The Lower Atmospheric Observing Facilities Workshop[*]

Meeting the Challenges of Climate System Science

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1. Introduction and Motivation

a. Structure and funding of the NSF LAOF centers and facilities

The Lower Atmospheric Observing Facilities (LAOF), with core support from the National Science Foundation (NSF) Division of Atmospheric and Geospace Sciences (AGS), include aircraft platforms, airborne and ground-based remote sensing instruments, and surface and sounding systems. Besides these platforms and instruments, LAOF also includes services related to instrumentation, observational data and an education component.

LAOF resources are offered through competitive awards by the NSF AGS, and also as part of collaborative programs with other NSF divisions, other agencies and institutions. The working definition of "lower atmosphere" may be described as extending from the planetary surface through the lower stratosphere. In some instances, the use of such facilities may be provided in support of middle or upper atmosphere research objectives. LAOF assets are currently located at the National Center for Atmospheric Research (NCAR) Earth Observing Laboratory (EOL), Center for Severe Weather Research, Colorado State University, the Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS) at the Naval Postgraduate School, and the Department of Atmospheric Science at the University of Wyoming. Additional coordinated observing systems and platforms are located at universities, government agencies and other institutions.

Traditional strengths of LAOF instruments, platforms and services have tended to emphasize microscale, mesoscale and synoptic meteorology, tropical meteorology, cloud and precipitation physics, airborne tropospheric chemistry, and other tropospheric airborne science not fitting these descriptions. Over the past decade atmospheric science has evolved rapidly toward interdisciplinary studies in response to advances in climate system science (CSS) as part of a broader impetus to understand the entire Earth System. In response to this trend there is increasing engagement of LAOF resources in climate system motivated research, often including oceanic, hydrologic, biogeosciences, upper troposphere and lower stratosphere (UTLS), cryospheric and related discipline applications. Such campaigns have become increasingly international, multifaceted, and often explore remote regions, literally from pole to pole.

b. Goals of the workshop

The Workshop: Meeting the Challenges of Climate System Science, sponsored by NSF/AGS and hosted by NCAR/EOL, was held on 18-19 June 2012 in Boulder, Colorado, followed by the Synthesis Committee meeting on 20 June 2012. A detailed Workshop agenda is provided in the Appendix. Owing to space and budgetary limitations and to facilitate meaningful breakout session discussions, the workshop registration was limited to approximately 100 participants. In the end, 119 participants from four countries (U.S., UK, Australia, China) were present. These participants represented several disciplines within CSS and the intersection of weather, chemistry, and climate, such as ecology, hydrology, oceanography, and atmospheric science. There was also a good mixture of participants in technology development and management, data service, science, and modeling. Recognizing that this workshop was schedule-conflicted with the NCAR Community Earth System Model (CESM) Workshop, there was an additional small-scale meeting in the spring of 2013 between LAOF Workshop organizers and CESM leaders to further refine the CESM needs of the LAOF.

The purpose of this workshop was to examine the LAOF assets in light of the above trends; identify weaknesses in the capabilities of existing and emerging tools, and in the modes of deployment supported by these systems. The specific questions to be addressed include:

- Is NSF-LAOF providing effective balanced support to the climate research community? How could it be improved?
- Is the climate research community making best use of the LAOF capability?

To the extent that gaps need to be filled, the findings and recommendations of this workshop will be carefully evaluated by the NSF/AGS and the institutions involved in support of LAOF. Toward that end, Linnea Avallone, NSF/AGS Program Director for LAOF, served in the capacity of NSF Liaison to the Workshop.

c. Challenges of climate research: Motivation for observations

Climate research includes observations, modeling, understanding, and applications, with observations being the foundation of the other three components. Since LAOF represents a small but critical component of the overall observing systems in the U.S. , our scope here is narrower: what are the challenges of earth system modeling that could be addressed with the help of LAOF?

In general, an Earth system model (ESM) includes the components of atmosphere, ocean (dynamics, physics, and chemistry), land, and cryosphere (e.g., snow, glaciers, sea ice). The atmospheric model usually includes a dynamic core (including numerical schemes and grid structure), subgrid parameterizations of physical and chemical processes (e.g., clouds, convection, aerosols, radiation, turbulence). The land model usually includes the energy and water fluxes, snow, soil temperature and moisture, ecosystem, and biogeochemistry. The improvement of these models, model parameters, boundary and other necessary datasets (e.g., soil texture, atmospheric concentration of trace gases), and initial conditions of model simulations all require observations.

As an example, the Community Atmosphere Model version 5 (CAM5), the atmospheric component of the NCAR Community Earth System Model (CESM1.0), can be run using several dynamical cores including finite volume (default), spectral element, Eulerian, and semi-Lagrangian. In addition, CAM5 can be run on several different grids. Supported grids for the finite volume dynamical core range from $0.23° \times 0.31°$ to $4° \times 5°$. CAM5's physics package includes a moist turbulence parameterization that considers explicitly the interactions between stratus clouds, radiation, and turbulence, a shallow convection parameterization, a cloud macrophysics scheme that forces complete consistency between cloud fraction and condensate, a prognostic, two-moment stratiform cloud microphysics scheme, shortwave and longwave radiation schemes, a three-mode aerosol scheme, and a new chemistry model that is fully interactive (Neale et al. 2010). The Community Land Model (CLM4), the land component of CESM1.0, also includes numerous processes related to the energy, water, and trace gas fluxes, and dynamic vegetation (Fig. 1) (Lawrence et al. 2011).

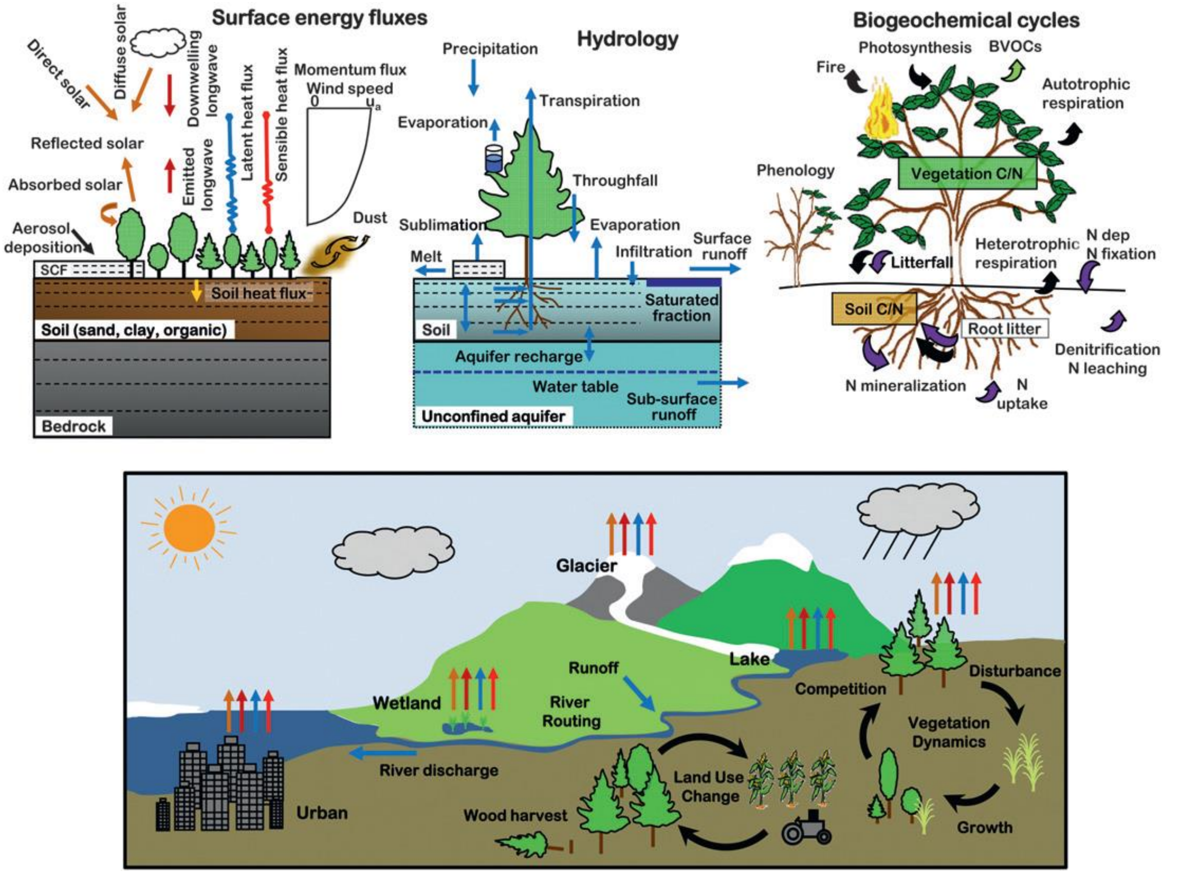

FIG. 1. Schematic representation of primary processes and functionality in the CLM4. Abbreviations are as follows: surface-canopy fluxes (SCF); biogenic volatile organic compounds (BVOC); and carbon and nitrogen (C/N). For biogeochemical cycles, black arrow denotes carbon flux, purple arrow denotes nitrogen flux. Note that not all soil levels are shown. Not all processes simulated in CLM4 are depicted. The flux arrows over each land type represent the solar radiation, longwave radiation, latent heat, and sensible heat fluxes that are calculated separately for each land type. Adopted from Lawrence et al. (2011).

Primarily due to limited computing power, model spatial resolution is limited with a horizontal grid spacing of ~1 degree for global climate modeling, ~0.2 degree for regional climate modeling, ~0.2 degree for global weather prediction, and ~0.05 degree for regional weather prediction. Therefore any processes (e.g., clouds, turbulence, topography) within each model grid cell must be parameterized using the grid cell average variables (e.g., temperature, humidity, wind). This represents a fundamental uncertainty of climate models. It can be reduced through improved understanding but cannot be removed. Making the subgrid parameterization even more challenging is the fact that different subgrid processes strongly interact with each other. For instance, aerosols, clouds, and radiation need to be considered together because of their interactions. Similarly, soil moisture, atmospheric boundary layer, and convection are closely coupled. Therefore, not only the parameterizations themselves but also the interactions of various parameterizations need to be realistic, and this requires extensive observational data for parameterization evaluation and improvement.

