Research to Operations and Applications

ARL's Research and Development (R&D) supports the NOAA goal of a Weather-Ready Nation, most specifically the objectives of "Healthy people and communities due to improved air and water quality services" and "A more productive and efficient economy through environmental information relevant to key sectors of the U. S. economy." ARL's R&D also supports the long-term goal of Climate Adaptation and Mitigation through the objectives of "Improved scientific understanding of the changing climate system and its impacts" and "Assessments of current and future states of the climate system that identify potential impacts and inform science, service, and stewardship decisions." Additionally, ARL's work contributes to NOAA's Science and Technology Enterprise via the objectives "A holistic understanding of the Earth system through research", "Accurate and reliable data from sustained and integrated Earth observing systems", and "An integrated environmental modeling system." In performing R&D relevant to NOAA's goals and objectives, ARL complies with NOAA's Annual Guidance Memorandum to accelerate the transition of research advances to applications and operations. Recipients of ARL's R&D include public, private and academic entities that utilize the products, services and new knowledge to:

- Effectively anticipate and respond to atmospheric events or conditions that affect public health and safety, the environment, the economy or homeland security.
- Advance scientific understanding of Earth's atmospheric system and its interactions so that integrated environmental models can be improved to provide more accurate forecasts for weather, climate, air quality and environmental trends and impacts.
- Foster the development of resilient ecosystems, communities and economies.
- Promote education and outreach to improve public understanding of the intersection of society, the economy and the environment in general and human-atmosphere interactions in particular.

The following information documents several of the most important contributions from recent ARL programs.

Atmospheric Dispersion and Boundary Layer Science

Dispersion Modeling

1. Nuclear

1.1 Regional Specialized Meteorological Centers (RSMC)
Research Description: One of the earliest HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) emergency response applications was developed by ARL to support emergency response functions associated with accidental radionuclide releases. This was prompted by the Chernobyl accident where a lack of communication among European countries prompted the International Atomic Energy Agency (IAEA) to request the World Meteorological Organization (WMO) to establish a group of operational National Meteorological Services (NMS) that could provide dispersion forecast products. There are now eight Regional Specialized Meteorological Centers (RSMCs) providing operational support for dispersion model products hosted by various countries. NOAA's National Center for Environmental Prediction (NCEP) operates the RSMC in Washington, DC. HYSPLIT is also the primary RSMC dispersion model hosted by the Australian Bureau of Meteorology (BoM) and the China Meteorological Administration (CMA).

Although the model's performance for the Chernobyl accident was reasonable, a more recent application following the Fukushima accident showed that HYSPLIT was substantially over-predicting wet deposition following comparison with initial observed data. The main difference between the two incidents was that the Fukushima release was relatively near the ground compared with the Chernobyl release, where a continuing fire lofted material much higher into the atmosphere. Therefore, HYSPLIT wet deposition was

updated to better depict the Fukushima data, incorporating a scavenging coefficient directly defined as a first-order time constant.

Research to Applications/Operations: RSMC Washington, composed of the National Weather Service (NWS) NCEP and ARL, responded to an initial request for support for the Fukushima-Daiichi event in Japan from the International Atomic Energy Agency (IAEA) on 14 March 2011 and then responded to an additional 21 requests from the IAEA between 11 March and 15 April 2011. The operational environment was not prepared to deal with multiple changes to the source term as new information was received and therefore simulations from the beginning of the release were not rerun during the event. This led to the development of the Transfer Coefficient Matrix (TCM) concept that can easily be applied in an operational environment to quickly calculate pollutant concentrations when detailed real-time source information is not yet available, but that can also be updated by the end user of the products with multiple emission scenarios without having to rerun the model from the start of the release. This approach allows the user to capture the full impact of an event as new information becomes available, and as an event unfolds.

The updated wet deposition model calculation developed following the Fukushima accident, was implemented into NCEP operations in April 2016. The new algorithm impacts both radiological and HYSPLIT volcanic ash applications. Also included in the NCEP implementation, was the conversion of high-resolution North American Mesoscale model (NAM) forecast model output (4 km) to a format suitable for input to HYSPLIT, down from the 12 km resolution used previously. This allows NWS Weather Forecast Office (WFO) forecasters to run HYSPLIT with this dataset via the NOAA Web Operations Center (WOC) interface. Similarly, NCEP now has the option to run radiological or volcanic ash applications with this dataset. Another NCEP implementation included creation of a high-resolution Global Forecast System (GFS) model dataset that is now the default meteorology for the radiological and volcanic ash NCEP applications. Model output in this file is on the GFS native levels and has a higher horizontal resolution than the traditional pressure-level file. The TCM calculation is currently being prepared for operational implementation in 2017.

1.2 Comprehensive Test Ban Treaty Organization

Research Description: A relatively new HYSPLIT application is to make use of an above-background measurement value as a starting point for an adjoint (backward integration of the dispersion model) to identify potential source locations. This is the approach taken by the Comprehensive Test Ban Treaty Organization (CTBTO) to analyze their monitoring network data. HYSPLIT is one of the models available to the CTBTO, an organization committed to ensuring compliance with the test ban treaty.

Research to Applications/Operations: The Department of State and NOAA entered into a Memorandum of Agreement in 2012 concerning in-kind contributions to the CTBTO Preparatory Commission (PrepCom). Under this agreement NOAA/NCEP agreed to become an operational center for CTBTO backtracking capabilities by utilizing the HYSPLIT dispersion model. The NWS Office of Science and Technology (NWS/OST) has developed a concept of operations document that NCEP will follow when responding to a CTBTO request.

