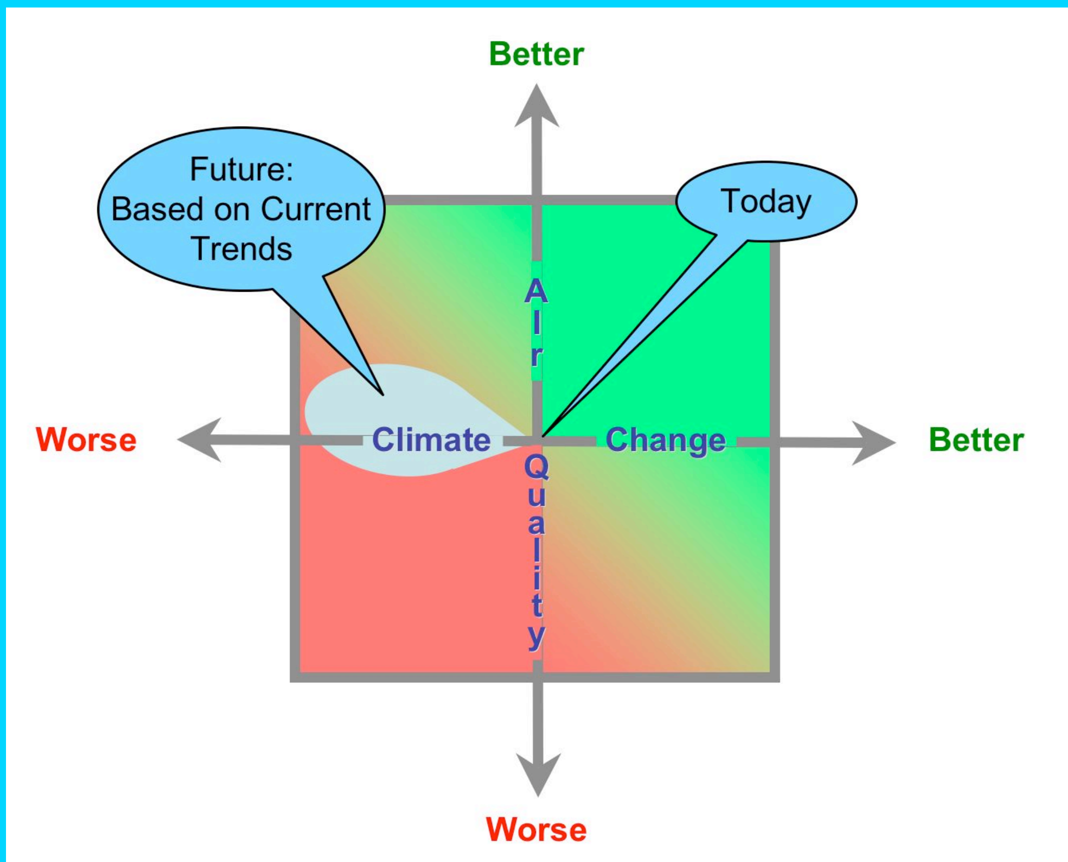
2010 CalNex

White Paper

Science to Support Decisions



Research at the Nexus of Air Quality and Climate Change

9 January 2008

Overview

The California Air Resources Board (CARB), the National Oceanic and Atmospheric Administration (NOAA) and the California Energy Commission (CEC) are proposing a joint field study of atmospheric processes over California and the eastern Pacific coastal region in 2010. This study will particularly emphasize the interactions between air quality and climate change issues, including those affecting the hydrologic cycle. It will constitute one of a series of comprehensive regional air quality and climate assessments conducted by NOAA and an expansion of CARB's leadership of California air quality studies. It will complement the ongoing CEC regional climate change studies, and cooperate fully with that program. This paper summarizes the policy-related interests that drive this study and the specific research goals that motivate CARB's, NOAA's and CEC's execution of this study. This multi-agency study will bring together specialized, complementary resources such that the outcome will be able to answer important scientific questions that have an impact on environmental policy.

