

ENERGY & ENVIRONMENT

Into the Air

How do oil and gas activities
affect climate, air quality?

Mercury Mystery

Investigating sources
of the neurotoxin

Troubled Waters

10 things you didn't know
about our watersheds

Skies of Blue

Cleaner cars, fewer pollutants



Table of Contents

2 Blade Runners

Small, unmanned planes may give unprecedented view of wind turbine wakes.

3 Wave of the Future

A CIRES doctoral student is developing a tool that determines the best spot to plant tidal turbines.

4 Soot Ended Little Ice Age

An industrializing Europe may have caused the abrupt retreat of Alpine glaciers in the 1860s.

4 Impacts of a Melting Arctic

CIRES studies the manifold implications of an increasingly ice-free Arctic.

5 Skies of Blue

Cleaner cars are emitting fewer pollutants.

6 Mercury Mystery

Investigating surprisingly high levels of the neurotoxin mercury in the air and ecosystems of the southeastern United States.

8 Waste Not

Curtailment of renewables means lost energy.

8 Getting the Carbon Out of US Energy

Can renewable energy provide power for everyone in the United States all the time?

9 Whither the Wind

Better observations improve wind energy forecasts.

10 Troubled Waters

10 things you didn't know about our watersheds.

12 Into the Air

In the United States today, there are more than 1 million active oil and natural gas wells. What does this mean for the air that we breathe and the warming of the atmosphere?

16 Portrait of a Joule

The invisible becomes visible in this photo gallery of energy production and the diverse environmental impacts.

18 Harvesting Energy

The growing role of biofuels raises questions about atmospheric impacts.

20 Deepwater Horizon

The BP oil leak is plugged, but new findings continue to gush forth.

21 Climate in the Classroom

CLEAN program gives educators tools for success.

22 Seismic Shift

Investigating the connection between oil and gas operations and earthquakes.

23 Thinking Outside the NOx

New instrument reveals hidden contributor to ozone pollution.

24 MySphere: Air Sleuths

CIRES scientists sniff out pollutants with a decked-out van.

Cover and this page:

An oil and natural gas drilling rig near Firestone, Colo., is one of more than 20,000 active oil and gas wells in Weld County, according to state numbers. The expansion of oil and gas development in Colorado—and elsewhere—has raised questions about air quality and climate impacts.

DAVID OONK/CIRES



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Energy & the Environment

“Every man casts a shadow,” Thoreau said. So, too, every energy source, renewable or fossil fuel-based, affects the environment. This issue of

ISTOCK

Spheres focuses on CIRES research that investigates the intersection of environmental science and energy. CIRES scientists study energy production’s “shadow,” and they also seek scientific understanding of the environment that can help others more successfully implement new energy sources.

This magazine is inspired by the CIRES Energy and Environment Initiative, led by CIRES Fellow Joost de

Gouw. “One thing we can be certain of is that our energy sources will change,” de Gouw says. “The initiative studies the environmental effects of new energy sources as they are developed, hopefully allowing society to make informed decisions on the viability.”

CIRES researchers study all aspects of the Earth system, including the atmosphere, hydrosphere, cryosphere, geosphere, and biosphere, so they are uniquely positioned to explore important questions about the energy/environment nexus. Since the initiative’s 2011 inception, CIRES researchers involved have published scores of papers that speak to the impact of energy on the environment. More: <http://cires.colorado.edu/science/initiatives/ee/>.

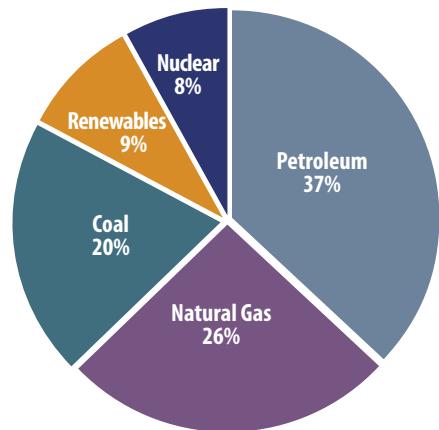
Los Angeles Air Quality, Then and Now



Downtown Los Angeles photos by the Herald-Examiner Collection (1968, left) and Gary Leonard (2005, right), courtesy of the Los Angeles Public Library (<http://www.lapl.org/#photo-collection>)

Energy Sources in the US

Source: U.S. Energy Information Administration



These sources of energy fuel households, companies, transportation, and electric power generation.

Meet the New Director

DAVID DOON/CIRES



On July 1, 2013, CIRES welcomed new director Waleed Abdalati, a professor in the Department of Geography at the University of Colorado Boulder. Abdalati previously directed the CIRES Earth Science and Observation Center (ESOC) and was NASA’s chief scientist in 2011 and 2012.

“It is an honor to serve as director of an organization full of such talented people doing such important work,” Abdalati says. In his vision for the institute, “the world is a better place because CIRES is in it.”

Some of the earliest windmills were less than 30 feet tall; the hubs of many modern wind turbines reach 350 feet into the air.

ISTOCK



The DataHawk micro plane takes a test flight on the south edge of Boulder, Colo., in April 2011.

BLADErunners

DAVID DOONKIGRES

Small, unmanned planes may yield unprecedented view of wind wakes

By Kristin Bjornsen

CIRES Fellow John Cassano's newest planes, the DataHawks, are small: They weigh less than 2 pounds, have about a 3-foot wingspan, and are made of foam. But with powerful electric engines, they fly nimbly even in 50-miles-per-hour winds. That's good, since this spring, Cassano will launch these unmanned aerial vehicles into wind farms, where they'll zip by turbines' giant rotating blades to measure turbulence.

"You can think of turbulence as gustiness—it's what makes flags flap in the wind instead of pointing straight," Cassano says. "When wind blows toward a turbine and a big blade passes through the air, that generates turbulence."

At wind farms, turbulence in a turbine's wake has several effects. For one, it reduces the energy available for turbines downstream because turbulence makes the airflow unsteady.

Turbulence also affects agriculture. In the early morning, the air near the ground is normally cold, and the air aloft is warmer. This structure, called a temperature inversion, traps cold air and moisture near the surface. But a turbine's spinning blades essentially "mix" the air, breaking up the inversion and moving warmer, drier air downward.

Sometimes this is beneficial. When farmers expect a frost overnight, for example, they sometimes turn on big field turbines to mix the air and warm the ground. "They'll even hire helicopters to fly near the surface to create turbulence," Cassano says.

Right now, however, scientific data on wind-turbine wakes and their effects are limited. Large research planes can't fly close to the blades, and expensive instrumented towers are stuck in one place. Enter Cassano's small unmanned aircraft: They make mea-

surements very close to the turbines and can monitor the wake's evolution downstream. With multiple planes, scientists also could study the air right before and right after it hits the turbine, to see how the air changes. "It gives a three-dimensional picture of the atmosphere," Cassano says.

The planes detect turbulence by taking high-frequency temperature measurements. Quickly fluctuating temperatures reveal the atmosphere's gustiness.

Cassano first started working with unmanned planes five years ago in Antarctica, using them to study the lower atmosphere. Those planes were built by two radio control (RC) plane hobbyists in Germany, who then taught Cassano how to fly them. To practice, Cassano installed flight simulators, with RC controls, on his computer.

"Playing video games as a kid definitely helped my learning curve," he jokes.

"A couple of my students haven't had the same success flying the planes, and I know their childhoods didn't include quite the same amount of gaming."

His skills will be put to the test in late spring when the first planes launch. CU-Boulder aerospace engineers built the DataHawks, and funding came from the CIRES Innovative Research Program (<http://cires.colorado.edu/science/pro/irp/>). Cassano and his team hope their detailed pictures of wind farm atmospheres are of such help to the industry that routine use of unmanned planes takes flight.

Did you know?

The words turbine and turbulence have similar roots. They both trace back to the Latin *turba*, for "confusion, crowd."

Wave of the Future



Jim Thomson (far left) of the University of Washington looks up as his team deploys equipment to measure tides and turbulence in Admiralty Inlet near Seattle.

DAVID MORIA

By Laura Snider

There are places in the coastal ocean—in straits and narrow entrances to some bays—where the channeled tide comes and goes with such speed that the water could turn the blades of underwater turbines, creating clean renewable energy.

Tidal turbines, wet versions of their windmill cousins, are still an emerging technology. And like wind turbines, their placement is crucial to their success.

CIRES doctoral student Katherine McCaffrey at CU-Boulder is creating a tool that could help future tidal-energy developers find the best spots to plant their turbines.

“The dynamics of the ocean and the atmosphere are governed by the same basic equations,” McCaffrey says. “I’m trying to come up with a way to describe ocean turbulence in the simplest and most helpful way.”

The amount of turbulence in the ocean is a product of the ocean-floor topography, the wind and waves at the surface, the geography of the region, and the velocity of the water as it rushes in and out with the tides. McCaffrey wants to develop a simpler way to describe the shape, size, and frequency of turbulence.

“Instead of needing to make all these measurements and do all these calculations, I propose a single parameter to represent many different characteristics of the flow,” she says.

Turbulent flows put uneven pressures on turbine blades, which can cause a lot of wear and tear on the equipment and decrease power output. Engineers could use McCaffrey’s rating system to decide where to place turbines on the ocean floor, and to make sure that the turbines are built to withstand the conditions in a particular area.



Learn about CIRES student fellowships

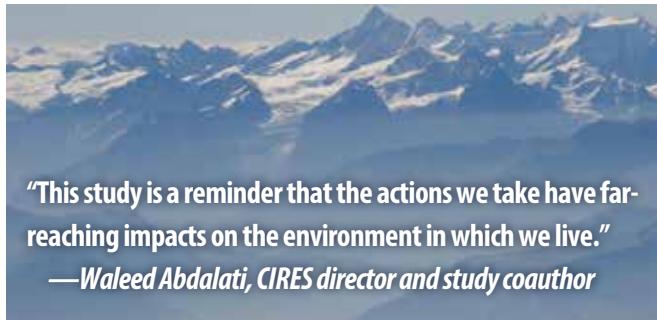
The long-established CIRES Graduate Student Research Fellowship aims to attract the most talented students to CU-Boulder at the outset of their graduate careers and to help those students conduct professional research and publish their results. From 2008 to 2013, CIRES and NOAA’s Earth System Research Laboratory (ESRL) in Boulder, Colo., also supported an ESRL-CIRES Fellowship; Katherine McCaffrey was a recipient. In 2012-2013, eight students received funding from either ESRL-CIRES or CIRES student research fellowships. These recipients are exploring topics such as electronic-waste management, the role of wildfire on landscape formation, climate adaption in East Africa, and more.