The system development is the result of dedicated efforts by ARL to provide HYSPLIT capabilities to produce backtracking results for multiple CTBTO monitoring sites. In order to provide required information to CTBTO, a Source Receptor Sensitivity (SRS) field matrix specific to each measured radionuclide sample and sampling site is determined. These SRS fields are computed by running HYSPLIT backwards in time but with pseudo releases corresponding to the measured radionuclide at the monitoring site. The resultant backward plume provides a grid of dilution factors that, along with the SRS fields, allows for a computation of an activity concentration (Bq/m^3) at any grid point. In addition, source location algorithms can be run to provide the most likely source location given the computed activity concentration and measurements. The HYSPLIT CTBTO system ultimately provides CTBTO with an SRS field text file that can be used for further computation of source strength and location. The HYSPLIT CTBTO system also provides the NCEP Senior Duty Meteorologist with likely dispersion plots that are used to verify a realistic simulation in comparison of the dispersion plume against analyzed winds in an area).

HYSPLIT dispersion for ATM backtracking response is primarily driven by the NCEP GFS Global Data Assimilation System (GDAS). Outputs are at 1-degree horizontal resolution and 6-hour time intervals back 30 days from the present. The RSMC-Washington CTBTO capability was demonstrated to the WMO Committee for Basic Systems (CBS) in 2014. The WMO/CBS and CTBTO representatives recommended implementation of the RSMC-Washington capability as it met all CTBTO requirements. The RSMC-Washington CTBTO capability was successfully implemented to NWS/ NCEP operations on September 30, 2014. One month of the most recent GDAS model output at one-degree resolution is available for the CTBTO application.

RSMC Washington participated in several CTBTO initiated requests to provide backtracking information for up to seven radionuclide monitors from April-September, 2014. The designation of RSMC Washington for the provision of atmospheric backtracking products was approved.

1.3 Nuclear Regulatory Commission

Research Description: A Memorandum of Understanding (MOU) was signed in 2015 between the U.S. Nuclear Regulatory Commission (NRC) and ARL with the purpose of allowing both parties to collaborate on research related to atmospheric transport and dispersion (ATD) of radiological contaminants. In particular, ARL will provide the NRC with its HYSPLIT dispersion model. The NRC will integrate HYSPLIT code into its MELCOR Accident Consequences Code System (MACCS) which is used by domestic and international organizations to assess potential consequences of severe nuclear reactor accidents involving the release of radioactive materials into the atmosphere. MACCS models atmospheric transport and deposition, emergency response actions, exposure pathways, health effects, and economic costs. Currently MACCS uses a traditional Gaussian plume segment model, and the NRC seeks to incorporate HYSPLIT as an alternative ATD model for use in MACCS. The NRC will provide feedback to ARL on HYSPLIT's radiological capabilities.

Research to Applications/Operations: HYSPLIT was incorporated into the MACCS code by Sandia National Laboratory and is currently undergoing evaluation. ARL also hosted a 1-day workshop and ARL seminar with the developers of MACCS code to get an update on the progress and to plan next steps.

1.4 Department of Energy Facilities

Research Description: Both the ARL Field Research Division in Idaho Falls and the ARL Special Operations and Research Division in Las Vegas have decades-long relationships with the U.S. Department of Energy (DOE) and its predecessors. These partnerships have included the development of dispersion models adapted for modeling radiological emissions from either accidents or routine emissions. In fact, the Idaho Falls division developed one of the first computer puff dispersion models, called MESODIF, back in the 1970s. Starting in the 2000s, ARL staff in Idaho Falls began development of a new radiological dispersion system based on HYSPLIT. This system has come to be known as HYRad.

Research to Applications/Operations: HYRad was designed using a client-server approach such that users log in via a browser, and the model computations take place on a server. The client interface has a map background that can be easily panned and zoomed. To shorten the time required to generate plume estimates, the system has a menu of preconfigured release scenarios developed in consultation with the DOE Idaho National Laboratory (INL). Currently, HYRad can use either meteorological tower observations or forecasts from the WRF model for input. The HYRad system is now the main plume modeling tool for operations at the INL, including applications in the INL Emergency Operations Center. This system has been accepted by the DOE-sponsored Subcommittee on Consequence Assessment and Protective Actions as part of its modeling toolbox for DOE applications. Moreover, other DOE laboratories, such as the Pacific Northwest National Laboratory, have expressed interest in adapting HYRad to their facilities.

2. Chemical

Research Description: Interest in shorter-range HYSPLIT applications increased after 9/11 with a request by the NWS for routine HYSPLIT forecasts at a number of fixed locations. At the same time an on-

demand capability was established through the 24/7 desk of the Senior Duty Meteorologist (SDM) at NCEP. Initially, a response was initiated by a telephone call to the SDM, followed by manual data entry, and the posting of results to a secure web page. This approach proved to be cumbersome and a dedicated system for Weather Forecast Office access was developed, hosted at NOAA's 24/7 web portal. A unique feature of this interface is that it links the Computer-Aided Management of Emergency Operations (CAMEO) chemicals database with HYSPLIT, permitting the WFO to select a realistic emission scenario and create output graphics linked with human exposure guidelines. A newer version exists that was developed in collaboration with the National Ocean Service's Office of Response and Restoration to include the source modeling features of their Areal Locations of Hazardous Atmospheres (ALOHA) model as part of the HYSPLIT chemical modeling package.

