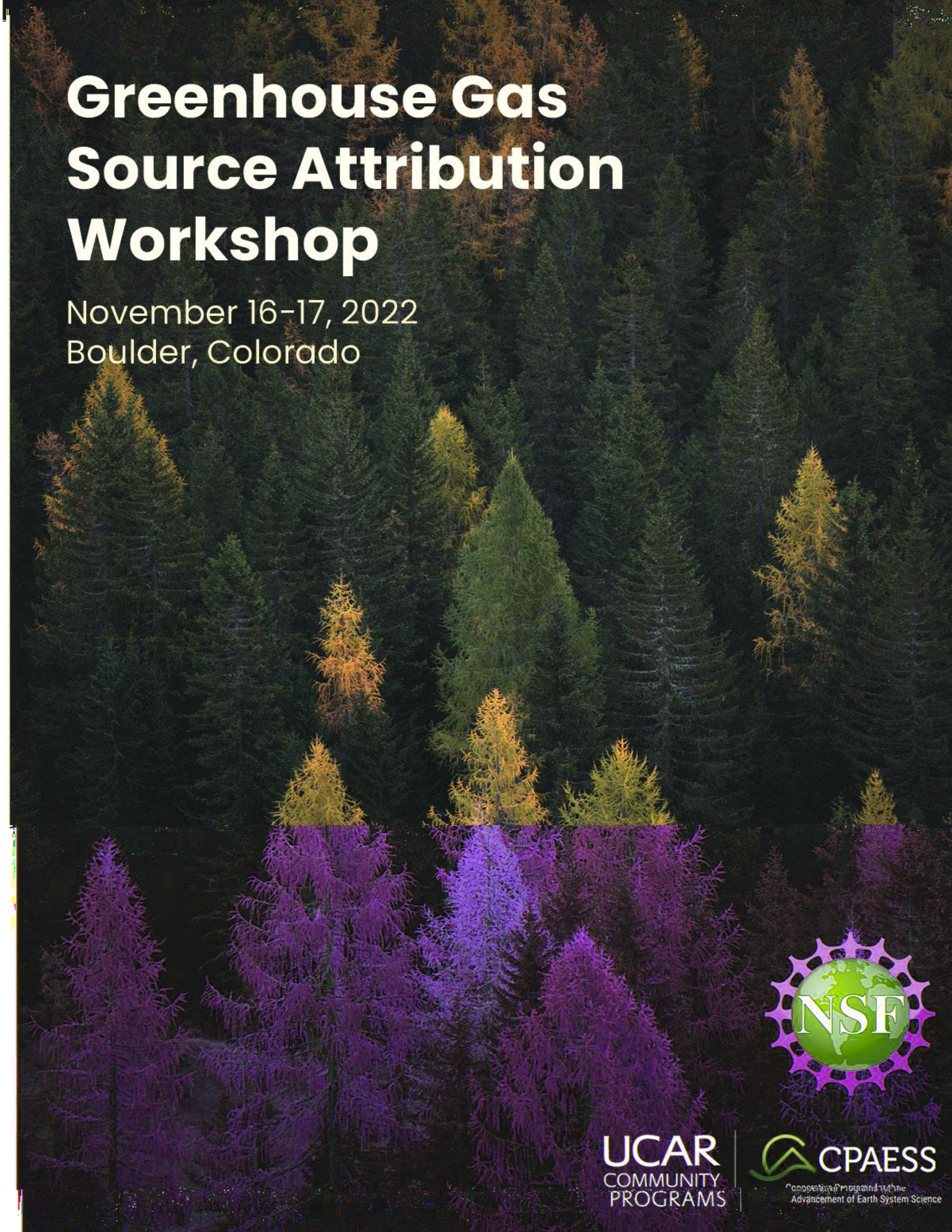
Greenhouse Gas Source Attribution Workshop

November 16-17, 2022
Boulder, Colorado



NSF

UCAR COMMUNITY PROGRAMS

CPAESS
Cooperative Programs for the Advancement of Earth System Science

Workshop Report
December 2022

Identifying Research Priorities and Resources for Reducing Uncertainty in the Attribution of Observed Greenhouse Gas Concentrations

Workshop facilitated by
UCAR/UCP Cooperative Programs for the Advancement of Earth System Science (CPAESS)
November 16–17, 2022

Proposal #: 2023-0050
Title: Greenhouse Gas Source Attribution Workshop
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1. Introduction

This report summarizes the findings of a 1.5-day workshop conducted on November 16-17, 2022, by the Cooperative Programs for the Advancement of Earth System Science (CPAESS) on behalf of the National Science Foundation (NSF). CPAESS is part of the University Corporation for Atmospheric Research (UCAR) Office of Programs (UCP).