For more info, go to: <http://cires.colorado.edu/education/cu/gsrff/>

Soot Ended Little Ice Age

By Kristin Bjornsen

In the 1860s, the European Alps' large glaciers abruptly started melting, ushering in the end of the Little Ice Age—decades before global temperatures began rising. To understand this enigma, Thomas Painter, a NASA Jet Propulsion Laboratory scientist, took a clue from literature. “We have these visions from Charles Dickens of a huge amount of soot being pumped into the atmosphere from smokestacks and railroads during Europe’s Industrial Revolution,” says Painter, a 2002–2003 CIRES Visiting Fellow still affiliated with CIRES’ National Snow and Ice Data Center. “I wondered if that soot, or black carbon, played a role in the glacier retreat.”



When black carbon settles on snow, it darkens the surface. Darker surfaces absorb more sunlight, so if enough soot is deposited onto snow and ice, it can accelerate melting. “Historical records suggest that by the mid-1800s, the air in some Alpine valleys was thick with pollution,” says coauthor Georg Kaser, with the University of Innsbruck, Austria. “Housewives in Innsbruck refrained from drying laundry outdoors.”

Painter and his team studied soot levels in ice cores from the Alpine glaciers. They also analyzed how wind patterns distribute pollutants and developed computer models to analyze soot’s impact on snowpack. They found that soot from an industrializing Europe likely caused the glaciers’ sudden retreat. The study appeared in the *Proceedings of the National Academy of Sciences* in late 2013.

Impacts of a Melting Arctic

By Kristin Bjornsen

In the last three decades, the extent of summertime Arctic sea ice (measured in September) has declined by more than 40 percent. Some effects are already being felt. “Without protective ice cover, shorelines are eroding, forcing entire towns to move,” says Mark Serreze, director of CIRES’ National Snow and Ice Data Center. “Ice loss is affecting ocean life, too—from the level of phytoplankton all the way up to polar bears and walrus.”

Researchers also have identified possible links between declining sea ice cover and extreme weather events in North America. “The ice loss helps warm the Arctic, which in turn may influence jet stream patterns in the atmosphere, though this is controversial,” Serreze explains.

Serreze and CIRES scientists John Cassano (principal investigator) and Julienne Stroeve recently received a NASA grant to study links between Arctic sea ice loss and changes in mid-latitude weather patterns. The work, beginning in 2014, complements extensive research they and others have conducted on processes of sea ice loss.

Meanwhile, less ice might also mean greater access to oil and natural gas resources. The Arctic Circle is estimated to have 90 billion barrels of oil and nearly 1.7 cubic feet of natural gas; energy companies are seeking long-term exploration and production permits. Royal Dutch Shell, for example, operates a \$5-billion Arctic drilling program, though it’s faced myriad problems,



An ice-free Arctic could open shipping lanes that are shorter (red) than usual ones (black).

such as lingering sea ice delaying operations and 45-foot seas that tore a drilling rig away from a tugboat. Shell’s difficulties make some question if drilling in the Arctic is economically viable. Predicting sea ice conditions remains tricky, and an unexpected ice floe can shut down an entire operation. “While we can predict fairly well general ice conditions out to about a week, seasonal forecasts are not very good,” Serreze says.

Declining sea ice may open new trade routes as well. In 2005, the Northern Sea Route along Russia and northern Europe opened for shipping. Icebreakers still help plow the path, which is 40 percent shorter than the Suez Canal route. Some day, the Northwest Passage, linking the Atlantic and Pacific, or a “cross pole” route across the Arctic Ocean may also open for summer shipping. Still, more shipping and drilling is “certain to impact the environment, possibly severely if there’s a major accident,” Serreze says.

Skies of Blue

Cleaner cars are emitting fewer pollutants

By Leigh Cooper

From Venice Beach to Disneyland, people in the greater Los Angeles area are breathing easier, as the addition of catalytic converters and the removal of some volatile compounds from fuel has improved LA air quality during the last half century. “Every generation of cars gets more efficient and burns fuel more cleanly,” says Carsten Warneke, a CIRES scientist at NOAA’s Earth System Research Laboratory (ESRL).

For the last 50 years, scientists have meticulously measured air pollution in the LA Basin, documenting the results of strict vehicle emissions policies initiated since the 1960s. Gasoline consumption has tripled in the basin since then, but vehicular emissions have declined. “All pollutants, such as nitrogen oxides (known as NO_x), particulate matter, and volatile organic compounds (or VOCs),

have dropped solidly since the ‘60s,” Warneke says. “VOCs are dropping at a rate of 7.5 percent per year, which is huge.”

CIRES and NOAA scientists and their colleagues collected some of the most recent data by flying instrumented research aircraft over the basin to study air quality and comparing those measurements to historical data. In the LA Basin, VOCs (which are mainly emitted from passenger cars), NO_x (which now has very large sources from diesel-fueled vehicles), and sunlight are the primary ingredients that form ozone, a pollutant harmful to human and plant health and a major component of smog.

“Policymakers at the time decided to reduce ozone

by reducing emissions of VOCs,” says Ilana Pollack, a CIRES scientist at ESRL. “Historical measurements spanning 50 years (1960 to 2010) show ozone and some other pollutants have decreased because of the strict emission standards placed on cars.”

Although ozone has been the primary target for reductions, the chemical reactions occurring in LA’s atmospheric soup form other gaseous pollutants as well. One of these, peroxyacetyl nitrate (PAN), causes eye

Beyond ozone pollution

Volatile organic compounds can react to create ozone, but they also can react in sunlight to produce fine airborne particles known as secondary organic aerosols (SOAs). SOAs have been linked to negative effects on human health and visibility and can also affect climate. Jose-Luis Jimenez, a CIRES scientist, studies the origin of these particles. Jimenez has used weekend traffic trends to determine whether diesel trucks, which decrease in number on weekends, have a greater influence on the production of SOAs than gasoline cars, which remain the same on weekends. Jimenez’s preliminary work points to gasoline cars as the main source of SOAs. “Where secondary organic aerosols originate is a very important question, because it influences the effectiveness of different possible policy approaches,” Jimenez says.

irritation. “The cleanup of LA’s air has reduced both ozone and PAN,” Pollack says. “Because of this, LA’s air has lost a lot of its ‘sting.’”

Emissions standards have had success beyond LA, and vehicle emissions have decreased nationwide, Pollack says. NOAA and CIRES researchers and their colleagues will soon compare the pollutant-forming atmospheric chemistry of LA with other regions of the country. Measurements from a 2013 field study in the southeastern United States—a region where cars, electric power plants, and vegetation emit pollutant precursors—will provide insight into how vehicle emissions interact with natural emissions to form pollutants.

MERCURY MYSTERY



For years, scientists have found high levels of the neurotoxin mercury in the air and ecosystems of the U.S. Southeast. Perplexingly, these hot spots occur upwind of coal-fired plants, a common source. Stranger still, the mercury amounts deposited by rainstorms into ecosystems seem to be determined by the chemistry of other compounds (halogens) some 10 miles high in the atmosphere. We spoke with CIRES Fellow Rainer Volkamer who is unraveling these riddles.

By Kristin Bjornsen

What are the main sources of mercury in the environment?

Coal burning and wastewater are two primary sources. Another is our “mercury legacy,” from the Gold Rush. Prospectors used mercury to extract gold from rock; the mercury then washed through rivers into the ocean. Volcanoes also contribute a little. Once these sources mobilize mercury into the air, water, and ecosystems, it stays mobile. It takes thousands of years to return mercury to a sediment state. So the key is preventing new human-caused inputs of mercury.

What is the likely source of the elevated mercury levels other scientists have found in the Southeast?

Since the mercury occurs upwind from coal plants, it clearly wasn’t emitted on U.S. soil. This mercury is more likely coming from the global atmospheric pool, located in the upper free troposphere, about 15 kilometers high. Data show that Asia is one growing contributor to that pool.

How does the global pool store mercury?

Our research suggests that bromine, a halogen element, plays a vital role in storing mercury in its water-soluble form in the upper troposphere. Bromine enters the atmosphere naturally from the ocean, either from breaking waves injecting sea salts into the air or from ocean

life emitting it in organic form. Using a new instrument [see “Scintillating science,” at right], we took the first vertical measurements of bromine oxide radicals above the eastern Pacific Ocean and found surprisingly high levels.

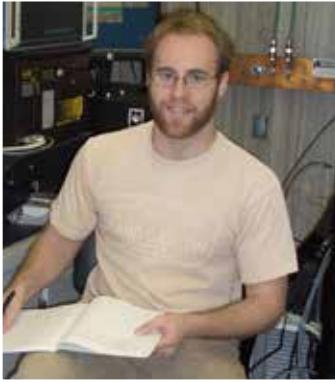
What we think is happening is that when mercury enters the air, bromine chemically reacts with it in what we term an oxidative process. This transforms the mercury into a water-soluble form that can stay high in the atmosphere for long periods of time and get transported intercontinentally. Thunderstorms can scavenge oxidized mercury from this global pool. Our measurements establish that bromine is more effective at supplying this global pool with oxidized mercury. Most models don’t represent bromine chemistry yet.

Why does a global atmospheric pool of mercury matter?

It affects whether local legislation, for example in the Southeast, can successfully control mercury pollution. General scientific consensus is probably not. Local regulations might provide benefits downwind from the power plants but not upwind. Because mercury is a global pollutant, we need a global approach.

You’ve also said the presence of a global pool can explain why rain doesn’t wash mercury out of the air. How is that?

Yes, we call this the lack of a washout effect. Typically, before a rainstorm, pollutant concentrations are higher;



Sean Coburn is a CIRES and Chemistry Ph.D. student whose work with Rainer Volkamer focuses on measuring bromine oxide in the U.S. Southeast.