Research to Applications/Operations: ARL and the Office of Response and Restoration (OR&R), successfully installed a new HYSPLIT web-based modeling system in September 2013 at the NOAA Web Operations Center (WOC). This system provides NOAA NWS forecasters with the ability to first simulate a release of a hazardous chemical to the atmosphere, using the extensive scenario-based source term configuration of the ALOHA model developed by OR&R and the
U.S. Environmental Protection Agency (EPA). The resulting plume was then simulated using the HYSPLIT model. Based on user input, the ALOHA model creates a time-varying release rate that is used by HYSPLIT for transport and dispersion calculations. The HYSPLIT system also has menu-driven capabilities to simulate the release of other hazardous pollutants to the atmosphere, such as smoke and radiological contaminants. A series of webinars were conducted by ARL and OR&R to familiarize NWS forecasters with the new system and its required and optional inputs.

3. Volcanic Ash

Research Description: ARL's involvement with modeling ash and other debris from a volcanic eruption dates back to Mt. St. Helens, when trajectory forecasts were provided using the Limited Fine Mesh (LFM) model. The concerns with forecasting ash movement became more serious after the KML aircraft encounter with the Mt. Redoubt plume in 1989 and the arrangements became more formal. HYSPLIT is the current plume model for the Washington Volcanic Ash Advisory Center (VAAC), the Air Force Weather Agency (AFWA), as well as for the VAACs in Australia and Argentina. Although volcanic ash modeling easily lends itself to Lagrangian approaches due to the point-source nature of the problem, there is considerable uncertainty in the source term mass, particle sizes, and plume heights. These can affect the transport direction and limit the development of a more quantitative prediction, a potential new requirement as a result of the large-scale shutdown of air traffic as a result of the Eyjafjallajokull eruption in spring 2010. ARL collaborates with NOAA's National Environmental Satellite Data Information Service (NESDIS) to incorporate better satellite based eruption and ash cloud distribution data for model initialization.

Research to Applications/Operations: A year before the Fukushima nuclear power plant incident, there was a long-lasting, time-varying eruption of the volcano Eyjafjallajokull in Iceland. A simple method to account for the time-varying eruption height was tested and implemented at NCEP a year later (2011). A first-order method for horizontal initialization of airborne ash from ash observations was also included in this implementation. Finally, a general upgrade at NCEP was to implement the multi-processor version of the HYSPLIT dispersion code that lessened the run-times for all the NCEP HYSPLIT applications, including for volcanic ash dispersion.

4. Smoke

Research Description: The NOAA Smoke Forecasting System integrates the NOAA NESDIS satellite information on the location of wildfires with NWS weather inputs from the NAM model and smoke dispersion simulations from the HYSPLIT model to produce a daily 48-hour prediction of smoke transport and concentration. The model also incorporates U.S. Forest Service estimates for wildfire smoke emissions based on vegetation cover. This system is intended as guidance to air quality forecasters and the public for primary fine particulate matter emitted from large wildfires and agricultural burning which can elevate particulate concentrations to unhealthful levels.

Research to Applications/Operations: The operational HYSPLIT model run at NCEP as part of the Air Quality Forecast Guidance (http://airquality.weather.gov) was improved by changing the legacy horizontal-puff vertical-particle configuration for smoke dispersion forecasting to a 3-d particle configuration due to increased computer capabilities. HYSPLIT was changed to use pre-computed random numbers for the turbulent dispersion, which affected all HYSPLIT applications at NCEP and improved run-times.

5. Dust

Research Description: ARL developed a dust emissions algorithm based on a 5-year climatology from MODIS Deep Blue satellite observations. These emissions, in conjunction with the meteorological fields generated by the NAM model, are used by the HYSPLIT model to estimate the transport, dispersion and deposition of dust over the continental US.

Research to Applications/Operations: This approach to estimate dust emissions was implemented at NCEP in 2011 as part of the Air Quality Forecast Guidance (http://airquality.weather.gov). As part of a Memorandum of Agreement between ARL and the University of Huelva, Spain, HYSPLIT has been applied to calculate the spatial and temporal distribution of dust originating from North Africa. The model has been configured to forecast hourly PM10 dust concentrations focusing on the impact over the Southern Iberian Peninsula. For this application emissions are calculated through an empirically derived algorithm based on satellite observations. In contrast to previous dust simulations using HYSPLIT, for this particular application of the model, the Global Eulerian Model (GEM) is invoked as a series of subroutines within the main HYSPLIT transport and dispersion code. Particles or puffs are always first released in the Lagrangian framework and carried within HYSPLIT until they exceed a certain age, at which point their mass is transferred to the GEM routines.

6. Real-time Environmental Applications and Display sYstem (READY)

Research Description: Public access to meteorological data and HYSPLIT trajectory and dispersion simulations is granted through the Real-time Environmental Applications and Display sYstem (READY), a web-based system developed and maintained by ARL (http://ready.arl.noaa.gov/). READY brings together the trajectory and dispersion model, graphical display programs, and textual forecast programs generated over many years at ARL into an easy-to-use form. Since its initial development in 1997, thousands of users) have generated products from READY for their day-to-day needs and research projects. Approximately 80,000 HYSPLIT simulations per month are computed on ARL servers via the READY system.

