National Aeronautics and
Space Administration

Earth at Night

EXPLORE
EARTH

Earth at Night

Our Planet in Brilliant Darkness

Cover image: This global view of Earth's city lights is a composite assembled from data acquired by the Suomi National Polar-orbiting Partnership (NPP) satellite. The data were acquired over nine days in April 2012 and 13 days in October 2012.
(Image credit: NASA's Earth Observatory/NOAA/DOD)

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Foreword

NASA's *Earth at Night* explores the brilliance of our planet when it is in darkness. It is a compilation of stories depicting the interactions between science and wonder, and I am pleased to share this visually stunning and captivating exploration of our home planet.

From space, our Earth looks tranquil. The blue ethereal vastness of the oceans harmoniously shares the space with verdant green land—an undercurrent of gentleness and solitude. But spending time gazing at the images presented in this book, our home planet at night instantly reveals a different reality. Beautiful, filled with glowing communities, natural wonders, and striking illumination, our world is bustling with activity and life.

Darkness is not void of illumination. It is the contrast, the area between light and dark, that is often the most illustrative. Darkness reminds me of where I came from and where I am now—from a small town in the mountains, to the unique vantage point of the Nation's capital. Darkness is where dreamers and learners of all ages peer into the universe and think of questions about themselves and their space in the cosmos. Light is where they work, where they gather, and take time together.

NASA's spacefaring satellites have compiled an unprecedented record of our Earth, and its luminescence in darkness, to captivate and spark curiosity. These missions see the contrast between dark and light through the lenses of scientific instruments. Our home planet is full of complex and dynamic cycles and processes. These soaring observers show us new ways to discern the nuances of light created by natural and human-made sources, such as auroras, wildfires, cities, phytoplankton, and volcanoes.

Science not only changes what we know, but also how we think about our place in the cosmos. I invite you to take a moment to discover our world at night through the eyes of space science. I have no doubt that inherent beauty of these images will inspire—feeding the soul and mind of the reader. As Vincent van Gogh said, “For my part I know nothing with any certainty, but the sight of the stars makes me dream.” I challenge you to look back from the stars to see Earth in a completely new way.

Thomas H. Zurbuchen

Associate Administrator

NASA Science Mission Directorate

Preface

To keen observers, the nocturnal Earth is not pitch black, featureless, or static. The stars and the Moon provide illumination that differs from, and complements, daylight. Natural Earth processes such as volcanic eruptions, auroras, lightning, and meteors entering the atmosphere generate localized visible light on timescales ranging from subsecond (lightning), to days, weeks (forest fires), and months (volcanic eruptions).

Most interesting and unique (as far as we know) to Earth, is the nighttime visible illumination emitted from our planet that is associated with human activities. Whether purposefully designed to banish darkness (such as lighting for safety, industrial activities, commerce, and transportation) or a secondary result of (such as gas flares associated with mining and hydrocarbon extraction activities, or nocturnal commercial fishing), anthropogenic sources of nighttime light are often broadly distributed in space and sustained in time—over years and even decades. Because these light sources are inextricably tied to human activities and societies, extensive and long-term measurement and monitoring of Earth's anthropogenic nocturnal lights can provide valuable insights into the spatial distribution of our species and the ways in which society is changing—and is changed by—the environment on a wide range of time scales.

Over the past four decades, sensitive imaging instruments have been operated on low-Earth-orbiting satellites to measure natural and human-caused visible nocturnal illumination, both reflected and Earth-generated. The satellite sensors provide unique imagery: global coverage yet with high spatial resolution, and frequent measurements over long periods of time.

The combined, multisatellite global nocturnal illumination dataset contains a treasure trove of unique information about our planet and our species—and the

interactions between society and natural processes. Beyond academic study, Earth nightlight measurements are being used to help save lives and property around the globe, by allowing accurate identification and monitoring of ongoing events like eruptions and fires even in remote locations, and by pinpointing and enabling quantitative tracking of regions of power outage and recovery following extreme weather events and geohazards in populated areas.

Earth at Night tells—in the words of the women and men, the scientists and engineers who are actually designing the instruments and conducting the analyses of Earth's nocturnal illumination imagery—the story of satellite measurements of global light in the night. It shows how ever-increasing instrument capability has improved the sensitivity, accuracy, coverage, and resolution of the observations. Through striking illustrations and clear explanations, the book summarizes many examples of analyses from the satellite nightlight data record—examples that themselves shine light on the ever-changing environment and our human impact on Earth.

This artful volume reaffirms our human ability to harness technology and science to observe and understand Earth for the benefit of all humankind. Above all, it once again illuminates the beauty and majesty of our home planet—at all hours.

Michael H. Freilich

Former Director, Earth Science Division
(October 23, 2010 – February 28, 2019)

NASA Science Mission Directorate

Acknowledgments

The images presented and discussed here are merely the surface results of years of work by thousands of scientists, engineers, technologists, outreach personnel, and representatives of many disciplines. While the material is in the public domain and free to use (as it comes from NASA funding), much of the information presented in this volume was developed by the staff of NASA's Earth Observatory website (*https://earthobservatory.nasa.gov*, search "Earth at Night"). We wish to acknowledge their seminal contributions to showing and explaining images of Earth at night for more than a decade.

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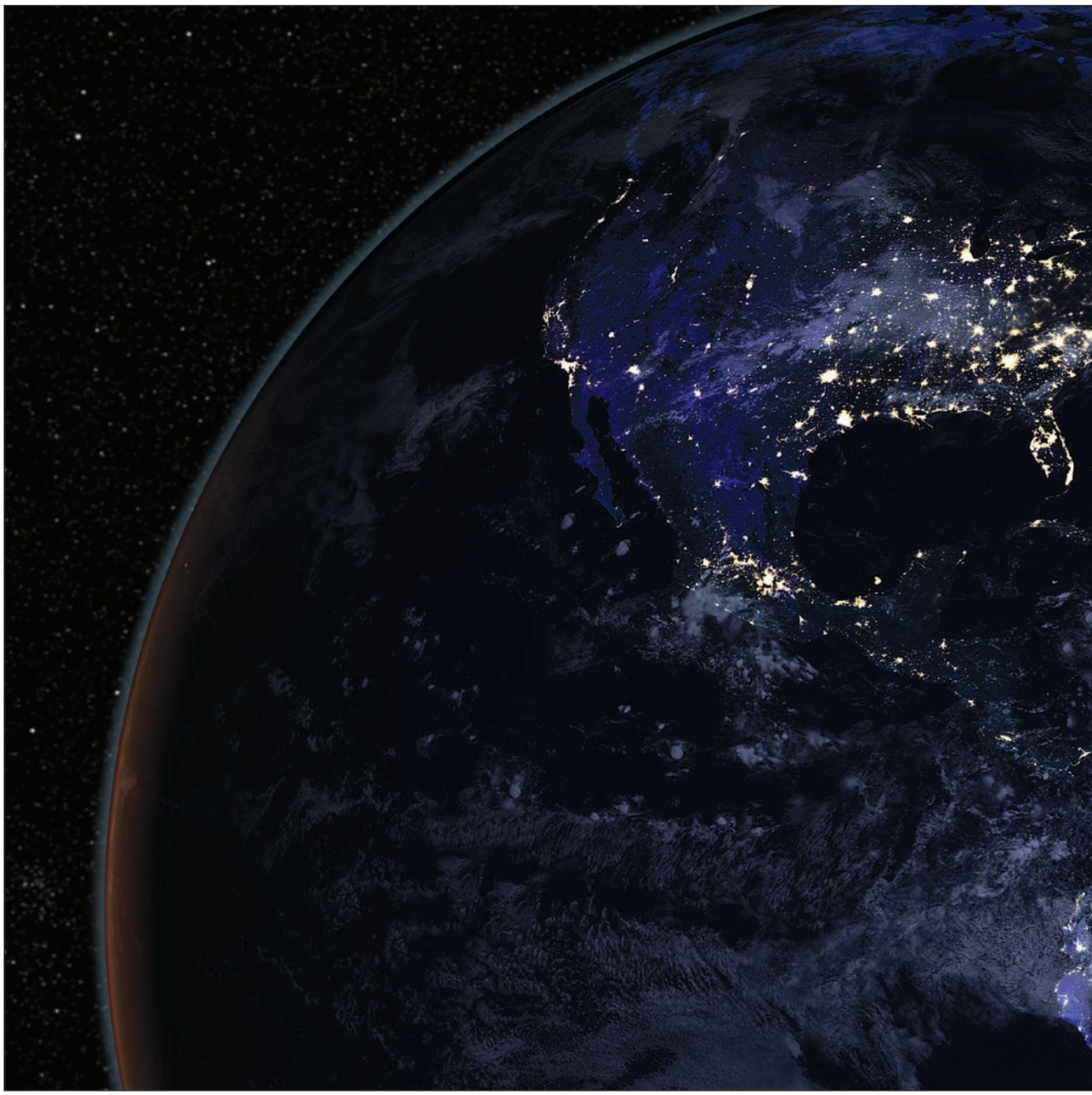
An Introduction to Nightlights



Dazzling photographs and images from space of our planet's nightlights have captivated public attention for decades. In such images, patterns are immediately seen based on the presence or absence of light: a distinct coastline, bodies of water recognizable by their dark silhouettes, and the faint tendrils of roads and highways emanating from the brilliant blobs of light that are our modern, well-lit cities.

Blue Marble Becomes Black Marble

[Right] Dubbed the "Blue Marble," this classic photograph of Earth was taken by the Apollo 17 crew on December 7, 1972.

The color of an object is actually the color of the light reflected while all other colors are absorbed. Most of the light that is reflected by clear, open ocean water is blue, while the red portion of sunlight is quickly absorbed near the surface. Therefore, very deep water with no reflections off the sea floor appears dark navy blue. Since approximately 70% of Earth's surface is covered by deep ocean water, Earth appears as a blue marble when viewed from space during daytime hours. Clouds suspended in Earth's atmosphere provide the white swirls.

Enshrouded in nighttime darkness, however, Earth appears more as a black marble from space—one shimmering with light. The human search for light in darkness is long-standing. Many of our myths and religions focus on this search, yet it is only within the past century that humans have gained the ability to take flight—first to the skies and later into space—providing new vantage points from which to view Earth and the twinkling lights below, clearly visible at night.

For nearly 25 years, satellite images of Earth at night have served as a fundamental research tool, while also stoking public curiosity. These images paint an expansive and revealing picture, showing how humans have illuminated and shaped the planet in profound ways since the invention of the light bulb 140 years ago.

These lights and the darkness tell stories about our planet—stories that this volume will present for your consideration. *Earth at Night* will show how humans and natural phenomena light up the darkness, and how and why scientists have observed Earth's nightlights for more than four decades using both their own eyes and spaceborne instruments. It is an engaging and fascinating story; come along for the adventure!

[Above] *NASA's Black Marble.* These images of Earth at night were created in 2012 over 9 days in April and 13 days in October. It took the Suomi National Polar-orbiting Partnership (NPP) satellite 312 orbits and 2.5 terabytes of data to get a clear shot of every parcel of Earth's land surface and islands. These new data were mapped over existing Blue Marble imagery to provide a realistic nighttime view of the planet. (See "Making a Cloud-Free, Global, Earth-at-Night Image Using NASA's Black Marble Product Suite" in *Appendix B* for technical details.)

Vision and Remote Sensing

Seeing Is Sensing

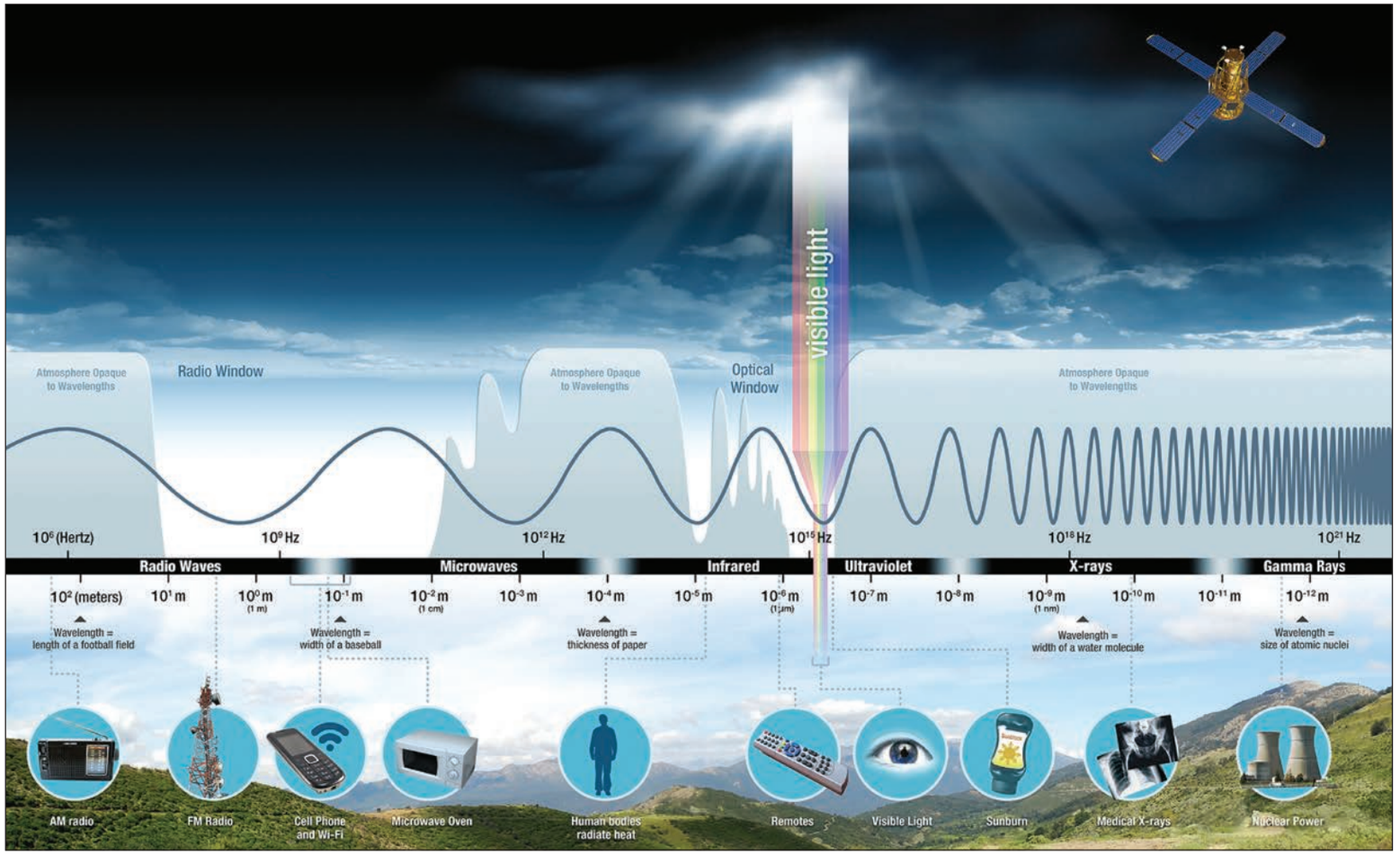
Seeing, or vision, is one of several senses we possess. When you see something, your visual system absorbs light—photons—and your brain processes the view into something you can understand and, perhaps, act upon.

Humans have long extended their visual capabilities with instruments—such as telescopes—to enable them to see across distances that their own eyes could never possibly see. This is a form of "remote sensing"—a capability that is at the core of our new understanding of how Earth "works."

Over time, science and technology developments have enabled us to create more-sensitive observing tools that far exceed the capabilities of relatively simple telescopes, providing the ability to see things we had never even dreamed of previously. Our technologies can record phenomena well outside the realm of human visual abilities—things like heat and moisture, the measurement of which would have seemed magical to our forebears. But when it comes to inspiring the human spirit, there's nothing quite like visible light, so light at night will be our focus here.

What Is Light?

Unless an object has a temperature of absolute zero (-273 °C) it reflects, absorbs, and emits energy—called electromagnetic radiation—in ways that depend on its physical and chemical properties. The amount of electromagnetic radiation an object emits depends primarily on its temperature. The higher the temperature of an object, the faster its electrons vibrate and the shorter the peak wavelength of the emitted



[Above] *Electromagnetic spectrum.* The electromagnetic spectrum is the range of energy waves of various wavelengths—from the very short gamma and X-rays [right], through longer ultraviolet, visible, and infrared light, to microwaves and very long radio waves [left].

radiation. Conversely, the lower the temperature of an object, the slower its electrons vibrate, and the longer its peak wavelength of emitted radiation. Given the wide range of temperatures in the universe, it should be clear that electromagnetic radiation has wavelengths that span a very wide range.

The electromagnetic spectrum is the range of traveling waves of energy that run from very short gamma and X-rays through ultraviolet light, visible light, microwaves, and out to long radio waves. Visible light is the quite narrow band that human eyes are adapted to see. But as noted earlier, humans are proficient at developing tools to extend the range of their capabilities. Using sensors on orbiting satellites, designed to detect multiple spectral-band combinations, scientists can “tune in” to study various aspects of Earth’s surface in ways not possible from a simple color photograph. Just as soils,

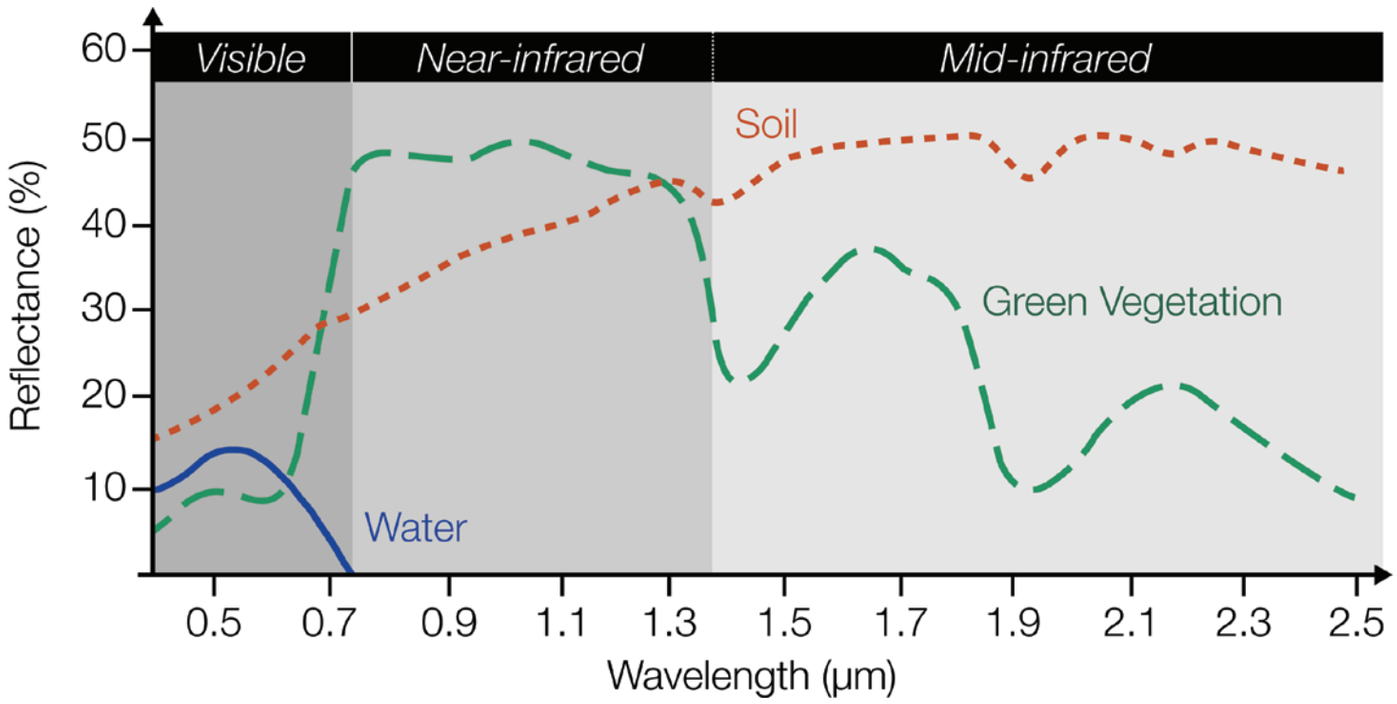
different plant types, plant health, the presence of water, bare rock, ice, and many other types of land cover each have unique "signatures" in the electromagnetic spectrum, different sources of light (e.g., incandescent lamps and LEDs) have their own unique signatures in the electromagnetic spectrum. Over time, scientists can observe and analyze changes in spectral signatures to detect changes in Earth's surface and identify various phenomena taking place (including those dealing with water, vegetation, soil, and the like—see the "Spectral signatures" figure below), sometimes based on lighting patterns.

Remote Sensing

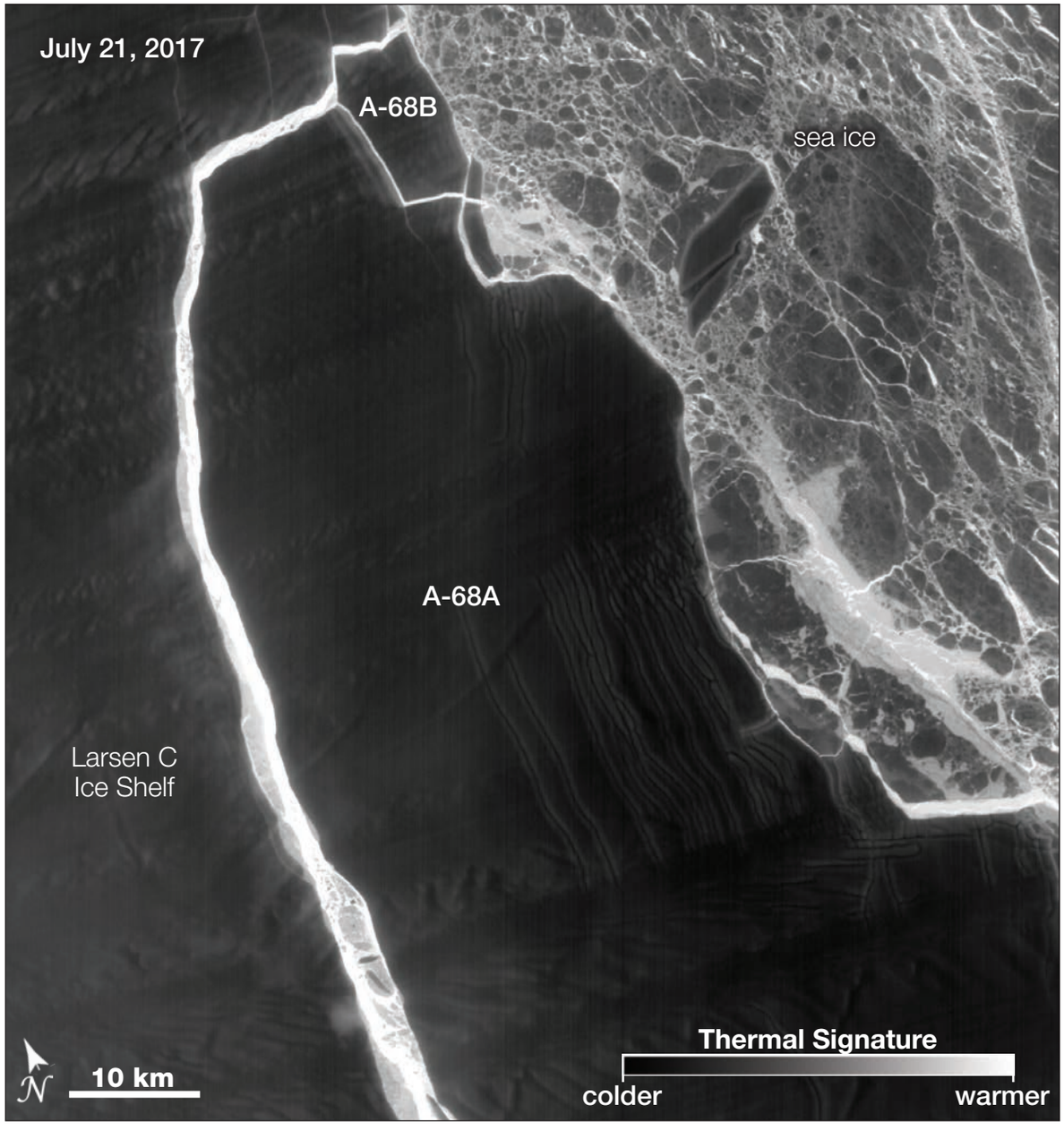
Placing vision-augmenting tools—sensors—on satellites that orbit Earth has expanded our ability to see our home planet in a new light.

Observing Earth from space using sensors on satellites (i.e., remote sensing) traces its origins to the early days of the space age—both Russian and American programs—when surface-imaging sensors first flew onboard aircraft and then later on spacecraft. With the emergence of manned space flight in the 1960s, Earth-orbiting cosmonauts and astronauts acted much like tourists by taking photos from the windows of their spacecraft.

[Below] *Spectral signatures.* Satellite instruments measure light emitted or reflected back to space at different wavelengths and create *spectral reflectance curves*. Differences in the shape of the "spectra" can be used to determine what the satellite is "seeing," such as soil, green vegetation, and water.



Credit: U.S. Geological Survey (USGS)/NASA



Credit: USGS/NASA

[Left] *Seeing ice at night.* A massive iceberg (A-68) first broke away from Antarctica's Larsen C ice shelf sometime between July 10 and July 12, 2017. The fractured berg (A-68A and A-68B) and shelf are visible in this image, acquired on July 21, 2017, by the Thermal Infrared Sensor (TIRS) on the Landsat 8 satellite. This false-color view shows the relative warmth or coolness across the region. White indicates where the ice or water surface is warmest; dark grays and blacks are the coldest areas of ice.

Remote sensing is more than simply taking pictures, however. It more fully describes the science—and art—of observing, identifying, and measuring an object without coming into direct contact with it. This process involves detecting and measuring radiation of different wavelengths emitted or reflected from distant objects or materials. Emitted light is comprised of photons in an excited state; for example, light coming from the Sun or a light bulb filament. Reflected light is light from another source bounced off an object's surface.

Orbiting Tools to Observe Nightlights

The original motivation for making low-light Earth observations was practical: military meteorologists wanted to track clouds and storms, smoke plumes, and dust storms at all hours, to better support military planning and execution. The Air Force, in particular, needed to provide more accurate and timely forecasts for pilots working at night over both land and sea.

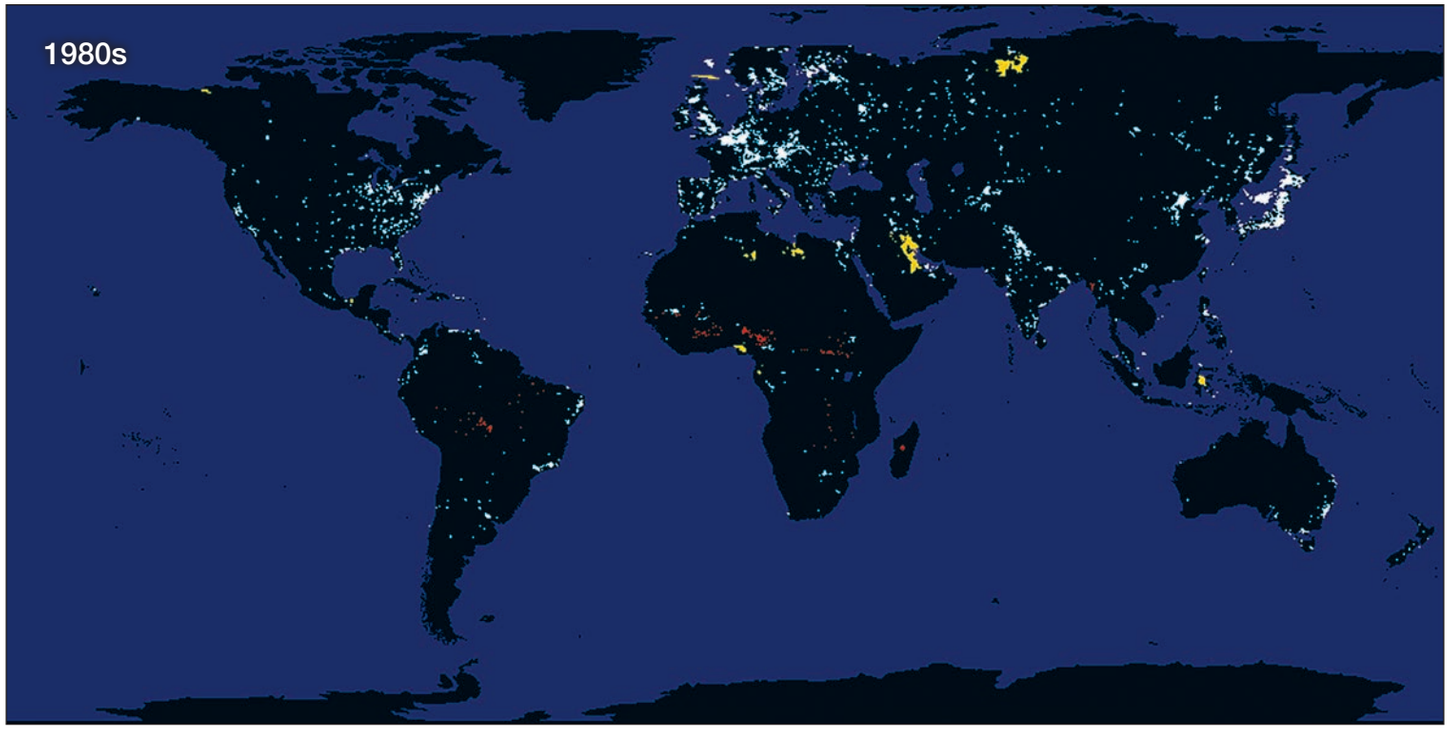
[Previous pages] *Vintage photos of Earth at night—NASA's Mercury-Atlas mission*. The photograph on page 10 was taken from NASA's unmanned Mercury-Atlas 4 mission on September 13, 1961. High clouds (white) are mixed with Earth's nightlights (yellow) on the right-hand side of the image, with Earth's horizon on the left-hand side. The handwritten annotation at the top (that appears backwards in that photo) indicates this was the 348th photograph taken on the MA-4 mission. The next photograph (page 11) taken by MA-4, number 349, depicts an even darker scene of Earth at night. The white line in this photo is due to a film artifact.

So, scientists have observed Earth's nightlights for more than four decades, first with astronaut photography and military satellites. Since the 1960s, the U.S. Air Force has operated the Defense Meteorological Satellite Program (DMSP), a series of 18 polar-orbiting satellites that observe clouds and other weather variables in key wavelengths of infrared and visible light. Starting in 1972, the DMSP satellites included the Operational Linescan System (OLS), which gives weather forecasters some ability to see in the dark.

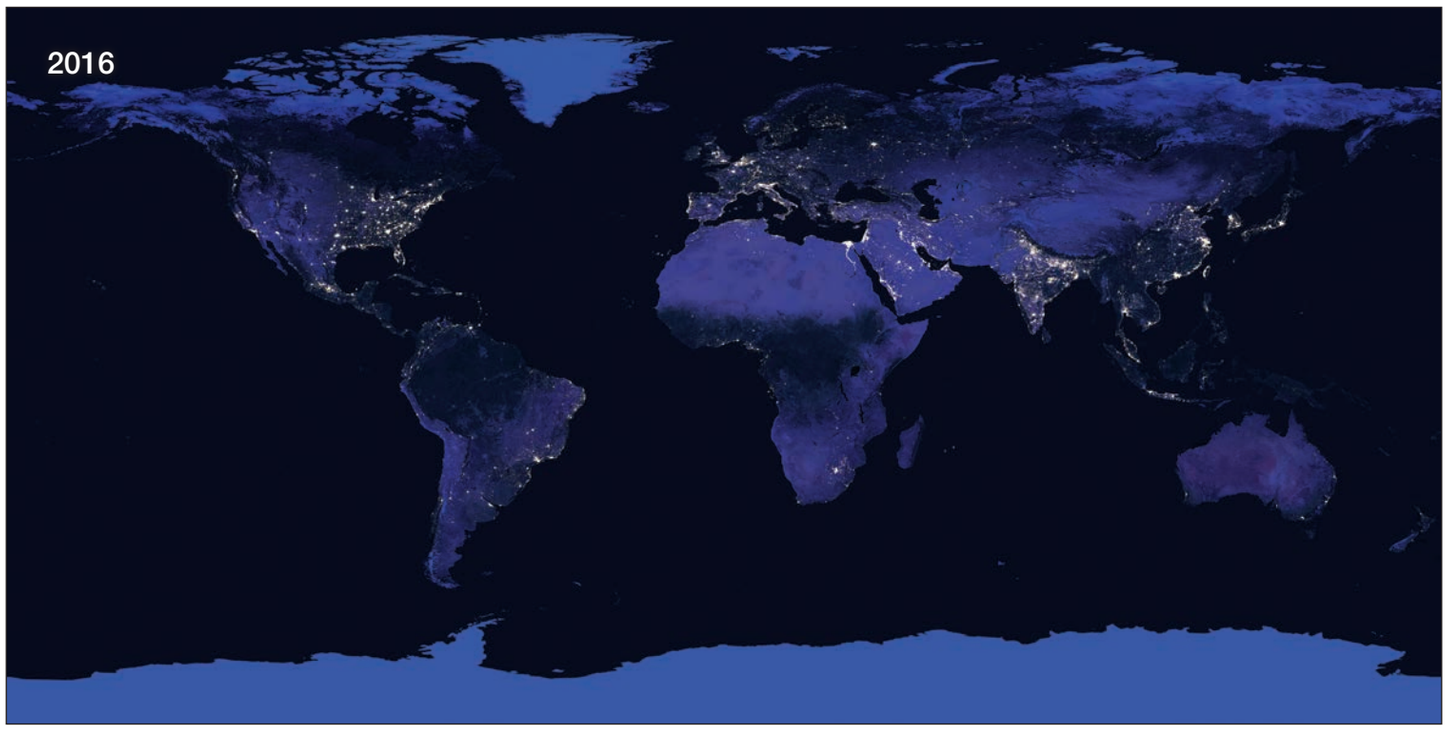
While DMSP has been a source of nighttime images for decades, until fairly recently the data were classified, which meant that only a few civilian scientists could conveniently gain access to study the data. The atmospheric science community was eager to have a more accessible night-vision tool to better understand weather and climate patterns and phenomena. Finally, in 2011, a new source of unclassified satellite images of Earth at night became available—one that improved upon the capabilities of OLS. The new low-light sensor was called the Visible Infrared Imaging Radiometer Suite (VIIRS), and was launched in October 2011 onboard the Suomi National Polar-orbiting Partnership (NPP) satellite—a partnership between NASA, the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Department of Defense.

VIIRS currently flies on Suomi NPP as well as on the NOAA-20 satellite (launched November 2017). The VIIRS "Day/Night Band," or DNB, can observe dim light down to the scale of an isolated highway lamp or fishing boat. It can even detect faint, nocturnal atmospheric light—known as airglow—and observe clouds lit by it. Through the use of its DNB, VIIRS has made the first quantitative measurements of light emissions and reflections from Earth's surface, distinguishing the intensity and the sources of nighttime light. The combination of these measurements gives us a global view of the human and natural light sources on Earth. Looking ahead, three more satellite missions are planned over the next decade, with a VIIRS instrument scheduled to be onboard each platform.

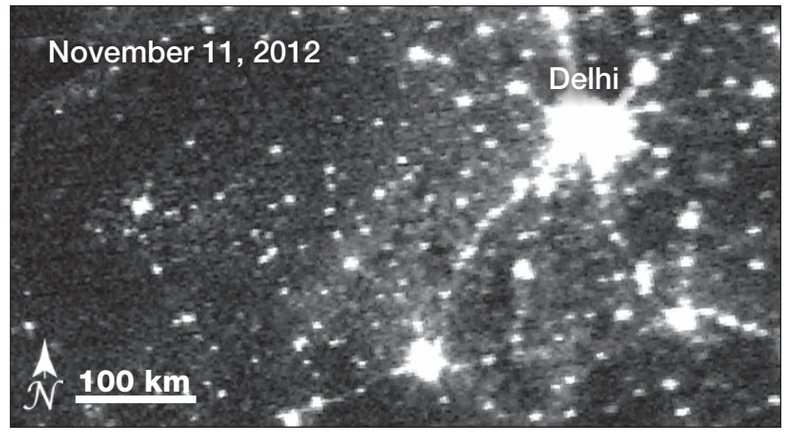
Thanks to advancements in sensor technology and improved optics, the VIIRS DNB is ten-to-fifteen times better than the OLS sensor at resolving the relatively dim



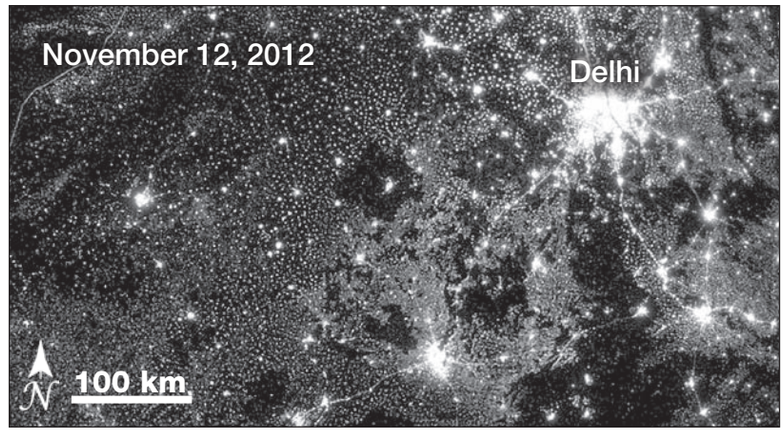
[Above] *Early map of Earth at night.* Technology has come a long way since the 1980s and 1990s. This map shows the visible light sources on Earth's surface as measured by the OLS on the DMSP satellites during the 1980s. White dots represent city lights, red dots represent forest fires, and yellow dots represent oil-well fires.



[Above] *The 2016 Black Marble.* The 2016 Earth at night image, dubbed NASA's *Black Marble*, was created with VIIRS DNB data from the Suomi NPP satellite. The data were acquired over 190 days in 2016. This translates into 5247 orbits and 42 terabytes of input data to get a cloud-free composite image of Earth's land surfaces and ocean.



OLS

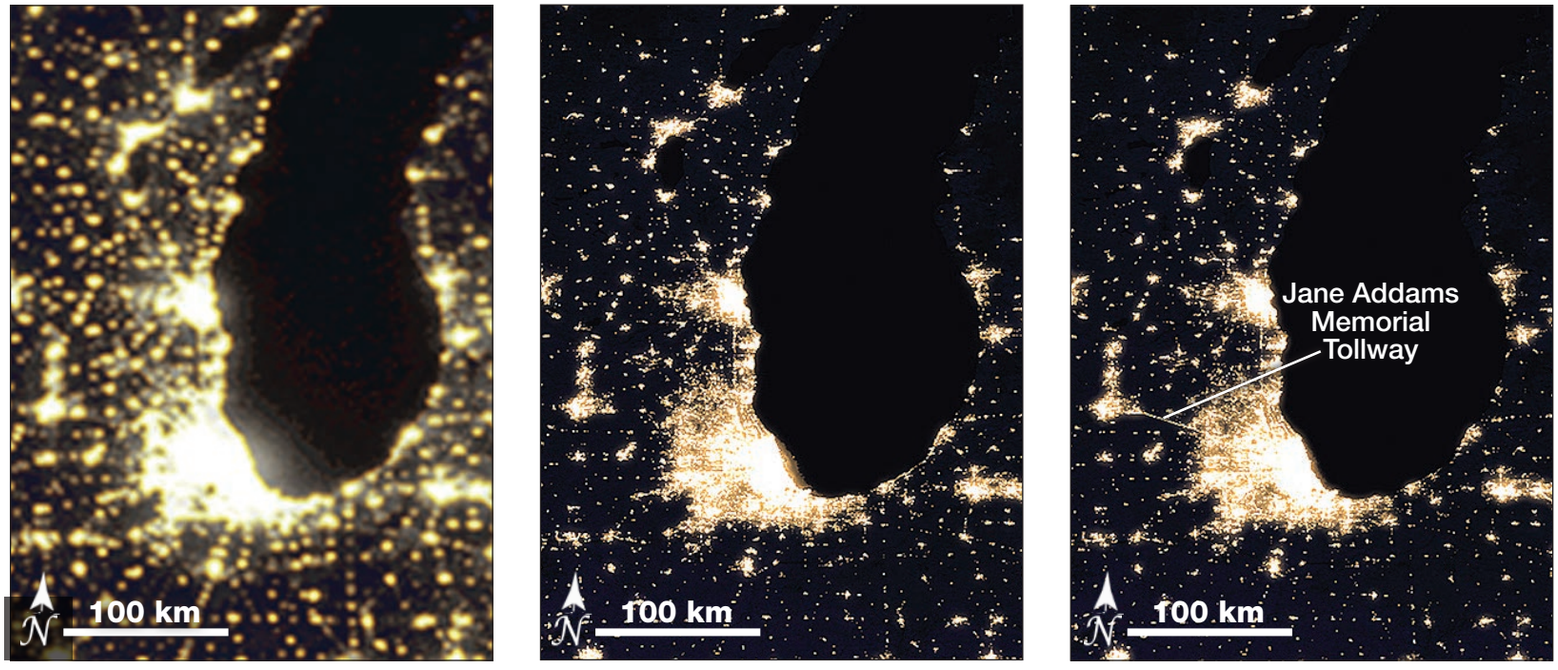


VIIRS

[Right] This image pair illustrates the differences in resolution between OLS and VIIRS. On November 11, 2012, the OLS on a DMSP spacecraft captured the top image of city, village, and highway lights near Delhi, India. For comparison, the VIIRS instrument on the Suomi NPP satellite acquired the bottom image showing this same area one night later.

lights of human settlements and reflected moonlight. Just like the picture on your television set, satellite images are made up of tiny squares. These squares are called pixels—short for picture elements—and represent the amount of reflected or emitted light energy recorded for that part of the image. Each VIIRS pixel covers a distance of roughly 0.46 miles (742 meters) across, compared to the 1.86-mile (3-kilometer) footprint of OLS. To learn more about the technical details of OLS and VIIRS, see *Appendix C*.

As they have done since the dawn of the space age, astronauts onboard the International Space Station (ISS) also take photographs of Earth at night. In fact, their images have even higher spatial resolution than images from VIIRS (typically tens-to-hundreds of meters per pixel). However, unlike satellites, astronauts are not looking at Earth 24 hours a day, 7 days a week, 365 days a year. Due to the orbit of the ISS, astronauts



2003 OLS 2012 VIIRS 2016 VIIRS

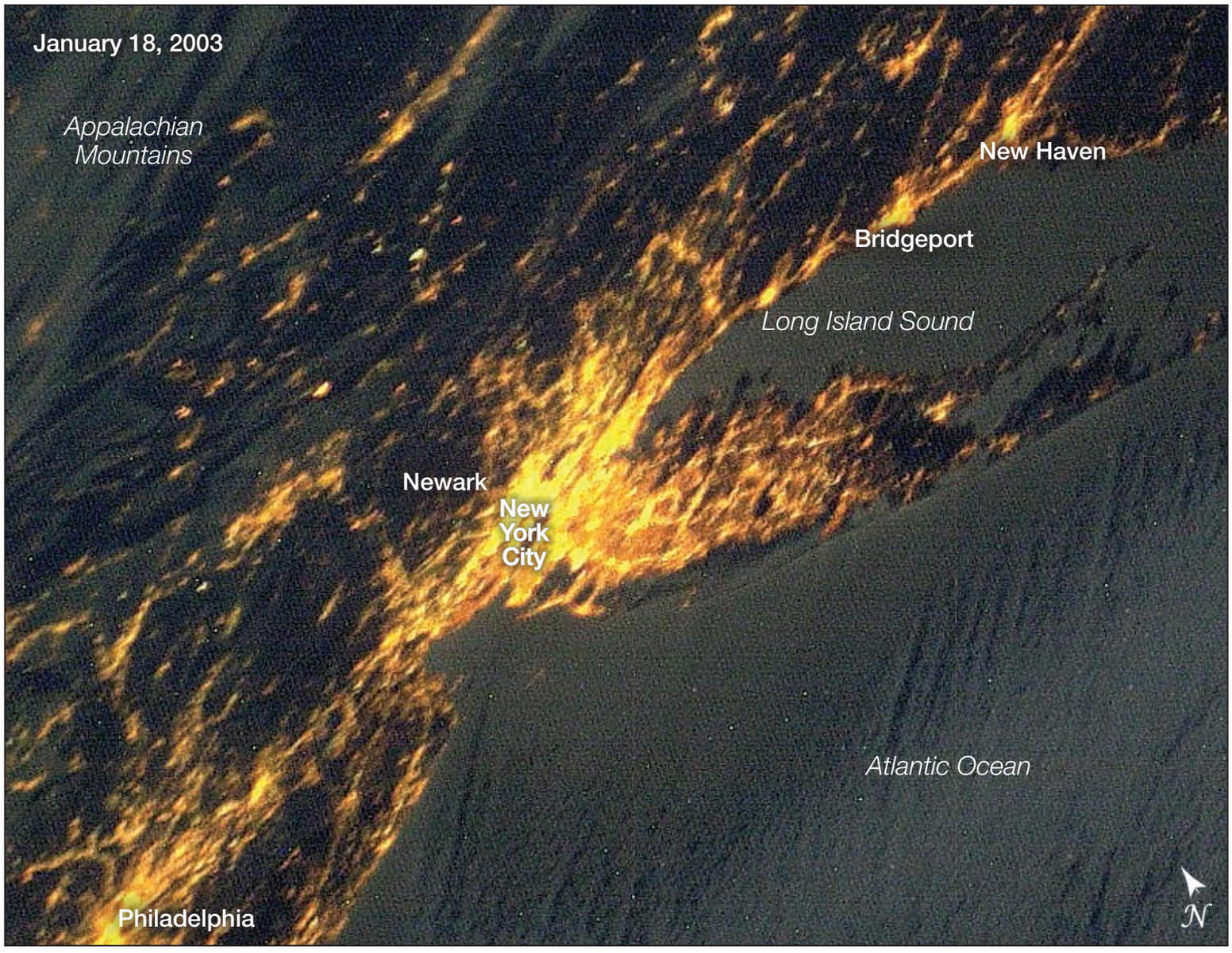
[Above] *Change Over Time—Chicago, Illinois*. These images show the area surrounding Chicago, Illinois, using nightlight data from the OLS onboard the DMSP released in 2003 (left), the VIIRS DNB in 2012 (middle), and the VIIRS DNB in 2016 (right). When you look at the images side by side, the OLS image appears coarse and blurry compared to the high-precision VIIRS images from 2012 and 2016. The most readily noticeable difference in these nighttime composite views of Chicago and surrounding areas in 2012 and 2016 is lighting along a recently expanded section of Interstate 90. This part of the highway, the Jane Addams Memorial Tollway, links Chicago with Rockford, Illinois, to the northwest.

cannot see the surface in the polar regions, although they can observe phenomena in the upper atmosphere. Also, the ISS passes over a given point on Earth every two or three days and at variable times, while, for example, Suomi NPP flies over the same point twice a day at roughly the same time each day. With their complementary capabilities of spatial resolution, timing, and quantitative accuracy, scientists are interested in making joint observations with VIIRS and the ISS.