A Unique Opportunity

The timing of this study and the availability of unprecedented resources for atmospheric research in California reflects the conjunction of interests among NOAA, CARB, and CEC in developing a unified understanding of the issues at the heart of coupled air quality and climate change problems. NOAA's research program embodies a "one atmosphere" perspective that addresses both air quality and climate change issues. This program utilizes state-of-the-art airborne, ship- and ground-based instrument packages, and is effected through regional assessments conducted throughout the U.S. This impels NOAA to seek out regional government and academic researchers to complement its own national-scale research efforts with local understanding of specific problems. California's evolving regulatory posture, including CARB's new initiatives focused on climate change and goods movement, demands much greater understanding of processes aloft and offshore to relate California conditions to continental and global processes and trends. CEC, through its Public Interest Energy Research (PIER) program, is charged with developing greater understanding of the effects of global pollution and climate change on California, with special emphasis on the impacts on air quality and water resources. A full investigation of these impacts requires a continental–to-hemispheric perspective. Thus NOAA's larger-scale perspective, capabilities and experience are an ideal complement to CARB's and CEC's deep understanding of local atmospheric issues in California.

California Leadership

California is the world's 12th largest source of carbon dioxide, the chief heat-trapping gas that causes global warming. The state has a responsibility to reduce its share of emissions, and by doing so can lead the United States—and the world—in developing the innovative policies and technologies needed to avoid the most dangerous consequences of global warming. (www.law.stanford.edu/program/centers/enrlp/pdf/AB-32-fact-sheet.pdf)

Cover Figure 1: Schematic diagram of the trade-offs between the implications for regional air quality and global climate change of new policies for management of the atmosphere. The gray ellipse approximately represents the direction of current trends in the U.S.

This opportunity will not reoccur. NOAA field programs, conducted every second year, follow a rotation to provide support to regions across the U.S. Thus their participation cannot be postponed. CARB is embarking on new regulatory activities that arise from Assembly Bill 32—Global Warming Solutions Act of 2006. These activities require scientific support. The timeline of this work makes a 2010 field study much more valuable than deferring to the distant future. The impacts of climate change are growing. CEC has a pressing need to understand these impacts. Together, these participants can generate a uniquely integrated view of atmospheric processes along the western boundary of North America. The cost for any one agency to undertake a field project of this scale would be prohibitive.

Planning of CalNex 2010 will be well-informed by utilizing results from research studies contracted by the CARB and CEC. CARB plans to capitalize upon two highly instrumented NASA aircraft platforms that will be temporarily available in California in July 2008. Only short-term measurements will be possible from these NASA platforms, but the results will be invaluable for characterizing the scope and scale of the spatial variability of atmospheric constituents from well over the Pacific Ocean, through the coastal zone, and inland. CEC with Scripps Institution of Oceanography will conduct a field study in 2008. Additional information on the CARB and CEC funded research efforts is included under the heading Planning and Integration of Research Programs.

The Synergy of NOAA, CARB, CEC and Other California Institutions

NOAA has the ability to study the atmosphere over large areas of ocean and land rapidly by employing large, richly instrumented, long-range aircraft, a fully capable oceanographic vessel and ground based instruments designed to study meteorologically driven transport patterns. These assets provide a unique capability to study the composition of the offshore marine troposphere (including intercontinental transport of pollution), the ocean-air interface in coastal and off-shore areas of California, the modification of marine air as it moves onshore through coastal cities and into interior areas of the State, the atmospheric boundary layer and regional air flow between multiple air basins. California offers a research environment rich in baseline data, an on-going atmospheric monitoring capacity (CARB and local air quality management districts) and existing strong academic research capabilities (e.g., the U.C. system and private universities such as Stanford and California Institute of Technology). CEC provides the expertise of the investigators currently funded by the PIER Program on regional climate modeling, use of research aircraft to monitor the effect of aerosols on cloud behavior and the long-term monitoring of transported pollutants aloft using unmanned aircraft.

This collaboration will link short-term data gathered during the field program to extensive surface observations, long term data sets, and California's advanced modeling capabilities for both regional air quality and climate.

Air Quality and Climate Change: Tradeoffs Facing Decision Makers

The challenge of properly managing California's atmospheric resources is complex, because management strategies must simultaneously deal with two interrelated environmental concerns:

air quality and climate change. These strategies must also effectively meet society's need for energy generation and demand for goods and services. The management of air quality is focused on limiting the levels of harmful pollutants and air toxics, improving atmospheric visibility and reducing acidic deposition to ecosystems. These air quality issues are usually considered from local to regional scales, although it is becoming clear that there are important global scale influences on the air quality in California. The mitigation of climate change effects requires controlling greenhouse gas emissions and reducing other radiative-forcing agents. Climate change is usually considered from a global perspective, but strong regional differences are expected in the effects of climate change. Thus, some climate change policies will have particularly large impacts in California, especially controls on short-lived climate forcing agents. The goal of the CalNex 2010 program is to study the important issues at the nexus of the air quality and climate change problems, and to provide scientific information regarding the trade-offs faced by decision makers when addressing these two inter-related issues.