NSF contracted with CPAESS to organize and facilitate this community workshop in order to better understand the scientific and technical strategies needed to better identify uncertainties in attributing the sources of greenhouse gas (GHG) emissions, with a focus on modeling and improved understanding and representation of planetary boundary layer (PBL) processes in advancing emission flux estimation. The workshop findings will inform ongoing activities of the Greenhouse Gas Monitoring & Measurement Interagency Working Group (GHG IWG), which is co-led by the White House Office of Management and Budget (OMB), Climate Policy Office (CPO), and Office of Science and Technology Policy (OSTP).

Motivation: The United States is among the parties to the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC). As part of the Paris Agreement, the White House has pledged to work toward a national reduction of 50 to 52 percent by 2030 from 2005 levels of economy-wide net greenhouse gas pollution, and to achieve economy-wide net-zero emissions by 2050. These pledges have been formally submitted to the UNFCCC as the nationally determined contribution (NDC) of the United States toward the overall Paris Agreement goals.

In order to meet the nation's annual reporting commitments to the UNFCCC, the Environmental Protection Agency (EPA) has calculated and released annual inventories of U.S. greenhouse gas emissions and sinks that extend back to 1990. The gases covered by these inventories include carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride, and nitrogen trifluoride. As documented by the EPA inventories, the nation's net GHG emissions decreased by 21.4 percent from 2005 to 2020.

Meeting the Paris Agreement pledges of even greater reductions by years 2030 and 2050 will require enhanced efforts across U.S. regions and sectors. Such efforts, in turn, will require GHG assessments that are more detailed in both time and space. The U.S. will need to develop and deploy advanced techniques, strongly tied to physical measurements of GHGs, to measure, monitor, report, and verify (MMRV) both emissions and removals of GHGs from the atmosphere, nationally and globally, across all regions and sectors. A strong, comprehensive MMRV program will support Federal, state, and local GHG mitigation in public and private sectors while advancing related scientific research and supporting international climate policy.

In support of the GHG IWG goal of developing a national GHG MMRV program, CPAESS conducted a workshop on November 16-17. Participants included 17 scientists working in specialties relevant to MMRV, including nine from UCAR/NCAR and eight from the federal and university sectors. The workshop was conducted at the UCAR Center Green facility in hybrid mode, with both in-person and remote participation.

2. Process

As articulated in background material informing this workshop, one of the goals of the GHG IWG is a comprehensive MMRV program that will include

- the ability to measure and monitor climatically important GHGs and attribute emissions and removals to specific sources;
- prompt reporting, to enable effective mitigation actions;
- sector-specific pilots, if needed, to aid agencies in implementing GHG measurement and monitoring protocols/methodologies; and
- a plan to make GHG data available in accessible formats that facilitate its dissemination and availability for use by Federal agencies, local, state, and tribal governments, the private sector, and the public, including through climate services information tools.

In support of this effort, workshop participants were asked to address the six questions below, as provided by NSF:

1. How can atmospheric dispersion modeling techniques provide reliable emission estimates in atmospheric inversion modeling that starts with GHG concentration data?
2. Are there measurement opportunities that can provide an improved understanding of turbulent processes and dispersion in the planetary boundary layer (PBL) that will contribute directly to the reduction in uncertainty in source attribution of GHG concentrations?
3. What processes need to be better represented in the models to minimize location and quantification uncertainties?
4. What are the advantages/disadvantages of the mixed method (Eulerian and Lagrangian) vs. pure Eulerian? How can we make their solutions converge for non-reactive species?
5. What protocols do we need to set in place for a robust intercomparison and assessment of the impact of improvements in modeling of the PBL and GHG exchanges between Earth's surface and its atmosphere?
6. What should be included in a work plan, and what resources are needed to address the research objectives identified above?

In order to address these questions and make the best use of the expertise on hand during the limited time available, the workshop began with an opening plenary session in which each question was considered and briefly discussed by participants. Breakout groups then approached each question in more detail and reported back in a brief plenary on the afternoon of Day 1. On the afternoon of Day 2, the groups reconvened to respond to feedback and input from Day 1 and to finalize their recommendations.

In the initial plenary, there was general agreement that Question 4 could be most efficiently addressed as part of Question 1. In particular, the issues raised by Question 4 are addressed in recommendations 3 and 5 for Question 1 below. It was also decided that Questions 3 and 5 would be best addressed by a single breakout group.