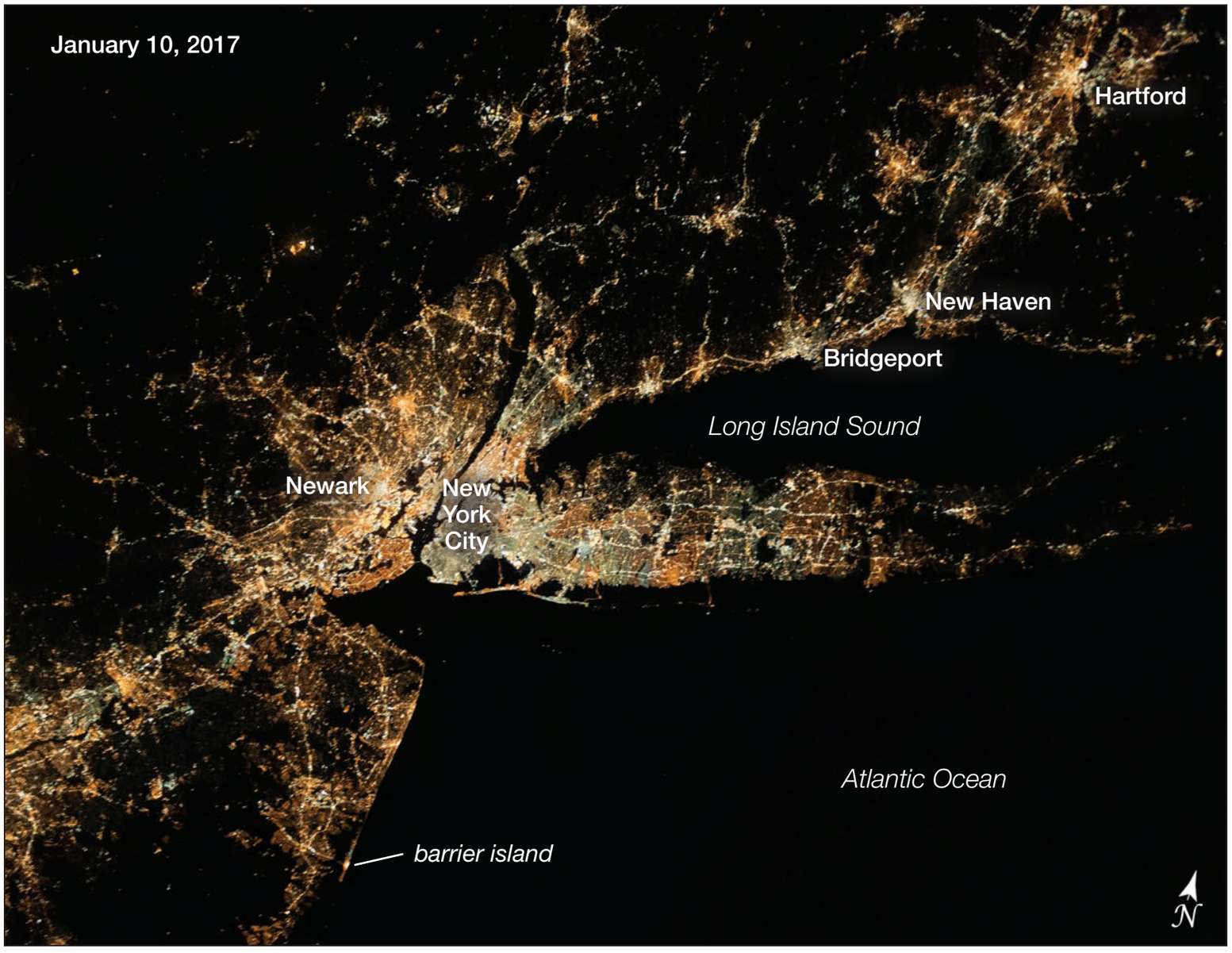
While scientists use multiple spectral band combinations covering different parts of the electromagnetic spectrum—such as visible and infrared—during nighttime hours, this book focuses mainly on the detection of visible light at night. For comparison, some daytime visible and infrared images will be shown alongside some of the nighttime visible images.

Improvements in ISS Photography—Northeastern United States

This pair of photographs, centered on New York City in the northeastern United States, shows improvements in camera technology used on the ISS over a 14-year time period. The image on the left was taken on January 18, 2003, with a Nikon D1 digital camera (3 megapixels), while the image on the right was take on January 10, 2017, with a Nikon D4 digital camera (16 megapixels).

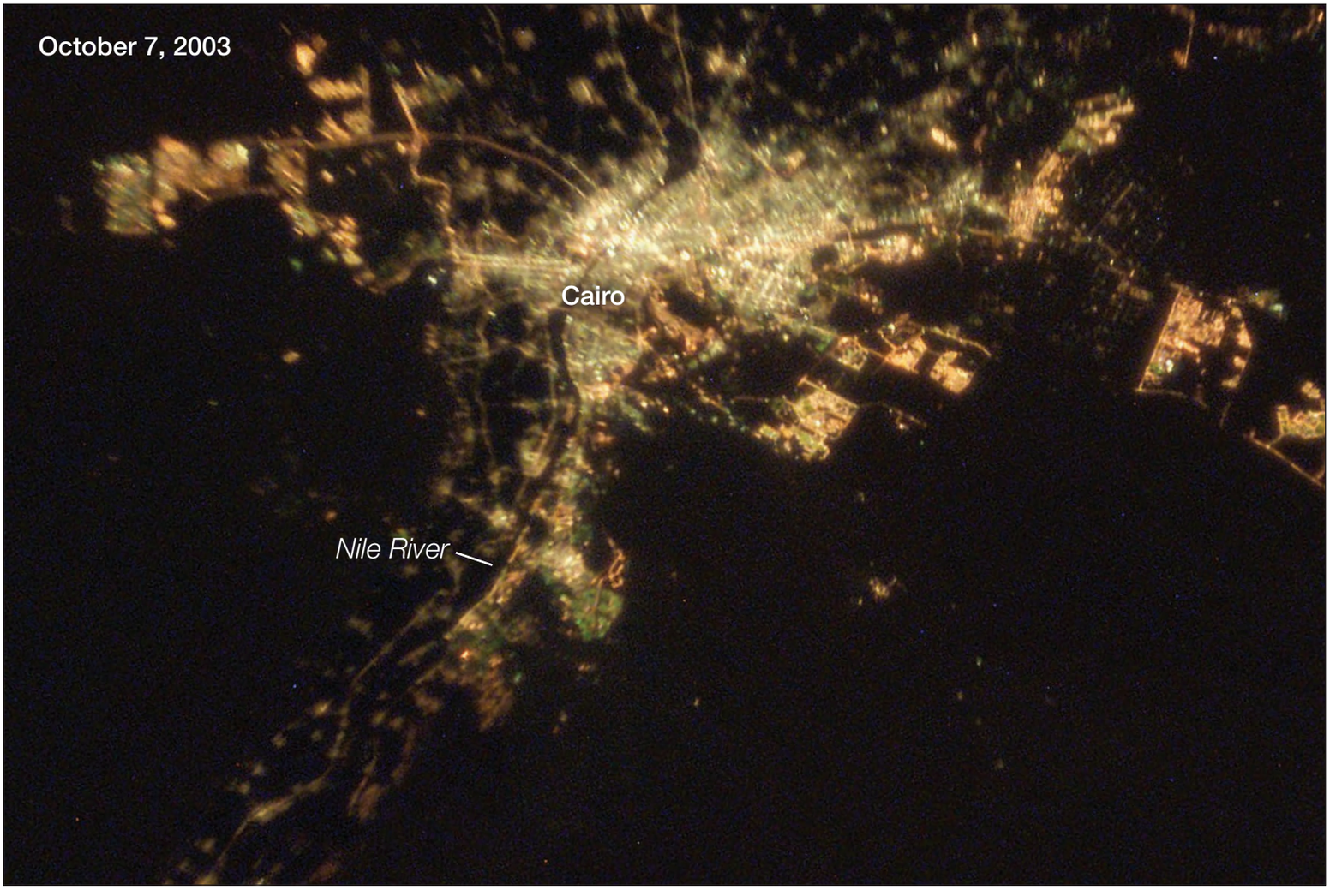


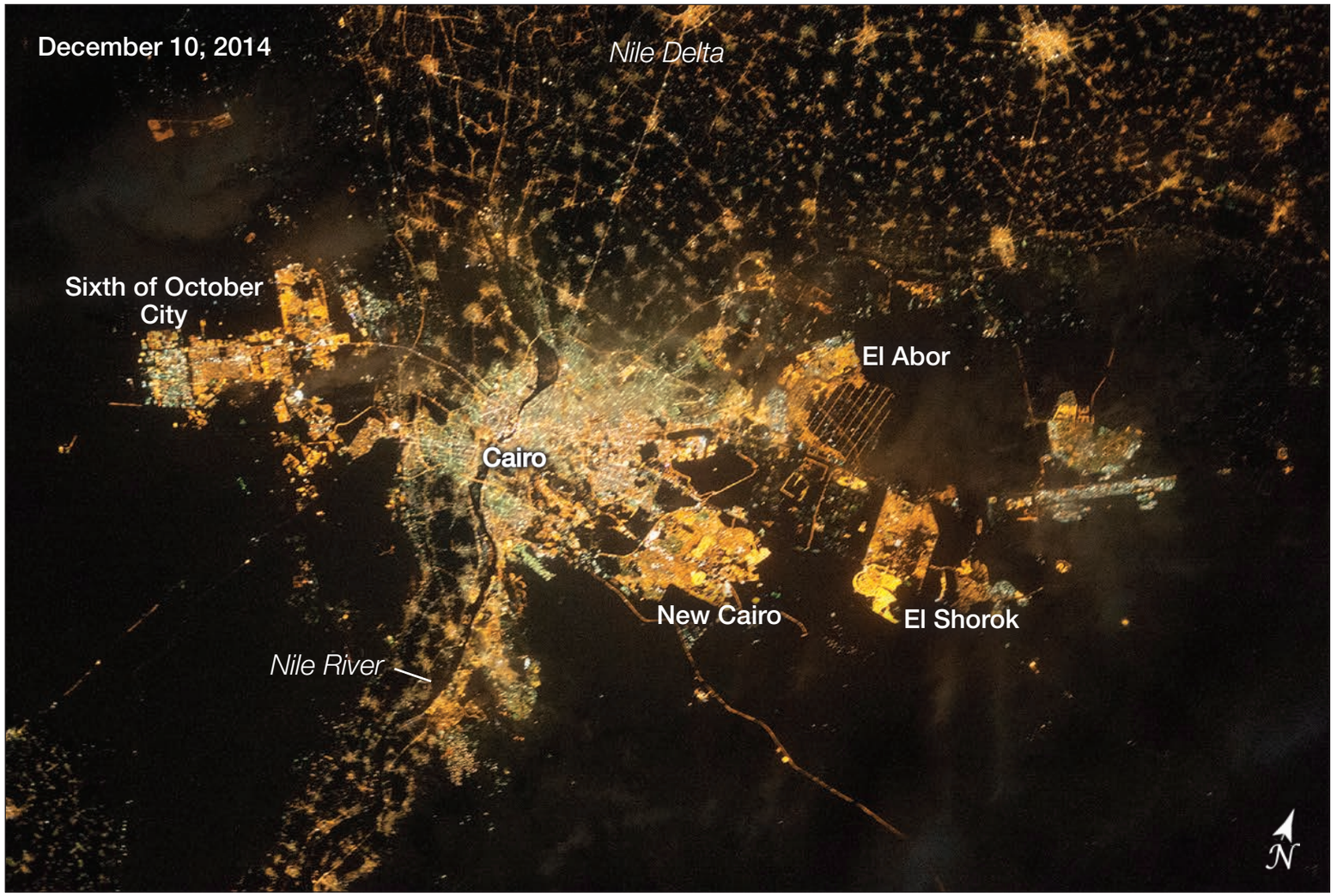
The 2003 image was taken from a vantage point well to the northeast of the cities, with the camera pointed westward back towards New York City and the coast. The result is that the perspective is distorted but still recognizable. Low clouds have formed over the waters of the Atlantic and have settled into some of the valleys of the Appalachian Mountains to the northwest.



Coming into Focus—Cairo, Egypt

This pair of photographs, centered on Cairo, Egypt, shows improvements in camera technology used on the ISS between October 7, 2003 (left) and December 10, 2014 (right). The 2003 photo was taken with a Kodak DCS 760c electronic still camera (6.3 megapixels), while the 2014 image was taken with a Nikon D4 digital camera (16 megapixels).

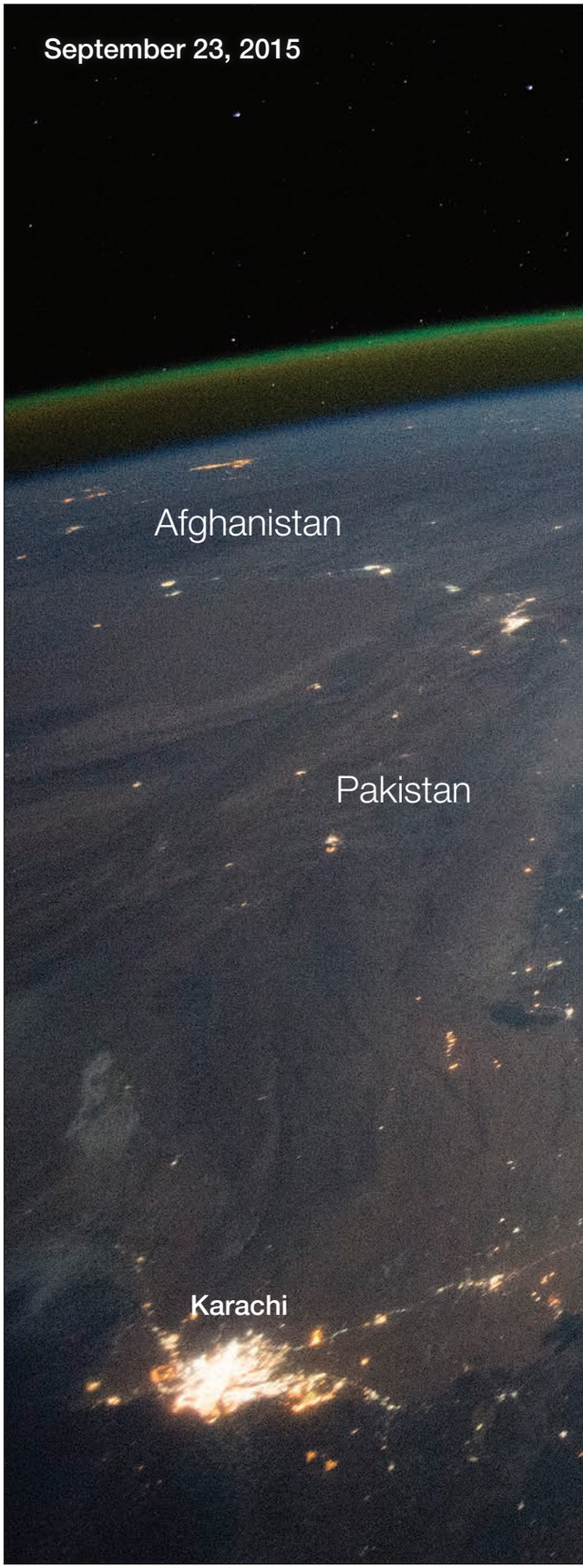



December 10, 2014
Nile Delta
Sixth of October City
El Abor
Cairo
New Cairo
El Shorok
Nile River
N

Where Do Nightlights Come From?

The night side of Earth twinkles with light, easily observed by orbiting satellites. The most obvious source comes from city lights, but as one looks closer, much more becomes discernible. Even at some distance from human settlements, light still shines: Wildfires and volcanoes rage; gas flares glow like candles; auroras dance across the polar skies; moonlight and starlight reflect off surface water, snow, and deserts; and clouds are easily seen. Even the air and ocean sometimes glow.

The "Nature's Light Shows" and "Human Light Sources" sections of this book feature images of natural and anthropogenic light sources to illustrate how scientists use nightlight data to study our changing planet and how decision makers, in turn, can use the knowledge gained for public benefit. Some of these applications include forecasting a city's energy use and carbon emissions, eradicating energy poverty and fostering sustainable energy development, providing immediate information when disasters strike, and monitoring the effects of conflict and population displacement.

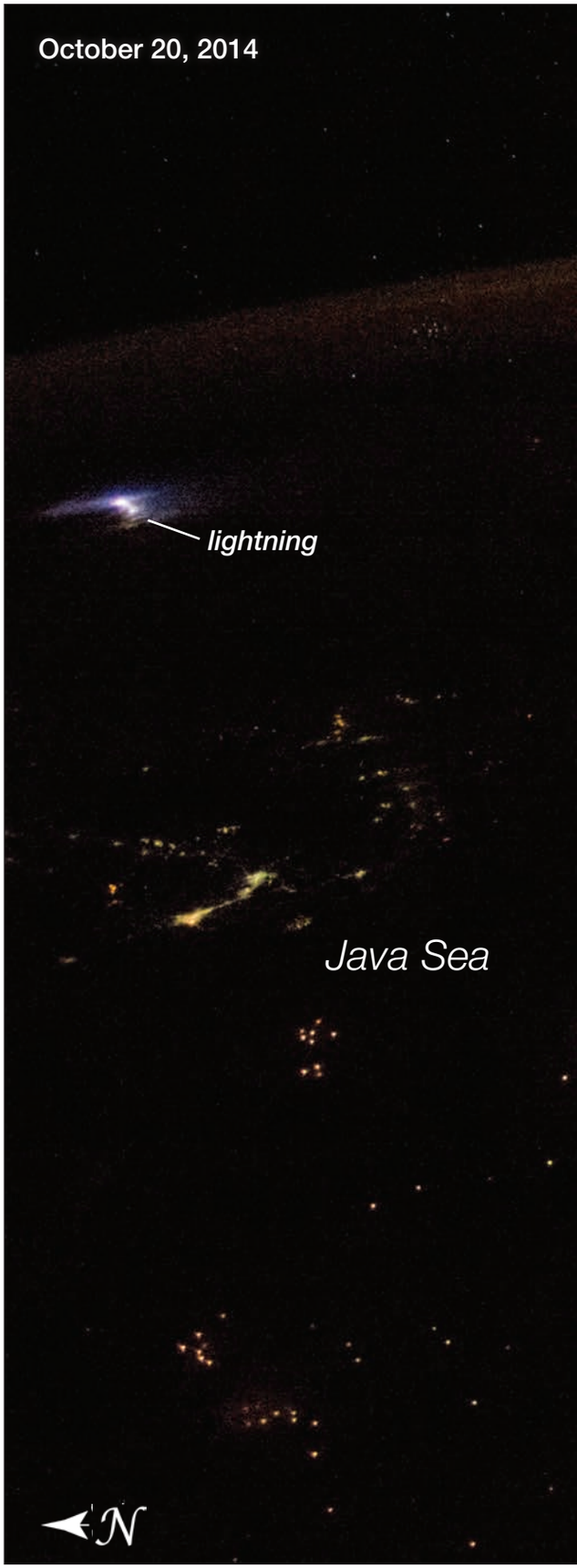


[Right] An astronaut onboard the International Space Station took this nighttime panorama while looking north across Pakistan's Indus River valley. The port city of Karachi is the bright cluster of lights facing the Arabian Sea, which appears completely black. City lights and the dark color of dense agriculture closely track with the great curves of the Indus valley. For scale, the distance from Karachi to the foothills of the Himalaya Mountains is 720 miles (1,160 kilometers). This photograph shows one of the few places on Earth where an international boundary can be seen at night. The winding border between Pakistan and India is lit by security lights that have a distinct orange tone.

airglow
Himalaya Mountains
India
border
Indus River Valley
N

Beyond City Lights—Java Sea

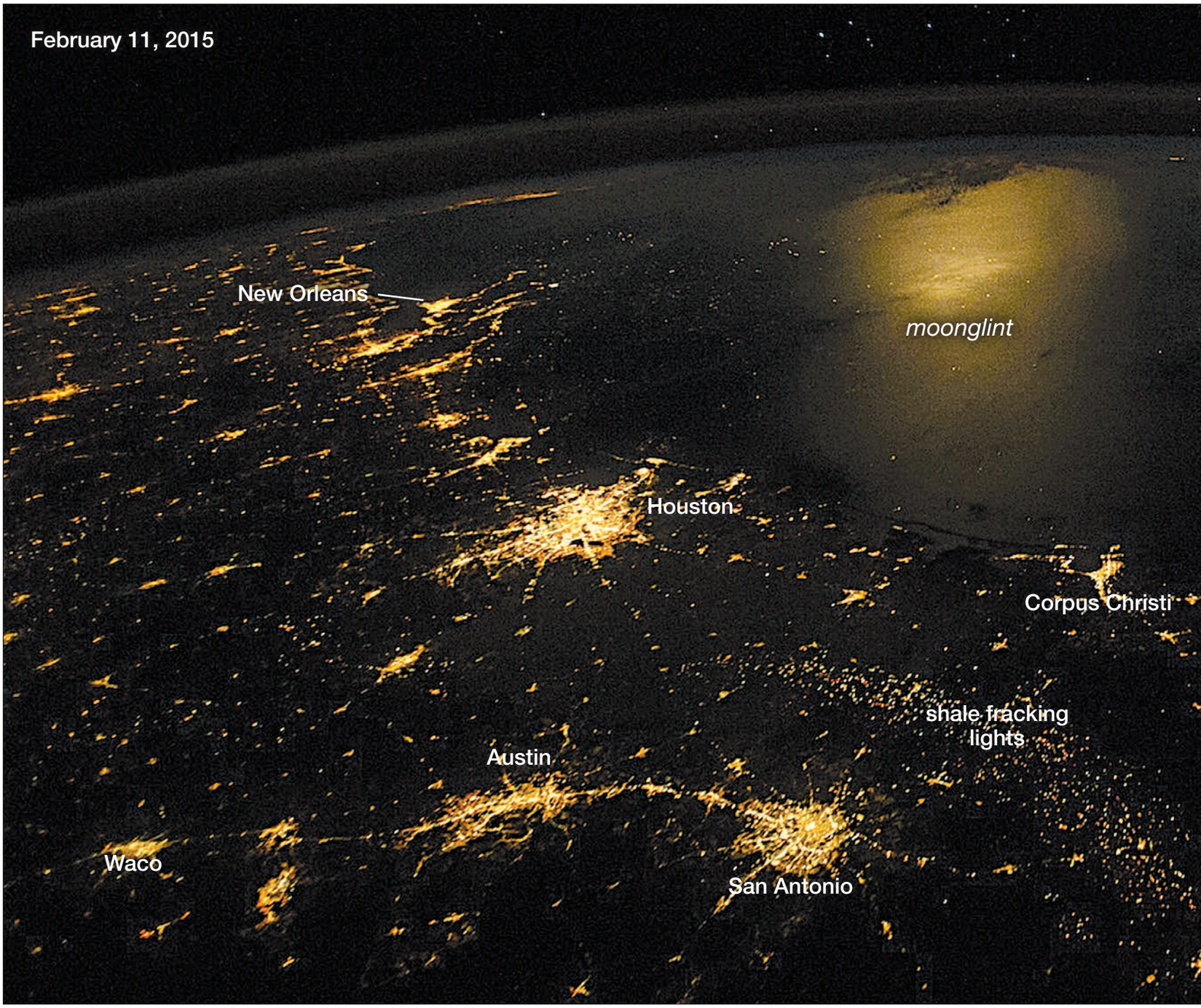
The visible lights produced by modern civilization are often obscured by the more intense light of the Sun during the day. However, as this photograph—taken over the Java Sea by a member of the Expedition 42 crew onboard the ISS—reveals, at night these "nighttime lights" become visible. To the discerning eye, these lights reveal intricate details of both natural phenomena and the unmistakable footprints of human civilization. The photo, taken on October 20, 2014, captured light from roads and cities, fishing boats, lightning, airglow, and even a few gas flares. North of the city of Surabaya, the capital of East Java province, large numbers of boat lights dot the darkened Java Sea. Many of these vessels are likely fishing boats using bright lights to attract squid and other sea life. According to one estimate based on satellite observations, there were over 500 fishing boats in the area on a single night in September 2014. The same study pointed out that two of the brighter points of light in the area are gas flares emanating from offshore oil infrastructure. In addition to the human activity, the photograph also showcases a few natural splashes of light and color. The blue-white patch on the far left is a flash of lightning, a common sight for astronauts. The glowing line along Earth's limb—or edge of the atmosphere—is airglow, a type of light that is produced by chemical reactions in the upper atmosphere. While airglow can also be green or blue, red airglow like this comes from excited oxygen atoms at heights of about 90 to 190 miles (150 to 300 kilometers).



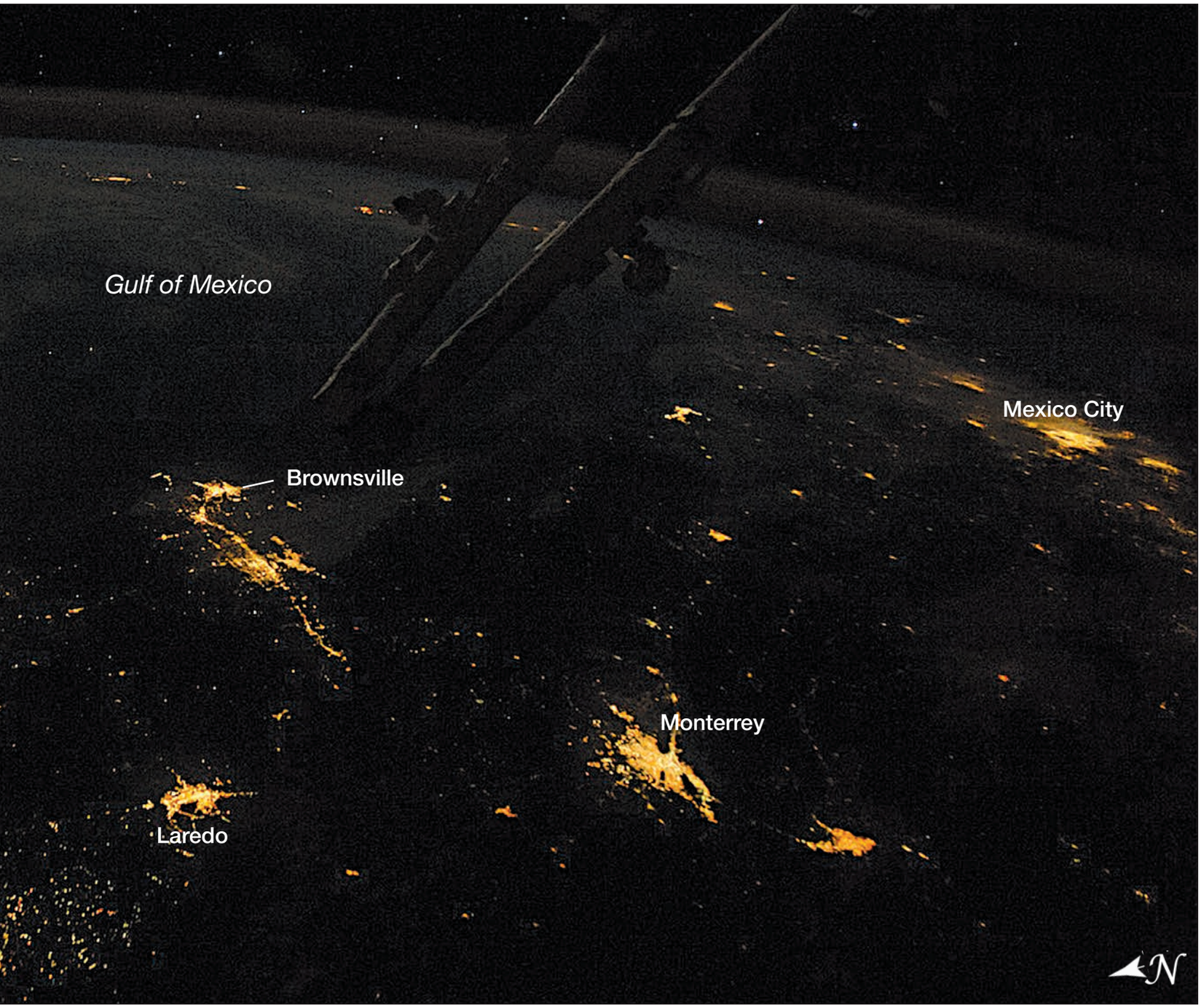
airglow
gas flare
Surabaya
boat lights

Moonlight, Old Lights, and New Lights—Gulf of Mexico

This wide-angle, nighttime photograph was taken on February 11, 2015, by ISS astronauts looking southeastward over the Gulf of Mexico. Moonlight reflects diffusely off the waters of the Gulf, making the largest illuminated area in the image. The sharp edges of light patterns from coastal cities trace the long curve of the shoreline from

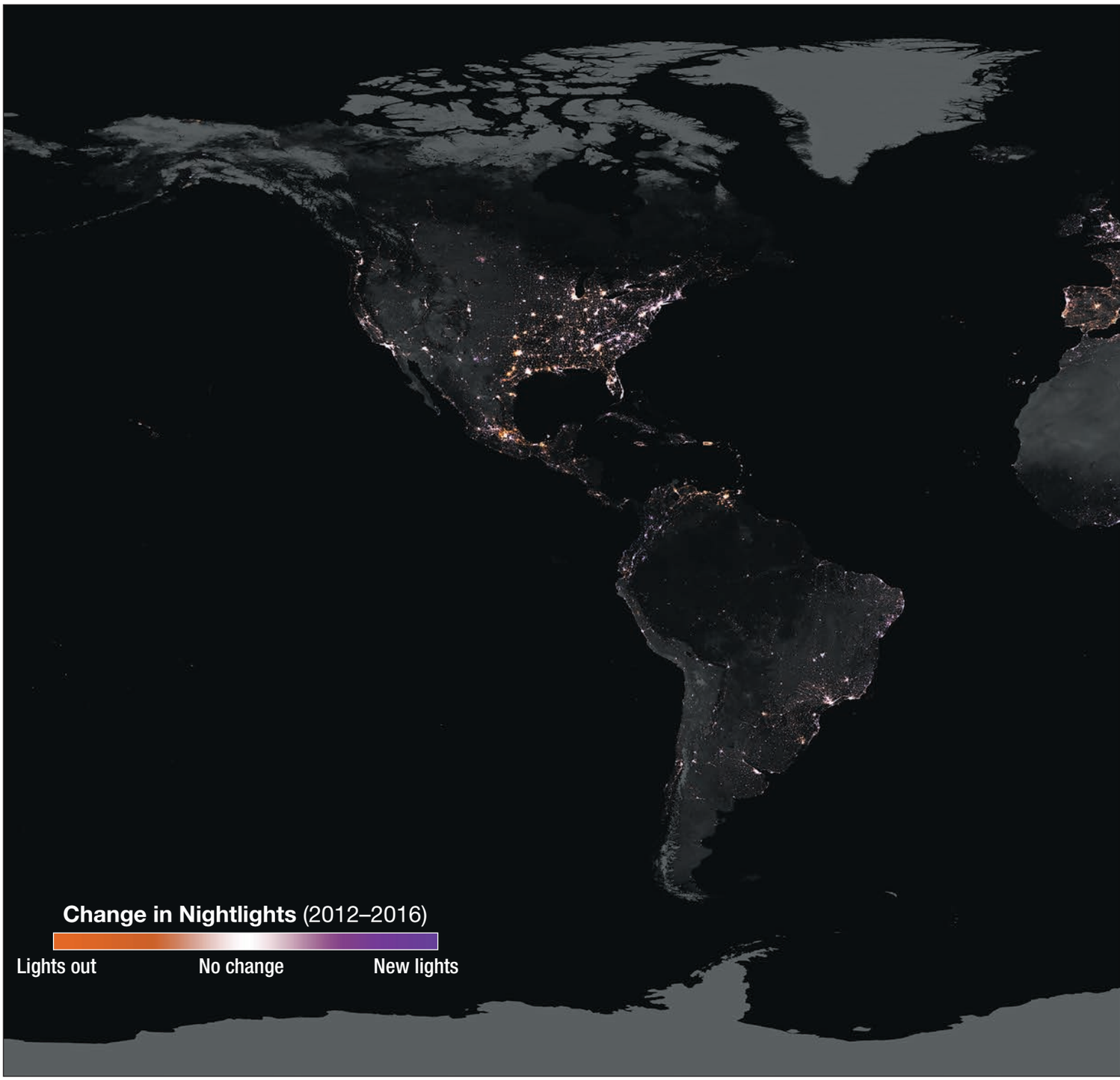


New Orleans, at the mouth of the Mississippi River, to Brownsville, Texas, in the westernmost Gulf. In recent years a new pattern of lights has appeared on the landscape and revealed the oil- and gas-production zone of south-central Texas. This long, less-dense swath of pinpoints spreads across 210 miles (330 kilometers) of what is now known as shale-fracking country.

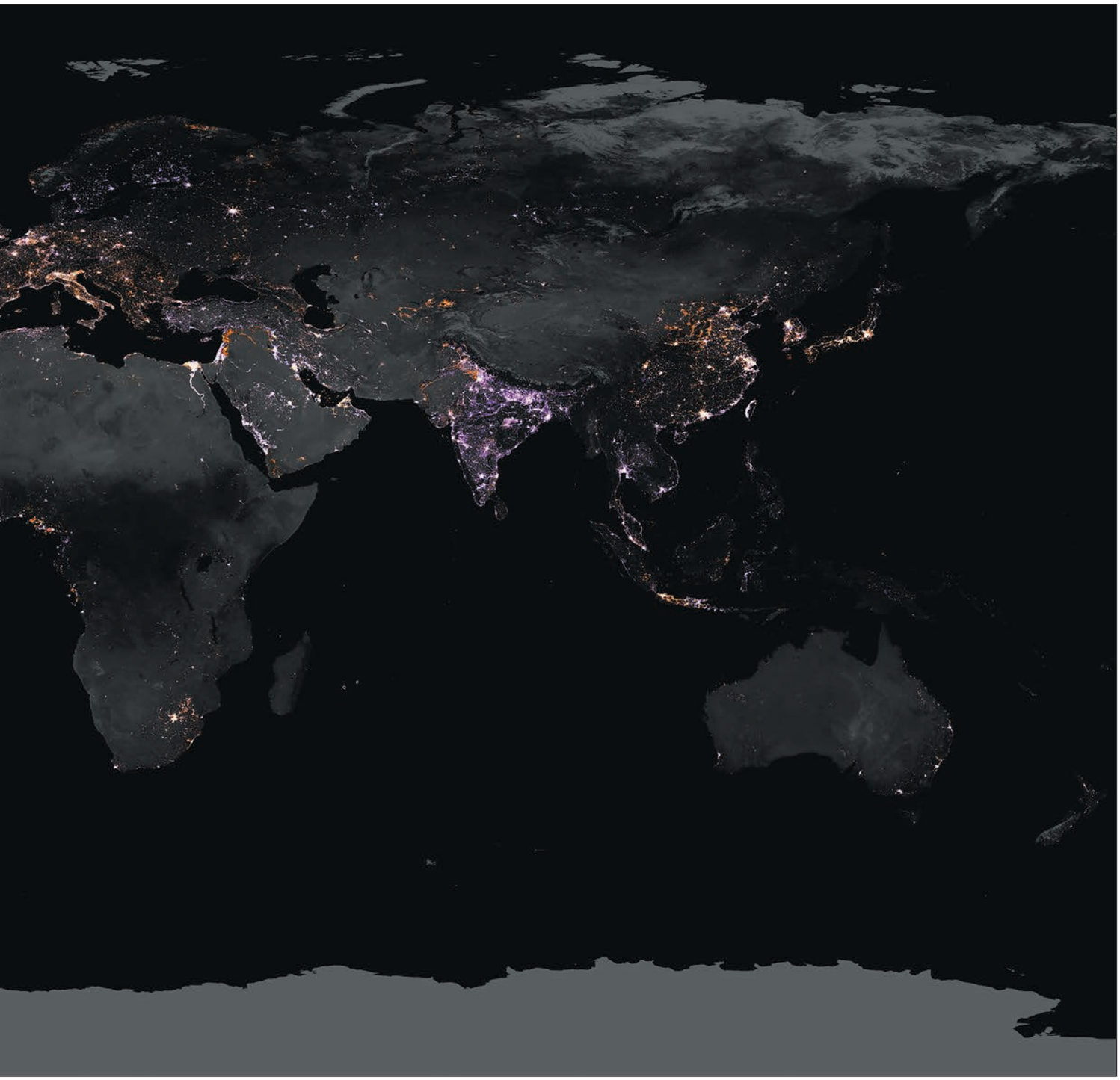


A World of Change

This map shows the change in lighting intensity from 2012 to 2016. The map was created using two separate nightlight datasets (from 2012 and 2016) derived using data from the VIIRS instrument on Suomi NPP. Dark purple represents areas with new light since 2012, while dark orange represents



areas where light existed in 2012 but no longer exists in 2016. Areas where lighting intensity stayed the same between 2012 and 2016 appear white. Varying shades of purple and orange indicate areas that have become brighter or dimmer since 2012, respectively. To view and learn about a few regional examples up close, see stories on pages 114–115 and 140–141.

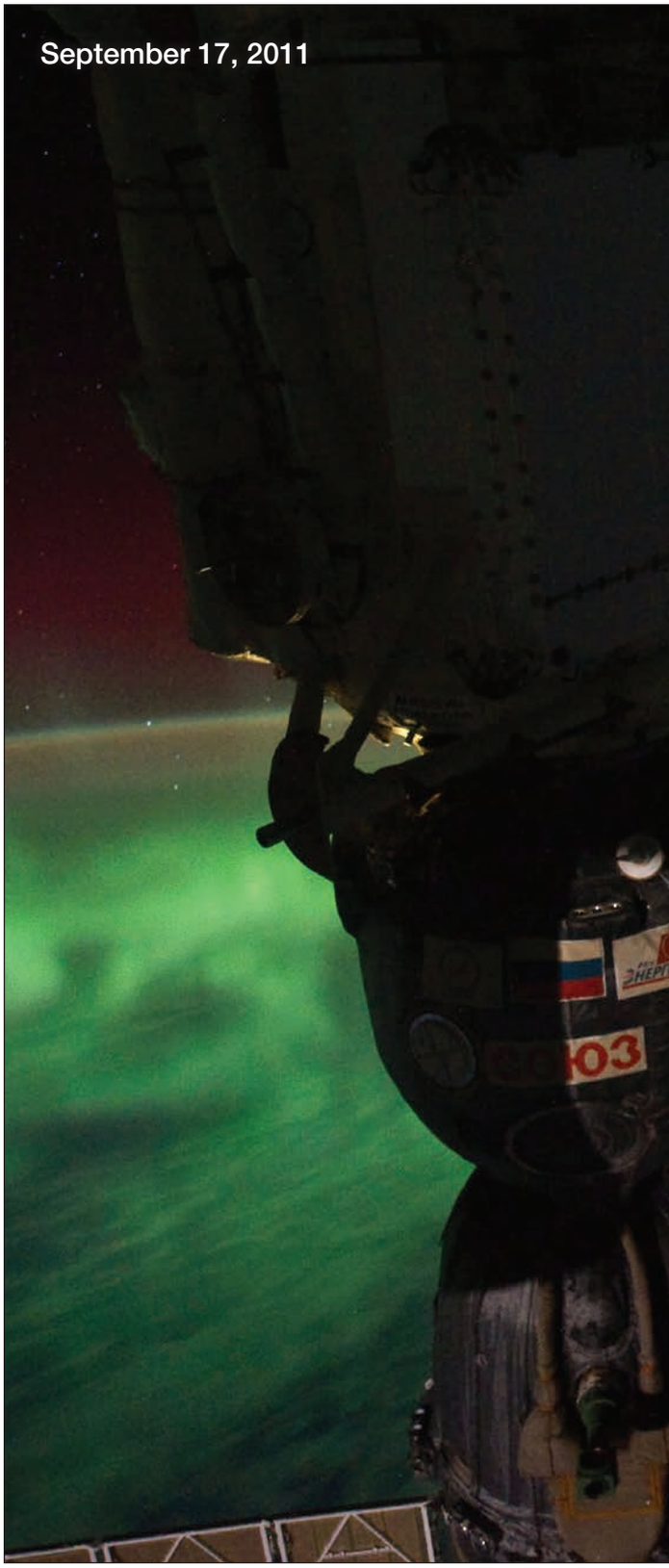


Nature's Light Shows

At night, with the light of the Sun removed, nature's brilliant glow from Earth's surface becomes visible to the naked eye from space. Some of Earth's most spectacular light shows are natural, like the aurora borealis, or Northern Lights, in the Northern Hemisphere (aurora australis, or Southern Lights, in the Southern Hemisphere). The auroras are natural electrical phenomena caused by charged particles that race from the Sun toward Earth, inducing chemical reactions in the upper atmosphere and creating the appearance of streamers of reddish or greenish light in the sky, usually near the northern or southern magnetic pole. Other natural lights can indicate danger, like a raging forest fire encroaching on a city, town, or community, or lava spewing from an erupting volcano.

Whatever the source, the ability of humans to monitor nature's light shows at night has practical applications for society. For example, tracking fires during nighttime hours allows for continuous monitoring and enhances our ability to protect humans and other animals, plants, and infrastructure. Combined with other data sources, our ability to observe the light of fires at night allows emergency managers to more efficiently and accurately issue warnings and evacuation orders and allows firefighting efforts to continue through the night. With enough moonlight (e.g., full-Moon phase), it's even possible to track the movement of smoke plumes at night, which can impact air quality, regardless of time of day.

Another natural source of light at night is emitted from glowing lava flows at the site of active volcanoes. Again, with enough


September 17, 2011

[Above] Astronauts onboard the International Space Station are treated to a spectacular display of the aurora australis while in orbit over Southern New Zealand on September 17, 2011.

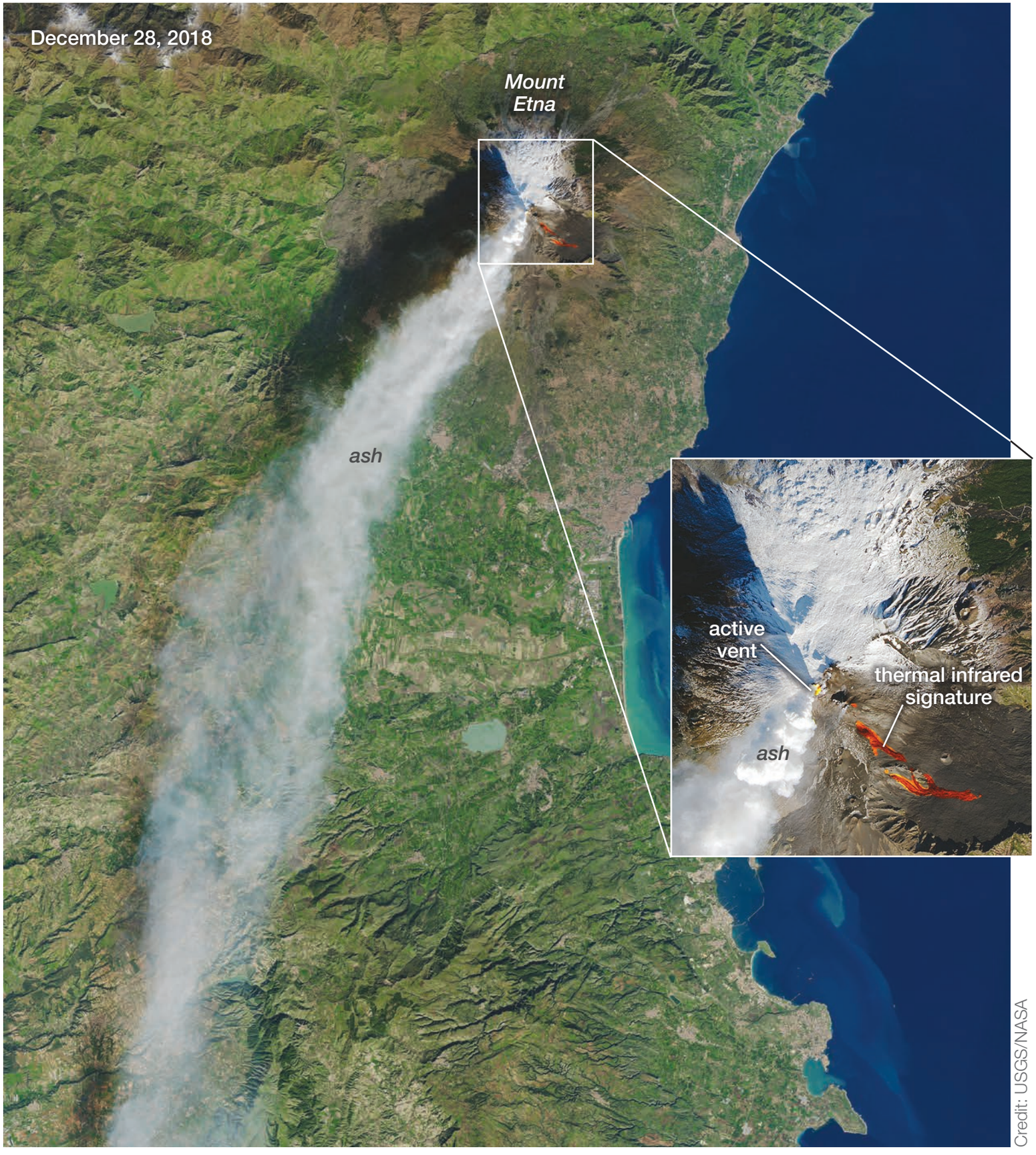
[Opposite page] For the first time in perhaps a decade, Mount Etna experienced a "flank eruption"—erupting from its side instead of its summit—on December 24, 2018. The activity was accompanied by 130 earthquakes occurring over three hours that morning. Mount Etna, Europe's most active volcano, has seen periodic activity on this part of the mountain since 2013. The Operational Land Imager (OLI) on the Landsat 8 satellite acquired the main image of Mount Etna on December 28, 2018. The inset image highlights the active vent and thermal infrared signature from lava flows, which can be seen near the newly formed fissure on the southeastern side of the volcano. The inset was created with data from OLI and the Thermal Infrared Sensor (TIRS) on Landsat 8. Ash spewing from the fissure cloaked adjacent villages and delayed aircraft from landing at the nearby Catania airport. Earthquakes occurred in the subsequent days after the initial eruption and displaced hundreds of people from their homes. For nighttime images of Mt. Etna's March 2017 eruption, see pages 48-51.

moonlight, we can even track volcanic ash plumes, which can be hazardous to airplanes in flight. The ash, made up of tiny pieces of glass and rock, is abrasive to engine turbine blades and can melt on the blades and other engine parts, causing damage and even engine stalls, with consequent danger to the plane's integrity and passenger safety. Volcanic ash also reduces visibility for pilots and can cause etching of windshields, further reducing pilots' ability to see. Nightlight images can be combined with thermal images to give a more complete view of volcanic activity on Earth's surface, as will be seen later.

