

NASA/TM-2011-217192



A State-of-the-Art Experimental Laboratory for Cloud and Cloud-Aerosol Interaction Research

*Need for a National Facility to Complement In Situ and Remote
Field Measurements for Improved Atmospheric Modeling and
Simulation—Background and Discussion*

*Charles M. Fremaux and Dennis M. Bushnell
Langley Research Center, Hampton, Virginia*

November 2011

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Report Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.
- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, and organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA STI Help Desk at 443-757-5803
- Phone the NASA STI Help Desk at 443-757-5802
- Write to:
NASA STI Help Desk
NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320

NASA/TM-2011-217192



A State-of-the-Art Experimental Laboratory for Cloud and Cloud-Aerosol Interaction Research

*Need for a National Facility to Complement In Situ and Remote
Field Measurements for Improved Atmospheric Modeling and
Simulation—Background and Discussion*

*Charles M. Fremaux and Dennis M. Bushnell
Langley Research Center, Hampton, Virginia*

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

November 2011

*“The importance of clouds in the climate system cannot be overemphasized”—
Akio Arakawa, 2004*

Available from:

NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320
443-757-5802

Table of Contents

Acknowledgments	2
Abstract	3
Introduction	4
Background	10
Summary of the State of the Art for Ground-Based Experimental Laboratories	14
Some High-Level Facility Requirements for Cloud Research via Ground-Based Laboratories	18
A Potential Approach to a Large Chamber for Cloud-Aerosol Research	22
Next Steps	24
Conclusions	25
References	26
Appendix	31
Partial List of Existing Ground-Based Aerosol and Cloud Chamber Research Facilities and Summary of Capabilities (from Ref. 52)	31

Acknowledgments

The authors would like to acknowledge organizations and individuals that provided review comments that improved the final version of this report. From NASA Langley Research Center, the following organizations contributed: Research Directorate, Science Directorate, Center Operations Directorate, and Engineering Directorate. Very helpful external reviews were provided by Dr. James D. Klett, Dr. Steven Ghan, and Dr. John H. Helsdon. Many valuable additional comments and ideas were provided by individuals inside and outside of NASA prior to and during the writing of the paper. Special thanks goes to Mr. Bradley Hallier of the Langley Aerospace Research Summer Scholars Program for putting together the extensive list of facilities that appears in the Appendix of this report.

Abstract

The state of the art for predicting future climate changes due to increasing greenhouse gasses in the atmosphere with high accuracy is problematic, notably due to need for greater sophistication in atmospheric modeling. Confidence intervals on current long-term predictions (on the order of 100 years) are so large that the ability to make informed decisions with regard to optimum strategies for mitigating both the causes of climate change and its effects is in doubt. There is ample evidence in the literature that large, if not the largest, sources of uncertainty in current climate models are various aerosol effects, with uncertainty levels ranging from 50% to 400% and greater. A significant deficiency in current capabilities is the lack of high-fidelity mathematical models for cloud-aerosol interactions. As exaflop-class computational capability begins to come on line over the next decade or so, much better modeling of these interactions will be needed to take advantage of significantly increased computational power and enable the high fidelity climate predictions needed by policy and decision makers in government and industry. One approach to furthering discovery as well as modeling, and verification and validation (V&V) for cloud-aerosol interactions is use of a "cloud chamber" with a significantly larger volume than is currently available. *Such a laboratory facility would be used in a complimentary role to in-situ and remote sensing field campaign measurement approaches (e.g., airborne and spaceborne instruments) to enable improved global climate modeling.* While it is recognized that reproducing all of the highly complex phenomena associated with these interactions is not feasible, it is suggested that the physics of certain key processes can be established in a laboratory setting so that relevant fluid-dynamic and cloud-aerosol phenomena (e.g., turbulent many-phase flow, convection, electrostatics, aerosol particle formation and growth, etc.) can be experimentally simulated and studied in a *controlled* environment using sophisticated instrumentation in a facility that is large enough so that wall effects are reduced to acceptable levels, and reasonable-scale cloud dynamics can be simulated. This report presents a high-level argument for significantly improved laboratory capability, and is meant to serve as a starting point for stimulating discussion within the climate science and other interested communities with regard to the need, requirements, and payoff for pursuing a large, state-of-the-art experimental facility for improving prediction of future climate states.

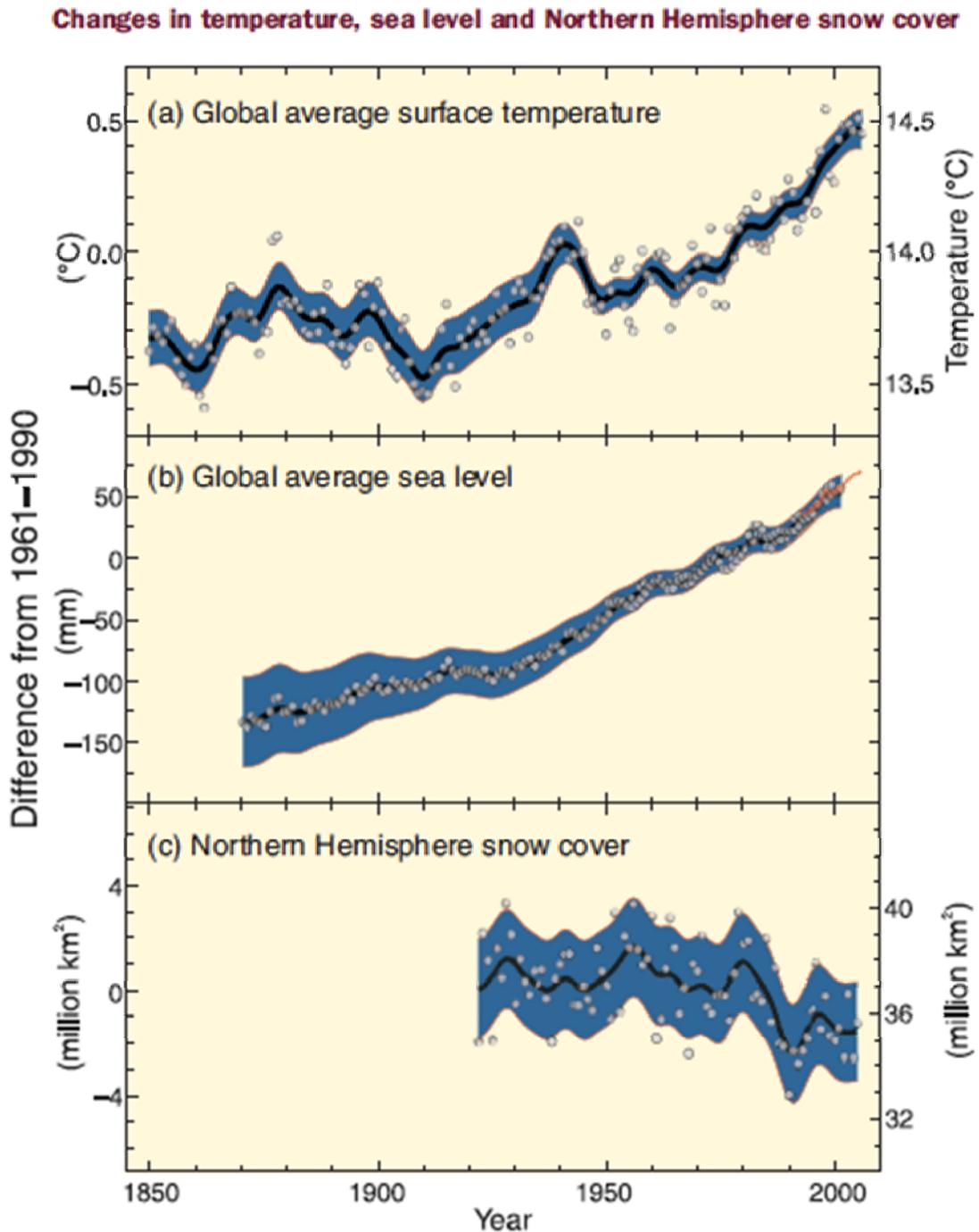
Introduction

Currently, there is wide agreement within the climate science community that the Earth's mean atmospheric temperature has risen over the last century relative to historical norms, and that this rise is being driven primarily by increased concentrations of natural and anthropogenic greenhouse gasses, although there is some disagreement as to whether increased greenhouse gas concentrations are due to natural cycles or human-induced activities. Water vapor is the most abundant greenhouse gas in the atmosphere, but increases primarily in carbon dioxide (CO₂), but also methane (CH₄), nitrous oxide (N₂O), chlorofluorocarbons (CFCs), and others are most associated with the rise in global temperature.

Globally and within the U.S., significant resources are being expended on measurements of atmospheric phenomena, and developing, testing, and refining climate models for predicting climate change and its impacts. Key policy- and decision-makers in government and industry require high-confidence projections of future climate states in order to make good decisions with regard to deployment of resources for reducing greenhouse gas sources, dealing with impacts due to climate change such as sea level rise, etc., and possibly even developing "engineering solutions" to mitigate undesirable climate changes.

While analyses of historical climate data indicate with fairly high certainty that mean global atmospheric temperature has risen since the late nineteenth century (the consensusⁱ estimate is in the range of 0.56 °C to 0.92 °C over the 100 years between 1906 and 2005 (Fig. 1)), and that mean sea level has risen over the same time interval by approximately 15 cm, the state of the art for predicting future climate changes with high accuracy is much more problematic. In fact, confidence intervals on current long-term predictions (e.g., by the end of the twenty-first century) are so large that the ability to make informed decisions with regard to optimum strategies for mitigating both the causes of climate change and its effects is in doubt. For example, over the *next* century, IPCC best-estimates¹ for global surface mean atmospheric temperature rise relative to the last two decades of the twentieth century (Table 1) vary by a factor greater than two (+1.8 °C to +4.0 °C). If the worst-case extremes of "likely" temperature increase (where likely is defined in Reference 1 as >66% probability of occurrence) are used, the spread is nearly a factor of six (+1.1 °C to +6.4 °C), as illustrated by the gray "best estimate" bars to the right of Figure 2. Similarly, sea-level rise predictions vary by a factor of greater than three (approximately +18 cm to +59 cm). While the reasons for the spread in the predictions are varied and complex (differing underlying assumptions, uncertainties in the modeled values, etc.), depending on whether the outcome is on one extreme of the predictions or the other, a different (likely significantly different) response by policy- and decision makers will be required. Making the "wrong" investments early on could have significant negative impact in the long run, ranging from needless expenditure of

valuable resources on one extreme to failure to deal with the problem sufficiently to prevent major environmental consequences at the other extreme.