> The goal of the CalNex 2010 program is to study the important issues at the nexus of the air quality and climate change problems, and to provide scientific information regarding the trade-offs faced by decision makers when addressing these two inter-related issues.

Although separate programs are in place to research and manage air quality and climate change, these concerns are not separate and in fact are intimately connected. These connections arise because many of the atmospheric species of concern are the same, and in many cases the sources of the agents are the same or intimately connected. For example, surface ozone is both an air pollutant and a greenhouse gas. Aerosols, known in the air quality community as particulate matter (PM), not only have significant and complex climate impacts, but also are an important air pollutant that has significant human health impacts, degrades visibility and contributes to acidic deposition. In many cases, efforts to address one of these issues can be beneficial in addressing the other, but in other cases policies addressing one issue can have unintended detrimental impacts on the other.

> Although separate programs are in place to research and manage air quality and climate change, these problems are not separate and in fact are intimately connected.

The complex roles that ozone and aerosols play in the atmosphere provide examples of such trade-offs. Reductions in the emissions of nitrogen oxides (NO_x) and/or volatile organic compounds (VOCs) to reduce ozone formation for improved air quality, also ameliorate climate impacts from ozone and VOCs. However, efforts to reduce emissions of PM and its precursors (SO_2, NO_x, VOCs, ammonia) for air quality improvement can lead to a further warming effect on the climate, because scattering of sunlight by aerosols masks as much as 50% of the present warming effect of greenhouse gases [*Ramanathan et al*., 2001]. Policy decisions also must recognize that some climate change impacts have a strong regional dependence, and not simply a uniform global impact. Where aerosol loadings are high, as in many of the populated areas of the globe, the regional cooling effects of aerosols can be much greater than the global averages that are usually discussed [*Ramanathan et al*., 2007]. Aerosols also play a complex role in climate interactions with the water cycle. Enhanced aerosol levels potentially can lead to decreases in the rainfall and snow pack in the Sierra Nevada Mountains. A PIER study [*Jacobson,* 2005] suggests that aerosols are already affecting precipitation in California.

The figure on the cover of this document illustrates, in a qualitative manner, the trade-offs faced by decision makers between the implications of new environmental policies for air quality on the one hand and climate change on the other hand. The center of the graph represents where we are in the U.S. today, given current air quality and the atmospheric levels of radiative forcing agents. Movement away from the center of the graph represents the effects of projected changes in industrial and urban emissions in response to growth, technology change and/or emission management strategies. Such changes will affect both air quality (upward if the effect is positive, downward if negative) and climate change (to the right if the effect is positive, to the left if negative). Clearly, the goal is to make decisions that have beneficial effects for both problems (i.e. win-win strategies that move us into the upper-right quadrant of the figure), and certainly avoid lose-lose strategies that move us into the lower-left quadrant. However, some of the possible emission control strategies will likely have positive effects on regional air quality and negative effects on global climate change (movement into the top-left quadrant), or vice versa (movement into the bottom-right quadrant).

The projected effect of current emission trends in the U.S. is approximately indicated by the gray ellipse in the cover figure. Over the past decades in the U.S., emissions reductions implemented for vehicles and point sources have significantly improved air quality in most metropolitan areas, while accelerating emissions of greenhouse gases have increased the net radiative forcing of the climate system. Overall, from 1990 to 2005, total emissions of CO_2 in the US are estimated to have increased by 20% (from 5062 to 6090 Tg per year) [*EPA*, 2007]. In recent years improvement in air quality in most regions of the U.S. has slowed. For example, Fig. 2 shows the trends in regional ozone concentrations in two California air basins. Therefore, as represented by the gray ellipse, recent current trends imply a shift of the state of the atmosphere primarily toward the left of the figure, i.e. toward worsening climate change impacts with only modest improvement in air quality.