Each of the resulting three groups (Q1/4, Q2, and Q3/Q5) addressed question 6 within their respective reports. Because of the limited time available, and the broad scope of activity considered by each group, the discussion of work plans and resources was restricted to consideration of the most important variables pertinent to any work plans that might later emerge.

Section 3 of this report (Responses to Questions from NSF) includes responses specific to each question. Section 4 (Overarching Findings) includes points of general consensus among workshop participants. The Appendix includes a list of participants and affiliations.

3. Responses to Questions from NSF

Breakout groups at the workshop developed the following responses to each of the questions posed by NSF. After the responses were compiled and edited, the full report was made available to all participants for additional feedback and revision prior to submission.

Q1: How can atmospheric dispersion modeling techniques provide reliable emission estimates in atmospheric inversion modeling that starts with GHG concentration data?

Breakout group participants: Jeff Anderson (Lead), Wayne Angevine, Jérôme Barré, James Hannigan, Pieternel Levelt, Israel López-Coto

Recommendations:

1. It is essential that a formal systems design process is followed before implementation of any MMRV system, in order to identify the most appropriate observations, models, and data assimilation (DA) techniques. Requirements and evaluation metrics must be clearly defined. Systems design experts should be funded to design the overall system, taking input from the literature and expert elicitation. The system will likely involve multiple observation types, models, and data assimilation techniques.

2. Robust, correct physics and dynamics are critical to the performance of any emissions estimation process. The PBL is critical, but does not stand alone: PBL representation depends on model components that include land/sea surface, convection, microphysics,

macrophysics (clouds), radiation, numerics, etc. We recommend that all these matters be considered in devising the system, its components, and any supporting research program(s).

3. Research should help identify and develop the most appropriate DA techniques for inverse modeling required for a monitoring system with the required accuracy and precision. The advantages of using several inverse-modeling/DA techniques instead of only one should be explored.

4. It is essential to have accurate a-priori and a-posteriori estimates of the uncertainty associated with the outputs of the monitoring and modeling systems. These should include estimates of the errors compared to independent observations, as well as estimates of the underlying fundamental limits in accuracy associated with the available observations and models. DA techniques should be developed to keep track of all errors (e.g., from in-situ, ground-based, and satellite observations and from modeling systems); this will allow for proper assessment of the collective error and the resulting uncertainty for the entire quantification system.

5. Lagrangian, forward Eulerian, and adjoint-based Eulerian modeling/DA systems have differing strengths and weaknesses, depending in part on the observational data they employ. For example, satellite observations and in-situ point observations have different spatial characteristics and may be best used with different DA techniques. These considerations should be clearly stated as part of the design of the modeling subsystem.

6. Improvements to and augmentation of observing systems, including observation types and the optimal spatial and temporal densities and precisions, may be obtained through appropriate observing system simulation experiments (OSSEs). It is essential that OSSEs explore the impact of all available and possible observations of the atmosphere and land surface, including in-situ and remote-sensing techniques and ground-, drone-, aircraft-, and satellite-based platforms. OSSE development will constrain and be constrained by the answers to recommendation 3 above.

7. New results indicate that observations of short-lived tracers contain valuable information about longer-lived species. We recommend that observations of short-lived tracers, both in situ and remotely sensed, be included in any system design exercise.

8. The quality of prior information and uncertainty (e.g. emissions inventories) is critical, and its propagation through a system to the final result should be well characterized (see recommendation 4).

9. Accurate land-surface and vegetation modeling is critical if GHG DA is to constrain anthropogenic emissions and provide the needed precision. Coupled Earth system DA needs to be envisioned with parameter estimation, including data from land surface and vegetation models that have been simplified (i.e., using “appropriate complexity”).

(Q6) What should be included in a work plan and what resources are needed to address research objectives identified above?

Our work plan is summarized in recommendation 1. The needed resources include:
- appropriate personnel for system design tasks
- significant computational resources that will be essential for OSSEs and related system design explorations
- DA systems compatible with the models and observations explored as part of the design process

Q2: Are there measurement opportunities that can provide improved understanding of turbulent processes and dispersion in the planetary boundary layer (PBL) that will contribute directly to the reduction in uncertainty in source attribution of GHG concentrations?

Breakout group participants: Holly Oldroyd (Lead), Ned Patton, Tirtha Banerjee, Heping Liu, Jose Fuentes

Recommendations:

1. **Synthesize existing datasets**. Obtaining a full assay of existing data across climatic and land-use types will be crucial for determining the extent of measurements needed in support of an MMRV. This dataset-synthesis process could embrace networking and team-building activities and pooling of resources such as instrumentation, protocols for data processing and sharing, and modeling tools. The synthesis process could also inform the identification of model deficiencies. Direct collaborations between specialists in modeling and in observations will be crucial to the dataset-synthesis process.