Climate models are usually evaluated using global gridded data from satellite remote sensing and reanalyses. Reanalyses are observationally constrained model estimates that have complete global coverage in space and time. These evaluations are most efficient in identifying the temporal and spatial distributions of model biases but are usually limited in identifying the causes for such biases. Such evaluations should be used with caution over data-sparse regions and for variables (e.g., clouds, and radiative fluxes, soil moisture) that are largely controlled by the underlying model. To evaluate model output, specific processes in the model and interactions of processes, it is necessary to conduct comprehensive “process scale” observations at specific locations.

In the current decade, as model grid cells shrink from 100km towards 10km or even 2km, mesoscale processes begin to be explicitly computed in climate models. In this case, a more direct type of model-data comparison becomes possible. It may now be possible to use LAOF-scale observations to test climate models directly. Good examples include orographic precipitation, mesoscale convective systems or even hurricanes.

Some of the perennial problems of CESM1 and its predecessors (as well as many other climate models) are the model-simulated double Intertropical Convergence Zone (ITCZ) over the tropical Pacific (when the observations show only one ITCZ), resolution dependence in simulating orographic precipitation and deficiency in simulating the amplitude and different phases of the Madden-Julian Oscillation (MJO) over the tropics.

For many climate scientists, the biggest challenge in climate modeling is the prediction of regional climate change over the next century. While many **global** predictions in the IPCC AR4 report are agreed upon by the contributing models, very few of the **regional** predictions are shared. A preliminary look at climate runs for the upcoming IPCC AR5 (i.e. CMIP-5) indicates a similar lack of agreement on the regional scale. This inability to predict future regional climates undermines the utility of models for climate change studies. This is where LAOF –type observations may play an important role. Better understanding and observations of mesoscale and regional processes may lead to improved regional model climate forecasts.

d. Role of LAOF-type observations in improved climate research and modeling

Recognizing the observing needs in climate research, the role of LAOF-type facilities includes:

- Discovery of new phenomena or mechanisms for inclusion in models: observations are not only for models but also for discovery and inspiration. Good examples include the discovery of the ozone hole over the Antarctic and the discovery of the Madden-Julian Oscillation (MJO).
- Physical process studies: good examples include the Variability of the American Monsoon System (VAMOS) Ocean-Cloud-Atmosphere-Land Study Regional Experiment (VOCALS-REX; http://www.eol.ucar.edu/projects/vocals/rex.html; Wood et al. 2011) and the recent Dynamics of the Madden-Julian Oscillation (DYNAMO) experiment over the Indian Ocean (http://www.eol.ucar.edu/projects/dynamo/)
- Parametrization development, including the **C**limate **P**rocess **T**eam (CPT) concept, advocated by the community and adopted by funding agencies (including NSF). The goal of CPT is to speed up the development of global coupled climate models and reduce uncertainties in climate models by bringing together theoreticians, field observationalists, process modelers and the large modeling centers to concentrate on the scientific problems facing climate models.

- Employing short term model predictions of weather and climate to better understand the interactions of different processes.
- Developing instruments that can be used for long term monitoring by the National Oceanic and Atmospheric Administration (NOAA), the Department of Energy (DOE) etc.
- Educating and inspiring students and the next generation of scientists, who will be critical to further understanding and predicting Earth's climate.

To fulfill these roles, existing LAOF facilities need to be fully and efficiently utilized, and emerging new technologies/platforms/data services should be critically evaluated.

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2. Terrestrial-Atmosphere Interface

a. Background

While the continents comprise approximately one third of the earth's surface, the global climate is strongly influenced by them. In part, this influence is due to human residence on the continents where we modify the landscape, utilize its resources and emit substances into the atmosphere. In addition, most humans experience climate change in a terrestrial context rather than an oceanic one. The terrestrial surface is much more variable and responsive than the ocean surface for two reasons. First, it has far less heat storage capability than the ocean. Changes in heat flux almost immediately modify surface temperature. Second, land surface roughness, albedo and water availability for evaporation vary over orders of magnitude spatially and temporally. Under certain circumstances, a vegetated land surface can evaporate more water vapor into the atmosphere than an open water surface. Mountains and these variable surface properties generate local circulations that modify weather patterns. An understanding of the terrestrial-atmosphere interface and the ability to monitor its properties are essential in climate studies.

Steve Hillebrand, U.S. Fish and Wildlife Service

b. Important science questions

The important science question for terrestrial-atmosphere interface falls into two categories: fluxes and two-way dynamic interactions. First is the question of how the physical conditions of soil and vegetation and the properties of the lower atmosphere determine the surface temperature and the momentum, heat and water fluxes. A similar set of questions relate to trace gases and aerosols. How do soils and vegetation control the emission and deposition of gases and aerosols?

The second question arises from the two-way interaction between the earth's land surface and the atmosphere. How and on what time scale does weather and climate impact the earth surface and vice versa. For example, how does drought alter soil structure, soil water and the state of vegetation? How does the state of the earth's surface alter boundary layer turbulence and the development of clouds and precipitation? Are there fast or slow feedback cycles that connect the atmosphere and terrestrial surface?

Several specific questions are proposed below to illustrate climate science at the terrestrial interface.

Surface fluxes:

- How are processes that alter land cover and land use (e.g. fire, ecosystem succession, wind-throw, urbanization) coupled to atmospheric processes?
- How does the spatial structure of a complex and heterogeneous land surface influence land-atmosphere fluxes?
- How do fluxes at the land-atmosphere interface respond to non-stationary forcing in the troposphere? Is there nonlinear amplification or suppression of these fluxes?
- How can we improve estimates of regional- to global-scale land-atmosphere fluxes of greenhouse gases, reactive gases, aerosols, momentum, sensible and latent heat fluxes and radiation?
- How can we improve predictions of these fluxes at time scales from days to centuries?
- How do the hydrologic dynamics of the land surface (rooting depth, soil moisture content, ground water table, ecosystem transpiration, permafrost, snow and ice cover) interact with the atmospheric boundary layer (ABL)?
- What are biogeochemical emissions from wildland fires and managed landscapes and what are the atmospheric consequences?

Processes at the top of the atmospheric boundary layer:

- What are the processes and regimes governing the transfer of energy, momentum, trace gases and aerosols across the top of the ABL and into the free troposphere?
- What do we need to measure to predict ABL height and how it will evolve during the day?
- What processes govern the dynamics, growth of stable boundary layers, and entrainment/detrainment at the stable boundary layer top?

Boundary layer clouds, chemistry and aerosols:

- What are the feedbacks between landscape heterogeneity, vegetation cover, trace gas fluxes and boundary layer clouds?

- How are land surface – ABL cloud feedbacks mediated by primary and secondary aerosols, cloud condensation nuclei (CCN), photosynthetically active radiation (PAR), precipitation and the surface energy balance?
- What are the direct and indirect effects of aerosol loading from fires and dust storms on regional ABL dynamics?
- What is the role of complex topography (including heterogeneous landscapes) in modulating surface exchanges, cloud formation and convective initiation?
- How does state of the ABL (e.g. temperature, relative humidity, pressure, wind and turbulence) influence atmospheric chemistry, especially the emission and oxidation of biogenic trace gases?

c. Observational challenges

The primary observational challenge for the terrestrial-atmospheric interface involves spatial heterogeneity. The land surface has complex patterns of vegetative cover and mountainous terrain, causing the lower atmosphere to have spatial variation too. While a single surface weather station might provide suitable local values, it does not provide information about the 3-D patterns of variability caused by heterogeneous land cover or just by turbulence. A related problem is that local measurements in complex terrain are often unrepresentative of larger regions. Measurements taken at different elevations on a flux tower, have a different “footprint” in regard to surface influence. Likewise, surface conditions at one site may be influenced by upstream sites. It is often difficult to obtain spatially compatible measurements of different surface climate variables. That is, local temperature and humidity values may be influenced by different upstream regions.

A new challenge has developed in regard to wind energy research. Long term climate records of wind and turbulence at heights of 100 to 200 meters are now requested, but the existing meteorological towers seldom reach such altitudes.

Another challenge involves the seasonal, decadal and centennial time scales characteristic of the evolution of the terrestrial surface. While satellites and operational weather and climate networks are well suited to long term monitoring, LAOF and the NSF-funded university community generally are not structured to undertake long-term field deployments, the National Ecological Observing Network (NEON) excepted.

The final challenge relates to newly identified variables in the climate system. Fluxes of aerosols and trace gases are now known to be important in climate. Full spectrum incident and reflected radiation measurements are also important. These challenges require new measurement technologies.

d. Key existing instruments (operational and research)

Many of the current ABL technologies are well-suited to the needs of climate science at the terrestrial interface. Key existing instruments include:

- Surface flux stations and towers
- Boundary layer profiling systems (e.g. tethered balloon, SODAR, lidar, RASS, etc.)
- Instrumented aircraft

- Satellite multispectral sensors
- Back-scatter and Doppler lidar and cloud radar
- Sub-surface moisture and trace gases
- Air and rain water sampling

Even with no further enhancements, these systems provide very useful data for climate science. Given their value, these instruments and their data sets have been underutilized for climate science at the terrestrial interface. This underutilization is due in part to inadequate knowledge of the existence of these assets on the part of scientists funded by NSF directorates outside of atmospheric sciences but heavily involved in climate research at the terrestrial interface. Thus, education and interaction with the fields of ecosystem sciences, hydrology, geosciences and social sciences is recommended.)

e. Promising new instruments (candidate LAOF instruments)

New instruments that would support climate sciences at the terrestrial interface include both the development of new technology and the addition of existing technology to the deployment pool. Our committee suggested expansion of the LAOF activity in both of these areas. We have chosen to organize our suggestions according to the type of measurement.

i. Aerosols

Atmospheric aerosols play a key role in modern climate science. Many aerosol categories are produced and removed at the terrestrial interface. Currently aerosol instrumentation is available on aircraft, but not generally for ground-based deployments. Aerosol flux measurements are rare. Terrestrial investigations would benefit from aerosol measurements that can be deployed within and above vegetation canopies. Aerosol particle measurements of interest include:

- Aerosol genesis
- Aerosol chemical characterization
- Aerosol sizing [nm to μm]
- Aerosol activation properties
- Aerosol fluxes

Additional sensors that would benefit the LAOF include lidars, particle mass spectrometers (PMS), scanning mobility particle sizers (SMPS), and fast response instruments that can track individual particles and their evolution at very short time-scales.

ii. Trace gases and isotopes

Biogeochemistry is a key component of the climate system, and measurements of greenhouse gases and associated tracers such as stable isotopes are critical to the study of the climate system at the terrestrial interface. Currently a limited suite of measurements is available on LAOF aircraft, and assets for ground-based measurements are very limited. Advances in laser-based *in situ* measurement technologies have made routine, highly-calibrated field measurements of many trace gases much more feasible. LAOF facilities do not include ready access to the previous generation of broad-band infrared gas analyzers, also valuable for relatively straightforward applications such as eddy covariance flux measurements of more accessible gases such as CO_2.

