. Res., 135, 274–284.

Carey, L. D., M. J. Murphy, T. L. McCormick, and N. W. S. Demetriades, 2005: Lightning location relative to storm structure in a leading-line, trailing stratiform mesoscale convective system. J. Geophys. Res., 110, D03105, doi:10.1029/2003JD004371.

Dye, J. E., and J. C. Willett, 2007: Observed enhancement of reflectivity and the electric field in long-lived Florida anvils. Mon. Wea. Rev., 135, 3362-3380. doi: 10.1175/MWR3484.1

Fuchs, B. R., S. A. Rutledge, E. C. Bruning, J. R. Pierce, J. K. Kodros, T. J. Lang, D. R. MacGorman, P. R. Krehbiel, and W. Rison 2015: Environmental controls on storm intensity and charge structure in multiple regions of the continental United States. J. Geophys. Res. Atmos., 120, 6575–6596. doi: 10.1002/2015JD023271.

Kuhlman, K. M., D. R. MacGorman, M. I. Biggerstaff, and P. R. Krehbiel, 2009: Lightning initiation in the anvils of two supercell storms. Geophys. Res. Lett., 36, L07802, doi:10.1029/2008GL036650.

Mecikalski, R. M., A. L. Bain, and L. D. Carey, 2015: Radar and lightning observations of deep moist convection across northern Alabama during DC3: 21 May 2012. Mon. Wea. Rev., 143, 2774-2794. doi:10.1175/MWR-D-14-00250.1.

Rison, W., P. R. Krehbiel, M. G. Stock, H. E. Edens, X.-M. Shao, R. J. Thomas, M. A. Stanley, and Y. Zhang, 2016: Observations of narrow bipolar events reveal how lightning is initiated in thunderstorms. Nat Commun, 7. doi: 10.1038/ncomms10721

Schultz, C. J., L. D. Carey, E. V. Schultz, and R. J. Blakeslee, 2015: Insight into the kinematic and microphysical processes that control lightning jumps. Weather and Forecasting, 151030091332000, doi:10.1175/waf-d-14-00147.1.

4.3 Chemistry and Convection

Convection plays an important role in vertically redistributing trace gases and aerosols throughout the troposphere and can even inject boundary layer tracers directly into the stratosphere. However, some of these trace gases and aerosols are partially removed by precipitation because of their affinity for dissolving into or activating into cloud droplets. Lightning in thunderstorms produces substantial amounts of nitrogen oxides, a key ingredient for ozone formation which will occur in the upper troposphere where ozone is a greenhouse gas. Yet other trace gases, such as short-lived halogens, that are convectively lofted in marine convection can subsequently deplete ozone in the lower stratosphere. Trace gases and aerosols can illuminate many aspects of convection that the community has few ways to observe. For example, measurements of trace gases and aerosols can be used to determine the level of maximum detrainment, which helps constrain updraft characteristics and entrainment estimates. High spatial and temporal resolution measurements, especially in the storm updraft regions, of trace gases, aerosols, cloud morphology, and state variables will take us to a new level of understanding of convective processing of atmospheric constituents.

Dr. Ken Pickering presented science frontiers for research on chemistry in convective clouds (https://www.eol.ucar.edu/system/files/C-RITE_Chemistry_Pickering.pdf).

The most important process in convective clouds for atmospheric composition is the vertical transport. Evaluations of convectionive-permitting simulations of carbon monoxide and ozone with observations from previous field campaigns have generally been good (Barth et al., 2007; Bela et al., 2016; Li et al., 2017). Thus, these and other trace gases that have chemical lifetimes greater than transport processes in convection and are insoluble (besides carbon monoxide and ozone, several hydrocarbons, methyl iodide, and dimethyl sulfide are good constituents) have been used to determine convective cloud characteristics, such as the level of maximum detrainment (e.g. Skamarock et al., 2000; Mullendore et al., 2005; Halland et al., 2009; Li et al., 2017). To improve understanding of convective transport for both constituent redistribution and cloud characteristics, bulk estimates from observations must become more frequent during a cloud lifetime and spatially resolved for scales of 10s of meters. It would be extremely helpful to have three-dimensional volumes of tracer concentrations, which is partially achieved with water vapor, ozone, and aerosol lidars, but there would be a large added value if CO, hydrocarbon, and halogen trace gases were measured more frequently from the PBL to the tropopause region.