Note: Observed changes in (a) global average surface temperature; (b) global average sea level from tide gauge (blue) and satellite (red) data; and (c) Northern Hemisphere snow cover for March-April. All differences are relative to corresponding averages for the period 1961-1990. Smoother curves represent decadal averaged values while circles show yearly values. The shaded areas are the uncertainty intervals estimated from a comprehensive analysis of known uncertainties (a and b) and from the time series (c). (WGI FAQ 3.1 Figure 1, Figure 4.2, Figure 5.1.3, Figure SPM.3)

Figure 1. Observed historical change in global average surface temperatures, average sea level, and northern hemisphere snow cover (from Ref. 1, Fig. 1.1, p. 31)

Table 1. Projected Global Average Surface Warming and Sea Level Rise at the end of the 21st Century (from Ref. 1, Table 3.1, p. 45)

Case	Temperature change (°C at 2090-2099 relative to 1980-1999) ^{a, d}		Sea level rise (m at 2090-2099 relative to 1980-1999)
	Best estimate	Likely range	Model-based range excluding future rapid dynamical changes in ice flow
Constant year 2000 concentrations ^b	0.6	0.3 – 0.9	Not available
B1 scenario	1.8	1.1 – 2.9	0.18 – 0.38
A1T scenario	2.4	1.4 – 3.8	0.20 – 0.45
B2 scenario	2.4	1.4 – 3.8	0.20 – 0.43
A1B scenario	2.8	1.7 – 4.4	0.21 – 0.48
A2 scenario	3.4	2.0 – 5.4	0.23 – 0.51
A1FI scenario	4.0	2.4 – 6.4	0.26 – 0.59

Notes:

- a) These estimates are assessed from a hierarchy of models that encompass a simple climate model, several Earth Models of Intermediate Complexity, and a large number of Atmosphere-Ocean General Circulation Models (AOGCMs) as well as observational constraints.
- b) Year 2000 constant composition is derived from AOGCMs only.
- c) All scenarios above are six SRES marker scenarios. Approximate CO₂-eq concentrations corresponding to the computed radiative forcing due to anthropogenic GHGs and aerosols in 2100 (see p. 823 of the WGI TAR) for the SRES B1, A1T, B2, A1B, A2 and A1FI illustrative marker scenarios are about 600, 700, 800, 850, 1250 and 1550ppm, respectively.
- d) Temperature changes are expressed as the difference from the period 1980-1999. To express the change relative to the period 1850-1899 add 0.5°C.

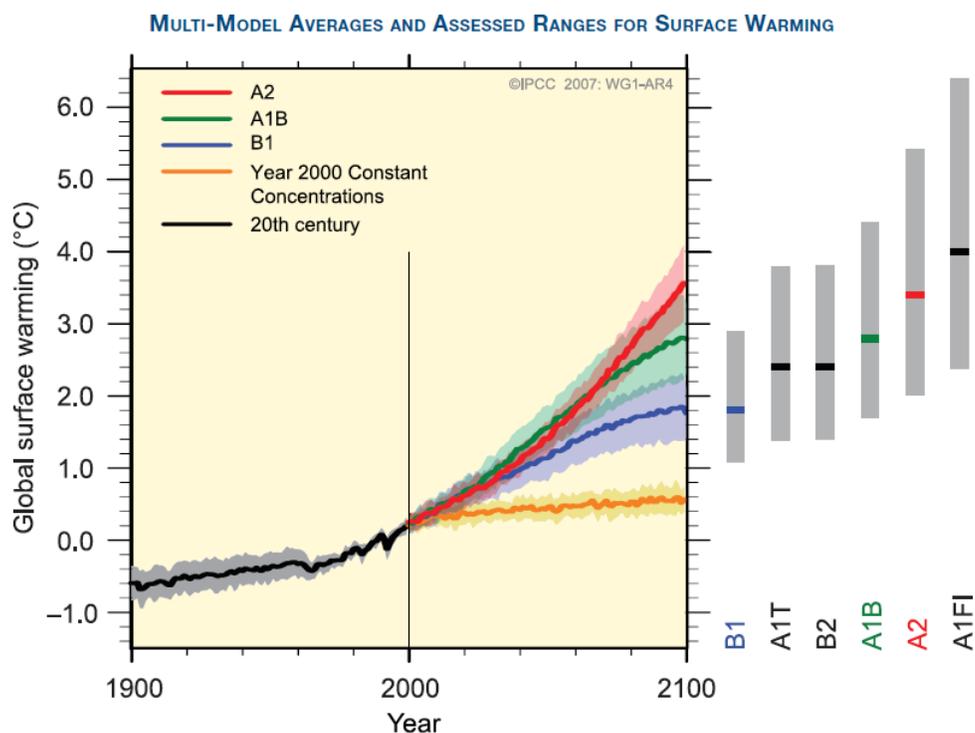


Figure SPM.5. Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ± 1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios. The assessment of the best estimate and likely ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints. (Figures 10.4 and 10.29)

Figure 2. Change in average measured (1900-2000) and predicted (2000-2100) surface temperature relative to 1980-1999 (from Ref. 2, Fig. SPM.5, Summary for Policymakers section, p. 14)

There is ample evidence in the literature (e.g. refs. 2 - 5, with many other examples cited later) that large, if not the largest, sources of uncertainty in current simulation climate models are various cloud and cloud-aerosol effects, with values ranging from 50% to 400% and greater. A significant deficiency in current capabilities is a lack of high-fidelity mathematical models for cloud effects and cloud-aerosol interactions. The following excerpt from the 2010 Department of Energy (DOE) Atmospheric System Research Science and Program Plan⁶ executive summary captures the issue succinctly:

Current climate models show a large spread in the values of projected climate parameters like surface temperature and precipitation, and this spread makes it difficult for policy makers to use such projections to develop national and international energy policy. The spread in climate model projections arises from two broad sources of uncertainty. First, scientists believe that anthropogenic *atmospheric aerosols* partially offset the global warming influence due to enhanced greenhouse gas concentrations, but because climate models are uncertain how to represent the complex aerosol lifecycle in the atmosphere, they are also uncertain about the impact of aerosols on climate. Second, *clouds* are a large source of uncertainty in climate models, particularly how clouds will respond to and interact with changes in atmospheric composition. Both aerosols and clouds influence *radiation and precipitation*, which together largely drive the global atmospheric circulation.

A primary cause of current high levels of uncertainty in future climate prediction by modeling is a low level of understanding of the underlying physical processes related to atmospheric aerosols and cloud-aerosol interactions as they pertain to climate change. As clearly noted by the IPCC in Reference 2:

Anthropogenic contributions to aerosols (primarily sulphate, organic carbon, black carbon, nitrate and dust) together produce a cooling effect, with a total direct radiative forcing of -0.5 [-0.9 to -0.1] $W\ m^{-2}$ and an indirect cloud albedo forcing of -0.7 [-1.8 to -0.3] $W\ m^{-2}$. These forcings are now better understood than at the time of the TAR (i.e., the third Technical Analysis Report produced by the IPCC in 2001) due to improved *in situ*, satellite and ground-based measurements and more comprehensive modeling, *but remain the dominant uncertainty in radiative forcing* (emphasis added). Aerosols also influence cloud lifetime and precipitation.

The mechanisms contributing to radiative forcing are summarized in Figure 3 from Reference 2. Note that the total (direct + cloud albedo) impact of aerosols on radiative forcing is second only to CO_2 , but that the uncertainties on these quantities are by far the largest of any of the components, and that the "level of scientific understanding" (LOSU) is "medium to low" for direct effects, and "low" for cloud albedo effects. The clear need for significantly better understanding of the physical mechanisms and processes underlying

atmospheric aerosols and cloud-aerosol interactions (as they relate to climate change) is the impetus for proposing that highly controlled experiments be conducted in a state-of-the-art laboratory. Only when the relevant underlying physical processes related to aerosols and cloud-aerosol interactions are much better understood, and those physical processes that are well understood are adequately accounted for, will uncertainties be significantly reduced. As much more powerful supercomputers begin to come on line

