UV-B Monitoring and Research Program

Measuring Ultraviolet Radiation and Studying its Effects on Agriculture, Human Health, and Climate

NATURAL RESOURCES
ECOLOGY LABORATORY
COLORADO STATE UNIVERSITY

Natural Resource Ecology Laboratory
Colorado State University
Fort Collins, CO 80523-1499

FROM THE DIRECTOR

In October 1992, in response to growing concerns for the global problems of ozone depletion and increasing levels of ultraviolet radiation reaching the Earth's surface, the USDA established its UV-B Monitoring and Research Program under the direction of Dr. James H. Gibson, who served at Colorado State University's Natural Resource Ecology Laboratory (NREL) as director from 1973 to 1984.

For over five decades, NREL has brought together scientists from different disciplines to examine complicated ecological problems – and to develop and contribute to solutions. The research conducted here spans the globe, focusing on more fully understanding the interactions that sustain our environment at local, regional, and global levels. NREL conducts interdisciplinary research within the setting of a land-grant university, making it the ideal home for the USDA UV-B Monitoring and Research Program.

Through this program, we provide data that is being used by scientists across the country and throughout the world to study the effects of UV-B on plants, ecosystems, humans, animals, aquatic life, and climate. We are working with collaborators on development of a model system to evaluate the impacts on agricultural crops, rangelands and grazing lands, of UV radiation alone, and in concert with other environmental stressors (such as drought, and temperature fluctuations, among others), to provide options to decision makers. The information we provide is contributing to solutions that will allow us to sustain a healthy quality of life on our planet – now and into the future.

I invite you to read about this vital work and to consider what you can do to safeguard the health of our environment.

Thank you for your interest in, and support of, our research that will help address problems of ozone depletion and increased UV radiation. Please contact me directly if you'd like more information.

Dr. Wei Gao, Director
USDA UV-B Monitoring and Research Program

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Published by the USDA UV-B Monitoring and Research Program

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Production: CSU Marketing and Brand Management

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Aerial view of Colorado State University campus

Located within Colorado State University's Natural Resource Ecology Laboratory (NREL), the USDA UV-B Monitoring and Research Program (UVMRP):

- manages a 41 station network to provide high-quality ultraviolet and other solar radiation measurements to study the spatial and temporal distribution of surface UV spectral irradiance and its impact on the biosphere;
- collaborates on conducting effect studies of the response of economically important crops to UV-B radiation and other environmental stress factors; and
- collaborates on developing the Climate-Agroecosystem-UV Interactions and Economic (CAIE) system, a comprehensive climate-crop-economic model that assists with predicting impacts of climate change, including UV radiation, on agriculture.

INTRODUCTION

Ultraviolet radiation is an important component of Earth's environment. Over time, all life on Earth has slowly evolved under the influence of UV radiation. In addition to its effects on humans, this UV energy has been studied on small and large organisms alike, from powdery mildew on wine-grape crops to large-scale rangeland grasses and forests.

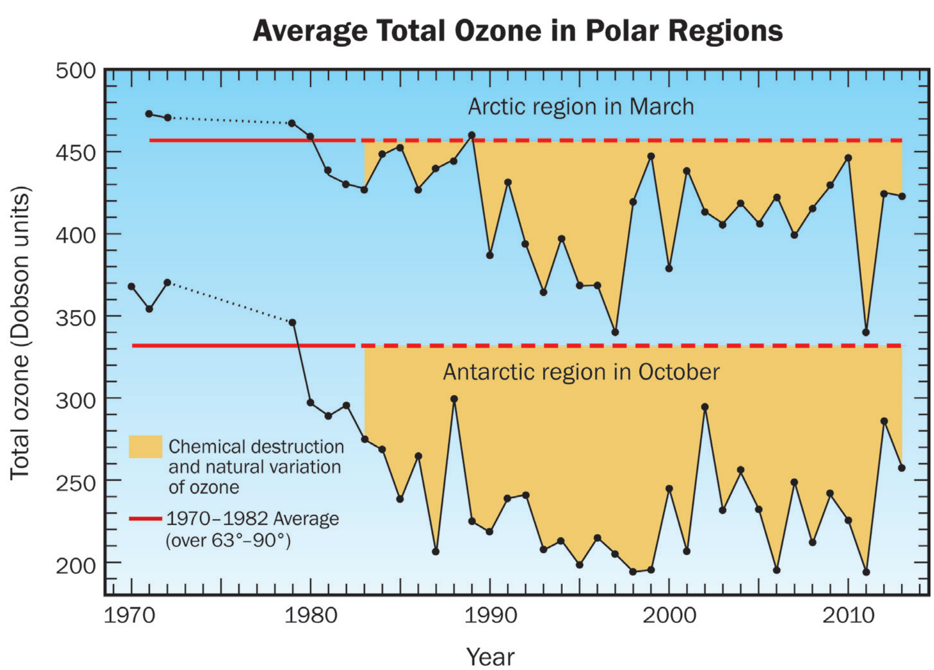
Because Earth's ecosystems have evolved slowly in concert with global climate change, any abrupt modification of UV levels must be taken seriously by the scientific community. Such an abrupt impulse was indeed detected in the mid-to-late period of the last century, when it was discovered that chemicals harmful to the Earth's protective ozone layer were being emitted by societies across the globe. Satellite measurements soon pointed to significant ozone depletions over Antarctic regions, and later measurements showed similar, though less dramatic and less frequent, ozone depletions over the Arctic region.

Because Earth's ecosystems have evolved slowly in concert with global climate change, any abrupt modification of UV levels must be taken seriously.

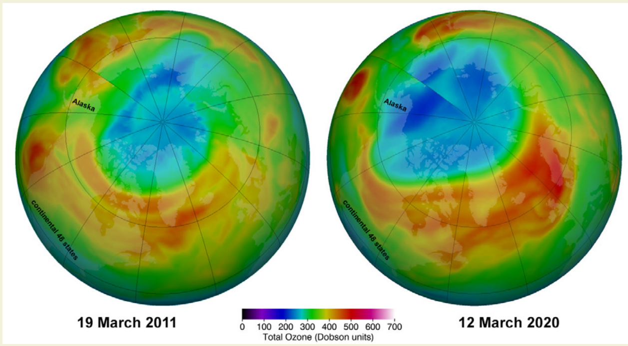
Since then, scientists in many disciplines have been investigating possible ramifications of changing UV levels. In 1991, as part of this response, the United States Department of Agriculture (USDA) investigated the need for a nationwide UV monitoring activity. Positive responses from the scientific community prompted USDA, in October 1992 to initiate the *UV-B Monitoring and Research Program (UVMRP)*. The program is tasked with establishing a UV climatology and studying the effects of UV radiation on a wealth of agricultural interests including crop plants, animals, rangelands, forests, and people involved in agricultural industries.

Evolving studies have shown that ozone is not the only important player in establishing UV levels – global climate change will continue to play a role, as well.

This brochure describes the UVMRP's history, measurement network, and current and future research efforts that are designed to guide government planners and inform the general public about the role UV radiation may play in the future.



The graph above charts depletion of ozone in the atmosphere over the Polar Regions. The horizontal red lines show average concentrations from 1970-1982. Shaded regions below the average lines show the amount of chemical destruction and natural variation.[1]



Data from NASA's spaceborne Ozone Monitoring Instrument (OMI) show averaged total ozone levels over the Arctic. Blues indicate where there is the least ozone, while yellows and reds indicate more ozone. In March 2011 (left), average ozone levels were at that time at record lows. In March 2020 (right), Arctic stratospheric ozone reached its new record low level of 205 Dobson units, shown in blue and turquoise, on March 12. (Images courtesy NASA Ozone Hole Watch.) [2]

UVMRP – RESPONDING TO GLOBAL CONCERNS

As a steward for agriculture, the USDA is tasked with maintaining a watchful eye on factors influencing the health of the nation's agricultural industry. During the past two decades of the 20th century, worldwide concern was focused on the health of a UV-blocking ozone layer, located high in the atmosphere, that was becoming depleted due to an increase of chlorofluorocarbons (CFC) in the stratosphere and an increase of methyl bromide, an agricultural fumigant. CFCs had become the working fluid of choice in the refrigeration industry before their adverse effects on the ozone layer were realized.