2. **Develop observational strategies targeting thermodynamics and dynamics in the atmospheric boundary layer (ABL), including the stable boundary layer, heterogeneous terrain/vegetation/land use, and complex topography across different climate zones.** Observations must go beyond the flat-terrain assumption to characterize the impacts of complex terrain and multi-scale surface heterogeneities. Vertical profiles of GHG concentrations, turbulent fluxes, wind speed and direction, temperature, and humidity will be needed to characterize the ABL and interpret and develop flux-gradient relationships beyond those applicable to non-idealized scenarios (see recommendation 4). These observational strategies should encompass:
    - measuring surface fluxes across spatial gradients of heterogeneous surfaces and elevations
    - obtaining the states of surface conditions such as temperature, soil/vegetation moisture, greenness, and spectral characteristics, as well as soil conditions (including temperature, heat fluxes, and moisture)

- continuous observation of ABL height, including entrainment and detrainment processes
- collocated observations of ABL vertical profiles, fluxes, concentrations, and surface states, in order to reconcile observations and processes across multiple scales
- observations and analyses of multi-scale interactions, such as overlapping turbulence, wave and sub-mesoscale motions in the stable atmosphere, and terrain-induced lee waves
- enhanced observations of PBL concentrations and fluxes at night, as there are significant uncertainties for periods of nighttime PBL stability and existing databases are sparse

3. **Develop new technologies to facilitate additional measurement opportunities, including large-scale networks.** These technologies should include inexpensive, small, portable, and robust sensors such as sonic anemometers and gas analyzers, as well as multi- and hyper-spectral sensors that could be employed in ensembles. The potential to retrofit open-source drone technology with these sensors should be explored. A variety of distributed and remote sensors could be made more affordable and accessible by developing and expanding activities such as the Center for Transformative Environmental Monitoring Programs (CTEMPs).

4. **Develop regional and global model components to complement observations.** Along with the modeling initiatives discussed elsewhere in this report, such model development could encompass:
    - new turbulence parameterizations for non-idealized terrain, including non-horizontal and discontinuous surfaces
    - algorithms that are robust for all atmospheric stabilities, especially for the stable atmosphere typical of nighttime and cold environments in which turbulence is intermittent and “contaminated” with motions related to jets and gravity waves and with sub-mesoscale motions
    - techniques that go beyond the commonly used Monin-Obukhov Similarity Theories (MOST) in order to more accurately parameterize the relationships between fluxes and scalar concentrations (including greenhouse gases), momentum, and energy for non-idealized conditions such as complex terrain, vegetated surfaces, and other surface discontinuities. Such activities must include urban areas that have a wide range of emissions sources, as well as transition zones between cities and surrounding areas.
    - improved multilayer canopy models, including improved modeling of plant biophysics coupled with canopy- and turbulence-resolved simulations of atmospheric dynamics
    - biogeochemical modeling of surface-layer processes over land and sea associated with GHG emissions
    - improved coupling of mesoscale and microscale models, such as the turbulence generation schemes employed in coupled WRF-LES simulations (Weather

Research and Forecasting–Large Eddy Simulation) to depict surface-layer turbulence and cloud-resolved processes
    - models linking PBL height evolution with surface energy balance and profiles of thermodynamic and dynamic states of the PBL. Such models could incorporate the effects of drought and convective precipitation, for example.

5. **Develop a more diverse workforce.** In addition to the opportunities for diversifying participation in science that are inherent throughout the recommendations of this report (see Overarching Findings), the observational demands of an MMRV could serve as an important mechanism for involving underrepresented communities—including first-generation students and minority-serving institutions—in the creation and deployment of climate-related technology. Such opportunities would grow with research and development toward a new generation of affordable sensors for MMRV-relevant processes. Developing open-source climate-related technologies could improve competition and inspire innovation, while also potentially helping to keep the resulting products affordable to a wide variety of institutions and other users.

(Q6) What should be included in a work plan and what resources are needed to address research objectives identified above?

The dataset-synthesis process discussed in recommendation #1 would be a natural foundation to support strategy and development of the activities discussed in #2 - #4. Meanwhile, plans to increase the diversity of the workforce involved in all of these activities should be developed as soon as possible, as discussed in recommendation #5 above and elaborated below in Section 4 (Overarching Findings). Regarding unique resources associated with this set of recommendations, addressing recommendation #2 above would benefit from targeted field campaign efforts to understand the impacts of heterogeneous environments under varying atmospheric stability conditions. Understanding the resource needs for recommendation #3 would require further study.

Q3: What processes need to be better represented in the models to minimize location and quantification uncertainties?