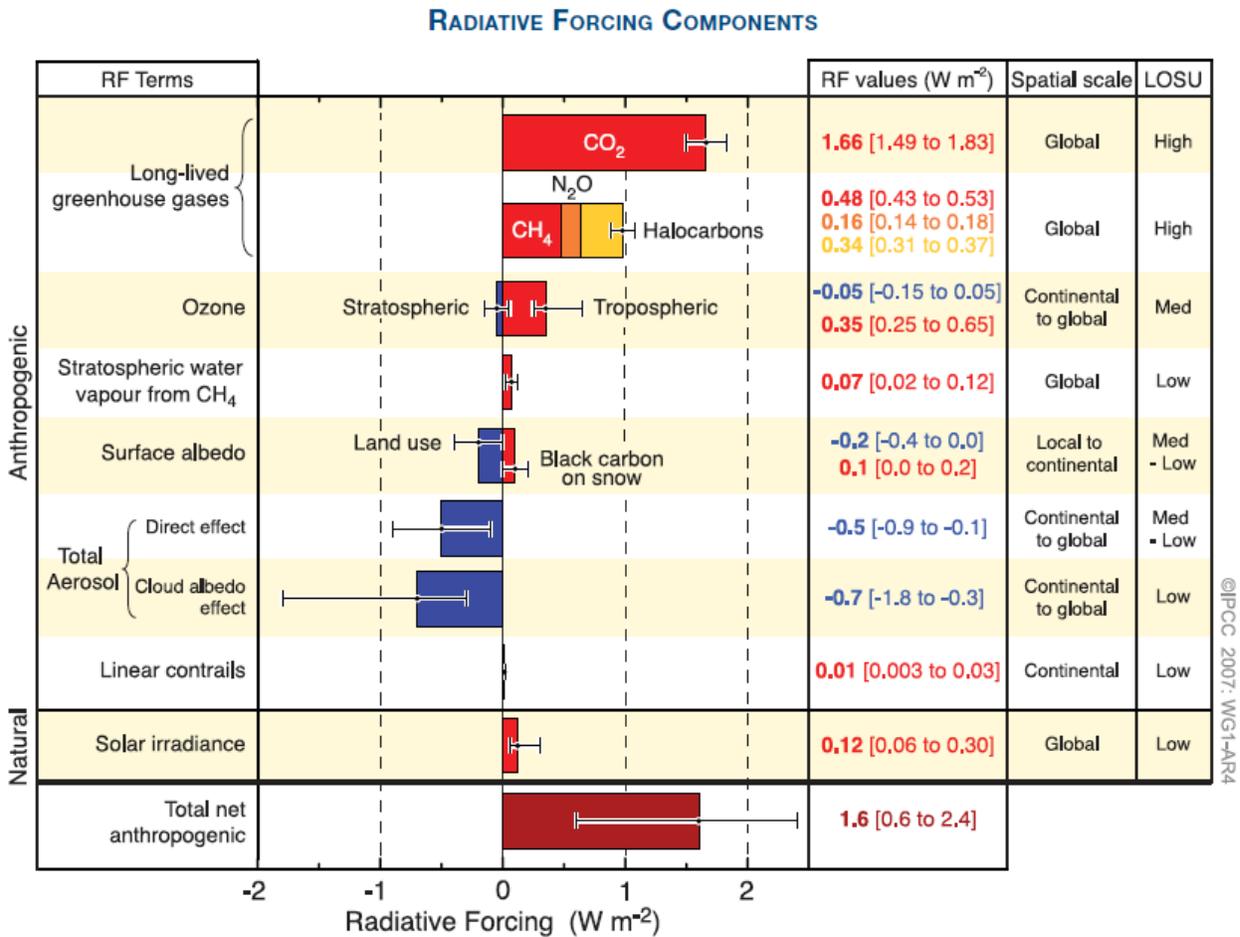


Figure SPM.2. Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. These require summing asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. The range for linear contrails does not include other possible effects of aviation on cloudiness. {2.9, Figure 2.20}

Figure 3. Anthropogenic and Natural Radiative Forcing Components Important to Climate Change (from Ref. 2, Fig. SPM.2, Summary for Policymakers section, p. 4)

over the next decade or so (likely exaflop-class computers, i.e., 10¹⁸ floating point operations per second), much better modeling of these interactions will be needed to take advantage of

significantly increased computational power and deliver the high fidelity climate predictions needed by policy and decision makers in government and industry.

There are, in addition, considerable and increasing concerns regarding the potential impact of "positive feedbacks". For example, warming-induced release of the massive amounts of fossil methane and methane clathrates (methane ice or "fire ice") present in the tundra and ocean sediments could have a major impact on temperature rise since methane is over twenty times more effective than CO₂ as a greenhouse gas. The tundra and oceans also contain massive amounts of fossil CO₂ that is being released as warming occurs. In addition, the ability of the oceans to absorb excess atmospheric CO₂ (i.e., "CO₂ uptake") is being reduced due to temperature rise, acidification, and reductions in algae. Another example of a positive feedback cycle is related to the planet's albedo, or the amount of solar radiation reflected back into space. As large ice sheets melt, albedo is reduced and average temperature is increased. Increased temperature results in more water being evaporated, and water vapor is a dominant greenhouse gas. Taken together, these positive feedbacks could evidently, from crude estimates, greatly accelerate the rate and increase the impacts of climate change. Reference 7 provides a discussion of the "cloud positive feedback" that is directly related to cloud-aerosol interactions.

One approach to furthering discovery as well as modeling, and verification and validation (V&V) for cloud-aerosol interactions is to use a "cloud chamber" with a significantly larger volume than is currently available. *Such a laboratory facility would be used in a complimentary role to in-situ field campaign measurement approaches (e.g., airborne and spaceborne instruments) to improve the fidelity of atmospheric models for climate change prediction.* It is recognized that reproducing all of the highly complex phenomena associated with these interactions in a laboratory setting is not feasible. However, it is suggested that the physics of certain key processes can be established so that important phenomena (e.g., turbulent many-phase flow, convection, turbulence, electrostatics, particle formation and growth, etc.) can be experimentally simulated and studied in a *controlled* environment using sophisticated instrumentation in a facility that is large enough so that wall effects are reduced to acceptable levels, and reasonable-scale cloud dynamics can be simulated. As discussed and suggested herein, controlled laboratory experiments in large-scale ground facilities appear to be a "missing link" in the quest for truly high fidelity climate change predictions going forward, but detailed analyses will have to be conducted in order to estimate the magnitude of uncertainty reduction that can ultimately be realized relative to the current field campaign state of the art.

Overall, it is obvious that prognostication of climate change over the next several decades to a century must be done with as much precision and accuracy as can be mustered due to the potentially massive impacts going forward on global econometrics, human health, standards

of living and national security. There is a possibility that global co-operation whilst working “climate change” as a “common enemy” could lead to greater global consilience. NASA Langley Research Center is assessing the need and requirements for a ground-based facility to experimentally simulate, both for discovery science and modeling, cloud-aerosol interactions with application(s) to their effects on climate change. Such a facility is envisioned as a national resource for developing critical aspects of climate models, calibrating computational methods, and understanding the physical processes underlying cloud-aerosol interactions through the study of meaningful but manageable “unit problems” at useful scales. This document outlines the impetus for considering the need for better understanding and representation of cloud-aerosol interactions in Global Climate Models (GCMs), some initial high-level requirements for a ground-based experimental facility, possible conceptual approaches to its design, and the next steps needed to assess the level of consensus for such a facility within the climate science community.

Background

A search of the pertinent literature reveals that, while the mean predicted trends appear to be consistent (e.g., that a rise in mean global temperature over a time scale of several decades will occur due to increasing levels of greenhouse gasses from a combination of anthropogenic and natural sources) there is wide acceptance within the climate science community that there are large uncertainties in these projections due to a number of factors. One of the largest sources of uncertainty appears to be lack of sophistication for representing cloud feedbacks (positive and negative) into the Earth's radiation budget in Global Climate Models^{4,5}, including forcing effects of aerosols as they interact with clouds. Large Eddy Simulations (LES) and other computational approaches use modeling to simulate complex atmospheric physics and chemistry, including the effects of aerosols, for predicting climate states (e.g., Ref. 8). These aerosol (and other particulate) effects are believed to be the source of phenomena ranging from “global dimming” (the reduction of direct solar radiation reaching the Earth's surface and thus reducing atmospheric temperature and partially counteracting temperature rise caused by greenhouse gas pollution), to changes in the global precipitation pattern. The discretization scale of most GCMs (on the order of 1 degree of latitude, or roughly 100 km) is also problematic in terms of predicting phenomena that are manifest at smaller scales such as cloud effects, and thus their impacts. Current practice is to parameterize cloud effects using bulk properties across a grid cell, even though the scale of individual clouds (and even cloud systems) can be many times smaller. While necessary due to the computational intensity of atmospheric simulations relative to current computer power, this compromise clearly introduces a source of uncertainty into the results. However, some recent simulations have been run at resolutions as low as 100m in order to resolve individual clouds with encouraging results (Ref. 9). Below are representative excerpts from a sampling of the contemporary literature

with regard to cloud and cloud-aerosol interactions and their impact on climate change predictions:

- "Estimates of Earth's climate sensitivity are uncertain, largely because of uncertainty in the long-term cloud feedback" - (Ref. 10)
- "Clouds have a strong influence on the Earth's radiative balance but are poorly represented in current climate models" - (Ref. 11)
- "Many of the uncertainties in Global Climate Models stem from poor representation of cloud processes that operate at fine scales" - (Ref. 6)
- "We do not know how much warming due to green-house gases has been canceled by cooling due to aerosols" - (Ref. 12)
- "The uncertainty in assessing anthropogenic aerosol impacts on climate must be much reduced from its current level to allow meaningful projections of future climate" - (Ref. 13)
- "The interactions between aerosols and clouds is probably the biggest uncertainty of all climate forcing/feedback processes" - (Ref. 13)
- "Modeling the cloud albedo effect from first principles has proven difficult because the representation of aerosol-cloud interactions and of clouds themselves in climate models are still crude" - (Ref. 14)
- "Variations of cloudiness by 5% translates to a degree of temperature change" - (Ref. 15)
- "Whether anthropogenic activity actually increases or decreases ice nuclei concentration is a matter of debate" - (Ref. 16)
- "The uncertainty in aerosol radiative forcing is typically greater than 100% and for some aerosol components it is more than 200%. The regional scale forcing can be significantly greater than the global average, as can the associated uncertainty" - (Ref. 17)
- "The indirect radiative effects of aerosols also includes effects on ice and mixed phase clouds but the magnitude of any indirect effect associated with the ice phase is not known" - (Ref. 3)
- "Aerosols represent the largest uncertainty in understanding how humans are changing our climate" - (Ref. 18)

- “Even small changes in ice formation could have a significant impact on the indirect forcing due to aerosols” - (Ref. 3)
- “Scientists have yet to untangle the interplay between pollution, clouds, precipitation and temperature” - (Ref. 19)
- “Global models suggest that sulfate aerosols produce a direct forcing in the Northern Hemisphere of the same order of magnitude as that from anthropogenic green house gases but opposite in sign. There is substantial uncertainty about the magnitude and spatial distribution of the negative forcing by aerosols. It is the opinion of this panel (the NRC) that the uncertainty in the magnitude of the effects of aerosols on climate is seriously hindering our ability to assess the effect of anthropogenic emissions on climate” - (Ref. 20)
- “Anthropogenic aerosols have the potential to introduce complex anomalies in the circulation and precipitation climatology thereby creating hazardous new hot spots in the water cycle.” - (Ref. 21)
- “Quantifying the indirect (cloud-aerosol) effects of aerosols is highly uncertain and remains one of the largest uncertainties in our efforts to calculate radiative forcing” - (Ref. 23)
- “The greatest uncertainty about aerosol climate forcing, indeed the largest of all the uncertainties about global climate forcing – is probably the indirect effect of aerosols on clouds” - (Ref. 24)
- "Estimates of Earth’s Climate sensitivity are uncertain largely because of uncertainty in long term cloud feedback" - (Ref. 10)
- “Accurate representation of cirrus clouds remains a challenge to climate modeling in part because of an incomplete understanding of ice formation mechanisms” - (Ref. 25)
- “The magnitude of the indirect effects (of aerosols) on clouds remains a mystery” - (Ref. 26)
- “The cloud-aerosol-precipitation processes are not taken into account as they should not because we do not recognize their importance but rather because we know too little on how to quantify them accurately in the weather and climate models, It appears we cannot get the climate system right without properly accounting for the aerosol-cloud-precipitation processes, the dynamic response of the clouds and the cascade of feedbacks” - (Ref. 27)
- “Aerosols and clouds play central roles in atmospheric chemistry and physics, climate, air pollution and public health. The mechanistic understanding and

predictability of aerosol and cloud properties, interactions, transformations and effects are, however, still very limited” - (Ref. 28)

- In Reference 29, the issue that was most uncertain to all fourteen experts was clouds, specifically whether or not clouds would exacerbate climate change by trapping more heat or ameliorate it by reflecting more sunlight.