> Current trends indicate slowing improvement in air quality in the U.S., along with accelerating increases in greenhouse gas

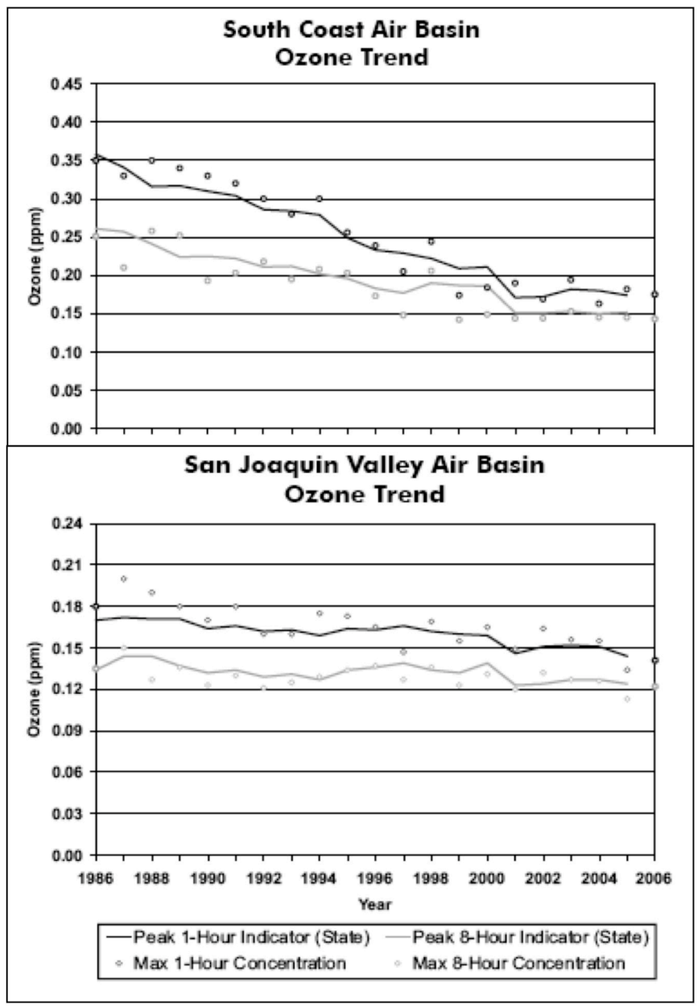


Figure 2: Trends in regional air quality over the past decade in two California air basins as represented by four metrics of maximum measured ozone concentrations [*CARB*, 2007].

This slow improvement in air quality is represented by a small displacement of the ellipse into the upper-left quadrant. The challenge for the future is to adopt new policies that slow the increase in radiative forcing and increase the current rate of improvement in air quality.

The State of California is a particularly appropriate locale for study of the issues at the heart of the coupled air quality and climate change problems. California has well-documented air quality problems and faces the difficult task of managing them with an increasing population and demand for goods and services. In addition, California has taken the lead in the Nation's effort to address global climate change and has proposed an ambitious program to control the emissions of greenhouse gases in the State. Thus, California is particularly interested in finding the most effective way to simultaneously manage the two challenges of air quality and climate change. In other words: how can the emissions of greenhouse gases, aerosols, other air pollutants and their precursors be reduced, such that benefits are maximized for both air quality and climate change? Characterization of the regional effects of climate change in California will also be of particular interest: What benefits will the people of California receive as a result of climate change mitigation? In the CalNex study, NOAA, ARB, and CEC researchers will lead a major multi-institutional intensive field program in California in 2010 focusing on the science that couples the air quality and climate change issues facing this State. In addition, many of the Nation's experts in air quality and climate change research reside in California, and their involvement in the field study will enhance the program and improve the communication of the scientific findings to the State's decision makers.

> California has well documented air quality problems and has proposed an ambitious program to control the emissions of greenhouse gases in the State.

CalNex 2010 Science Questions

The following preliminary list of science questions have been developed for guiding the field research of CalNex 2010. They are intended to be 1) feasible to address in the context of the proposed study 2) specific enough to provide a needed focus, but 3) general enough to cover the scientific issues of immediate policy interest. They will be revised as needed to form the basis of the Science Plans that will be developed by the participating agencies. These questions fall into three broad categories.

Emissions

A. **How can we improve the emissions inventory for greenhouse gases, ozone and aerosol precursors** including emissions from soil, ships, agriculture and other non-industrial or transportation related processes? What measurements can help validate the use of satellite data for biogenic VOC and NOx emission inventories?