Volkamer photographed this thunderstorm during a science flight over the Pacific Ocean. These storms can reach up 10 miles into the atmosphere, pulling mercury down lower where rain can wash it into ecosystems and water bodies.

then after the storm, those pollutants can disappear as the rain “washes” the atmosphere. But mercury concentrations stay high in rainwater from the beginning to the end of storms. We think that thunderstorms are reaching into the global pool, scavenging mercury, and “stirring” it through the air. That means raindrops are cleaning mercury from the air, but it’s immediately being replaced by mercury from the pool. So water-soluble mercury is being continuously washed out and continuously supplied [by halogen chemistry].

Do atmospheric halogens have other implications?

Yes, halogens also destroy tropospheric ozone pollution. Right now, emission scenarios from the Intergovernmental Panel on Climate Change predict unhealthy summer ozone levels throughout the Northern

Hemisphere by the end of the century. Our discovery of the high halogen levels means the atmosphere has a larger ability to cleanse itself than originally thought, so the air might not get as dirty as fast. That’s the good news.

And the bad news?

Through various chemical reactions, halogens also lengthen the lifetime of methane, a greenhouse gas, which means global warming could occur faster than models predict.

What’s next?

In spring 2014, we’ll fly over the western Pacific Ocean to check if what we’ve seen over the eastern Pacific is representative globally.



Volkamer’s Differential Optical Absorption Spectroscopy instrument hangs under the aircraft’s wing.



Volkamer and the NSF/NCAR Gulfstream V research aircraft in Broomfield, Colo.

Scintillating science

Measuring bromine in the atmosphere is tricky business. Because bromine radicals are very reactive and short-lived, “if you suck air through an inlet tube to analyze them, these radicals can get lost along the way,” Rainer Volkamer says. To solve this problem, Volkamer and his team custom built a new instrument, dubbed Differential Optical Absorption Spectroscopy (DOAS). Instead of taking air samples, DOAS looks at scattered sunlight. As sunlight travels through the atmosphere, it interacts with gases and particles. Different gases and particles scatter and absorb light differently at different “colors.” The DOAS instrument measures the absorption of bromine oxide radicals over a range of colors and altitudes. From this, DOAS can detect the amount of bromine in the air. “We quantify levels of bromine oxide radicals that had previously not been possible to detect,” Volkamer says.

Waste Not

Curtailment of renewables means lost energy

By Leigh Cooper

In the world of electricity, generators must provide the exact amount of energy, second by second, that users demand. But some conventional power plants, fueled by coal or nuclear, cannot be turned on and off like a light switch. So when demand drops very low, instead of reducing nuclear or coal production, which can't easily drop below a certain base load, the power grid reduces production of renewable energy—below the amount these sources potentially could provide.



Such reductions, called curtailment, allow energy production to equal energy demand, but also permit potential energy to drift away in the wind. Xi Wang, a CIRES graduate student with the Center for Science and Technology Policy Research, and her colleagues at the National Renewable Energy Laboratory, recently reported on curtailment practices worldwide.

They found that countries interested in bolstering the renewables industry are attempting to mitigate curtailment, because high curtailment levels discourage investors: No

one wants to produce energy they can't sell.

Mitigation strategies vary from changes in energy markets to government incentives. "In many areas, for example, renewable energy generators now can offer bids into a wholesale electricity market," Wang says. "If their bid is accepted, their energy is dispatched. When renewables can bid into the market like other generation sources, they know they're competing based on market demands." In other regions, especially Europe, energy providers compensate renewable-energy producers for curtailed energy.

Curtailment takes another form too: Construction of transmission lines is expensive and can lag behind construction of wind and solar farms, so at times, not all the energy from a wind or solar farm can be transported to cities. So, completing transmission projects would also help maximize renewables' potential. "We hope other regions encountering increasing curtailment can better plan by incorporating some of these successful mitigation strategies," Wang says.



Getting the Carbon Out of US Energy

By Katy Human

Proponents of renewable energy often bemoan the "fact" that wind and solar energy can't reliably provide power for every person in the United States, all the time. But CIRES researcher Christopher Clack, NOAA's Sandy MacDonald, director of the Earth System Research Laboratory, and their colleagues aren't convinced. For one thing, few of the researchers analyzing wind and solar potential have a background in meteorology, even though it's weather that primarily drives that potential.

So the NOAA and CIRES team created a mathematical model that incorporates all aspects of the U.S. energy system. The researchers started with the location of current coal, gas, and nuclear plants and the costs of installing new transmission lines. They included the hourly ups and downs of power demand everywhere in the continental United States and the prices people pay for their power, now and projected into the future. And they included hour-by-hour weather information, so they knew when and where wind turbines might spin and solar panels produce energy. Importantly, they included a national system of wind and photovoltaic solar power plants, with details such as location and size to be determined by the model runs.

"In essence, we created a national energy simulator," says Clack. "We can use it to answer critical questions about renewable energy: its affordability, reliability, and the possibility of renewables meeting our growing energy needs."

Clack, MacDonald, and their colleagues can, for example, insist that the model never allow an area to go without power; ask it to optimize renewables' role in the power supply system; or have it minimize future costs. They can ask it to "solve" the challenge of creating a transmission system that allows for widescale use of renewables. The computerized system is so sophisticated, it takes a week to run simulations. Preliminary results are promising, with more to come in 2014...



DEWIS SCHROEDER/ARL

Whither the Wind

Better observations improve wind energy forecasts

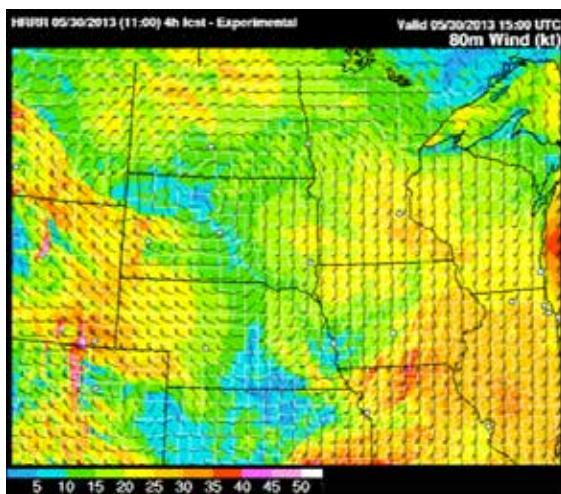
By Katy Human

The wind may be a potent source of power, but wind is as variable as the weather, gusting hard one night and calming the next morning. So in 2011, CIRES and NOAA researchers teamed up with colleagues in the Department of Energy (DOE) and two private wind energy companies, to see if they could improve forecasts of the winds relevant for modern wind turbines, whose hubs tower about 350 feet above the surface, with blades that reach even higher. Better forecasts might help producers anticipate and plan for changes in power supply, which could make energy cheaper.

After two years of experiments with innovative instrument arrays in and near wind farms and high-resolution modeling updated with new weather information each hour, the partnership is paying dividends: “We can improve the accuracy of wind energy forecasts by capturing additional meteorology data and using those data in our weather forecast models,” says Laura Bianco, a CIRES researcher at NOAA’s Earth System Research Laboratory in Boulder, Colo.

Led by CIRES’ Joe Olson, Bianco and colleagues at NOAA, AWS Truepower, WindLogics, the DOE, and the National Renewable Energy Laboratory ran a series of “data denial” experiments, with sophisticated supercomputers and models. In one set of model runs, they used real-time weather data gathered at wind farms in Texas, Minnesota, and other parts of the upper Midwest. Those data came from extensive instruments set up for the experiment: devices called sodars and wind-profiling radars and anemometers, which captured measurements of wind speed and direction and other data important for understanding weather.

In a second set of model runs, the research team “denied” those additional data from the weather models, so the models used only the usual sources of data, including



The High-Resolution Rapid Refresh model forecasts wind speed and direction (color and barbs) for May 30, 2013.

measurements made at weather stations scattered much more widely around the Texas and Midwestern regions.

It was rewarding, Bianco says, to find that the additional data made a statistically significant improvement in the forecasts of sudden changes in the speed or direction of wind, for example. If such sudden increases or decreases in winds aren’t forecast, power suppliers may be forced to draw upon reserve sources of power, which can increase cost.

Next, the researchers will look into the economic impact of the additional data and sophisticated modeling efforts: Would the improved forecasts from this project economically help wind energy companies, by helping operators maximize their use of relatively cheap wind power, or minimize reliance on “backup” sources of power, such as gas-fired power turbines?

Learn more about the Wind Forecast Improvement Project: <http://www.esrl.noaa.gov/psd/psd3/wfip/>.

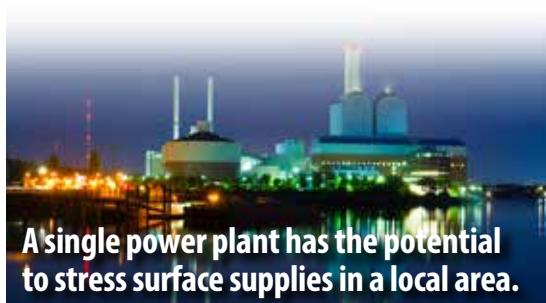
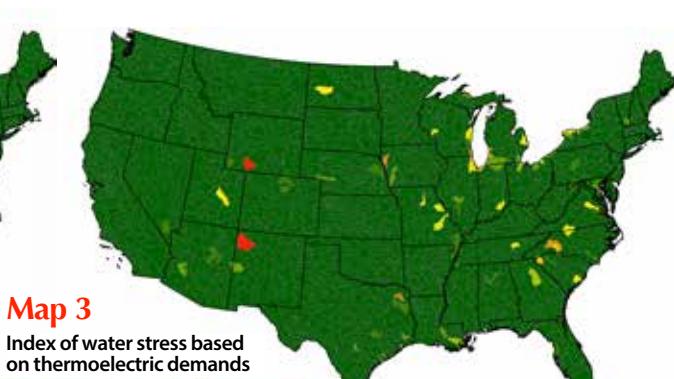
Troubled Waters