Based on recent reports (e.g., Ref. 2), typical uncertainties for various impacts of aerosols upon climate forcing are in the $\pm 50\%$ to $\pm 100\%$ range, but with several at much greater uncertainties of up to 400%. The current state-of-the-art for developing atmospheric simulation models relies almost primarily on *in situ* and remote-sensing field measurements of atmospheric state using ground based, airborne, or spaceborne instruments. The use of highly sophisticated instruments and sensing techniques in real-world atmospheric measurements produces very high quality data for analysis and modeling. However, the information produced by such field campaigns is, by its nature, “all inclusive” and “contemporary”, i.e., the entire panoply of physical mechanisms and interactions present in the atmosphere locally and currently are represented, but the ability to assess the impact of particular constituents or processes in controlled and repeatable ways (i.e., as in a laboratory setting) is either very difficult or impossible. Thus, potential changes to such physics and interactions that might be induced going forward by various impacts of climate change are not accessed. Without accurate, valid modeling of the requisite physics writ large these current field campaigns cannot be projected forward to yield what is really required – accurate “predictions” and impacts of various mitigation approaches. As noted in Reference 3: “Projections of a future indirect effect are especially uncertain because empirical relationships between cloud droplet number and aerosol mass may not remain valid for possible future changes in aerosol size distributions”. Although the empirical formulations noted in Reference 3 have been superseded by those that are more physics-based in the current generation of climate models (as noted in Reference 4), significant work remains to be done before the all of the relevant physics are captured. The field campaigns are essential to studying the factors that control behavior of the current atmosphere, but are far from what is required to develop and calibrate high-fidelity physical models for predicting future changes. For such modeling, laboratory studies are required so that unit problems and discovery can be undertaken under controlled conditions in a cost effective and expeditious manner. “The key to reducing aerosol RF uncertainty estimates is to understand the contributing processes well enough to accurately reproduce them in models” (Ref. 13). Currently in the U.S., ground-based laboratory facilities (excluding the ground-based atmospheric measurement field campaign instruments just noted) appear to be primarily used for instrument calibration and some limited science for understanding fundamental physics on a small scale, e.g., cloud microphysics. Examples of some processes that could benefit from highly controlled laboratory experiments are briefly summarized in a later section of this report.

Summary of the State of the Art for Ground-Based Experimental Laboratories

A review of the literature reveals that the state of ground-based facilities for experimentally simulating and studying cloud phenomena (excluding those for instrument calibration, small-scale experiments, and educational instruction) is at a low ebb, far more conspicuously in the U.S. than in Europe. The appendix of this report summarizes the facilities that were identified during a recent literature survey. While this list is not exhaustive, it does provide a good indication of breadth, location, and overall capabilities of current facilities.

In the U.S., while fairly large facilities (e.g., cloud chambers) were in use during past decades, few if any of these appear to be operational today. In the mid 20th century, cloud chamber laboratory facilities of various types and sizes were relatively common, contributing much to the understanding of cloud microphysics. In the later portions of the 20th century, interest shifted into the emerging numerical simulation arena as a companion to field campaigns and, in the U.S., cloud chamber and other laboratory studies were deemphasized and most were decommissioned. A workshop on “The Future of Laboratory Research and Facilities for Cloud Physics and Cloud Chemistry” (Ref. 30) was held at Boulder, Colorado in 1985. The report from that workshop states that “...laboratory research over the past two decades (i.e., since the 1960s) has declined to such an extent that scientific progress toward understanding many processes occurring in the atmosphere is being impeded”. Additionally stated in that report is the following conclusion: “Triple (i.e., two types of precipitation particles and cloud) and triple-plus interactions need to be understood and facilities with new capabilities are required to carry out the necessary studies; these points are certain. Many of the problems and costs involved in tackling triple and triple-plus interactions with new equipment may demand a consolidation of resources into a single National Facility, or a set of facilities that would be suitable for a wide variety of experimental work that cannot be undertaken with existing facilities.” The report goes on to recommend facilities in the 80m to 120m-size range to enable studies of cloud-aerosol interactions, as illustrated in Figure 4.

More recently, Reference 31 indicates that 10m clouds, a size that could be studied in a 100m facility, are of interest to atmospheric aerosol-cloud interaction dynamics. Also, “To study clouds and aerosols one must deal with processes occurring and interacting in more than 12 orders of magnitude, changes on the microphysical clouds (6m-10m) may produce dramatic changes on the regional climate and whole hydrological cycle” (Ref. 32).

In the intervening twenty-six years since the laboratory workshop cited in Reference 30 was held, climate change concerns have become both more worrisome and more immediate, with concomitant requirements for ever-more-accurate climate projections at the regional

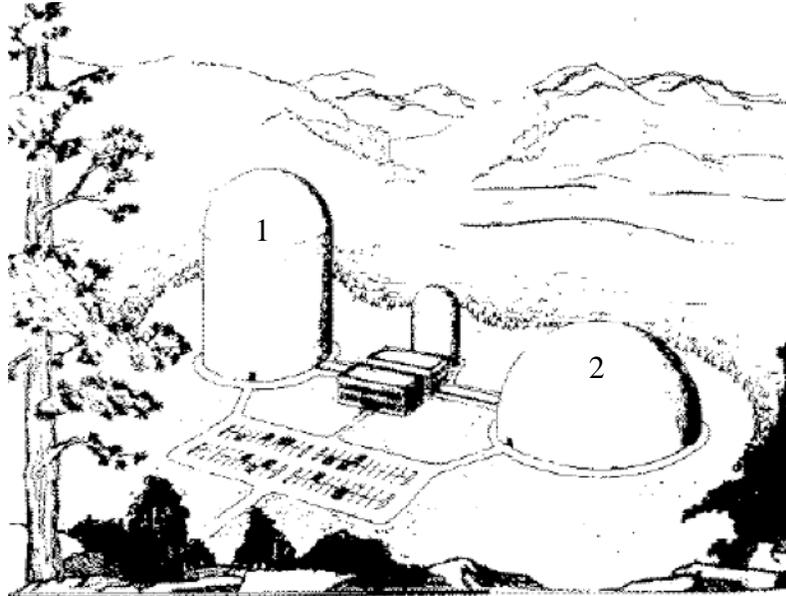


Figure 4. Concept for a national cloud and precipitation research facility from 1985 facilities workshop. 1: diameter 80m, height 120m, 2: diameter 120m, height 60m. (Ref. 30)

and global levels. Also during this timeframe, cloud chamber laboratory climate studies in the U.S. have even further atrophied. The promise shown by advanced atmospheric simulation techniques (both as a predictive tool, and as a way to make those predictions at lower cost than via ground-based experiments), coupled with availability of "current atmosphere" data from sophisticated in situ and remote-sensing field measurements, was a primary driver for this shift in emphasis. However, in hindsight, it is clear that high fidelity climate predictions must rely on a "three legged stool" of field measurements, modeling/simulation, *and* sophisticated laboratory experimentation, and that the de-emphasis of the latter over the past few decades has resulted in an "out of balance" situation that is hampering predictive capability just when it is needed most.

A direct analogy to the situation in climate prediction is the imminent demise of aerodynamic wind tunnels that was predicted with the advent of sophisticated computational fluid dynamic (CFD) codes for solving the Navier-Stokes equations that began in the 1970s ("there will be no need for wind tunnels within ten years..."), and continued in the decades that followed. However, in the forty years since then, while CFD has made great inroads into high-fidelity aerodynamic prediction and many wind tunnels have closed (more due to a significant reduction in the number of aircraft development efforts, e.g., due to the end of the Cold War, than to a reduction in need for high-fidelity experimental data in any given project), it appears that the aerospace community is

realizing that this assumption was premature and shortsighted, and that some minimum set of wind tunnels will be required for decades to come for conducting controlled experiments for advanced aerodynamic modeling, validation and calibration of computational tools, and database development for configurations in flow regimes in which CFD is not yet capable of providing the "final answer" prior to flight. So, while Boeing used CFD to significantly reduce the number of wing sets that were wind tunnel tested for the 787 Dreamliner compared to earlier aircraft, it could not have accomplished the task without the concurrent use of high quality experimental data from large wind tunnels, both for data generation and for computational tool validation. Climate prediction methods appear to have followed a path similar to that of the aerospace community, but have gone even farther in that there are few if any large experimental facilities in operation today.

Needless to say, the suggested 100m class facilities called for at the 1985 workshop were never constructed. There have been attempts to secure funding for larger scale facilities (i.e., larger than contemporary facilities), but to-date none of these proposals has been successful (Ref. 33). Besides cloud chambers, other facilities such as specially designed vertical wind tunnels have been used to simulate the dynamics of raindrops and other particulates in the atmosphere (e.g., Refs. 34-36). While not emphasized in this report, improved wind tunnel capability for studying, e.g., aerosol particle and ice crystal formation and growth, should also be considered.