The VIIRS DNB takes advantage of moonlight, airglow (the atmosphere's self-illumination through chemical reactions), zodiacal light (sunlight scattered by interplanetary dust), and starlight from the Milky Way. By using these dim light sources, the DNB can detect changes in clouds, snow cover, and sea ice. Geostationary Operational Environmental Satellites (GOES), managed by the National Oceanic and Atmospheric Administration (NOAA), orbit over Earth's equator, offering uninterrupted observations of North America, whereas high-latitude areas such as Alaska benefit from polar-orbiting satellites like Suomi NPP. Polar-orbiting satellites provide significant overlapping coverage at the poles, enabling more data to be acquired in these regions. For example, during polar darkness (i.e., winter months), VIIRS DNB data allow scientists to observe sea ice formation and snow cover extent at the highest latitudes, in addition to spotting where there is clear water for ships to pass through.

The use of nightlight data by weather forecasters is growing as the VIIRS instrument can be used to see clouds at night when they are lit by moonlight and lightning. Scientists use nightlight data to study nighttime behavior of weather systems, including severe storms, which can develop and strike populous areas at night as well as during the day. Combined with thermal data, visible nightlight data can also be used to see clouds at various heights in the atmosphere at night, such as dense marine fog, which allows weather forecasters to issue marine advisories with higher confidence than ever before and, therefore, greater utility—see "Marine Layer Clouds—California" on page 56.

In this section of the book you will see how nightlight data are used to observe nature's spectacular light shows across a wide range of sources.



Credit: USGS/NASA

Fires

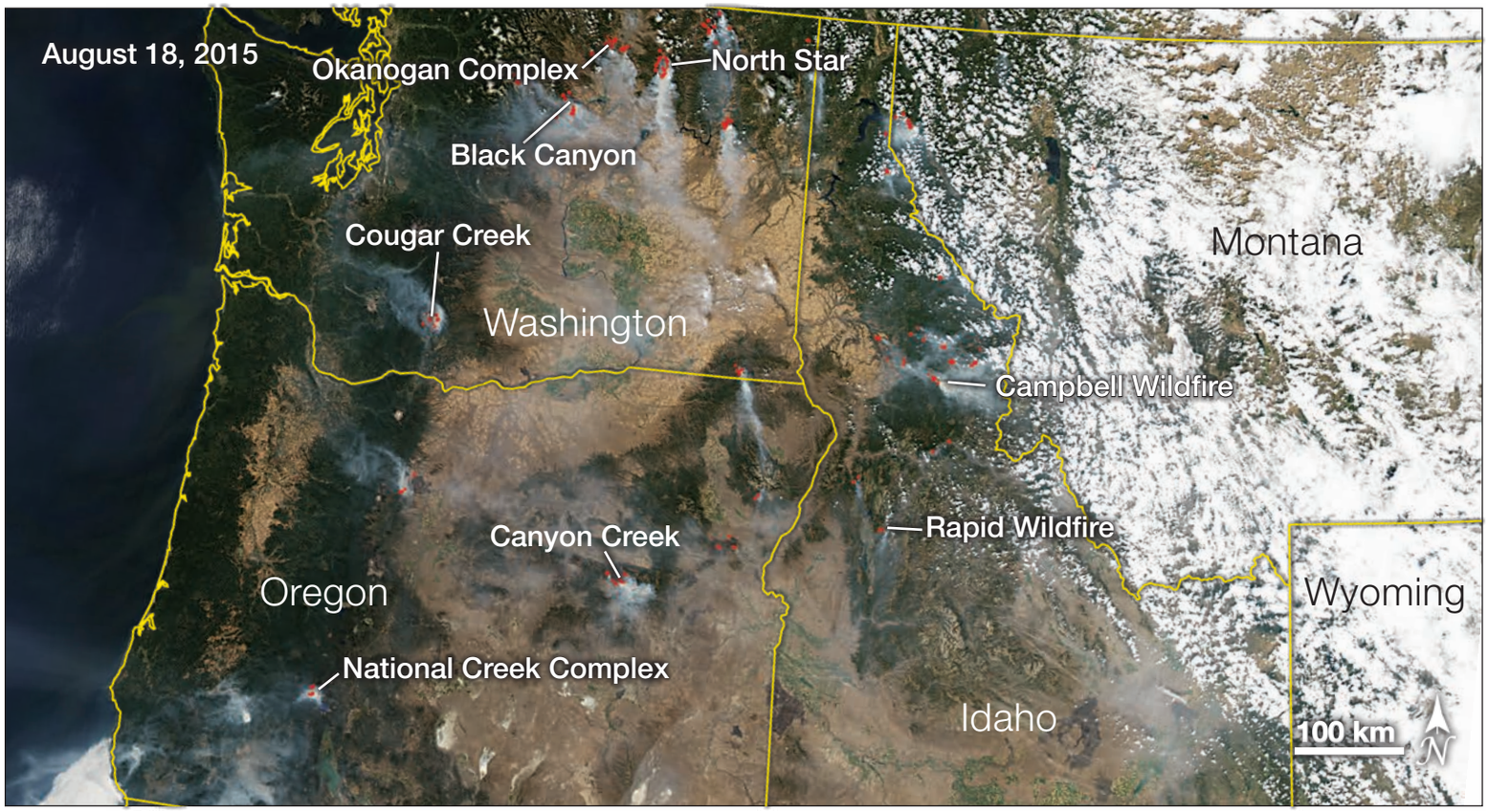
Tracking Fires Day and Night—Northwest United States

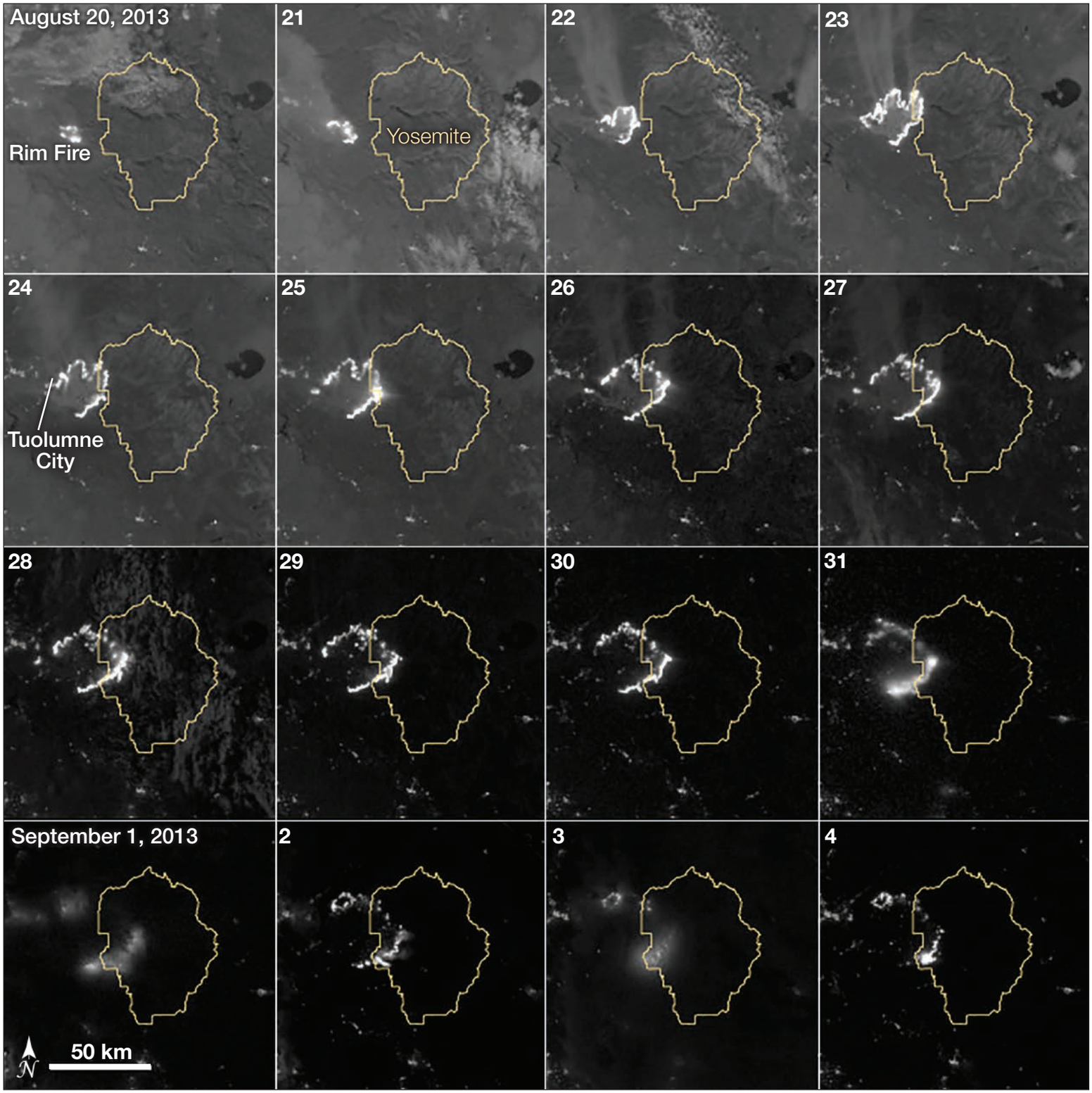
In summer 2015, wildfires raged across the western contiguous United States and Alaska. Many of those fires burned in the Northwest United States, visible in these images from late August. The nighttime image (top, opposite) was acquired in the early morning (local time) on August 19, 2015, by the VIIRS DNB on the Suomi NPP satellite. Labels point to the large, actively burning fires in the region.

The daytime image (bottom, opposite) shows the same area in natural color, acquired during the afternoon on August 18, 2015, with the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite. Red outlines indicate hot spots where MODIS detected unusually warm surface temperatures, generally associated with fires. Thick plumes of smoke are visible emanating from the hot spots.

According to the Northwest Interagency Coordination Center, the Okanogan Complex Fire in Washington was among the larger active fires; as of August 20, the fire had burned 91,314 acres (143 square miles, or 370 square kilometers). In Oregon, the Canyon Creek Complex Fire had burned 48,201 acres (75 square miles, or 195 square kilometers), destroyed 26 residences, and threatened another 500. Both fires were less than 40 percent contained at the time the images were acquired.

August 19, 2015
Okanogan Complex
North Star
Black Canyon
Seattle
Spokane
Cougar Creek
Montana
Washington
Campbell Wildfire
Portland
Canyon Creek
Rapid Wildfire
Oregon
Wyoming
National Creek Complex
Boise
Idaho
100 km
N


August 18, 2015
Okanogan Complex
North Star
Black Canyon
Cougar Creek
Montana
Washington
Campbell Wildfire
Canyon Creek
Rapid Wildfire
Oregon
Wyoming
National Creek Complex
Idaho
100 km
N


August 20, 2013
Rim Fire
21
Yosemite
22
23
24
Tuolumne City
25
26
27
28
29
30
31
September 1, 2013
2
3
4
N
50 km

Progression of the Rim Fire—Yosemite, California

The winter of 2012–2013 was among the driest on record for California, setting the stage for an active fire season in the summer of 2013. At the time, the Rim Fire was the third largest in California since record-keeping began in 1932.

The VIIRS DNB on the Suomi NPP satellite tracked the growth of the fire between August 20 and September 4, 2013. The brightest, most intense parts of the fire glow white. Pale gray smoke streams away, generally to the north. Thin clouds obscured the view on some days, particularly August 31, September 1, and September 3. On August 20, the Moon was full, so the landscape reflected a large amount of moonlight. The background grew progressively darker as the new Moon approached on September 5.

The perimeter of the fire changed along different fronts from day to day, depending on winds and firefighting efforts. On August 24, firefighters focused on containing the western edge of the fire to prevent it from burning into Tuolumne City and the populated Highway 108 corridor. They also fought the eastern edge of the fire to protect Yosemite National Park (outlined in yellow). These efforts are evident in the images: Between August 23 and 24, the eastern edge held steady, the western edge receded, and the fire grew in the southeast.

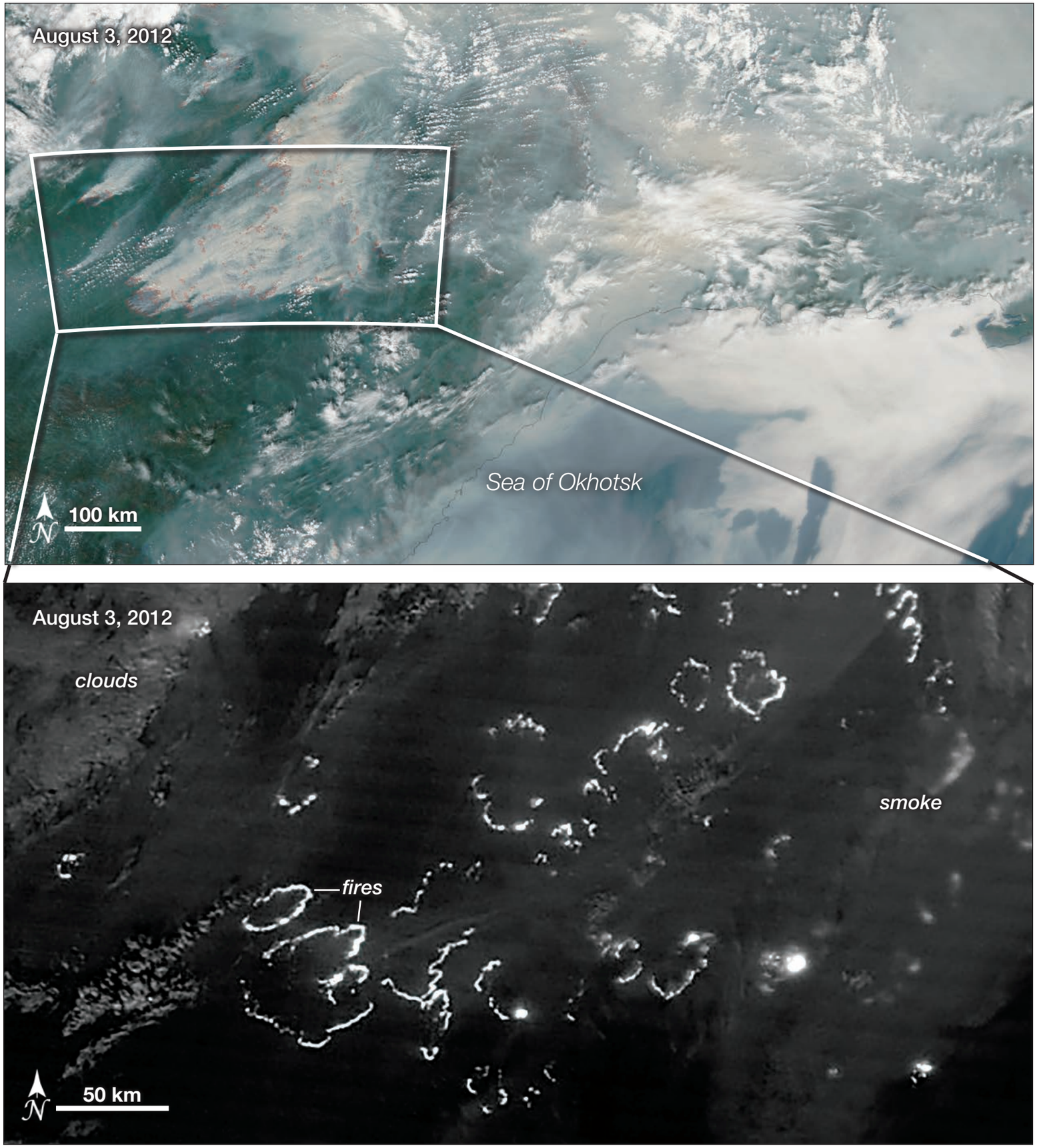
On the morning of August 25, 2013, fire managers reported that the blaze was growing in the north and east. With the fire burning aggressively and moving east into Yosemite, August 26 and 27 proved challenging days for firefighters. But over the next few days, they began to gain control after a series of burnout operations along the fire's northern and eastern edges. On August 29, the evacuation advisory for Tuolumne City was lifted. The southeastern flank continued to burn intensely into the first week of September.

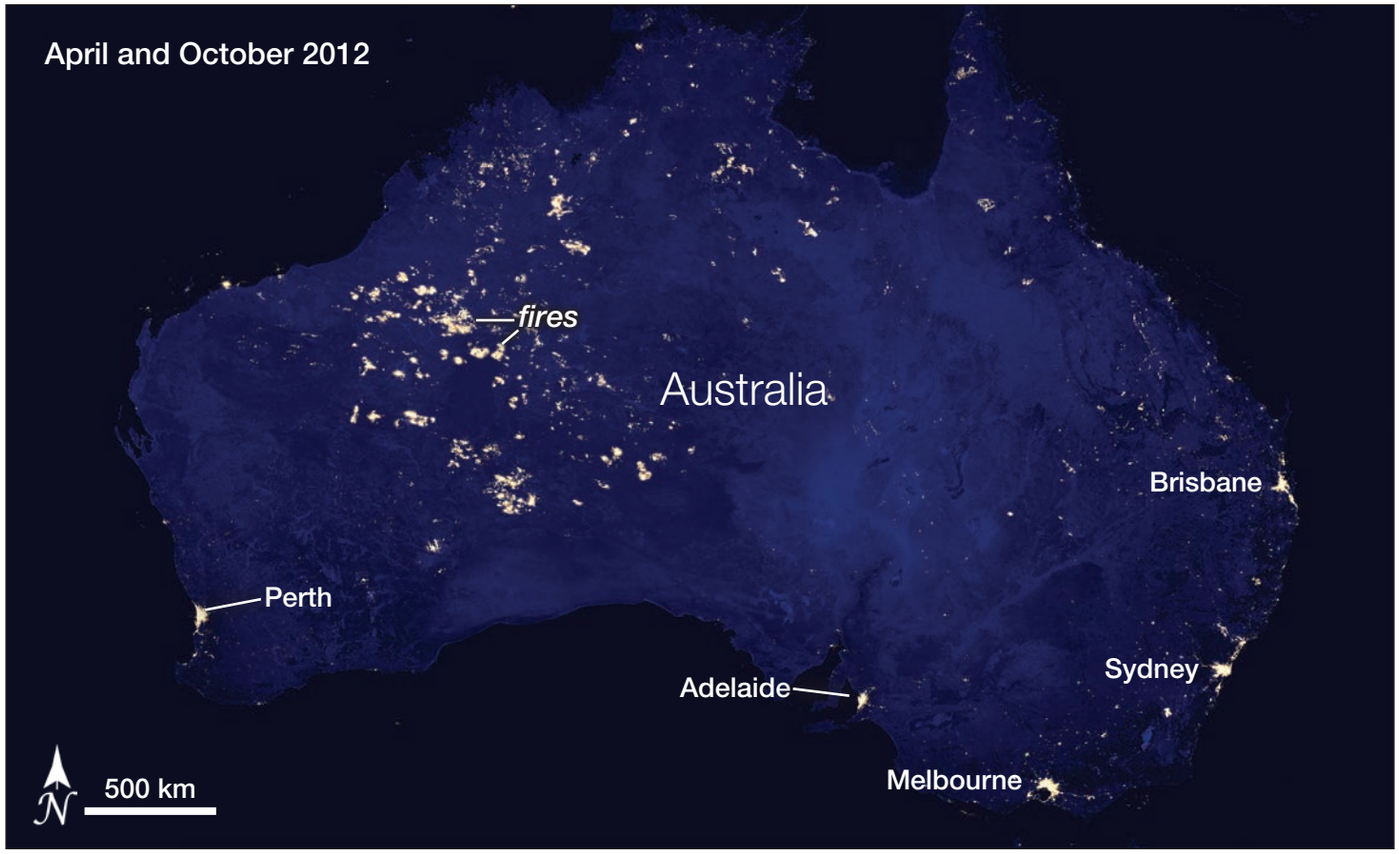
Spreading Like Wildfire—Yakutia, Siberia, Russia

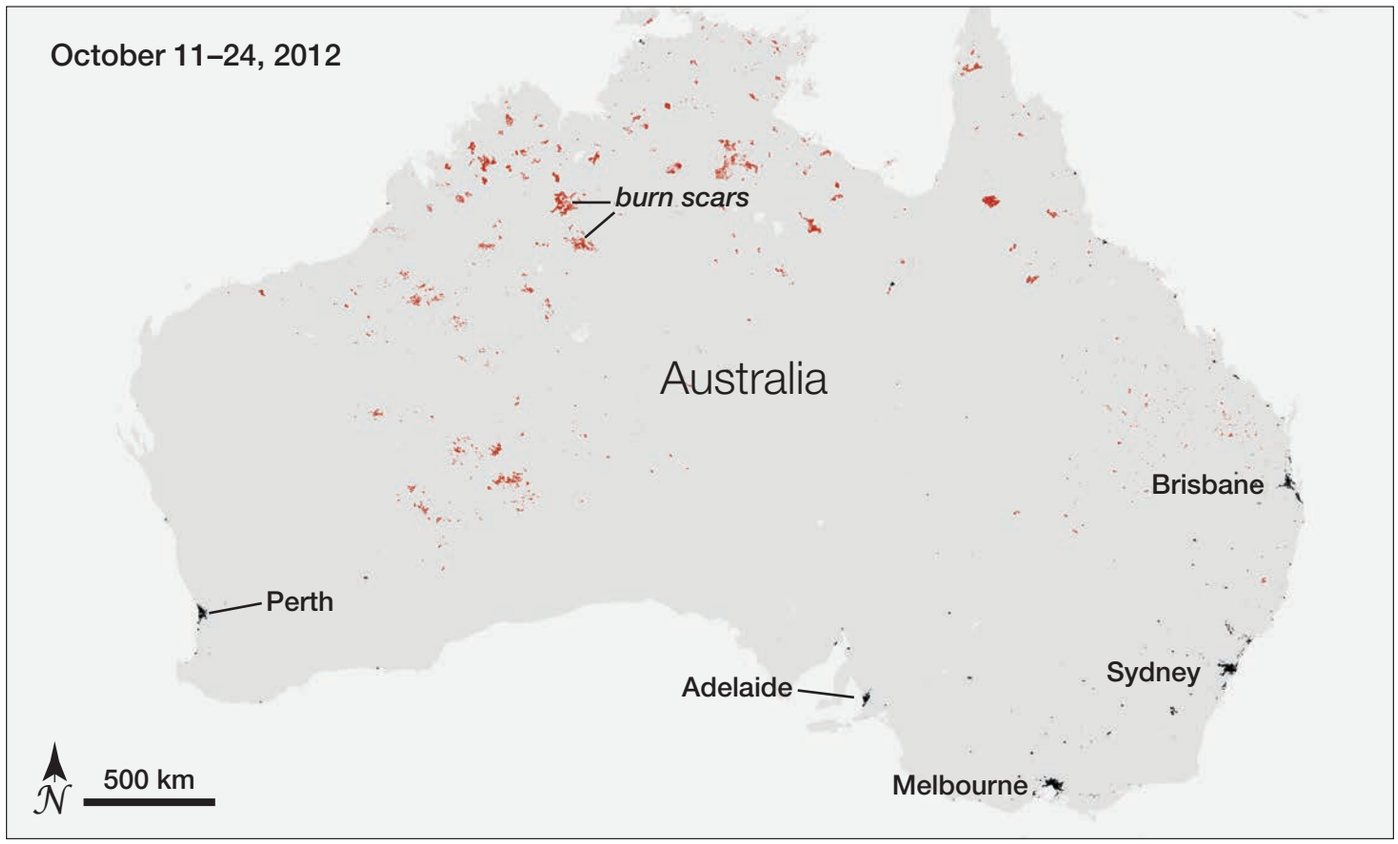
On August 3, 2012, the MODIS instrument on NASA's Aqua satellite acquired a daytime view of a group of wildfires blazing in eastern Siberia, as shown in the top panel. The fires detailed in the white box were burning in the southeastern part of Yakutia, near the port city of Yakutsk along the Lena River. Red dots indicate hot spots where MODIS detected unusually warm surface temperatures associated with fires. Smoke is visible emanating from the hot spots.

The VIIRS DNB on Suomi NPP acquired a nighttime image of that same group of fires on the same date, as seen in the bottom panel. In this image, the brightest fires are white; smoke is light gray.

The vast majority of Russian wildfires occur in Siberia, generally along the southern border with China and Mongolia.


August 3, 2012
Sea of Okhotsk
100 km
N
August 3, 2012
clouds
smoke
fires
50 km
N


April and October 2012
fires
Australia
Brisbane
Perth
Sydney
Adelaide
Melbourne
500 km
N


October 11–24, 2012
burn scars
Australia
Brisbane
Perth
Sydney
Adelaide
Melbourne
500 km
N

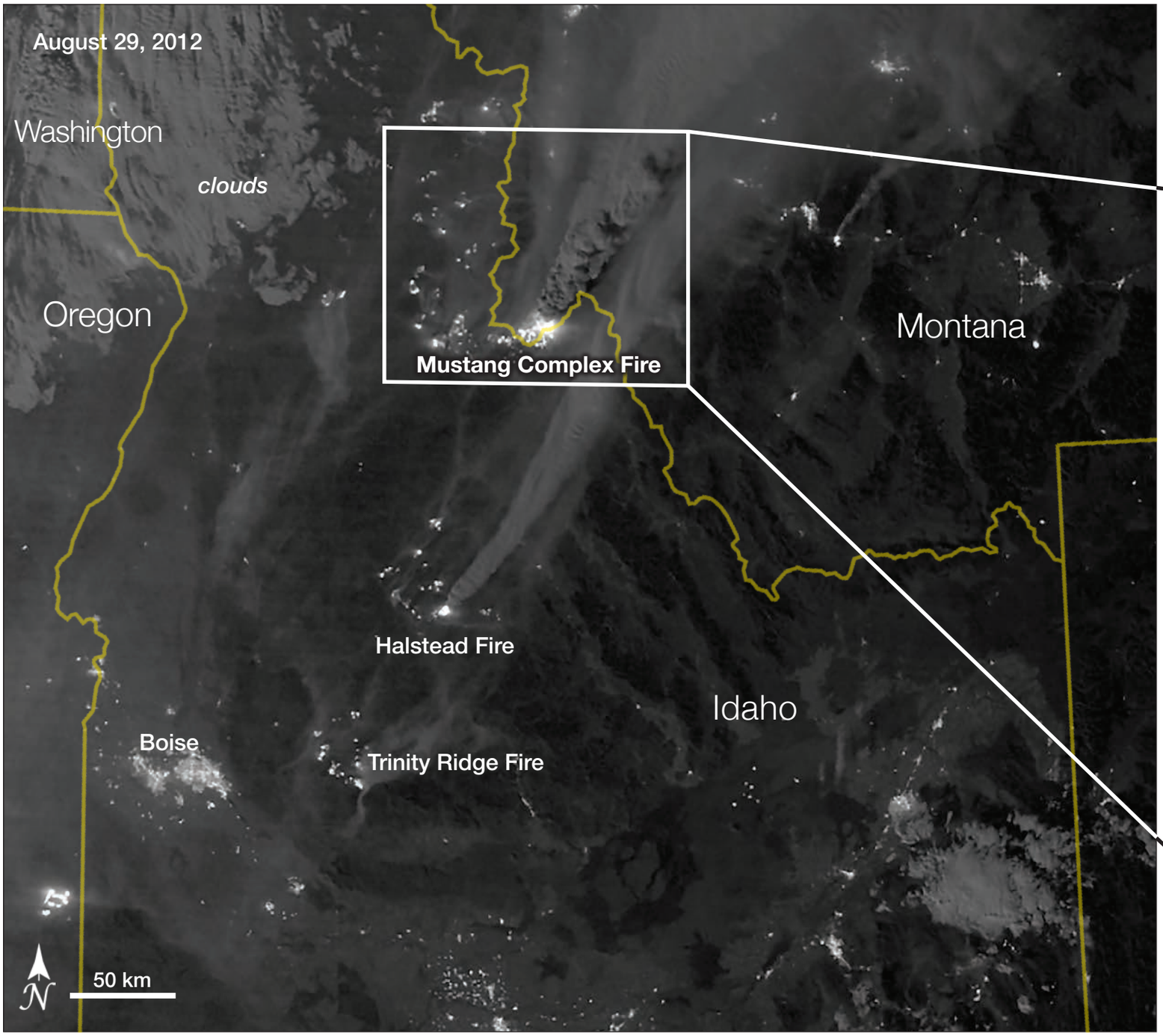
City Lights, or Not—Australia

The top image at left shows the nightlights of Australia as observed by the VIIRS DNB on the Suomi NPP satellite in April and October 2012. The composite image includes manmade light sources and the light from wildfires.

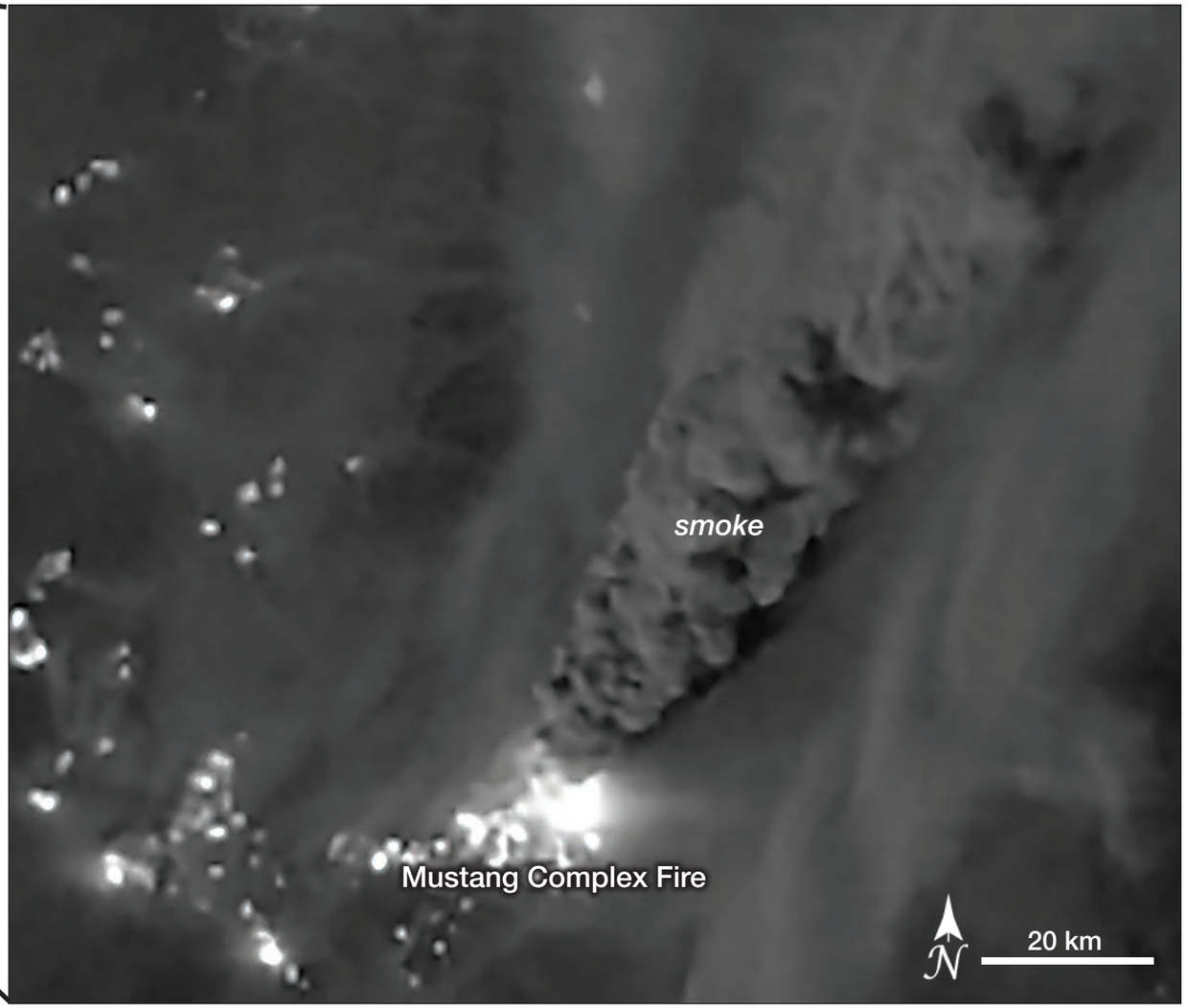
The lower map is a mosaic showing the burned areas of the landscape (red) from October 11–24, 2012, combined with urban areas (black). The data were collected by the MODIS instruments on NASA's Terra and Aqua satellites. In effect, the lower map shows where fires burned that month. Though many rural areas of interior Australia are dry and relatively barren by some standards, there is still enough vegetation to burn. Not every light in the night view matches up with a fire—partly because the fire map does not include fires from April and partly because not every fire leaves a scar that is detectable from space. Even simple cloud cover could prevent burn scars from being observed. Aside from the fires, some of the nightlights appearing in uninhabited areas can be attributed to lightning, flares of natural gas and other activities from oil drilling or mining operations, and fishing boats—all of which can show up as points of light.

Billowing Smoke in the Night—Idaho and Montana

On August 29, 2012, the VIIRS DNB on the Suomi NPP satellite captured this nighttime view of wildfires burning in Idaho and Montana. When the image was acquired, the Moon was in its waxing gibbous phase (i.e., it was more than half lit but less than full). Numerous hot spots from the Mustang Complex Fire are visible in northern

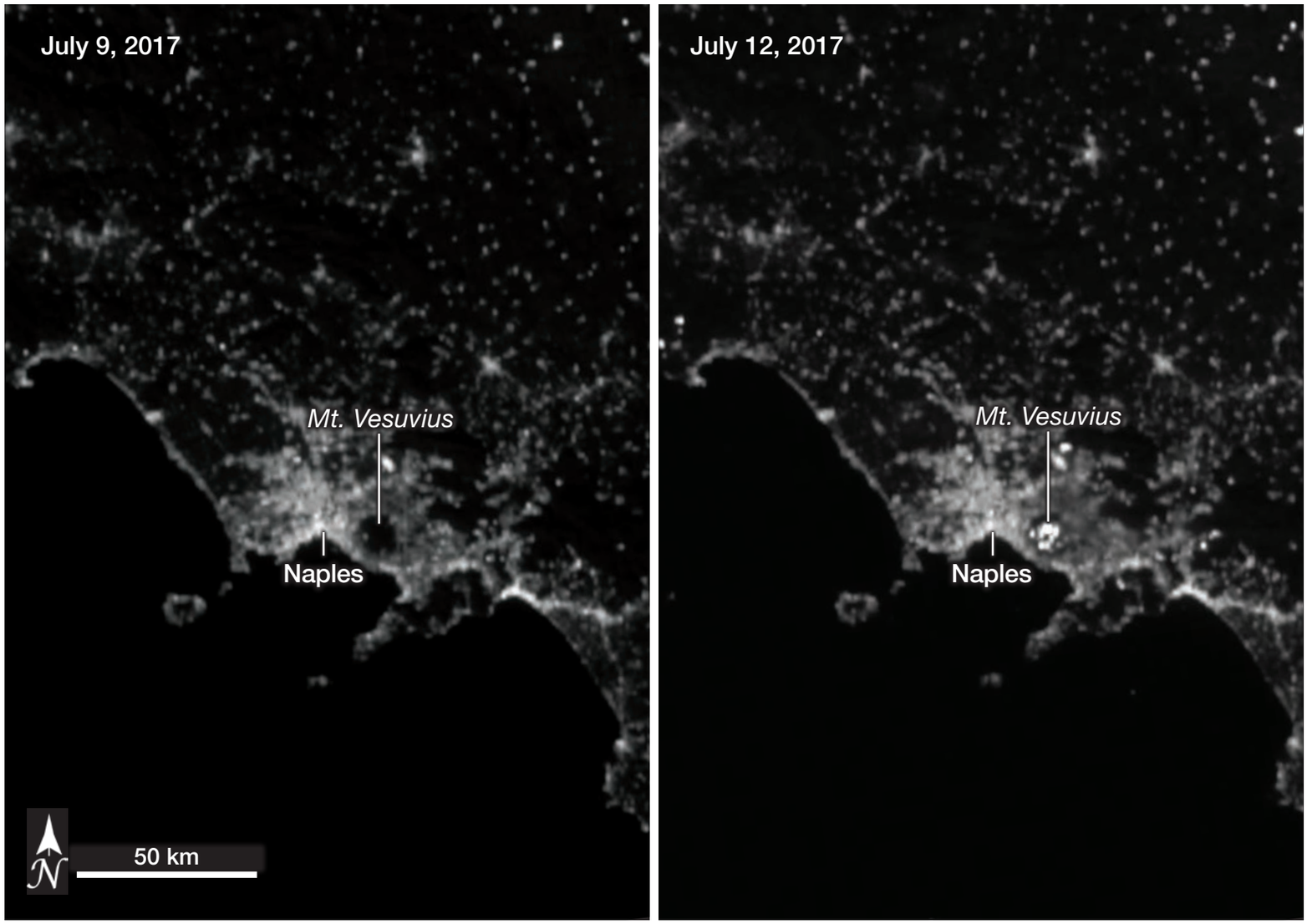


Idaho. A plume of thick, billowing smoke streams west from the brightest fires near the Idaho–Montana border. The Halstead and Trinity Ridge fires are visible to the south. In addition to the fires, city lights from Boise and other smaller cities appear throughout the image. A bank of clouds is located west of the Mustang Complex, over southeastern Washington and northeastern Oregon.



Fires Light Up Mount Vesuvius—Naples, Italy

The forest preserve on Mount Vesuvius normally keeps the Italian mountain shrouded in darkness when viewed in nighttime photographs by astronauts or in satellite images of Naples. However, that was not the case on July 12, 2017, when the VIIRS DNB on Suomi NPP captured an image (below, right) of wildfires lighting up the slopes of the volcano. For comparison, the July 9, 2017, image (below, left) was taken before the fires began. The July fires burned much of the woodlands in Vesuvius National Park, which was established in 1995. The park protects more than 600



types of plants, 100 species of birds, and many small mammals and reptiles. Mount Vesuvius is best known for a catastrophic eruption in 79 A.D. that destroyed the cities of Pompeii and Herculaneum. Its last major eruption occurred in 1944.

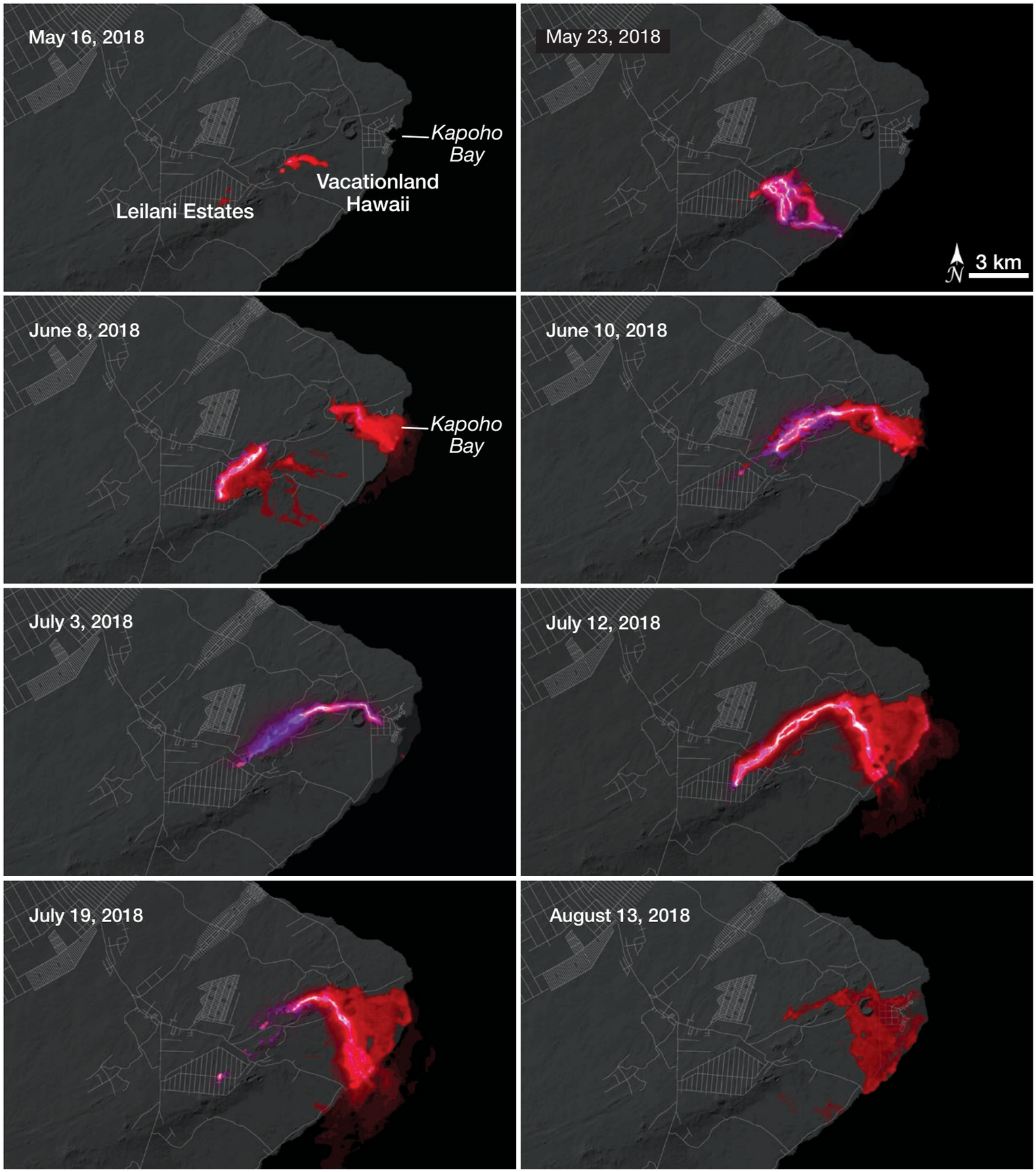
For comparison, the MODIS instrument captured this daylight image (below) of the fires (red dots) on July 12. Note how the extent of Naples and the area around the volcano are less clearly defined.

Volcanoes

The Infrared Glows of Kilauea's Lava Flows—Hawaii

In early May 2018, an eruption on Hawaii's Kilauea volcano began to unfold. The eruption took a dangerous turn on May 3, 2018, when new fissures opened in the residential neighborhood of Leilani Estates. During the summer-long eruptive event, other fissures emerged along the East Rift Zone. Lava from vents along the rift zone flowed downslope, reaching the ocean in several areas, and filling in Kapoho Bay.

A time series of Landsat 8 imagery shows the progression of the lava flows from May 16 to August 13. The night view combines thermal, shortwave infrared, and near-infrared wavelengths to tease out the very hot lava (bright white), cooling lava (red), and lava flows obstructed by clouds (purple).


May 16, 2018
Kapoho Bay
Vacationland Hawaii
Leilani Estates
May 23, 2018
N
3 km
June 8, 2018
Kapoho Bay
June 10, 2018
July 3, 2018
July 12, 2018
July 19, 2018
August 13, 2018

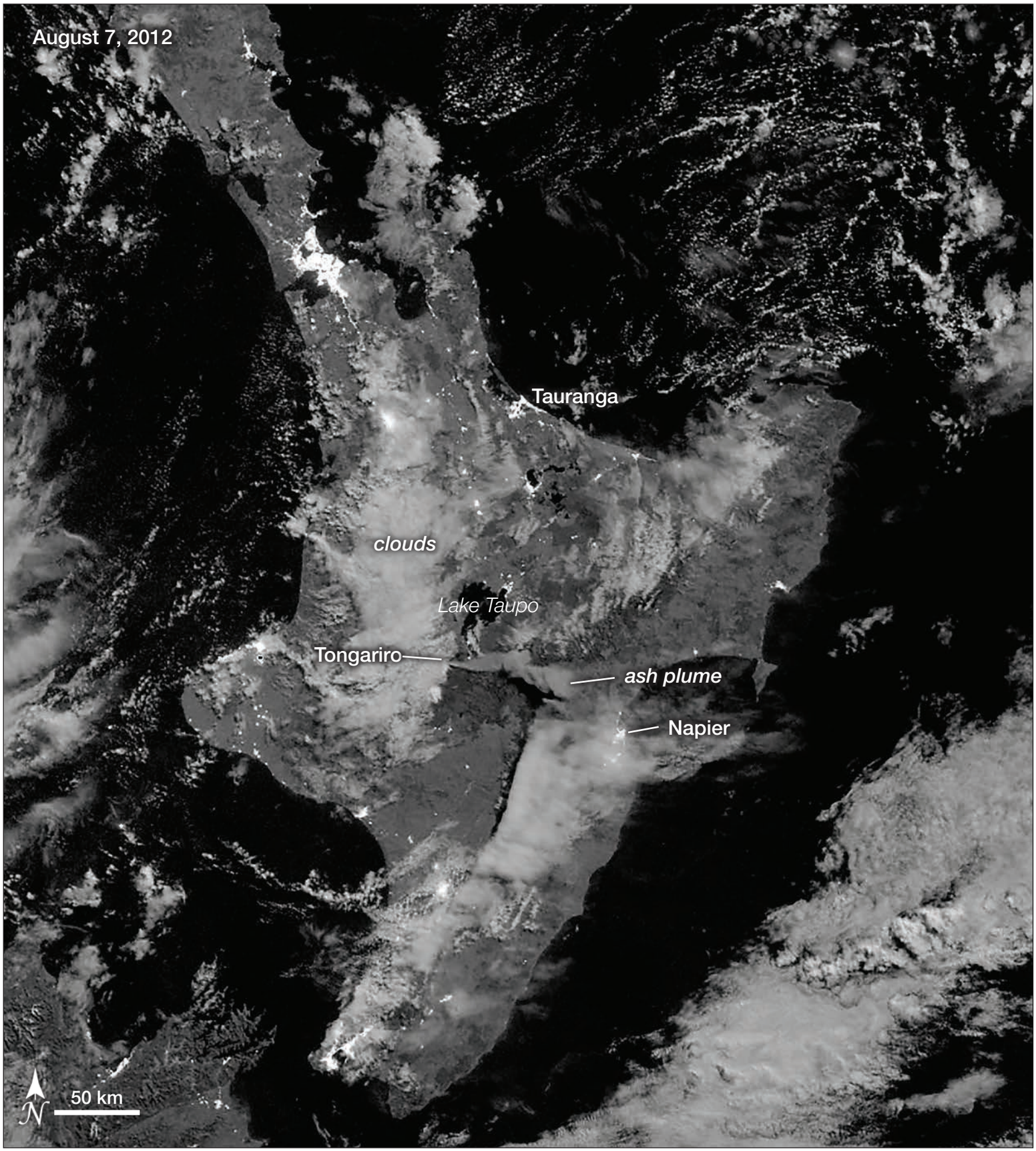
Mount Tongariro Erupts—New Zealand

Late on August 6, 2012, New Zealand's Mount Tongariro erupted for the first time in 115 years, spewing a cloud of ash over North Island, closing roads, and cancelling domestic flights. The image at right, observed by the VIIRS DNB on Suomi NPP, shows Mount Tongariro as it appeared at 12:55 a.m. New Zealand time on August 7.