In response to this issue, the USDA established the UV-B Monitoring and Research Program in October 1992, under the Cooperative State Research, Education and Extension Service (CSREES), later restructured as the National Institute of Food and Agriculture (NIFA). Colorado State University in Fort Collins was selected as the UVMRP headquarters.

One of UVMRP's initial tasks was to deploy a network of UV-B and solar radiation monitoring stations throughout the United States to provide information on the geographical distribution and time-based trends of UV-B radiation, which is the portion of the total UV spectrum most damaging to plants and human skin. This baseline information is critical for the assessment of potential impacts of increasing UV-B radiation levels on agricultural crops, forests, and humanity in general.

Some predictions indicate it may take another 50 years before ozone concentrations return to normal levels.

Prior to the establishment of this program, only limited information was available to make such an assessment – and the geographic distribution and quality of this information was insufficient to meet the requirements of the USDA.

As a result of international cooperation to limit CFCs (The Montreal Protocol)[3], the protective ozone layer appears to be returning to long-term levels. However, the present recovery period is still relatively small for a statistically important change in the ozone trend, while the year-to-year variability of the total ozone column is very substantial.

Stratospheric ozone over the Arctic waxes and wanes with the seasons in a usually predictable pattern. However, there have been three episodes of *significant* loss of ozone over the Arctic since that nascent minor depletion in March 1990, which prompted USDA to investigate the need for a nationwide network to monitor atmospheric UV. These three significant events were March 1997[4], March 2011[5] and March 2020[6]. While each of them has 'healed' itself, this latest 2020 hole took substantially longer to heal than the prior depletions. Scientists studying these three significant Arctic ozone depletion events attribute them to changes in the circulation patterns of the Arctic air masses, changes which they determine are a consequence of planet-wide climate change. (See page 21 for additional information.)

HEART OF THE PROGRAM – THE MONITORING NETWORK

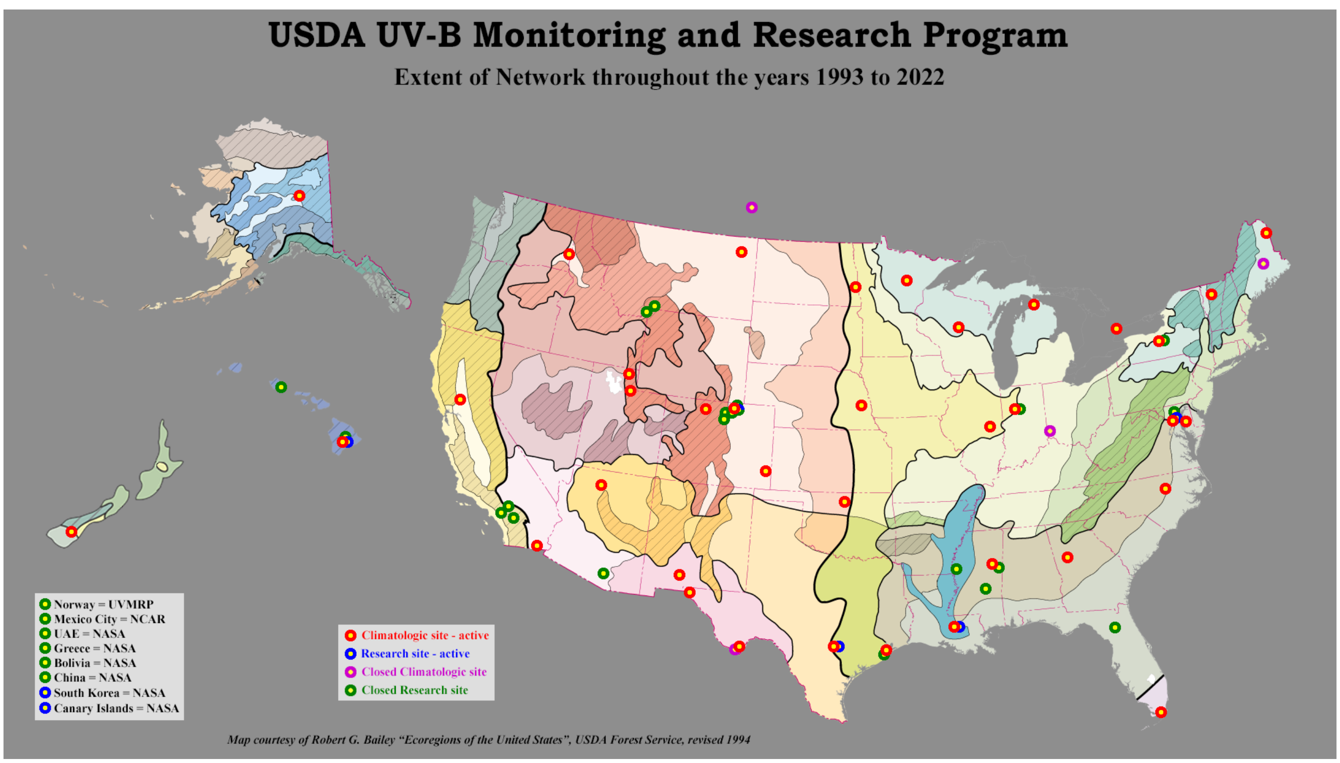
UVMRP began deploying instruments to agriculturally and ecologically diverse sites in the early 1990s, which today has grown to a network of 37 climatological and 4 long-duration research sites. Those sites:

- **provide information to the agricultural community** and others about the climatological, geographical, and temporal distribution of UV-B irradiance; or in other words, develop a UV climatology for the United States;
- **furnish baseline information necessary** to support evaluations of the potentially damaging effects of UV-B upon agricultural crops and forests; and
- **provide in-situ data** in support of the development of a regional-scale modeling system to study potential future impacts of changing climate on crop production.

The network spans 27 states in the United States plus one Canadian province and the South Island of New Zealand. Instruments are deployed in 20 different ecoregions. The climatological sites are located primarily in rural areas, close to or within agricultural research experiment stations or outreach facilities for use in local- and regional-scale research.

Today the network has grown to 37 climatological and 4 long-duration research sites.

Measurements are taken every three minutes and data are downloaded each night to UVMRP headquarters. The measurements are calibrated, checked for quality, and processed into various data products. UVMRP provides information to the agricultural community, and all other interested users, via its web page at **http://uvb.nrel.colostate.edu**.



Cumulative extent of the UVMRP monitoring network throughout the years of its existence, including all short-term study sites and the current 37 climatological stations and 4 long-duration research sites

Home screen of the UVMRP web page at **http://uvb.nrel.colostate.edu**

The data assist scientists in relating changes in stratospheric ozone to changes in UV radiation, and in improving the understanding of other mechanisms of climate change that control UV radiation transmission through the atmosphere, such as changing cloud characteristics. Both are critical in assessing the impacts of changing UV-B radiation on agricultural systems.

UVMRP provides information to the agricultural community, and all other interested users, via its web page at http://uvb.nrel.colostate.edu.