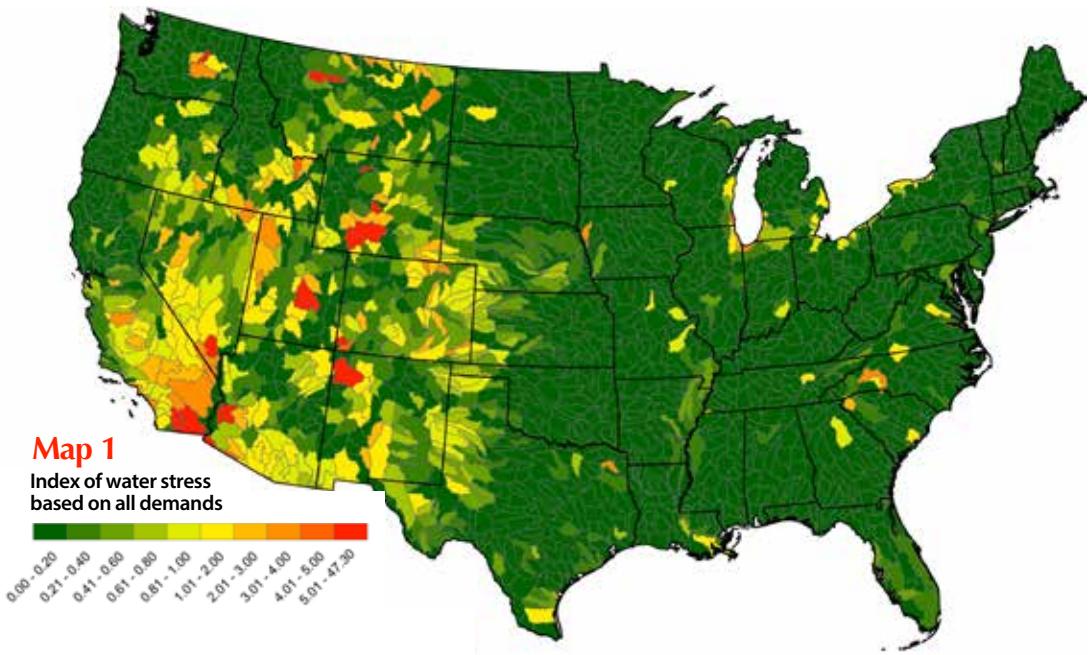
10 things you didn't know about our watersheds

By Kristin Bjomsen

Kristen Averyt, associate director for science at CIRES, recently led a comprehensive analysis of the nation's surface water during the last 10 years, including water demands from power plants, agriculture, and cities. Here are some of the findings reported in full in *Environmental Research Letters* in September 2013.

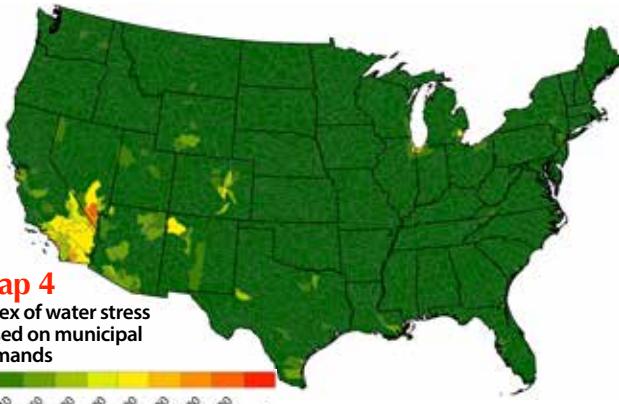
1. Nearly **1 in 10 U.S. watersheds** is “stressed,” with demand for water exceeding 100 percent of natural supply. Yet freshwater ecosystems can be negatively impacted long before this if insufficient water remains for plants and wildlife in that area.
2. The **U.S. West is the most vulnerable** to water stress because the margin between average demand and average supply is small, so slight changes in either supplies or demands can figuratively drain the cup. This region also relies heavily on imported and stored water to supplement natural supplies.
3. In the U.S. West, **irrigated agriculture** typically accounts for more than **80 percent of total water withdrawals** and contributes most to water stress (see Map 2).
4. **Power plants**, which use water for cooling, account for **49 percent of total water withdrawals in the United States**. Map 3 shows where these electric power plants are the most significant contributors to water stress, even in the water-abundant East and Midwest.
5. “A **single power plant** has the potential to stress surface supplies in a local area,” says coauthor James Meldrum, a researcher in the Western Water Assessment, a program of NOAA and CIRES. “With the potential for increasing water stress in the next few decades across parts of the United States, power plants—and our access to electricity—may be at risk if water is not adequately considered in planning.”





Map 1
Index of water stress
based on all demands

6. In southern California and the Las Vegas area, **thirsty cities most greatly stress the surface water**. Municipal and industrial water use alone withdraws more than the natural supply in these areas. Agriculture and power plants exacerbate that stress (see Map 4).
7. To **bridge the gap** between demand and natural supply, stressed areas usually import water from other watersheds, store water in reservoirs, and overdraw groundwater.
8. **Groundwater resources represent 23 percent of annual water use nationwide**. In many areas, it's unclear how much groundwater remains. For some aquifers, however, water managers have a better idea. For example, "Aquifers underlying the Central Valley in California and the Ogallala, which spans the area between Nebraska and Texas, are being drawn down more rapidly than they are being recharged," the researchers write.



Map 4
Index of water stress
based on municipal
demands

9. **Climate change will increase stress** in coming years. "By midcentury, we expect to see less surface water supplies in several regions of the United States," Averyt says. "This is likely to create growing challenges for farms, electricity suppliers, and cities, as there may be more demand for water and less to go around."
10. Some **solutions** include increased water conservation, reuse, and efficiency. Studies like this one can also help, by identifying in detail the sectors contributing to water stress.



In southern California and the Las Vegas area, thirsty cities stress water supplies.

ISTOCK

"Stress as it's indicated in our analysis is like the engine light going on in a car. It could be the engine is about to blow up, or it could be a low tire. It means we need to take a closer look at what's happening to our water supply."

—Kristen Averyt

Into the Air

In the United States today, there are more than 1 million active oil and natural gas wells. New technologies mean producers can extract oil and gas from new regions and formations and the production of this so-called unconventional oil and natural gas has risen quickly. What do these and other changes in the energy sector mean for the air we breathe? For the already warming atmosphere? Could leakage of methane, a potent greenhouse gas, and other gases along the natural gas supply chain erode the climate benefits of cleaner-burning natural gas? CIRES scientists are seeking quantitative answers to those questions, developing new measurement and analysis techniques to investigate the atmospheric impacts of oil and natural gas activities, from production to use.

Towering science

About 20 miles north of Denver, next to Erie High School, a tower soars nearly 1,000 feet into the air, tall as a 90-story skyscraper. There are no floors or offices in this structure, though, just a metal lattice studded with inlet valves and instruments, and an elevator barely big enough for three people. The tower, at the Boulder Atmospheric Observatory (BAO), was erected in 1977, and scientists now use it for diverse research projects. In the last few years, CIRES and NOAA atmospheric scientists working at the tower noticed surprisingly high levels of methane, a potent greenhouse gas, and chemicals called volatile organic compounds (VOCs) in the atmosphere. VOCs can react to create surface ozone pollution. CIRES and NOAA researchers chased down clues from the tower to figure out the chemicals' origins. Two published studies are detailed below.

Fuel for ozone pollution

In the winter of 2011, Jessica Gilman, a CIRES research chemist at NOAA's Earth System Research Laboratory (ESRL), and colleagues were working at the BAO to better understand nighttime chemical reactions that can affect air quality. They found themselves surprised at the observed levels of VOCs.

"Average levels of the VOC propane were higher than the range of values reported for 28 U.S. cities," Gilman says. "They were four to nine times higher than in Houston, Texas, and Pasadena, California."

A component of raw natural gas, VOCs such as propane and ethane can leak during oil and gas extraction, like bubbles escaping from a soda can. VOCs can then react in the air to form lung-damaging ozone pollution.



NOAA's Boulder Atmospheric Observatory includes this 985-foot-tall tower for science, near Erie, Colo.

DAVID OONIK/CIRES

By Katy Human



DAGEN HUGHES/HENDRIX COLLEGE

Researcher Jessica Gilman (CIRES and NOAA) next to the whole air samplers aboard the NOAA WP-3D aircraft. Each sampler holds a “snapshot” of ambient air collected every few minutes during a research flight. Scientists on the ground then analyze each gas sample for hundreds of different compounds.

Cars, vegetation, livestock, and other sources also emit VOCs.

To track down the source of the Front Range VOCs, Gilman’s team analyzed more than 550 air samples from the tall tower’s base. They characterized 53 chemicals and compared results to the composition of raw natural gas, a process that amounts to chemical fingerprinting.

“Each source has its own specific composition; cars look like one thing, trees like another,” Gilman says. “Just like your nose knows what a flower smells like, or coffee, or a farm, our instruments can ‘smell’ and identify oil and natural gas emissions. The signature is a very clear, robust marker.”

Reading that signature, Gilman and her colleagues found that oil and natural gas activities accounted for 55 percent of the VOC reactivity that contributed to ozone formation in this region.