In Europe the situation appears to be somewhat better (Ref. 37), with updated cloud chambers being built and utilized for climate issues, but these are far smaller than the 100m class facilities called out in the 1985 laboratory workshop. European Simulation Chambers for Investigating Atmospheric Processes (EUROCHAMP-2) is a highly integrated consortium of sixteen chamber facilities operated by fourteen partner organizations from eight European countries organized in 2009 as a follow-on to EUROCHAM-1 (2004 - 2009). Although there are no EUROCHAMP facilities that approach the scale of that being discussed in this report, there are some relatively large chambers of recent vintage. The largest appears to be Aerosols Interaction and Dynamics in the Atmosphere (AIDA)^{37,38} in Germany for studying cloud dynamics and cloud-aerosol interactions on a small scale. This chamber (Fig. 5) has a volume of 85 m³, a temperature range of -90 °C to +50 °C, reduced pressure capability, can introduce trace gasses, and has highly sophisticated instrumentation, allowing AIDA to carry out aerosol and cloud experiments over a full range of tropospheric and stratospheric temperatures and pressures.

Another example of a modern facility is LACIS, or Leipzig Aerosol Cloud Interaction Simulator operated by the Leibniz Institute for Tropospheric Research in Germany (Ref. 39). This facility is highly specialized to study cloud-aerosol interactions. LACIS consists of a

large outer shell containing a highly instrumented flow tube. The exterior of the facility is shown in Figure 6. The temperature capability of the facility is $-60\text{ }^{\circ}\text{C}$ to $+40\text{ }^{\circ}\text{C}$.

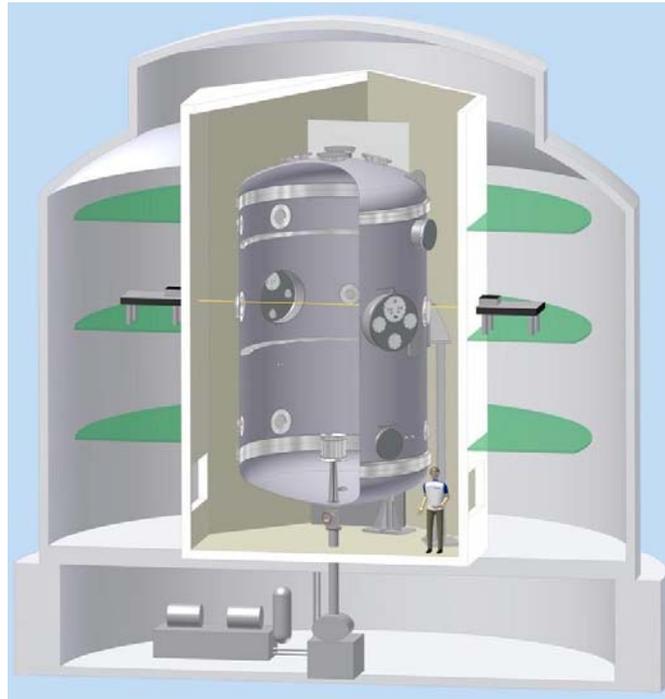


Figure 5. AIDA cloud chamber (Ref. 38, public domain image courtesy of Karlsruhe Institute of Technology)



Figure 6. LACIS cloud-aerosol interaction facility (Ref. 39, public domain image courtesy of Dr. Frank Stratmann/EUROCHAMP)

Some High-Level Facility Requirements for Cloud Research via Ground-Based Laboratories

Clearly, depending on the intended use of the facility, a "cloud chamber" can take on one of several incarnations. For example, as noted earlier, specialized vertical wind tunnels, or "cloud tunnels" have been successfully used to simulate processes such as rain drop and ice crystal formation and dynamics within clouds. However, a ground facility for experimentally simulating an actual cloud (even a small one) would necessarily have to be quite large. If it is assumed, e.g. as in Reference 31, that clouds with length scales as small as 10m play an important role in climate physics, then a facility with dimensions 5 to 10 times the cloud scale might be required to keep wall effects and other unwanted influences to acceptable levels during experiments. Also, wall temperatures would likely have to be precisely regulated in order to provide conditions for conducting meaningful experiments. This high degree of temperature control could be accomplished via the use of super-insulated walls, active temperature regulation, or a combination of the two methods. Additionally, the need for specialized instrumentation, possibly sophisticated flow (and phase) control, and other considerations would have to be taken into account. A sampling of the physical mechanisms and processes requiring improved discovery, quantification as well as modeling and V&V, individually and in various concert using laboratory chambers includes (but is not limited to):

- Gas phase photo-chemical reactions of volatile organic compounds, including effects of inorganic acids on secondary organic aerosol size and mass, and heterogeneous chemical reactions
- Effects of innately anisotropic turbulence upon cloud condensation nuclei (CCN) and ice forming nuclei (IFN), i.e., micro-scale turbulence accelerates cloud formation, changes collision frequency and triggers precipitation, and turbulence causes rapid growth in droplet size.
- Dampening effects of aerosols upon turbulence
- Discovery and modeling regarding the physics, etc., associated with the initiation of precipitation, especially for ice clouds
- Ice nucleation mechanisms, including the inhibiting effects of organic content, the efficiency of lead-containing particles, etc.
- Trace gas effects, including concentrations of nitric acid (HNO_3) on CCN number and effectiveness, and impacts upon hygroscopicity
- Effects of dynamic motions, convection, and shear, at the cloud and larger scales upon aerosol interactions and behavior, including coalescence, evaporation,

collisions, coagulation, condensation, activation, glaciation, aggregation and sedimentation

- Possibility of major effects of cosmic rays and ion-induced nucleation and electro-scavenging on ice formation, along with effects of solar radiation and photo-chemistry
- Effects of solar heating of black carbon aerosols upon their activation into drops and CCN effectiveness
- Effects of film-forming compounds upon CCN effectiveness
- Atmospheric and self-induced electric field effects (including lightning) on collision frequency and ice nucleation. Some observations indicate greatly enhanced ice nucleation.
- Aerosol effects upon cloud cellular convection
- Aerosol effects upon cloud formation mechanisms (gravity, Parker-Jeans, collisional, etc.) and turbulence in clouds
- Aerosol effects upon cloud radiation influences , writ larg
- Aerosol effects on cloud "edge" dynamics and details
- Effects of biologics on CCN including surface chemistry, hygroscopicity, and contact angle alterations
- Methane influences on sulfate and production of other aerosols

The major cloud-aerosol interaction processes to be simulated include agglomeration, coagulation, coalescence, the various phase changes including areas with significant knowledge gaps such as ice cloud formation, nucleation, deposition, catalysis, electrification, chemical changes writ large, and convection (including turbulence and precipitation). The independent parameter spaces include altitude/pressure, temperature, moisture, convection/turbulence, radiation (including ultraviolet and cosmic rays), chemical composition(s), initial aerosol compositions/size/geometry/number density, electrostatic fields, various "bio effects", and doubtless others. Clearly, there are myriad physical mechanisms and processes related to clouds, precipitation, aerosol interactions, etc., that are not as yet well understood which could benefit greatly from study in a highly-capable, well-designed laboratory (*why* does precipitation occur? *how* do ice clouds form and grow? do we fully understand the impact of the biologics, e.g., bacteria, algae, pollen, on atmospheric chemistry and dynamics?).

In Reference 40, it is stated that “Since ice formation in clouds is not yet fully understood it is recommended that further *laboratory studies* and in situ measurements be conducted to clarify the nucleation mechanisms” (emphasis added). Similarly, from Reference 18: “Obviously deconvoluting the relative impact of each property on CCN activation is *more straight forward in well controlled laboratory experiments*”. Also, “In contrast to field observations, laboratory studies allow one to examine (ice) crystal growth processes and the effect of each environmental variable under controlled conditions” (Ref. 41). And “Significant advances in laboratory data and modeling techniques are needed for a number of important aerosol systems” (Ref. 17). Thus, laboratory studies are essential for providing necessary information for input into more detailed atmospheric models”.

In their 2010 Atmospheric System Research Science and Program Plan (Ref. 6), the DOE Office of Science devoted significant attention to the need for better laboratory facilities for cloud and aerosol studies, such as: “Laboratory studies are essential to unraveling processes involving chemical reactions and composition-dependent aerosol microphysical properties” and “What is clearly needed to advance understanding of cloud as well as aerosol formation is a dedicated consolidated laboratory facility in the U.S. capable of conducting experiments under controlled conditions....such a facility would be a bold breakthrough-science-type initiative that would lay a firm foundation for systematically improving cloud and aerosol processes/properties modules as well as serve as an incubator for the development of new cloud and aerosol instruments designed for field deployment”.

To the extent that the various scientific and modeling shortfalls and physical issues discussed herein are affected by cloud-level turbulence and convection, a large-scale cloud chamber/laboratory appears to be required to conduct controlled experiments, as noted in Reference 42: “One principle continuing difficulty is that of incorporating, in a physically realistic manner, the microphysical phenomena in the broader context of the highly complex macrophysical environment of natural clouds”. While it is recognized that a parametric approach can become so far removed from the situation of interest that it is no longer useful, the long history of ground-based laboratory experiments in any number of scientific disciplines shows that meaningful results that provide a better understanding of underlying physics are obtainable via thoughtful experiment design.

The motion of air within clouds is in general turbulent, and the characteristics of this turbulence are a function of the details of cloud formation, interactions, and internal dynamics. The literature concerning the effects of this turbulence upon cloud-aerosol interactions indicates the following (refs. 43 to 47):

- Cloud turbulence applicable to droplet scales is substantially anisotropic due to localized actions of buoyancy & evaporation

- Turbulence affects particle-droplet collision and coalescence processes, greatly changes localized relative velocities, and triggers rain showers
- Higher levels of turbulence result in faster droplet growth and condensation, where the increases are a function of turbulence amplitude and other detailed characteristics
- The vertical transport of aerosols can be dominated by turbulence
- Turbulence bridges droplet growth by condensation and coagulation
- Turbulence contributes to the formation of high ice crystal concentration
- "Without turbulence only 7% of the total mass was observed in droplets with sizes over 100 microns, while with moderate turbulence this increased to 79%" (ref. 43)

Overall, the interactions between cloud microphysics and turbulence have not been studied in detail, and would benefit from the availability of a highly capable ground facility. Based on existing techniques in current wind tunnels and other research facilities, it is feasible to generate and control air turbulence of varying scales, frequencies, amplitudes, etc., for parametric studies in a cloud chamber. Potential techniques include production of local shear/convection, "artificial" turbulence (i.e., turbulence generated outside the chamber and "injected"), and utilization of other turbulence production approaches including buoyancy, localized heating, chemical reactions, and possibly application of magnetic fields. Turbulence is generated in many ways in both nature and by technology, and these mechanisms should be studied to identify and select the most promising candidates for providing dynamic fields in the ranges required. A detailed study must be conducted with regard to the type(s) of turbulence required (scale ranges, degree of anisotropy, functional dependence on velocity and temperature fields, discrete dynamic features, etc. - all of which have been found to be important for understanding cloud-aerosol interactions) and the best methods for generating such turbulence in a chamber. Such a study would be a foundational step toward realizing a large laboratory for cloud-aerosol research.