Additional sensors that would extend LAOF's ability to contribute to terrestrial interface climate science would include expanded capacity to measure these gases from aircraft, and, to the extent possible, multiple ground-based sensors that could be used for both flux and atmospheric mixing ratio measurements. Trace gases and associated tracers of interest include greenhouse gases (CO_2, CH_4, N_2O, H_2O), and gases frequently used as tracers to help interpret biogeochemical processes ($^{13}CO_2$, $^{13}CH_4$, $H_2{}^{18}0$, DHO, CO, COS, and $^{14}CO_2$). In addition, ground-based measurements of reactive trace gases (O_3, VOCs, SO_x, NO_x, HO_x) would complement the existing assets for airborne measurements of these gases, which are often involved in atmospheric aerosol chemistry.

Continuous *in situ* sensors exist for many of these gases. Instruments capable of measuring with high absolute accuracy as well as with speed and precision are needed for eddy covariance flux measurements, but at present are not possible for all of these species. In some cases (e.g. $^{14}CO_2$) only flask sampling is feasible. Thus LAOF would benefit from the capability to collect flask samples. Excellent flask sampling systems have been developed by NOAA's Global Monitoring Division (GMD) and by NCAR for flight level airborne sampling.

Atmospheric profiles of these species would be beneficial. Aircraft, of course, provide one means for measuring profiles. An additional technology that would be beneficial is the aircore technology developed by NOAA GMD which enables a complete atmospheric profile to be collected in a tube released at high altitude from a balloon and allowed to fall to earth. The tube of air can then be analyzed using a variety of gas analyzers. Remote sensing (e.g. lidar) would also be beneficial, but such sensors are still under development for most species. Development efforts or partnerships with agencies or companies already developing such instrumentation could open entirely new research avenues.

iii. Multidimensional characterization of the thermodynamic and dynamic states of the ABL and near subsurface

The temporal and spatial complexity of the terrestrial surface, in contact with the rapidly evolving atmospheric state, dictates that we move climate science at this interface beyond the simplest questions of the mean vertical structure of the ABL. This requires the capability to observe in both space and time, driving the need for expanded technology. The observing capability should ideally extend from ground water to convective cloud top, encompassing the domain of the direct physical interactions between the terrestrial surface and the atmosphere. These observations would keep pace with the advancing numerical models which are already capturing complex patterns above and below the earth's surface.

A number of instruments and platforms are suggested to expand LAOF's capabilities in this area:

- *Remote sensing of the atmosphere*: Doppler lidar, both ground-based and airborne, was strongly recommended as a rapidly maturing technology that is well-suited for land-atmosphere interaction research and is not currently available through LAOF. Thermodynamic (water vapor, temperature) profilers with capabilities similar to Doppler lidar would also be beneficial, though these instruments are not yet commercially available and require significant development.

Additional remote sensing of ABL clouds and aerosols was also requested, suggesting multifrequency and polarization sensitive radar and lidar. DoE's Atmospheric Radiation Measurement (ARM) program has made substantial progress in climate-relevant cloud and aerosol remote sensing and could serve as a partner and/or model in this area.

- *Aircraft in situ sensors*: Aircraft *in situ* sensors are also a natural choice for addressing issues of spatial complexity at the terrestrial interface. LAOF currently offers aircraft platforms and sensors suited to, and fairly frequently used for, this sort of investigation. Improved flight level sensors, when included in the standard airborne package, quickly impact a broad range of observational programs.

- *Towed instrument package*: For boundary layer studies, new controlled towed vehicle (CTV) instruments would allow simultaneous low altitude multi-level surveys to provide information about turbulent structure and vertical gradients of physical properties.

- *Unmanned instrument platforms*: An important new approach is the use of small unmanned aircraft to survey regions over a few tens or hundreds of kilometers with miniaturized instruments.

- *In situ sensor networks*: Distributed sensor networks measuring state variables at and below the terrestrial interface would greatly benefit climate science studies at the terrestrial interface. Substantial advances in developing low to moderate cost, low power, wireless sensor networks bring the promise of instrument networks that can measure land-atmosphere interactions with a resolution and detail similar to what can currently be obtained only at a limited number of points, or through numerical simulations. The continued development of CentNet as a requestable LAOF is strongly recommended, as well as the potential for expanding the variety of variables and numbers of sensors that can be supported in observation networks like CentNet. The ability of such systems to obtain continuous data complements the spatially extensive but temporally limited nature of aircraft measurements.

- *Distributed sensors:* CentNet should endeavor to include meteorological variables (temperature, pressure, relative humidity, winds), radiation (upwards and downwards short- and long-wave, direct and diffuse incoming photosynthetically active radiation), soil and hydrologic properties (precipitation, snow depth, soil moisture and temperature, water table depth, stream flow, partitioning of evaporation and transpiration, rooting depth, soil nitrogen and carbon content, soil texture), and vegetation properties (sapflux, LAI, leaf water potential, leaf nitrogen and carbon, specific leaf area, species distribution, biomass). Some of these soil and biological properties are not yet feasible from remote sensor networks, but are valuable data for providing the biological and hydrologic context needed to interpret surface flux measurements.

- *Subsurface remote sensing*: Measurements of subsurface properties can be difficult to obtain with *in situ* sensors. Technologies such as radar soil moisture remote sensing and ground penetrating radar would support research at the terrestrial interface. An important new technology is COSMOS using cosmic ray neutrons to obtain average soil moisture and measurement over a 600 meter region.

- *Land surface remote sensing*: Measurement of the spatial and temporal variation in properties of the terrestrial surface is critical to climatic studies at the terrestrial interface. While this is done to some extent from satellite platforms, higher resolution, high information content remote sensing can be conducted from aircraft platforms or towers, and are a strong complement to space-based products. Measurements that would benefit climate studies include lidar measurements of vegetation structure, leaf area index and digital elevation, and passive hyperspectral measurements that can document vegetation indices, vegetation fractional cover, vegetation type, leaf nitrogen content and specific leaf area. Considerable resources are already available from NASA centers, and NEON is developing an airborne land surface remote sensing capability. Partnerships with these organizations would greatly benefit terrestrial interface climate science studies.

- *Flux measurements*: Much research at the terrestrial interface is geared toward the measurement of fluxes between the earth's surface and the atmosphere. Fluxes can be measured in a variety of ways, some of which have been described above. In general, however, the ability to measure these fluxes, especially water vapor, greenhouse gases, sensible heat flux and radiative energy, are necessary elements of many climate science studies. Challenges include separation of components of these fluxes (e.g. respiration and photosynthesis, evaporation and transpiration). Expansion of LAOF's capabilities in flux measurements will significantly benefit climate science at the terrestrial interface.

f. Broader issues

For climate applications, new modes of platform and instrument deployment may be needed. The earth’s surface changes significantly on time scales longer than the usual two-week to two-month LAOF deployment. Examples include the natural seasonal cycle in vegetation and soil water and the change in land use as crops are planted and harvested. LAOF may have to design new strategies for longer duration deployments.

The Workshop did not include a focus on urbanization, the urban-atmosphere interface, or the interactions between natural landscapes and pollutants in otherwise pristine regions. A recent report of the National Research Council, 2012, examines issues related to the effects of urbanization on the atmospheric boundary layer and the built environment surface.

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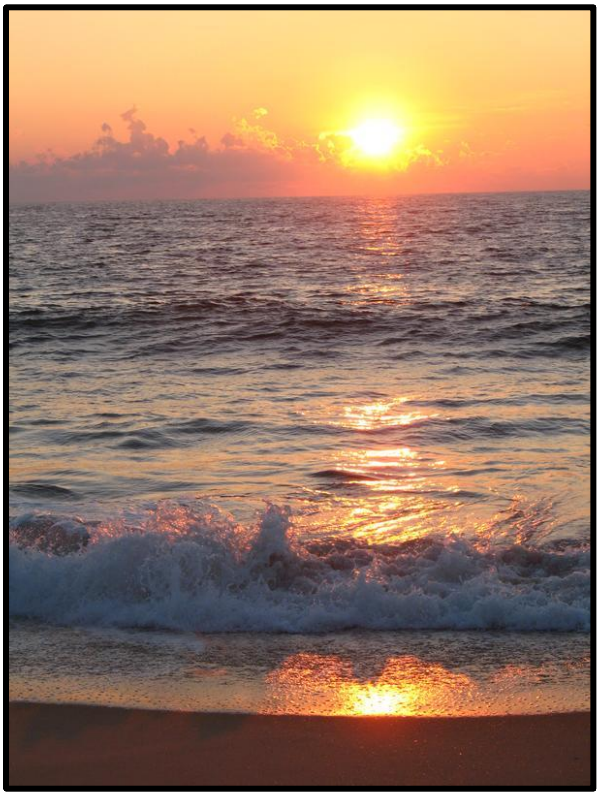
3. Ocean-Atmosphere Interface

a. Background

The global ocean comprises approximately two-thirds of the earth's surface and exerts a strong control on global climate. For many years, atmospheric climate modelers considered the oceans as an unchanging substrate beneath the atmosphere, but this viewpoint is obsolete today. The two-way interaction between the atmosphere and ocean is clearly evident on climatological, seasonal and even storm time scales. As with the continents, the oceans exchange heat, water, particles and trace gases with the atmosphere. Unlike the continents, the oceans store and transport vast amounts of heat. Surface properties such as roughness and albedo vary across the ocean expanse due to surface waves and whitecaps but are less variable than on land. The ocean surface temperature is influenced by radiation, evaporation, upwelling and horizontal transport by ocean currents. Gaseous exchange between the ocean and atmosphere is modified by wind speed, temperature and biological productivity.