Research to Applications/Operations: Some of the new products incorporated into the READY system over the past five years include:

- Development of a TCM web site for the WMO's model simulations of the radionuclide dispersion and deposition from the Fukushima Daiichi nuclear power plant accident for the local scale (http://ready.arl.noaa.gov/READY_fdnppwmo.php) and long-distance transport (http://ready.arl.noaa.gov/READY_fdnpp.php).
- Enhancement of HYSPLIT verification using the Data Archive of Tracer Experiments and Meteorology tracer archive.
- Replacement of the Rapid Update Cycle (RUC) with the Rapid Refresh (RAP) model out to +18 hrs.
- Creation a HYSPLIT Forum to allow better communications between users of HYSPLIT and model developers.
- Addition of a 2 km Hawaii NAM NEST grid and a 12 km Alaska NAM grid to READY.
- Addition of the 0.5 degree GFS forecast data and the 32 km North American Regional Reanalysis (NARR) data from 1979 to the present.
- Extension of the 1 degree GFS data from 192 to 240 hrs.
- Addition of the High Resolution Rapid Refresh (HRRR) meteorological forecast data to READY applications.

Dispersion Measurements

1. Upgrade of ARL Mesonets

Research Description: Mesonets are automated networks for the collection of meteorological data across mesoscale areas. ARL Field Offices have operated and maintained meteorological mesonets at several locations for decades. Updates and upgrades are required from time to time in order to replace aging equipment and infrastructure. The 22-station network in southern Nevada was completely replaced in 2015. Improvements included replacing 2D sonic anemometers with 3D sonic anemometers that include a direct measurement of turbulence and the ability to sample at a higher rate. A temperature level (near tower top) was added. A total solar radiation sensor was installed to be used with the dual temperatures for an improved atmospheric stability determination. In addition, each site has a tipping bucket rain gauge, pressure sensor, relative humidity sensors (coupled with the temperature sensors), a lower temperature sensor, and a GPS antenna. Following this upgrade, all 22 stations have the same configuration.

Research to Applications/Operations: The mesonet upgrade in southern Nevada was completed in December 2015 and became operational in February 2016. The improvements provide better atmospheric stability classification for dispersion modeling, improved data for local forecasting and weather surveillance for the safety of people and the protection of property, and are available for use in NOAA forecast models.

2. Roadway Emissions

Research Description: The EPA has been developing improved dispersion models to estimate population exposure to pollutant emissions from roadways. One factor that has become relevant to such modeling is the widespread use of sound barriers along major freeways. These barriers are installed to limit noise, but they also affect pollutant concentrations both on the roadways themselves as well as on the other side of the barriers. In 2008, ARL conducted a tracer study to evaluate the effects of sound barriers on roadway dispersion. A mock sound barrier was constructed using straw bales, and concentration measurements were collected both on the side of the barrier with the tracer source (the mock roadway) and the opposite side (representing nearby exposed populations). The concentrations were compared with those from a nearby identical tracer source that lacked a sound barrier.

Research to Applications/Operations: The results from the straw-bale study were used by the EPA in developing a new roadway dispersion model called R-LINE. This model has a plume growth parameterization based on the ARL tracer study. R-LINE is a desktop application, but the EPA has also developed a web-based version called C-LINE. Both R-LINE and C-LINE are relatively new, so they have not yet completed the review procedures required before they can officially be used in regulatory applications.

Boundary Layer

1. Unmanned Aircraft Systems (UAS)

Research Description: ARL worked with the NOAA Unmanned Aircraft Systems (UAS) Program and the Office of Marine and Aviation Operations' (OMAO) Aircraft Operations Center (AOC) to develop the capability to fly a small UAS (sUAS) for boundary layer research. This is the first time NOAA has received Federal Aviation Administration (FAA) certification to fly a sUAS with a weather observing payload inside the continental U.S. The payload of the sUAS, approximately ten pounds up to an altitude of 250 meters above ground level, includes a small downward-looking infrared camera, a visible camera, and a radiosonde package to measure air temperature and relative humidity. This is an emerging technology that provides NOAA with an inexpensive observing platform to obtain critical missing data between land-based measurements and satellite remote sensing measurements. By using the sUAS, observations can be obtained both vertically and horizontally to acquire an accurate picture of the scale and extent of the temperature and moisture fields.

Research to Applications/Operations: ARL has flown the sUAS during several NOAA field studies. As part of the NOAA Convective Initiation Study funded by the Disaster Relief Appropriations Act of 2013, the sUAS collected boundary layer measurements to better understand thunderstorm genesis mechanisms (convective initiation) in the southeastern United States. In 2016, the sUAS is being used in the NOAA Verification of the Origins of Rotation in Tornadoes EXperiment-Southeast (VORTEX-Southeast) field campaign in Alabama to help understand the formation, intensity, structure and path characteristics of tornadoes. The sUAS was also used to determine storm damage assessment for an EF2 tornado near Huntsville, AL, in 2016 for the Huntsville WFO.