B. **What emissions** (natural and anthropogenic) and processes lead to sulfate formation over California coastal waters and in urbanized

> Both climate change and air quality problems originate from society's increased emissions of radiative forcing agents (CO_2, CH_4, N_2O, halocarbons, black carbon, aerosols) and air pollutants and their precursors (VOC, NOx, SO_2, CO, air toxics). Our understanding of these emissions on both regional and global scales is critically limited.

coastal areas? What is the contribution from ship emissions? How does Southern California compare and contrast with the San Francisco Bay Area?

C. **What sources and processes contribute to atmospheric mercury** concentrations in California?

Chemical Transformation and Climate Processes

> Critical uncertainties remain in our understanding of 1) the processes by which primary emissions are transformed within and removed from the atmosphere, and 2) how aerosols interact with the radiation flux in the atmosphere.

D. **How important are chemical processes occurring at night** in determining transport and / or loss of nitrogen oxides, reactive VOC and ozone? Do regional models in California adequately represent these processes and their effect on air quality?

E. **What are the sources and physical mechanisms that contribute to high ozone concentrations aloft** that have been observed in Central and Southern California?

F. **Are there significant differences between Central Valley and South Coast Air Basin precursors or ozone formation chemistry?** Will meteorological and/or precursor differences between the Central Valley and the South Coast Air Basin lead to different chemical transformation processes and different responses to emissions reductions? What is the importance of natural emissions to the ozone formation process? Are there regional differences in the formation rates and efficiency for particulate matter as well?

G. **What are the impacts of aerosols in California on radiative forcing and cloud formation?** What are the most important precursors and formation processes for secondary organic aerosol? What is the role of aqueous phase processes in atmospheric transformations?

Transport and Meteorology

> Climate change and air quality problems have both global and regional scale aspects that interact through atmospheric transport. Critical uncertainties remain in our understanding of these interactions.

H. **What are proper oceanic boundary conditions** for coastal and regional atmospheric chemistry modeling? Are there variations in oceanic boundary conditions in northern and central California vs. the southern part of the state? What physical and chemical changes occur as a parcel of air moves from off-shore, through the shore zone, and inland?

I. **How best can we characterize and model air flow** over coastal waters and the complex terrain of California? For example: what is the best representation of air flow in the southern San Joaquin Valley, particularly with respect to flow between the San Joaquin Valley and South Coast Air Basin versus recirculation north along the Sierra Nevada and Coastal ranges?

J. **What are the major deficiencies in the representation of chemistry and meteorology in research and operational models** and how can models be improved through the collection of additional measurements? What physical and chemical processes are not captured well by available models? Is there an optimum grid resolution to capture all of the relevant physical and chemical processes that occur?

K. **What are the important transport corridors for key chemical species** and under what conditions is that transport important?
L. **What is the relative roles of regional (North American) sources and long range transport (from East Asia) on aerosol forcing over California?**

It is expected that CalNex 2010 will be able to address each of the science questions listed above, although with differing degrees of emphasis. Prioritization of topics will occur during planning and execution of the study. The instruments that can be deployed on the various platforms and surface sites, and for how long they can be deployed, will be determined when there is clear understanding regarding the resources available for CalNex 2010. During the field study, the day-to-day deployment of the mobile platforms will determine the emphasis on particular questions.

Planning and Integration of Research Programs

The major research efforts proposed here are planned for 2010. This work will complement ongoing programs. The season and length of time of the major platform deployments in 2010 has not yet been determined. It may be possible to deploy one or both of the NOAA aircraft during two shorter deployments (3 to 4 weeks) in different seasons (for example, early spring and summer), or a single longer deployment (approximately 6 weeks). The NOAA ship will be available for only a single deployment, which has tentatively been scheduled for summer, but it may be possible to modify that schedule if the scientific objectives dictate.

Planning decisions for CalNex 2010 measurements will be informed by ongoing studies. These research efforts will yield important data sets, and will also serve to refine plans for CalNex 2010. A highly leveraged opportunity in 2008 is the presence of two comprehensively instrumented NASA aircraft, which will be temporarily located in California for deployment in the International Polar Year research. CARB has contracted with NASA to make limited flights over California and the eastern North Pacific during summer 2008. The NASA DC8 will characterize atmospheric composition through in situ measurements, and the NASA P3 will examine vertical profiles of radiative fluxes and in situ aerosol properties. This study will include 25 flight hours of each aircraft during a one-week period following the NASA International Polar Year deployment.