The volcano lies in a mostly undeveloped part of the country. The 6,490-foot (1,978-meter) peak is a popular spot for hikers and is right next to Mount Ngauruhoe, the stand-in for Mount Doom in the "Lord of the Rings" movies. Both Tongariro and Ngauruhoe are part of the circum-Pacific seismic belt or "Ring of Fire" region, known for its seismic activity and volcanism.

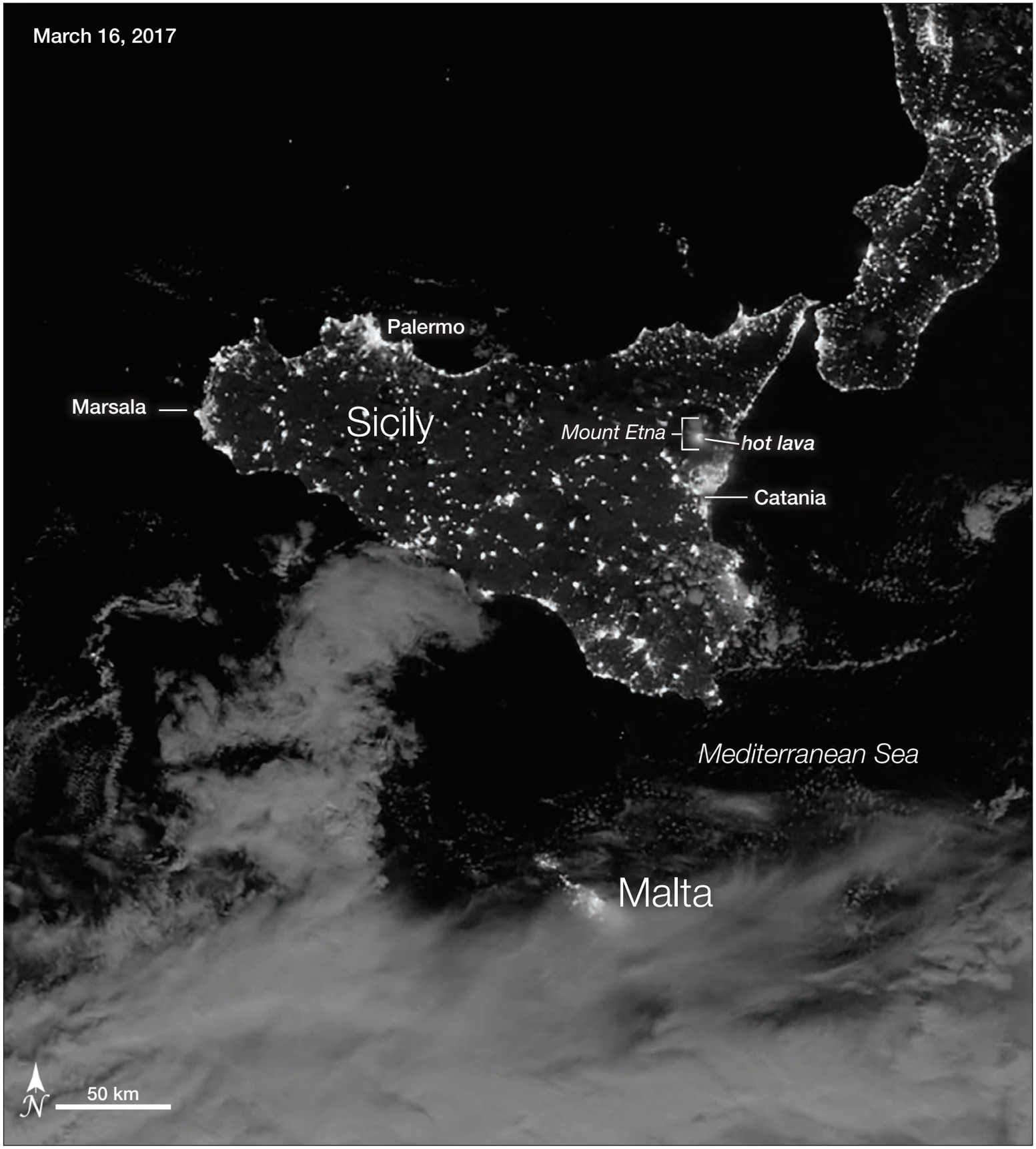
Tongariro sent ash at least 20,000 feet (6,100 meters) into the air. Because of the impact to aircraft operations, the New Zealand Civil Aviation Authority issued advisories to reroute air traffic around the ash plume so as to avoid damage to aircraft engines as happened in 1989 when a KLM Boeing 747 commercial jet flew into an ash plume produced by Alaska's Mt. Redoubt, which resulted in damage to all four engines. Swift, skillful piloting kept this incident from being a tragedy, as all engines were subsequently restarted, and the aircraft landed safely.

The first appearance of the ash plume occurred far downwind of Tongariro in thermal imagery, as ash was lofted high enough to produce a strong thermal contrast in the atmosphere. Images from the VIIRS DNB can be combined with thermal images such as from VIIRS (not shown here) to give a more-complete view of such activity on Earth's surface. Getting thermal data closer to a volcano with conventional infrared sensors is difficult, but VIIRS can detect such signals close to the source and lower in the atmosphere than other sensors.


August 7, 2012
Tauranga
clouds
Lake Taupo
Tongariro
ash plume
Napier
N
50 km

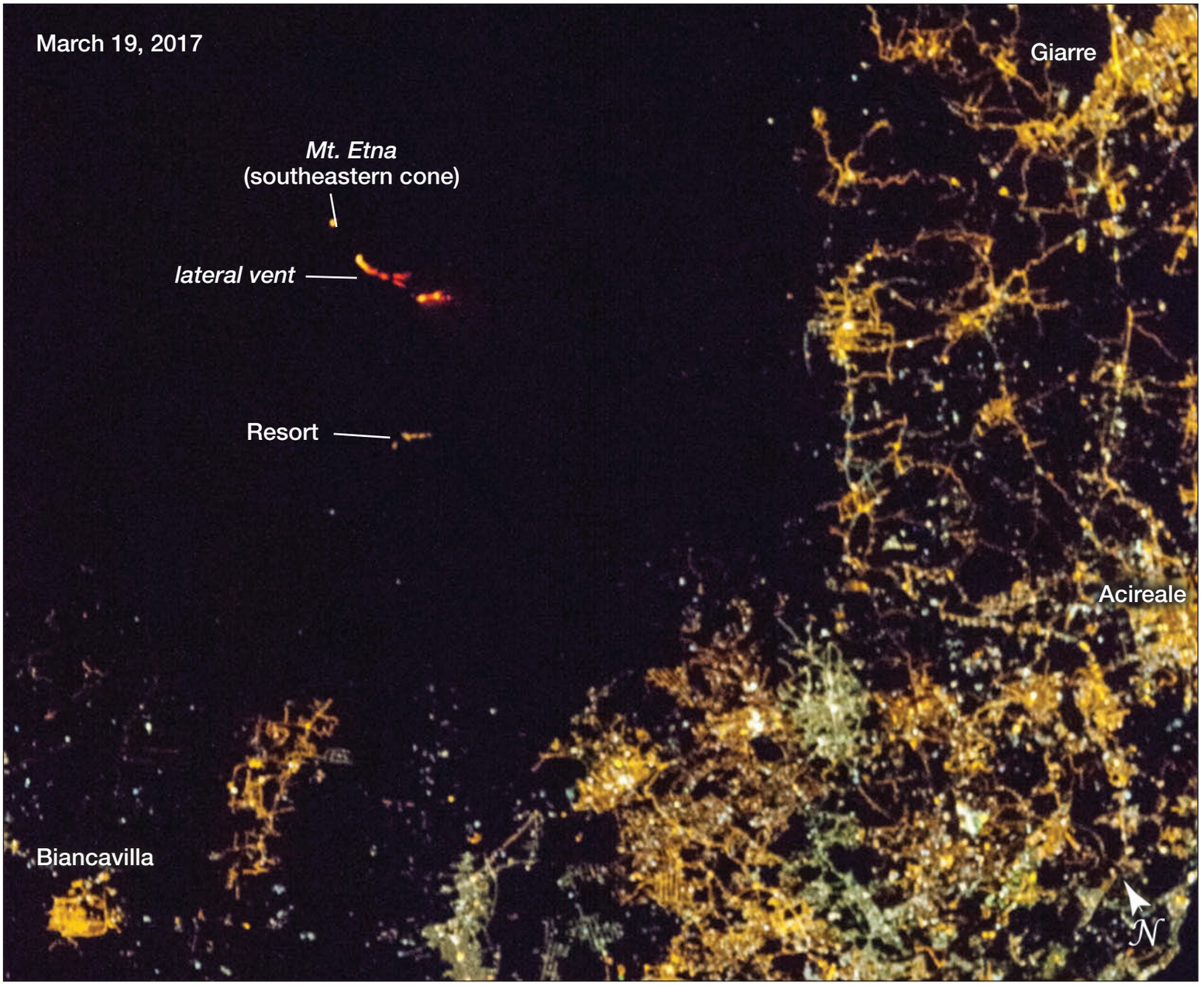
Nighttime Glow at Mount Etna—Italy

At about 2:30 a.m. local time on March 16, 2017, the VIIRS DNB on the Suomi NPP satellite captured this nighttime image of lava flowing on Mount Etna in Sicily, Italy. Etna is one of the world's most active volcanoes.


March 16, 2017
Palermo
Marsala
Sicily
Mount Etna
hot lava
Catania
Mediterranean Sea
Malta
N
50 km

Mount Etna Erupts—Italy

The highly active Mount Etna in Italy sent red lava rolling down its flank on March 19, 2017. An astronaut onboard the ISS took the photograph below of the volcano and its environs that night. City lights surround the mostly dark volcanic

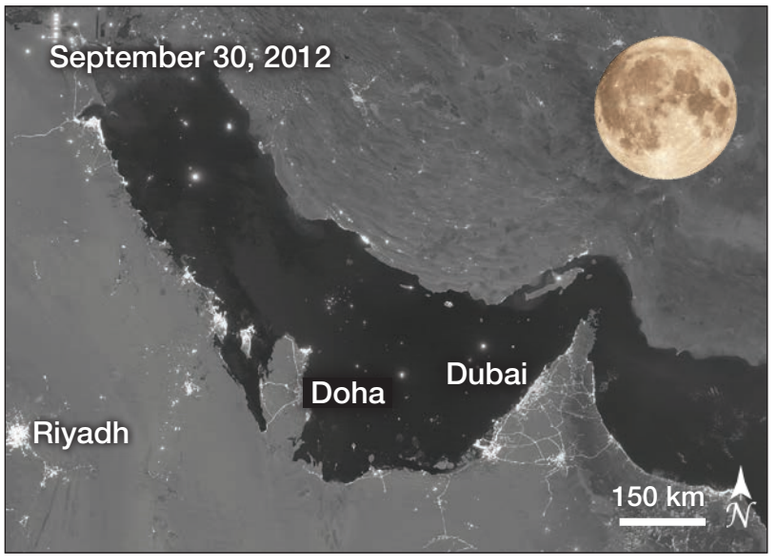


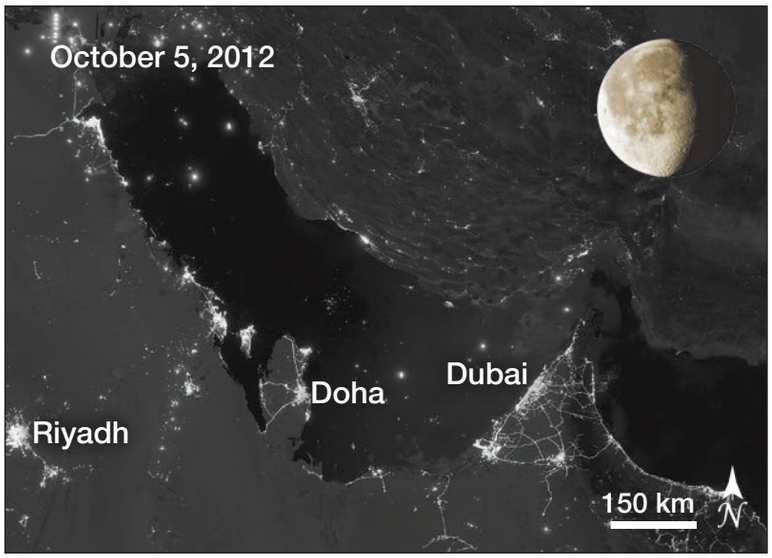
mountain. On the previous day, the Operational Land Imager (OLI) on Landsat 8 acquired this natural-color image (below) of an ash plume emanating from the summit and the flank.

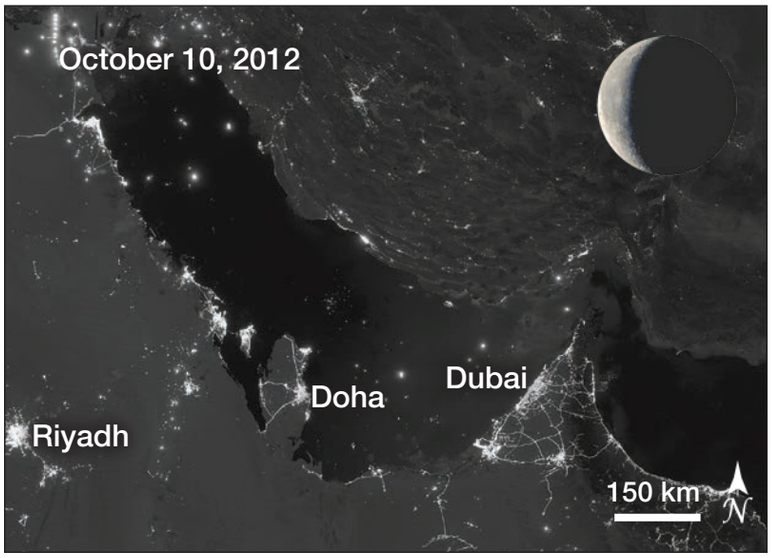
Moonlight and Moonglint

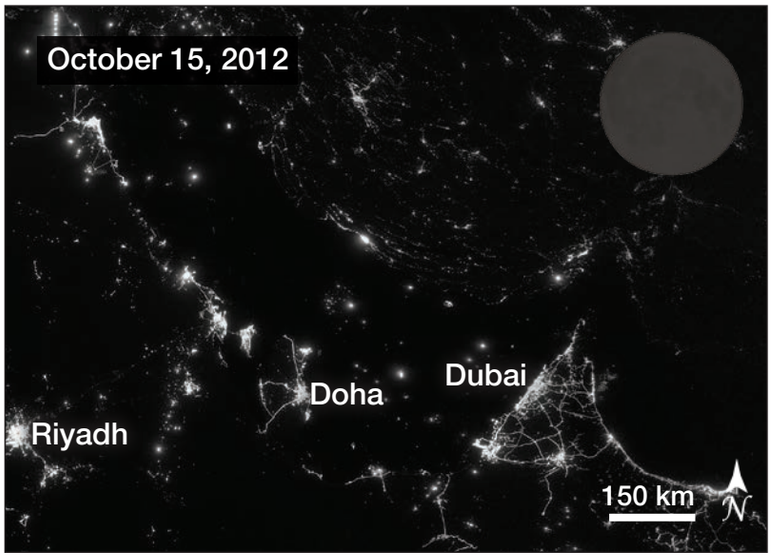
Moon Phases—Persian Gulf

The VIIRS DNB on the Suomi NPP satellite captured these nighttime views of the Persian Gulf region on September 30 and October 5, 10, and 15, 2012. Each image includes an inset of the Moon in one of four different phases. September 30 shows the Persian Gulf by the light of the full Moon; October 15 shows the effects of a new Moon. As the amount of moonlight decreases, some land surface features become harder to detect, but the lights from cities and ships become more obvious. Urbanization is most apparent along the northeastern coast of Saudi Arabia, in Qatar, and in the United Arab Emirates (UAE). In Qatar and UAE, major highways can even be discerned by nighttime lights.


September 30, 2012
Doha
Dubai
Riyadh
150 km
N


October 5, 2012
Doha
Dubai
Riyadh
150 km
N


October 10, 2012
Doha
Dubai
Riyadh
150 km
N

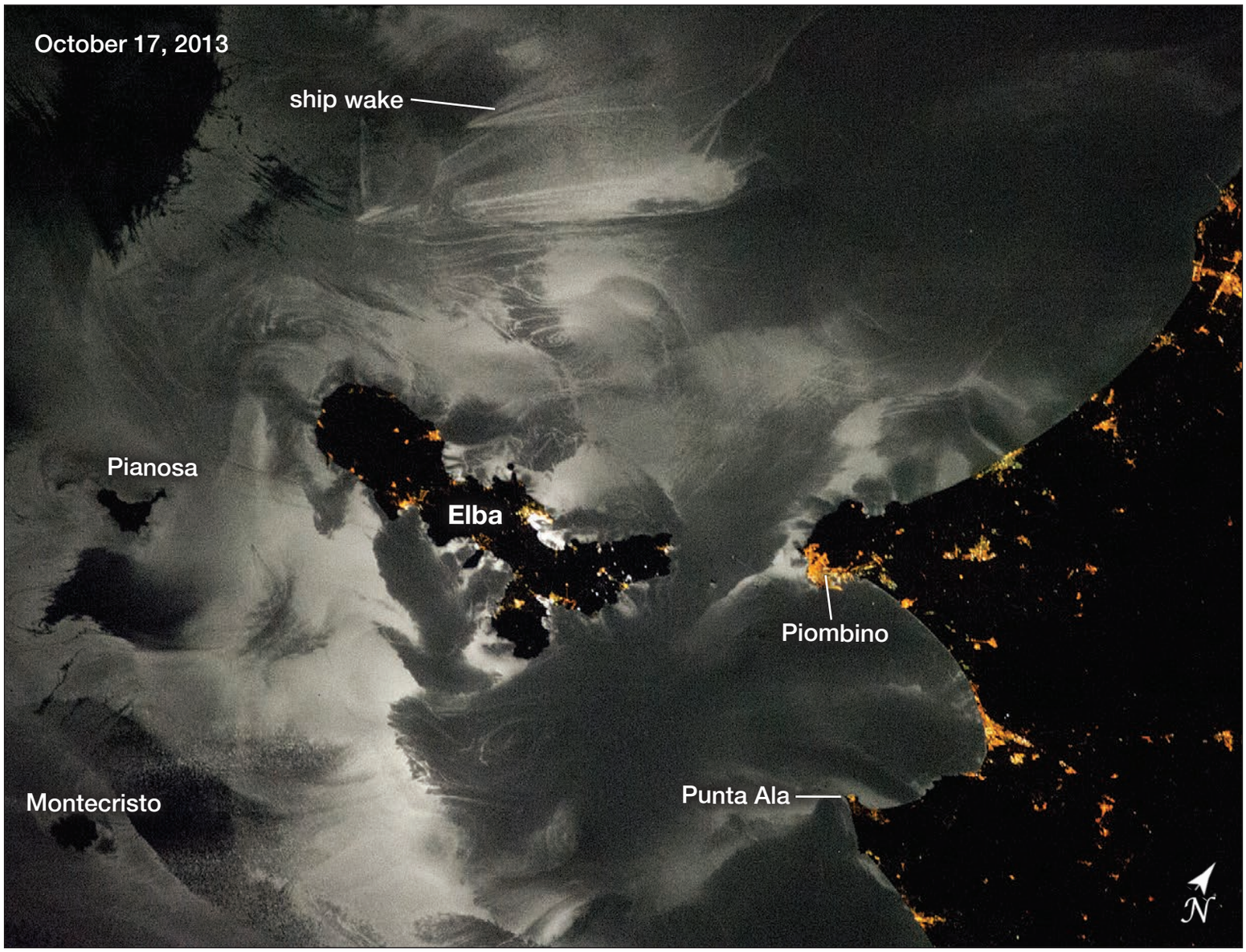

October 15, 2012
Doha
Dubai
Riyadh
150 km
N

Moonglint—Elba and the Mediterranean

A crew member onboard the ISS took this photograph of the northern Mediterranean Sea and some coastal Italian towns and islands on October 17, 2013. The reflection of the Moon on the sea surface—moonglint—reveals highly complex patterns. The strongest reflection is near the center of the Moon's disc, which brightens the water around the island of Elba. In these complex patterns, the dark areas of the sea surface can sometimes make islands, such as Montecristo and Pianosa, harder to see.

The reflection off sea surfaces captures many different natural processes but also some made by humans. North of Elba, waves trailing behind ships make a classic V-shaped pattern. The meandering line coming off Montecristo Island is an island wake, a result of alternating vortices of wind that develop on the downwind side of the island. This wake is the strongest evidence that a northeast wind was blowing (right to left in this image) on the night of the photo. A shorter, meandering wind pattern is being shed off Punta Ala on the mainland. Smoother surfaces, protected from wind, are usually brighter because they are a better mirror for moonlight.

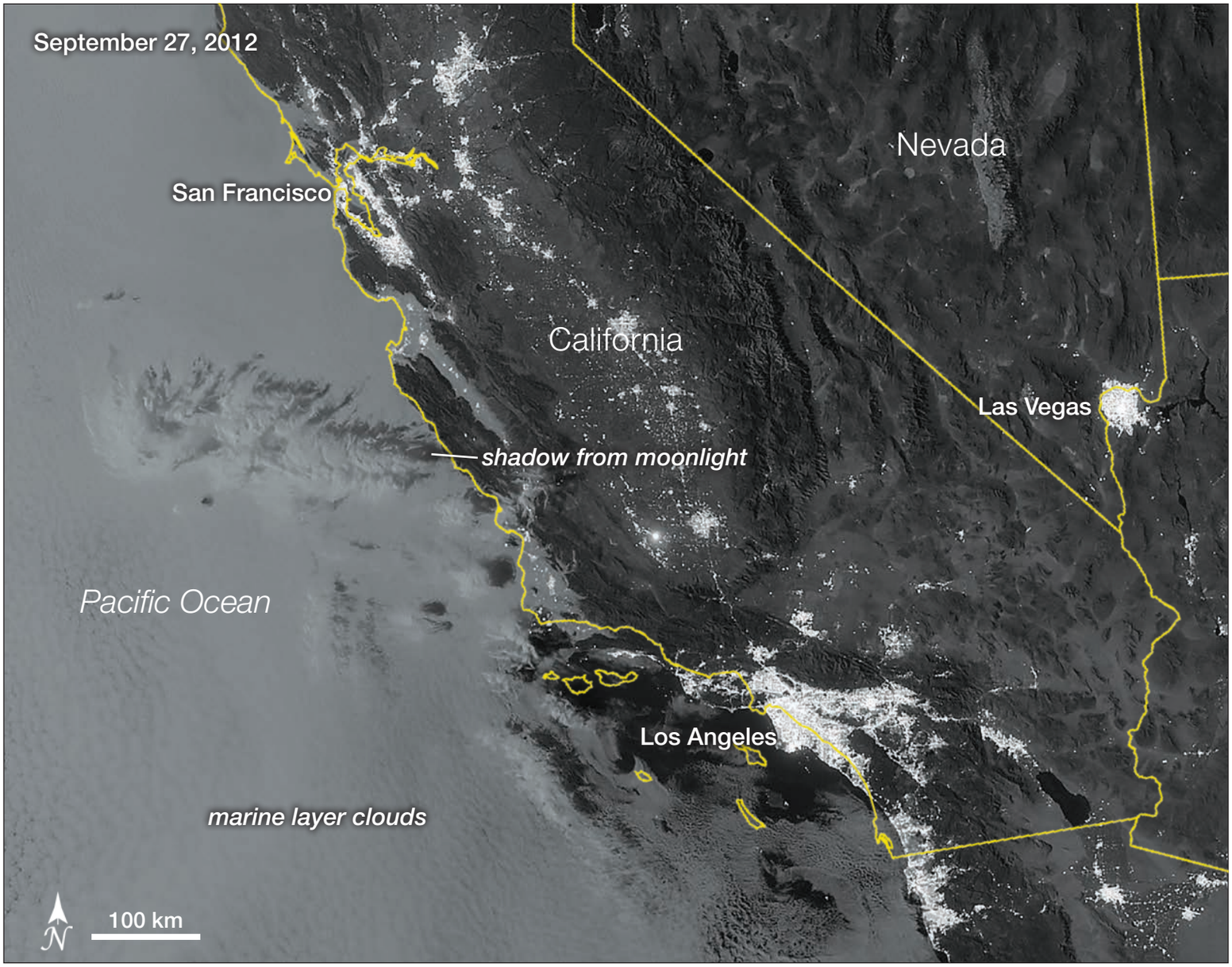
The sea surface also displays numerous tight swirls known as gyres. The broad swath of parallel lines (top left) is probably part of the larger circulation of the sea, which usually experiences north-flowing currents around Elba.


October 17, 2013
ship wake
Pianosa
Elba
Piombino
Montecristo
Punta Ala
N

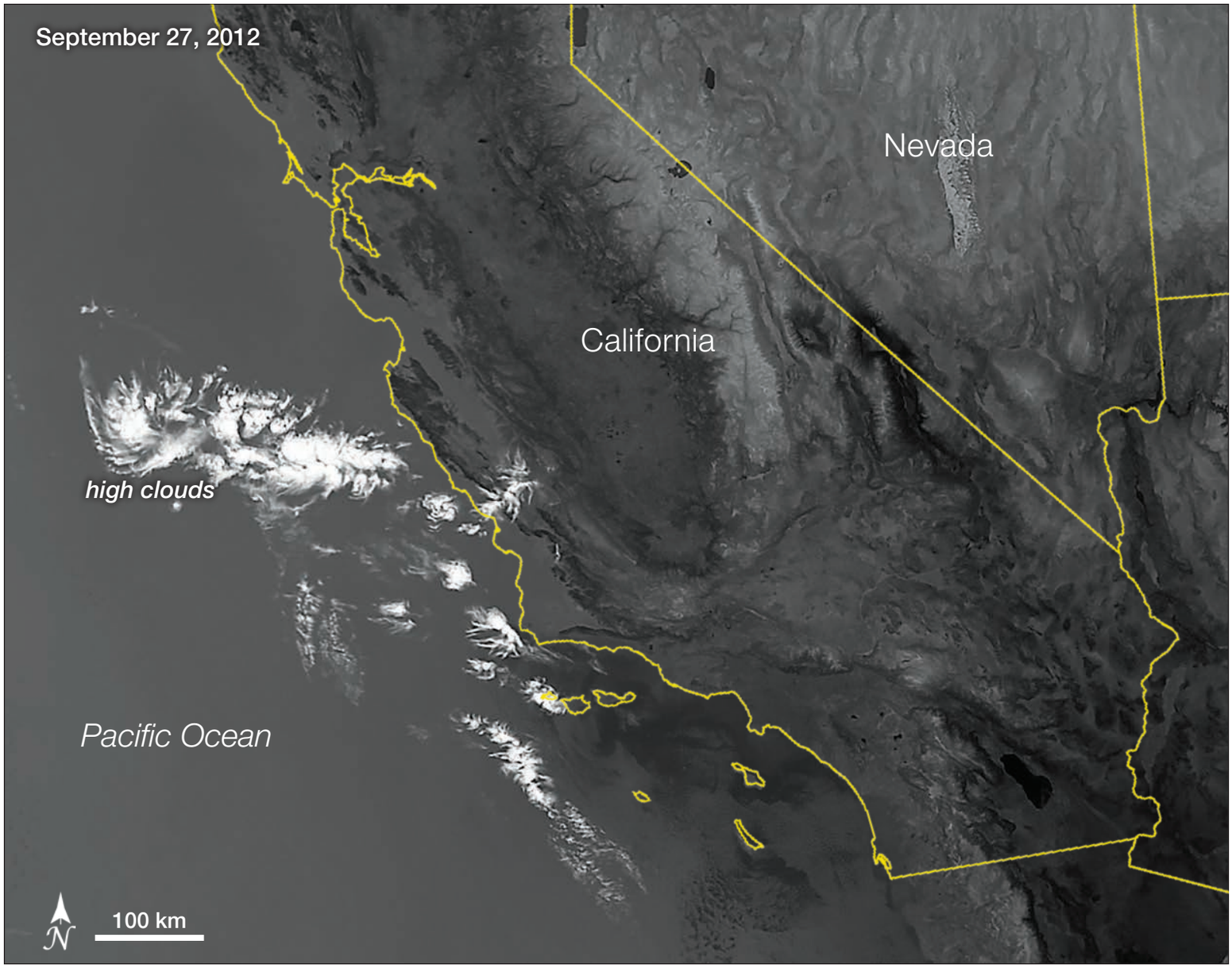
Clouds and Lightning

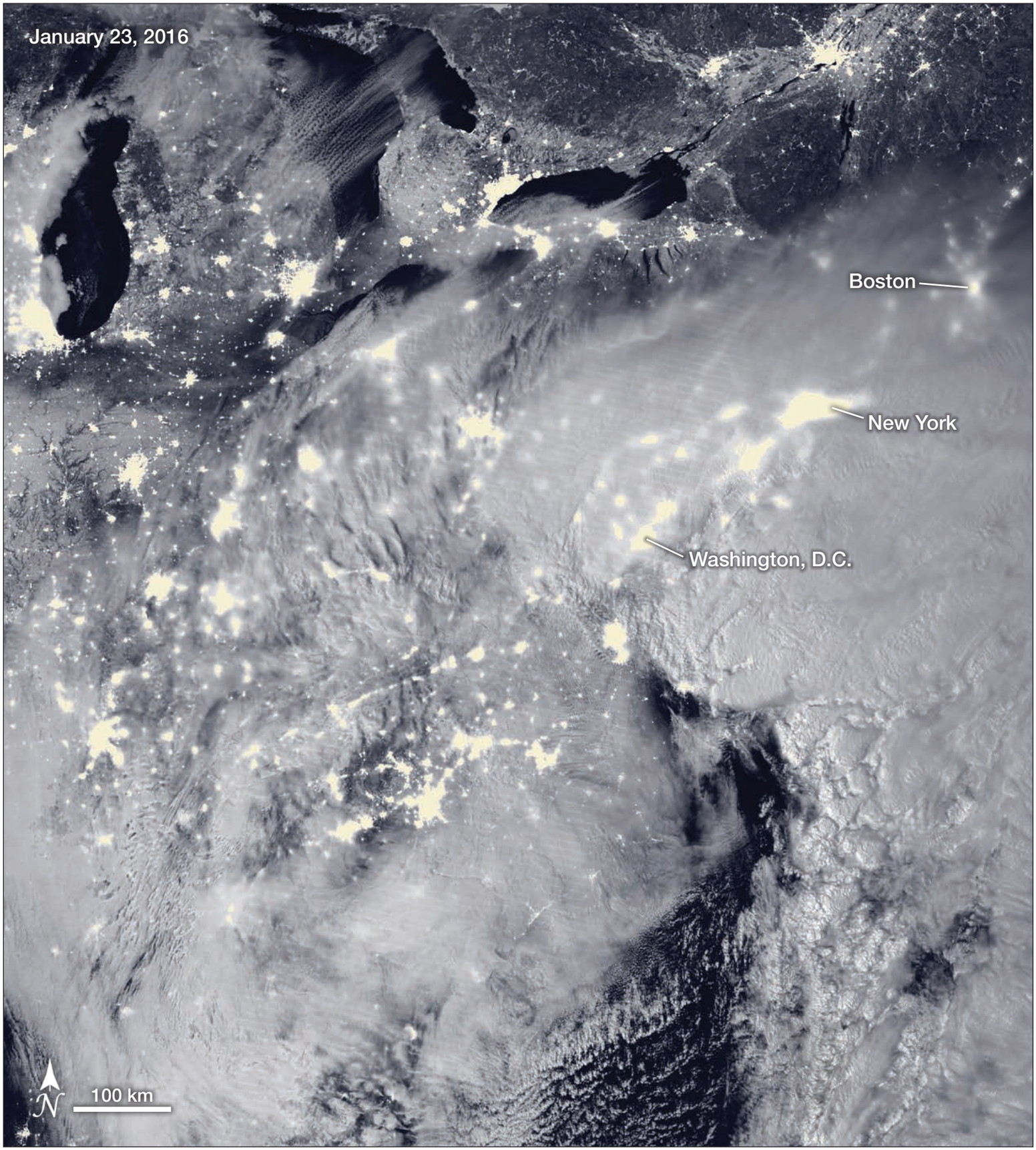
Marine Layer Clouds—California

On September 27, 2012, the VIIRS DNB on the Suomi NPP satellite captured this nighttime view of low-lying marine layer clouds along the coast of California (see below). An irregularly shaped patch of high clouds hovered off the coast of California, and moonlight caused the high clouds to cast distinct shadows on the marine layer clouds below. VIIRS acquired the image when the Moon was in its waxing gibbous phase.



Low clouds can pose serious hazards for air and ship traffic, and satellites have had difficulty detecting them in the past. To illustrate this, the image on this page shows the same scene as viewed by the VIIRS thermal infrared band used by meteorologists to monitor clouds at night. Only high clouds are visible; the low clouds do not show up at all because they are roughly the same temperature as the ground.



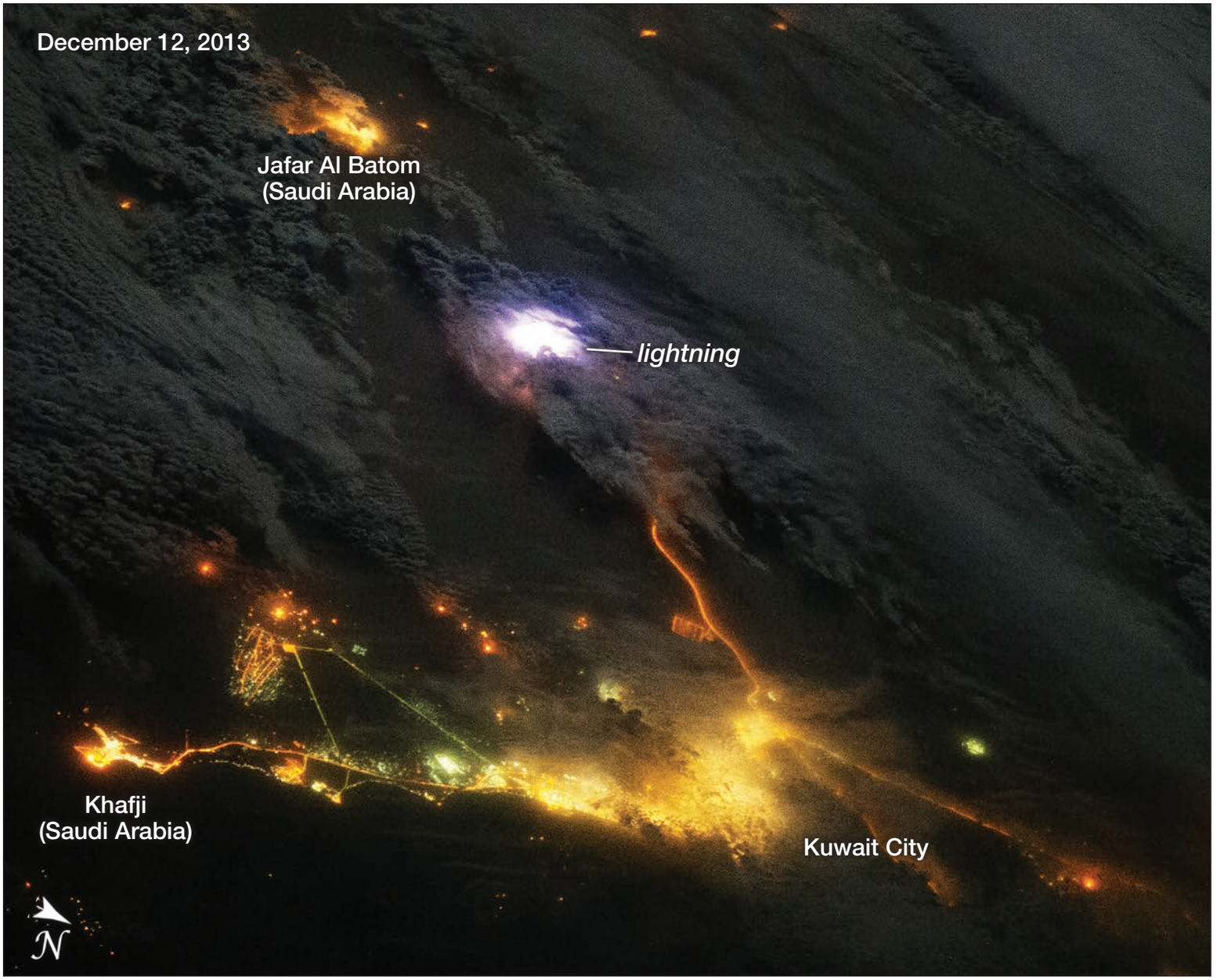

January 23, 2016
Boston
New York
Washington, D.C.
N
100 km

A Blizzard by Moonlight—Northeastern United States

A massive winter storm system pummeled the eastern United States in late January 2016, when two low-pressure systems merged into a potent nor'easter that dropped heavy snow from Virginia to New England. By late afternoon on January 23, snowfall totals were approaching records in several states and hurricane-force winds were battering the coastlines and leading to serious flooding. The VIIRS DNB on the Suomi NPP satellite acquired this image of the storm system at 2:15 a.m. Eastern Standard Time on January 23, 2016. Notice that the lights from the major cities along the East Coast of the United States are blurred in places by cloud cover.

Sensing Lightning from the ISS—Saudi Arabia and Bolivia

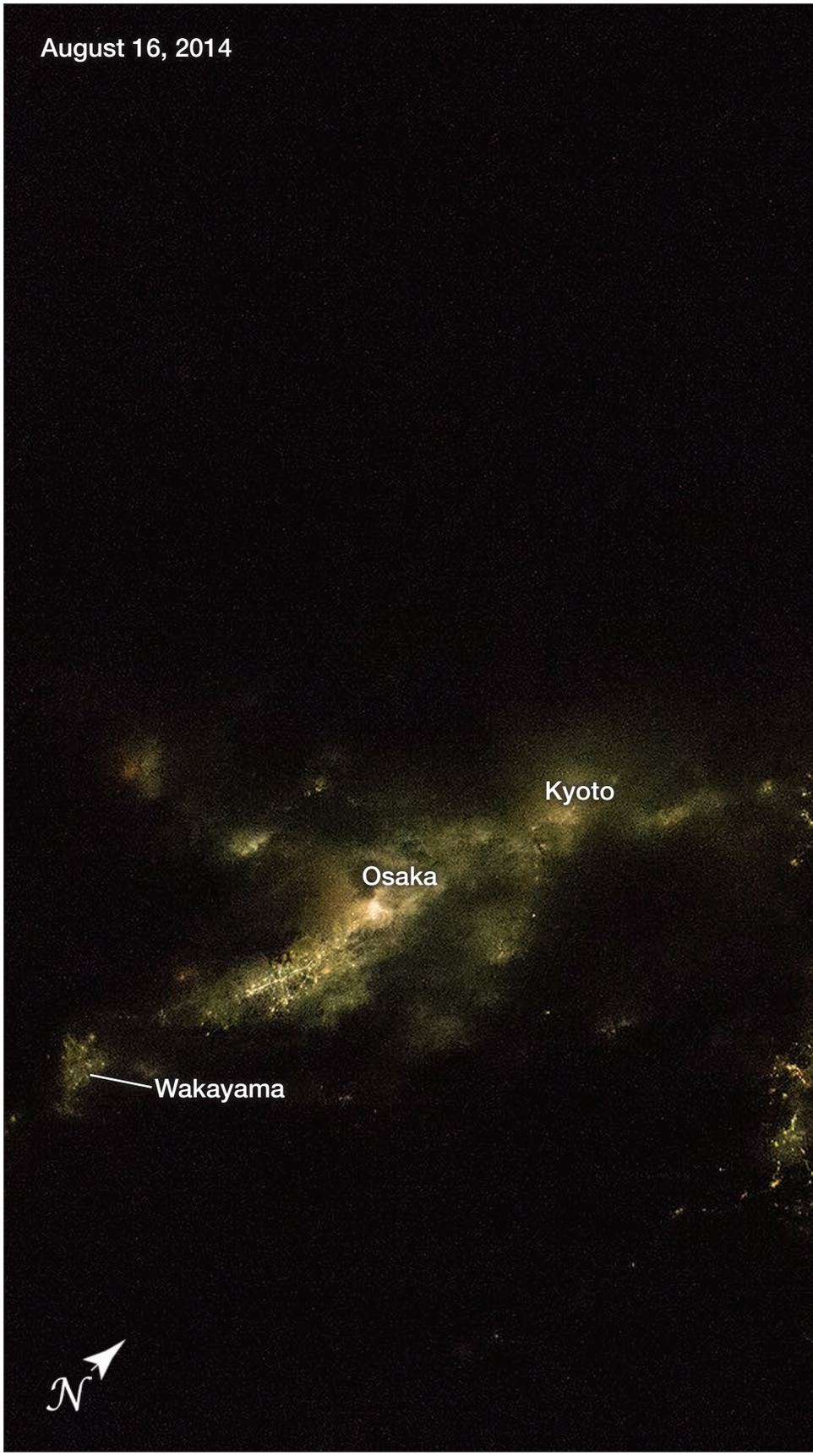
Lightning flashes about 50 times per second across all of Earth's atmosphere. That's 4.3 million times a day and roughly 1.5 billion times a year. The December 12, 2013 photograph (below, left), snapped by an astronaut onboard the ISS, shows a white flash of



lightning amidst the yellow city lights of Kuwait and Saudi Arabia. On another occasion, seen in the January 9, 2011 photograph (below, right), an astronaut onboard the ISS captured a close-up of a lightning flash beneath a thunderhead over Bolivia.

Lightning—Japan

Astronauts captured this photograph of south-central Japan on August 16, 2014, as the ISS was passing over the western Pacific Ocean. The brightest spot in the center of the photo is the port city of Nagoya, the third largest metropolitan area in Japan. To the left, the lights of the urban areas of Osaka, Kyoto, and Wakayama pierce through clearings in the cloud cover. (Note that north is to the upper right in this image.) Much of the scene is obscured by cloud cover, although a lightning storm lights up the clouds to the north. Note how the lightning is much whiter than the yellow and orange hues of city lights.