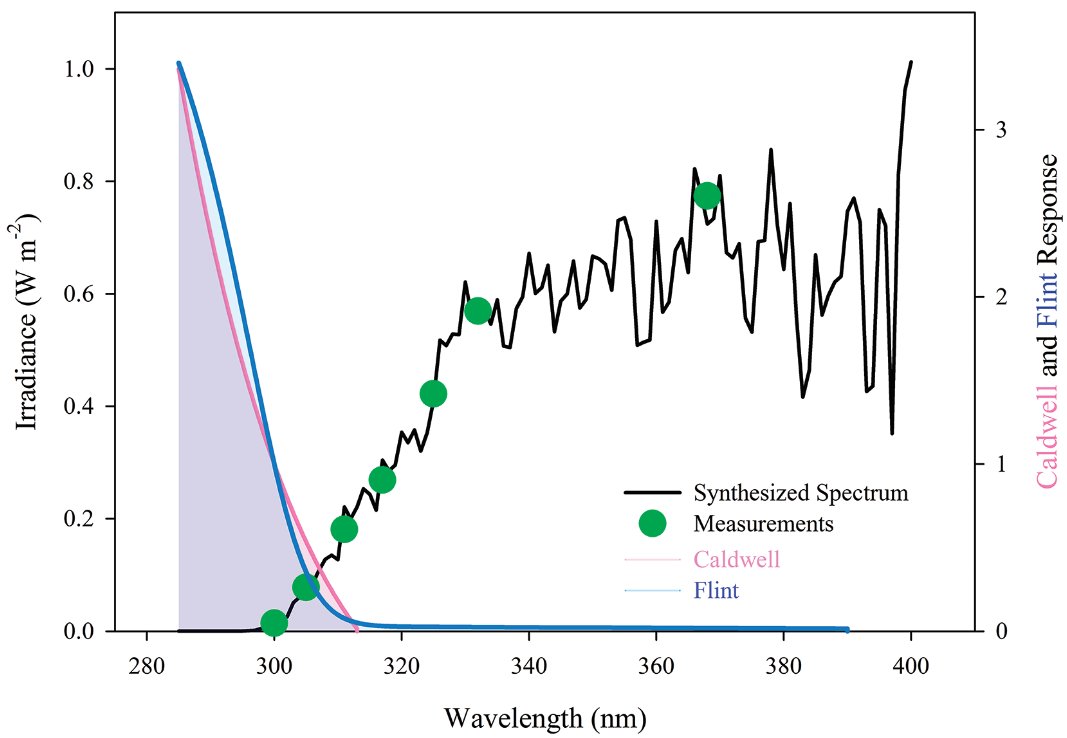
How Is UV Radiation Measured?

UV radiation is measured using special photosensitive detectors that have heightened sensitivity in the UV portion of the electromagnetic spectrum. The light that our eyes can see, referred to as the *visible portion* of the spectrum, is normally measured by devices called silicon detectors, but those detectors do not respond very efficiently to UV radiation without special adaptations. In addition, for agricultural research, it is necessary to split up UV radiation into smaller segments, called *spectral bands*, since some plants are damaged by only a portion of the UV spectrum. Scientists are continually studying which parts of the UV spectrum are most damaging to different plant species. These response functions are called *action spectra*.

UV radiation is typically measured using single-detector instruments that measure the total sky UV radiation, and UVMRP uses a version called a broadband UV-B radiometer at each of its sites to maintain backward compatibility with past research efforts. To further meet the USDA's needs, UVMRP helped develop an instrument capable of making solar measurements with higher spectral resolution of spectral bands, to allow for processing data in a way that can be used with any action spectrum in the UV.

Also, for some applications and for calibration purposes, knowledge of the amount of UV radiation that comes from the direction of the Sun, or *direct radiation*, is required separately from the amount that comes from the entire hemisphere of the sky, which is called *total hemispheric radiation*. The separation of these components is accomplished by using a rotating shadowband that shades the instrument from the Sun during a portion of the measurement cycle. These instruments are called UV Multi-Filter Rotating Shadowband Radiometers, or UV-MFRSRs.

This UVMRP climatological monitoring station northeast of Fort Collins at the CSU Central Plains Experimental Range (CPER) shows the array of instruments (from left to right): VIS-MFRSR, UVB-1, PAR, temperature/humidity (behind, in radiation shield), UVA, UV-MFRSR, LICOR photometer (facing downward to measure the surface albedo, particularly looking for snow). In the enclosures are a barometer, dataloggers, and power and communications components.



An example of a synthetic spectrum (black line) calculated from measured narrowband irradiance at eight MFRSR channels (green solid circles), and the Caldwell (pink area) and Flint (blue area) biological spectral weighting functions (BSWF). The definition and importance of these two BSWFs can be found in Caldwell 1971 and Caldwell 1986. The MFRSR values are combined with knowledge of the amount of UV radiation at the top of the atmosphere to construct the entire solar UV spectrum, as indicated by the black line.[7,8]

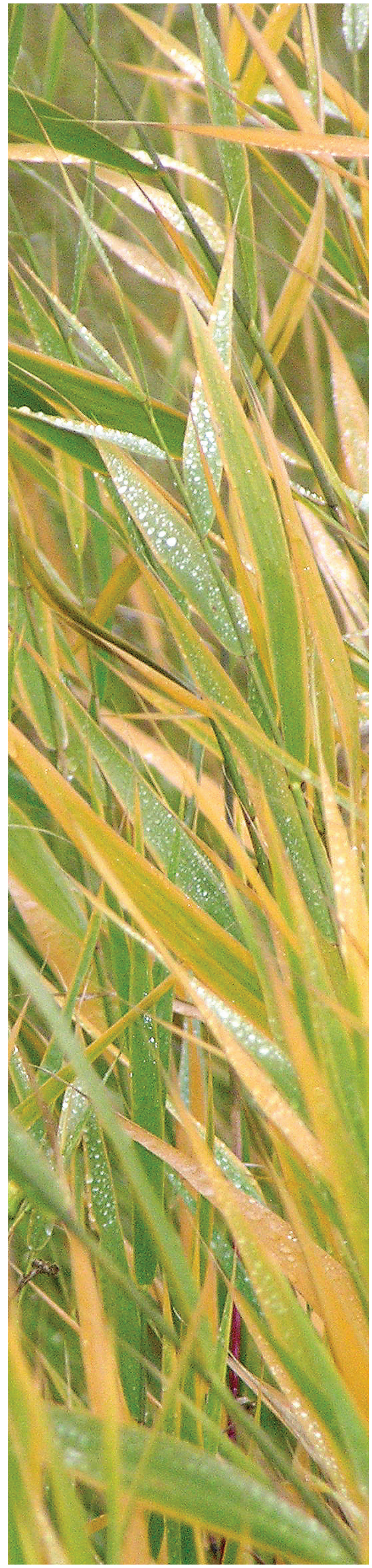
What Other Measurements Are Important?

Although the initial impetus for UVMRP involved tracking UV-B radiation, agricultural researchers have other important concerns. Through the process of photosynthesis, plants grow by combining ground nutrients, water, and atmospheric carbon dioxide into carbohydrates and oxygen. Plants accomplish this by using energy from visible light trapped by chlorophyll. The portion of the visible light needed for this process is called *Photosynthetically Active Radiation*, or PAR, and it is measured by a photometer on the UVMRP instrument stand.

Through the process of photosynthesis, plants grow by combining ground nutrients, water, and atmospheric carbon dioxide into carbohydrates and oxygen. Plants accomplish this by using energy from visible light trapped by chlorophyll.

Additionally, a *visible-spectra shadowband radiometer*, or Vis-MFRSR, is used to provide supplementary spectral resolution by measuring specific wavelengths in the visible part of the Sun's radiation. To help interpret the performance of all the radiometers on the instrument stand, UVMRP makes ancillary measurements of air temperature, relative humidity, surface pressure, and reflected solar radiation, in addition to specific internal instrument checks.

UVMRP field technician George Janson evaluating the electronic performance of the datalogger at the network monitoring site at University of Michigan Biological Station at Douglas Lake, MI.



How Is Measurement Quality Maintained?

UVMRP field technician William Durham evaluating the alignment of a prototype solar tracking apparatus for potential use to direct a beam of sunlight onto an instrument undergoing repairs in the UVMRP maintenance lab.

UVMRP has been monitoring UV radiation for more than 28 years, and instruments in the network require periodic checks and maintenance. One of the most important checks is verifying that the detector's output signals are maintaining accuracy.

Calibration of the instruments is checked in a couple of ways.

- First, the manufacturer delivers the instruments with initial calibration information.

- Second, the UV-specific instruments periodically receive calibrations traceable to the National Institute of Standards and Technology (NIST), which are performed at the Central UV Calibration Facility operated by the National Oceanic and Atmospheric Administration (NOAA) in Boulder, Colorado.

After a period of deployment from one to three years, the instruments are sent to NOAA's Mauna Loa Observatory in Hawaii to receive intermediate calibrations using the signal of the Sun on clear days. The MLO site is optimal because of its location at 11,400 feet above sea level – most changes in the atmosphere above this level occur slowly, which allows signals to behave predictably.