2. Cooperative Research and Development Agreement with Duke Energy Generation

Research Description: As an outcome of discussions between Duke Energy Generation (Duke Energy) and ARL following the American Meteorological Society (AMS) Summer Community Meeting, August 2009 in Norman, Oklahoma, NOAA and Duke Energy signed a Cooperative Research and Development Agreement (CRADA) to conduct atmospheric boundary layer research using Duke's renewable energy facilities as research testbeds. A meteorological research facility was established at Duke Energy's Ocotillo Wind Farm located south of Big Spring, Texas, within the West Texas Permian Basin. Coupled with Duke Energy's Ocotillo operational hub-height weather measurements, ARL acquired surface energy-balance observations and multiple levels of mean and turbulent winds and temperature. The joint NOAA/Duke Energy research program, as outlined in the CRADA, has taken two complementary tracks: (1) an evaluation of the predictive skill of current mesoscale numerical weather prediction models for surface and hub-height (80m) mean wind speeds and (2) an evaluation of physical parameterizations of the atmosphere used to model surface layer atmospheric components. The NOAA HRRR model and the NOAA NCEP 4km and 12km North American Mesoscale models (NAM4 and NAM12 which are current state-of-the-science numerical weather prediction models) were selected for evaluation against the Ocotillo research database.

Research to Applications/Operations: The focus of the ongoing Ocotillo Research has been the acquisition of a long-term, high-quality record of both mean and turbulent winds and temperatures at multiple vertical levels for a measurement site that does not significantly void the assumptions of horizontal homogeneity and stationarity. These data have been used to establish the predictive skill for HRRR and NAM predictions of mean wind speed at 10m and 80m (hub height). The NAM models' prediction of 10m and 80m mean wind speed as well as turbulence fluctuation in winds and temperatures were used to develop model skill scores for observed mean and fluxes of heat and momentum within the atmospheric surface layer for the Ocotillo Research station. ARL has maintained a quarterly technical interchange meeting with Duke Energy to discuss ongoing measurement activities. A recent Duke Energy white paper generated under the NOAA/Duke Energy CRADA associates a 15% reduction in model uncertainty with an annual cost benefit of nearly $50k per turbine. ARL has developed a probabilistic site-specific adjustment to the NAM12 forecast to address potential reduction in model uncertainty. Analyses of the Ocotillo database have been presented to other researchers in NOAA. Following additional analysis, Duke Energy plans to utilize these results to maximize efficiency in day-to-day operations and optimize energy grid balance.

3. DCNet

Research Description: DCNet is an ARL research dispersion and meteorological monitoring network designed as a prototype urban testbed. The urban monitoring system was proposed in 2003 in response to a data call from NOAA concerning meteorological aspects of the events of September 11th. The questions asked were simply "how many?" and "where to install?" urban meteorological monitoring stations, in order to provide first responders with accurate, timely, and appropriate transport and dispersion information. The first DCNet stations (Herbert Hoover DOC Building, National Academy of Sciences, NOAA SSMC#3, and Navy Annex) were installed in the fall of 2003. The DCNet system established the core urban observation system supporting NOAA's UrbaNet program goal establishing the utility of incorporating other public and private meteorological monitoring networks to support atmospheric transport and dispersion assessments and forecasts.

Research to Applications/Operations: At its peak, there were 17 DCNet meteorological observation sites operating within the National Capital Region (NCR). As part of the urban testbed program, ARL operated two DCNet style stations in New York City (Times Square and Manhattan) for five years before transferring the New York stations to the Department of Homeland Security. Observations from the DCNet system have been used to establish the efficacy of acquiring meteorological observations from private networks to support atmospheric transport and dispersion forecasting. The DCNet system has been declared a national security asset by the Pentagon Force Protection Agency and Homeland Security. Currently, the DCNet monitoring system has been reduced to seven stations operating within the central metro DC area, with scheduled termination on June 1, 2016. The next year (2016-2017) should provide for the transition of the remaining DCNet stations to an operational user in the District of Columbia.

Atmospheric Chemistry and Deposition

Air Quality Forecasting

1. Adaptation of NAQFC to Non-hydrostatic Multiscale Model on the B-grid (NMMB) Meteorological Fields

Research Description: The NWS requested that the NOAA National Air Quality Forecasting Capability (NAQFC) be transitioned to NMMB, the upgraded operational regional meteorological model, in 2011 to maintain operational products of the NAQFC. The largest programmatic difference in NMMB compared to its predecessor was the use of Arakawa B-grid staggering instead of the E-grid staggering used by the NMM. Other differences in the two meteorological models included small improvements, mainly in temperature and moisture fields. Coding modifications in NAQFC to accommodate the change in grids was modest, but extensive testing was performed to ensure there was no degradation in NAQFC forecast performance.

Research to Applications/Operations: A particular focus of this research was to quantify the impact of NMMB on the forecast performance of NAQFC during the ozone season. Retrospective simulations using the upgraded NAQFC system were performed for a recent hot summer across multiple weeks to confirm that there was no performance degradation as compared to the previous operational system. Results indicated that the grid change and small improvements in temperature and moisture fields led to modest improvement in forecast performance. The NAQFC upgrade was accepted and implemented by NCEP in October 2011.