“Oil and natural gas operations are the dominant wintertime source of volatile organic compounds that act as starting ingredients for ozone pollution,” Gilman says. The work was published in 2012 in the journal *Environmental Science and Technology* with coauthors Brian Lerner, William Kuster, and Joost de Gouw, all CIRES scientists at NOAA.

continued on page 14

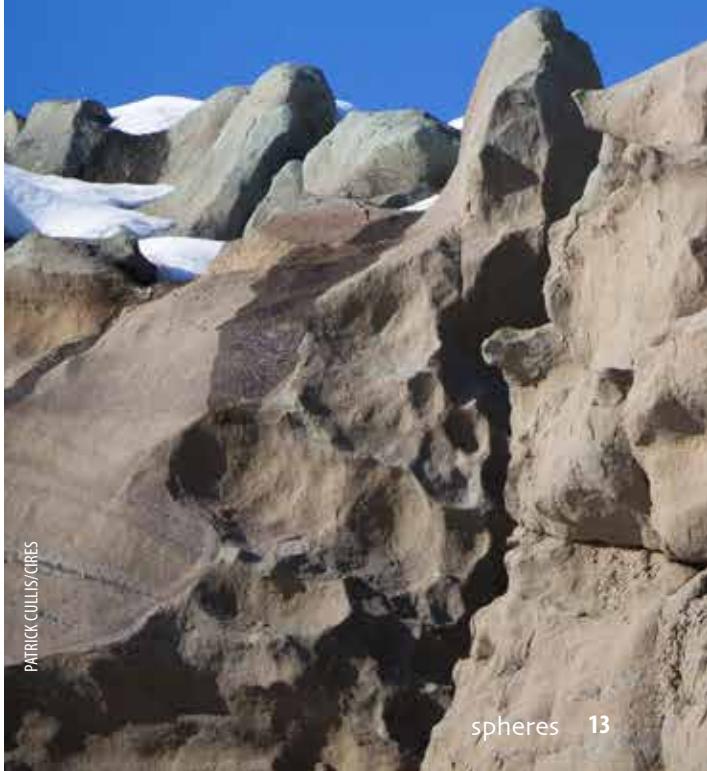
High ozone in winter

Ozone pollution is supposed to be a summertime problem, in big cities with lots of traffic. So when wintertime ozone levels occasionally skyrocketed at a handful of sparsely populated Western sites in recent years, CIRES and NOAA scientists took notice. During the winters of 2012, 2013, and 2014, they focused their attention and instruments on Utah’s Uintah Basin, a region of intense natural gas exploration and development.

There, ozone some days shot to 120 parts per billion (averaged over eight hours; the health-based standard is 75). Ozone is a regulated pollutant because it can damage people’s lungs, crops, and other plants.

Results are beginning to emerge: Ozone exceedances occurred during cold months when snow coated the ground and temperature inversions trapped gas field emissions in the bowl-shaped basin. Some researchers also measured surprisingly high levels of air toxins, such as benzene. More detailed results will be published in 2014. Stay tuned...

A balloon lofts an ozone-measuring instrument high into the atmosphere above Fantasy Canyon, Utah.



PATRICK CULLIS/CIRES

Into the Air...

continued from page 13

Gilman and her colleagues continue to use the chemical fingerprinting technique. During the summer of 2013, she was part of a major mission to better understand air quality and climate in the U.S. Southeast. The international research team used aircraft to collect air samples from a wide region that included cities and towns, dense forests, and three of the country's biggest shale plays, where natural gas is extracted.

Gilman worked in a Tennessee airport hangar, churning through samples as they came off flights. Her results may help scientists understand what sources contribute to the region's haze, which often tints the Smoky Mountains purple, and may help explain why the Southeast has not warmed as much as other regions.

More methane than estimated

A few years ago, as part of a separate study, routine atmospheric measurements at the BAO also turned up surprisingly high concentrations of chemical pollutants. CIRES researcher Gabrielle Pétron used a mobile laboratory to search for sources.

Pétron, who works at ESRL, outfitted a passenger car and later a van with sensitive instruments designed to measure in real time methane, carbon dioxide, carbon monoxide, and ozone, and to collect air samples for later chemical analysis of several VOCs.

She and her colleagues drove along public roads in northeast Colorado, targeting areas downwind of many possible sources: landfills, feedlots, and oil and gas operations. Onboard instruments let them identify plumes of air rich in emissions.

After thousands of readings and analysis of dozens of air samples on NOAA's ultra-sensitive instruments, her team identified a key source for methane and other chemical pollutants: oil and natural gas operations in northeastern Colorado. Fossil fuel extraction at more than 14,000 active wells and the associated operations and equipment were leaking about twice as much methane into the air as previously estimated: about 4 percent of all the methane extracted by producers in the region. That's close to three times the 1.4 percent leak rate estimated on average for the country, Pétron reported in a *Journal of Geophysical Research* paper in 2012.

The researchers also found that the carcinogenic gas benzene came from two major sources: oil and natural gas activities and vehicle combustion exhaust.

Since the original data were collected in 2008, Pétron and her colleagues have continued their fieldwork, using increasingly sophisticated instruments for airborne and ground-based measurements. She anticipates publishing updated data from Colorado's Front Range in 2014.

Methane, nationwide

Human sources—including cattle farms, landfills, and natural gas extraction—pump 1.5 to 1.7 times more methane into the atmosphere than previously estimated, according to a 2013 *PNAS* study. The Harvard-led work, including CIRES and NOAA, compared inventory-based estimates of methane emissions to those based on atmospheric observations.

The inventory-based or "bottom-up" estimates measured an industry's total impact by starting with the emissions of a single cow, for example, or a valve in a pipeline. The new study used direct measurements of methane and other gases to trace the greenhouse gas back to its sources. In some areas, the bottom-up and atmosphere-based estimates were similar.

In others, they differed: In the south-central United States, the new estimate for methane from fossil fuel operations was twice the previous amount.



STOCKXCHANGE

A look at Utah

On a winter day in Utah's Uintah County in 2012, CIRES and NOAA researchers tested out a new way to measure methane emissions from a natural gas production field. Given ideal conditions that day, the team determined that more than 120,000 pounds of methane poured out of the field into the air every hour—that's 6 to 12 percent of the average hourly natural gas production in the region. The results appeared in *Geophysical Research Letters* in 2013.

Search for the missing leak

In Los Angeles, scientists and state officials already knew there was a mismatch between inventory-based estimates of methane emissions and levels of the gas in the air. The inventories included a diversity of sources of the greenhouse gas: the La Brea Tar Pits, livestock, landfills, and more. But the estimates were too low by about 35 percent. CIRES' Jeff Peischl and colleagues figured out where the extra methane came from: fossil



fuel sources. Their chemistry analysis, published in 2013 in the *Journal of Geophysical Research*, identi-

fied leaking pipeline and distribution systems, geological seeps, and emissions from the local oil and gas industry.

STOCKXCHANGE



ISTOCK

Power plant emissions down

CIRES, NOAA scientists find switch to natural gas power plants means fewer air pollutants

Power plants that use natural gas and a new technology to squeeze more energy from the fuel release far less of the greenhouse gas carbon dioxide than coal-fired power plants do, according to CIRES-led research published in early 2014 in the journal *Earth's Future*. The so-called “combined cycle” natural gas power plants also release significantly less nitrogen oxides and sulfur dioxide, which can worsen air quality.

“Since more and more of our electricity is coming from these cleaner power plants, emissions from the power sector are lower by 20, 30, even 40 percent for some gases, since 1997,” says lead author and CIRES Fellow Joost de Gouw.

De Gouw and his colleagues—CIRES’ Greg Frost and NOAA’s David Parrish and Michael Trainer, all from ESRL—analyzed data from systems that continuously monitor emissions at power plant stacks around the country. Previous airplane-based studies have shown these stack measurements are accurate for carbon dioxide (CO₂) and for nitrogen oxides and sulfur dioxide. Nitrogen oxides and sulfur dioxide can react in the atmosphere to form tiny particles and ozone, which can cause respiratory disease.

To compare pollutant emissions from different types of

power plants, the scientists calculated emissions per unit of energy produced, for all data available between 1997 and 2012. During that period of time, on average:

- Coal-based power plants emitted 915 grams of CO₂ per kilowatt hour of energy produced;
- Natural gas power plants emitted 549 grams of CO₂ per kilowatt hour; and
- Combined cycle natural gas plants emitted 436 grams of CO₂ per kilowatt hour.

Between 1997 and 2012, the fraction of U.S. energy produced from coal decreased from 83 to 59 percent, and the fraction from combined cycle natural gas plants rose from none to 34 percent. In combined cycle natural gas plants, operators use two processes in tandem to convert a higher fraction of heat into electrical energy.

That shift in the energy industry meant that power plants, overall, sent 23 percent less CO₂ into the atmosphere last year than they would have had coal been providing about the same fraction of electric power as in 1997, de Gouw says. The switch led to even greater reductions in the power sector’s emissions of nitrogen oxides and sulfur dioxide, which dropped by 40 percent and 44 percent, respectively.

At concentrating solar thermal plants (CSP) similar to this one in New Mexico, mirrors focus sunlight to generate heat used to produce electricity. Most CSPs require water for cooling, and CIRES' Kristen Averyt and colleagues in the Western Water Assessment study the water-resource consequences of these plants and other sources of power (see page 10).

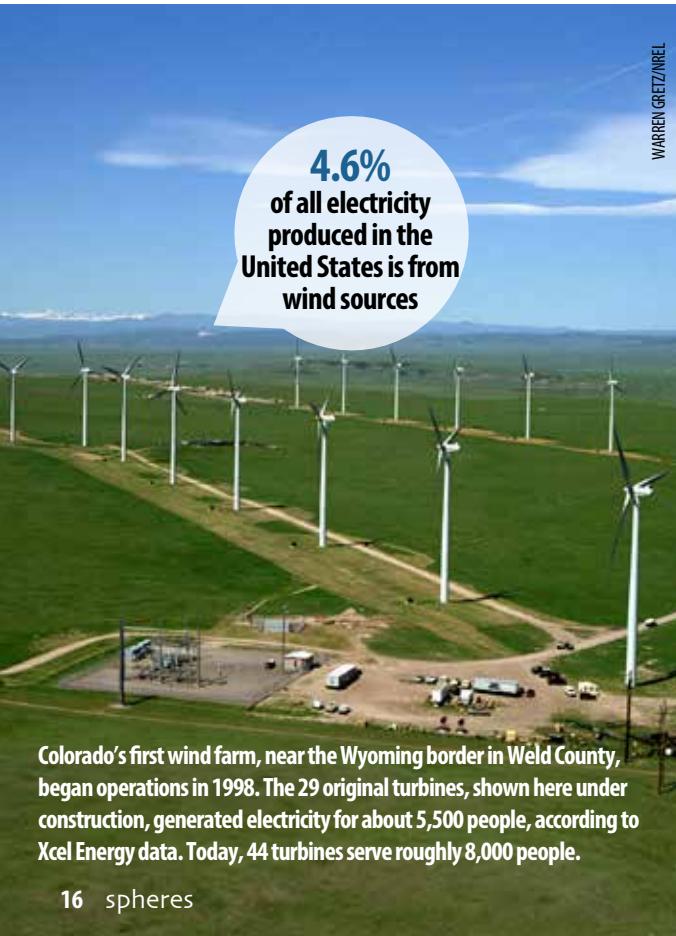
Up to 1,000 gallons of water needed per megawatt-hour of electricity produced



Portrait of a Joule

4.6% of all electricity produced in the United States is from wind sources

WARREN GRETZ/NREL



Colorado's first wind farm, near the Wyoming border in Weld County, began operations in 1998. The 29 original turbines, shown here under construction, generated electricity for about 5,500 people, according to Xcel Energy data. Today, 44 turbines serve roughly 8,000 people.