Despite years of research to understand the relationship between NOx production and lightning characteristics, we have not been able to apply NOx production from single (or a small number) of case studies to the regional and global scales with confidence, leaving estimates of global lightning NOx production with uncertainties of a factor of four. These uncertainties are likely related to uncertainties in flash characteristics, such as the flash rate and flash length. Recent work has shown some correlation between the estimated production of NOx from lightning and flash extent (Pollack et al., 2016), indicating that this method is a promising pathway forward. Further improvements for this method are to obtain measurements of nitric oxide and nitrogen dioxide in storm cores near the lightning flashes, giving better information on the NO_x production from flashes whose characteristics are observed by lightning mapping arrays.

The influence role of convectionv on ozone in the upper troposphere, where ozone is a greenhouse gas, can only be estimated by knowing the concentrations of ozone precursors in convective outflow regions. These precursors are NOx and volatile organic compounds (VOCs), and the products of VOC oxidation, especially formaldehyde and peroxides, but also methanol and acetone to some extent. These key HOx (and therefore ozone) precursors are partially soluble making them prone to removal by precipitation (e.g. Barth et al., 2007; 2016; Bela et al.,2016; Fried et al., 2016). The largest uncertainty in predicting convective transport of these species is the role of the ice particles and whether dissolved gases are retained or degassed when cloud drops freeze (Barth et al., 2001; 2007). While the recent work of the DC3 field campaign analysis points to some gases (CH_3OOH) being retained while others (CH_2O, H_2O_2) are not, laboratory studies (Jost et al., 2017) find opposite results (e.g. high retention of CH_2O in freezing cloud droplets caused by riming at temperatures below freezing). To better understand the convective transport of soluble trace gases, frequent measurements of these soluble trace gases along with passive, insoluble trace gases (listed above) in the inflow region, storm core, and anvil region are needed. Collection of cloud ice, snow, and graupel and subsequent chemical analysis would provide needed information on whether soluble trace gases exist in frozen cloud particles.

Ozone production in the upper troposphere downwind of convection and ozone loss in storms with high NOx concentrations (which titrates the ozone) and in the lower stratosphere (by halogen species) are critical to estimate the impact of ozone on the climate. Nearly all estimates of upper-tropospheric ozone production are from model simulations. The DC3 field campaign began to address obtaining measurements of ozone production by sampling ozone and its precursors (NOx, NOy, HOx, and VOCs) and photolysis rates at multiple downwind locations from convection (Barth et al., 2015). More of these measurements should be pursued to obtain ozone production estimates under a variety of chemical and storm environments.

Convective outflow regions are one of the most important regions for new particle formation (NPF), which has been observed many times (Clarke et al., 1998). These new particles are important for the radiation balance and growing to become cloud condensation nuclei. Further understanding of the magnitude and precursors of new particle formation in convective outflow regions is needed because most previous studies have inferred NPF via downwind data and model simulations (e.g. Ekman et al., 2008). Interestingly, NPF has been inferred to occur in clouds (Murphy et al., 2015), suggesting measurements of aerosol size distributions, aerosol composition, and precursor trace gases are needed within clouds as well as in outflow regions.

Pyroconvection can very quickly loft particles and gases into the upper troposphere and lower stratosphere, affecting radiation characteristics in the atmosphere. Fire plumes can also be entrained into convective clouds downwind of active fires (Apel et al., 2015; Barth et al., 2015). Measurements of the composition of the fire plumes along with the convective clouds (either pyroconvection or downwind convection) can illuminate the physical and chemical processing of the emitted trace gases and aerosols by the cloud. Further, these trace gases can be used to determine entrainment rates into convective clouds at altitudes of the mid-troposphere (3-8 km), where fire plumes often occur (depending on the thermodynamic state of the atmosphere).

In summary, to advance scientific understanding of convective processing of trace gases and aerosols, high-resolution temporal measurements of ozone, NOx species, soluble trace gases and aerosols (including aerosol composition), and passive, insoluble trace gases are needed in inflow, outflow and in convective clouds. A storm penetrating aircraft will significantly advance our knowledge by obtaining these measurements in storm cores of strong convection. Interstitial cloud measurements require having aircraft inlets suitable for removing cloud particles from the inlet of the instrument. These measurements must be in conjunction with observations of lightning flash rates, size, and energy and with observations of the storm environmental conditions, including thermodynamics and photolysis rates. Also highly desired is the collection (or use of the counterflow virtual impactor) and chemical analysis of cloud hydrometeors to improve understanding of wet scavenging.