2. NAQFC 2012 Emission Projection and Updates

Research Description: Over the past five years, ARL has developed, tested, and transitioned several state-of-the-art emissions forecasting systems to the NWS NCEP. These systemsprovide real-time emissions data to drive NAQFC air quality forecast operations, including the systems to support ozone forecasts over the continental U.S. (CONUS), Hawaii and Alaska, and the recent system to support both O_3 and $PM_{2.5}$ over CONUS. Air quality forecasting systems, such as the NAQFC, are only as good as the emissions inputs. In particular, it is often challenging to provide accurate estimates of NO_x emissions for time-sensitive applications such as NAQFC, given the rapid implementation of emissions controls and other socioeconomic events that affect emissions loading. NAQFC relies on the National Emissions Inventory (NEI) to account for thousands of anthropogenic emission sources and other emission models for natural sources. The substantial costs and effort entailed in collecting data relevant for compiling the NEI are prohibitive for frequent and timely updates of NO_x emissions using conventional emissions modeling approaches. As a result, the emissions data used in the NAQFC were several years behind the forecasting year, imposing uncertainties on air quality forecasting. Major updates were performed in 2012 for the US and Canadian sources. The US off-road emissions in the 2005 NEI were replaced with the projected emissions data (version 2012cs) prepared for the Cross-State Air Pollution Rule (CSAPR) (US EPA, 2011). These data are produced by the National Mobile Inventory Model (NMIM) which utilizes the NR05d-Bond-final version of the NONROAD model to project emissions for 2012 based on future-year population estimates and control programs. US mobile source emissions from the 2005 NEI were then

scaled down by using the CSAPR 2005–2012 emission projection factors. The CSAPR projection for mobile sources was derived from the MOtor Vehicle Emission Simulator (MOVES) version 2010 run for NMIM 2012 estimates. Aggregated state-level data from the CSAPR run were used in the subsequent emission projection. The projected 2012 scenario represents the best estimate for future years without the implementation of additional controls on Electricity Generation Units.

Research to Applications/Operations: ARL recommended the new emissions updates to NCEP, who conducted their own evaluation and promoted the updated emissions system into operation on May 1, 2012. The 2012 emissions projections considerably reduced the high bias of summertime ozone forecasts. The system continued to be used in the operational forecasts until May 1, 2016, when an improved emissions data assimilation system (see Item 4 below) was implemented to replace the 2012 system.

3. Upgrade of Base Emissions Inventory from NEI 2005 to NEI 2011

Research Description: ARL has developed a comprehensive emissions modeling system that leverages data collected by U.S. EPA, DOE, NOAA, NASA and other federal agencies to provide updated emissions estimations. The ARL systems are specially tailored to support the NAQFC with a number of unique features, including well-studied emissions inventories, weather-aware adjustment, and emissions data assimilation with fused ground and satellite observations. The time lag inherent in emissions inventory updates is a bottleneck for NOAA to improve the accuracy of O_3 and $PM_{2.5}$ forecasts. Outdated national emissions inventories result in systematic biases in NAQFC forecast performance. Therefore, a primary task for ARL is providing the most up-to-date emissions possible for the forecasting system. In 2015, ARL worked to replace the NEI 2005 base emissions inventory with the updated NEI 2011 inventory from the U.S. EPA.

Research to Applications/Operations: For FY2016 operations, the emissions inventories for all operational NAQFC systems are based on EPA NEI 2011 with observation-based adjustments for 2016. Future forecast years will continue to use NEI 2011 as the base inventory with appropriate adjustments derived from data gathered from U.S. EPA, DOE, NOAA and NASA.

4. Update of Mobile NO_x Emissions in NAQFC

Research Description: Nitrogen oxide (NO_x = $NO+NO_2$) emissions have been declining significantly for many years. Recent EPA mobile source national emissions inventories overestimated NO_x emissions, and as time advanced the base inventory years (2005 and 2011) were increasingly out of date. For the NAQFC, such systematic overestimations and time lags were problematic, resulting in less than optimal ozone forecasts. ARL initiated research to develop an emissions data assimilation capability to rapidly refresh NO_x emission data using fused ground and satellite observations. Ground NO_x measurements were obtained from the EPA Air Quality System (AQS) monitoring network. Satellite NO_2 column data were obtained from the Ozone Monitoring Instrument (OMI) aboard the NASA Aura satellite. A weighting function was derived to combine the AQS-based and OMI-based rates of change to obtain merged state-level emissions adjustment factors. These factors are then used to adjust emissions inventories to drive NAQFC operations.

Research to Applications/Operations: The rapid refresh NO_x adjustment procedure was implemented in all NAQFC operational systems in May 2016 and resulted in immediate and sustained improvement in ozone forecast performance.

5. Suppression of Fugitive Dust Emissions by Snow/Ice

Research Description: ARL has been working towards a weather-aware emissions modeling capability. Research performed to better understand the speciated biases of $PM_{2.5}$ forecasts led to the realization that the climatologically-based fugitive dust emissions (dust aerosols emitted from paved and unpaved road, agricultural operations, mining/quarrying, and other miscellaneous sources) were continuing during the winter even when snow or ice covered the ground surface. Thus, a significant portion of the observed wintertime high bias of $PM_{2.5}$ forecasts was attributed to excess emissions of fugitive dust. Research to examine suppression of fugitive dust emissions for grid cells covered by snow or ice was conducted and

proved to be effective in reducing wintertime high bias in $PM_{2.5}$ forecasting. An emission adjustment module was designed for the developmental $PM_{2.5}$ forecasting system to suppress fugitive dust emissions, if a model grid was covered by ice or snow as predicted by the NMMB snow cover fraction.

Research to Applications/Operations:
An NAQFC fugitive dust emission module was tested for January 2014 and January 2015 whereby dust emissions were suppressed when NMMB predicted snow and ice cover. Regional improvement occurred, which reduced over-estimation of surface $PM_{2.5}$ mass concentration by as much as 50%. The scheme became part of the 2015 implementation bundle to NCEP for the NAQFC $PM_{2.5}$ forecast.