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b. Important science questions

The important science questions for the ocean-atmosphere interface fall into two general categories; fluxes and two-way dynamic interactions. First is the question of how interfacial fluxes of momentum, heat, water, gases and particles are modulated by the states of the sea surface and lower atmosphere and by the microscopic physical properties of the air-sea interface. For momentum flux, questions include: What is the drag coefficient over a wide range of wind speed, including the high wind conditions of Southern Ocean cyclones, the Greenland tip Jet and tropical cyclones? How does spray affect drag coefficient? What are the effects of non-equilibrium wave fields on drag? How is the seasonal dependence of exchange influenced by extreme events?

Equally important are questions related to the fluxes of aerosols, trace gases, and water and carbon isotopes. What are the regional ocean contributions to aerosol, including aerosol size and composition? What atmospheric phenomena govern transport and deposition of iron and other trace constituents related to ocean fertilization and productivity? To what extent are interfacial fluxes modulated by mesoscale oceanic and atmospheric circulations versus long range transport, extensive coastal upwelling, etc.? Of what magnitude and sign are CO_2 and O_2 fluxes in high latitude, high-wind seas, such as the Southern Ocean? What atmospheric and tropical oceanic phenomena and processes most heavily influence ocean acidification and coral reef bleaching.

Second is the broader question of how the atmosphere and ocean interact dynamically. That is, how do changes in one sphere influence the other, and react back upon the first. Questions include: Under what conditions does the marine boundary layer approach thermal equilibrium with the mesoscale ocean sea surface temperature (SST) field? Do SST gradients play a role in the triggering of atmospheric moist convection? Is there a coherent, coupled, ocean-atmosphere response to the occurrence of convective rainfall and related winds (western boundary currents, near-equatorial regions)? What is the recovery time for ocean mixed layers and atmospheric marine boundary layers following episodic disturbances? To what extent are oceanic biogenic aerosols and gaseous emissions ultimately responsible for indirect effects on clouds and precipitation?

c. Observational challenges

The ocean-atmosphere interface is a difficult environment for installing and maintaining instruments. Problems occur with respect to platform degradation in high winds and seas, corrosion, tethering, cargo ship collisions and communication. The NSF- and Office of Naval Research (ONR)-funded oceanographic institutions have made outstanding progress on air-sea interaction instruments with buoy designs but several types of measurement are still limited. In particular, measurements of fluxes and the structure of the first hundred meters of the ABL, while common over land, are rare over the sea. LAOF profiling and flux technologies have rarely been applied to the ocean ABL.

An exception is the use of research aircraft. The NSF-funded LAOF activities have contributed significantly to air-sea interaction through low flying instrumented aircraft. While aircraft missions are duration-limited and weather-limited, they provide detailed information at altitudes above 50 meters or so. The challenge is how to expand the duration and scale of ocean flux measurements and expand the scope of these measurements beyond simple momentum, heat and water vapor. As an example, how do we observe the flux of particles on and off the ocean surface?

d. Key existing instruments (operational and research)

Today, aircraft, ships, buoys and satellites are the dominant platforms for air-sea interaction research. A number of orbiting satellites do most of the long-term global monitoring of sea state and mean atmosphere and ocean quantities. Detected quantities include surface wind, surface wave roughness, sea surface skin temperature, and surface chlorophyll. Active and passive sensors observe a number of proxy variables and well-tested algorithms convert these proxies into physical quantities.

Oceanographic ships are often equipped to measure air-sea quantities. Ship-launched balloons can probe the lower atmosphere and expendable bathythermograph measurements (XBTs) can profile the first few hundred meters of the sea. Ships can observe ocean currents with the Acoustic Doppler Current Profiler (ADCP) and water properties with onboard sensors. Precipitation and heat and moisture fluxes can be determined if the disturbing influence of the ship's hull can be corrected. Radars and lidars can be mounted on ships too. The key problem is the high cost of ship deployments and the number of staff required. They are not suitable for long-term flux monitoring or for process studies covering a large ocean area.

Buoys are invaluable for long-term atmosphere-ocean interface monitoring. They provide continuous observations of wind speed and direction, air and water temperature, wave height and period, and a few other variables. Rarely, however, do they observe momentum, heat, water vapor or other fluxes. The best example of a large buoy array may be the Tropical Atmosphere Ocean (TAO) array on the tropical Pacific Ocean which observes the state of the El Niño-Southern Oscillation (ENSO) cycle. From this array too, fluxes are missing. Deployed buoys are difficult and expensive to maintain but their impact on both science and operations has been impressive.

Research aircraft have played a major role in air-sea studies, especially because of their ability to quickly survey small regions of the ocean with measurements of thermodynamic quantities, winds, radiation, aerosols and trace gases. During ascents and descents, vertical profiles are obtained. During horizontal legs, momentum, heat and moisture fluxes are determined. The main limitations are their cost, payload, duration and range. They are not suitable for continuous monitoring of large areas.

e. Promising new instruments (candidate LAOF instruments)

- Eddy correlation fluxes from buoys; robust and rugged sensors and systems, typically for long-time series, including rare events.
- Ship-board Wave and Surface Current Monitoring System (WaMoS) radar (scatterometry for waves and currents), airborne backscatter lidar, wind profiles/turbulence
- Unmanned aircraft with miniaturized sensors
- Controlled Towed Vehicle (CTV)
- Manned aircraft with improved remote sensing instruments; e.g., sea spray and surface salinity
- Manned aircraft with improved flight level aerosol, trace gas and isotope sensors
- Improved ship-borne meteorological radar.

f. Broader issues

The improvement in air-sea research instrumentation will require a closer collaboration between AGS and the Division of Ocean Sciences (OCE) within NSF, atmospheric and oceanographic institutions and university departments, as well as key federal agencies such as NOAA, DOE and NASA, each of which has mission objectives in oceanic region monitoring**.** Atmospheric researchers should be better served on oceanic platforms and oceanic researchers should be better served on airborne platforms.

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4. Cryosphere-Atmosphere Interface

a. Background

The cryosphere encompasses sea ice, lake ice, river ice, snow-covered land and ice, glaciers, ice caps, ice sheets, frozen ground, and permafrost. These frozen conditions are mostly found at high latitudes and on high terrain, but their areal coverage varies widely with season and with climate change. This definition of cryosphere includes both terrestrial and ocean regions, thus overlapping with Chapters 2 and 3 of this report. These frozen regions share important unifying properties, however, such as high albedo, low roughness and the energetics of phase change between liquid water and ice. The cryosphere regions are mostly remote from the advanced science institutions with inhospitable working conditions for field scientists.

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b. Important science questions

As in the previous two Chapters, the important science questions for the cryosphere-atmosphere fall into two categories: fluxes and two-way dynamical interactions. A good example of an important cryosphere-atmosphere process is the ice-albedo feedback. The ice-albedo feedback is widely believed to explain why the high northern latitudes have warmed more than the rest of the globe in the last hundred years. The details of this feedback are not completely understood, however. For example, what are the relative contributions of albedo changes from snow-covered land, sea ice melt ponds, increased open water or cloudiness? The new record for Arctic sea ice loss in September 2012 has brought the issue of ice-albedo feedback into public view. Progress will require better monitoring of heat fluxes and better observations of the cryosphere-atmosphere interaction.

Related questions regard the fate of ice sheets. Prediction of ice sheet melt or collapse requires a full glaciological-dynamical approach, but some of the ice loss mechanisms specifically involve the ice-atmosphere interface. For example, the increasing summer surface melt area on Greenland's ice cap, providing melt water to moulins and sub-glacial rivers, is driven by cryosphere-atmosphere heat fluxes.

On decadal time scales, the release of greenhouse gases from thawing permafrost and warming shelf sediments adds a cryospheric dimension to global warming scenarios. Furthermore, the replacement of tundra with advancing boreal forest alters the albedo and hydrology of high latitude regions. How well do we predict these changes in the cryosphere-atmosphere interface?

The mixed phase clouds and variable aerosol and pollutant concentrations pose another set of questions for the polar regions. Do multi-level tropospheric clouds warm or cool the climate? How do clouds interact radiatively with snow and sea ice? How does the arctic region balance its heat budget?

c. Observational challenges

Observations at polar sites are challenging because of their extreme climate conditions and their remoteness. We need to instrument a broad range of cold environments including open ocean, sea ice, glacial ice, barren land, snow-covered land, high mountains, etc. Riming, snow and ice drift and ionospheric disturbances must be guarded against. Access to these sites is usually possible only in the sunlit summer months.

d. Key existing instruments (operational and research)

Many of the key instruments for high-latitude interface studies are the same as for low latitude work. The LAOF and related instruments that are important for cryosphere investigations are vertical profiling systems (e.g. radisondes/tethersondes/dropsondes/profilers), flux tower measurements, radiative measurements, cloud radar, and aircraft platforms (characterization of clouds, and top-down surveying). Measurements need to be made in such a fashion that the radiative forcing can be determined and the energy balance can be closed. Various arrays of hydro-ecological sensors in the permafrost are already in place. Observations from space play an especially critical role in polar regions.

Most of our current knowledge of the cryosphere-atmosphere interface comes from small-scale projects, a few international projects and satellite monitoring. The historical Surface Heat Budget of the Arctic Ocean (SHEBA) and Arctic Transitions in the Land-Atmosphere System (ATLAS) datasets, the International Arctic Research Center (IARC) permafrost observatory data and the Canadian Snow and Ice dataset were very helpful to gain insight into processes and short-term variability. Other success stories are the Boreal Ecosystem-Atmosphere Study (BOREAS), NASA campaign on ecosystems/hydrology, International Polar Year (IPY) and the surface radar (e.g., WSR-88D/NEXRAD data) of the conterminous United States to assess the partitioning between cloud water and cloud ice (e.g. Sellers et al. 1995, Gottschalck et al. 2005). Important existing observations are satellite and newly declassified submarine data for sea-ice/snow-cover distribution, albedo, surface temperature and other snow and sea-ice characteristics derivable thereof. Moored and drifting buoys are relevant for monitoring the sea-ice-ocean-atmosphere interface (e.g., wind, temperature, trace gases, aerosols) and profiles of salinity, temperature, etc. in the ocean and underneath sea-ice. Even though ocean buoys are currently not supported by LAOF, they are important to any LAOF-style mesoscale or process-specific field program.