Most of the an-going CEC research program is focused in the winter and spring seasons and is designed to address the effect of aerosols on the hydrologic cycle and regional climate.
The CEC has contracted with the Scripps Institution of Oceanography to use unmanned aircraft to determine the concentration of black carbon aloft during different parts of the year, and will also conduct preliminary measurements to determine how black carbon and aerosols are affecting the atmospheric energy budget. Scripps will also continue to measure the amount of black carbon deposited to the snow pack in the Sierra Nevada to estimate its effect on snow albedo.

Planning for CalNex and the interpretation of the resulting data sets will benefit from collaboration with the NOAA Hydrometeorological Testbed (HMT) and Coastal Weather and Air Quality programs that have been collecting observations in California since 1997. Multiple years of surface observations, profiling radars, and satellite observations provide the opportunity to place the relatively short-term CalNex 2010 observations into the larger context of the climate-weather connection that links the background state determined by global climate to the particular local and regional weather phenomena that occur during the study. These ongoing studies use observations, reanalysis and forecast models focused on the year-to-year variability of seasonal events to better understand the temporal and spatial variability of California weather events.

Science Synthesis and Assessment: Providing Timely and Relevant Information for Policy Makers

Scientific research often proceeds at a measured pace with findings reported in due course in scholarly journals. However, the rapid pace of climate change and air quality policy development often requires a more demanding schedule. As a result, intensive field studies, such as the one planned in this document, have often been criticized for not providing results on a time scale to most effectively guide policy decisions. NOAA, ARB, and CEC have employed three mechanisms to meet this challenge: formulation of Fact Sheets and Synthesis Reports that provide the most relevant results of a field study, and the organization of informal presentations and conferences tailored to transfer scientific results to both scientific and lay audiences. These are executed on an accelerated schedule that meets the requirements of policy makers while still providing sufficient time for accurate scientific analysis of the data.

The International Consortium for Atmospheric Research on Transport and Transformation (ICARTT) study provides a successful example of fact sheets rapidly disseminating findings to policy makers. In the months following the field work, nine two page "Fact Sheets" were developed to present the most relevant study findings as rapidly as possible. Each Fact Sheet addresses a single issue and provides the essential background, findings and conclusions as clearly and concisely as possible – hence the two page format. All nine ICARTT Fact Sheets are available from the ICARTT web site (http://esrl.noaa.gov/csd/ICARTT/).

A different approach was used in the Second Texas Air Quality Study (TexAQS II). Early in the study planning process, a Rapid Science Synthesis team was formed, which developed a well-defined approach for obtaining the required experimental data or model calculations, evaluated this information as it became available during the execution of the study, formulated significant "Preliminary Findings" for each question immediately upon completion of the study, and produced a "Final Report" within ten months of the study conclusion. These reports can be found at http://esrl.noaa.gov/csd/2006/.

Fact Sheets, Synthesis Reports, and tailored presentations could play important roles in the CalNex 2010 Study. Such opportunities will become clear as the study progresses. It may well be that the climate research aspects will be more heavily represented in the Fact Sheets, since this research area has not been the focus of as much study in California as has air quality.

CalNex 2010 Research Platforms and Instrumentation

Figure 3: NOAA WP-3D Orion.

NOAA WP-3D Lockheed Orion

During intensive field campaigns, one of NOAA's four-engine Lockheed WP-3D Orions (Figure 3) is instrumented to provide a highly sophisticated airborne air chemistry and aerosol research platform. This aircraft makes in situ measurements of a wide suite of atmospheric species, most on a one-second time scale, which gives approximately 100m spatial resolution. The operating range of the WP-3D is ample to permit sampling of the primary pollution source regions, and to follow the transport and transformation of their emissions throughout California and surrounding regions. Figure 4 shows the range of the WP-3D operating out of the Los Angeles area with a range of 700 nautical miles, assuming a return to the base of operations. This operational range is based upon a maximum instrument load in the fuselage and in external pods under the wings.