Breakout group participants: Christopher Loughner (Lead), Benjamin Gaubert, Xin-Zhong Liang, Brian Medeiros, Wenfu Tang, Helen Worden

Recommendations: The discussion and recommendations below address the three categories of processes most relevant to Question 3—PBL structure and evolution, GHG and GHG-related emissions, and atmospheric chemistry—and the modeling developments needed to reduce uncertainties in each.

1. **Address uncertainties in PBL structure and evolution that impact GHG transport and evolution**. In both dynamic and inverse models, PBL height and turbulent mixing

are fundamental in bridging satellite total column and/or in-situ concentrations and ground-based surface fluxes of GHGs.

- Pollutant transport within models is affected by PBL height, wind direction and speed and their profiles, stability and turbulence parameters, convective transport, surface heat, moisture and momentum fluxes, and surface layer treatment.
- Aerosols are affected by and impact PBL structure/energetics via surface emissions and aerosol-cloud-radiation interactions.
- Parameterizations of the stable PBL, especially for the nighttime boundary layer over land, need to be improved. Poor representation of stable boundary layers across modeling approaches (e.g., Earth system modeling, numerical weather prediction, and large eddy simulation) is a longstanding issue.
- Complex topography and spatial heterogeneity (coastlines, mountains, urban environments, and other variations in surface characteristics and land use) must be addressed.

2. **Coordinate efforts with the air quality (AQ) community to address common GHG- and AQ-related emissions**. Emissions influencing GHG concentrations as well as air quality (AQ) both involve similar sources. Integrated AQ/GHG modeling systems, especially emissions-processing systems and inventories, will benefit the AQ and GHG modeling communities. Such systems can improve estimates of emissions from fossil fuels, as well as emissions of other atmospheric constituents that can influence GHG concentrations and AQ.
    - Anthropogenic emissions are typically updated more frequently for AQ models than for GHG emission inventories. Updating the latter more frequently should benefit top-down emission estimates of anthropogenic GHGs.
    - Similarly, reducing the uncertainties in biological and biomass-burning emissions will provide more confidence in top-down emissions estimates of anthropogenic GHGs. Integrating biological fluxes and biomass-burning emissions relevant to AQ and GHG concentrations, and evaluating the resulting modeling systems, should thus be a priority.
    - Variables relevant to biomass burning emissions include fire radiative power (FRP), burned areas, emission factors, fuel load, combustion completeness, diurnal variation, biomass burning sources for heating and cooking, and plume injection heights.
    - Models should be improved and optimized for the treatment of non–fossil-fuel emissions, including dust aerosols, sea salt, and other emissions from vegetation, soils, wetlands, agricultural areas, and landfills.
    - Models of land and ocean biogeochemistry remain highly uncertain. There is a need to improve and develop prediction capability in the representation of carbon and nitrogen cycles in earth-system models, including their interactions and feedback.

3. **Advance constituent data assimilation and prediction capability**. A DA and inversion system is needed that depicts the coupled tropospheric chemistry system, particularly OH and O_3 precursors (CO, CH_2O, NO_2, aerosol optical depth). Such a modeling system could also include synergies and assimilation/inversions specific to methane. Improvements in uncertainty related to DA of PBL observations should be assessed. Other needed activities:
    - include methane/CO/CO_2 isotopes in chemistry-climate models
    - update and assess more complex tropospheric chemistry mechanisms (e.g. those involving halogens and volatile organic compounds)
    - improve representation of stratospheric/tropospheric exchange in global and regional models
    - include two-way feedback between aerosols and meteorology
    - investigate atmospheric chemistry, biogeochemical, and biogeophysical feedbacks in coupled land-atmosphere-vegetation interactions

(Q6) What should be included in a work plan and what resources are needed to address research objectives identified above?

Systematic review of modeling systems:
- Assess current modeling capabilities (for both dynamic and inverse modeling)
- Determine connections/commonalities between approaches for both PBL and emissions modeling (e.g., land model components shared for NWP, ESM, others)
- Identify gaps in each modeling approach (especially gaps that are filled by other approaches and that extend across spatiotemporal scales).