Clearly, the literature has many examples of major gaps in the knowledge necessary to adequately model cloud-aerosol effects for both regional and global climate projections. It is recognized that no single ground facility can duplicate the myriad complex interactions found in nature, or even some of the most difficult phenomena individually (e.g., cloud-top radiative cooling as a driving mechanism for turbulence), but with the still ambitious goal of conducting high-fidelity experiments on unit problems in a large chamber, there is a very detailed set of capabilities required, including the capacity to *independently* vary turbulence dynamics (shear, level, scale, etc.) and a host of other parameters. Additional major "issues"

that need to be addressed to enable relevant unit experiments include wall effects (thermal, radiation, convection) and reconciling dynamic interactions at scales (Reynolds number) beyond those achievable in even a 100m class chamber. However, it is worth noting that a tremendous amount of the requisite research regarding these issues could be, and should, be, conducted in small(er) scale chambers.

A Potential Approach to a Large Chamber for Cloud-Aerosol Research

Although a ground facility for simulating even small clouds could be massive, precedent exists for the construction of the basic shell of such a facility. Clearly wall effects (thermal, fluid boundary, etc.) would need to be minimized. It is assumed that fluid boundary conditions can be mitigated both by the scale of the facility (i.e., keeping the area of interest a sufficient distance from the walls) and by applying flow-control technologies if needed. Strict control of heat transfer for establishing and maintaining thermal boundary conditions might be accomplished via the use of highly insulated walls, active temperature regulation, or a combination of the two.

If very large scales and extremely efficient insulation are required for such a facility, a precedent exists in the petroleum industry, which has been constructing ever-larger cryogenic storage facilities for liquefied natural gas (LNG) since the 1960s. Current state-of-the-art storage facilities have volume capacities in the 2×10^5 m³ range and can store liquefied methane at -160 °C at atmospheric pressure with a minimum of "boil off" due to superb insulation characteristics. Typical construction consists of a pre-stressed concrete outer shell, a high-performance insulation blanket, and an inner nickel alloy shell. An example of one of the largest facilities in existence is El Paso Corp.'s Elba Island, Georgia facility with a diameter of 88m (similar to the LNG tank shown in Figure 7). Even larger facilities are being proposed, such as a Japanese design for a 95m-diameter tank shell.

It is difficult to determine how much of the cost of such an LNG storage facility is germane to a potential large cloud chamber since it is unknown how much of the cost of these facilities is related to specific technical or regulatory requirements, industry-specific equipment, etc. Additionally, unit cost estimates for existing and proposed facilities available in the open literature are scarce. A 2006 publication (Ref. 48) states that unit volume costs for an LNG storage facility is in the \$400/m³ range. The 88m-diameter Elba Island tank has an approximate gross volume of 2.3×10^5 m³, resulting in an estimated (tank only) cost of $\$92 \times 10^6$. Conversely, a smaller facility (the 62m diameter LNG tank at Mt. Hayes, B.C., Canada, Ref. 49) was completed in the late 2000s and has a cost 2007 estimate (couched as a 90% confidence estimate since the facility was not completely finished at the time of the writing of the report) given as $\$186 \times 10^6$. Given the spread of these two figures, it is clear that significantly more research will be required to formulate a more precise estimate.

Clearly, if a smaller scale facility with less extreme insulation characteristics is deemed adequate, then it follows that the cost of the basic structure could be lower than that for the LNG storage tank analogy used here.



Figure 7. Example of Large Cryogenic Storage Tank for Liquefied Natural Gas (public domain image courtesy of ferc.gov)

Beyond a suitable containment structure, equipment for producing the desired fluid states and conditions for particular experiments, and instrumentation are the most critical aspects of the facility. While there will be no attempt to produce an exhaustive list, it is clear that a large suite of sophisticated equipment and instruments would be “core” to practically any experiment that could be envisioned. As a starting point, the descriptions of the European facilities noted above (particularly Refs. 38 and 39) provide insight for the beginnings of such a list:

- Temperature control
- Humidity control
- Flow conditioning (setting desired flow state, control of wall effects, generation and control of turbulence scale and intensity, etc.)
- Aerosol generation
- Water droplet/ice crystal injectors/other particle injectors
- Spectrometers (infrared, particle, mass, etc.)

- Particle counters and sizers (condensation particle counters, cloud condensation nucleus counters, etc.)
- Particle imagers and trackers
- Differential mobility analyzers
- Gas chromatographs
- Hygrometers
- Trace gas analyzers/monitors

Ultimately, the user community will drive sensor and instrumentation requirements, so the facility will have to be designed with the flexibility to adapt other more specialized devices on an as-needed basis. For example, in such a large facility, the need to track individual trajectories within large groups of interacting particles will be a key capability. Equally as important, sensors are poised for a revolution in miniturization, cost reduction, capability, and speed, making it likely that by the time a large facility could be designed and built, much better technology in this area can be leveraged to improve the scientific experimnts conducted.

Clearly, a large, highly instrumented facility with many unique capabilities would have many uses other than direct cloud-aerosol interaction discovery and modeling. Other potential uses in terrestrial climate science include, but are not limited to, instrumentation and sensor development for field measurement campaigns, direct validation and calibration numerical simulations, studies of the impacts of aircraft operations upon climate, “pollution” studies, and ideation of approaches to mitigate climate change including emissions designed to alter hygroscopicity to enhance aerosol negative feedback (as one example). Additionally, atmospheric studies of planets and moons, free space optical communication through clouds, and many other important and useful technologies could be enabled in a facility of this type if the right discipline constituencies are engaged.

Next Steps

This report articulates the need and high-level requirements for a large ground facility to compliment and augment current and future atmospheric-science field measurments with the goal of strengthening the understanding of clouds and cloud-aerosol interactions and their impact on prediction of climate change. There is ample evidence in the recent technical literature that there are many major gaps in state-of-the-art modeling of climate dynamics on regional and global scales, and that these gaps are (and will continue) hobbling our ability to predict future climate states with the accuracy and precision needed for decision makers to optimally deploy resources.

A consensus among the climate science experts needs to be reached before further progress can be made. A workshop, along the lines of the 1985 gathering noted in Reference 30, could be convened to update and refine both the need and more detailed requirements for a large ground facility. It is suggested that a "virtual workshop", similar to that used for a recent modeling and simulation state-of-the-art assessment (Ref. 50) is an efficient way to gather inputs from a large, geographically dispersed group of participants. However, a traditional "face to face" workshop can also be accomplished if that approach is found to be preferable. If the scientific community endorses a large scale chamber, next steps are the specification of the capabilities and parameter ranges to be "designed in", evaluation of candidate engineering approaches, and rough order of magnitude (ROM) cost estimates.

Conclusions

Based on a review of the literature, it appears that many researchers in the climate science field are in agreement that highly-fidelity climate change projections are highly dependant upon cloud-aerosol interactions and that modeling, and indeed even understanding, such interactions are at the present time in a grossly unsatisfactory state. There are myriad 2, 3, and 4-phase phenomena that are dependent upon details of specific chemistry, radiation, and numerous other parameters including turbulence that require detailed study and understanding. Such detailed scientific work is extremely difficult to conduct with data extracted from field campaigns alone.

There is an immense amount of laboratory research required to approach the accuracy and precision needed for believable climate projections going forward. It is of interest that a large-scale chamber, necessary to begin to sort out the cloud level changes in aerosol impacts, physics, and behaviors, would probably take the better part of a decade to authorize and construct. In that same time frame the computing machines will advance to the exaflop stage, which is still far less capability than needed to ab-initio simulate all of the multitudinous cloud and aerosol issues. Thus, modeling will be required for decades to come, making climate change prediction an "experimental science". A key part of that experimental effort needs to be a resurgence of serious, detailed, and creative laboratory studies. It is upon the need for discovery and modeling of these cloud-level interactions that the justification for a 100m class cloud chamber rests. The overall justification for cloud-aerosol interaction research, for both discovery and modeling, could not be stronger as exemplified by this quote from Reference 51: "(The study's author) has shown that in model runs using an AGCM, the warming effect of doubling CO₂ concentration may be offset by reducing an assumed (cloud) droplet effective radius of 10 microns to a value between 7.9 and 8.6 microns". In other words, a change in the assumed magnitude of an cloud parameter in a climate model of only 15% to 20% has the potential to mask the projected impact of large changes in greenhouse gas concentration. It is clear that we simply must

significantly improve the modeling of the cloud-aerosol effects. Coupling a large, high-capability ground facility for advanced model development, science, and discovery with state-of-the-art in situ field measurements offers a way to address climate change in a rational manner.

References

1. IPCC, 2007: *Climate Change 2007: Synthesis Report*. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.
2. IPCC, 2007: Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
3. Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (eds.): *Climate Change 2001: The Scientific Basis*. Cambridge University Press, 2001.
4. Ghan, S., and Schwartz, S.: Aerosol Properties and Processes - A Path from Field and Laboratory Measurements to Global Climate Models. *Bulletin of the American Meteorological Society*, July 2007, pp. 1059 - 1083.
5. Lauer, A., Hamilton, K., Wang, Y., Phillips, V., and Bennartz, R.: The Impact of Global Warming on Marine Boundary Layer Clouds Over the Eastern Pacific - A Regional Model Study. *Journal of Climate*, Vol. 23, Nov. 2010, pp. 5844 - 5863.
6. Atmospheric System Research (ASR) Science and Program Plan, U. S. Dept. of Energy Office of Science, Jan. 2010.
7. Chen, J-P, Hazra, A., and Levin, Z.: Parameterizing Ice Nucleation Rates Using Contact Angle and Activation Energy Derived From Laboratory Data. *Atmospheric Chemistry and Physics*, Vol. 8, 2008, pp. 7431 - 7449.
8. Feingold, G. and Kreidenweis, S.: Aerosol-Cloud-Chemistry Interactions in Large a Eddy Simulation. 21st Annual AAAR Conference, October 7-11, 2002.
9. Jones, G. S.: "Climate Tackles Clouds - 'Project Athena' Wraps Up 6 Months of Sims, Produces more than 900 TB of Data", Sept. 23, 2010, <http://www.nics.tennessee.edu/climate-tackles-clouds>.