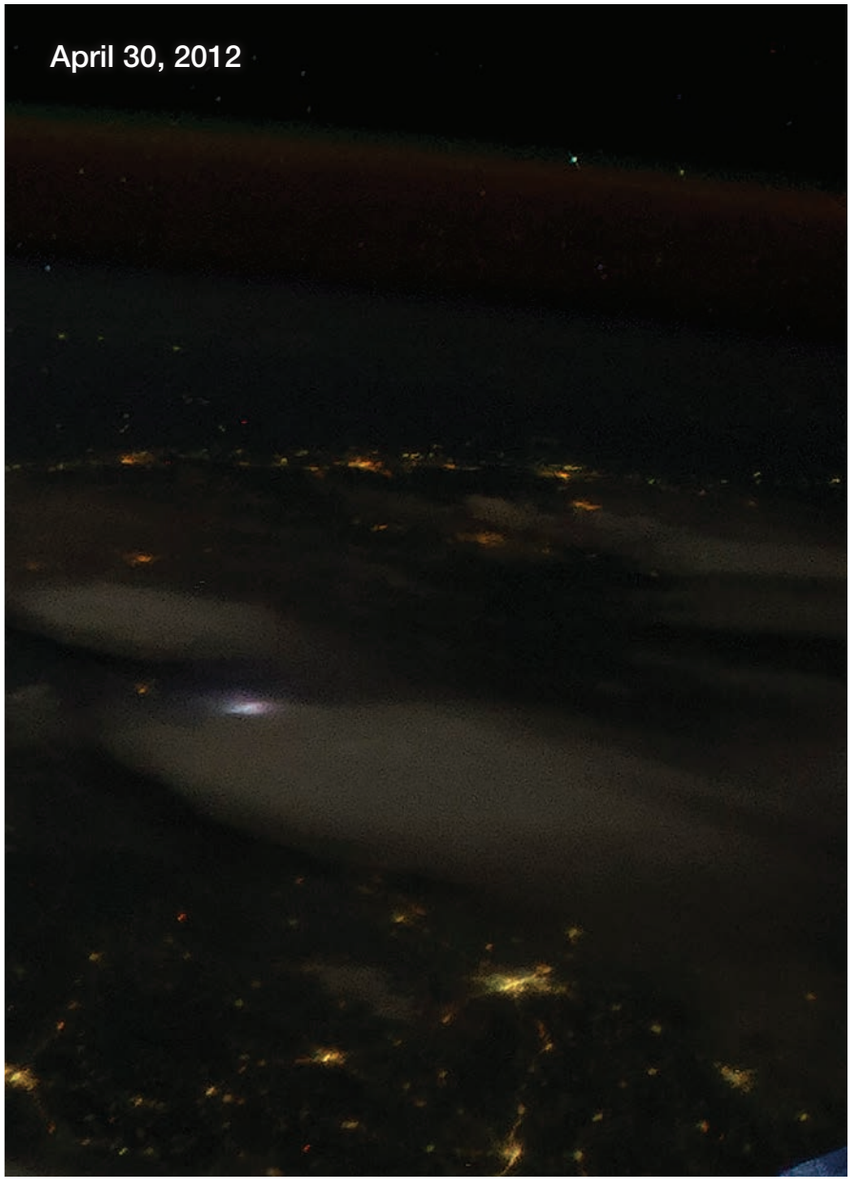


lightning
Nagoya

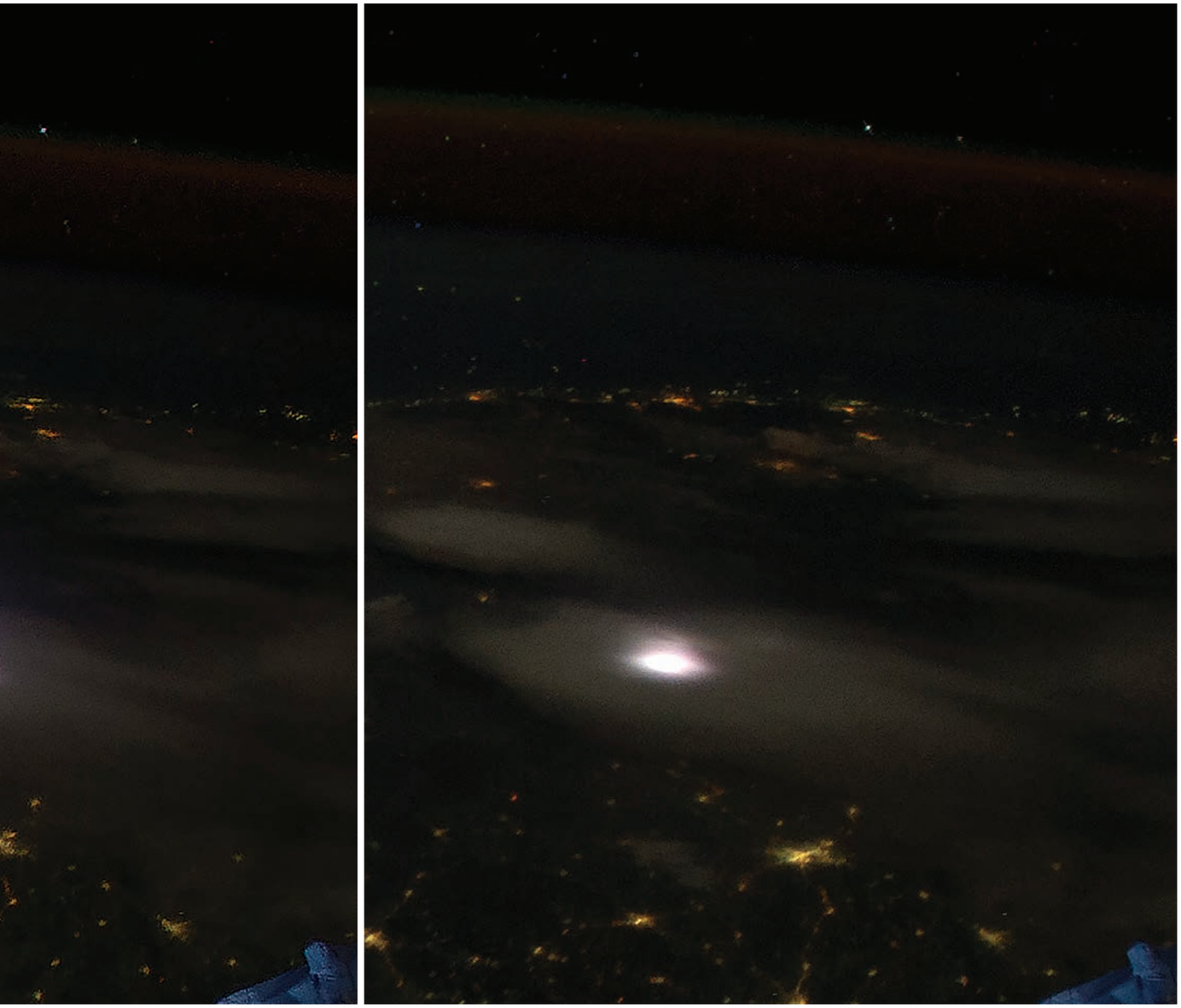
Elusive Sprite Captured from the ISS—Southeast Asia

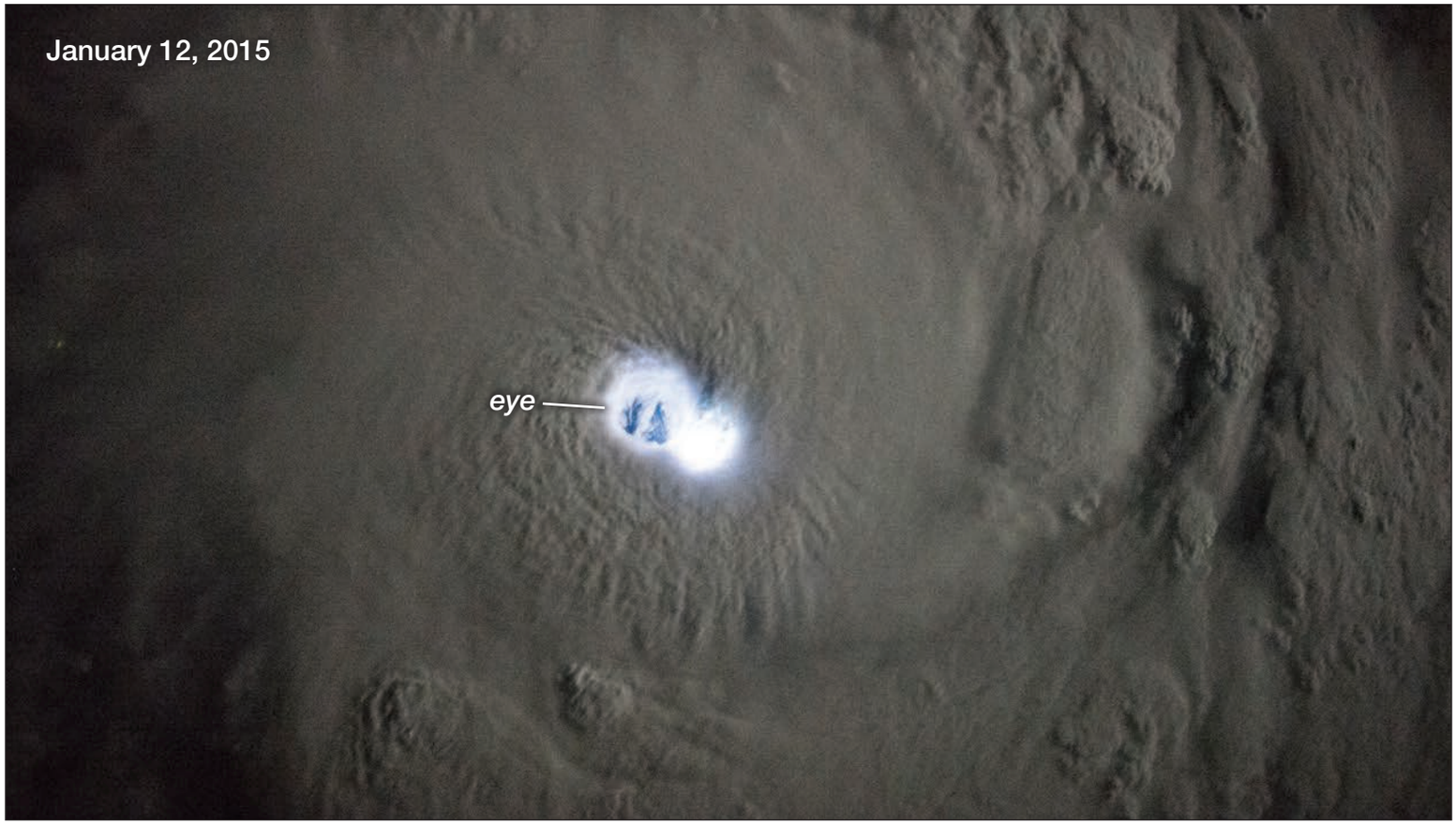
They were once so elusive that scientists gave them a mystical name. Red sprites are short-lived, red flashes that occur about 50 miles (80 kilometers) up in the atmosphere. With long, vertical tendrils like a jellyfish, these electrical discharges can extend 12 to 19 miles (20 to 30 kilometers) into the atmosphere and are connected to thunderstorms and lightning.

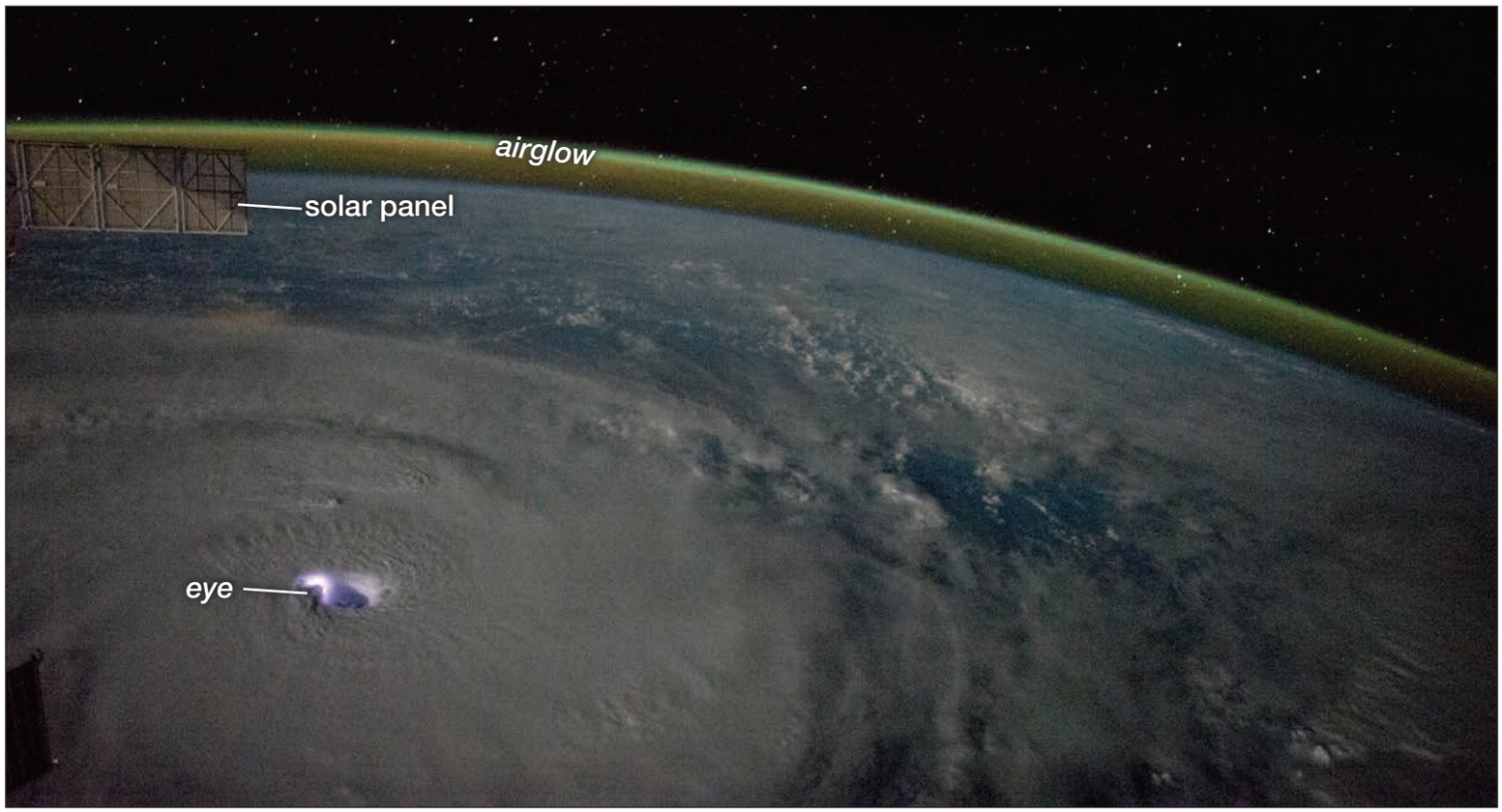
These three serial images, part of a time-lapse movie collected from 13:41 to 13:47 UTC on April 30, 2012, show a red sprite (center image) captured with a digital camera by



Expedition 31 astronauts on the ISS as they traveled southeast from central Myanmar (Burma) to just north of Malaysia. Red sprites are difficult to observe because they last for just a few milliseconds and occur above thunderstorms—meaning they are usually blocked from view on the ground by the very clouds that produce them. The sprites send pulses of electrical energy up toward the edge of space—into the electrically charged layer known as the ionosphere—instead of down to Earth's surface. They are rich with radio noise, and can sometimes occur in bunches.




January 12, 2015
eye


airglow
solar panel
eye

The Electric Eye of Cyclone Bansi—Indian Ocean

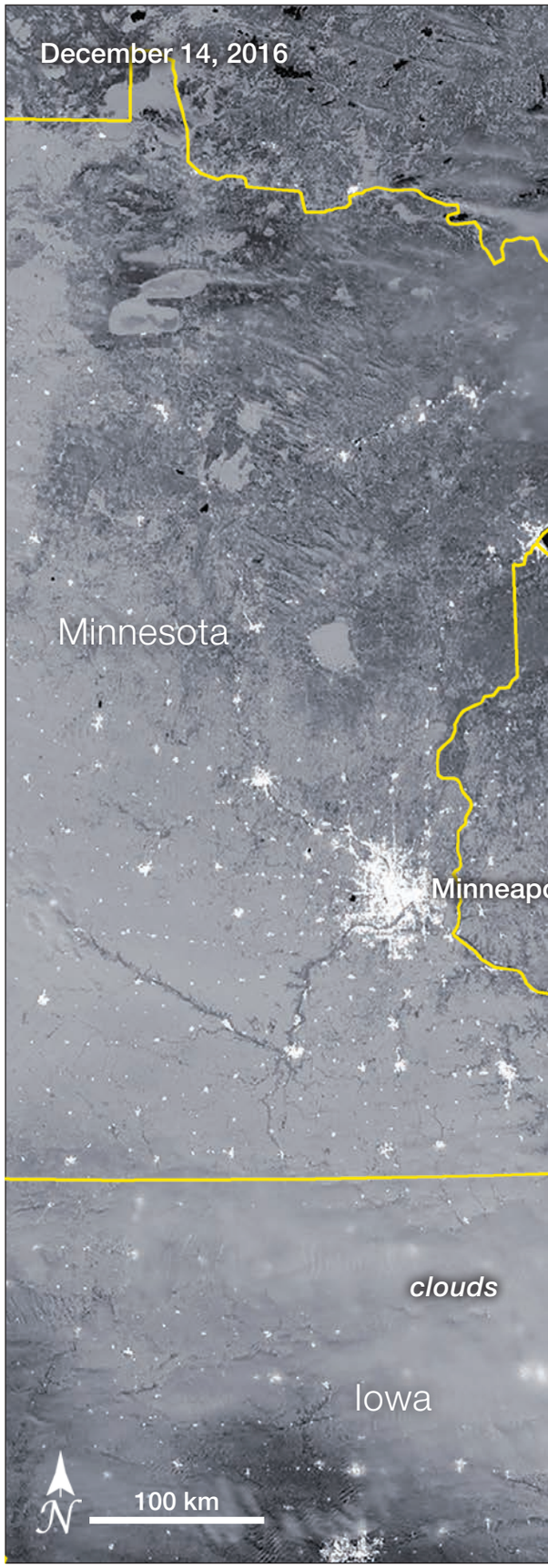
Though these images may look like they come from a science fiction movie, they are in fact photographs of tropical cyclone Bansi as seen at night by astronauts on the ISS on January 12, 2015. The images were taken when the ISS was east of Madagascar. The dim swirl of the cloud bands covers the ocean surface in both night images. The eye of the cyclone is brilliantly lit by lightning in or near the eye wall. The low-light settings of the camera used to take the image accentuate the contrast.

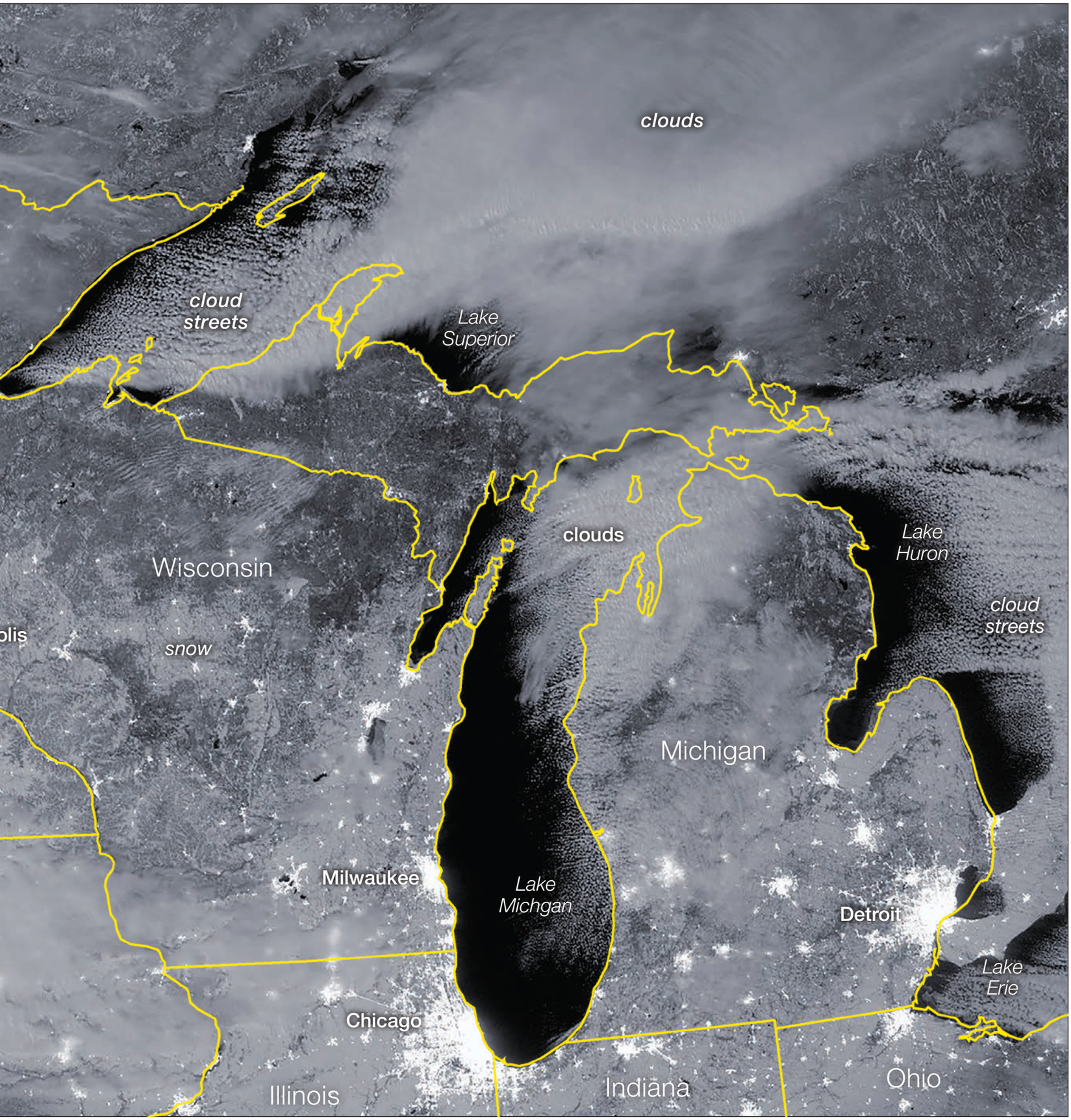
In the bottom image, the camera also accentuates the yellow-green airglow above Earth's limb, an atmospheric phenomenon frequently reported by astronauts. Stars appear above the airglow layer, and the solar panels of a docked Russian spacecraft jut into the upper left of the image.

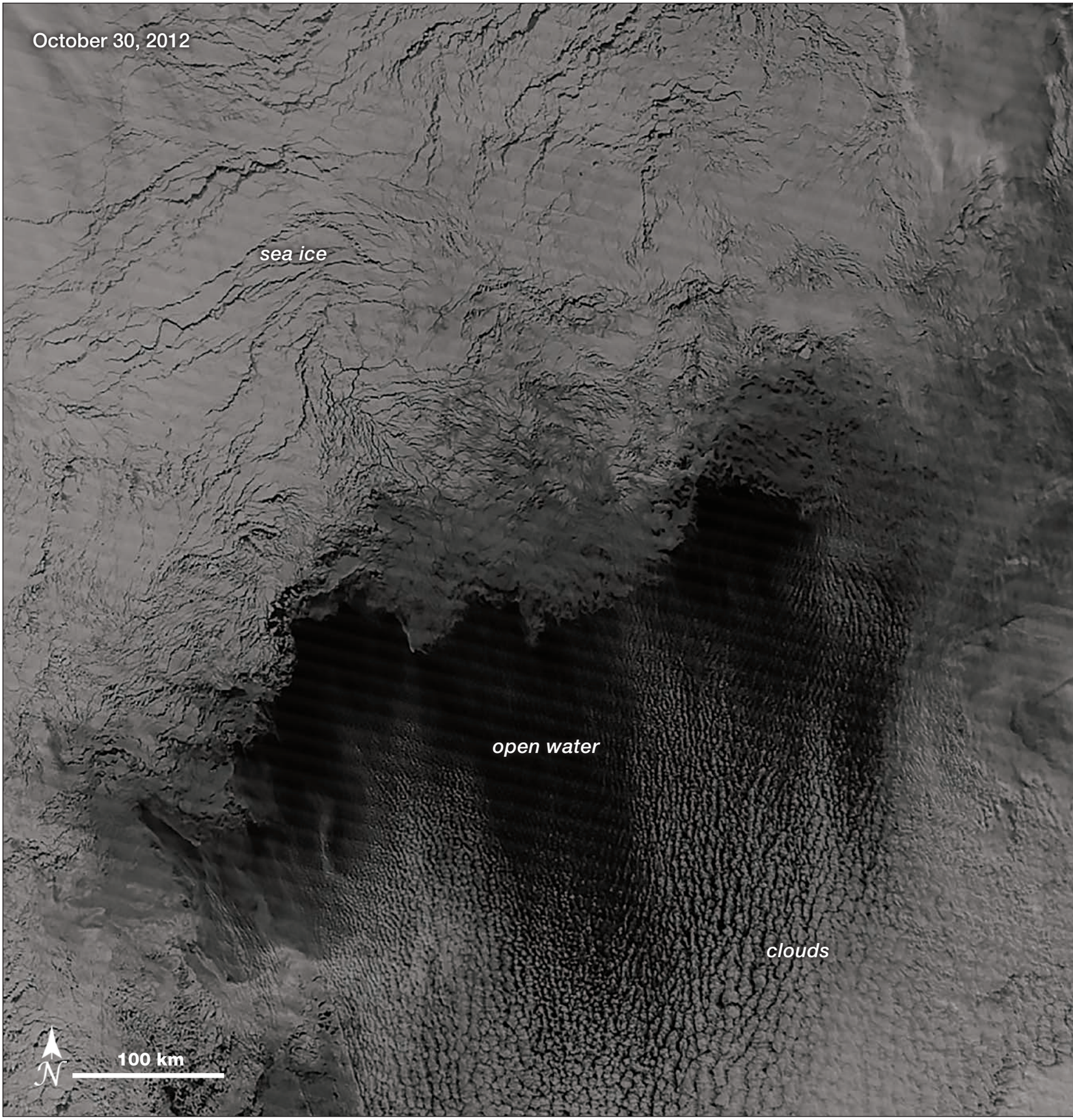
Snow and Ice

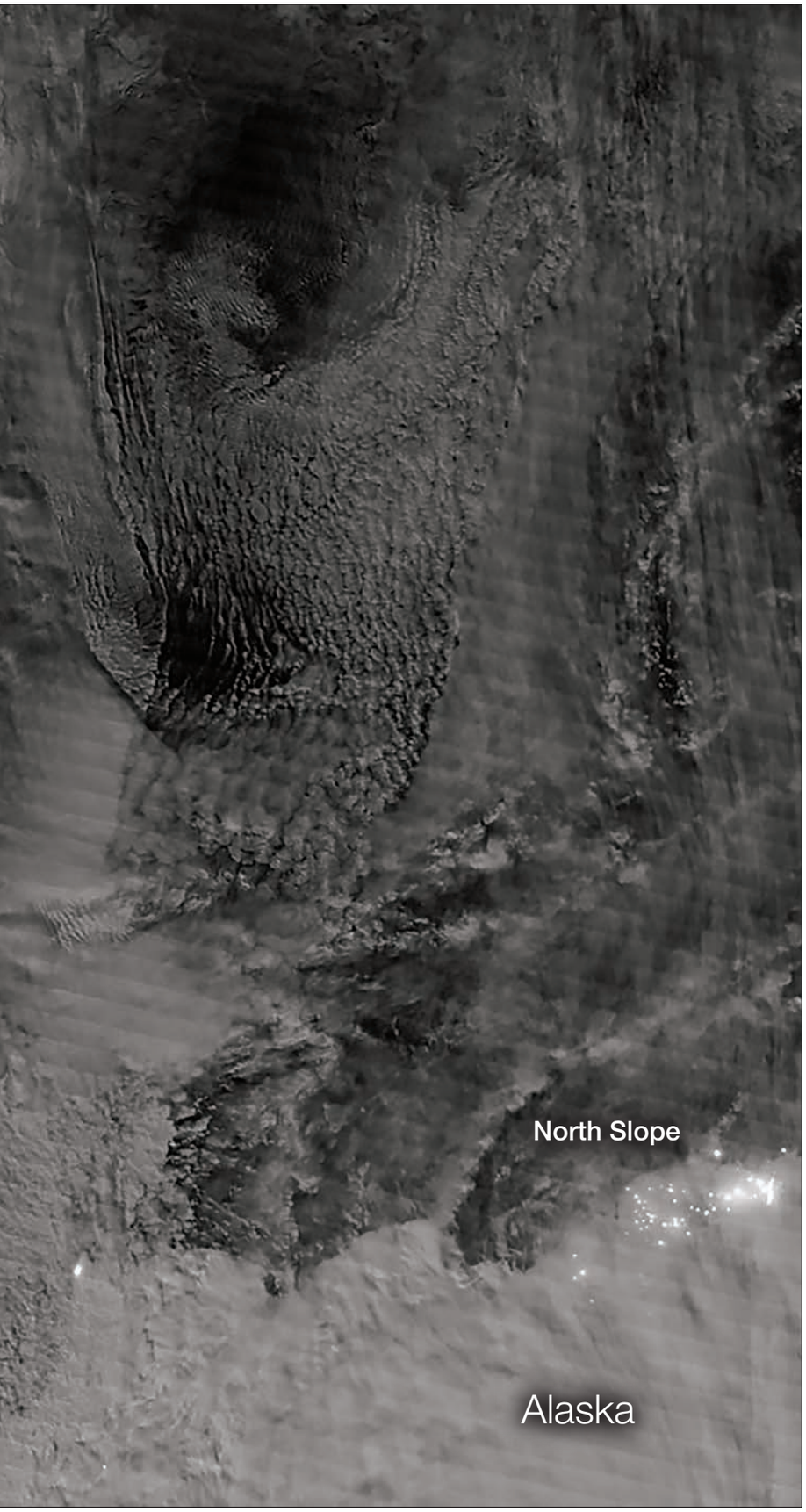
Snow Cover—Great Lakes Region, United States

An Arctic air mass brought snow to communities around the Great Lakes on December 14, 2016. The lake-effect snow came on the heels of an earlier accumulation that dumped several feet of snow in some areas the week before. The VIIRS DNB on the Suomi NPP satellite captured this image on December 14. The instrument can detect faint light sources—in this case, the reflection of the full Moon on the fresh snow. Clouds blur the landscape in the bottom left part of the image. Parallel rows of clouds, called cloud streets, appear above Lake Huron and Lake Superior. These clouds are created by cold, dry air blowing over a lake and accumulating water vapor.




clouds
cloud streets
Lake Superior
clouds
Lake Huron
cloud streets
Wisconsin
snow
olis
Michigan
Milwaukee
Lake Michgan
Detroit
Lake Erie
Chicago
Illinois
Indiana
Ohio


October 30, 2012
sea ice
open water
clouds
100 km
N



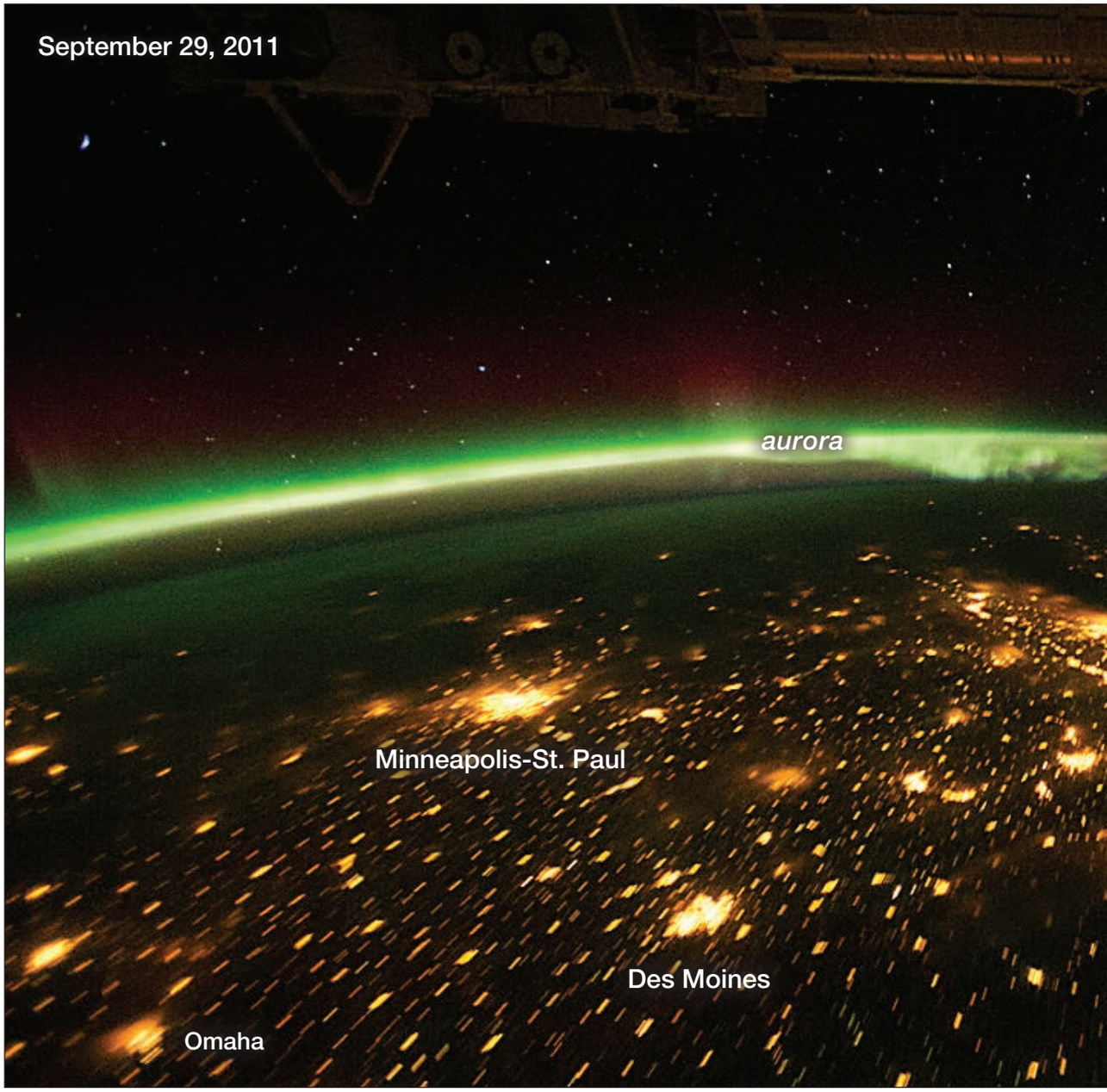
Polar Darkness—The Arctic

Scientists watched the Arctic with particular interest in the summer of 2012 when the areal extent of Arctic sea ice set a new record low. The behavior of sea ice following such a low extent also interests scientists, but as Arctic sea ice was advancing in the autumn of 2012, so was polar darkness. Fortunately, the VIIRS DNB on the Suomi NPP satellite can see in the dark and acquired this nighttime view of sea ice north of Russia and Alaska on October 30, 2012. During polar darkness (i.e., winter months), VIIRS DNB data allow scientists to observe sea ice formation and snow cover extent at the highest latitudes and to identify clear water where ships can safely navigate.

Auroras

Aurora Borealis—Midwestern United States

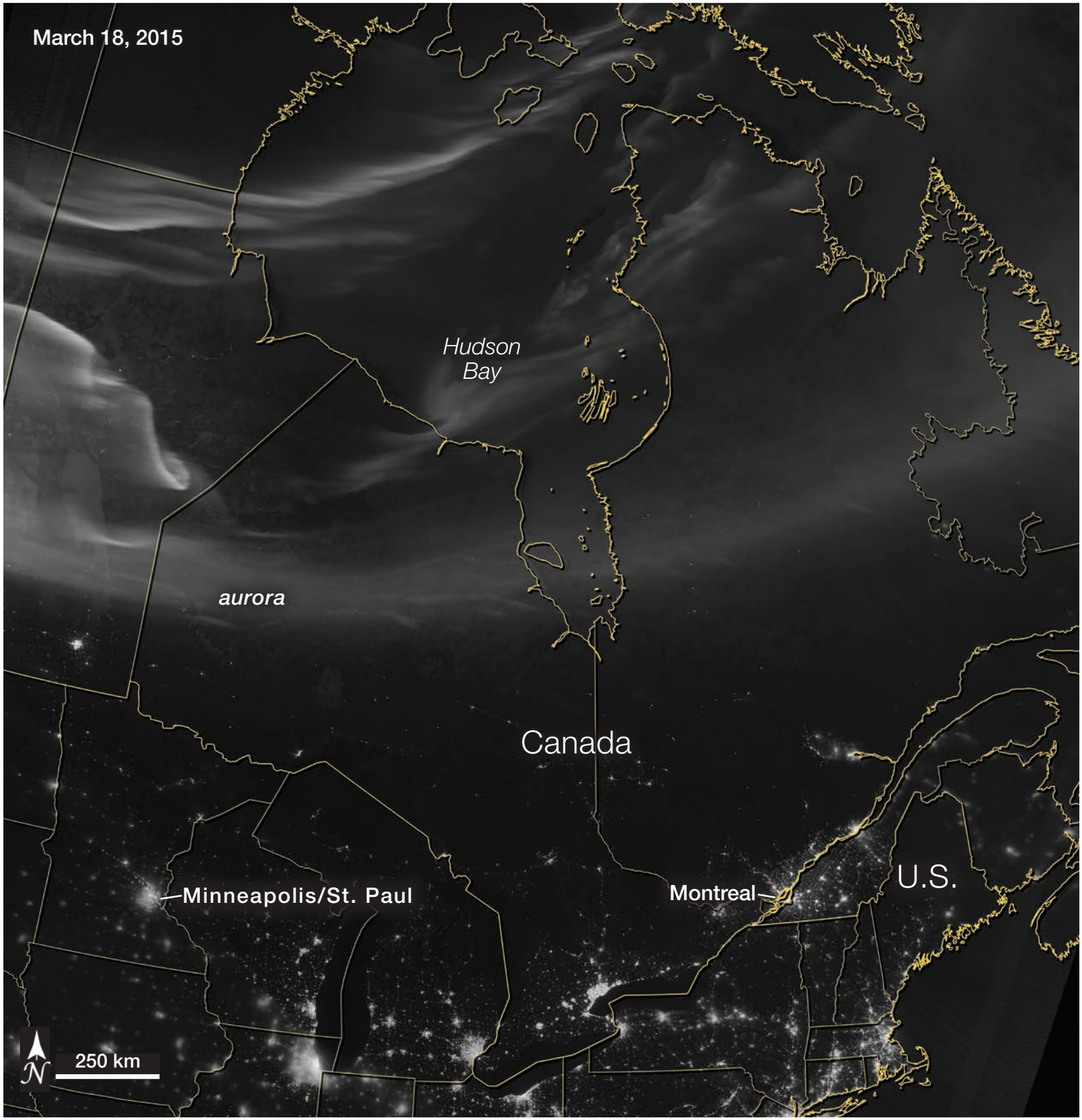
When viewed from the ISS, the night skies are illuminated with light from many sources. For example, the Midwestern United States presents a nighttime appearance when viewed from orbit, not unlike a patchwork quilt. The artificial light from human settlements appears with a characteristic yellow tinge, and the green light of the



aurora borealis shines brightly—even seeming to reflect off Earth's surface in Canada—in this view from the ISS taken on September 29, 2011. A small white patch of light is almost certainly lightning from a storm on the East Coast (image right). Part of the ISS appears across the top of the image.

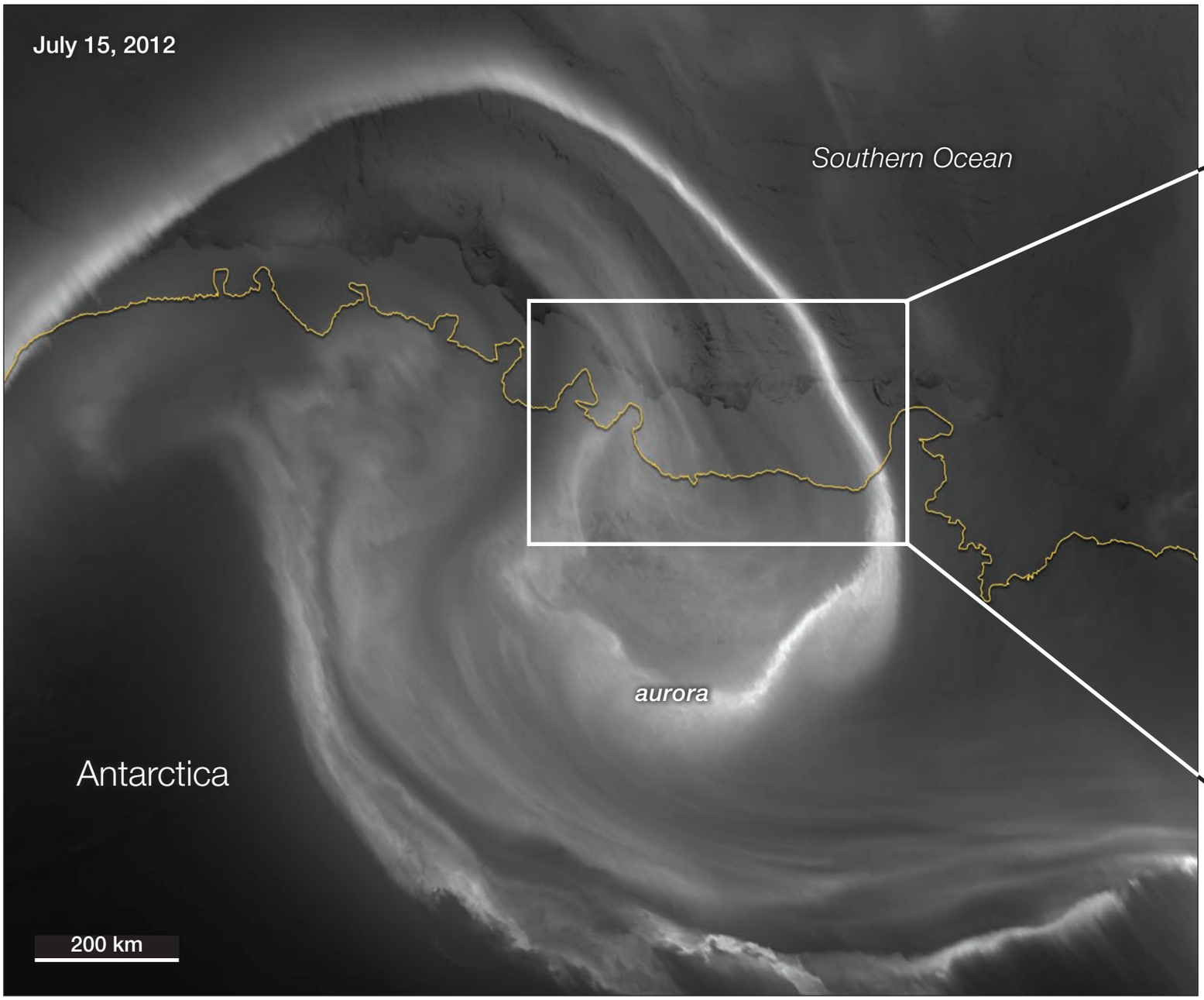
Looking Down at the Aurora—Northern Hemisphere

Even Earth's skies were celebrating St. Patrick's Day on March 17, 2015, as a severe geomagnetic storm—the strongest of the past decade—painted the sky with green, red, and blue auroras from New Zealand to Alaska. The storm conditions provided a fantastic opportunity for aurora viewing from above. On Sunday, March 15, a coronal mass ejection released large amounts of plasma and an accompanying magnetic field from the Sun, causing the aurora borealis to reach as far south as the central and southern United States, as shown on the image at right. The VIIRS DNB on the Suomi NPP satellite acquired this view of the aurora around 1:30 a.m. Eastern Daylight Time on March 18, 2015. Auroras appear as white streaks over Hudson Bay, southern Canada, and the northern United States.

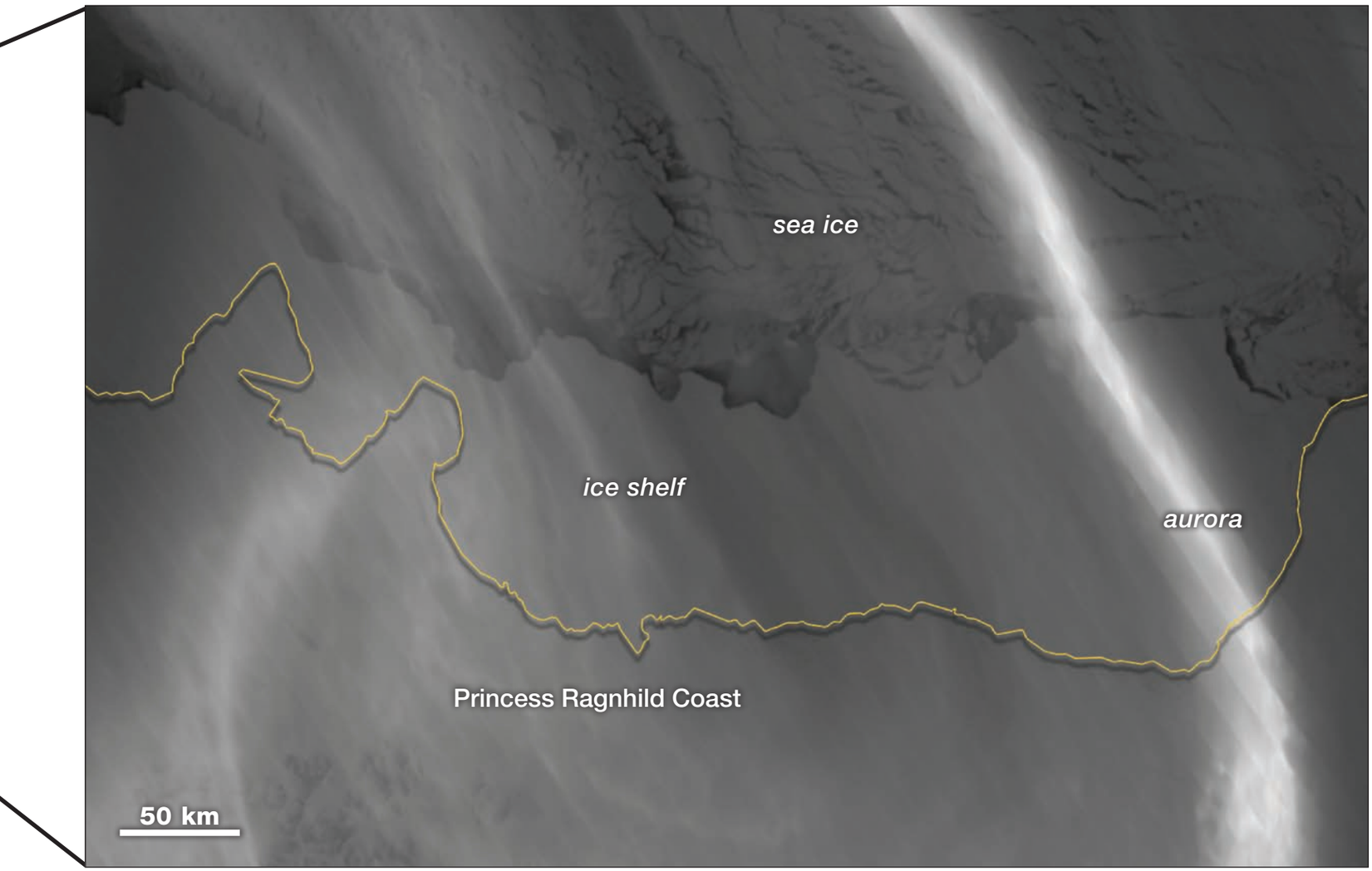

March 18, 2015
Hudson Bay
aurora
Canada
U.S.
Minneapolis/St. Paul
Montreal
N
250 km

Aurora Lights Up the Night—Antarctica

On July 15, 2012, the VIIRS DNB on the Suomi NPP satellite captured this night-time view of the aurora australis over Antarctica's Queen Maud Land and the Princess Ragnhild Coast. The slightly jagged appearance of the auroral lines is a function of the rapid dance of the energetic particles at the same time that the satellite is moving and



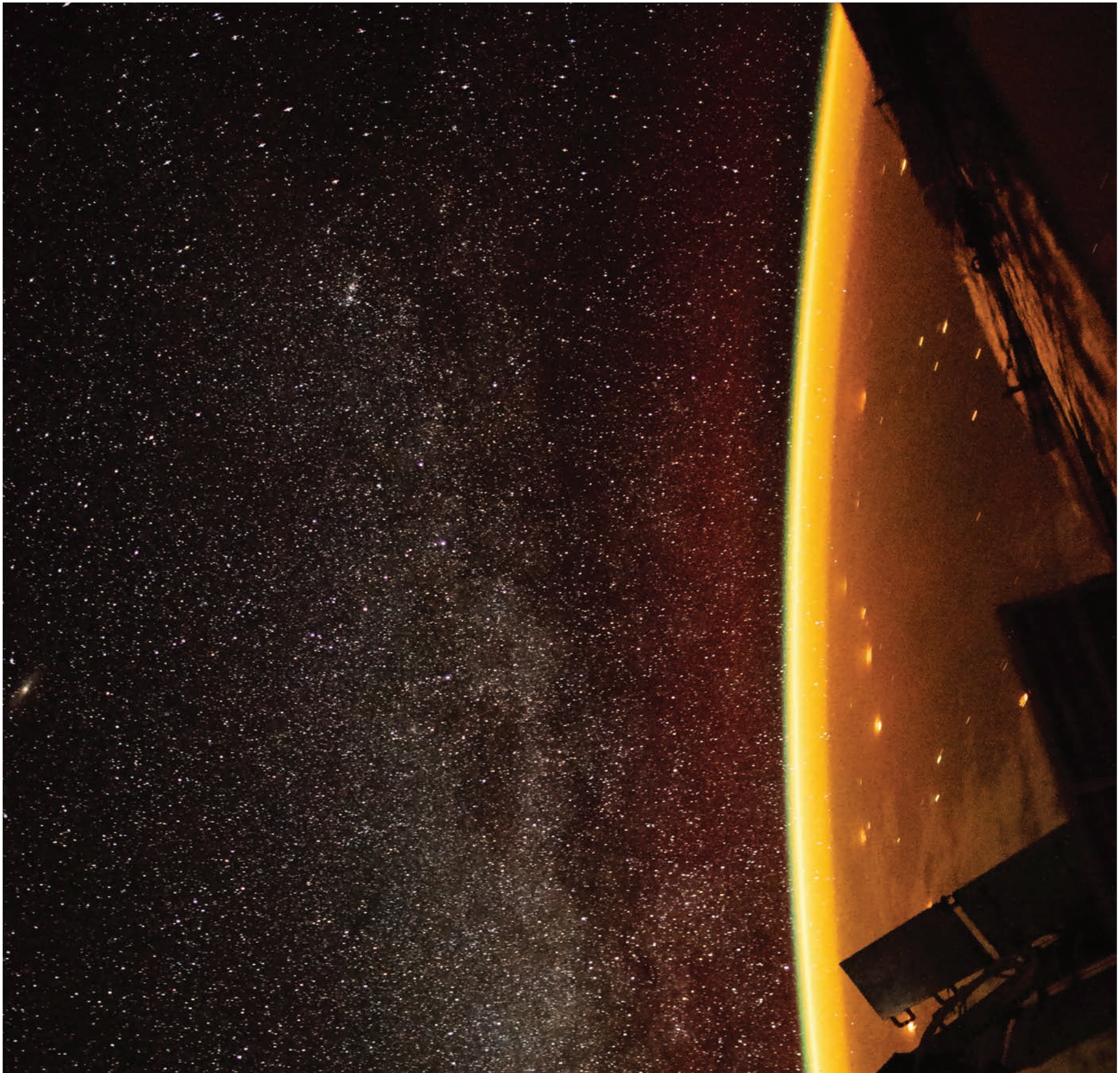
the VIIRS sensor is scanning. The white box in the left image depicts the area shown in the close-up image at right (below). Light from the aurora was bright enough to illuminate the ice edge between the ice shelf and the Southern Ocean. At the time, Antarctica was locked in midwinter darkness and the Moon was a waning crescent that provided little light.