Polar-orbiting satellites are important in high latitudes for monitoring snow and ice. With modern multi-spectral sensors, they can also address issues related to mixed phase clouds. Cloudsat and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) data have shown that in the sub-arctic and arctic, mid-level clouds have higher ice content than in mid-latitudes.

e. Promising new instruments (candidate LAOF instruments)

- Unmanned aerial vehicles (UAVs) deployed from shore, ice floe and ship
- Polarametric radar and lidar for mixed phase clouds
- Eddy-Flux measurement systems over land, sea and sea ice.
- Controlled Towed Vehicle (CTV)
- Improved airborne chemistry, isotope and aerosol measurement
- Distributed snow and soil moisture measurements systems (e.g., Centnet, COsmic-ray Soil Moisture Observing System (COSMOS)
- Improved airborne sea- and ice-surface measurements

f. Broader issues

Due to the special challenges of cryosphere-atmosphere science, the development of new observing technologies, by itself, will not be sufficient for climate studies. New strategies for deploying instruments and organizing field campaigns will be required. An exciting initiative would be the installation of one or two new observational “supersites” in the Arctic. At the moment, the coastal Barrow supersite is producing valuable coordinated data, but it is representative of neither the pure terrestrial nor pure ocean cryosphere-ocean interface. To resolve this problem a new sea-ice supersite (like SHEBA) and a new land supersite should be established. Transitional areas have to be identified and instrumented along transects to capture changes. These sites could include:

- Both the state variables and fluxes should be monitored to close the energy and water balances
- Measurements of trace gas and aerosol fluxes
- Multiple back-scatter lidars for cloud and aerosol properties
- Doppler lidars for wind and turbulence characteristics
- UAVs for sea-ice and snow distribution, albedo and cloud properties
- Cloud-radars plus radiation measurements need to be made concurrently, to explore the cloud-ice of Arctic/subarctic low and mid-level clouds and their role in climate (cooling/warming).
- Over land, priority should be given to measuring snow and ice wetness and thaw detection and monitoring, and characterization of surface albedo. Measurements of thawing permafrost would also be desirable. Centnet and COSMOS could be useful.
- Over the sea, subsurface temperature and salinity should be monitored.

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5. Free Tropospheric Physics

a. Background

The free troposphere is defined as that region of the atmosphere that lies above the atmospheric boundary layer (ABL) but below the tropopause. It comprises about 75 percent of the atmospheric mass. The key processes in the free troposphere include vertical and slant convection, fronts and storms, clouds, precipitation generation, chemical reactions and radiation. The free troposphere interacts with the atmospheric boundary layer (Chapters 2, 3 and 4) below and the stratosphere (Chapter 7) above.

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b. Important science questions

The free troposphere has been a focus of atmospheric science for decades, starting with the use of kites and weather balloons over 100 years ago. Traditionally, the subject has been subdivided into airflow dynamics, radiation, cloud physics and chemistry. In recent years, these subjects have drawn closer together and it is increasingly common to read of research projects that span across these subjects. Another important relationship is between weather and climate in the free troposphere. While these subjects are often treated separately, they are intimately linked. Climate patterns generally control the occurrence of weather events (e.g. cyclones, super-cell storms). Conversely, weather events are associated with fluxes and transformations of energy that impact large scale circulation and climate.

Some major climate questions for the free-troposphere are:

- What are the key processes and factors in mixed-phase clouds that determine precipitation, tropospheric heating and chemical transport?
- What role do convective clouds play in larger-scale weather and climate, and can their role ever be properly parametrized?

- What are major sources and sinks of aerosols that ultimately seed clouds and interact with radiation (i.e., heterogeneous chemistry, nucleation of liquid droplets and especially of ice particles, particle growth, scavenging, biogeochemistry impacts)? How much are aerosols warming or cooling our atmosphere (i.e. climate sensitivity)?
- What is the role of small-scale turbulent entrainment on cloud penetration, cloud physics and precipitation occurrence?
- What are the interactions between dynamics and microphysics that control the evolution of deep convection and the vertical profile of latent heating?

c. Observational challenges

The atmospheric science community has made remarkable progress on free tropospheric research over the last decades. There has been a steady development of new *in situ* and remote sensing instruments. Still there are many unmet challenges for free tropospheric research. Several fundamental problems relate to clouds and aerosols. In both stable and convective situations, we don’t have the ability to map out the three-dimensional and time-changing fields of velocity, radiation, cloud particle phase and size and aerosol distribution. First is the need for new instruments that will measure physical and chemical quantities accurately and in harsh environments. A second issue is the access to dangerous environments such as those with tornadoes, severe turbulence, large hail, aircraft riming from super-cooled water, etc. New storm penetrating aircraft, robust *in situ* instruments or new remote sensing techniques are needed. A third problem is the cost of complex instrument deployments. With each new project, experiment designs become more complex and more expensive. A new paradigm of field project design may be needed.

In developed nations, field projects can be nicely integrated into the existing operational observing networks. In other parts of the world, with less observational infrastructure, field projects must stand alone. Deployment duration is also a concern. Typically, a field project has a duration barely long enough to capture a few examples of the targeted phenomena. For future projects related to seasonal variation or climate change, such duration is insufficient.

d. Key existing instruments (operational and research)

The observational system for the free troposphere includes operational and research components. The key instruments are:

- The global rawinsonde network
- Geostationary and polar orbiting satellites (imagery and profiling)
- GPS delay and occultation systems
- Operational and research radars
- Backscatter, Doppler, DIAL and Raman lidars
- Surface-based wind profilers
- Research aircraft with *in situ* and remote sensors including clouds, chemistry and aerosols
- Dropsondes from aircraft
- Instrumented commercial aircraft

e. Promising new instruments (candidate LAOF instruments)

There are a large number of new ideas for improving the LAOF technology for free tropospheric research. They include:

- Improved airborne weather and cloud radars including new technology and new platforms
- Improved ground-based radars with dual wavelength, polarization, Doppler, for better particle characterization
- Improved ground-based and airborne lidar systems as profilers for wind, aerosol, water vapor and trace gases
- Improved aircraft flight-level measurements of trace gases, isotopes, small aerosols and mixed-phase cloud particles
- Unpiloted instrumented vehicles
- New storm penetrating aircraft (e.g.. A-10) with robust instrumentation.

f. Broader issues

An important issue in free troposphere research is the relationship between physical and chemical measurement. At the moment, the NSF LAOF is not heavily involved in the development of chemical instrumentation. Yet, the simultaneous measurement of physical and chemical quantities is of increasing importance. In part this is due to the utility of trace gases and aerosols as tracers in air motion studies. In other cases the aerosols may impact clouds, radiation fields or human health.

For existing LAOF instrumentation, their deployment needs to be more flexible. The technology for *in situ* and remote sensing measurements is surging with advances being supported by both the facilities and direct PI funding. The evolution of instrumentation from the laboratory to deployability under LAOF has worked well over a long period of time with NSF and university support to provide the community with well-characterized and reliable systems. For example, the Wyoming Cloud Radar and Wyoming Cloud lidar can be deployed on both the University of Wyoming King Air (UWKA) and the C-130. However, some thought should be given to increasing the availability of these systems by motivating the facilities to implement a higher level of standardization of mounting, wiring, and data acquisition than presently exists.

A related issue is the future of airborne research platforms for atmospheric research. The current fleet of research aircraft is active and highly capable, but some changes are either inevitable or required. An example is the potential loss of the NOAA and NRL P-3 aircraft, and the future of airborne radar such as ELDORA. In addition, the future of storm-penetrating aircraft is unclear.

A number of mid-latitude tropospheric research projects have been carried out over the last few decades. Examples include the Genesis of Atlantic Lows Experiment (GALE) and the Terrain-Induced Rotor Experiment (T-REX), each of which has led to new insights and applications. Each project brings improved sensors and improved array design, but these projects often become more expensive too. A challenge for the future is to make field projects more cost effective by more fully utilizing operational infrastructure and ensuring that each new project has several new types of sensors.

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6. Tropical Waves, Cloud Systems, and Cyclones

a. Background

The tropical and equatorial zones of the earth's atmosphere deserve special attention due to their enormous area, their influence on global weather and climate and their wide range of unique phenomena. For example, the tropics have high annual mean temperature with weak temperature seasonality, high water vapor concentrations, a deep troposphere and a weak Coriolis force. They are the home of the migrating ITCZ, the belts of deserts and rain forests, variable ENSO, MJO and monsoons, towering cloud clusters and tropical cyclones. According to theories of the general circulation, the tropics export heat and water vapor to the rest of the globe. The tropical regions are mostly remote from the advanced scientific institutions and have weather services with fewer advanced observational technologies.

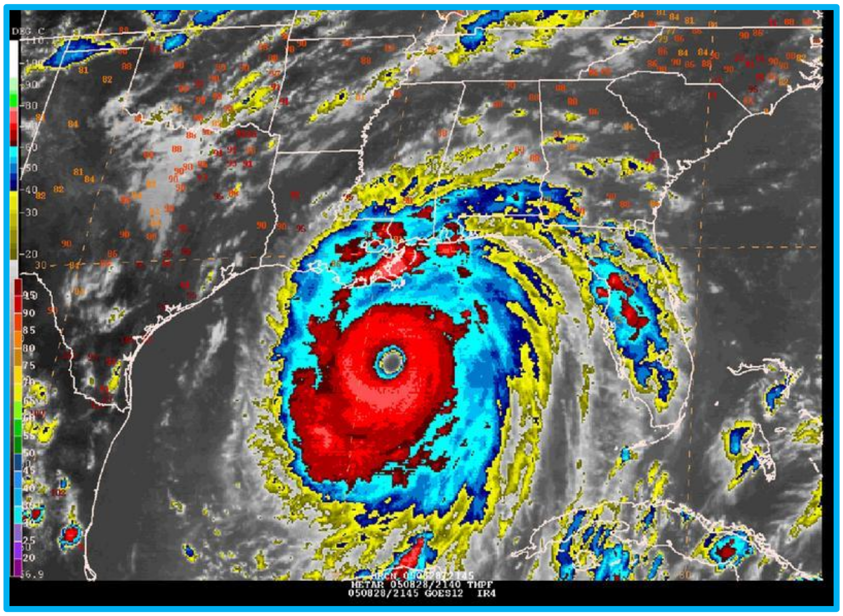

Image generated by Jeff Weber, University Corporation for Atmospheric Research

b. Important science questions

The field of tropical meteorology is well developed and several important questions have attracted wide interest. They include:

- Why do current climate models poorly represent the ITCZ structure?
- Why do most climate models poorly represent ENSO and the MJO?
- How sensitive are tropical cyclones to aerosol concentration, wind shear and SST?
- Why are continental drought and monsoon events apparently so sensitive to slight SST changes?
- How accurately do we predict climate feedbacks from multi-level clouds in the tropics, including high ice clouds?
- How are convective clouds and precipitation triggered in the tropics?
- How do land/sea contrasts and mountains generate tropical disturbances?