6. NAQFC Ported to Upgraded NCEP Computational Platform
Research Description: The NWS requested in May 2013 that the NAQFC system be ported from NCEP's IBM-AIX system "Stratus" to a new Gnu/Linux based supercomputer system called "Tide" by September 2013. Results from simulations from both systems were required to be identical.

Research to Applications/Operations: The engineering task was accomplished on time. The NAQFC forecasts were transitioned to NCEP's "Tide" computing system in September 2013.

7. Limited Public Distribution of $PM_{2.5}$ Forecasts as Developmental Product
Research Description: In addition to the NAQFC operational suite, ARL created a developmental version of the air quality forecasting system that forecasts both ozone and $PM_{2.5}$, rather than only ozone as in the operational NAQFC. The developmental system had been running daily pseudo-operationally since 2009. However, the developmental system generated greater ozone from its gas phase chemistry mechanism and exacerbated the already high ozone biases of the operational system. ARL studied the difference between the gas mechanisms of the two systems and adopted a heuristic approach to increase the photolysis frequency for the Organic Nitrate (NTR) species by a factor of ten due to a rough estimate based on NASA's DISCOVER-AQ campaign measurements. This approach reduced ozone biases of the developmental system, making it eligible for operational implementation.

Research to Applications/Operations: From 2009 through 2014, the developmental $PM_{2.5}$ forecast was released to a select group of local air quality forecasters around the country. Over this time, ARL studied the performance of the developmental system and responded to feedback from the focus group. The resulting changes eventually resulted in the transition described below in item 8.

8. Transition of $PM_{2.5}$ Forecasts to Operational Product
Research Description: The developmental $PM_{2.5}$ forecasting system lacked dynamic lateral boundary conditions (LBC) to account for dust and wildfire-smoke plumes from outside the forecast domain. To address this problem, ARL included the NCEP global aerosol component (NGAC) to provide LBC for NAQFC. The number of vertical layers in the model was increased by 50% adding extra resolution in the planetary boundary layer and near the tropopause to better capture fine features between the global NGAC and regional NAQFC systems. The seasonal biases in $PM_{2.5}$ forecasts with over-prediction in winter and under-prediction in summer have been reduced steadily between 2009 and 2014 due to upgrades of physical processes in NMMB, reduction in NO_x emissions, and modulation of fugitive dust emissions from snow/ice covered grid cells.

Research to Applications/Operations: NGAC generated multiple season inputs for the NAQFC, especially for summer wildfires in Canada and for late summer/early fall dust events from the Sahara Desert. The NGAC dust component was approved for operations in September 2015. NAQFC produced improved results by reducing summertime low-biases in the $PM_{2.5}$ forecast for the Southeastern U.S. when NGAC-captured dust intrusions were reflected in elevated concentrations in crustal elements in NAQFC's LBC. As a result of these and other improvements noted above, in January 2015 the developmental $PM_{2.5}$ product was transitioned to NCEP as the operational ozone and $PM_{2.5}$ NAQFC system.

Deposition

1. Atmospheric Fate and Transport Modeling of Globally Emitted Mercury
Research Description: A special version of the HYSPLIT model (*HYSPLIT-Hg*) with added capability to simulate atmospheric mercury has been under continuous research, development, and application at ARL since 1999. Numerous pre- and post-processing programs have also been developed for use with the HYSPLIT-Hg model. A primary focus of this work has been to develop and enhance the ability to estimate quantitative source-attribution information for sensitive ecosystems like the Great Lakes, i.e., the relative contributions of different source *types* and source *regions* to atmospheric mercury deposition to a given ecosystems. HYSPLIT-Hg contains mercury-specific algorithms to simulate phase partitioning, chemical equilibrium and transformation, and wet/dry deposition phenomena. The model can be run in Lagrangian mode ("plume"), Eulerian mode ("gridded"), or an integrated combination of the two approaches in which emitted mercury is first considered in a plume and then transferred to a global grid for simulation of more distant fate/transport. Modeling results are evaluated by comparison against ambient measurements. While the HYSPLIT-Hg modeling results have long been encouragingly consistent with measurements, recent results, reflecting the cumulative impact of model improvements, have demonstrated the closest and most detailed match yet between modeled and observed concentrations and deposition.

Research to Applications/Operations: The evolving HYSPLIT-Hg modeling system has been and continues to be used in several applications, including the following, during the 2011-2015 period covered by this review:

- The modeling system has been applied to estimate the source-attribution for atmospheric mercury deposition to the Great Lakes under the auspices of the Great Lake Restoration Initiative (GLRI). Annual assessment projects have been funded through GLRI during each year for FY2010-FY2015. Final Reports for these assessments covering FY10-FY13 are available at http://www.arl.noaa.gov/documents/reports/. Work is ongoing on assessments commissioned with FY14 and FY15 GLRI funds.

- The modeling system is being used to support the State of Maryland's mandated Total Maximum Daily Load (TMDL) analysis for mercury for several water bodies in the State that have excessive mercury contamination. This TMDL work is ongoing with active collaboration with State environmental scientific and management personnel.

- The modeling system is being used to support an assessment requested by the International Joint Commission (IJC) regarding the potential impacts of energy generation technology on mercury deposition in the Great Lakes Basin.