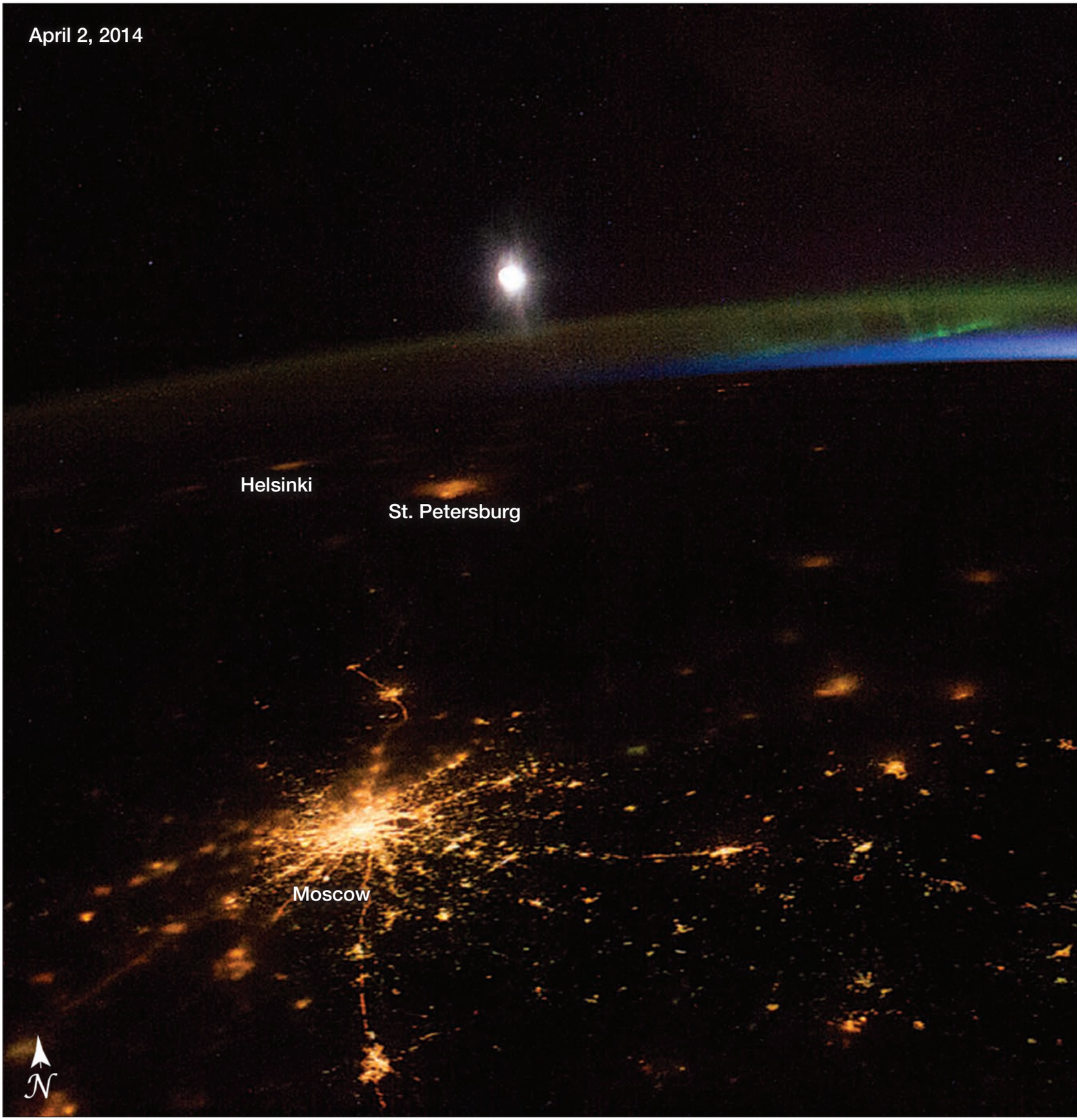


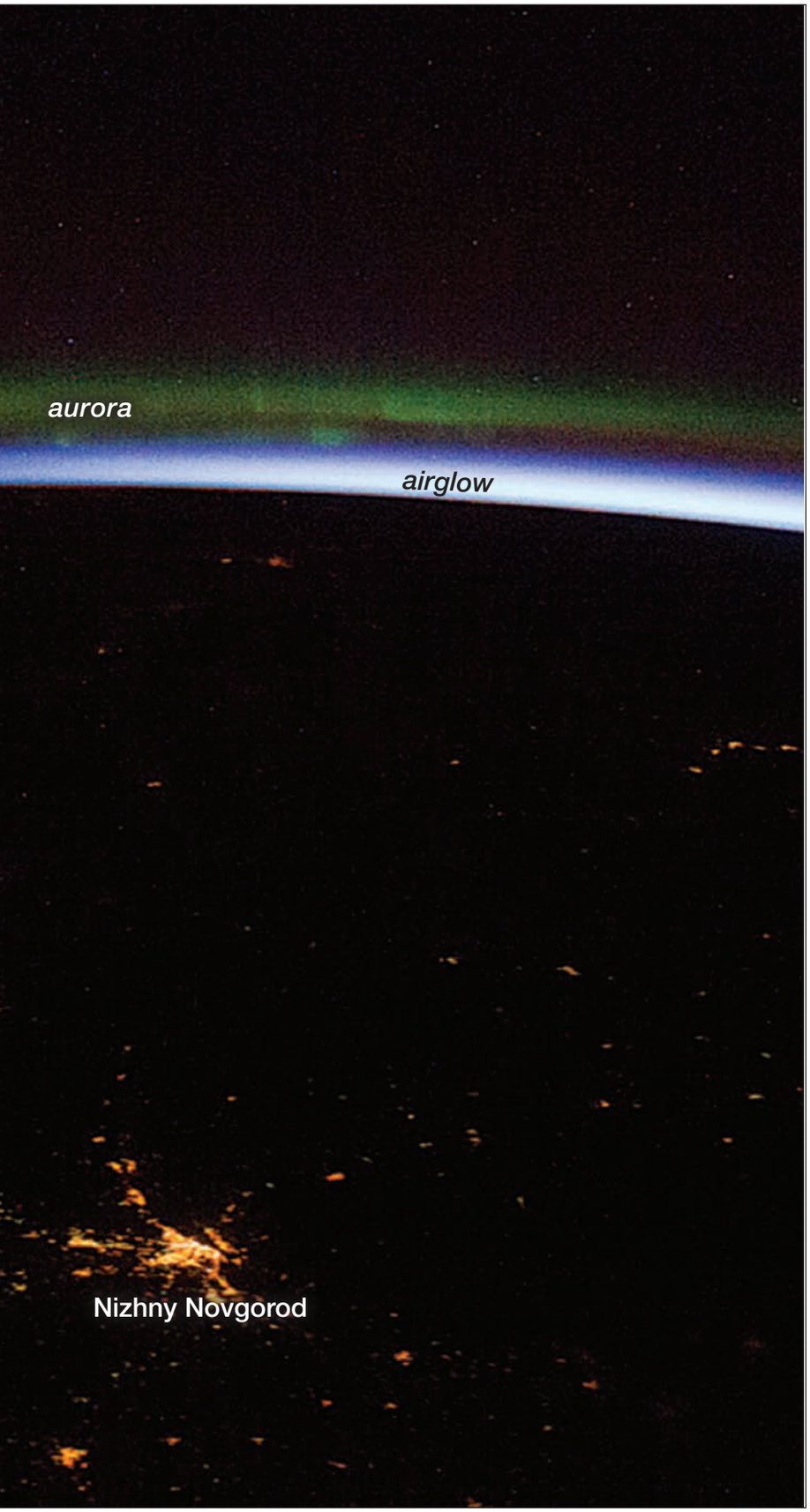
Airglow

Airglow—Australia

On October 7, 2018, an astronaut onboard the ISS shot this photograph at an altitude of about 250 miles (400 kilometers) over Australia. In this view, stars appear more numerous along the image center where the plane of the disk-shaped Milky Way galaxy extends into space. The orange colors enveloping Earth are known as airglow—diffuse bands of light that stretch roughly 50 to 400 miles (80 to 645 kilometers) into our atmosphere. This type of airglow is known as chemiluminescence, or nightglow. More than just a pretty light show, airglow reveals some of the workings of the upper reaches of our atmosphere. Studying airglow can help scientists learn about the movement of particles near the interface between Earth and space, including the connections between space weather and Earth weather. Airglow reveals some of the conditions of the upper atmosphere, such as its temperature, shape, and the amounts of different types of gases.




April 2, 2014
Helsinki
St. Petersburg
Moscow
N

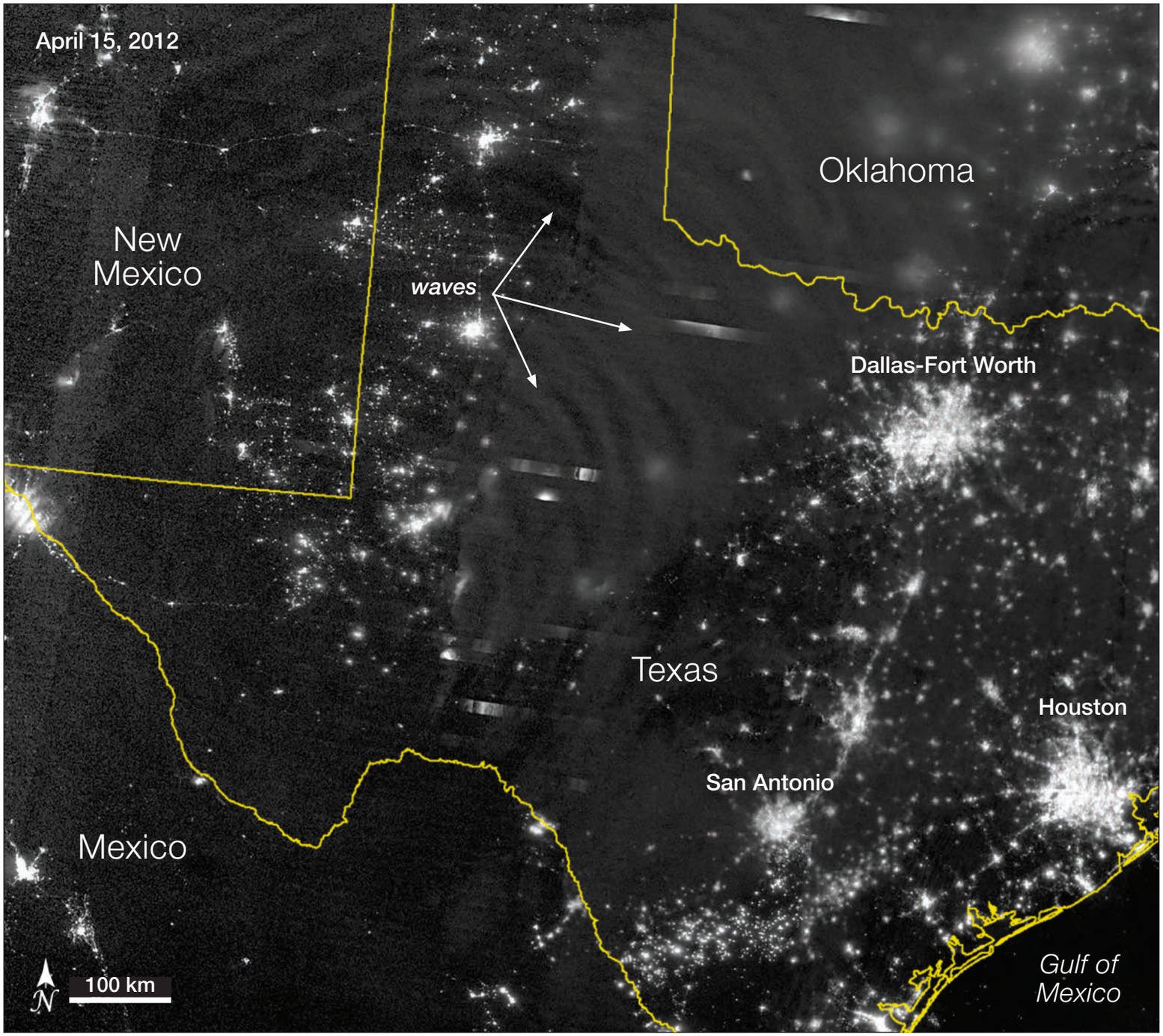


Night Colors—Russia

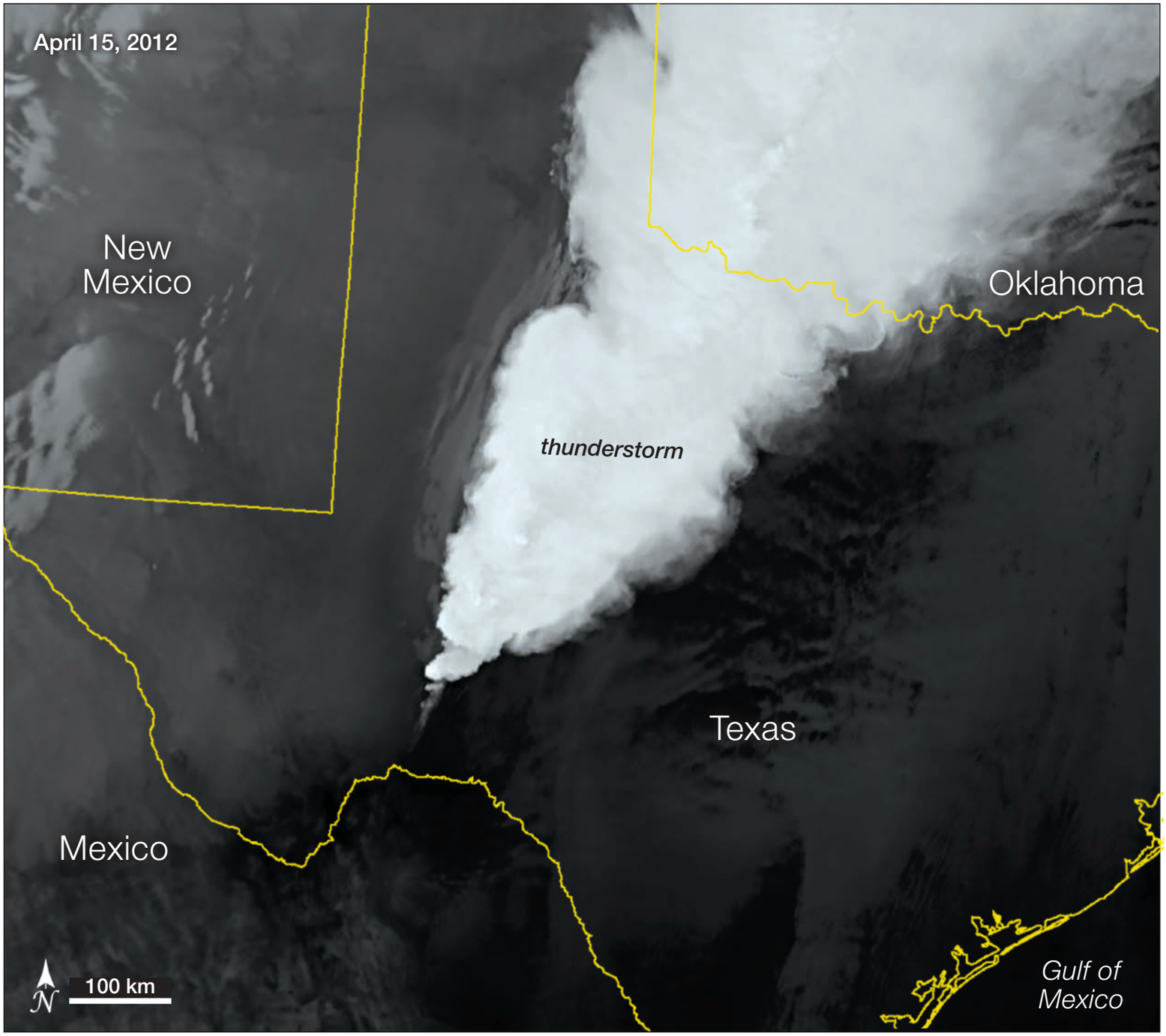
A thin green line of the aurora borealis crosses the top of this photograph, taken by an astronaut on the ISS on April 2, 2014. The Moon appears as a white disc just above the aurora. Airglow appears as a blue-white cusp along Earth's limb. Russia's capital city, Moscow, makes a splash of yellow light and is easily recognized by the radial pattern of its highways. Other cities are Nizhny Novgorod [250 miles (400 kilometers) from Moscow], Saint Petersburg [388 miles (625 kilometers) away], and Finland's capital city Helsinki [about 545 miles (876 kilometers) away].

Waves in Airglow—Texas

As shown in the left image (below), in April 2012 waves in Earth's airglow spread across the nighttime skies of Texas like ripples in a pond. In this case, the waves were provoked by a massive thunderstorm. The VIIRS DNB on the Suomi NPP satellite captured these glowing ripples in the night sky on April 15, 2012. The right image (next page)



shows the thunderstorm as observed by a VIIRS thermal infrared band. This thermal band, which is sensitive only to heat emission, is not sensitive to the subtle visible-light wave structures seen by the VIIRS DNB. Clouds appear white because they are cooler than Earth's surface.



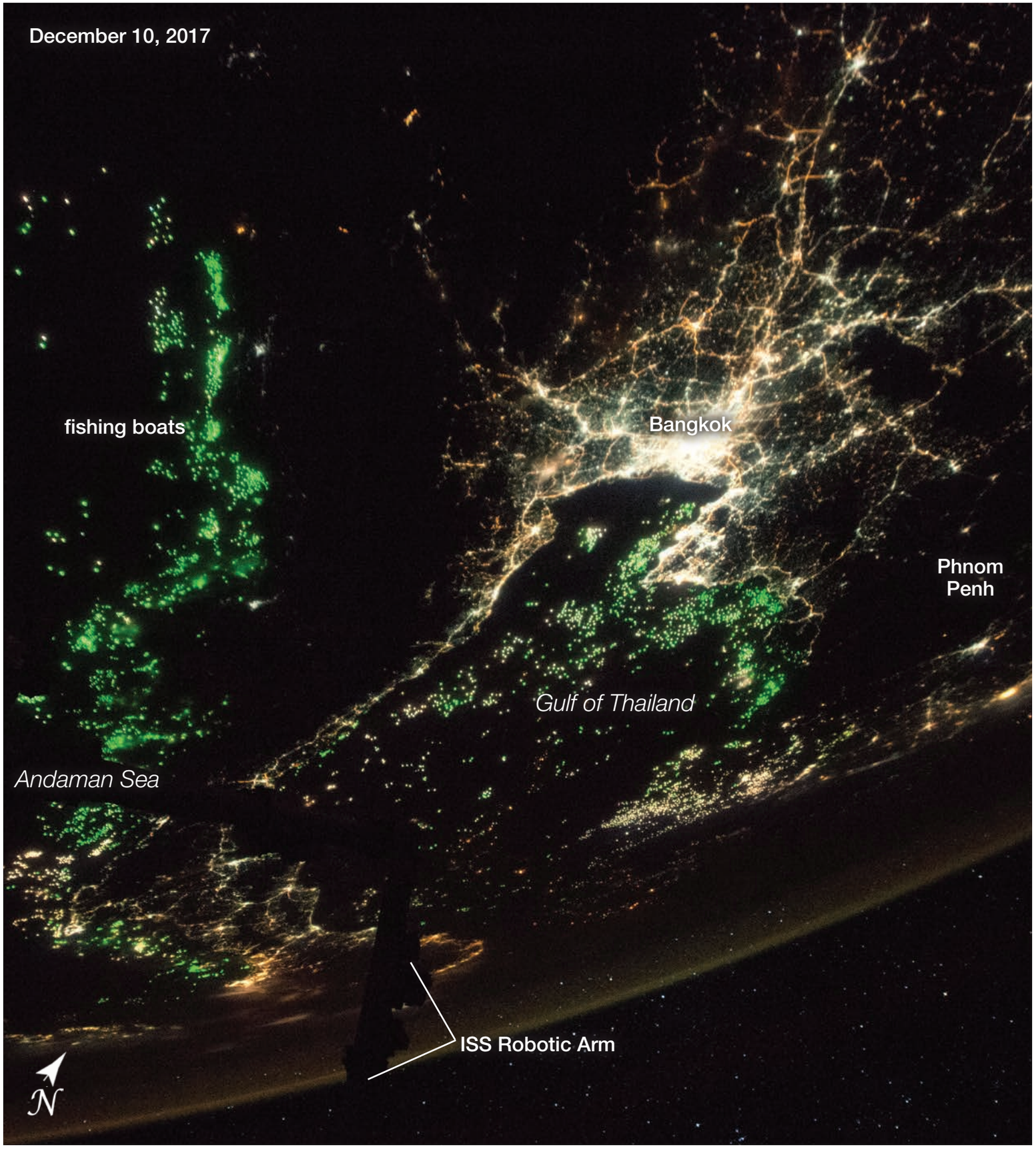
[Opposite page] This photograph, taken by an astronaut from the ISS on December 10, 2017, shows the city of Bangkok, the capital and largest city in Thailand, illuminated by city lights. The adjacent waters of the Andaman Sea and Gulf of Thailand are illuminated by hundreds of green lights on fishing boats. Fishermen use the lights to attract plankton and fish, the preferred diet of commercially important squid. As the bait swims to the surface, the squid follow to feed and get caught by fishermen. The same fishing practices are used off the Atlantic coast of South America. The border between Thailand and neighboring Cambodia to the east is distinguished by a marked difference in the number of city lights. Cambodia is less urbanized and its population is smaller than that of neighboring countries. The majority of Cambodia's population lives in rural farming areas where electricity is sparse.

Human Light Sources

Viewing Earth at night from space reveals a distinctly human story. As one gazes upon the points of light in images captured from orbiting sensors, discerning eyes begin to see the fingerprints of human presence: from the glow of megacities and the pinpoints of bright light produced by fleets of fishing boats at sea, to gas flares glowing like candles in the darkness, lights show where we have made our homes, established industries, mined natural resources, and built roads. Patterns are everywhere.

It quickly becomes evident looking at nightlight data that human activity is highly influenced by Earth's natural features and processes, or physical geography. For example, the vital link between humans and water is quite clear. Nearly half the world's population lives along or near coastlines. Others live along rivers and freshwater bodies. Most population centers tend to be along coastlines, near rivers, or near major overland transportation hubs (e.g., highways, railroads) that cut slivers of light through the darkness between cities. In general, our species tends to avoid settling in regions with harsh climates (or if we do, we set about transforming them into something more pleasant), in mountainous areas with steep terrain, and where basic resources like food and water are limited (e.g., deserts). Accordingly, more light is clustered around regions where the climate is moderate, terrain is flat, resources are plentiful, and soil is fertile.

Areas with the brightest light are generally the most urbanized—but not necessarily the most populated. When a city or country is thriving, electricity is used to keep businesses, schools, and factories bustling with activity. Lights show how far urban sprawl extends, as well as areas where growth is occurring or where growth has not yet occurred. Cities usually have many people concentrated in a small area, so electricity usage is high. Poor areas may have large populations but low availability or use of electric lights. These signals from anthropogenic nightlights provide clear indicators of how we've settled our planet and—with some analysis—what we do with our energy.


December 10, 2017
fishing boats
Bangkok
Phnom Penh
Gulf of Thailand
Andaman Sea
ISS Robotic Arm
N

Urban Structure

Constrained by Geography—Reno, Nevada

Styling itself as "the biggest little city in the world," the city of Reno, Nevada, is located in Truckee Meadows, along the expansion-limiting eastern foothills of the Sierra Nevada near the California border. It forms part of the Reno–Sparks metropolitan area—the largest such area in northern Nevada, and the second largest in the state after Las Vegas.

On January 28, 2013, when an astronaut took this photograph, the Moon was in a waning gibbous phase (98 percent of full), providing enough illumination of the ground so that the topography surrounding the Reno–Sparks area (accentuated by snow cover) is clearly visible.

The relatively isolated nature of the city within the surrounding terrain is highlighted in this nighttime image taken from the ISS. The major industrial and commercial areas of both Reno and Sparks are brightly lit at image center. The major street grid is visible as orange linear features adjacent to these industrial/commercial areas; in contrast, the more outlying residential areas appear dark. The Reno–Tahoe International Airport is visible as a dark, dagger-shaped region.

January 28, 2013
snow
Reno
residential
Sparks
airport
residential
snow
N

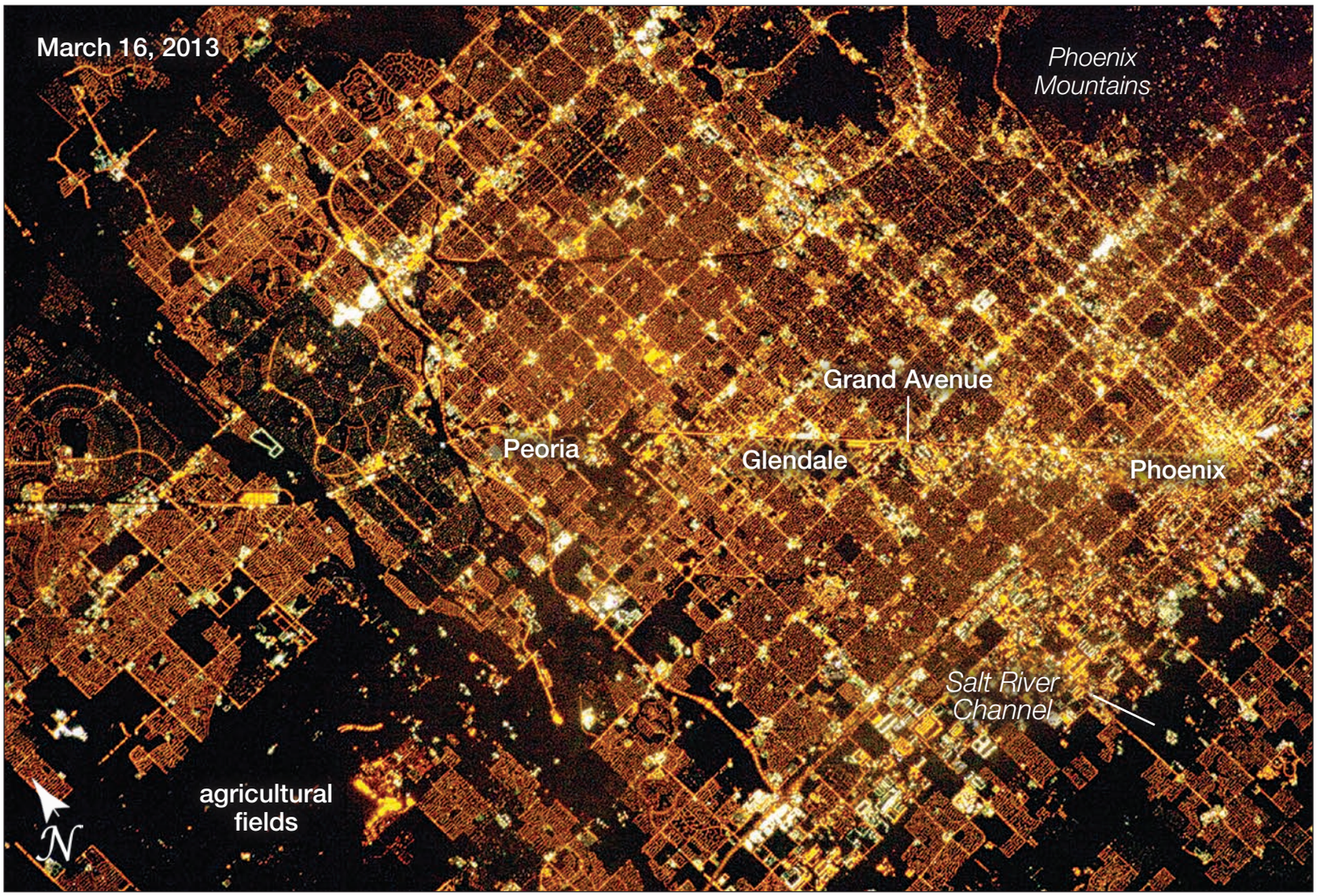
Grid of City Blocks—Phoenix, Arizona

Like many large urban areas of the central and western United States, the Phoenix metropolitan area is laid out along a regular grid of city blocks and streets. While visible during the day, this grid is most evident at night, when the pattern of street lighting is clearly visible from the low-Earth-orbit vantage point of the ISS.

This astronaut photograph, taken on March 16, 2013, includes parts of several cities in the metropolitan area, including Phoenix (image right), Glendale (center), and Peoria (left). While the major street grid is oriented north-south, the northwest-southeast oriented Grand Avenue cuts across the three cities at image center. Grand Avenue is a major transportation corridor through the western metropolitan area; the lighting patterns of large industrial and commercial properties are visible along its length. Other brightly lit properties include large shopping centers, strip malls, and gas stations, which tend to be located at the intersections of north-south and east-west trending streets.

The urban grid encourages growth outwards along a city's borders by providing optimal access to new real estate. Fueled by the adoption of widespread personal automobile use during the twentieth century, the Phoenix metropolitan area today includes 25 other municipalities (many of them largely suburban and residential) linked by a network of surface streets and freeways.

While much of the land area highlighted in this image is urbanized, there are several noticeably dark areas. The Phoenix Mountains are largely public parks and recreational land. To the west, agricultural fields provide a sharp contrast to the lit streets of residential developments. The Salt River channel appears as a dark ribbon within the urban grid.

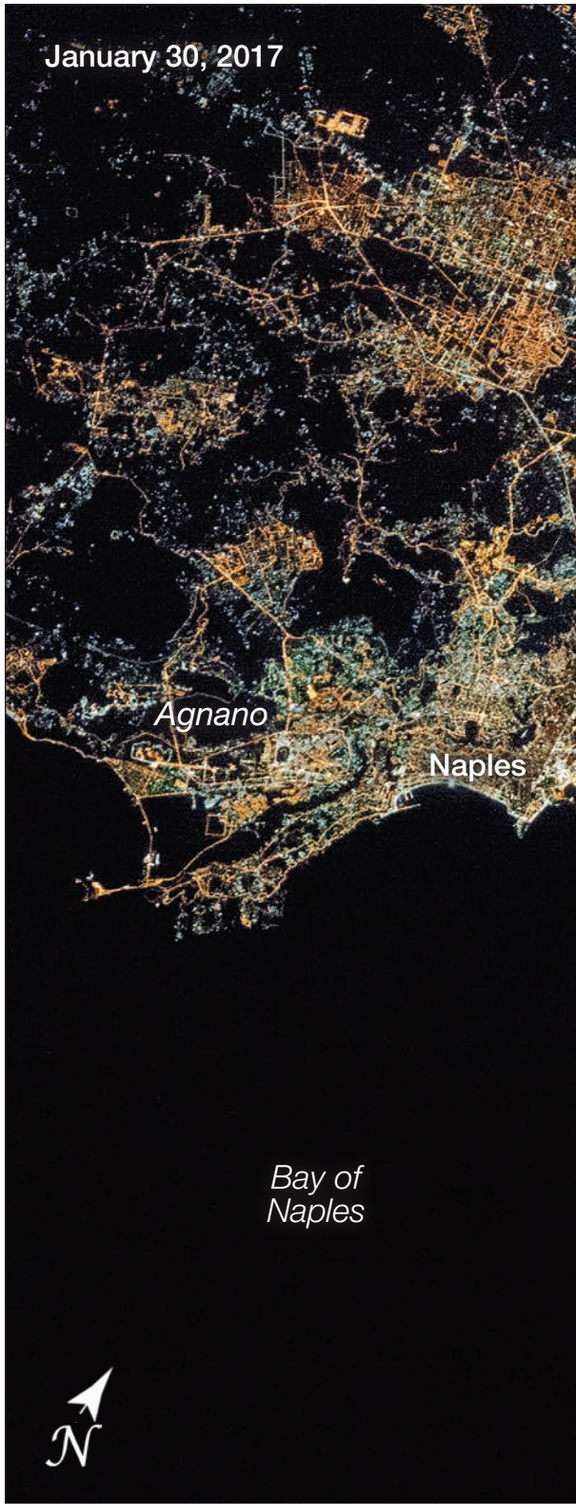

March 16, 2013
Phoenix Mountains
Grand Avenue
Peoria
Glendale
Phoenix
Salt River Channel
agricultural fields
N

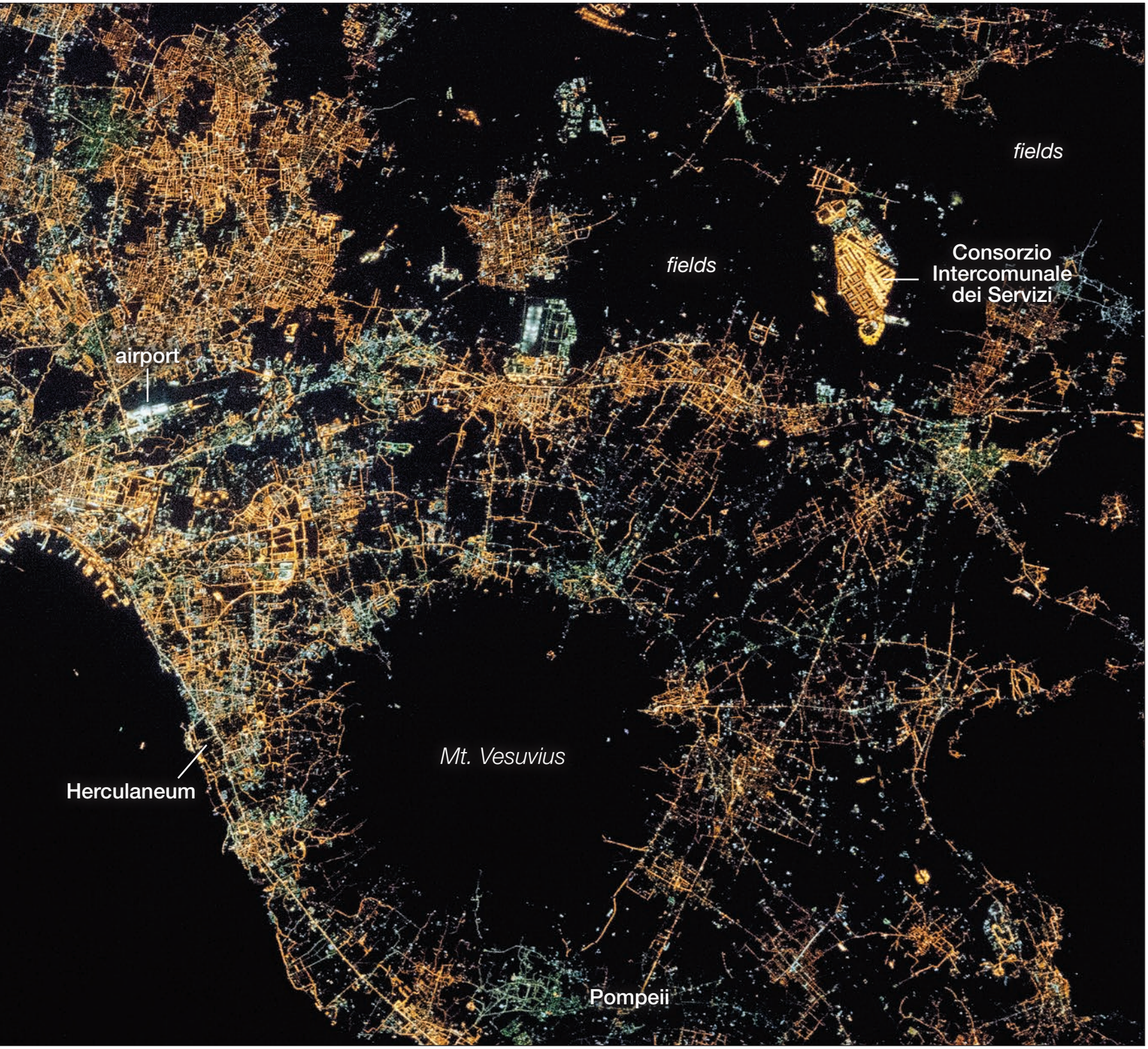
Unpopulated Slopes of an Active Volcano—Naples, Italy

An astronaut onboard the ISS took this photograph of the city lights of Naples and the Campania region of southern Italy on January 30, 2017. The Naples region is one of the brightest in Italy. Roughly three million people live in and around this metropolitan area.

The large black circular area in the photo is Mount Vesuvius, the only active volcano on Europe's mainland. Although any volcanic activity can endanger surrounding communities, eruptive pyroclastic flows of superheated ash and gas are among the most dangerous, moving at speeds of hundreds of kilometers per hour. Vesuvius has erupted on numerous occasions throughout history. Probably the most famous of those eruptions occurred in 79 A.D., when pyroclastic flows destroyed the cities of Pompeii and Herculaneum, trapping more than 16,000 people. Such historic catastrophes—and the fact that 600,000 people currently live in the immediate vicinity—are why the volcano is one of the most heavily monitored in the world, with several dozen sensors located at many points on and around the cone.

The different colors of lights in the scene reflect some of the history of development in the area. The green lights are mercury vapor bulbs, an older variety that has been replaced in newer developments by yellow-orange sodium bulbs. To the northeast, the lightless gaps between the homes and businesses are agricultural fields. The bright yellow-orange complex amidst the fields is the Consorzio Intercomunale dei Servizi, the largest commercial facility in Europe. A regional view of Italy appears on page 92.




fields
fields
Consorzio
Intercomunale
dei Servizi
airport
Mt. Vesuvius
Herculaneum
Pompeii

Dazzling Coastlines—Italy

City lights clearly delineate the boot of Italy in this panorama taken by astronauts onboard the ISS on October 21, 2014. Looking east on this clear night, the pattern of nightlights shows populations concentrated mainly along the coastlines, but also in the Po River Valley of northern Italy. Some of the brightest clusters of lights are Rome and nearby Naples (see image on previous page), along with the island cities of

Cagliari on Sardinia and Catania on Sicily. The small, dark, circular patch dangerously close to Catania marks the unpopulated slopes of the active volcano Etna. Hazy lights, as over the Po Valley and Rome, probably indicate thin clouds above. The island of Malta, which is the tenth smallest and fifth most densely populated country in the world, appears in the lower right. Airglow is vivid in this night shot.

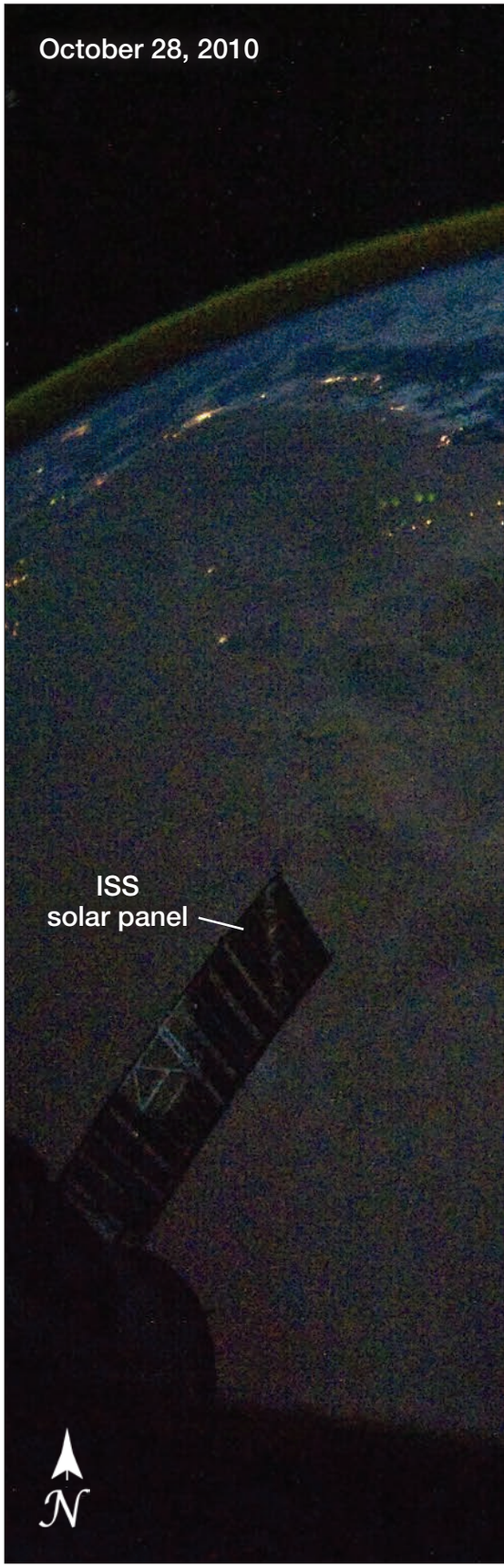
Living on Fertile Land—Nile River, Egypt

The Nile River was the center of ancient Egyptian civilization—the lifeline for one of history's first great empires. Annual floods helped bring silt to the soil, which allowed generation after generation to grow crops. Today's nighttime lights show clearly that Egypt's population is, as it was in ancient history, almost completely concentrated along the Nile Valley—a small percentage of the country's land area, the remainder of which is desert.

The Nile River and its heavily populated delta look like a brilliant, long-stemmed flower in this photograph of the southeastern Mediterranean Sea, as seen from the ISS on October 28, 2010. The Cairo metropolitan area forms a particularly bright base for the flower. The smaller cities and towns within the Nile Delta are harder to see during the day amid the dense agricultural vegetation. However, these settled areas and the connecting roads between them become clearly visible at night. Similarly, urbanized regions and infrastructure along the Nile River become apparent.

Another brightly lit region visible along the eastern coastline of the Mediterranean is the Tel Aviv metropolitan area in Israel (image right). To the east of Tel Aviv lies Amman, Jordan. The two major water bodies that define the western and eastern coastlines of the Sinai Peninsula—the Gulf of Suez and the Gulf of Aqaba—are outlined by lights along their coastlines (image lower right). The city lights of Paphos, Limassol, Larnaca, and Nicosia are visible on the island of Cyprus (image top).

Scattered blue-grey clouds cover the Mediterranean Sea and the Sinai, while much of northeastern Africa is cloud-free. A thin yellow-brown band tracing Earth's curvature at image top is airglow.



airglow
Mediterranean Sea
Cyprus
Paphos
Larnaca
Nicosia
Limassol
Tel Aviv
Amman
Cairo
Egypt
Gulf of Suez
Gulf of Aqaba

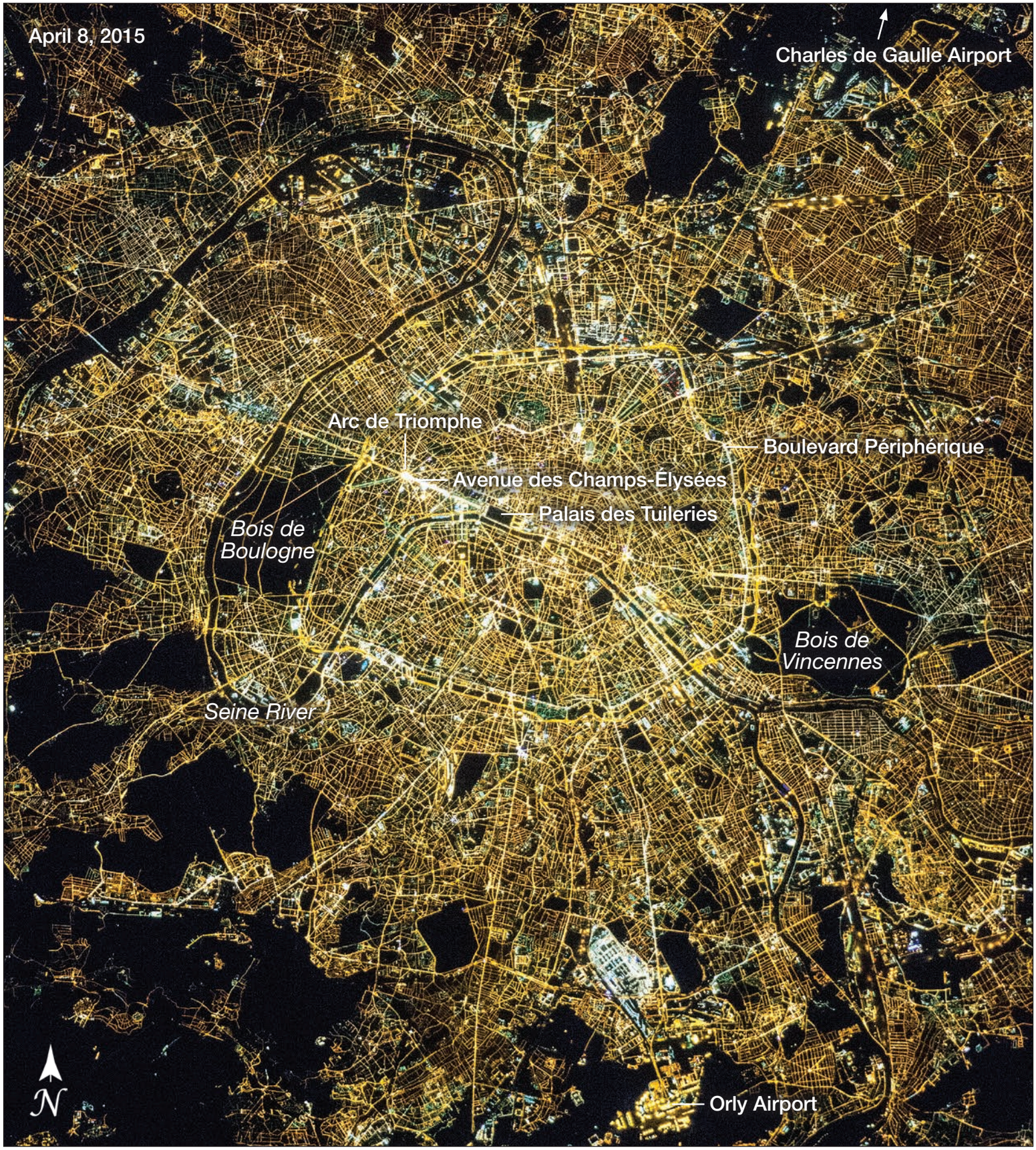
The Winding Seine River and the City of Light—Paris, France

Around local midnight on April 8, 2015, astronauts onboard the ISS took this photograph of Paris, often referred to as the "City of Light." When viewed from low Earth orbit, the pattern of the street grid dominates the Parisian night, providing a completely different set of visual features from those visible during the day. For instance, the winding Seine River is a main visual cue by day, but here the thin black line of the river is hard to detect until you focus on the strong meanders and the streetlights on both banks.