References

Apel, E. C., R. S. Hornbrook, A. J. Hills, N. J. Blake, M. C. Barth, A. Weinheimer, C. Cantrell, S. A. Rutledge, B. Basarab, J. Crawford, G. Diskin, C. R. Homeyer, T. Campos, F. Flocke, A. Fried, D. R. Blake, W. Brune, I. Pollack, J. Peischl, T. Ryerson, P. O. Wennberg, J. D. Crounse, A. Wisthaler, T. Mikoviny, G. Huey, B. Heikes, D. O'Sullivan and D. D. Riemer, 2015: Upper tropospheric ozone production from lightning NOx-impacted convection: Smoke ingestion case study from the DC3 campaign, *J. Geophys. Res. Atmos.*, **120**, doi:10.1002/2014JD022121.

Barth, M. C., A. L. Stuart, and W. C. Skamarock, 2001: Numerical simulations of the July 10 Stratospheric-Tropospheric Experiment: Radiation, Aerosols and Ozone/Deep Convection storm: Redistribution of soluble tracers, *J. Geophys. Res.*, **106**, 12,381-12,400.

Barth, M. C., S-W Kim, W. C. Skamarock, A. L. Stuart, K. E. Pickering, L. E. Ott, 2007: Simulations of the redistribution of formaldehyde, formic acid, and peroxides in the July 10, 1996 STERAO deep convection storm. *J. Geophys. Res.*, **112**, D13310, doi:10.1029/2006JD008046.

Barth, M. C., C. A. Cantrell, W. H. Brune, S. A. Rutledge, J. H. Crawford, H. Huntrieser, L. D. Carey, D. MacGorman, M. Weisman, K. E. Pickering, E. Bruning, B. Anderson, E. Apel, M. Biggerstaff, T. Campos, P. Campuzano-Jost, R. Cohen, J. Crounse, D. A. Day, G. Diskin, F. Flocke, A. Fried, C. Garland, B. Heikes, S. Honomichl, R. Hornbrook, L. G. Huey, J. Jimenez, T. Lang, M. Lichtenstern, T. Mikoviny, B. Nault, D. O'Sullivan, L. Pan, J. Peischl, I. Pollack, D. Richter, D. Riemer, T. Ryerson, H. Schlager, J. St. Clair, J. Walega, P. Weibring, A. Weinheimer, P. Wennberg, A. Wisthaler, P. Wooldridge, and C. Ziegler, 2015: The Deep Convective Clouds and Chemistry (DC3) Field Campaign, *Bull. Amer. Meteor. Soc.*, **96**, 1281–1309, doi: http://dx.doi.org/10.1175/BAMS-D-13-00290.1.

Barth, M. C., M. M. Bela, A. Fried, P. Wennberg, J. Crounse, J. St. Clair, N. Blake, D. R. Blake, C. R. Homeyer, W. H. Brune, L. Zhang, J. Mao, X. Ren, T. Ryerson, I. B. Pollack, J. Peischl, R. C. Cohen, B. A. Nault, L. G. Huey, X. Liu, and C. A. Cantrell, 2016: Convective Transport and Scavenging of Peroxides by Thunderstorms Observed over the Central U.S. during DC3, *J. Geophys. Res.*, 121, doi:10.1002/2015JD024570.

Bela, M., M. C. Barth, O. B. Toon, A. Fried, C. R. Homeyer, H. Morrison, K. A. Cummings, Y. Li, K. E. Pickering, D. Allen, Q. Yang, P. O. Wennberg, J. D. Crounse, J. M. St. Clair, A. P. Teng, D. O'Sullivan, L. G. Huey, D. Chen, X. Liu, D. Blake, N. Blake, E. Apel, R. S. Hornbrock, F. Flocke, T. Campos, G. Diskin, 2016: Wet Scavenging of Soluble Species in DC3 Deep Convective Storms Using Aircraft Observations and WRF-Chem Simulations, *J. Geophys. Res.*, 121, doi:10.1002/2015JD024623.