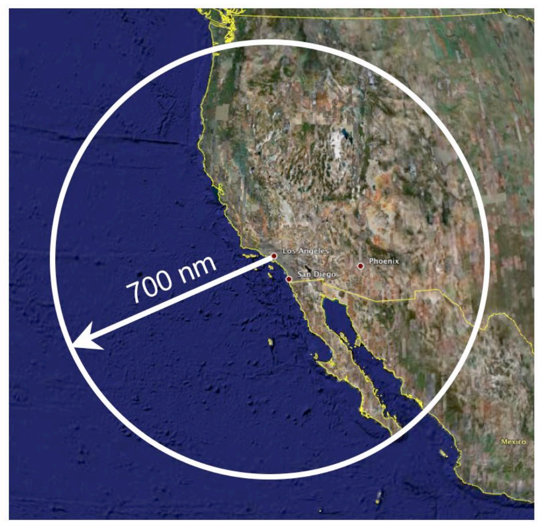


Figure 4. Operating range of the NOAA WP-3D Aircraft.

Species measured by the WP-3D can include:

- Primary pollutants: CO, NO, NO_2, SO_2, NMHC, CO_2, NH_3, PM, oxygenated VOC, black carbon, and targeted greenhouse gases.
- Secondary species: O_3, CH_2O, other aldehydes, PAN-type compounds, HNO_3, NO_3, N_2O_5, sulfuric acid, hydroxyl and peroxy radicals, aerosol size distribution and chemical composition.
- Other parameters: H_2O, aerosol extinction and absorption, cloud properties including cloud condensation nuclei, actinic flux and broadband radiation.

NOAA Twin Otter Remote Sensing Aircraft

A differential absorption lidar (DIAL) will be deployed on a NOAA Twin Otter aircraft for remote sensing of local and regional ozone and aerosol distributions. This instrument is designed to characterize the three-dimensional structure of pollution plumes within the boundary layer and to measure variability in mixing layer height (e.g. Figure 5). Airborne remote sensing enables tracking of plumes from urban areas and point sources, identification of isolated regions and layers of high ozone concentration, observations of atmospheric layering as characterized by aerosol and ozone structure, and investigation of local meteorological effects such as sea breezes, urban heat islands and orographic effects on pollution transport and mixing. The remote measurements will also provide information on the three-dimensional representativeness of in situ observations made by the WP-3D.

NOAA R/V Ronald H. Brown

An instrumented ship is an ideal platform to study the meteorological and chemical processes occurring within port areas (e.g. Long Beach, San Francisco Bay) and along the coast of California. The NOAA *R/V Ronald H. Brown* can be used to investigate air masses as they move offshore or onshore and study the chemical transformations in the polluted marine boundary layer. Indeed, deployment of this ship during ICARTT in 2004 and TexAQS in 2006 demonstrated the value of this platform for characterizing the marine boundary layer. Measurements from on-shore sites alone yield data that are frequently difficult to interpret due to contamination by local land-based sources, while aircraft measurements have only short duration within the marine boundary layer and result in limited data sets. The instrumentation available for the ship includes in situ measurements comparable to those on the WP-3D aircraft plus remote sensing instruments including O_3/aerosol lidar, radar wind profiler, Doppler lidar, C-band radar and radiosondes. In addition, NOAA will deploy light weight unmanned aircraft systems from the ship to conduct detailed vertical structure measurements of water vapor, temperature and aerosol and ozone concentrations in the offshore atmosphere.

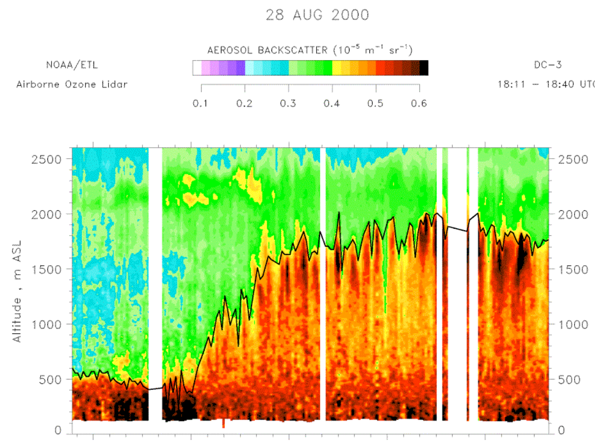


Figure 5: Vertical profile of lidar-observed aerosol backscatter showing a sharp change in mixing layer height at the Gulf of Mexico coast.