The brightest boulevard in the dense network of streets is the Avenue des Champs-Élysées, the historical axis of the city, as designed in the seventeenth century. This grand avenue joins the site of the former royal Palais des Tuileries—whose gardens appear as a dark rectangle on the river—to the star-like meeting place of eleven major boulevards at the Arc de Triomphe. This famous plaza is also referred to as the Étoile, or "star."

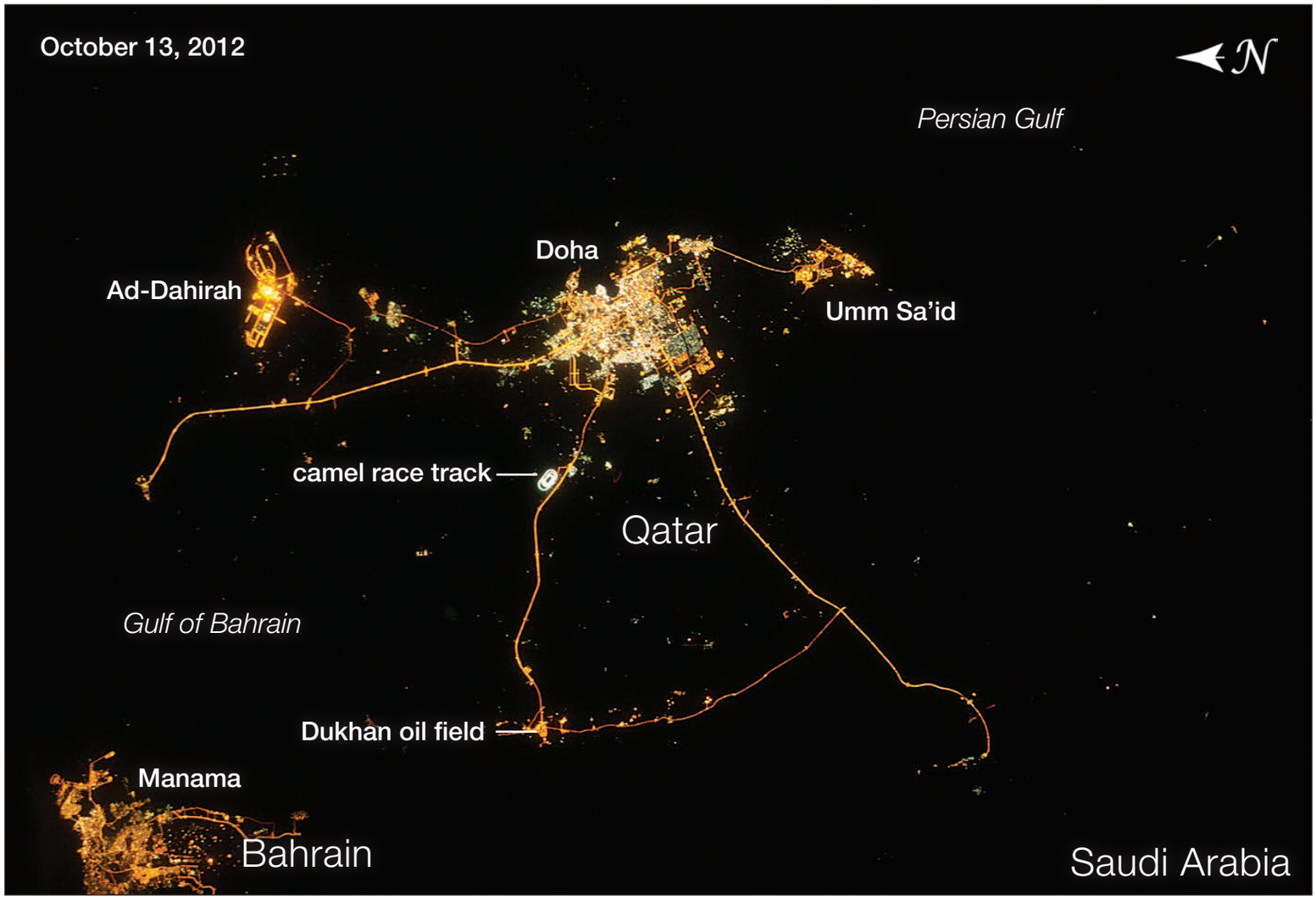
The many forested parks of Paris stand out as black polygons—such as the Bois de Boulogne and Bois de Vincennes. The Bois de Boulogne is crisscrossed by a few roads and lighted paths.

Orly airport is distinguished by very bright lights next to the dark areas or runways and surrounding open land. Paris's great ring road, the Boulevard Périphérique, encloses the city center.

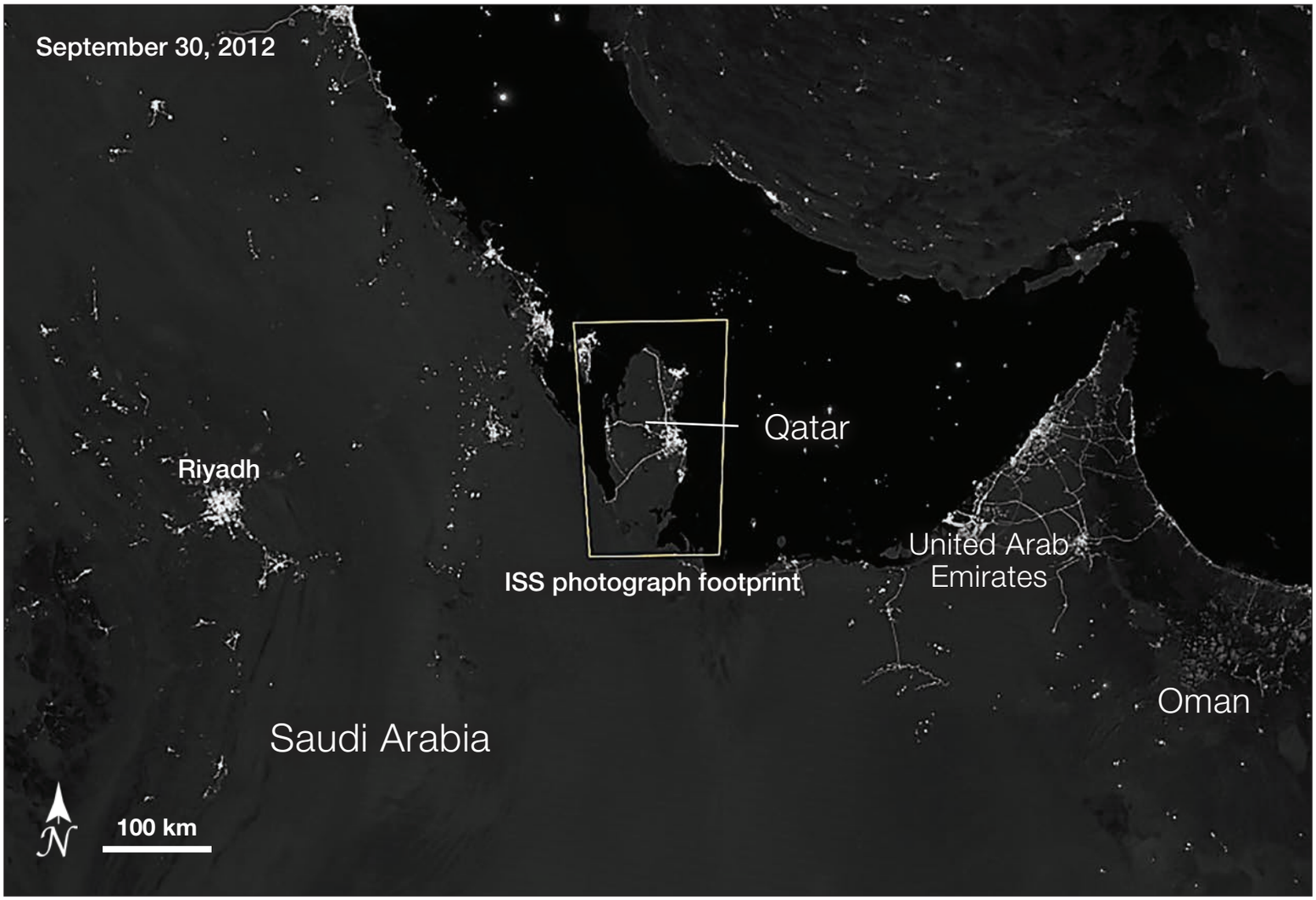

April 8, 2015
Charles de Gaulle Airport
Arc de Triomphe
Boulevard Périphérique
Avenue des Champs-Élysées
Palais des Tuileries
Bois de Boulogne
Bois de Vincennes
Seine River
N
Orly Airport

Lighting Paths to Oil—Qatar

In the photograph below, taken from the ISS on October 13, 2012, the nightlights of Qatar show informative demographic detail that is very difficult to discern in daylight images—especially in deserts, where even large cities can be hard to see. The brightest group of lights at image center is the capital city, Doha, with the neighboring smaller ports of Ad-Dahirah and Umm Sa'id to the north and south. (Note that north is to the left in this image, due to the path of the ISS orbit.) Highways are clearly visible leading west from the capital to the Dukhan oil fields, to Saudi Arabia, and to the north of the country where—judging by the lack of nightlights—the population is probably very low. The relatively minor coastal road between the oil fields and the Saudi frontier also stands out.

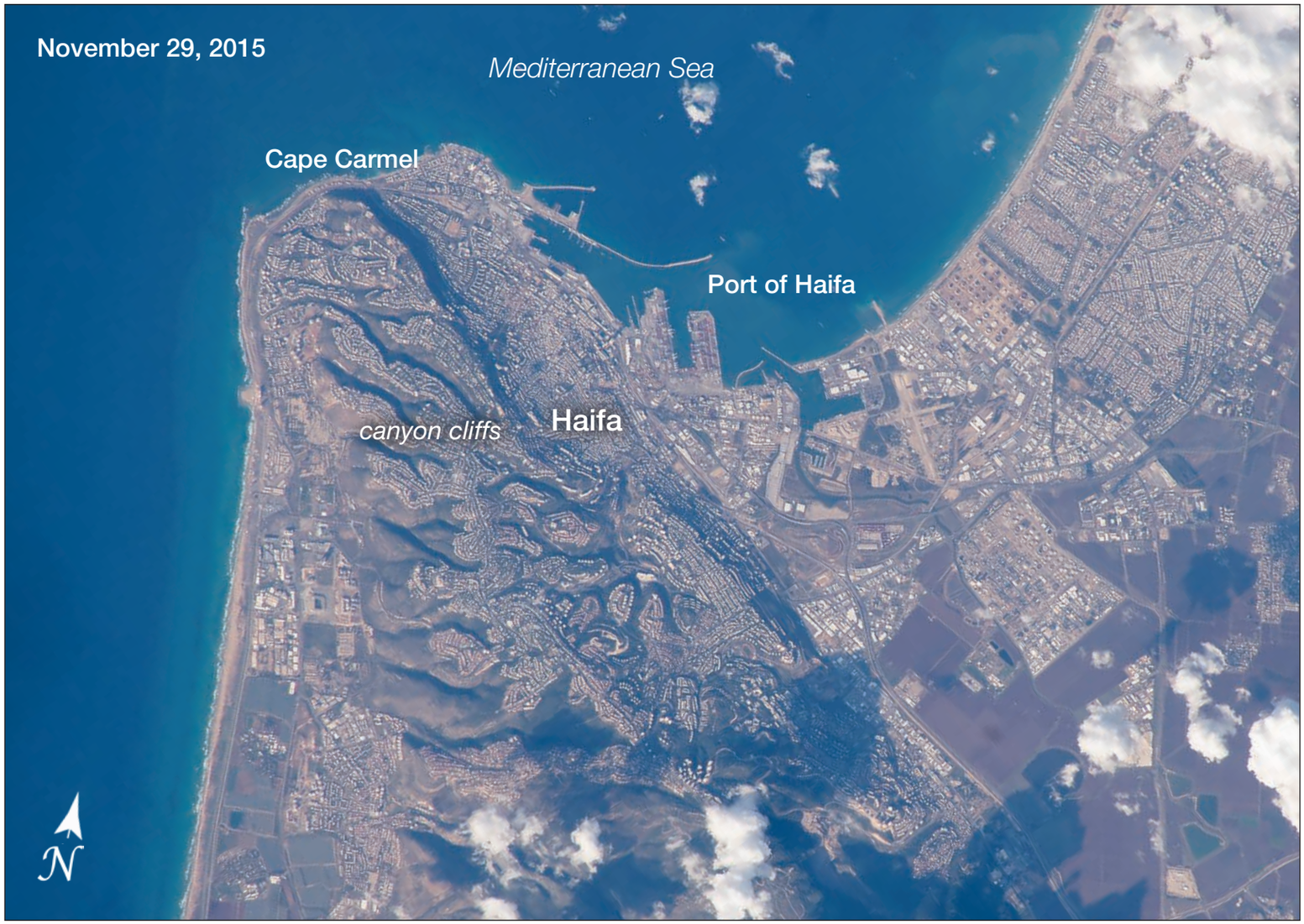


Almost the entire island nation of Bahrain appears at lower left, with the capital city of Manama nearly as bright as the lights of Doha. The difference in light intensity reflects a difference in population: Doha has 1.45 million inhabitants, while the dense Manama metropolitan area has a population of 1.2 million. The thumb-shaped Qatari peninsula, so well-known in Middle Eastern geography, does not show up at all in this nighttime photograph. However, in the image below, the low-light imaging bands of VIIRS on the Suomi NPP satellite showed the Qatari peninsula and the long arm of the Gulf of Bahrain on a moonlit night. The image was acquired during the early morning hours of September 30, 2012, two weeks before the ISS photograph at left.



Snaking Along Canyon Cliffs—Haifa, Israel

In geography training, astronauts are taught to concentrate on the shapes of coastlines because they are a first-order visual cue when circling the planet—and often uniquely shaped. The nose of Cape Carmel and the bay that protects the Port of Haifa are shapes that can tell crews where they are. In the daylight image of the port city of Haifa on Israel's Mediterranean coast (below), the strong visual line of the coast contrasts with the subtle city colors. The night image (right) shows different city



neighborhoods in a way that is difficult to see during the day. The brilliant port lights contrast with somewhat dimmer residential areas. Straight roads of the older residential neighborhoods are easily distinguished from the winding roads that follow the canyon cliffs. The industrial district just east of the port has areas of green and blue lights and a less-dense street pattern. Surrounding farmlands are so dark that they can be confused with the sea.

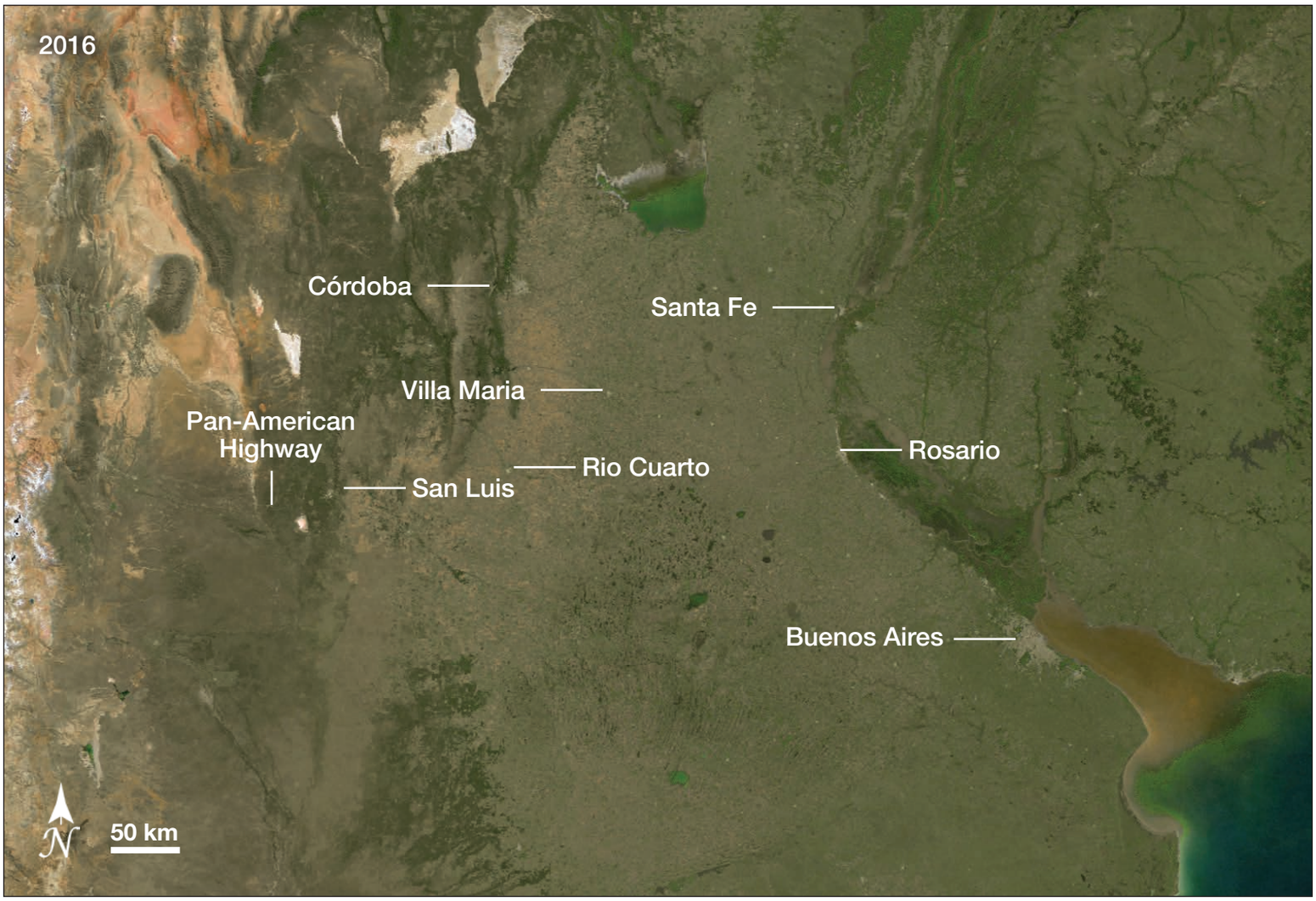
Differences in Socio-Economic Strategies—Korean Peninsula

Unlike daylight images, lights at night illustrate dramatically the economic significance of cities, as gauged by relative size. Usually, nightlights can be used to gauge a region's population: more people mean more lights. But the Korean Peninsula has a different story to tell. Flying over East Asia, astronauts on the ISS took this night image of the Korean Peninsula on January 30, 2014. In this north-looking view, it is immediately obvious that Seoul is a major city and that the port of Gunsan is minor by comparison. There are 25.6-million people in the Seoul metropolitan area—more than half of South Korea's citizens—while Gunsan's population is 280,000. North Korea is

almost completely dark compared to neighboring South Korea and China. Its capital city, Pyongyang, appears like a small island, despite a population of 3.26 million (as of 2008). The light emission from Pyongyang is equivalent to the smaller towns in South Korea. Coastlines are often very apparent in night imagery, as shown by South Korea's eastern shoreline, but the coast of North Korea is difficult to detect. These differences are illustrated in the significant differences in per capita power consumption between the two countries, with South Korea at 10,162 kilowatt hours and North Korea at 739.

Now You See Them, Now You Don't—Argentina

When viewed from a satellite during the day (image below), the landscape of central Argentina shows barely a sign of human settlement. But by night (right image), the evenly spaced points of light that reveal the presence of population centers puncture the darkness. It's no mistake that these lights appear roughly every 20 to 30 miles (every 30 to 50 kilometers), as many of the towns grew up around railway stations. Maps from the middle of the twentieth century show the network of railway lines that gave shape to this curious configuration. Today, cars have outpaced trains in popularity, but the mark of the railways remains emblazoned in the terrain. Some tracks are still visible from space, such as those running parallel to the road between Córdoba



and Villa Maria. The same is true of the line that runs northeast through Rio Cuarto. Highways now connect the "dots"—and these cities.

The nighttime image below shows Argentina's nightlights as observed by the VIIRS DNB on the Suomi NPP satellite in 2016. The natural-color image on the left shows the same area by day with a cloudless composite from the MODIS instruments on the Aqua and Terra satellites. Fields for growing crops and raising cattle dominate the landscape. Most people reside in the country's main cities, including Córdoba and Santa Fe. A mere 10 percent of Argentina's population lives in rural areas, according to the Food and Agriculture Organization of the United Nations.

A Well-Lit Border, Indus River—Pakistan

Like the Nile River Valley (shown on page 94), the Indus River Basin in Pakistan is an ancient seat of civilization. In spite of the arid conditions that make it difficult to grow food in the rest of the region, people have lived and farmed in the river's fertile floodplain for millennia. In modern times, the sinuous shape of the Indus River emerges even in nighttime satellite imagery, based on data collected in 2016 by the VIIRS DNB on the Suomi NPP satellite. Though the river itself is only barely visible, the dark crops and vegetation growing along its banks help reveal the general shape of the river. The brighter, more reflective land beyond the dark band of farmed land is desert. Many of the largest cities and towns in Pakistan are clustered along the Indus. Karachi lies along the southernmost stretch of the river, near where it empties into the Arabian Sea at the Indus River Delta. Other brightly lit cities along the river include Hyderabad, Larkana, and Sukkur. The border between Pakistan and India stands out among the nightlights of this region. For security purposes, India has installed thousands of kilometers of floodlights along the border, a feature bright enough to be seen from the ISS.

Indus River
Larkana
Sukkur
International Border
India
Hyderabad

Urban Development

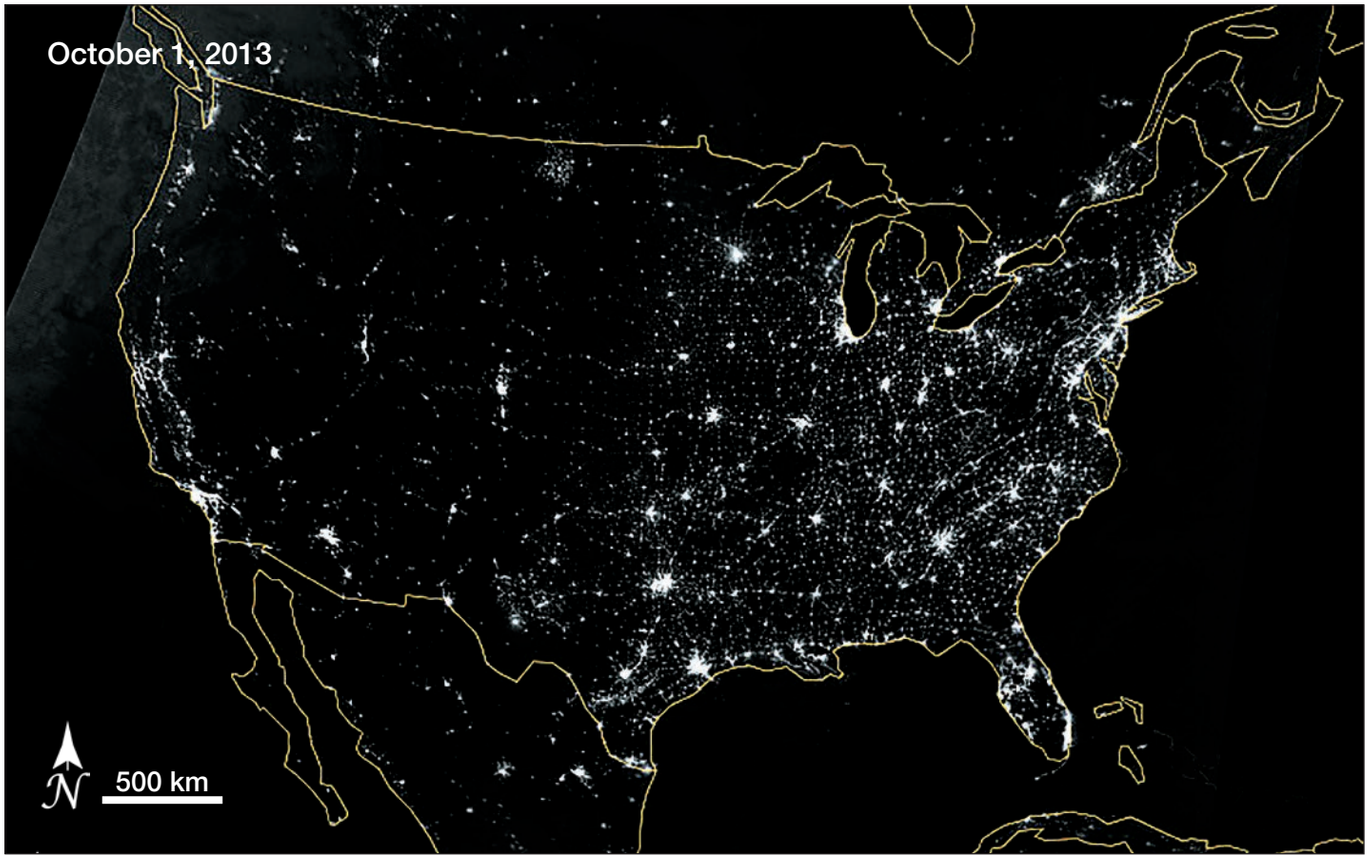
Lighting Paths—Across the United States

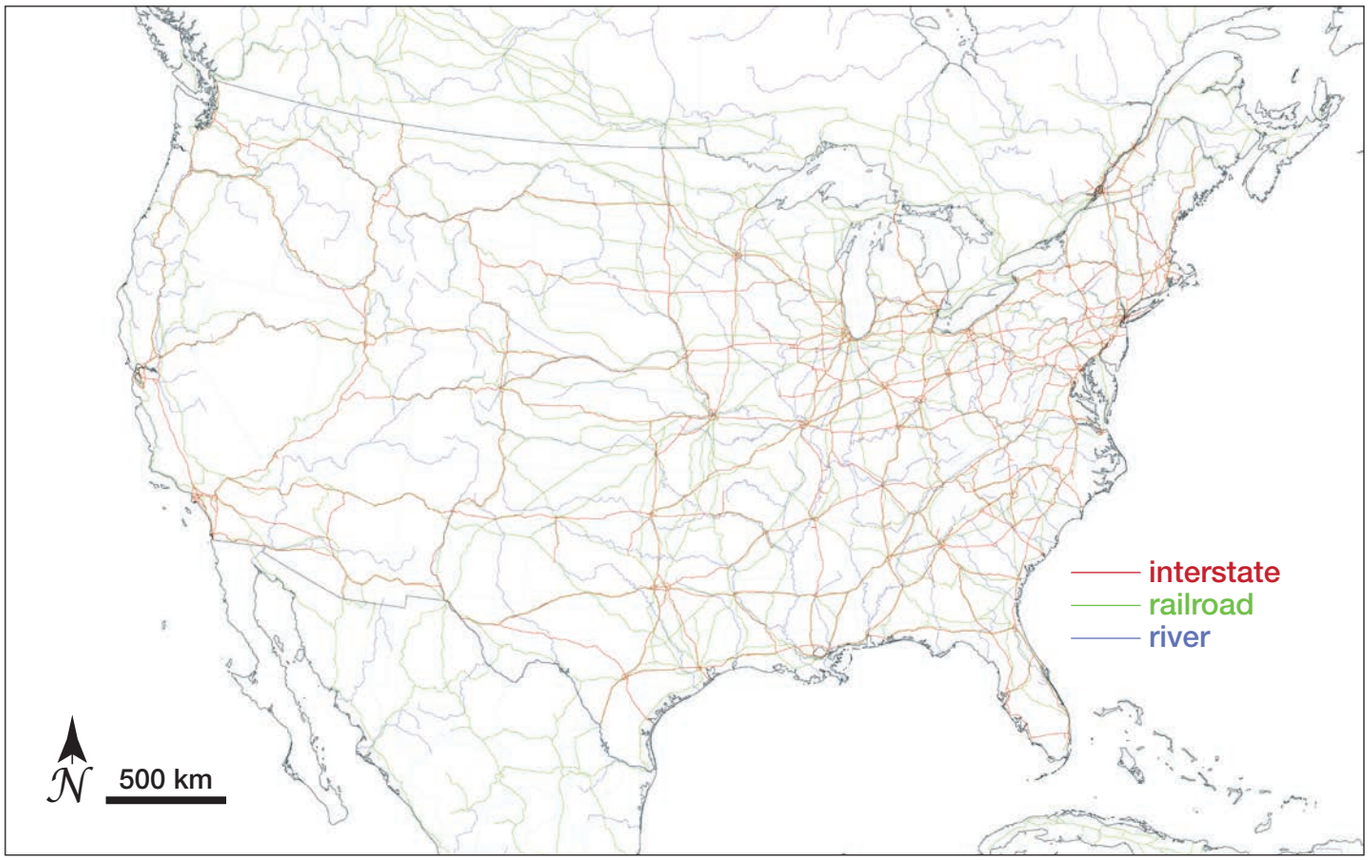
The United States has more miles of roads than any other nation in the world—4.1 million miles (6.6 million kilometers) to be precise, which is roughly 40 percent more than second-ranked India. About 47,000 miles (75,639 kilometers) of those roads are part of the Interstate Highway System, established by President Dwight Eisenhower in the 1950s. The country also has 127,000 miles (204,000 kilometers) of railroad tracks and about 25,000 miles (40,000 kilometers) of navigable rivers and canals (not including the Great Lakes). The imprint of that transportation web becomes easy to see at night.

The VIIRS DNB on the Suomi NPP satellite acquired this nighttime view (top image, right) of the continental United States on October 1, 2013. The roadway map (bottom image, right) traces the path of the major interstate highways, railroads, and rivers of the United States. Comparing the two images, you quickly see how the cities and settlements align with the transportation corridors. In the early days of the republic, post roads and toll roads for horse-drawn carts and carriages were built to connect eastern cities like Boston, New York, Baltimore, and Philadelphia, though relatively few travelers made the long, unlit journeys. Railroads became the dominant transportation method for people and cargo in the middle of the nineteenth century, establishing longer links across the Nation and waypoints across the Midwest, the Great Plains, and the Rockies. Had nighttime satellite images existed in that era, they probably would show only dim pearls of light around major cities in the east and scattered across the country; the strands of steel tracks and cobbled roads that connected them would be invisible from space.

Eventually, cars and trucks became the dominant form of transportation in the United States. Drivers then needed roads and lighting to keep them safe on those roads. As the Nation grew in the twentieth century, the development of new cities and suburbs often conformed to the path of the interstate highways, adding light along the paths between the cities.

Over the years, the length of navigable rivers has been a constant, as is their relative lack of light. Even today the only light seems to be the occasional port cities along riverbanks and the light of ships themselves.

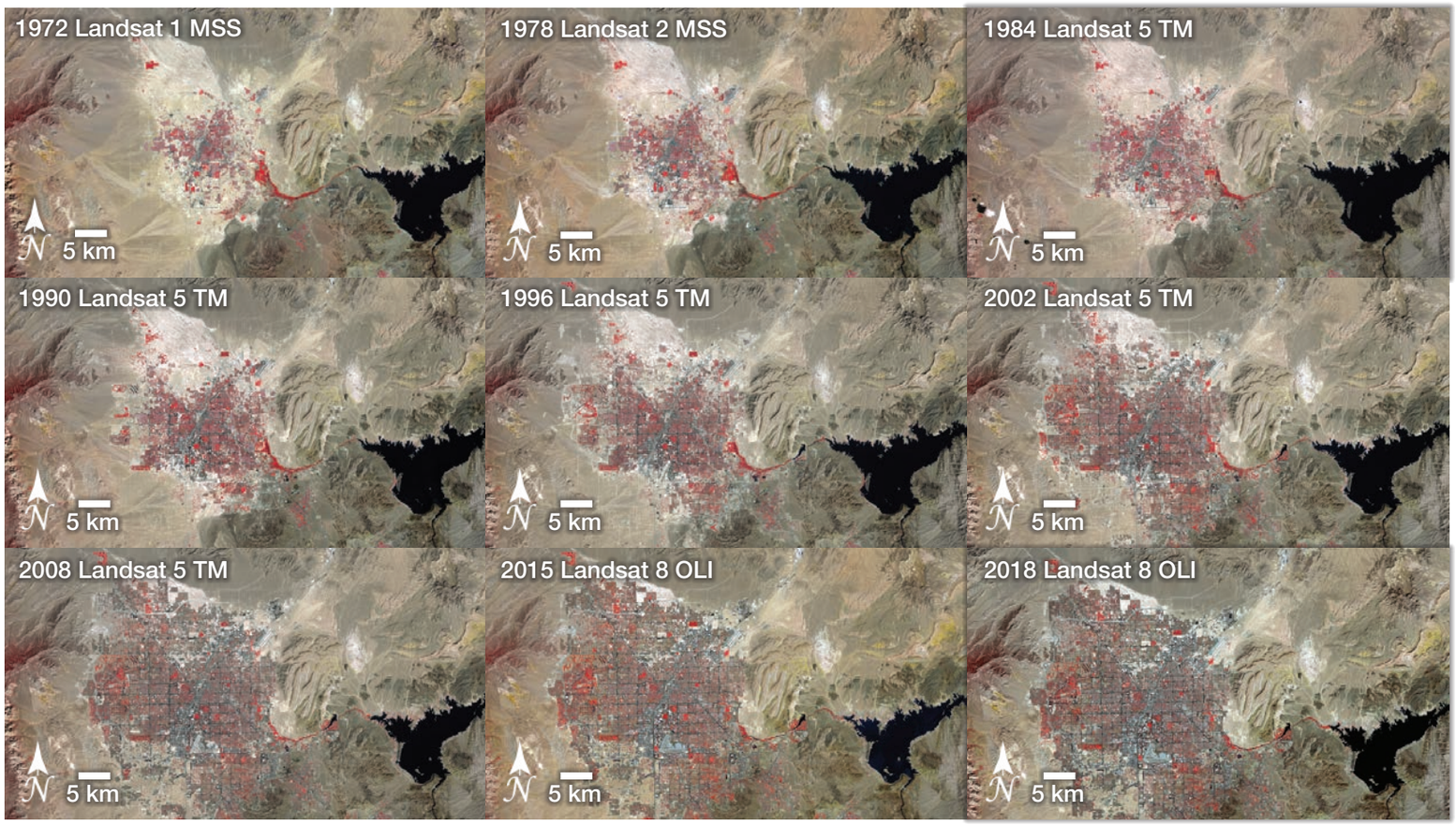

October 1, 2013
N
500 km


interstate
railroad
river
N
500 km

The Brightest Spot on Earth—Las Vegas, Nevada

The city of Las Vegas was established in 1905. Its grassy meadows and artesian springs attracted settlers traveling across the arid Desert Southwest in the early 1800s. In the 1930s, gambling became legalized and construction of the Hoover Dam began, resulting in the city's first growth spurt. Since then, Las Vegas has not stopped growing. Population has reached nearly two million over the past decade, making this one of the fastest growing metropolitan areas in the world. The series of false-color Landsat images (top image grid, right) show the rapid urbanization of Las Vegas between 1972 and 2018. The city streets and other impervious surfaces appear gray, while irrigated vegetation appears red. Over the years, the expansion of irrigated vegetation (e.g., lawns and golf courses) has stretched the city's desert bounds.

While the city is famous for its casinos and resort hotels—Las Vegas bills itself as "the entertainment capital of the world"—the wider metropolitan area includes several other incorporated cities and unincorporated areas (not part of a state-recognized municipality). The surrounding darkness of the desert in the astronaut photo from the ISS (bottom image, right), taken on November 30, 2010, presents a stark contrast to the brightly lit street grid of the developed area. The famous Vegas Strip is reputed to be the brightest spot on Earth due to the concentration of lights on its hotels and casinos. The tarmac of McCarran International Airport appears dark by comparison, while the airstrips of Nellis Air Force Base on the northeastern fringe are likewise dark. The dark mass of Frenchman Mountain borders the city to the east.

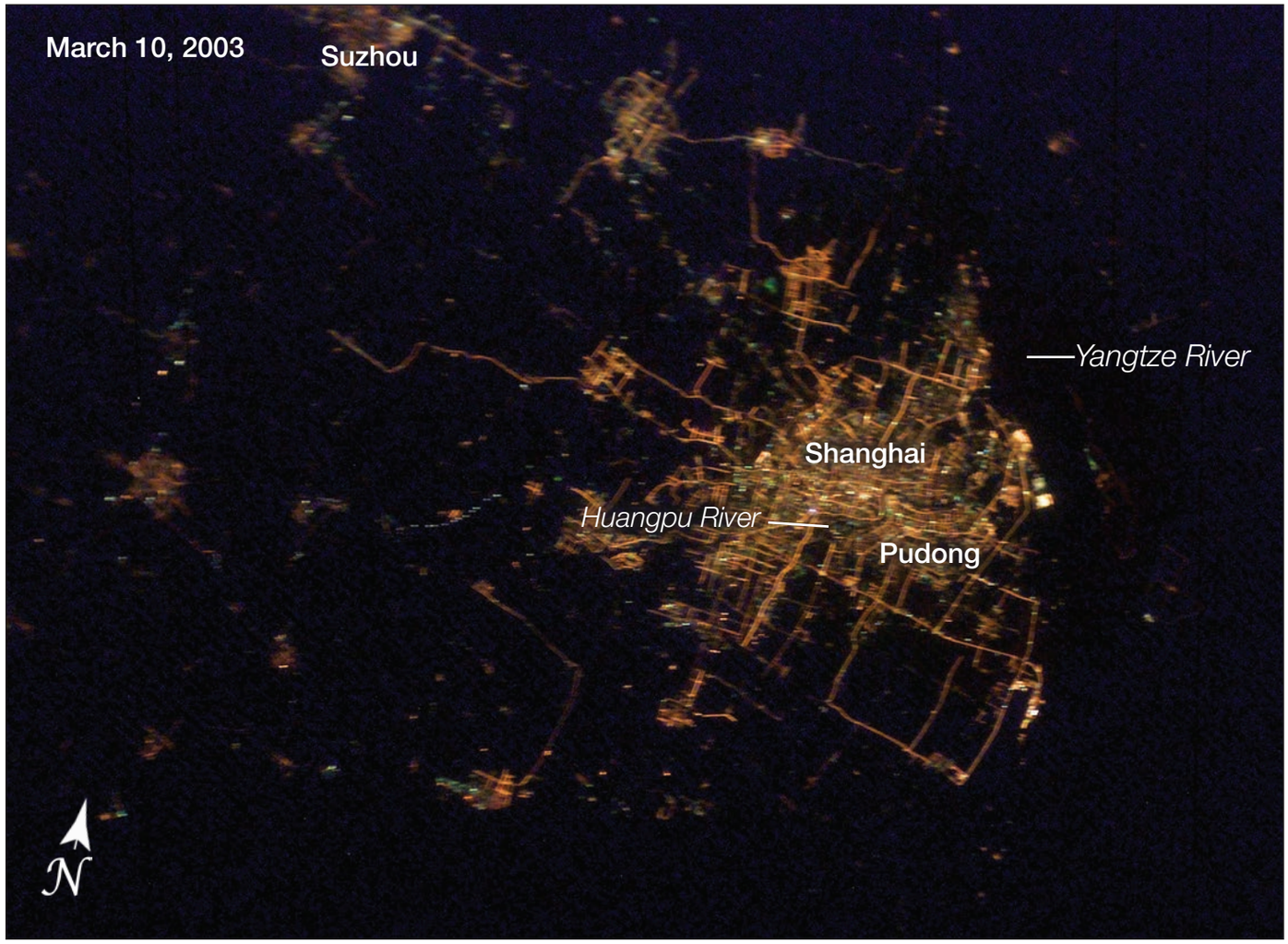

1972 Landsat 1 MSS
1978 Landsat 2 MSS
1984 Landsat 5 TM
1990 Landsat 5 TM
1996 Landsat 5 TM
2002 Landsat 5 TM
2008 Landsat 5 TM
2015 Landsat 8 OLI
2018 Landsat 8 OLI
N
5 km

November 30, 2010
Las Vegas Strip
McCarran Airport
Nellis Air Force Base
Frenchman Mountain
N

Rapid Urban Growth—Shanghai, China

These nighttime photographs taken by astronauts onboard the ISS reveal the unprecedented growth of Shanghai, China, between March 10, 2003 (below) and February 28, 2018 (right). The city of Shanghai sits along the delta banks of the Yangtze River along the eastern coast of China. The city proper is the world's most populous city.

The surge in China's urbanization began in the 1980s when the Chinese government began opening the country to foreign trade and investment. As markets developed in "special economic zones," villages morphed into booming cities and cities grew into sprawling megalopolises. In 1982, Shanghai was a relatively compact industrial city of 12-million people; however, that number grew to 24 million by 2016. Much of the growth

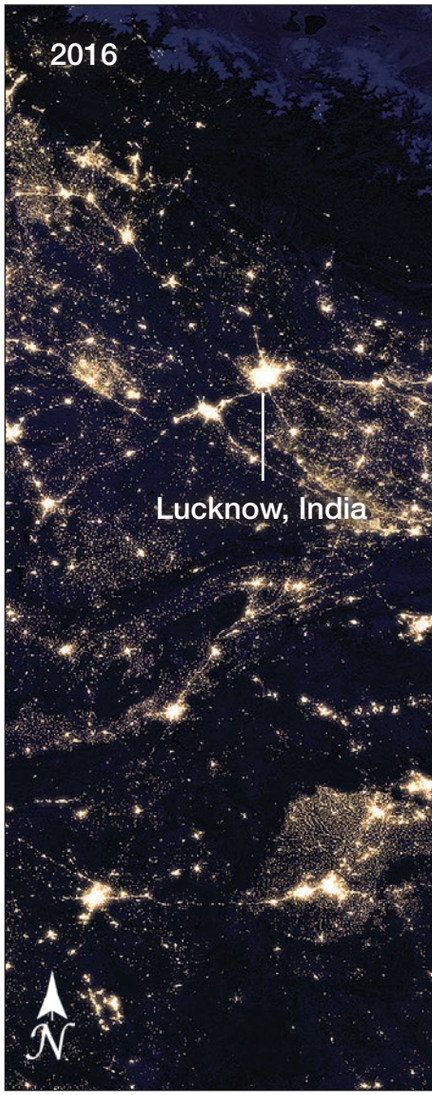


has occurred in new satellite developments like areas to the west of the city (for example, Suzhou, at the upper left of the image on the right).

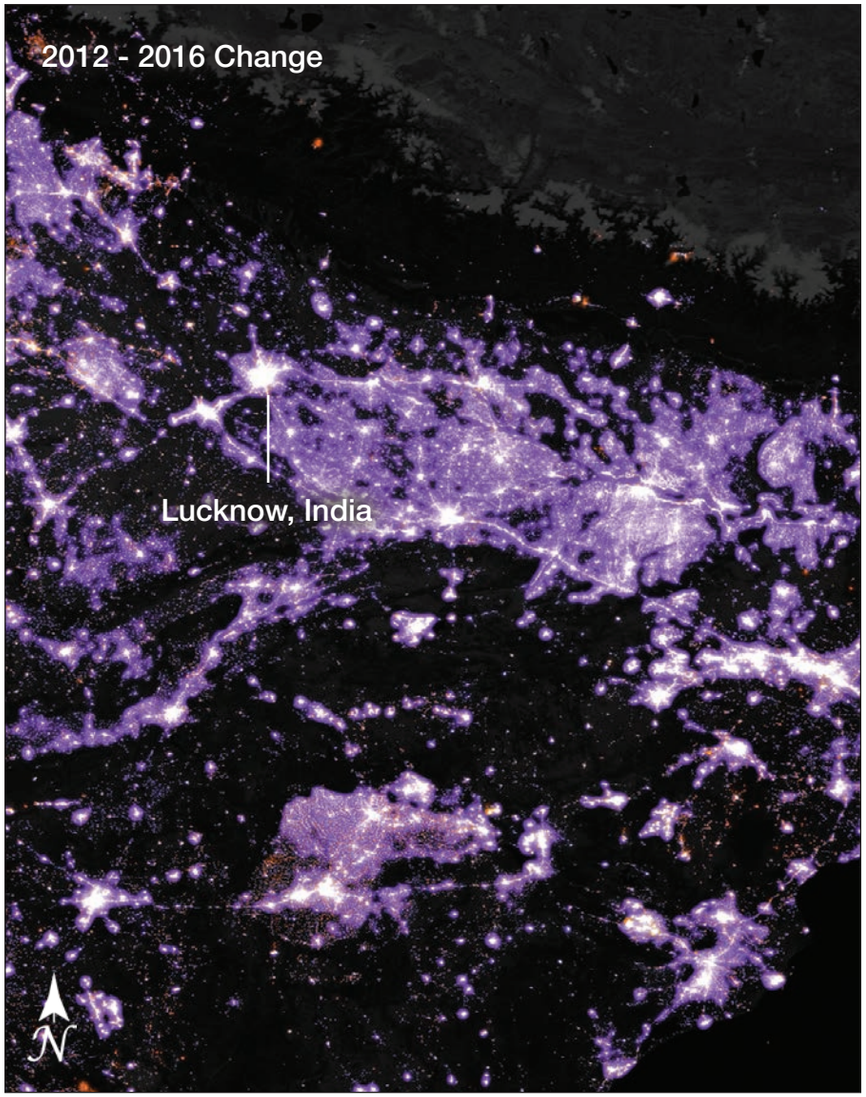
The rapid pace of development has changed Shanghai's natural ecosystems. Wetlands in the region have declined due to sea level rise, erosion, dredging, and the construction of water-storage infrastructure. The creation of new coastal land—by piling sediment onto tidal flats in a process called land reclamation—has also played a key role. Despite the dizzying pace of urbanization, there are signs that Shanghai's growth may be tapering off. Officials announced that they will cap the city's population at 25 million in the hopes of easing the pressure on the environment, infrastructure, and city services.