During deployment at field sites, calibrations are checked monthly for consistency and updated on an ongoing basis.

Three UV-MFRSR instruments occupy the UVMRP's intercomparison calibration site at NOAA's Mauna Loa Observatory on the Big Island of Hawaii. MLO is a world-renowned facility used by many atmospheric researchers for similar calibration of their instruments, due to the high altitude and clear air found at this location.

Who Uses the Data?

Our data is available to anyone via the program's web page. On average annually, more than 8,000 visits from across the globe are recorded on the website.

We receive requests for large amounts of data, which we are able to provide by creating files made accessible to the user via special instructions. The data are used by scientists for plant, animal, and atmospheric research. Collaborations include partners from government (USDA-APHIS, USDA-ARS, NSF-NCAR, NOAA, NIST, DOE, NASA, and the Smithsonian) and land-grant universities (University of Maryland, Mississippi State University, University of Illinois, Purdue University, Colorado State University, North Carolina State University, Utah State University, Washington State University, University of California-Davis, and Cornell University), among others.

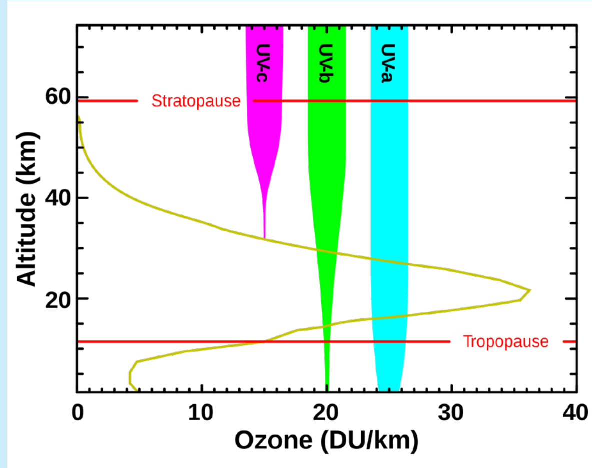
Our personnel interact with scientists from the health fields, various biological research projects, materials scientists, and the general public.

Our personnel interact with scientists from the agronomy and ecology sciences, health fields, various biological research projects, materials scientists, and the general public. We also provide custom-processed data in different formats and for specific end user needs.

How Does the Atmosphere Affect UV Radiation?

The main factors influencing the amount of UV radiation arriving at a point on the Earth's surface include the angle between the Sun's rays and a line perpendicular to the surface, the nature of the cloudiness, the amount of ozone through which radiation must pass, the amount of aerosol and pollutants, and the number of air molecules along the path, which is measured by surface pressure.

Where you are located has a major effect on the UV-B radiation that you may receive for a given exposure time. For example, if you're in Las Cruces, New Mexico, at 32.6° north latitude on a clear day on June 21, with an ozone level of 300 DU, you would receive UV-B radiation 1.24 times greater than the radiation you would receive in Seattle, Washington, at 47.7° north latitude under the same atmospheric conditions.

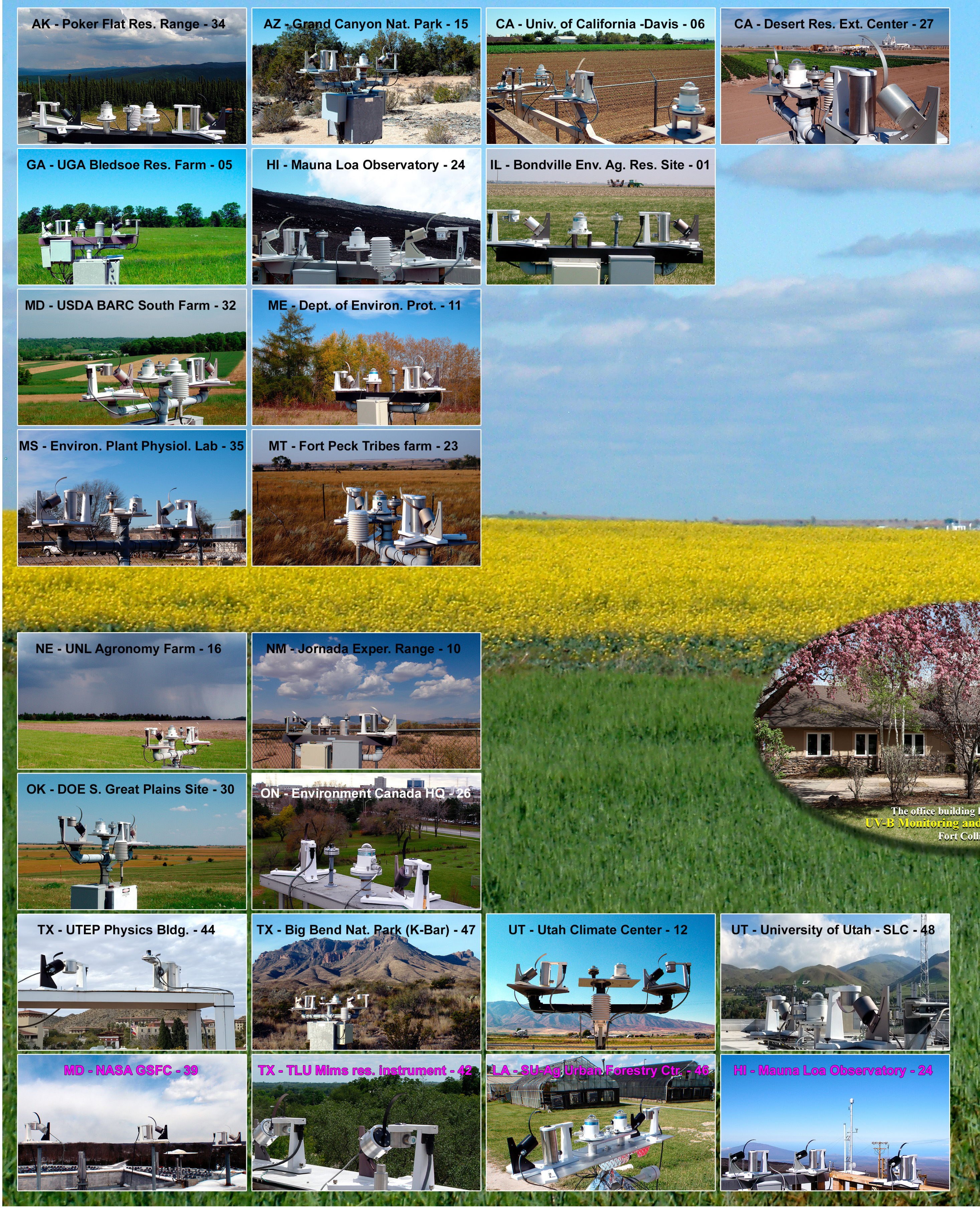


This image shows levels of ozone at various altitudes and related blocking of several types of ultraviolet radiation. The ozone concentrations shown are very small, typically only a few molecules of O_3 per million molecules of air. But these ozone molecules are vitally important to life because they absorb biologically harmful ultraviolet radiation from the Sun.

Three different types of ultraviolet radiation are based on the wavelength of radiation: UV-A, UV-B, and UV-C. The figure also shows how far into the atmosphere each of these three types of UV radiation penetrates. UV-C (red) is entirely screened out by ozone at around 35 km altitude. On the other hand, we see that most UV-A (blue) reaches the surface, but it is not as genetically damaging and thus not as concerning. It's the UV-B (green) radiation that can cause sunburn and genetic damage, resulting in skin cancer, for example, if exposure to it is prolonged.