- To what degree can cumulus parameterization in coarse models represent the multi-scale processes in the tropics? Why are climate models so sensitive to these parameterizations?

c. Observational challenges

The array of weather and climate instrumentation in the tropics has improved markedly in recent years. An excellent example is the permanent TAO array of buoys and ocean thermistor chains in the equatorial Pacific Ocean. Equally impressive are a series of intensive tropical field campaigns over the oceans using ships and aircraft, such as Barbados Oceanographic and Meteorological Experiment (BOMEX), the GARP Atlantic Tropical Experiment (GATE), the Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment *(*TOGA COARE*)*, the Winter Monsoon Experiment (MONEX) and recently Dynamics of the Madden-Julian Oscillation Experiment (DYNAMO). In addition, cloud, precipitation and SST monitoring satellites have filled in the basic climatology of the tropical oceans. Over land in the tropics, where weather systems and intrument arrays are heterogenous, patterns are difficult to diagnose.

The remaining observational challenges relate mostly to the properties and mechanisms of tropical disturbances. A key limitation in this regard is the spatial and temporal resolution of our observing systems. If we cannot resolve the dominant scales associated with tropical phenomena, we will not be able to understand them. In addition, more complete measurements of radiant fluxes, trace gas and aerosol distributions are needed to address important climate issues.

d. Key existing instruments (operational and research)

Below, we identify some of the instruments that have successfully monitored tropical climate and disturbances.

Temperature and water vapor

- Upsondes and dropsondes
- GPS delay and radio occultation (satellite, airborne, and ground-based)
- Atmospheric Infrared Sounder (AIRS) (satellite)
- Differential absorption and Raman lidars (ground-based and airborne)
- Multi-channel microwave radiometer (AMSU and MWR)
- Isotopes with flask and cold trap sampling (airborne/shipborne/ground-based)

Winds, Clouds and precipitation

- Rain gauges and disdrometers
- Geostationary and Polar-orbiting satellites with IR/VIS, TRMM TMI/PR, AMSU, CloudSat, etc.
- Land- and ship-based Dual-Polarization dual wavelength radar
- Airborne radar and lidar (e.g., dual-Doppler)
- Aircraft flight level thermodynamic and cloud physics data

Air-sea fluxes

- Surface waves and winds
    - Wave and Surface current Monitoring System (WaMoS)

    - 2D spectra via Wide-Swath Radar Altimeter (WSRA)
    - Wave breaking (high resolution video imaging)
    - Synthetic Aperture Radar (SAR)
    - Airborne lidar
    - Stepped Frequency Microwave Radiometer (SFMR)
    - Scatterometer
- Air-deployed co-located dropsondes and Airborne eXpendable BathyThermographs (AXBTs)
- Ship-based direct flux measurements (with sonic anemometers), effective up to about 30 m/s

e. Promising new instruments (candidate LAOF instruments)

A number of new and promising instruments have been identified for application to the tropical atmosphere.

Temperature and water vapor

- Automated sounding launchers (ships and land)
- GPS radio occultation (satellite, airborne, and ground-based)
- DIAL and Raman lidar
- Multi-Channel Microwave Radiometer (MWR)
- Automated remote soundings with large number of sondes
- Isotopes with real-time spectral analysis (airborne/shipborne/ground-based)

Winds, clouds and precipitation

- Land/ship-based radar (multi-frequency, dual-polarization, Doppler)
- Airborne radar (dual-Doppler, dual-polarization, dual-wavelength)
- Solid-state phased-array radar

Air-sea fluxes

- Airborne sensing of breaking waves and sea spray
- Dropsonde with SST/upper ocean temperature capability
- UAV with multi-sensors launched from shore and/or ships (e.g., SIO ScanEagle)
- Use of controlled towed vehicle (CTV) from aircraft
- Use of direct covariance flux sensors on buoys
- surface waves (2D spectra, breaking, e.g, Wide Swath Radar Altimeter or WSRA)
- surface winds (SFMR, scatterometer, wind profilers)

f. Broader issues

While the new instruments mentioned above hold great promise, there are other difficulties to be overcome. Instrument deployment is a key issue. The tropical region is mostly ocean and the countries of the tropics have limited observing resources. Thus, except for satellites, long term instrument deployment is difficult and expensive. Even conventional research aircraft are challenged in the tropics with the breadth of the oceans, the incidence of severe weather and the height of the tropopause. The inherent challenge of tropical research can be overcome with enhanced collaboration and leveraging between partner programs and agencies that have on-going, long-term monitoring facilities, such as NSF/OCE, NOAA, NASA, and DOE. As examples, NASA's new Global Precipitation Measurement (GPM) , GOES-R, JPSS, and Cosmic satellite systems represent opportunities to collaborate with LAOF-scale field programs.

As described above, the requirement for greater spatial and temporal resolution is essential to answer the questions in section b. Many of the new instrument systems will help achieve this objective.

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7. The Upper Troposphere and Lower Stratosphere (UTLS)

a. Background

The Upper Troposphere/Lower Stratosphere (UTLS) is the atmospheric layer surrounding the tropopause. The altitude of the UTLS varies a great deal with latitude, because the tropopause height varies. The tropical tropopause is at an altitude of about 18 km while the polar tropopause is closer to 6 km. The tropopause height also varies with season and with storm passage.

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The importance of the UTLS derives, in part, from it being the region where tropospheric air enters the stratosphere from below in the tropics, and where stratospheric air enters the troposphere from above in the extratropics. Thus, it is the region where tropospheric trace species, such as carbon monoxide, enter the stratosphere and where stratospheric species, such as ozone, enter the troposphere. Other aspects of the UTLS are also important. Stratospheric air with high potential vorticity can be an important factor in storm intensification. Shear in this region can also be important in determining the evolution of gravity waves, baroclinic instability and high clouds, and thus plays an important role in stratosphere/troposphere interactions. Furthermore, the radiative effects of ozone and water vapor in the UTLS have disproportionately large impacts on surface climate. We can imagine the UTLS region analogous to the ABL in that it has special properties controlling the fluxes between the troposphere and stratosphere.

b. Important science questions

Three sets of science questions are organized below. The first set concerns the processes that control the two-way constituent transport between the troposphere and stratosphere:

- What processes determine the distribution of UTLS water vapor and clouds and their changes with time?

- What processes control the stratosphere/troposphere exchange of gases that affect tropospheric and stratospheric ozone?
- How does moist convection influence the chemical composition of the UTLS region, and how does this vary as a function of location and season?
- What scales and processes are crucial to the characterization of constituent mixing in the vicinity of the extra-tropical tropopause?

The second set of questions concerns how the flux of momentum through the UTLS by gravity waves controls the circulation in the stratosphere and higher atmospheric layers:

- How do gravity waves determine the large-scale atmospheric structure, cirrus cloud distribution, mixing, and temperature fluctuations in the UTLS region?
- How do tropospheric weather patterns and mountains modulate the upward flux of gravity wave energy?
- How does the refraction of gravity waves by lateral wind shear alter the geographic distribution of wave energy flux?
- How does gravity wave breaking in the stratosphere generate patterns of secondary gravity waves, including down-going waves?
- How can observations of gravity waves associated with convection, jet emission, and fronts be used to improve gravity wave source treatments in climate models?

The third set of questions concerns how water vapor, clouds and ozone in the UTLS influence climate:

- What can observations tell us about the role of radiative balances (including ozone effects) in the UTLS in constraining the properties of high clouds and what its climate effects in the future may be?
- What controls the lifetime of cirrus clouds in the UTLS?

c. Observational challenges

The challenges of UTLS arise in part from the high altitude of the tropopause; ranging from 6km in the polar regions to 18km near the equator. Several extant research aircraft (e.g. the NSF/NCAR G-V) can easily reach the former, but only a few (e.g. ER-2 or Globalhawk) can reach the latter. Research aircraft observations of the UTLS are infrequent and local. Satellite sensors usually get a good view of the UTLS but may not be able to resolve its detailed structure or active mesoscale processes. Balloons easily reach the UTLS but their measurements are usually limited to wind and temperature. Only a few sounding systems are able to measure the trace amounts of water vapor, ozone and other gases in that region. Long-term monitoring of the UTLS is difficult but important. Important processes such as gravity waves, cirrus layers and deep convection are transient and local.

d. Existing instruments (operational and research)

Global monitoring of the UTLS is done with satellites and the global radiosonde system. Satellite-borne nadir-viewing and limb-scanning sensors can continuously map the large scale temperature, aerosol and trace gas composition in the UTLS. The radiosonde network measures winds and temperatures with greater vertical resolution than satellites but with coarser horizontal resolution.

Recent advances in sounding technology include GPS position finding, improved sensor calibration and higher data rates giving better vertical resolution. During special research programs, frequent (e.g., 3 hourly) balloon launches allow the phases of gravity waves to be tracked in the stratosphere. While operational sensors cannot observe trace gases or even water vapor in the stratosphere, special research-grade sensors can measure these quantities.

The trace gas composition of air in the UTLS region can be determined from research aircraft, ozone sondes and limb-scanning satellites. There are limitations to these measurements regarding altitude and geographic coverage, temporal coverage and the number of species observed. The detection of thin cirrus and low concentrations of water vapor is a particular problem.

The observation of gravity waves in the UTLS today is done primarily with balloon soundings and research aircraft. These data can be used to compute wave momentum and energy fluxes. These two observational technologies provide scant spatial and temporal coverage, however. Further aloft, satellites provide much more comprehensive detection of gravity waves, but with little ability to identify wavelengths and to quantify energy and momentum fluxes.