- The modeling system is being used to improve understanding of observations made at ARL's atmospheric mercury measurement sites as well as other measurement sites. A manuscript describing this work is in review at the journal *Elementa*.

Monitoring of Atmospheric Mercury

1. Improvements to Standard Operating Protocols in the Atmospheric Mercury Network (AMNet)
Research Description: ARL was a key contributor to the design and adoption of standard operating protocols (SOPs) implemented at the inception of the AMNet monitoring network. AMNet was established in 2009 for the purpose of measuring atmospheric mercury fractions that contribute to dry and total mercury deposition. There are currently over 20 active AMNet sites in the U.S., and three of these are flagship sites operated by ARL. Recent research at ARL's Mauna Loa Observatory site has confirmed previous findings of artifacts and inadequacies in current measurement methods for gaseous oxidized mercury; has identified previously unknown artifacts and biases in the measurement of particulate-bound mercury; and has documented the effects of improving measurement accuracy by altering current

network SOPs. ARL partnered with the NADP to host an international mercury measurement workshop September 22-24, 2015 at the NOAA Center for Weather and Climate Prediction in College Park, MD. The overall goal of the workshop was to exchange information and results of recent research characterizing measurement biases and artifacts in the monitoring methodology in AMNet. Approximately twenty-five mercury measurement specialists from the private sector, state agencies, universities, and foreign national program offices participated in the workshop.

Research to Applications/Operations: ARL produced a summary of workshop proceedings along with a concrete set of recommendations to NADP regarding the possible modification of the measurement and data reduction SOPs employed in AMNet. This proof-of-concept effort, if adopted, is designed to improve the accuracy and robustness of atmospheric mercury measurements currently deployed in national and global monitoring networks.

2. Calibration Tools for Mercury Measurement

Research Description: ARL has also developed improved calibration hardware to better assess the overall accuracy of mercury measurement and detect fictive mercury loss and artifacts within the sampling systems deployed in AMNet.

Research to Applications/Operations: ARL is pursuing a Cooperative Research and Development Agreement (CRADA) with the Tekran® Corporation for the possible distribution of this calibration tool to the global mercury research community.

3. Back-Trajectory Analysis to Support Interpretation of Atmospheric Mercury Measurements

Research Description: The HYSPLIT model is being used to estimate back-trajectories of air masses arriving at mercury measurement sites in order to assess source-receptor relationships. For example, the geographical distribution of back-trajectories of air masses associated with high mercury concentrations are compared with the distribution associated with low concentrations. Trajectory paths for any given group of air masses are summarized and compared by analysis of HYSPLIT trajectory end-point results in a range of post-processing routines and applications (e.g., ArcMap). A powerful set of scripts has been developed that can be customized for a wide range of situations that enable the user to efficiently carry out extensive analyses. The approaches developed have also been applied to other air pollutants.

Research to Applications/Operations: The suite of back-trajectory analysis scripts, programs and tools has been applied in numerous situations, including the following:

- The back-trajectory modeling system was used to analyze nine years of hourly mercury measurements at ARL's Beltsville and Grand Bay long-term measurement sites. More than 80,000 back-trajectories were computed and analyzed in this application, and the results have been submitted to Atmospheric Environment.

- The back-trajectory modeling system was used to analyze air masses associated with different mercury isotopic concentrations measured near the Gulf of Mexico (Rolison, J.M., et al. (2013), Isotopic Composition of Species-Specific Atmospheric Hg in a Coastal Environment. *Chemical Geology* 336, 37-49).

- The back-trajectory modeling system was transferred and taught to scientists outside of NOAA in numerous instances. Examples include customized, detailed, hands-on seminars for:
    - Scientists attending the 2015 International Conference on Mercury as a Global Pollutant in South Korea;
    - Scientists at numerous universities (e.g, University of Maryland, Clarkson University, Rutgers University, Florida State University, Texas Christian University, Baja University (Mexico), others);

- Scientists at numerous agencies and institutions (e.g., US EPA, USGS, Clark County (NV), Red Cliff Band of Lake Superior Chippewa, Desert Research Institute, others).

Climate

1. Global Climate Observing System (GCOS) Reference Upper-Air Network (GRUAN)

Research Description: The Global Climate Observing System (GCOS) Reference Upper-Air Network (GRUAN) is an international reference-observing network, designed to fill an important gap in the current global observing system. GRUAN measurements provide long-term, high-quality climate data records from the surface, through the troposphere, and into the stratosphere. The goal of GRUAN is to develop climate quality reference upper-air observations to examine stratospheric and tropospheric temperature trends over a 50-year period. ARL provided oversight and guidance for the GRUAN manual and GRUAN guide to operations and public availability for the first data product.

Research to Applications/Operations: The GRUAN Manual describes mandatory operating protocols which describe what is expected of network sites, the GRUAN Lead Centre, and the Working Group on GRUAN to achieve the goals of GRUAN. The manual may be found at: https://www.wmo.int/pages/prog/gcos/Publications/gcos-170.pdf.

The GRUAN Guide provides both mandatory operating requirements and guidelines on how to achieve the operating protocols specified in the GRUAN manual. The Guide may be found at: https://www.wmo.int/pages/prog/gcos/Publications/gcos-171.pdf.

GRUAN data are available via a public website: http://www.dwd.de/EN/research/international_programme/gruan/data.html.