Ozone screens out most UV-B, but some reaches the surface. If the ozone layer were to decrease, more UV-B radiation would reach the surface, causing increased genetic damage to living things.[9]

Climatological (37) and Research (4) and Closed (4) network sites [number is order of esta

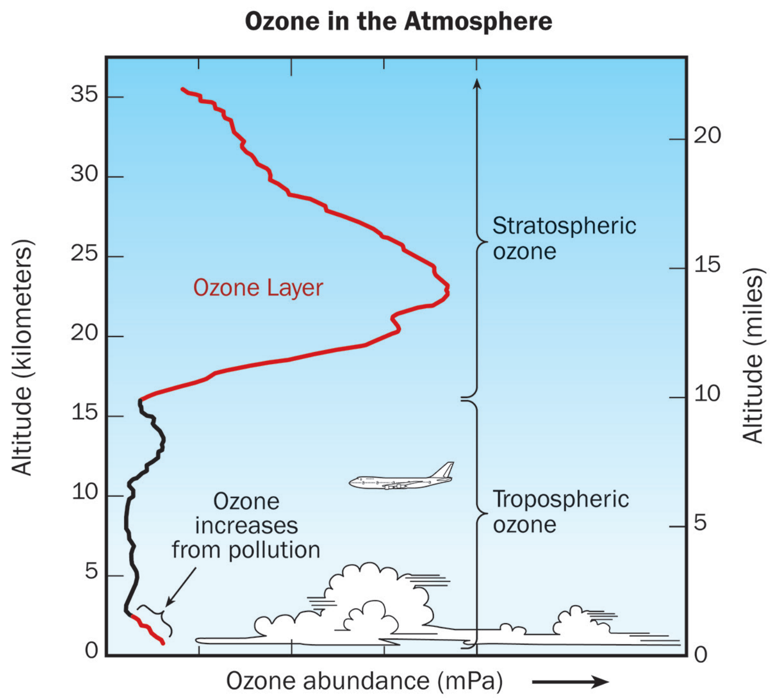


ablishment] - arrayed in site code alphanumeric order from left to right, top to bottom

At lower latitude the Sun is higher in the sky, resulting in a shorter path length through the atmosphere and higher UV-B radiation levels.

Clouds and pollution, which scatter radiation, also have a significant effect on UV-B levels at the Earth's surface. Clouds not only block direct exposure to the Sun's UV rays but also scatter the radiation to other parts of the sky and affect what is called *diffuse radiation*. Other factors affecting UV amounts include the Earth's reflective surfaces and canopies that provide partial or complete shade from the Sun.

All these factors govern the amount of UV radiation that actually penetrates a particular location at a particular time, making it challenging to precisely measure UV radiation at the Earth's surface.



Ozone is present mainly in the lower and uppermost parts of the atmosphere. Its formation in the upper atmosphere is a natural process that results from photochemical reactions. In the lower portions of the atmosphere, pollution interacts with sunlight to form tropospheric ozone. The ozone in the upper atmosphere provides nearly all the protection from the Sun's UV radiation. [10]

Grade-school children and teachers exploring crops growing adjacent to the UVMRP climatological monitoring site at University of California's Desert Research and Extension Center, in Holtville, CA

Effects of UV-B Radiation on Leaf Appearance

The exposure of cotton plants to UV-B resulted in leaves producing insufficient chlorophyll (chlorosis) that later resulted in the premature death of cells (necrotic spots). Plants under 16kJ treatment developed symptoms much earlier than those exposed to 8kJ UV-B radiation. UV-B radiation reduced leaf thickness and increased the number of palisade layers.[11]

A leaf-litter decomposition experiment using aspen (Populus tremuloides) to study effects of UV-B radiation on litter decomposition in relation to water availability and associated biotic activity. Litter decomposition rates vary across biomes, and patterns of decay indicate UV-B radiation accelerates litter decay in environments where precipitation is infrequent. The lack of water reduces biotic activity such that litter decay due to UV-B radiation (photodegradation) increases considerably.[12]

UVMRP field technician Scott Simpson evaluating a potential location for use of a UVMRP portable network station to augment existing meteorological instruments to assist with a research project investigating the effects of UV radiation on the ecosystem.

MORE THAN A MONITORING NETWORK … UNDERSTANDING THE EFFECTS

Even as UVMRP began providing radiation data to the agricultural research community in the 1990s, it soon became evident that the effects of radiation on plants, animals, and ecosystems in general were not well understood. Thus, providing data was only part of the role of assessing damage or benefits to agricultural interests.

As part of its overall mandate, UVMRP began conducting "effects" studies designed to establish levels of UV-B that are harmful to crops in particular. These studies are continuing at Mississippi State University (MSU) and Colorado State University to evaluate the isolated and combined effects of UV-B and other environmental stressors on agriculture. At MSU, primary studies at the *Soil-Plant-Atmosphere-Research (SPAR)* facility use plant-growth chambers that control the enclosed environments over a wide range of set points such as atmospheric CO_2 concentrations, ambient temperature, humidity, UV-B radiation, soil water and nutrients, and other parameters specific to the researcher's needs.

Overall, two-thirds of 680 tested cultivars have shown damage from increased levels of UV radiation.

How Will Global Climate Change Affect UV?

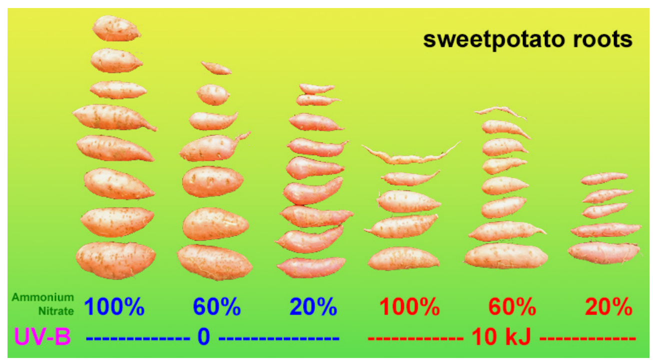
UVMRP collaborators have conducted important studies by exploring the effects of increasing levels of UV-B. The ability to control various atmospheric parameters has resulted in a finding that, although it might take a substantial increase in UV-B radiation (perhaps up to three times ambient levels) to substantially damage crops, it may require a smaller dosage increase to damage plants already stressed by drought or increased levels of carbon dioxide. This brings into play the role of changing climate as a player in the effects of UV-B. Additionally, a changing climate may alter the amount and/or type of cloudiness, which would be a key component in affecting the amount of UV-B reaching the surface.

Along with responding to changing climate, UV-B radiation may have a more active role in climate change itself. Research is being conducted at UVMRP to study the effects of UV-B on litter decomposition under rangeland grasses and forests. Soil decomposition releases nitrogen and carbon into the atmosphere and thus has the capability to modify the way the atmosphere affects broader solar and infrared radiation budgets that are primary controllers in the overall climate-change scenario.

A litter decomposition experiment is located at the Central Plains Experimental Range (40°49'N, 104°46'W) in north-central Colorado. Each tent covers 1.4 m² area and is topped with Lexan (UV block material) or Solacryl (UV pass material), solid transparent water-shedding sheets. Findings show that productivity and seasonal standing biomass of the dominant grass were negatively affected by passing UV in the dry years; forage quality increased when UV was passed compared with blocked.[13]

At the Soil-Plant-Atmosphere-Research (SPAR) facility at Mississippi State University, ten naturally-lit, controlled environment chambers are uniquely useful for studying canopy and ecosystems or small-plot responses to combinations of variables in controlled field-like environments. These capacities allow simultaneous determination of several plant responses (e.g., canopy photosynthesis, respiration, transpiration, tissue temperatures, growth, and development of organs) to precisely controlled conditions (e.g., temperatures from 5 to 45°C, CO_2 concentrations from 150 to 1,000 ppm, ultraviolet-B radiation from 0 level to several times ambient levels) and the ability to manipulate a wide range of water and nutrients through a set of sensors and program algorithms. The gas-exchange processes and many soil and aerial environmental conditions are measured and/or adjusted on a 10-second basis in each SPAR unit.

Dr. Raja Reddy assessing UV-B impacts on cotton leaves in the SPAR chamber.



Reduction of yield (size) shown above is primarily due to elevated UV-B radiation on sweetpotato cultivars Beauregard, Hatteras and Louisiana 1188, respectively.[18]

These SPAR-based studies continue to examine the effects on specific individual crops of cotton, corn, soybean[14], wheat, and rice[15], sweet potato, basil [16] and Brassica carinata. Earlier studies of sorghum, barley, cucumber, spinach, and lettuce were conducted in greenhouses and at open-air research fields. Historically, agricultural researchers have discovered that two-thirds of 680 tested cultivars have shown damage from increased levels of UV radiation. Prior research by UVMRP collaborators also examined UV-B and other stressors effects on trees (both deciduous and coniferous), wine grapes, forage used by rabbits, rangeland plants, nematodes, soil arthropods, and the decomposition of leaf litter.