Integration of AQ/GHG/DVM (Dynamic Vegetation Model) modeling systems, especially those pertaining to emissions inventories and dynamic representations:
- Integrate all inventories and models of anthropogenic emissions and develop dynamic GHG emissions capabilities when applicable
- Integrate biological flux models including wetlands modeling and soil microbiology
- Integrate fire emissions models and plume rise algorithms
- Evaluate biological flux models and fire emissions estimates and plume rise algorithms
- Facilitate/promote intercomparison of OH fields from process-based atmospheric chemistry models and other forms of OH estimation, e.g., from methyl-chloroform inversions, but also with DA and inversions of OH and O_3 precursors. The goal is to address aerosols, O_3, and OH sensitivities to inform synergetic and efficient AQ/GHG emission reduction scenarios and to reduce uncertainties in methane emissions and growth rate attribution.
- Utilize ensembles within an atmospheric transport and inversion modeling framework

Observation-based evaluation of PBL-related variables:
- PBL height
- Wind and thermodynamic profiles, including TKE (Turbulence Kinetic Energy) profiles
- Entrainment/detrainment processes

- Turbulence parameters
- Surface heat, momentum, and moisture fluxes
- Aerosol effects on PBL processes

Create eddy-resolved benchmark simulations with high spatial resolution:

- Provides for lower-resolution/parameterized modeling approaches and for machine learning approaches to develop improved or new features in lower-resolution models.
- Allows for process-oriented analysis of boundary layer dynamics.

Ensure careful treatment of vertical layers in PBL and near surface:

- Note that more vertical layers do not necessarily mean better representation of the PBL processes
- Improve representation of the near-surface layer in the models
- Address gap between bottom of the lowest model layer (such as in CESM) and the actual land surface

Resource needs under this set of recommendations include appropriate staffing support to conduct the identified work plan tasks, along with computational resources supporting the modeling and data science efforts.

Q4: What are the advantages/disadvantages of the mixed method (Eulerian and Lagrangian) vs. pure Eulerian? How can we make their solutions converge for non-reactive species?

See Question 1 above, particularly recommendations 3 and 5.

Q5: What protocols do we set in place for a robust intercomparison and assessment of the impact of improvements in modeling of the PBL and GHG exchanges between Earth's surface and its atmosphere?

Breakout group participants: Brian Medeiros (Lead), Christopher Loughner, Benjamin Gaubert, Xin-Zhong Liang, Wenfu Tang, Helen Worden

Recommendations:

1. **Develop modeling intercomparison projects (MIPs) centered on MMRV of GHGs.** There is a long history of model intercomparison studies, and the design of one or more MIPs in support of an MMRV system should build upon successes of the past. The RCEMIP project (Radiative Convective Equilibrium MIP) is an especially instructive example, as it has incorporated global, regional, column, and LES models into a common intercomparison framework. Other useful examples include the GEWEX Cloud System Study, the TransCom2 intercomparison of three-dimensional transport and

concentration of SF_6, and an intercomparison project that involved data from the Orbiting Carbon Observatory-2 platform. MIP activities in support of an MMRV system should:

- adopt a detailed, specific protocol, such as intercomparisons involving the DOE/ARM single-column model or an international land surface model
- evaluate with an independent set of observations, perhaps derived from one or more dedicated field campaigns
- specify common surface and/or boundary-condition input data
- conduct an interagency inverse-model intercomparison to separate flux and transport uncertainties and assess model errors
- employ the HYSPLIT DATEM evaluation system with archived tracer studies to evaluate dispersion models, including any modeling-system updates
- define target quantities for assessing model errors (e.g., structural uncertainties)
- set constraints on target quantities such that any large model spread in experiments can point to areas where improvement may be needed
- to the extent possible, span the variety of models used for different aspects of GHG/PBL modeling (Earth system, NWP, single-column, land surface, LES, inverse) and accommodate varying levels of chemistry complexity

2. **Adopt a standard definition of PBL height.** We acknowledge that “PBL height” has many interpretations and that it is often not a well-defined quantity in actual geophysical flows. In any model evaluation, a consistent definition—e.g., based on turbulent kinetic energy (TKE) profiles—should be adopted. Common quantities of interest used in inversions (e.g., PBL and mixing) should be compared as well.

3. **Withhold an independent set of observations for verification.** Sources could include one or more field campaigns and/or tower-based mesonet stations. Most useful would be vertically resolved measurements of temperature, winds, moisture, and radiation at high temporal resolution.

4. **Develop standards for software diagnostics and validation**. Standardized observation datasets will be needed (e.g., using the ARM or obspack data formats). Model benchmarking (e.g. Ilamb, MELODIES-MONET) would provide consistent, quantitative diagnostics/metrics that allow models or model versions to be compared to each other and/or to reference data. These activities could be coordinated with the Data Assimilation Research Testbed (DART) and/or the Developmental Testbed Center (DTC).