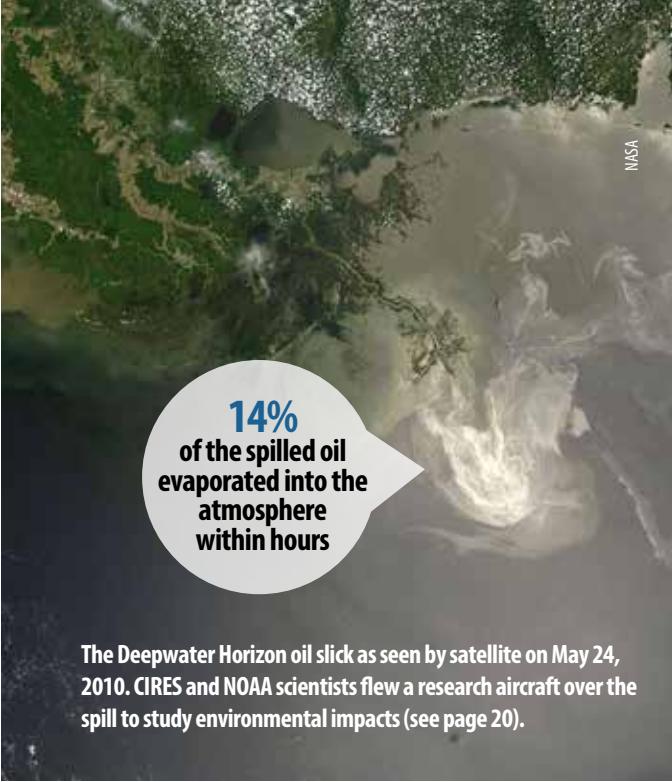
176.8 billion barrels of oil estimated in Alberta, Canada's tar sands

ISTOCK



Shao-Meng Li, a 2012-13 CIRES visiting fellow, studies air pollution from oil sands production in Alberta, as part of Canada's new environmental monitoring program to examine the air, water, and ecosystem impacts of oil sands mining activity.

Energy and Environment



NASA

14%
of the spilled oil
evaporated into the
atmosphere
within hours

The Deepwater Horizon oil slick as seen by satellite on May 24, 2010. CIRES and NOAA scientists flew a research aircraft over the spill to study environmental impacts (see page 20).



ECOFLIGHT

482,822
producing gas wells
in the United States

Aerial photo of natural gas wells in the Green River Basin of Wyoming. CIRES scientists study air quality impacts of natural gas production across the United States (see pages 12-15).

Our energy comes from many sources, each with its own environmental impacts—some of them invisible and some of them quite visible, as captured here.



NASA

**Natural gas flares
from Bakken oil field
in North Dakota**

NOAA's Chris Elvidge and his CIRES colleagues create the Earth at Night image by compositing images from the NOAA-NASA Suomi NPP satellite. With the Suomi NPP, scientists can distinguish among city lights, fires, volcanoes, and gas flares and determine size, temperature, and radiative heat for all types of night fires.

HARVESTING

The growing role of biofuels By Leigh Cooper

Carsten Warneke, a CIRES atmospheric chemist with NOAA, spent a summer in the cornfields of northern Colorado, studying chemicals emitted from the crops and marveling at the vigorous plants. "It's really amazing how fast corn grows," Warneke says. "On some days, when the weather was good, it grew almost an inch per day."

He and his colleagues had good reasons for plunking themselves down in the middle of Colorado State University's cornfields to watch corn grow. The demand for biofuel crops, such as corn, is soaring. Federal regulations passed in 2005 and 2007 require that biofuel must be mixed with gasoline, in increasing amounts, with the goal of fostering a renewable, domestically produced transportation fuel. In 2010, most gasoline at U.S. pumps contained 10 percent ethanol, made primarily from corn, compared to 1 to 2 percent in the early 2000s.

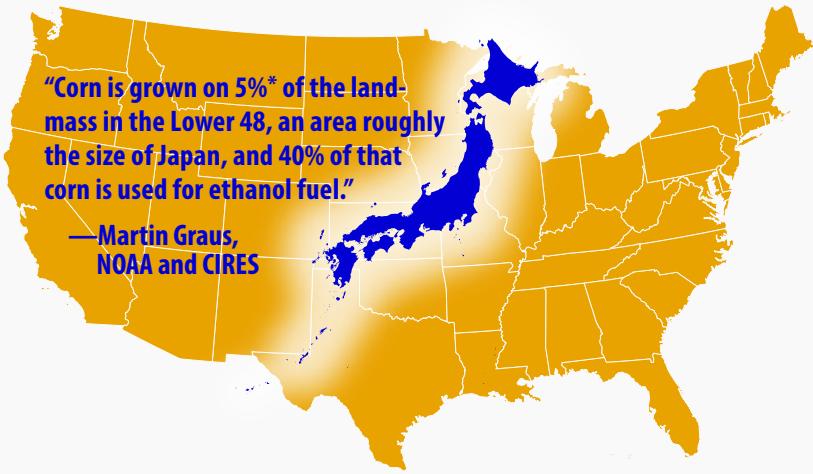
And atmospheric researchers are eager to know the effects this shift has had on air quality and climate. Plants naturally emit chemicals called volatile organic compounds (VOCs), which can contribute to the formation of the regulated pollutant ozone. VOCs can also influence

regional and global climate by enabling the formation of aerosols, tiny airborne particles that alter the amount of radiation the atmosphere absorbs and reflects.

But what VOCs do biofuel crops, especially corn, emit and how might they affect regional air quality, the team wanted to know. From their investigations, they discovered that "corn's main VOC emission is methanol, which is not very reactive in the air," Warneke says. "This means the air quality implications of growing corn are expected to be relatively small."

Comparing crops

Along with corn ethanol, the federal regulations also require that some of the biofuel added to gasoline comes from non-starch feedstock, such as switchgrass, instead of corn. The rule's motivation: Non-starch feedstocks do not compete as a food source, and in some places, they can be grown using less energy and water. So industry and scientists are investigating woody plant and grass alternatives, such as switchgrass and poplars, to feed ethanol production. They're also looking at the environmental impacts of each.



"Corn is grown on 5%* of the land-mass in the Lower 48, an area roughly the size of Japan, and 40% of that corn is used for ethanol fuel."

**—Martin Graus,
NOAA and CIRES**

Until now, few studies have measured the volatile organic compound emissions of crops, even common ones like corn, which are potentially significant sources.

*U.S. Department of Agriculture figure

G ENERGY



MARTIN GRAUS/CIRES

CIRES' Allyson Eller (in front) and Rui Li (background) set up a pole for corn height measurements during a 2011 study in Colorado.

In one study, CIRES scientist Martin Graus and his team measured the VOC emissions of 30 species of poplar trees, a potential source of cellulosic ethanol. Emissions increased when the plants were photosynthesizing and growing faster, and the genetic strain of the plants made

a difference, too. Some VOC emissions from poplars were significantly higher than from corn and from switchgrass. At present, the use of poplars and other woody species for ethanol production is in its infancy.

Informing decisions

With half of all ethanol expected to come from non-starch feedstock in the near future, these studies may help guide decisions concerning which biofuel crops to grow. "Whenever you change an existing ecosystem, it's better to be informed beforehand about what's going to happen after you make a big change than having to dial back and fix it," Graus says.

The scientists' research to quantify VOC emissions from crops may also help improve the accuracy of climate and air quality forecasts. Current models don't differentiate emissions from different crop varieties—corn versus wheat, for example.

"If you want to study the atmospheric chemistry of a continent or a large region, you need to know which sources are putting chemicals into the big chemical reactor we call the atmosphere," Graus says.

Biofuels wafting in the air

Ethanol, now used commonly in U.S. gasoline mixtures, is turning up in urban air at more than six times the levels measured a decade ago, according to research led by CIRES and NOAA scientists.

Using research planes, Joost de Gouw, a NOAA-funded CIRES scientist, and his colleagues measured urban air quality during four research campaigns between 2002 and 2010. "The rise of ethanol in urban air is consistent with the rise in ethanol use," de Gouw says. "It should not have been unexpected perhaps, but it was certainly striking."

Ethanol itself is not considered very reactive, but it can be oxidized to create acetaldehyde, a hazardous pollutant and precursor for ozone formation. Surprisingly, though, de Gouw found that in Los Angeles, despite increases in atmospheric ethanol concentrations, acetaldehyde had decreased. "The reason is that acetaldehyde is formed from ethanol but also from a lot of other pollutants," de Gouw says. "And all of those pollutants had gone down as motor vehicle emissions became (or grew) cleaner over the years." (See "Skies of Blue," page 5.)

In the future, shifts in fuel composition and biofuel use could further affect the atmosphere's composition and chemistry. "As we develop new fuels, we need to know how the atmosphere is affected so we can make the best choices," de Gouw says.

DEEPWATER HORIZON

The BP oil leak is plugged, but new findings continue to gush forth

By Laura Snider

On an April day in 2010, a drilling rig in the Gulf of Mexico erupted into flames after an onboard explosion. Oil gushed from a well on the ocean floor for 87 days before it was capped in July.

While the oil spilled, scientists from CIRES, NOAA, and other institutions used their expertise to study the environmental impacts. The researchers had already loaded a NOAA WP-3D research plane with a bevy of sensitive scientific instruments to measure air quality in California. NOAA decided to divert the plane to the Gulf of Mexico so the scientists could make two flights over what would become one of the largest accidental oil spills in history.

The information collected by the research plane was immediately useful to emergency responders on the ground. These responders were concerned about the air-quality impacts of fires lit to burn crude oil off the ocean surface. The levels of toxic organic compounds and other air pollutants measured by CIRES and NOAA scientists from the aircraft were within acceptable limits.