Combining the data from the monitoring network and satellite products, UVMRP collaborators also studied the uptake of vitamin-D and the effects of UV-B on skin cancer in humans.[17]

This study examined the effect of ambient and elevated UV-B radiation and nitrogen-deficiency on sweetpotato cultivars Beauregard, Hatteras and Louisiana 1188. Most of the plant parameters which were measured [photosynthesis, chlorophyll fluorescence, stomatal conductance, transpiration rate, water-use efficiency, growth and development (leaf area, leaf thickness, vine length, total dry weight, number of roots), combined response index (CRI) and UV-B sensitivity index (USI)] showed reduction and loss of yield due to dysfunction of photosynthesis, with cultivar Beauregard more sensitive to UV-B than cultivars Hatteras and Louisiana 1188. Elevated UV-B inhibited the growth of sweetpotato, but no significant interactive effect between nitrogen and UV stressors was found, though optimal nitrogen did offset some UV-B stress.[18]

PUTTING IT ALL TOGETHER – MODELING OUR UNDERSTANDING

To study the possible effects of global climate change on agricultural interests, UVMRP activities are focused on challenging our current understanding of factors that influence the quantity and quality of plants that may be stressed by climate change, using an integration of observed data, mathematical models, and remote-sensing technology.

This research will help develop solutions to allow producers to cope with detrimental effects and ensure future agriculture and livestock quality and productivity.

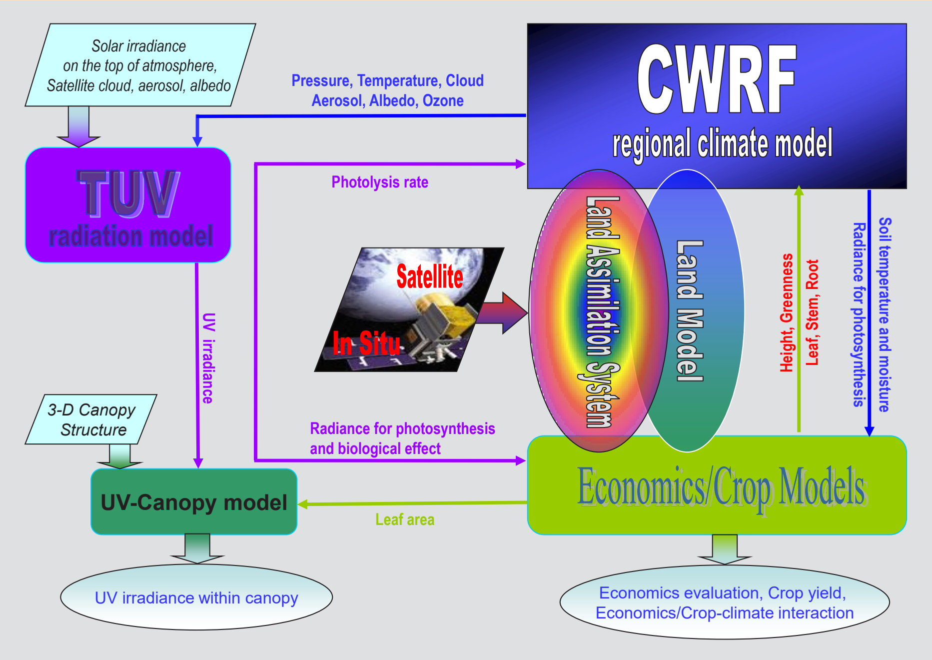
With collaborators from the University of Maryland and Mississippi State University, UVMRP is developing the *Climate-Agroecosystem-UV Interactions and Economic (CAIE)* system.

This system will be capable of achieving credible and quantitative assessments of key stress factors in addition to evaluating alternative cultural practices for sustainable agriculture production. This provides decision makers with the scientific foundations that measure potential risks, determine optimal practices, design effective policies, and identify adaptation/mitigation strategies to achieve sustainable food and biofuel pathways.

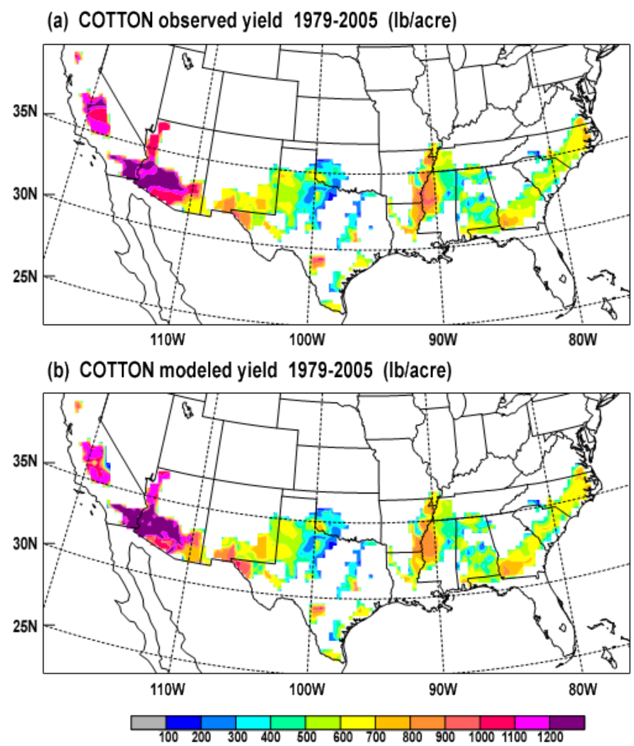
The CAIE system takes advantage of satellite and in-situ observations, functional algorithms developed in effects study, and the established regional-climate, ecosystem/crop, and economic models to represent the multi-scale interactions and coevolution of crop production, water supply, agricultural economy, and climate and hydrologic processes in response to major environmental forcings and human interventions. As such, the CAIE system can quantify the impacts of climate changes and extremes, key environmental forcings, and human interventions on the resilience of U.S. agriculture and water resources, and to identify sustainable food and bioenergy crop production pathways to contain these impacts.

The development of the CAIE system is a long-term research effort. Once completed, it will cover economically important crops such as cotton, corn, soybean, wheat, rice, other staple crops, biofuel crops, as well as grassland and rangeland plants.

Remarkably, initial testing of this approach – comparing 27 years of historic yield data with what the model predicts for cotton over the 16-state cotton belt – has shown the simulated versus actual crop yield has agreement to -/+10 percent at 87 percent of sites.



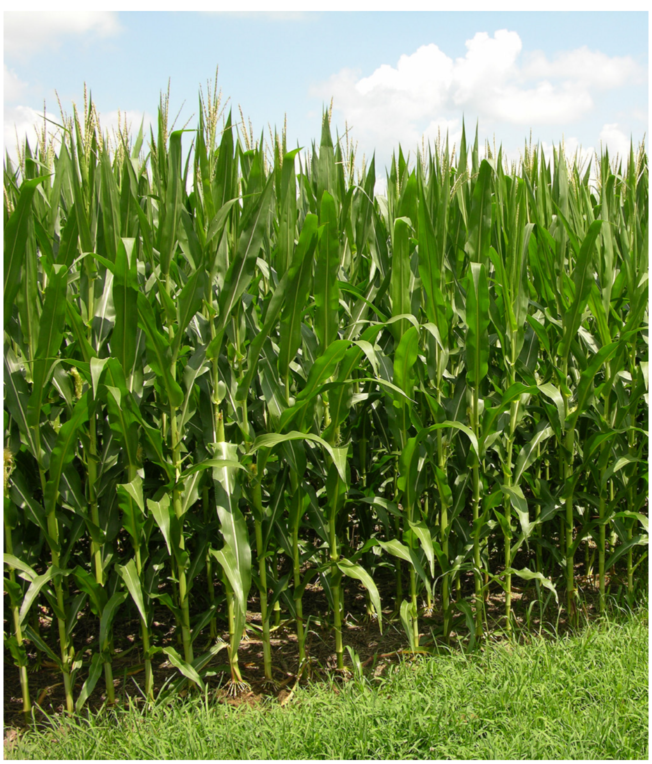
The Climate-Agroecosystem-UV Interactions and Economic (CAIE) system couples state-of-the-science modeling capabilities, driven by exogenous forcings and regional land/water use practices, to predict scale-aware metrics responsive to decision support needs. The system includes climate models, radiation models, ecosystem models, crop growth models, economics models, and satellite and in-situ observations. The model coupling among the components is scale-dependent in time and space, and able to address system uncertainty and risk analysis.[19]