(Q6) What should be included in a work plan and what resources are needed to address research objectives identified above? In concert with the recommendations above, any work plan should include the following themes and resources:

- An inverse model MIP, perhaps involving multiple agencies and coordinated by NSF and incorporating datasets and observations that are user-friendly

- An emphasis on ensemble approaches (across cases) to account for the large internal variability inherent in near-surface transport processes
- Evaluation of varying model types, including NWP, dispersion, biochemistry, and atmospheric chemistry
- Data-driven experimental design
- Metrics for benchmarking
- Common test cases across PBL regimes
- One or more synthetic datasets derived from OSSEs
- One or more field campaigns
- Broad community participation/buy-in

Resource needs will include support for logistical issues, cyberinfrastructure, and staffing to enact the work plan and associated analysis activities. Logistical support would include project support for organizing task teams and coordination among them, as well as for virtual and in-person collaborative workshops. The cyberinfrastructure considerations range from computational resources for running models and performing analysis to archival storage for the data along with a community portal for data access. Community engagement is critical for success of model comparison, and specific community tasks include contributing model results to a common repository, developing standards for PBL height and other relevant diagnostics used for validation and evaluation, and co-designing diagnostic software.

4. Overarching Findings

Participants in this workshop greatly appreciated the opportunity to provide feedback to the creation of an MMRV system that will be crucial to the national goals being pursued by the White House and the GHG IWG toward meeting Paris Agreement pledges. Below are some general points that emerged in discussion beyond the question-specific responses above.

Gather additional community input. Although a wide range of expertise was represented at the workshop, participants stressed that their conclusions should not be seen as definitive representations of the full research community whose work will be relevant to creating an MMRV system. The GHG IHG and those tasked with building the MMRV system should seek out additional scientific and technological perspectives as their work evolves.

Enhance diversity, equity, and inclusion within the workforce. The ongoing need for diversification within the science disciplines pertaining to MMRV creation, and within STEM science in general, was recognized and emphasized by participants. As highlighted in the response to Question 2, the creation of climate-related technologies essential to an MMRV system could be amenable to a broad range of involvement across diverse groups and constituencies. More generally, ensuring diversity within the pipelines that funnel students from K-12 to undergraduate to graduate and postgraduate work will result in a STEM workforce—both within this endeavor and beyond it—that reflects the U.S. population more fully and equitably.

Engage impacted communities in MMRV activities. Because some communities are disproportionately vulnerable to the greenhouse-gas emissions that fuel climate change, and/or to the effects of climate change itself, there should be concerted efforts to involve such communities in the creation and deployment of an MMRV system.

Address scale and culture gaps. In order to produce the strongest scientific outcomes, the process of creating an MMRV should consider two long-recognized disciplinary gaps:

- There is a “scale gap” between modeling and analysis focused on (a) sub-mesoscale processes, including turbulent eddies and atmospheric chemistry, and (b) larger-scale atmospheric processes, from mesoscale to global scale, that shape and are shaped by smaller-scale processes.
- A “culture gap” separates the physical-science communities that are focused primarily on modeling the Earth system (at various scales) and those that primarily observe it (again at various scales).

Efforts to bridge these gaps along the path to building an MMRV system will not only improve the final product but could also yield broader benefits to the relevant scientific communities and the research they carry out. Centering science communities around the core science challenge, and including impacted communities in co-development of strategies to address MMRV needs, may be one potential strategy.

5. Appendix

Workshop participants

Jeffrey Anderson	NCAR Computational and Information Systems Laboratory
Wayne Angevine	CIRES/NOAA
Tirtha Banerjee	University of California, Irvine
Jérôme Barré	UCAR/UCP Joint Center for Satellite Data Assimilation
Jose Fuentes	Pennsylvania State University
Benjamin Gaubert	NCAR/ACOM
James Hannigan	NCAR/ACOM
Pieternel Levelt	NCAR/ACOM
Xin-Zhong Liang	University of Maryland
Heping Liu	Washington State University
Israel López-Coto	Stony Brook University/NIST Special Programs Office
Christopher Loughner	NOAA Air Resources Laboratory
Brian Medeiros	NCAR Climate and Global Dynamics Laboratory
Holly Oldroyd	University of California, Davis
Edward (Ned) Patton	NCAR Mesoscale and Microscale Meteorology Laboratory
Wenfu Tang	NCAR/ACOM
Helen Worden	NCAR/ACOM

**ACOM = Atmospheric Chemistry Observations & Modeling Laboratory*

Workshop organization

Hanne Mauriello	UCAR/CPAESS (PI and workshop planning)
Cindy Bruyère	UCAR/CPAESS (co-PI and workshop planning)
Wendy Gram	UCAR/COMET (facilitation)
Bob Henson	Independent (writing/editing)
Glen Romine	NCAR Directorate (workshop planning)
Maggie Costley	UCAR/CPAESS (event planning)