Clarke, A. D., J. L. Varner, F. Eisele, R. L. Mauldin, D. Tanner, and M. Litchy, 1998: Particle production in the remote marine atmosphere: Cloud outflow and subsidence during ACE 1, J. Geophys. Res., 103(D13), 16397, doi:10.1029/97JD02987.

Ekman, A. M. L., R. Krejci, A. Engström, J. Ström, M. de Reus, J. Williams, and M. O. Andreae, 2008: Do organics contribute to small particle formation in the Amazonian upper troposphere? Geophys. Res. Lett., 35, L17810, doi:10.1029/2008GL034970.

Fried, A., M. C. Barth, M. Bela, P. Weibring, D. Richter, J. Walega, Y. Li, K. Pickering, E. Apel, R. Hornbrook, A. Hills, D. D. Riemer, N. Blake, D. R. Blake, J. R. Schroeder, Z. J.

Luo, J. H. Crawford, J. Olson, S. Rutledge, D. Betten, M. I. Biggerstaff, G. S. Diskin, G. Sachse, T. Campos, F. Flocke, A. Weinheimer, C. Cantrell, I. Pollack, J. Peischl, K. Froyd, A. Wisthaler, T. Mikoviny, and S. Woods, 2016: Convective Transport of formaldehyde to the upper troposphere and lower stratosphere and associated scavenging in thunderstorms over the Central United States during the 2012 DC3 study, *J. Geophys. Res.*, 120, doi: 10.1002/2015JD024477.

Halland, J. J., H. E. Fuelberg, K. E. Pickering, and M. Luo, 2009: Identifying convective transport of carbon monoxide by comparing remotely sensed observations from TES with cloud modeling simulations, Atmos. Chem. Phys., 9, 4279-4294, doi.org/10.5194/acp-9-4279-2009.

Jost, A., M. Szakáll, K. Diehl, S. K. Mitra, and S. Borrmann, 2017: Chemistry of riming: the retention of organic and inorganic atmospheric trace constituents, Atmos. Chem. Phys., 17, 9717-9732, https://doi.org/10.5194/acp-17-9717-2017.

Li, Yunyao, K. E. Pickering, D. J. Allen, M. C. Barth, M. M. Bela, K. A. Cummings, L. D. Carey, R. M. Mecikalski, A. O. Fierro, T. L. Campos, A. J. Weinheimer, G. S. Diskin, M. I. Biggerstaff, 2017: Evaluation of deep convective transport in storms from different convective regimes during the DC3 field campaign using WRF-Chem with lightning data assimilation, *J. Geophys. Res.*, 122, doi:10.1002/2017JD026461.

Mullendore, G. L., D. R. Durran, and J. R. Holton, 2005: Cross-tropopause tracer transport in midlatitude convection, J. Geophys. Res., 110, D06113, doi:10.1029/2004JD005059.

Murphy, B. N., J. Julin, I. Riipinen, and A. M. L. Ekman (2015), Organic aerosol processing in tropical deep convective clouds: Development of a new model (CRM-ORG) and implications for sources of particle number, J. Geophys. Res. Atmos., 120, 10,441–10,464, doi:10.1002/2015JD023551.

Pollack, I. B., C. R. Homeyer, T. B. Ryerson, K. C. Aikin, J. Peischl, E. C. Apel, T. Campos, F. Flocke, R. S. Hornbrook, D. J. Knapp, D. D. Montzka, A. J. Weinheimer, D. Riemer, G. Diskin, G. Sachse, T. Mikoviny, A. Wisthaler, E. Bruning, D. MacGorman, K. A. Cummings, K. E. Pickering, H. Huntrieser, M. Lichtenstern, H. Schlager, and M. C. Barth, 2016: Airborne quantification of upper tropospheric NOx production from lightning in deep convective storms over the United States Great Plains, *J. Geophys. Res.*, **121**, doi:10.1002/2015JD023941.

Skamarock, W. C., J. Powers, M. C. Barth, J. E. Dye, T. Matejka, D. Bartels, K. Baumann, J. Stith, D. D. Parrish, and G. Hubler, 2000: Numerical simulations of the 10 July STERAO/Deep Convection Experiment Convective System: Kinematics and transport, *J. Geophys. Res.*, **105**, 19,973–19,990.