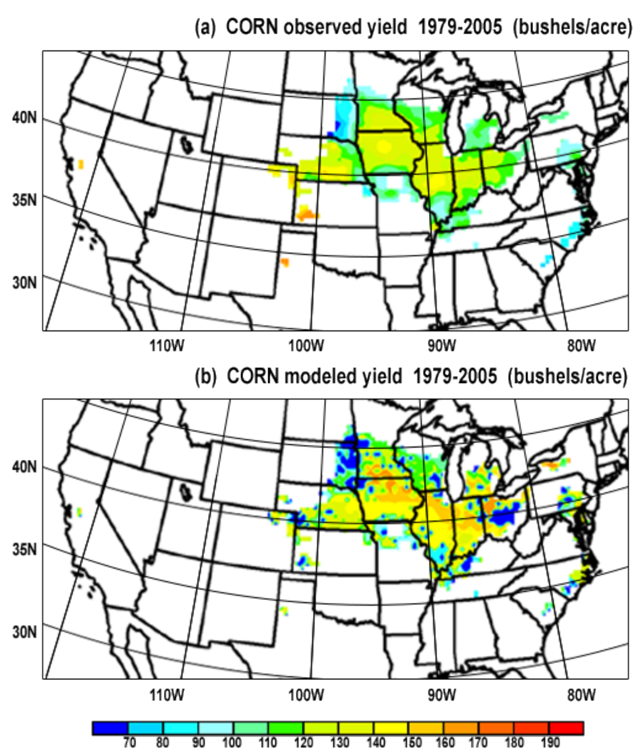


*These pairs of maps compare actual (observed) crop yield to simulated (modeled) crop yield using the **C**limate-**A**groecosystem-UV **I**nteractions and **E**conomic impacts (CAIE) regional-scale crop model, currently under development by UVMRP and collaborators at University of Maryland and Mississippi State University.*[20,21]

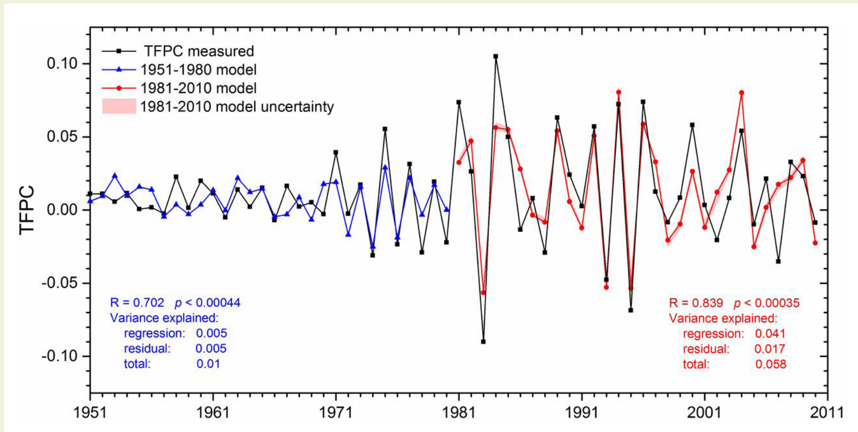
The upper pair of maps show COTTON in the 18-state cotton belt, for the years 1979 to 2005. Actual (observed) yield is the upper map, with simulated (modeled) yield displayed on the lower map, to show that the accuracy of the CAIE model is -/+ 10% throughout the region.[20]

The lower pair of maps show CORN over the 14-state corn belt, for the years 1979 to 2005. Actual (observed) yield is the upper map, with simulated (modeled) yield displayed on the lower map, to show that the accuracy of the CAIE model is -/+ 10% throughout the region.[21]





Quantifying the relationships between total factor productivity (TFP) of the US agricultural economy and climate is critical to understanding whether current US agricultural productivity growth will continue into the future. We analyze correlations between regional climate variations and national total factor productivity change (TFPC), identify key climate indices, and build a multivariate regression model predicting the growth of agricultural TFP based on a physical understanding of its historical relationship with climate. In summary, US agricultural TFPC correlated significantly with both temperature and precipitation in certain seasons over broad regions. These regions are all areas of major US agricultural production, including crops, livestock, and nursery products.[22]



Measured and simulated TFPC variations. The simulations include those by model 1 for 1951–1980 and by model 2 for 1981–2010. Also shown are the correlation coefficient (R) of the simulated with measured TFPC, the p value of the regression, and the explained, residual, and total variance for each period. The shaded area represents uncertainty in the 1981–2010 regression model, showing the 25th to 75th percentile range of submodel simulations when using 28-year bootstrap samples.[22]

UV Plant Litter Decomposition Model

One of the more recent efforts developed by scientists at UVMRP and NREL is a model that simulates the most important processes in the life cycle of rangelands and forests. The *DayCent-UV* model, designed to run on time scales from days to centuries, simulates photosynthesis, plant production, carbon allocation, disturbances such as fire and grazing, and management practices such as fertilizer and irrigation, as well as others.

Recent literature found that UV radiation significantly affects the amount of carbon and nitrogen released into the soil and atmosphere via its role in litter decomposition. The three most potential mechanisms: direct photolysis, facilitation of microbial decomposition, and microbial inhibition effects, were incorporated into *DayCent-UV*. Sensitivity analysis showed photodecay accelerated C and N cycling, suppressed microbial N immobilization and did not impact plant productivity. Validation results showed that the modified model *DayCent-UV* can simulate the linear carbon loss and persistent net N release on the annual scale, and other ecosystem dynamics on the seasonal scale observed at several semi-arid sites in the western U.S.

The outcome of this research will lead to a quantitative assessment of U.S. agricultural, economic impacts, adaptation measures, and policy changes in response to global climate change.

Economic Model

UVMRP and various collaborators conduct modeling of the potential impacts of global climate change on crop production in the United States. Moreover, changing levels of harvest amounts will have economic impacts in years to come, so it is critically important for decision-makers and growers to be aware of any such impacts in advance, if possible.

What currently is lacking is the ability to evaluate economic consequences at national levels by means of predicted climate variability/change and crop responses on regional-to-local scales. UVMRP therefore is committed to developing a feasible approach that links climate and crop predictions with economic model simulations of collective agricultural productivity at state and national levels.

The outcome of this research will lead to a quantitative assessment of total agricultural output and associated economic impacts, adaptation measures, and policy changes in response to global climate change.

HOW WILL UVMRP EVOLVE?

The UVMRP network is now in an exciting time of transition in a number of ways.

- **We are continuing to learn** how UV radiation interacts with a wide variety of crop plants and the large-scale rangelands of the western United States.

- **We are constantly evaluating and updating** our climate modeling expertise, which prepares us to assimilate data from next-generation satellites and surface data networks.

- **We continue to examine** how our surface instrument network can be updated to better quantify the amounts of radiation in different portions of the UV and visible solar spectrum, and we are refining in-house calibration procedures to provide the highest-quality measurements possible.

- **Our staff's expertise is expanding** to enable us to work together across scientific disciplines from the atmospheric to ecological science regimes. Moreover, our computer resources are expanding to handle more complex modeling and data processing, including neural networks and machine learning, to allow faster user access to our data products.

- UVMRP scientists and collaborators are continually exploring an emerging eco-science that we are calling *UV agroclimatology.*

As food and fiber requirements of the United States and the world increase, and as we become better aware of how a changing climate will affect the UV and visible radiation available to agricultural activity, UVMRP will strive to provide the knowledge base to better equip decision-makers who face the challenges of coming decades.