Ground-Based Measurements

<u>Upper-air observations</u> California experiences a heterogeneous and complex diurnal cycle of meteorology caused by its proximity to the Pacific Coast, large urban areas and a variety of heterogeneous land-surface types that produce local circulations, and varying synoptic regimes experienced during different seasons. A characterization of the meteorological processes controlling the stagnation and transport of atmospheric pollutants within, and into and out of California is therefore required in order to address the identified science questions. NOAA and partners in CalNex 2010 will enhance the upper-air observing system in selected regions of California by deploying a network of integrated boundary layer observing systems similar to that deployed in the 2000 CCOS study (Figure 6). These instruments provide continuous profiles of wind speed and wind direction in the boundary layer and lower free troposphere and derived mixing heights. Each profiler will also include a radio acoustic sounding system (RASS) for temperature profiling.

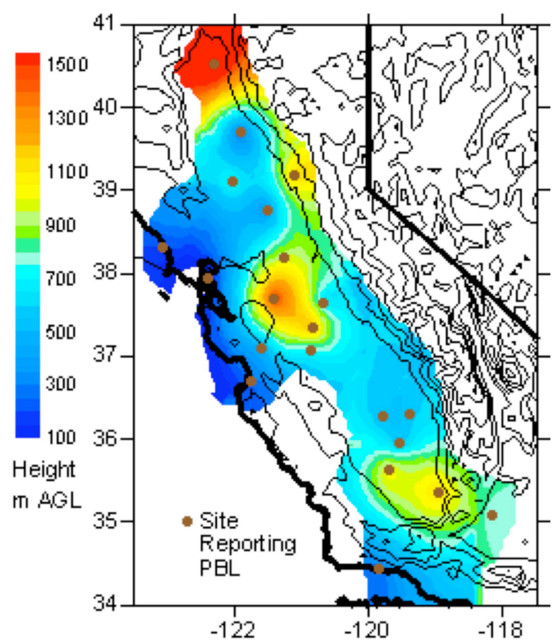


Figure 6. Profiler derived PBL depth field at 1500 PST on 31 July 2000. The dots indicate radar wind profilers deployed for CCOS .

Ground-based chemical measurements Surface "super-sites" have been found to be very useful for complementing and extending the measurements available from aircraft. These sites include both in situ and remote instrumentation comparable to the WP-3D and *Ronald H. Brown* instrument packages plus instrumentation that cannot be deployed on either platform. It will be highly desirable that CalNex 2010 deploy one or more such sites. Development of more definite ideas will be a goal of the ongoing planning process. Suggestions include a series of three sites at progressively further downwind distances from a particular urban area, or within the Central Valley.

Satellite Observations

Retrievals of aerosol and trace gas information from current research and operational satellites have great potential to assist in several of the CalNex 2010 science objectives. Instruments on NASA and NOAA satellites are currently able to observe several of EPA's criteria pollutants and to determine aerosol distribution and transport. Satellite measurements can also be used to infer the distribution of droplet sizes in clouds. While polar-orbiting satellites (e.g., MODIS) provide coverage once a day globally, geostationary satellites (e.g., GOES) provide coverage over the continental United States once every fifteen minutes. It will be very important to integrate the satellite instrumentation community into the CalNex planning process, as a multiple platform and sensor approach, integrating *in situ* and satellite data with modeling, will be essential to address CalNex science objectives.

References

CARB (2007), The California Almanac of Emissions & Air Quality - 2007 Edition, California Air Resources Board, Planning and Technical Support Division, Sacramento, CA.

EPA (2007), Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2005, EPA-430-R-07-002, U.S. Environmental Protection Agency, Washington D.C.

Jacobson, M. (2007), Effects of Anthropogenic Aerosol Particles and Their Precursor Gases On California and South Coast Climate. CEC-500-2005-003 California Energy Commission, Sacramento, CA.

Ramanathan, V., P. J. Crutzen, J. T. Kiehl and D. Rosenfeld (2001), Aerosols, Climate, and the Hydrological Cycle. Science, 294, 2119-2124.

Ramanathan, V., F. Li, M.V. Ramana, P.S. Praveen, D. Kim, C.E. Corrigan, H. Nguyen (2007), Atmospheric Brown Clouds: Hemispherical and regional variations in long range transport, absorption, and radiative forcing, *J. Geophys. Res.*, 112, D22S21, doi:10.1029/2006JD008124.