10. Dessler, A. E.: A Determination of the Cloud Feedback from Climate Variations Over the Past Decade. *Science*, Vol. 330, Dec. 2010, pp. 1523 - 1527.
11. Nenes, Athanasios: Description of Research, <http://nenes.eas.gatech.edu>.
12. Bader, D.C., Covey, C., Gutowski, W.J., Held, I.M., Kunkel, K.E., Miller, R.L, Tokmakian, R.T., Zhang, M.H.: *Climate Models: An Assessment of Strengths and Limitations, Final Report, Synthesis and Assessment Product 3*. U.S. Dept. of Energy Climate Change Science Program, 2008.
13. Chin, M., Kahn, R. A., and Schwartz, S. E. (eds.): *Atmospheric Aerosol Properties and Climate Impacts, Chapter 4 - Way Forward*, U.S. Climate Change Science Program and the Subcommittee on Global Change Research, 2009.
14. McKittrick, R., et al.: *Independent Summary for Policymakers, IPCC Fourth Assessment Report*. The Fraser Institute, 2007.
15. Motl, Lubos: "Forbush Decreases Confirm Cosmoclimatology", <http://wattsupwiththat.com/2009/08/04/a-link-between-the-sun-cosmic-rays-aerosols-and-liquid-water-clouds-appears-to-exist-on-a-global-scale/>.
16. Hoose, C., Lohmann, U., Erdin, R., Tegen, I.: The Global Influence of Dust Mineralogical Composition On Hetrogeneous Ice Nucleation In Mixed-Phase Clouds. *Environmental Research Letters*, Vol. 3, pp. 1-14.
17. Kulmala, M. et al.: Introduction: European Integrated Project On Aerosol Cloud Climate and Air Quality Interactions [EUCAARI]- Integrating Aerosol Research From Nano to Global Scales. *Atmospheric Chemistry and Physics*, Vol.9, 2009, pp. 2825-2841.
18. Prather, K.A., Hatch, C.D., and Grassian, V.H.: Analysis of Atmospheric Aerosols. *Annual Review of Annalytical Chemistry*, Vol. 1, 2008, pp. 485-514.
19. Schiermeier, Q.: The Real Holes in Climate Science. *Nature*, Vol. 463, Jan. 21, 2010, pp. 284 - 287, <http://www.nature.com/news/2010/100120/full/463284a.html>.
20. Panel on Aerosol Radiative Forcing and Climate Change: "A Plan for a Research Program on Aerosol Radiative Forcing and Climate Change", National Research Council, 1996.
21. Sud, Y.C. et al.: Sensitivity of Boreal-Summer Circulation and Precipitation to Atmospheric Aerosols in Selected Regions, Part 1: Africa and India. *Annals of Geophysics*, Vol. 27, 2009, pp. 3989-4007.
22. Penner, J.E. et al.: Model Intercomparison of Indirect Aerosol Effects. *Atmospheric Chemistry and Physics*, Vol. 6, 2006, pp. 3391-3405.

23. Lauer, A. et al.: Simulating Marine Boundary Layer Clouds Over the Eastern Pacific in a Regional Climate Model With Double-Moment Cloud Microphysics. *Journal of Geophysical Research - Atmospheres*, Vol. 114, D21205, IPRC-625, 2009.
24. Tao, W.-K. et al.: Role of Atmospheric Aerosol Concentration On Deep Convective Precipitation: Cloud Resolving Model Simulations. *Journal of Geophysical Research - Atmospheres*, Vol. 112, D24S18, 2007.
25. Abbatt, J.P.D. et al.: Solid Ammonium Sulfate Aerosols as Ice Nuclei: A pathway For Cirrus Cloud Formulation. *Science*, Vol. 313, 22 Sept. 2006, pp. 1770-1773.
26. Sassen, K., and Khvorostyanov, V.I.: Cloud Effects From Boreal Forest Fire Smoke: Evidence For Ice Nucleation From Polarization Lidar Data and Cloud Model Simulations. *Environmental Research Letters*, Vol. 3, 2008, 025006, 12 pp.
27. Rosenfeld, D.: Aerosol-Cloud Interactions Control of Earth Radiation and Latent Heat Release Budgets. *Space Science Reviews*, 2006, Springer, Vol. 125, pp. 149-157.
28. Poschl, U., Rudich, Y., and Ammann, M.: Kinetic Model Framework For Aerosol and Cloud Surface Chemistry and Gas-Particle Interactions – Part 1: General Equations, Parameters and Terminology. *Atmos. Chem. Phys*, Vol. 7, 2007, pp. 5989-6023.
29. Biello, D.: How Close Are We to Catastrophic Climate Change?. *Scientific American - Observations*, 28 June 2010,
<http://www.scientificamerican.com/blog/post.cfm?id=how-close-are-we-to-catastrophic-cl-2010-06-28>.
30. List, R., Hallett, J., Warner, J., and Reinking, R.: The Future of Laboratory Research and Facilities for Cloud Physics and Cloud Chemistry - Report on a Technical Workshop Held in Boulder, Colorado 20-22 March 1985. *Bulletin of the American Meteorological Society*, Vol. 67, No. 11, Nov. 1986.
31. Koren, I., Oreopoulos, L., Feingold, G., Remer, L., and Altaratz, O.: How Small is a Cloud?. *Atmospheric Chemistry and Physics*, Vol. 8, 2008, pp. 3855 - 3864.
32. Koren, Ilan: "On the Link Between Cloud Aerosol Interaction and Climate Change", Environmental Sciences and Energy Research, Weizmann Institute of Science, <http://www.weizmann.ac.il/ESER/People/Ilan/research-ilan.html>.
33. Helsdon, J.: "Re: Underground Cloud Facility", private communication to D. Bushnell, Sept. 8th, 2010.
34. Vohl, O., Mitra, S. K., Wurzler, S. C., and Pruppacher, H. R.: A Wind Tunnel Study of the Effects of Turbulence on the Growth of Cloud Drops by Collision and Coalescence. *Journal of the Atmospheric Sciences*, Vol. 56, 1999, pp. 4088 - 4099.

35. Wang, P. K., and Pruppacher, H. R.: Acceleration to Terminal Velocity of Cloud and Raindrops. *Journal of Applied Meteorology*, Vol. 16, 1977, pp. 275-280.
36. Beard, K. V., and Pruppacher, H. R.: A Wind Tunnel Investigation of the Rate of Evaporation of Small Water Drops at Terminal Velocity in Air. *Journal of the Atmospheric Sciences*, Vol. 28, pp. 1455-1464.
37. Barnes, I., and Rudzinski, K. J. (eds.): *Environmental Simulation Chambers: Application to Atmospheric Chemical Processes*. NATO Science Series IV: Earth and Environmental Series - Vol. 62, Springer, 2006.
38. Anon.: "AIDA Chamber Description", <http://www.eurochamp.org/chambers/aida/>.
39. Stratmann, F.: "Leipzig Aerosol Cloud Interaction Simulator (LACIS)", Leibniz Institute for Tropospheric Research, <http://www.eurochamp.org/chambers/lacis/>.
40. Levin, Z., and Cotton, W.R. (eds.): *Aerosol Pollution Impact on Precipitation*. Springer, 2009, 386 pp.
41. Song, N., and Lamb, D.: Experimental Investigations of Ice in Supercooled Clouds. Part 1: System Description and Growth of Ice by Vapor Deposition. *Journal of the Atmospheric Sciences*, Vol. 51, No.1, Jan. 1994, pp. 91-103.
42. Pruppacher, H. R., and Klett, J. D.: *Microphysics of Clouds and Precipitation*, Kluwer Academic Publishers, 1997.
43. Riemer, N., and Wexler, A.: "Growing Cloud Droplets in Moderate Turbulence", *BAMS* Vol. 86, No. 5, May 2005, pp. 632-633.
44. Pinsky, M.B., Khain, A.P.: "Turbulence Effects on Droplet Growth and Size Distribution in Clouds - A Review", *J. Aerosol Science*, Vol. 28, No. 7, Oct. 1997, pp. 1177-1214.
45. Gu, Yu, and Liou, K.N.: "Interactions of Radiation, Microphysics, and Turbulence in the Evolution of Cirrus Clouds", *J. Atmos. Science*, Vol. 57, August 2000, pp. 2463-2479.
46. Duru, P., Koch, D.L., and Cohen, C.: "Experimental Study of Turbulence-Induced Coalescence in Aerosols", *International Journal of Multiphase Flows*, Vol. 33, 2007, pp. 987-1005.
47. Vohl, O., et al.: A Wind Tunnel Study of the Effects of Turbulence on the Growth of Cloud Drops by Collision and Coalescence", *Journal of Atmospheric Science*, Vol. 56, 1999, pp. 4088-4099.

48. Powell, J.: Liquefied Natural Gas – Market Challenges and Opportunities for Innovation. *Hydrocarbon World*, Dec. 2006.
49. Anon.: "Mt. Hayes LNG Storage Facility - Submitted to British Columbia Utilities Commission by Terasen Gas, Inc.", June 2007.
50. Malik, M. R., and Bushnell, D. M. (eds.): *Role of Computational Fluid Dynamics and Wind Tunnels in Aeronautics R&D*, NASA Technical Publication (publication pending).
51. Bower, K.N., and Choulaton, T.W.: A Parameterization of the Effective Radius of Ice Free Clouds For Use in Global Climate Models, *Atmospheric Research*, Vol. 27, 1992, pp. 305-339.
52. Hallier, B.: Aerosol and Climate Modeling - A Summary of Existing Aerosol and Cloud Chamber Research Facilities, NASA Langley internal white paper, July 2010.