In the LAOF aircraft fleet, only the NGV twin-jet aircraft can operate in the UTLS at some latitudes. With a ceiling of about 14 kilometers, it reaches the UTLS easily in the mid and high latitudes but it cannot reach the tropical tropopause. It can carry a wide range of sensors with application to UTLS science issues. With its dropsonde capability, it can observe wind, temperature and humidity profiles beneath the aircraft.

e. Promising new instruments (candidate LAOF instruments)

Advances in UTLS science require the LAOF extend its observational capabilities in directions described below.

- Extend dropsonde capabilities in UTLS to include trace species measurements (water vapor to detection limit 1 ppm, precision 0.3 ppm, O_3, CO, cloud, etc.)
- Improve airborne and high altitude balloon capabilities (accurate water vapor measurements, additional species, isotopes of water, HO_x, remote sensing from aircraft, cirrus cloud measurements)
- Increase UTLS remote sensing capabilities on NCAR aircraft. Particularly important would be a vertically pointing lidar capability on the NSF/NCAR G-V, which would contribute to studying mean structures, clouds and gravity waves,
- Make the GlobalHawk technology available to the NSF science community
- Make stratospheric drifting balloons and balloon dropsonde platforms available to the NSF science community

f. Broader issues

Below we indicate a number of specific field measurement programs that would advance our understanding of the UTLS. This list emphasizes the need for close collaboration between LAOF and NASA and between LAOF and atmospheric chemistry measurement groups.

- Make high-resolution measurements of chemical composition in the vicinity of the extratropical tropopause to better understand the role of small-scale filamentary structures in stratosphere/troposphere exchange and tropopause sharpening.
- Make regular survey aircraft measurements of UTLS (constituents, including very short-lived substances, or VSLS). Incorporate ground-based measurements (e.g., lidar, high-resolution balloon measurements) as part of the campaign design.
- Execute tropical observational campaigns involving super-pressure balloons and/or Global Hawk, for example, releasing dropsondes measuring ozone, water vapor, and meteorological variables under various cloud conditions.
- Enhanced balloon launches making frequent ozone and water vapor measurements.
- Make aircraft measurements in the vicinity of mountains, jet streaks, fronts, and deep convection to characterize the gravity wave spectrum and compare with results from mesoscale models, satellite observations, high-resolution radiosondes, and super-pressure balloons. Use these *in situ* measurements to develop a transfer standard to GPS measurements, thus enabling global information to be obtained over extended periods.
- We note that the aforementioned capabilities will also be useful in polar observational campaigns. We also recommend that multi-agency consultation take place in the planning of the measurement campaigns above, and also cooperate to blend different organizational capabilities. For instance, we envision the deployment of the proposed extended dropsonde capabilities on NASA high-flying unmanned aircraft, such as the Global Hawk, as well as from high altitude drifting balloons.

References and additional readings

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8. Summary and Conclusions

In this concluding Chapter, we discuss the basic principles by which LAOF can evaluate different instrument development programs. We also identify those aspects of climate research and climate modeling that would most benefit from LAOF-type observations. Finally, we give several examples of high-priority observational problems or instrument development projects.

a. Basic principles governing the evolution of LAOF

i. Innovation

An important factor in the choice of LAOF platforms and instruments is the degree of innovation. Every few years a significant new instrument idea appears that addresses a major question in climate research using a new measurement principle. These truly innovative ideas should be given a high priority for purchase, development or deployment. In a tight budget, it may be necessary to slow or reduce other instrument development or deployment activities to fund revolutionary new observing systems.

ii. Criticality and uniqueness

When a new instrument or platform addresses a critical need in climate science, it should be given a high priority. Occasionally different types of instruments can be used to measure the same physical quantities. The uniqueness of a proposed new instrument program is the degree to which no other existing instruments can observe the target quantity. Uniqueness may argue in favor of a new instrument, but not always. Frequently it is better to measure important physical quantities using redundant methods based on different physical principles.

iii. Breadth of application

In some cases, a proposed new instrument will address questions in several research areas. When such a proposal can be identified, it should be given the highest priority. In addition to its broad application, it will help to foster cooperation between different groups of researchers.

iv. Representativeness

A frequent problem in the atmospheric sciences is the lack of representativeness of measurements. No matter how accurate a measurement is, it may not be of great use unless it is representative of a larger region. This is a particular problem in heterogeneous landscapes and high gradient regions. Observing systems that address this problem using spatial or temporal averaging, or some other method, deserve special priority.

v. Timeliness

The development of a new instrument system may take many years and proceed through several phases. When a major investment is requested, often it is the more advanced development programs that are more predictable and will give a bigger return on investment. Newer initiatives can often be nurtured with a smaller investment.

vi. Cost of development or acquisition and deployment

In times of limited budgets, the cost of instruments or platforms may enter priority decisions at LAOF. Differences in cost will be a factor in deciding between instruments with similar capabilities.

vii. Collaborating agencies, institutions and industry

A good sign that a new instrument has broad application is if more than one environmental agency or institution has expressed interest. The likelihood of cost sharing adds to the argument for development.

viii. Commercial availability

In many cases, components or full instrument systems can be purchased from the private sector more effectively than with LAOF development. This is especially true when large numbers of sensors must be deployed.

ix. Educational uses for LAOF

The health of the observational side of atmospheric science requires an effort in training students in the use of LAOF. Over the last few years, some very effective educational programs have been designed and run within LAOF with good outcomes. Without trained scientists, the LAOF will not contribute as it should to climate research in the long term.

x. Historical use

In times with limited funding, choices may have to be made between existing instrument upgrade and deployment and new instrument development. The long-term trend in demand for the existing instrument may provide guidance. If the demand has been steadily falling, investment in a new technology may be appropriate.

b. Climate modeling applications of LAOF observing systems

[This section includes ideas from a March 21, 2013 discussion with the NCAR CESM Chair Marika Holland, and CESM Working Group Co-Chairs Jean-Francois Lamarque, David Lawrence and Richard Neale.]

i. Evaluation and improvement of climate models with LAOF process resolving data.

Not long ago, when climate models were run with 200km spatial resolution, climate model verification was limited to large scale data sets such as fields from radiosonde and satellite systems. Today, with model resolutions reaching 25km, new types of verifications are possible. On these smaller spatial scales, results from LAOF instrument deployments can be directly compared with model output. This new verification possibility marks a real turning point in Earth System Model (ESM) development and use. It holds the promise of improving the representation and impact of gravity waves, organized convection and other mesoscale processes on regional and global climate. Thus, LAOF is poised to have a major impact on climate modeling.

ESMs are increasingly able to handle trace gases, isotopes and aerosols in their core computations, marking a significant advance in environmental modeling. At issue however, is the degree to which gas, isotope and aerosol fluxes and concentrations can be initialized and tested. On the global scale, satellites may provide the needed measurements. On the smaller scale however, the LAOF will be essential. The LAOF must ensure that it has the required capability.

As the accuracy of ESM calculations become more critical and controversial, the physics behind the parametrized sub-grid processes will become more important. Examples would include the climate sensitivity to small-scale processes such as dry air entrainment into clouds, aerosol impact on cloud lifetime and reflectivity, auto-conversion of cloud droplets to rain drops, embedded convection in stratus clouds. These problems will never be solved without a strong and well-focused LAOF.

ii. Known problems in current climate models

There is widespread agreement in the climate modeling community that certain aspects of model performance need improvement. A few examples of improvement include:

- The double ITCZ and the convergence zone in the southern tropical Pacific
- Biases in the number of Tropical Atlantic hurricanes
- Sensitivity to cloud parameterization
- Arctic sea ice distribution and resultant surface air and sea temperature errors
- Underestimates of gas exchange at the ocean surface; including chlorofluorocarbon (CFC) tracers
- Scale dependence of orographic precipitation
- Poor aerosol source distribution and over-estimated indirect aerosol effect
- Uncertainties in the cause-effect relationship between SST and surface energy budgets
- Continental surface energy budgets under drought conditions
- A dry bias in subtropical arid zones
- Mixed clouds radiation and transport effects

Improvement in these and other areas of model prediction will require new modes of field project design, targeting known errors in ESMs.

iii. New modes of deployment for climate application

The increased application of LAOF to climate problems may require new modes of instrument and platform deployment. In current practice, moderate and large LAOF deployments are done for periods of time ranging from two weeks to two months. The duration of these projects is often determined by the probability of encountering the targeted phenomena. Projects of longer duration are costly, they stretch the effectiveness of LAOF personnel and they conflict with other proposed projects. As the motivation for field projects shifts toward climate, it may be necessary to design strategies for longer and/or more creative modes of deployment. Improvement in these and other areas of model prediction will require field project design targeting known errors in ESMs.

Field projects should be encouraged with stronger input from the global modeling community. As a generic example, we envision projects to determine fluxes of non-conventional quantities from various land, ocean or snow surfaces. Such projects would require state-of-the-art surface flux measurements together with low-level aircraft surveys. The surface station network should capture the surface heterogeneity. The aircraft would be equipped with fast response eddy-correlation sensors for conventional and non-conventional fluxes as well as down-looking remote sensing instruments. The aircraft could be deployed for multiple two-week periods in opposite seasons. In this way, both the weather cycle and the seasonal cycle would be captured. Such a deployment strategy would be useful in almost every climate zone and surface type, e.g., tropical and polar seas, forests, savannas and deserts, sea ice, agricultural and complex terrain. Flux results should be carefully compared with model predictions. It is critical that the analysis of these new data sets be analyzed by multi-disciplinary teams of experts and that the data sets be properly archived.

iv. Data stewardship and availability among the climate community

The quality assessment, archiving and availability of hard-won LAOF project data sets have always been an important goal. It is even more important today. First, these older data sets may have a larger community of users than ever before, if the climate community begins to use them for model verification. A good example is the old BOMEX and GATE data sets that are widely used today, decades after their collection. Second is the possibility that old project data sets may have historical value in an era of climate change. Traditionally LAOF has done a good job in integrating deployments with data archive, access, and discovery. More efforts are still needed to ensure the user-friendliness in interdisciplinary studies (e.g., adequate metadata, common data format).

v. Training and collaboration

There is a great need for the training of graduate students and postdoctoral researchers in data-model integration. Possible approaches include: sending students and postdocs working on field experiments to NCAR to work with ESM scientists; and sending students and postdocs working on ESMs to participate in field experiments.