NSF Greenhouse Gas Workshop Agenda

Meeting Dates & Times
16 November 2022, 8:30 am – 4:30 pm MST
17 November 2022, 12 pm – 4 pm MST

Meeting Location
Boulder, CO & remotely via Zoom

Meeting Information
Meeting location
Center Green 1 (CG1) 2126

Zoom Link
https://us06web.zoom.us/j/84450001103?pwd=ays4VWpZSzhRaXFTN3VMQ09jeWs2UT09
Meeting ID: 844 5000 1103
Passcode: 143831

Wednesday 16 November 2022
All times in MST

8:30 - 10 am Welcome & Introductions
Welcome from UCAR and NSF
Logistics
Attendee Introductions
Review of meeting agenda

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10 – 10:15 am Break

10:15 – 11:30 am Full Group discussions - All Questions

11:30 am – 12 pm Synthesis of Breakout Session
- High level report out from breakout groups
- Question leads & groups for afternoon breakout groups

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12 – 1 pm Lunch

Lunch will be on your own. Please note that the Center Green cafeteria is not open but feel free to bring your own lunch, walk over to Foothills cafeteria, or leave campus for lunch.

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1 pm – 3 pm Breakout Group Discussions by Question

Develop answers to each question, with all groups also addressing the final question as relevant to their question & answer: *What should be included in a work plan and what resources are needed to address research objectives identified in the following 5 questions?*

- Question 1 Breakout Group
  - Question 1: *How can atmospheric dispersion modeling techniques provide reliable emission estimates in atmospheric inversion modeling that starts with GHG concentration data?*
  - Jeff Anderson (Lead), Wayne Angevine, Domingo Munoz-Esparza, Jérôme Barré
  - Q1 Notes linked HERE.
- Question 2 Breakout Group
  - Question 2: *Are there measurement opportunities that can provide improved understanding of turbulent processes and dispersion in the Planetary Boundary Layer (PBL) that will contribute directly to the reduction in uncertainty in source attribution of GHG concentrations?*
  - Holly Oldroyd (Lead), Ned Patton, Tirtha Banerjee, Heping Liu, Jose Fuentes,
  - Q2 Notes linked HERE.
- Question 3 Breakout Group
  - Question 3: *What processes need to be better represented in the models to minimize location and quantification uncertainties?*
  - Christopher Loughner (Lead), Helen Worden, Benjamin Gaubert, Wenfu Tang, Lixin Lu
  - Q3 Notes linked HERE.
- Question 4 Breakout Group
  - Question 4: *What are the advantages/disadvantages of the mixed method (Eulerian and Lagrangian) vs pure Eulerian? How can we make their solutions converge for non-reactive species?*
  - Jim Hannigan (Lead), Pieternel Levelt, Israel Lopez-Coto, Kevin Gurney
  - Q4 Notes linked HERE.
- Question 5 Breakout Group
  - Question 5: *What protocols do we set in place for a robust intercomparison and assessment of the impact of improvements in modeling of the PBL and GHG exchanges between Earth's surface and its atmosphere?*
  - Brian Medeiros (Lead), Xin-Zhong Liang, Atul Jain, Branko Kosovic, Pierre Gentine
  - Q5 Notes linked HERE.

2:30 – 2:45 pm Break

3 - 4:30 pm Report Out from Question Breakout Groups

Overview of response to each question

- Is the response complete or is more discussion, research, input, etc. needed?

Plan to complete responses on Thursday afternoon

Thursday 17 November 2022

All times in MST

12 - 12:15 pm Recap from Day 1 discussions

Questions and action items for Day 2

12:15 - 12:45 pm Share Final Recommendations for Q2

Questions and action items for Day 2

12:45 - 1:45 pm Breakout Group Discussions by Question, Part 2

Continue and complete answers to each question, with answers in Question Note documents

1:45 – 2 pm Break

2 pm – 3:15 pm Final Recommendations from Full Group

Review recommendations for each question

- Is the response complete?
- What other information, data, input is needed to finalize the answer and what is the plan to find that information?
- Does each recommendation include what should be included in a work plan and the resources needed to address the research objectives?

Determine next steps including review of final report

3:15 - 3:30 pm Report Out to NSF

Overview of workshop outcomes for NSF

3:30 - 4 pm Final Questions, Timeline & Thank yous

Plans for writing and reviewing workshop report

- Review by workshop participants Nov 29 - Dec 6 but ideally Dec 3
- Follow up external review by non-participants
- Final report to NSF no later than Dec 23

THANK YOU - we really appreciate everyone's time, excellent ideas, and participation overall!!