Appendix

Partial List of Existing Ground-Based Aerosol and Cloud Chamber Research Facilities and Summary of Capabilities (from Ref. 52)

1. DOE Facilities at Pacific Northwest National Lab (PNNL)

Atmospheric Research Chamber

- Aerosol formation and transformation
- Role of aerosols as condensation nuclei
- Aerosol processes associated with anthropogenic, biogenic, and biomass burning compounds

Ice Nucleation Chamber

- Artificial clouds under precisely controlled temperature and super saturation conditions
- Isolation of particles from aerosol to study ice nucleation
- Portable to study ambient aerosols

2. UC Riverside Atmospheric Process Lab

- Aerosol formation and evolution in the troposphere
- Consists of two 90 m³ reactors
- No cloud process abilities
- Supported by EPA

3. DRI Ice Physics Lab

- Static diffusion chamber
- Ice nucleation and electrification studies
- Produces study on ice habits on glass fiber
- Not highly subscribed

4. DRI Storm Peak Lab

STORMVEx

- Location: 3220 m high mountain in Colorado
- Equipment for airborne cloud research
- Will study situ cloud and precipitation property measurements

ISPA

- Studies effects of pollution aerosols on snow growth by riming and snowfall amounts on the ground
- Results have implications for water resources in the inner mountain west
- Supported by Nevada, NSF, DOE

5. NASA GRC Particulate Aerosol Lab (SE-11)

- Provided aerosol and ice particle measurements during recent ACCRI tests
- Flow through chamber (N₂)
- Pressure: Sea level to 50,000 ft
- Temp: Ambient to -70C
- Humidity: 0-100% (RH_i)
- Chamber Velocity: 0.5 to 3 m/s
- 3 Windows and panel for probe insertion
- Capability for exhaust introduction
- Studied effect of soot and sulfuric acid on ice formation

6. Leipzig Aerosol Cloud Interaction Chamber

- Investigates physical and chemical processes in the polluted troposphere
- Flow through chamber
- Flow tube 1-10 m in length
- Temp: -40C min
- Used for CCN studies

7. AIDA

- Location: Germany, Karlsruhe Institute of Technology
- Size: 4 m diameter, 7 m high, 84.5 m³
- Pressure: 0.01 to 1013 hPa
- Temp: 183K to 323K
- Uses air as working fluid
- Ice saturations achieved by expansion
- Wall temperature actively controlled
- Used for both IN and CCN studies
- Many techniques for generating test aerosols
- Capability for addition of instruments

8. National Institute of Radiological Sciences

- Location: Japan
- Volume: 25 m³

- Radon-aerosol chamber
- Temp: 278-303K
- Humidity: 30-90%
- Pressure between inside and outside of chamber can be negative
- Particle Concentration: 10^8 - 10^{10} m⁻³

9. Institute of Chemistry and Dynamics of the Geosphere (ICG)

- Volume: 260 m³
- Studies reactions of the surface of aerosols
- Uses high resolution FTIR spectroscopy to track gas concentrations
- Equipped with a scanning electrostatic classifier

10. ARM Mobile Facility (AMF)

- Tracks interaction between clouds and aerosol particles
- Measures optical, chemical, physical, and cloud activation properties
- Equipped with many additional inlets to enable additional equipment to be added
- Condensation Nuclei Counter
- Multiple-Supersaturation Cloud Nuclei and Condensation Nuclei Counter
- Particle/Soot Absorption Photometer

11. Meteorological Research Institute Cloud Simulation Chamber

- Location: Tsukuba, Japan
- 1 pressure vessel and one temperature vessel
- Volume: 1.4m³
- Pressure: 1000 to below 30 hPa
- Temp: 30 to -100C
- Chamber Velocity: 0 to 30 m/s
- Studies cloud formation and ice properties

12. Colorado State University

- Continuous Flow Diffusion Chamber
- Studies ice formation on aerosol particles
- Some funding from NASA

13. Energy Research Center of the Netherlands

- Location: Netherlands
- Used to study the cloud activation of ambient aerosol
- Very high flow rate (30m³/min)

- Uses forward scattering spectrometer probe for measuring cloud droplet number concentration
- Uses high-flow cascade impactors for chemical characterization of aerosol
- Compared the number of cloud droplets created in clean marine air vs. polluted marine air

14. Vector GmbH Bremen Aerosol Chamber

- Location: Germany
- Volume: 9 m³
- Used to study α -Pinene ozonolysis in the presence of ammonium sulfate or sulfuric acid seed particles

15. Oak Ridge National Lab Environmental Sciences Division

- Mission: “(1) investigation of particle behavior in the atmosphere and industrial workplaces, (2) interactions of engineered and anthropogenic pollution particles with biological systems, and (3) development of advanced instrumentation and measurement methodology”
- Relation to Jaguar (largest existing supercomputer) (see below)
- Funding sources include DOE and DOD

16. European Supersites for Atmospheric Aerosol Research (EUSAAR)

Aspvreten Research Station (ASP):

- Location: About 80 km south of Stockholm at the Baltic coast
- Determines the physical and chemical properties of the aerosol and contains additional meteorological instruments as well as basic instrumentation for gaseous compounds
- Measures particle size distribution from 10 to 500 nm
- Particle mass in two fractions, PM₁₀ and PM_{2.5}
- Particle mass, carbonaceous material (Organic Carbon, Elemental Carbon)
- Black Carbon, soot
- Meteorological conditions
- Tracks air pollution levels over time

Zeppelin Research Station (ZEP):

- Location: Svalbard’s west coast, 474m above sea level in an undisturbed Arctic environment
- Owned by the Norwegian Polar Research Institute and is used mostly by the Norwegian Institute for Atmospheric Research

- Performs studies on the atmosphere, snow and ice properties, and Earth's energy balance

BEO Moussala Research Station (BEO):

- Location: High mountain in Bulgaria away from pollution
- Equipped with meteorological instrumentation, O₃ and NO_x concentration equipment, devices for radio aerosol research, X-ray fluorescence analysis, neutron and gamma measurements
- Run by the Bulgarian Academy of Science

Cabauw Experimental Site for Atmospheric Research (CBW):

- Location: An agricultural area in the western part of The Netherlands
- Has a variety of air masses around from clean maritime to continental polluted
- Measures land atmosphere interaction and cloud, aerosol and radiation interaction
- Also measures aerosol properties, aerosol optical depth using a CIMEL sun photometer, and aerosol extinction and backscatter profiles using a backscatter lidar
- Run by KIMI

Finokalia Research Station (FKL):

- Location: SE Mediterranean away from local sources of pollution
- Air is representative of synoptic scale atmospheric composition
- Equipped with in-situ meteorological instrumentation as well as continuous measurements of gaseous (O₃, CO, NO_x, and NO_y), particulate (optical properties, chemical composition, mass, and mass size distribution) and wet deposition
- Location has frequent dust events which is ideal for studying the interaction of gaseous compounds with heterogeneous surfaces (like dust and sea-salt)
- Run by the Environmental Chemical Processes Laboratory

Harwell Research Station (HWL):

- Location: Harwell, United Kingdom
- Used as a rural station representative of large scale air masses affecting Southern England
- Equipped with in-situ meteorological instrumentation as well as continuous measurements of gas phase (O₃, NO_x, SO₂) and particulate (mass concentration, size distribution, chemical composition) pollutants
- Run by University of Birmingham

High Altitude Research Station Jungfraujoch (JFJ):

- Location: Jungfraujoch, Switzerland
- Located far from local pollution sources; well suited to determine the background above a continental area
- Equipped with a full suite of gas phase components (measures both situ and column properties), and aerosol measurements are performed by PSI
- The station is within clouds 40% of the time, making it well suited for cloud-aerosol interaction study
- Run by the International Foundation High Altitude Research Stations Jungfraujoch and Gornergr

JRC-Ispra Atmospheric Research Station (JRC):

- Location: JRC-Ispra, Italy
- Located tens of kilometers from local sources of pollution and is representative of the regional polluted background
- Equipped with in-situ meteorological instrumentation along with continuous measurements of gaseous, particulate (optical properties, size distribution, chemical composition) species
- Will use LIDAR in future
- Run by the Institute for Environment and Sustainability of the EC - DG Joint Research Centre

REPORT DOCUMENTATION PAGE

*Form Approved
OMB No. 0704-0188*

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) 01-11-2011			2. REPORT TYPE Technical Memorandum		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE A State-of-the-Art Experimental Laboratory for Cloud and Cloud-Aerosol Interaction Research					5a. CONTRACT NUMBER	
					5b. GRANT NUMBER	
					5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Fremaux, Charles M.; Bushnell, Dennis M.					5d. PROJECT NUMBER	
					5e. TASK NUMBER	
					5f. WORK UNIT NUMBER 432938.08.01.07.43	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NASA Langley Research Center Hampton, VA 23681-2199				8. PERFORMING ORGANIZATION REPORT NUMBER L-20045		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001				10. SPONSOR/MONITOR'S ACRONYM(S) NASA		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) NASA/TM-2011-217192		
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category 09 Availability: NASA CASI (443) 757-5802						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT The state of the art for predicting climate changes due to increasing greenhouse gasses in the atmosphere with high accuracy is problematic. Confidence intervals on current long-term predictions (on the order of 100 years) are so large that the ability to make informed decisions with regard to optimum strategies for mitigating both the causes of climate change and its effects is in doubt. There is ample evidence in the literature that large sources of uncertainty in current climate models are various aerosol effects. One approach to furthering discovery as well as modeling, and verification and validation (V&V) for cloud-aerosol interactions is use of a large "cloud chamber" in a complimentary role to in-situ and remote sensing measurement approaches. Reproducing all of the complex interactions is not feasible, but it is suggested that the physics of certain key processes can be established in a laboratory setting so that relevant fluid-dynamic and cloud-aerosol phenomena can be experimentally simulated and studied in a controlled environment. This report presents a high-level argument for significantly improved laboratory capability, and is meant to serve as a starting point for stimulating discussion within the climate science and other interested communities.						
15. SUBJECT TERMS Climate; Clouds; Aerosols; Greenhouse effect; Global warming; Facilities						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (Include area code)	
U	U	U	UU	41	STI Help Desk (email: help@sti.nasa.gov) (443) 757-5802	