The data also have had a lasting scientific impact. Since the spill, CIRES Fellow Joost de Gouw, in collaboration with NOAA's Tom Ryerson and other CIRES and NOAA scientists, have made a number of important findings. For example, they learned how to estimate using only airborne measurements the amount of oil leaking thousands of feet beneath the water; they observed a rapid and efficient aerosol formation from crude oil vapors; and they were able to quantify the amount of black carbon pumped into the air by the surface fires (1 million pounds).

Even four years later, the data are yielding discoveries. Because the atmospheric chemistry that occurs after an oil spill has not been well studied, it wasn't immediately obvious to the scientists what all the measurements meant. For example, they might measure a compound in the air but not know the starting ingredients or chemical reaction that created the compound. So de Gouw and his colleagues are now recreating oil spill condi-

tions in the laboratory to understand the big picture.

"Looking at crude oil vapors in the lab has answered some of our questions about our measurements," he says. In that vein, a graduate student mimicked the aerosol formation that results from those crude oil vapors in the lab and "got results that were amazingly similar to what we saw over the Gulf oil spill," he says.

CIRES and NOAA researchers also have combined their atmospheric data with information collected by oceanographers to get a better handle on where, exactly, all that oil went. "From the oil composition, we knew that several compounds were released at the bottom of the sea but never made it to the surface," de Gouw says. "Those compounds were removed—dissolved and chewed up—by microbes in the water."

The value of the data collected and scientific discoveries made has led NOAA to consider outfitting a research plane with fast-response capabilities to quickly estimate the severity of future oil spills and analyze emissions.

"Scientifically, we were charging into new territory, and it was a great tribute to our team that we gleaned so much information from just two flights," de Gouw says.



NOAA

Oceanography professor Laura Tenenbaum introduces the Stabilization Wedges Game to her students at Glendale Community College, Calif.

ANDREW YEFETZ

Climate in the Classroom

CLEAN program gives educators tools for success

By Kristin Bjornsen

Laura Tenenbaum's students at Glendale Community College in California don't want to talk about climate change. They want to talk about climate change solutions. "They're past the debate of whether global warming is real," says Tenenbaum, an oceanography professor as well as a communication specialist for NASA's Global Climate Change webpage (<http://climate.nasa.gov>). "They want to move forward."

Helping Tenenbaum spark that conversation is the CIRES-led Climate Literacy and Energy Awareness Network. This online database contains about 580 rigorously reviewed materials for teaching climate and energy science in grades 6 through college. Tenenbaum has been involved with CLEAN since its beginning in 2010, using, reviewing, and contributing materials.

Last November, she tried out a classic CLEAN activity: the Stabilization Wedges Game, created by experts at Princeton, BP, and Ford. Students must pick and choose various carbon-cutting strategies (represented by wedges). Their goal: Keep Earth's CO₂ emissions flat.

With some groups of students speaking English and oth-

ers Armenian, Japanese, and Korean, the room hummed with debate. Some groups chose mostly green wedges (renewables and biostorage); others favored yellow (efficiency and conservation) with a little blue (fossil-fuel-based actions). And one group opted for red (nuclear power). "Europe already uses it, so regarding everything—cost and how we'd have to adapt—we thought nuclear was best," sophomore Daniel Hwang says.

For many students, this was the first time they'd pondered energy use. They're not alone. According to a 2009 report from the nonprofit Public Agenda, 40 percent of Americans can't name a fossil fuel, and 51 percent can't name a renewable energy source. Teachers are key for bridging that gap, but in today's sea of information, finding scientifically sound and engaging materials can be challenging.

"Many educators see the importance of teaching about climate change, especially solutions, but often lack formal training in climate or energy science, so they look for trusted educational sources," says CLEAN project manager Anne Gold, with CIRES. "The CLEAN collection has become such a source by providing scientifically correct and classroom-effective resources."

Back in the classroom, things heated up over whether developed countries should cut more carbon than developing ones. "I was surprised most groups didn't want rich countries to give up more," Tenenbaum says.

But Tenenbaum was seeking that kind of autonomous decision making. "Having grown up with standardized testing, the kids are obsessed with the 'right' answer and memorization," Tenenbaum says. She often tells them no teacher, book, or website knows best; they have to work together to solve the world's problems. The wedge game drove that home: "Afterward, the students said, 'Now we get it, about understanding concepts and not looking for THE answer,'" Tenenbaum says. "For me, that was huge."



At a glance

The Climate Literacy and Energy Awareness Network (CLEAN, cleanet.org) is led by CIRES' Education Outreach, TERC, and the Science Education Resource Center. Funded by the National Science Foundation, Department of Energy, and NOAA, CLEAN provides the:

- 1) CLEAN Collection: High-quality, digital teaching materials on climate and energy, including hands-on activities, demos, videos, and experiments.
- 2) Teaching Climate and Energy: Background info that summarizes essential principles of climate and energy literacy and provides teaching tips.
- 3) CLEAN Community: Vibrant network of educators, professionals, and citizens with weekly virtual meetings, active listserv, and webinar recordings.

SeismicSHIFT

Investigating the connection between oil and gas operations and earthquakes

By Kristin Bjomsen

Close to midnight on August 22, 2011, residents in Trinidad, Colorado, awoke to a shaking that toppled chimneys, collapsed roofs, and caused mudslides. The magnitude 5.3 earthquake was Colorado's largest since 1967.

At the time, media reported it as a natural earthquake, but ongoing research by Matthew Weingarten, a CU-Boulder Ph.D. candidate, points to a possible human trigger: coal-bed methane mining in the nearby Raton Basin. There, operators drill into coal seams and pump out groundwater, allowing methane to flow out. They then dispose of the briny wastewater in dedicated injection wells.

"We are studying the relationship between the highest volume wastewater wells and the largest magnitude earthquakes to see if there's a connection," says Weingarten, who is part of CIRES' Energy and Environment Initiative. In 2014, he'll submit this work for publication.

A connection wouldn't be unprecedented. The first documented example of human-induced earthquakes occurred in the 1960s at Denver's Rocky Mountain Arsenal. For several years, chemical-weapons manufacturers dumped waste fluids down a 12,045-foot-deep injection well. They stopped the practice in 1966 after it set off a series of temblors up to magnitude 4.8.

On shaky ground

Today, uncharacteristic earthquake activity in the U.S. midcontinent has rekindled the topic. Starting in 2001, in states such as Colorado, Oklahoma, Arkansas, Ohio, and Texas, the number of earthquakes has dramatically increased, from a steady rate of 21 midcontinent earthquakes per year to 188 earthquakes in 2011.

A 2012 National Research Council report, along with other studies, confirmed that oil and natural gas opera-

tions are partly responsible. With more than 1 million active wells in the United States, these operations can *extract* large fluid volumes (for example, by draining reservoirs of oil-water mixtures) and also *add* large volumes, by pumping wastewater into deep wells. Both can destabilize the subsurface. The number of induced earthquakes is thought to be in the hundreds.

"That's out of nearly 90,000 operational injection wells, so the risk of any given well triggering an earthquake is relatively small," Weingarten says. "Since, however, these earthquakes can occur in places where buildings aren't constructed to withstand them, they can pose significant risks to people and property."

Assessing the risk

While geologists understand the basic mechanism behind induced earthquakes, they don't know which injection wells will cause tremors. To investigate this, Weingarten and an interdisciplinary team, with funding from the U.S. Geological Survey John Wesley Powell Center, are modeling underground pressure changes from wastewater injections.

"We want to know actual numbers: how the pore pressure changes after an injection and how much pressure is needed for an earthquake to occur in a given area," he says. "That might help us pinpoint where we can inject fluids more safely." Since most faults in Earth's subsurface are critically stressed, even small pressure changes on faults can trigger earthquakes. "So with the large number of injection wells, it's actually a mystery why there aren't *more* induced quakes," Weingarten says.

Listening for tremors

One possibility is that more earthquakes are, indeed, occurring—we just don't see them. Using data from the national network of seismometers, Weingarten is reviewing the locations of earthquakes and injection wells nationwide and whether there's a correlation. However, the national network misses some earthquakes smaller than magnitude 3. Because these micro-earthquakes can lead up to larger ones, scientists need better seismic monitoring to quantify the hazard.

"With a more sensitive network, we could say, 'OK, this injection well turned on, and we're now seeing lots of little earthquakes. This is not a good place to inject. We should shut down the well before bigger earthquakes happen,'" he says. "That's the ultimate goal."

Better monitoring and a better idea of wells prone to trigger quakes could help prevent them. "To protect lives and structures, we need to account for this modern-day risk," he says.



Matthew Weingarten samples a geologic layer used for disposal of mining wastewater in Raton Basin, Colo. (July 2013).

MATTHEW WEINGARTEN/CU-BOLDER

Thinking Outside the NO_x

New instrument reveals hidden contributor to ozone pollution

By Kristin Bjornsen

When CIRES scientist Robert Wild stepped out of the car in Uintah Basin, Utah, during winter 2013, he caught a whiff of something acid. “Other researchers also smelled that characteristic scent of ozone,” Wild says.

Sure enough, field measurements showed ozone levels that far exceeded the national ambient air quality standard (see “High ozone in winter,” page 13). This was surprising. Ozone pollution is produced mainly through reactions involving a group of compounds known as NO_x. This includes nitric oxide (NO) and nitrogen dioxide (NO₂), which are released from tailpipes, power plants, biomass burning, and oil and gas operations. But in Uintah Basin, home to about 10,000 active oil and natural gas wells, NO_x emissions alone couldn’t explain such elevated ozone pollution.

Part of the answer came from a novel instrument developed by Wild and his colleagues Pete Edwards (CIRES), William Dubé (CIRES), and Steven Brown (NOAA). This instrument does two groundbreaking things: First, through four cavities, it measures four types of gases simultaneously; the previous instrument could measure only two.

Secondly, it measures a group of compounds called NO_y. This class includes nitric acid and organic nitrates. In the atmosphere, NO_x oxidizes into NO_y over time. However, it turns out NO_y can revert back to NO_x under certain conditions—thereby serving as a reservoir for NO_x and influencing ozone production.

With the instrument, the researchers discovered that the NO_y and NO_x maintained NO_x at a level most effective for ozone formation in the conditions present in Utah. In other words, the NO_y and NO_x created a “perfect storm” for ozone pollution.