The interactions between LAOF and ESM scientists also need to be enhanced by involving LAOF scientists in ESM activities (including giving presentations, e.g., at the CESM Annual Meeting and Working Group meetings) and involving ESM scientists in LAOF activities (including field experiment planning).

c. High priority instrument/platform projects for LAOF

In this section we give a few examples of high priority problems and instruments that satisfy the criteria in **Section 8a** and with impact on climate research as outlined in **Section 8b.** These examples are not meant to be exclusive nor are they in priority order.

i. Airborne radar

Research-grade airborne radar such as Eldora and the Wyoming cloud radar have made a major impact on our knowledge of precipitating weather systems over the sea and remote land areas. While the new satellite-borne radar systems add to our capability, they do not replace the need for aircraft radar. If the community loses this facility, our progress on important cloud-climate processes will stagnate. Advances in airborne precipitation radar, including polarimetric capabilities would impact the problems discussed in at least Chapters 5 and 6 of this report.

ii. Ground-based radar

Surface-based research radar such as CHILL and S-POL continue to add to our understanding of precipitating systems. The addition of Ka band to S-POLKa has demonstrated the estimation of total cloud water content and relative humidity in the vicinity of tropical cumuli, and the capability to discriminate between cloudy air and clear air Bragg scatter at S-band. The addition of polarimetric capabilities at W-band would further efforts to characterize hydrometeor phase and type and the radiative transfer properties in non-precipitating clouds When combined with airborne sensors, ground-based radar can tackle key climate problems such as convective transport. The current use and possibilities for upgrades for CHILL and S-POL should be evaluated. Advances in this area would impact the problems discussed in at least Chapters 2, 5 and 7 of this report.

iii. Aerosol monitoring

While impressive advances have been made in detecting and characterizing aerosol from aircraft, much more remains to be done. Measurements of aerosol concentrations and fluxes from meteorological towers and ocean buoys are needed. Advanced surface and aircraft-based lidars for aerosol mapping and identification would be helpful. Advances in aerosol monitoring would impact the problems discussed in all the thematic Chapters 2-7 of this report.

*iv. Trace gases and isotope*s

The observations of trace gases and isotopes have been shown to contribute to our knowledge of eco-system function, the hydrologic cycle, radiative forcing, atmospheric chemistry, cloud physics and climate change. The development of suitable instruments has been done by various private companies, university departments and in ACD at NCAR. Ideally, these measurements should be coordinated with LAOF-type measurements of wind, turbulence, thermodynamics and cloud particles. Some new collaborations may be required for this to happen. Advances in this area would impact the problems discussed in all the thematic Chapters 2-6 of this report.

v. Representative surface properties and fluxes

The measurement of representative physical quantities in complex terrain is an important challenge. While satellites fill part of this need, their observations are indirect. Local measurements are needed. The CentNet, COSMOS, CTV, UAV, surface-based remote sensing programs all hold some potential in this regard. Advances in this area would impact the problems discussed in at least Chapters 2-4 of this report.

vi. Flux monitoring from the ocean and cryosphere

While flux tower networks such AmeriFlux have contributed significantly to our knowledge of momentum, heat, and water vapor fluxes over land, such long-term observations are missing over the ocean and cryosphere. LAOF expertise in flux measurements might be able to contribute to this broad problem. Advances in this area would impact the problems discussed in at least Chapters 3 and 4 of this report.

vii. Vertical profiling of physical properties

There is an emerging potential for determining vertical profiles of wind, temperature, humidity, aerosols, trace gases and isotopes in the boundary layer using a combination of radar and lidar remote sensing. Even flux profiles might be determined if the instruments are fast enough. In principle, such “virtual towers” could be deployed in any climate zone, impacting Chapters 2-4. Their vertical reach might include the less understood middle and upper parts of the boundary layer.

Final remarks

As discussed in Chapter 1, two specific questions from NSF/AGS are:

- Is NSF LAOF providing effective balanced support to the climate research community? How could it be improved?
- Is the climate research community making best use of the LAOF capability?

Chapters 2-7 represent our assessment in response to these questions, while recommendations are presented in Sections 8a-c.

For the first question, "Is NSF LAOF providing effective balanced support to the climate research community," the answer is "Yes" but with limitations. LAOF instrument development and deployment programs have had a deep and lasting impact on the atmospheric research community. Most of the LAOF-supported studies have focused on atmospheric processes with direct impact on climate. This is especially true in "process studies" where improved understanding of weather disturbances have improved both parameterizations in climate models and model verification.

Two new challenges confront LAOF in regard to climate applications. First, climate problems require a greater emphasis on certain climate-critical physical quantities. These include surface fluxes, aerosol properties and transport, mixed-phase clouds, water and carbon isotopes, spectral radiation and storm- scale transports. An impressive number of new observational technologies are poised to fill these needs. Second, climate problems require, in some cases, an extension of LAOF deployments to larger spatial scales and longer deployments. In this regard, new field research strategies may have to be developed. These strategies may include better coordination of research and operational facilities, longer or repeat deployments, and new permanent observing sites in the low or high latitudes.

For the second question, "Is the climate research community making best use of the LAOF capability," the answer is "No." We believe that current observational facilities and data are underutilized by the modeling community. To fill this gap, the LAOF and climate modeling communities have to work together. As the first step, the Annual CESM Workshop should invite leading scientists/technologists from the LAOF community to discuss LAOF capability and data. The CESM community should also be invited to provide feedback on the recommendations in Chapter 8 here, and on the LAOF facilities and data (for climate research) to be planned by NSF/AGS and the institutions involved.

To implement the recommendations here, multi-disciplinary collaboration and cooperation from funding agencies are needed. Within NSF, this would at least involve AGS, OCE, the Division of Earth Sciences (EAR), the Directorate for Biological Sciences (BIO), and the Office of Polar Programs (OPP), as well as several cross-cutting programs. Among agencies, this would at least involve NSF, NOAA, DOE, NASA, ONR, and the U.S. Geological Survey (USGS). These efforts would not only provide cost-sharing but also ensure the wide application of, and better return on, the investment.

Acknowledgements

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APPENDIX - AGENDA

Lower Atmospheric Observing Facilities Workshop

National Center for Atmospheric Research
Center Green Campus
18-19 June 2012

Monday 18 June

0800	**Brief Opening Remarks –** L. Avallone, NSF; R. Wakimoto, NCAR: V. Grubišić, EOL	
0815	**Current NSF/AGS Lower Atmospheric Observing Facilities and Services** (25+5)	
	Surface-based facilities (EOL, CSU, CSWR)	S. Cohn, EOL
	Aircraft (WYO, NPS/CIRPAS, NCAR)	A. Rodi, U. Wyoming
	Data Services	M. Daniels, EOL
0945	**Break**	
1010	**Emerging Technologies/Platforms** (12+3)	
	A10 aircraft	H. Jonsson, NPS/CIRPAS
	COSMOS	M. Zreda, U. Arizona
	DIAL Thermodynamic Profiling	K. Repasky, MT State U.
	CASA	D. McLaughlin, U. Mass.
	HCR, HSRL	J. Vivekanandan, EOL
1125	**Atmospheric Chemistry Instrumentation** (20+5)	A. Guenther, NCAR/ACD
1150	**Other Agency Facilities** (15+5)	
	DOE ARM	Beat Schmid, Pacific NW Nat'l. Laboratory
	NOAA	Russ Schnell, NOAA ESRL
1230	**Buffet Lunch**[*] (payment required for NCAR and federal employees)	
1315	**Topical Lectures** (30+5)	
	Terrestrial Interface (ABL, Bio, Hydro, Urban)	D. Baldocchi, U. California, Berkeley
	Ocean Interface (Phys, Chem, Biochem)	R. Weller, Woods Hole Oceanographic Inst.
	FreeTroposphere Physics	C. Bretherton, U. Washington
1500	**Break 25min**	
1525	**Topical Lectures** (30+5)	
	UTLS	D. Hartman, U. Washington
	Tropical Free Waves	C. Zhang, U. Miami
	Cryosphere Interface	N. Molders, U. Alaska
1710	**End Oral Presentations**	

Tuesday, 19 June

Topical Breakout Sessions, Co-Chairpersons

Terrestrial Interface (ABL, Bio, Hydro, Urban)
Ana Barros, Duke U.
Helen Cleugh, CSIRO/CAWCR

Ocean Interface (phys, chem, biochem)
Chris Fairall, NOAA ESRL
P. Sullivan, NCAR/MMM

Cryosphere Interface, Polar Studies
Glen Liston, Colorado St. Univ.
Mark Serreze, Nat'l. Snow, Ice Data Cntr., CU

Free Tropospheric Physics (cloud, precipitation, aerosol, radiation)
Alan Blyth, Leeds U.
Kimberly Prather, Scripps Inst. Oceanography

Tropical Free Waves, Cyclones
Shuyi Chen, U. Miami, RSMAS
Stephan Tulich, U. Colorado/NOAA

UTLS Region (phys, dynam, chem)
Marv Geller, Stoneybrook U.
Laura Pan, NCAR/ACD

0830 Plenary "marching orders"

0845 Breakout Sessions A - distillation of prominent science questions, experimental methodologies

Break (as you wish)

1115 Summary Reports –Breakout Sessions A (5+2 min ea.)

1200 Buffet Lunch[*] (payment required for NCAR and federal employees)

1300 Breakout Sessions B – priority objectives, observing facility gaps, applicable technologies

Break (as you wish)

1530 Breakout B - Summary Reports

1615 Plenary Discussion - explore common ground, low hanging fruit, trans-disciplinary requirements

1715 Adjourn Open Sessions

Wednesday 20 June, 0900 -1330, Synthesis Committee Meeting (by invitation)

The synthesis committee will engage in structured discussions for the following purposes:

- **Integrate findings and recommendations derived from the topical inputs**
- **Provide overarching findings and recommendations derived from considerations such as scientific and technological readiness, urgency, breath of applications, other pivotal considerations.**
- **Draft a report that summarizes highlights and recommendations for distribution to participants and other interested parties.**
- **Distill a high-level summary for a widely circulated publication and website postings.**

Members

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Bruce Albrecht, UM/RSMAS
Roni Avissar, UM/RSMAS
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