PNAS

Determining climate effects on US total agricultural productivity

Xin-Zhong Liang[a,b,1], You Wu[c,b], Robert G. Chambers[d,1], Daniel L. Schmoldt[e], Wei Gao[f,g,1], Chaoshun Liu[h,i], Yan-An Liu[h,i], Chao Sun[a], and Jennifer A. Kennedy[b]

PNAS PLUS

International Journal of Hygiene and Environmental Health

Skin cancer incidence is highly associated with ultraviolet-B radiation history

Ni-Bin Chang, Rui Feng, Zhiqiang Gao, Wei Gao

JOURNAL OF ATMOSPHERIC AND OCEANIC TECHNOLOGY VOLUME 31

A New Cloud Screening Algorithm for Ground-Based Direct-Beam Solar Radiation

MAOSI CHEN, JOHN DAVIS AND WEI GAO

AGRONOMY JOURNAL, VOL. 94, MAY–JUNE 2002

A Geometric Ultraviolet-B Radiation Transfer Model Applied to Vegetation Canopies

Wei Gao,* Richard H. Grant, Gordon M. Heisler, and James R. Slusser

1 July 2001 / Vol. 40, No. 19 / APPLIED OPTICS 3149

Direct-Sun column ozone retrieval by the ultraviolet multifilter rotating shadow-band radiometer and comparison with those from Brewer and Dobson spectrophotometers

Wei Gao, James Slusser, James Gibson, Gwendolyn Scott, David Bigelow, James Kerr, and Bruce McArthur

Agronomy Journal • Volume 104, Issue 3 • 2012

Physical Modeling of U.S. Cotton Yields and Climate Stresses during 1979 to 2005

Xin-Zhong Liang,* Min Xu, Wei Gao, K. Raja Reddy, Kenneth Kunkel, Daniel L. Schmoldt, and Arthur N. Samel

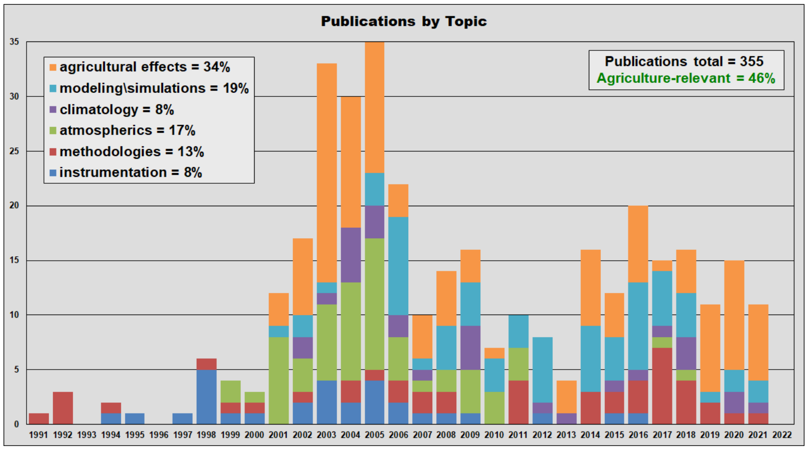
AMERICAN METEOROLOGICAL SOCIETY SEPTEMBER 2012 BAMS | 1363

REGIONAL CLIMATE-WEATHER RESEARCH AND FORECASTING MODEL

BY XIN-ZHONG LIANG, MIN XU, XING YUAN, TIEJUN LING, HYUN I. CHOI, FENG ZHANG, LIGANG CHEN, SHUYAN LIU, SHENJIAN SU, FENGXUE QIAO, YUXIANG HE, JULIAN X. L. WANG, KENNETH E. KUNKEL, WEI GAO, EVERETTE JOSEPH, VERNON MORRIS, TSANN-WANG YU, JIMY DUDHIA, AND JOHN MICHALAKES

A sampling of research papers published by UVMRP scientists.

A sampling of the text books edited and co-authored by UVMRP scientists.



UVMRP publications history from inception to the present

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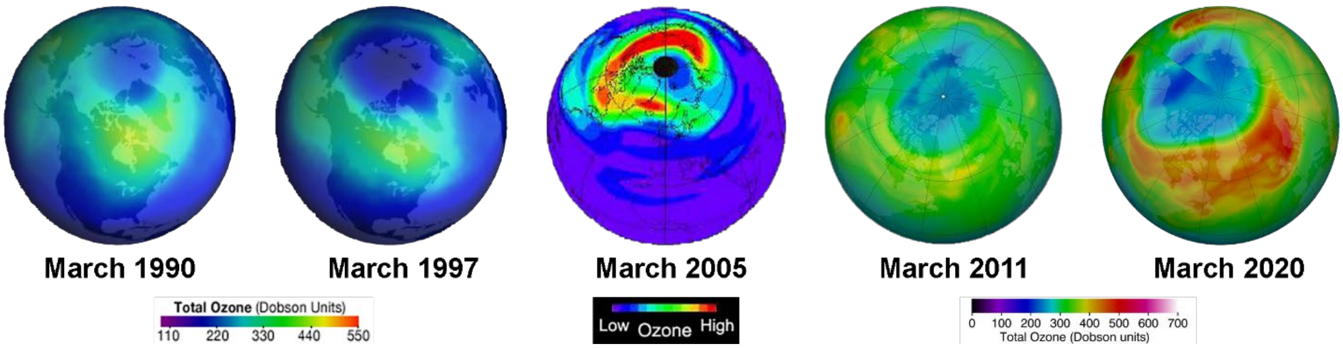
ARCTIC ozone – significant depletion events



Since the discovery in 1985 of the Antarctic ‘ozone hole’ it has been the ‘poster child’ for climate change, with a commensurate intensity of media attention and scientific research. Its lesser cousin, the Arctic ‘ozone hole’, in the immutable words of comedian Rodney Dangerfield, “… gets no respect.” True, the persistence and extent of Arctic ozone depletion events pale in comparison to those of the Antarctic. However, while the Antarctic hole is arguably receding in duration and intensity, research studies of the Arctic ozone hole have shown it has a tendency toward an increasing presence (see figure above), since that nascent minor depletion in March 1990 which prompted USDA to initiate and fund the UVMRP.

> *“… and we should invest in long-term monitoring, even when it seems to yield no immediate insights or benefits. … Although satellites can give global coverage, there are often differences between sensors in each new generation of satellites, and so there is still the need for ground-based results — even today for ozone. But in periods of economic decline there is always a temptation to suspend long-term monitoring programmes that don’t have any obvious immediate utility. … But it is programmes such as these that provide the crucial evidence for political decisions governing the future of our planet.”*[27]
> *Jonathan Shanklin, co-discoverer of the 1985 Antarctic ozone hole, in “Reflections on the ozone hole”;* ***NATURE****|Vol 465|6 May 2010*

"The Arctic has been getting colder and is becoming more like the Antarctic; this could lead to more dramatic ozone loss in the future over the Northern Hemisphere, where many people live," said Dr. Azadeh Tabazadeh, lead author of a paper published in the May 26, 2000 issue of the journal Science and a scientist at NASA Ames Research Center. “Arctic stratospheric ozone depletion is closely linked to the occurrence of low stratospheric temperatures. There are indications that cold winters in the Arctic stratosphere have been getting colder, raising the question if and to what extent a cooling of the Arctic stratosphere may continue into the future.”[23]

Then in March 2005, Science News published a study led by the University of Colorado at Boulder which indicates that two natural atmospheric processes, solar storms and Arctic winds, in winter 2004 caused the largest decline in upper stratospheric ozone ever recorded over the far Northern Hemisphere.[24]

Then in an April 2011 news blog for the journal Nature, editor Quirin Schiermeier noted “Stratospheric ozone loss in the Arctic has this year [2011] reached a level never observed before in the northern hemisphere. Observations made since January from the ground and from balloons show that 40% of ozone molecules have been destroyed over the Arctic. The highest ozone loss previously measured in early spring, when ozone depletion reaches its maximum, was 30% in 2005.”[25]

And in a March 2020 ‘Nature News’ blog, editor Alexandra Witze noted “A vast ozone hole — probably the biggest on record in the north — has opened in the skies above the Arctic. It rivals the better-known Antarctic ozone hole that forms in the southern hemisphere each year.”[26]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