To measure NO_y, one of the instrument’s cavities heats the air sample to 700 degrees Celsius. The NO_y compounds break apart in the heat and reform as NO_x, which lasers then measure. “This is a new, simpler technique for measuring NO_y,” Edwards says. “Usually it’s measured with a much bigger, heavier instrument.”

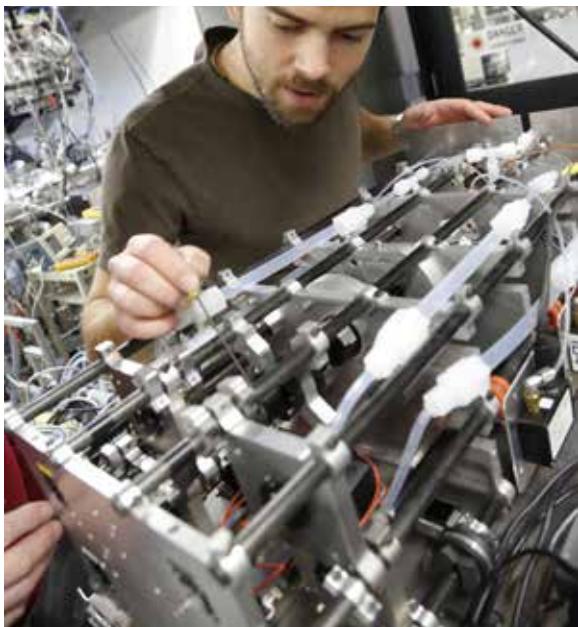
The greatest challenge was getting everything to fit. “We doubled the number of measurements but shrank the instrument’s size,” Wild says. Compactness is important for the next phase: putting the instrument on a mobile platform. In summer 2014, the team will place it in a van and examine traffic emissions along Colorado’s Front Range.

“This instrument really helps us understand emissions, how nitrogen is processed, and ultimately what causes these high-ozone events,” Edwards says. 



DAVID DOONK/CIRES

Robert Wild (left), Steven Brown (middle), and Bill Dubé (right) next to their custom-built instrument, dubbed NO_xCaRD (for NO_x Cavity Ring Down), designed to measure important precursors to ozone formation.



DAVID DOONK/CIRES

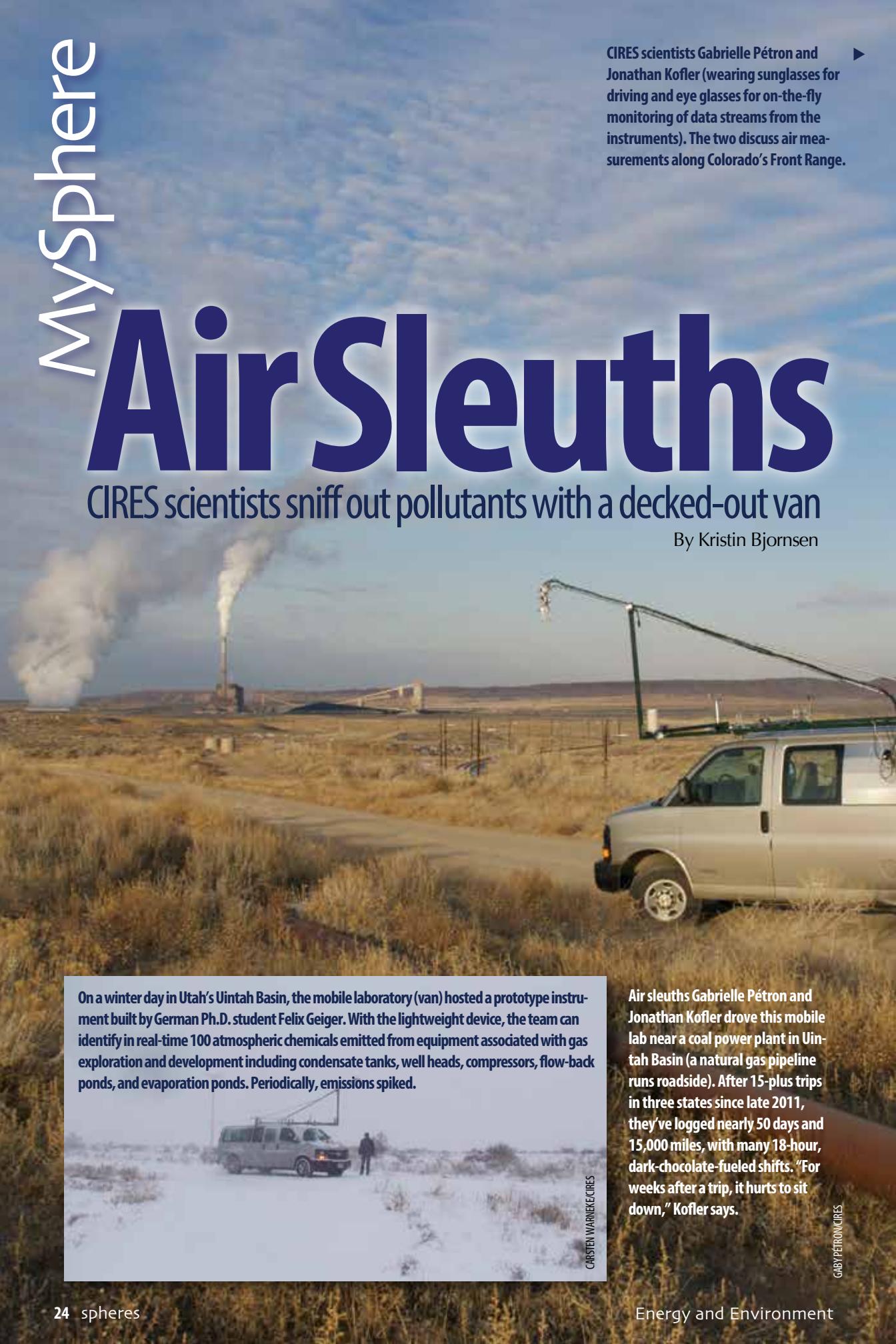
Robert Wild maintains the NO_xCaRD instrument at NOAA’s Earth System Research Laboratory.

CIRES scientists Gabrielle Pétron and Jonathan Kofler (wearing sunglasses for driving and eye glasses for on-the-fly monitoring of data streams from the instruments). The two discuss air measurements along Colorado's Front Range.

Air Sleuths

CIRES scientists sniff out pollutants with a decked-out van

By Kristin Bjornsen



On a winter day in Utah's Uintah Basin, the mobile laboratory (van) hosted a prototype instrument built by German Ph.D. student Felix Geiger. With the lightweight device, the team can identify in real-time 100 atmospheric chemicals emitted from equipment associated with gas exploration and development including condensate tanks, well heads, compressors, flow-back ponds, and evaporation ponds. Periodically, emissions spiked.

Air sleuths Gabrielle Pétron and Jonathan Kofler drove this mobile lab near a coal power plant in Uintah Basin (a natural gas pipeline runs roadside). After 15-plus trips in three states since late 2011, they've logged nearly 50 days and 15,000 miles, with many 18-hour, dark-chocolate-fueled shifts. "For weeks after a trip, it hurts to sit down," Kofler says.

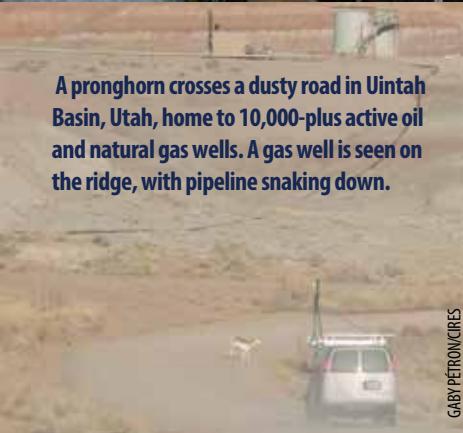


CARSTEN WARNER/CIRES

GABY PETRON/CIRES



DAVID DOONK/CRES



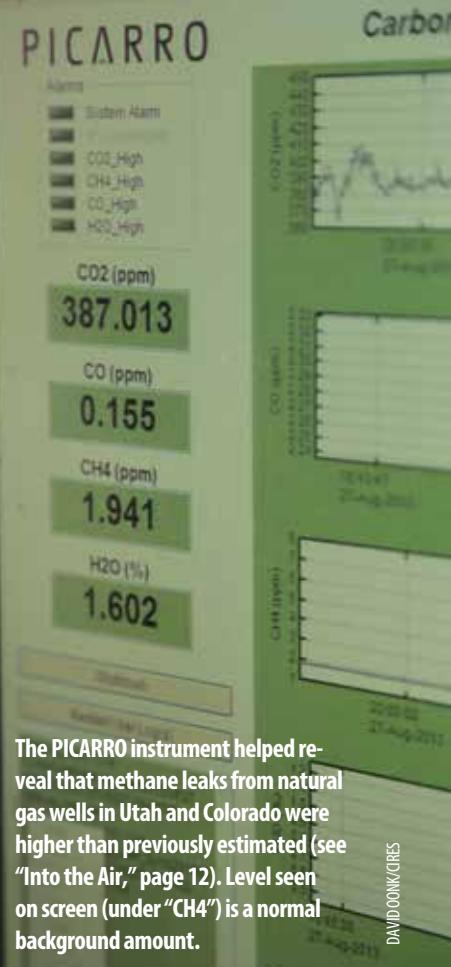
A pronghorn crosses a dusty road in Uintah Basin, Utah, home to 10,000-plus active oil and natural gas wells. A gas well is seen on the ridge, with pipeline snaking down.

GABY PETRON/CRES



Flask sampling unit. One case compresses air into a glass flask; the other stores 12 flasks for in-depth analysis back at the lab.

DAVID DOONK/CRES



The PICARRO instrument helped reveal that methane leaks from natural gas wells in Utah and Colorado were higher than previously estimated (see "Into the Air," page 12). Level seen on screen (under "CH₄") is a normal background amount.

DAVID DOONK/CRES



Air inlet cup and tubes at end of boom, which can hinge 26 feet high. Monitoring of wind direction prevents measurement of van's exhaust.

DAVID DOONK/CRES



DAVID DOONK/CRES



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