Turning Up the Lights—India

Images of Earth at night are being used by scientists and decision-makers to monitor gradual changes driven by urbanization and electrification. Upon assuming leadership in 2014, India's Prime Minister Narendra Modi pledged to electrify the nation and, in 2015, launched a program to electrify every village in the country. The image on the left (below) and the middle image (below) were created using two separate nightlight datasets from the VIIRS DNB on the Suomi NPP satellite for 2012 and 2016, respectively. The image on the right (below) shows the change in lighting intensity that results from



combining the 2012 and 2016 images. Purple shades indicate areas that have more lights in 2016 than in 2012. Huge swaths of northern India—relatively dark in the 2012 night image—are lit up in the image from 2016. Orange shades indicate areas that have become dimmer since 2012. The dark area to the north (top) of the images is Nepal, which is almost completely lacking in observable lighting, clearly demonstrating the differences in stages of development between the two countries. To view global changes in lighting intensity from 2012 to 2016, see page 26 of this volume.

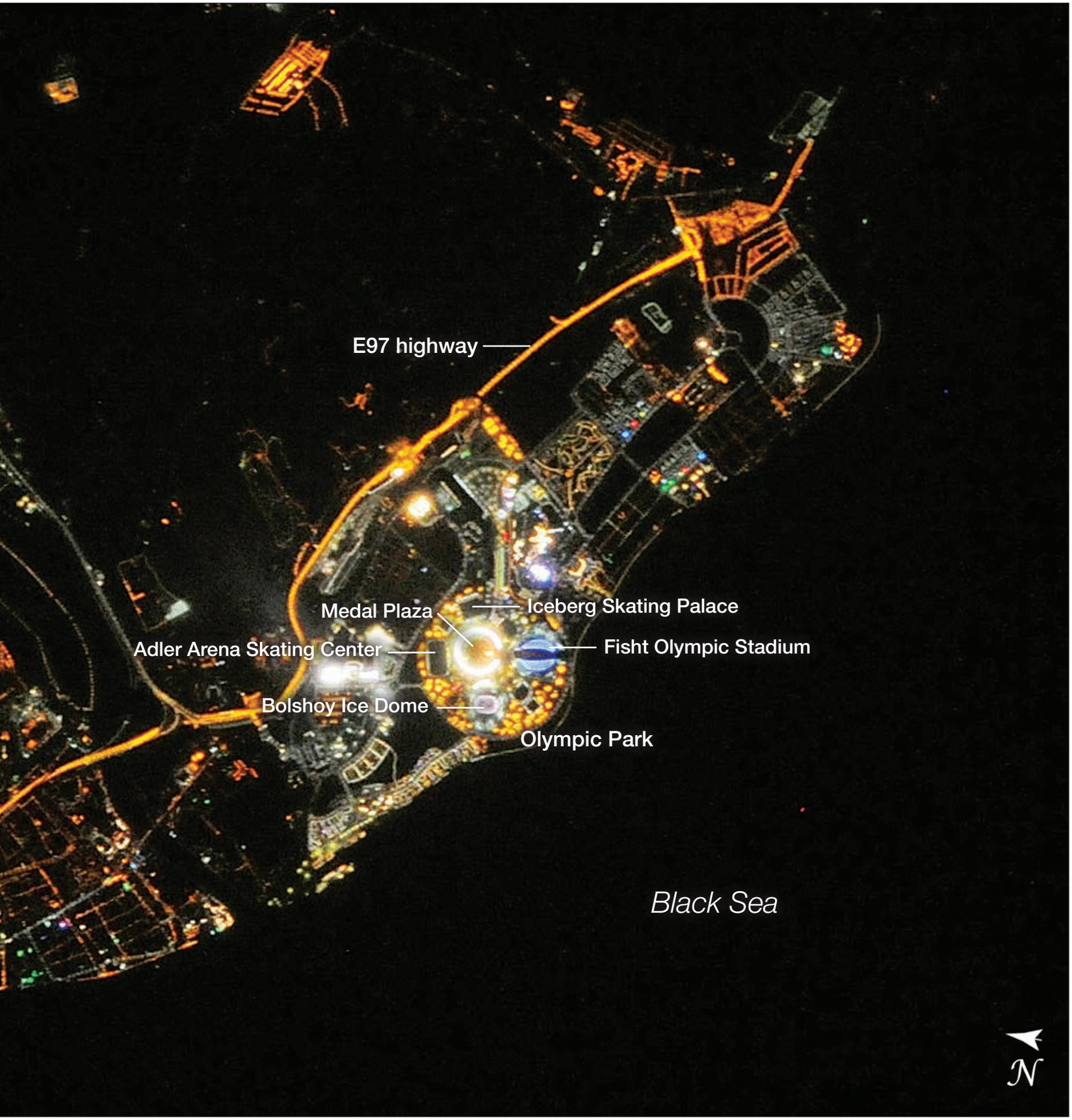


Change in Nightlights (2012-2016)

lights out — no change — new lights

Olympics at Night—Sochi, Russia

Three months after an out-of-this-world hand-off of the event-opening Olympic torch outside their orbiting home, the astronauts and cosmonauts on the ISS got to look down on that flame from above. On the evening of February 10, 2014, an ISS Expedition 38 crew member captured this digital photograph of Sochi, Russia, along the coast of the Black Sea. In the image, the Olympic flame burns in the circular Medals Plaza, ringed in gold and bright white lighting in the center of the Olympic Park. The oval-shaped Fisht Olympic Stadium is lit in blue and stands near the shore to the south. (Note that, owing to the orbit of the ISS, south is to the right in this image.) The Adler Arena Skating Center and the Iceberg Skating Palace both appear as black rectangles north and east of the Medals Plaza, and the Bolshoy Ice Dome has a pink tint and stands to the west. The A-class European Highway, E97, cuts diagonally through the image as it connects the north and south Black Sea regions.


E97 highway
Medal Plaza
Iceberg Skating Palace
Adler Arena Skating Center
Fisht Olympic Stadium
Bolshoy Ice Dome
Olympic Park
Black Sea
N

Power Outages

Hurricane Maria

Hurricane Maria into the Night—Puerto Rico

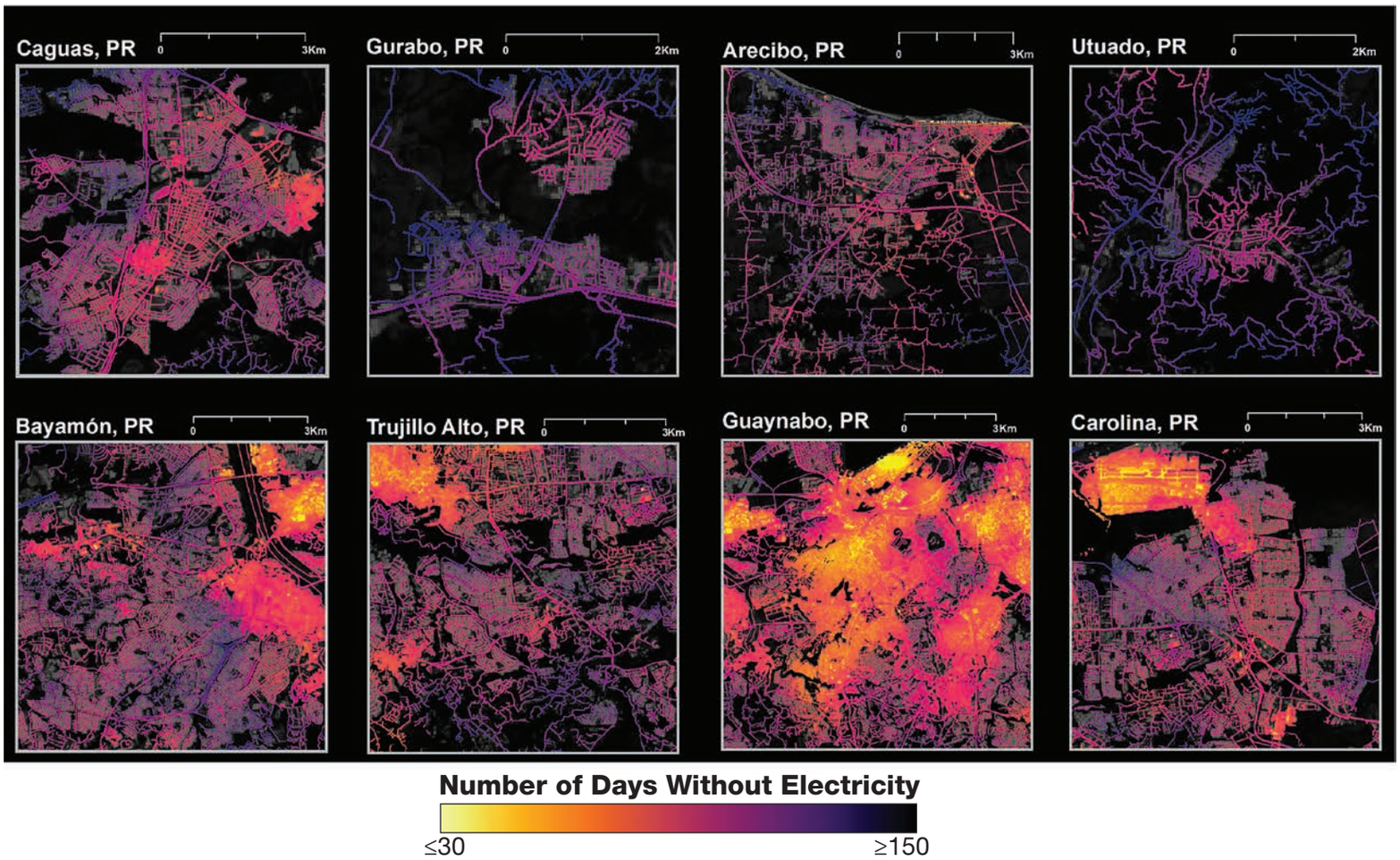
This composite image shows Hurricane Maria on September 20, 2017, as it made landfall near Yabucoa, Puerto Rico. Data from the Geostationary Operational Environmental Satellite 13 (GOES–13) acquired at 6:15 a.m. local time is overlaid on true-color data from the MODIS instruments on the Terra and Aqua satellites and nightlight data from the VIIRS DNB sensor.

Lights Out—Puerto Rico

Hurricane Maria struck Puerto Rico with devastating force in September 2017. Flooding, downed trees, and toppled power lines made many roads impassable. Most of the electricity grid and telecommunications network were knocked offline, leaving 1.5 million people without power. For many locations power wasn't restored for weeks and even for up to 11 months in some locations. The long power outages, in part, led to the historic property, economic, and life losses in the storm's aftermath. While 64 people died from direct storm impacts (i.e., via structural collapse, flying debris, floods, and drownings), an estimated 700 to 8400 excess deaths were associated with long-duration disruptions to essential services.

The image grid at right shows the number of days that different neighborhoods in Puerto Rico were without power following Hurricane Maria. As shown in the top row, urban centers (e.g., Caguas and Arecibo) recovered much faster than adjacent rural towns (e.g., Gurabo and Utuado, respectively). The bottom four images show different areas of the San Juan metropolitan region. Even within San Juan, some neighborhoods recovered more quickly than other neighborhoods, based largely on how modern grid connections were and whether neighborhoods were close to roads, hospitals, and schools that needed priority attention.

The images are derived from data obtained by the VIIRS DNB on the Suomi NPP satellite to generate a data product suite called Black Marble—see *Appendix A* to learn how this product is generated. The Black Marble product suite enables near-real-time, daily monitoring of nightlights globally, in big cities, and in remote and isolated areas that may be difficult to reach. In addition to detecting power outages, the Black Marble product suite can be used to track the speed of recovery (i.e., power restoration) at a



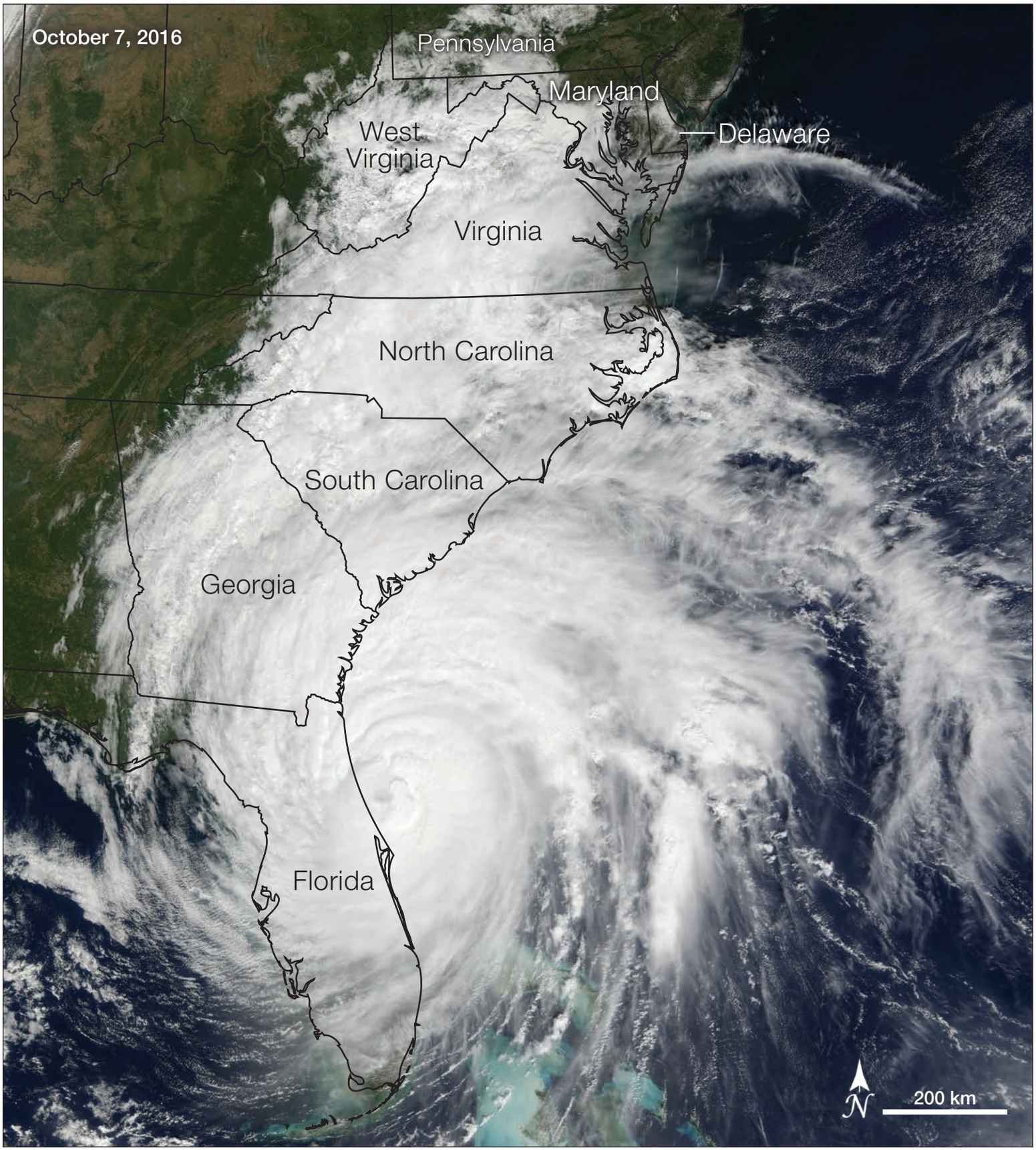
neighborhood level—a capability that previous nightlight products and imagery did not have, as more than half of the daily data was corrupted by moonlight.

To respond to storms like Maria, disaster responders need data, not only about who has lost access to electricity, but also for how long. These data need to be continuously collected, available in real time, and resolved at the street level, so that decision-makers can understand who has been most affected, what is the capacity of the affected communities to cope, and where to send aid. The high resolution of the Black Marble product suite, when combined with high-resolution demographic data, can help provide such vital information.

Hurricane Matthew

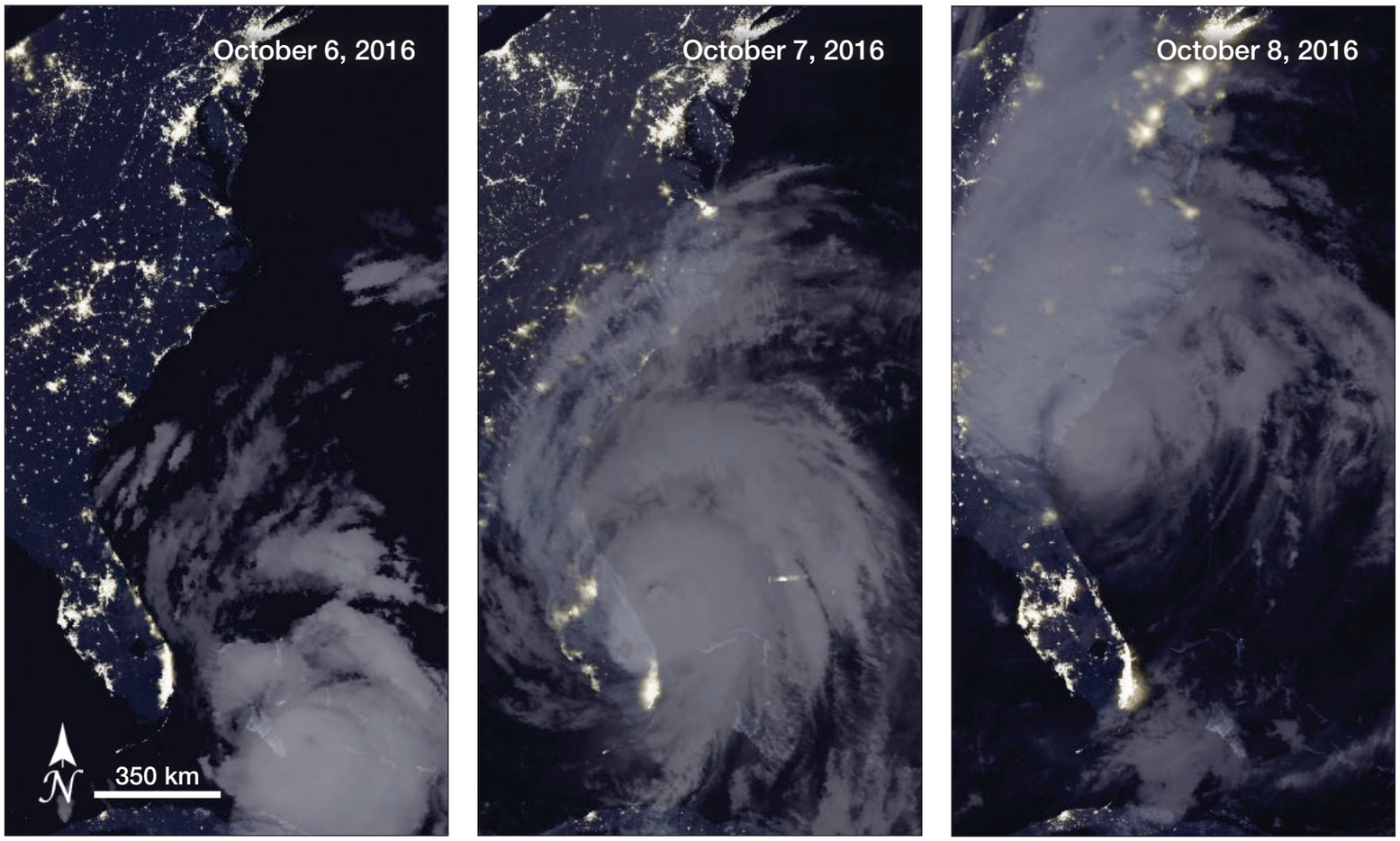
Hurricane Matthew Brushes Florida Coast—Southeast United States

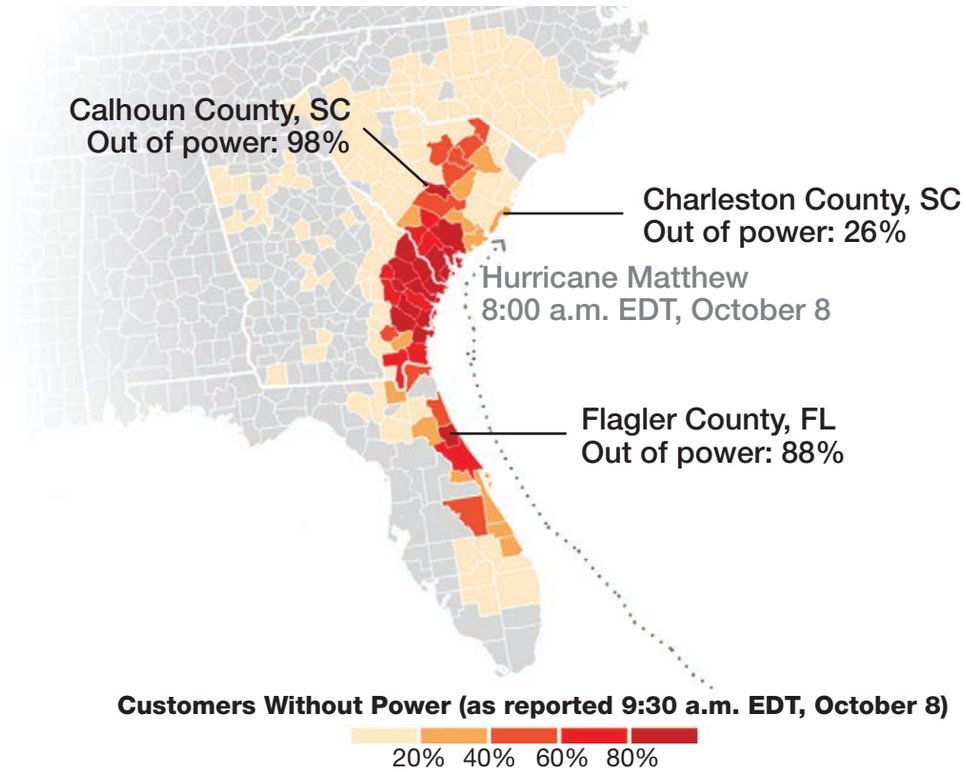
Hurricane Matthew strengthened to a major hurricane on September 30, 2016. After it made landfall in Haiti on October 4, the hurricane leveled entire villages. On October 7, 2016, the storm's western eyewall brushed parts of Florida. This natural-color image was acquired at 12:00 noon (local time) on October 7, 2016 by the MODIS instrument on NASA's Terra satellite. An hour before the image was taken, Matthew was located roughly 35 miles (55 kilometers) northeast of Daytona Beach, Florida, and headed toward the north-northwest at a pace of 13 miles (20 kilometers) per hour. It had top sustained winds of 120 miles (195 kilometers) per hour, with higher gusts.


October 7, 2016
Pennsylvania
Maryland
Delaware
West Virginia
Virginia
North Carolina
South Carolina
Georgia
Florida
N
200 km

Lights Out After Matthew—Southeast United States

After grazing Florida and Georgia, Hurricane Matthew plowed into South Carolina, southeast of McClellanville, as a Category 1 storm. Strong winds, falling trees, and storm surge flooding knocked out power in coastal areas of all three states. From space, the outages were clearly visible—and especially at night. The VIIRS DNB on the Suomi NPP satellite captured these three nighttime images of the Atlantic coast. The image on the top left was acquired at 3:14 a.m. Eastern Daylight Time on October 6, 2016; the top middle image shows the same area at 3:14 a.m. on October 7; the top right image was acquired at 2:14 a.m. on October 8. Infrared observations collected by the GOES East satellite were layered on the VIIRS data to make the clouds associated with Matthew more visible. Notice how many cities and towns on the eastern coast of Florida lost power on October 7. In particular, Flagler County, Florida, and Calhoun County, South Carolina, suffered many outages. The map (bottom, right) is based on data from power companies on October 8, 2016.

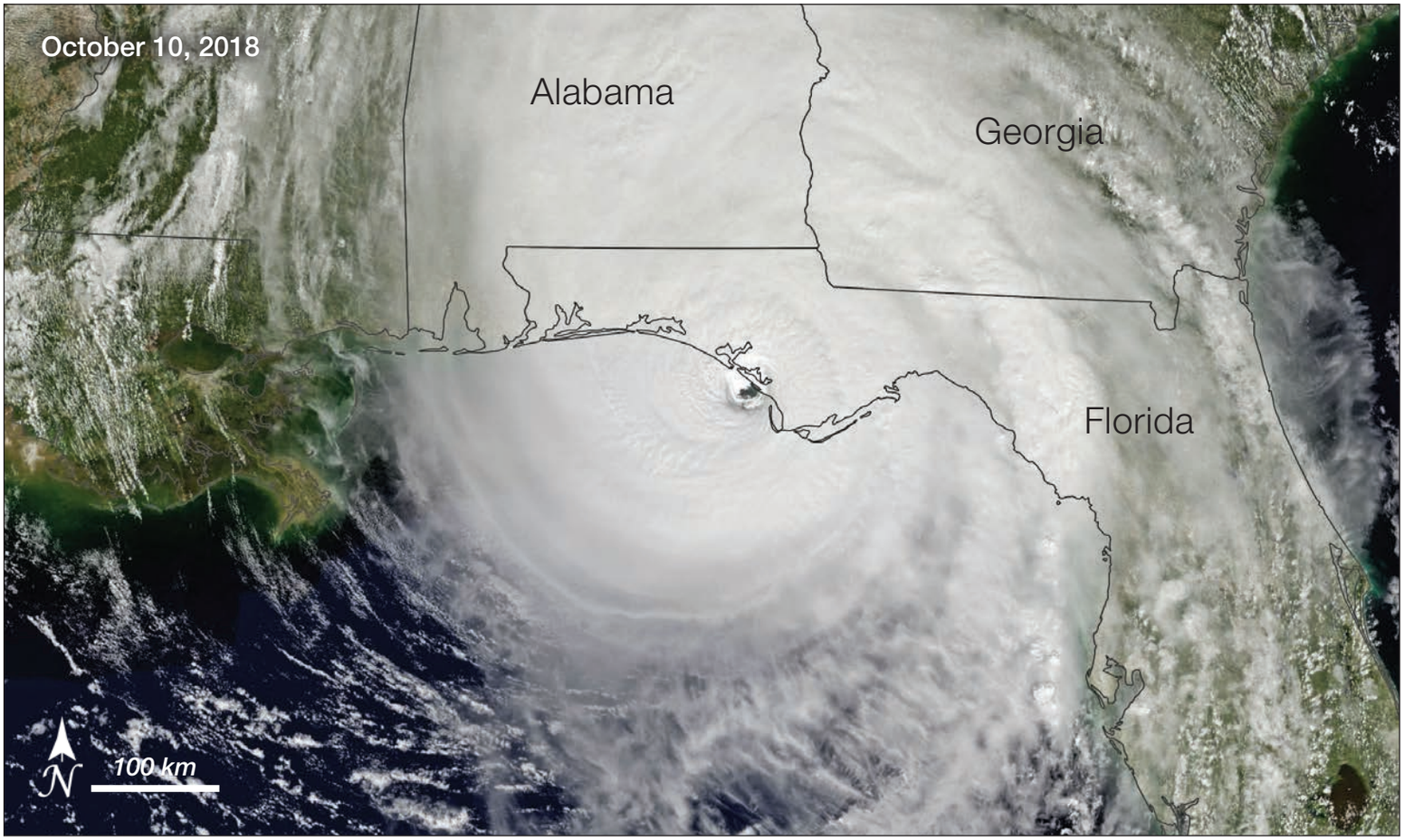

October 6, 2016
October 7, 2016
October 8, 2016
N
350 km


Calhoun County, SC
Out of power: 98%
Charleston County, SC
Out of power: 26%
Hurricane Matthew
8:00 a.m. EDT, October 8
Flagler County, FL
Out of power: 88%
Customers Without Power (as reported 9:30 a.m. EDT, October 8)
20% 40% 60% 80%

Hurricane Michael

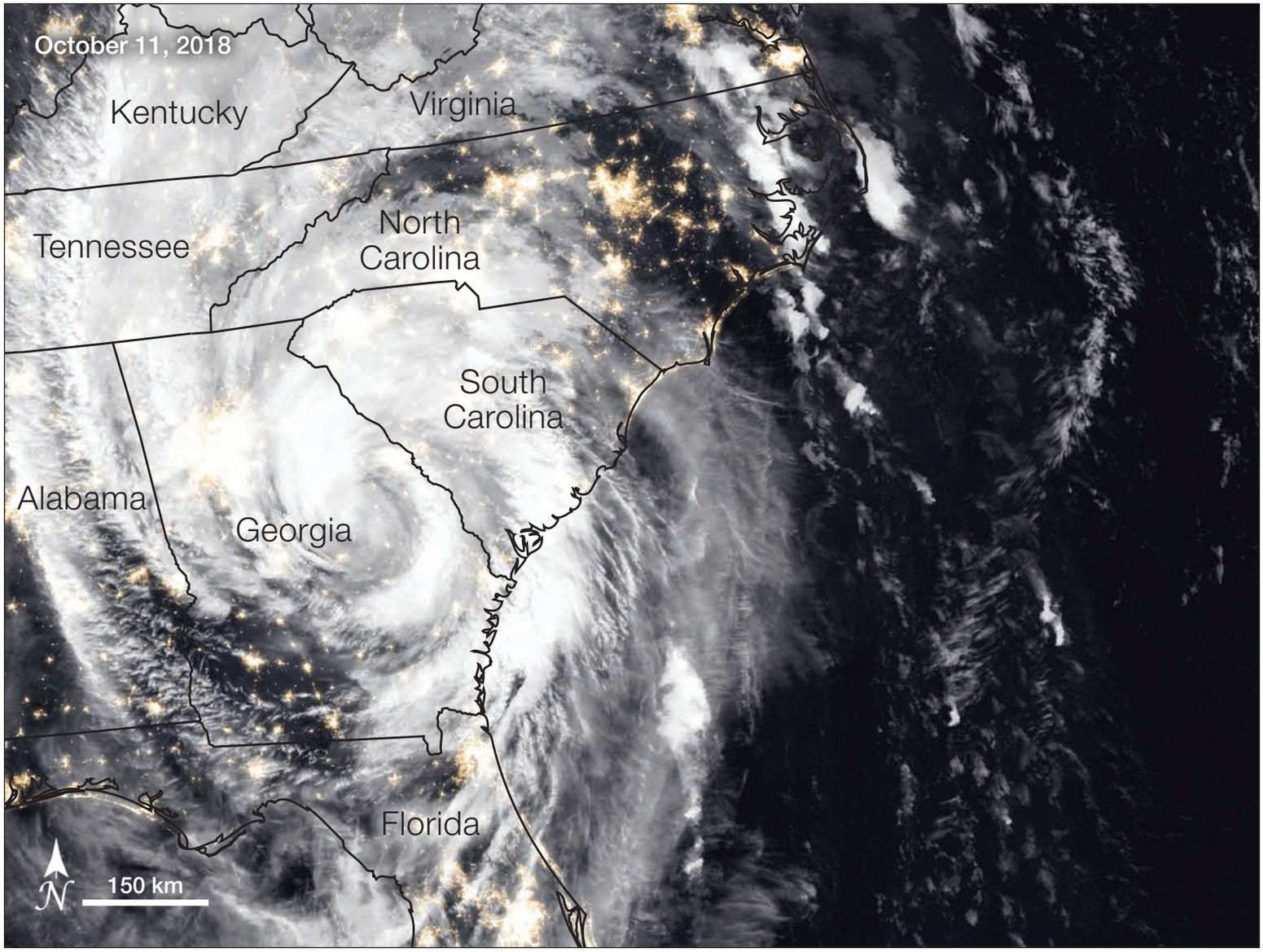
Florida Slammed by Hurricane Michael—Florida Panhandle

At approximately 1:30 p.m. Eastern Daylight Time on October 10, 2018, Hurricane Michael made landfall near Mexico Beach, Florida. Wind speeds were estimated to be 155 miles (250 kilometers) per hour, which made the Category 4 hurricane the strongest on record to hit the Florida Panhandle. In April 2019 the National Hurricane Center announced that it had reclassified Michael as a Category 5 storm with 160-mile (257-kilometer)-per-hour winds. The storm destroyed homes and knocked out electric power in the area. The Geostationary Operational Environmental Satellite 16 (GOES–16) acquired data for the composite image below around 1:00 p.m. Eastern Daylight Time on October 10. GOES–16 data were overlaid on a MODIS Blue Marble image of Earth.



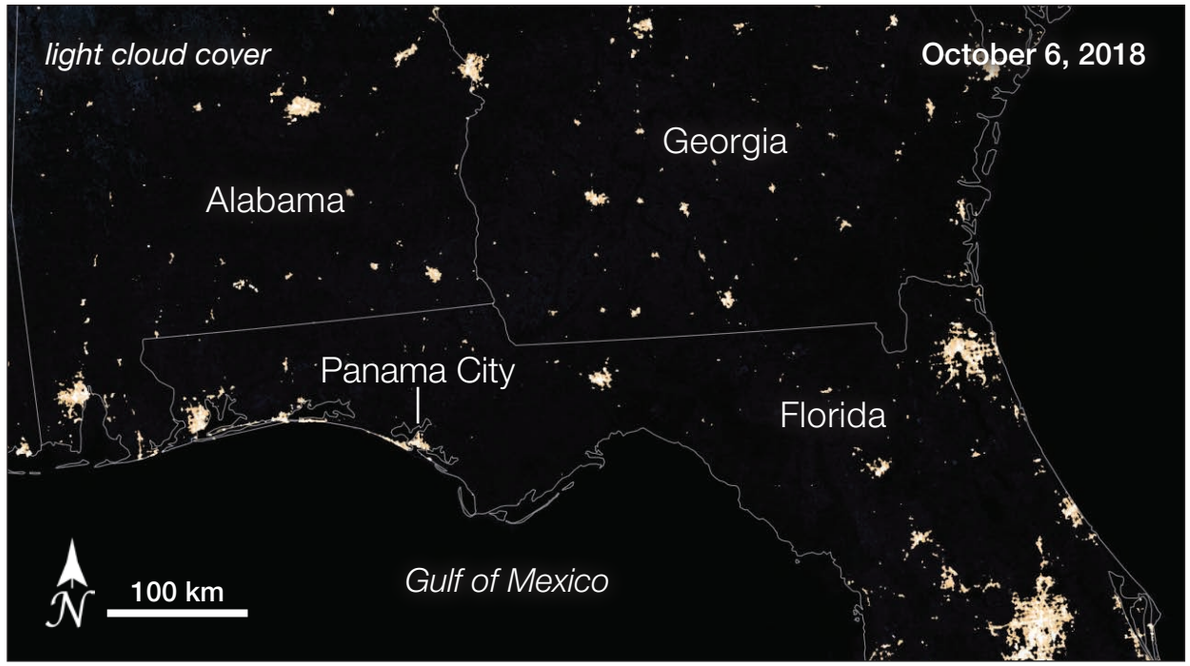
Michael Churns at Night—Florida Panhandle

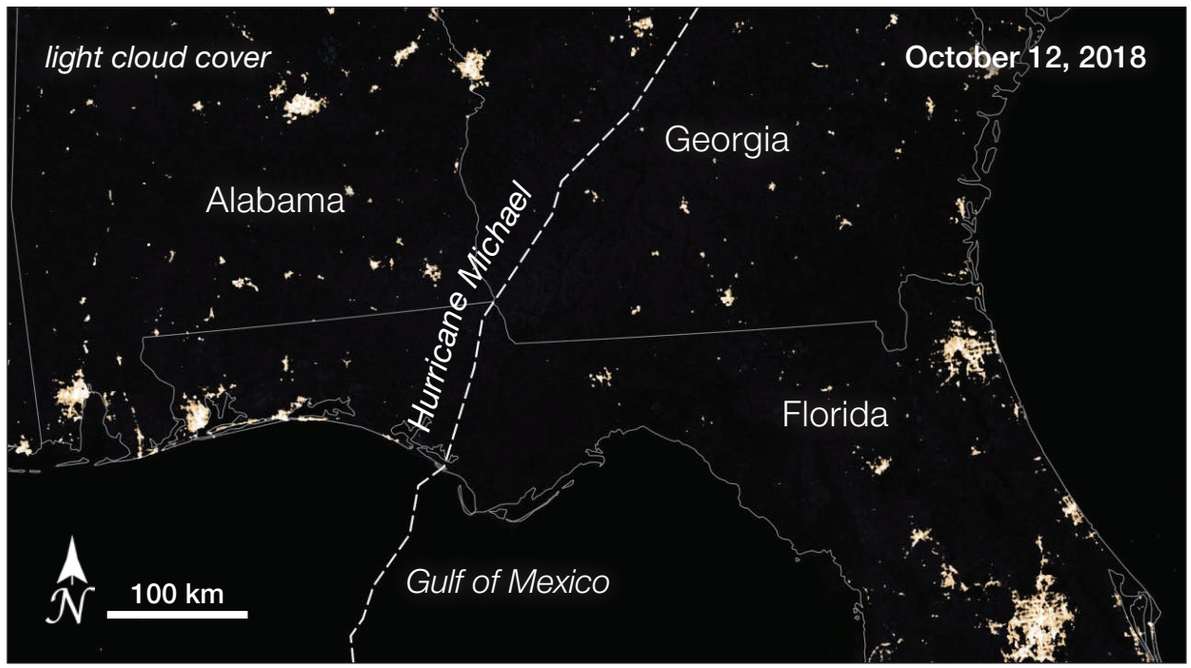
Hurricane Michael weakened throughout October 10 and was downgraded to a tropical storm by October 11. The VIIRS DNB on the Suomi NPP satellite acquired data for the composite image below in the early morning hours of October 11, as the storm passed over Georgia and South Carolina. The false-color image shows infrared signals from VIIRS known as brightness temperature, which helps distinguish the shape and temperature of the clouds. The image was overlaid on data from the VIIRS DNB.



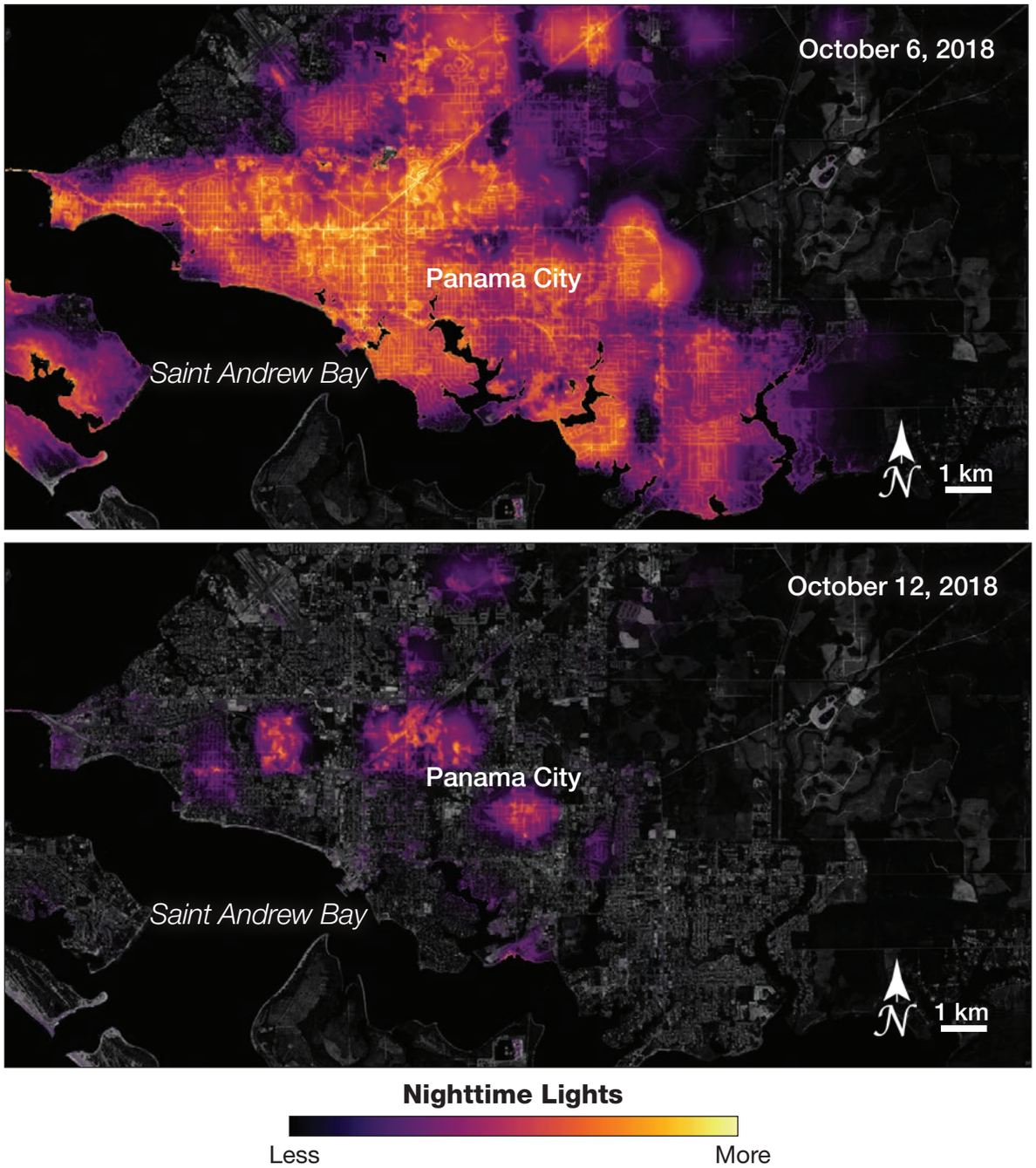
Lights Out in Michael's Wake—Florida Panhandle

After making landfall as a Category 5 storm on October 10, 2018, Hurricane Michael knocked out power for at least 2.5 million customers in the southeastern United States, according to the Edison Electric Institute. These images of nighttime lights in Florida, Georgia, and Alabama come from the Suomi NPP satellite and were acquired on October 6 and October 12, 2018. The first set of images (below) shows a natural view





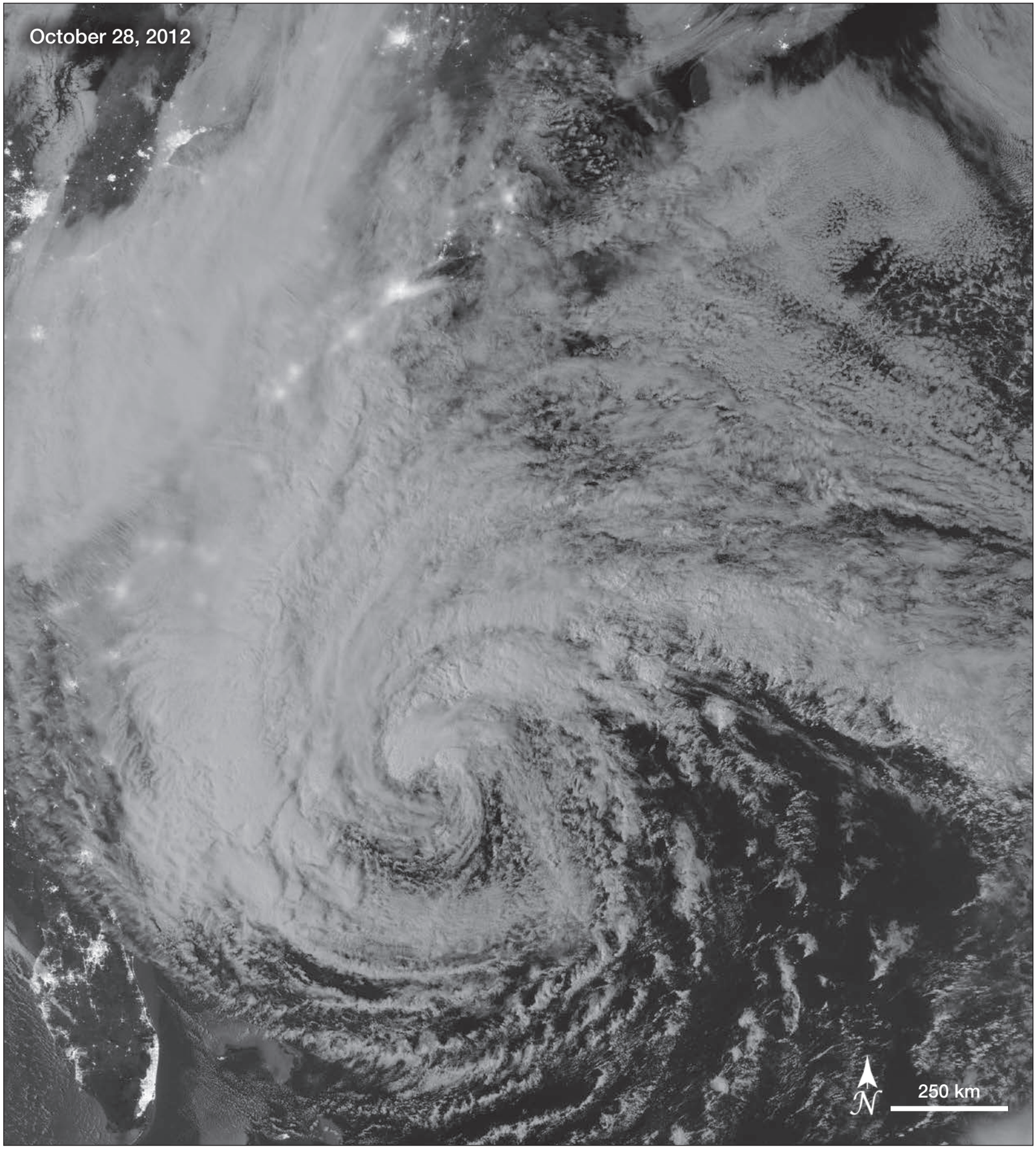
of nightlights from the VIIRS DNB. The second pair of images is a data visualization of where lights went out in Panama City, Florida. A team of scientists from NASA processed and corrected the raw data to filter out stray light from the Moon, fires, airglow, and any other sources that are not electric lights. Their processing techniques also removed other atmospheric interference, such as dust, haze, and thin clouds.



Hurricane Sandy

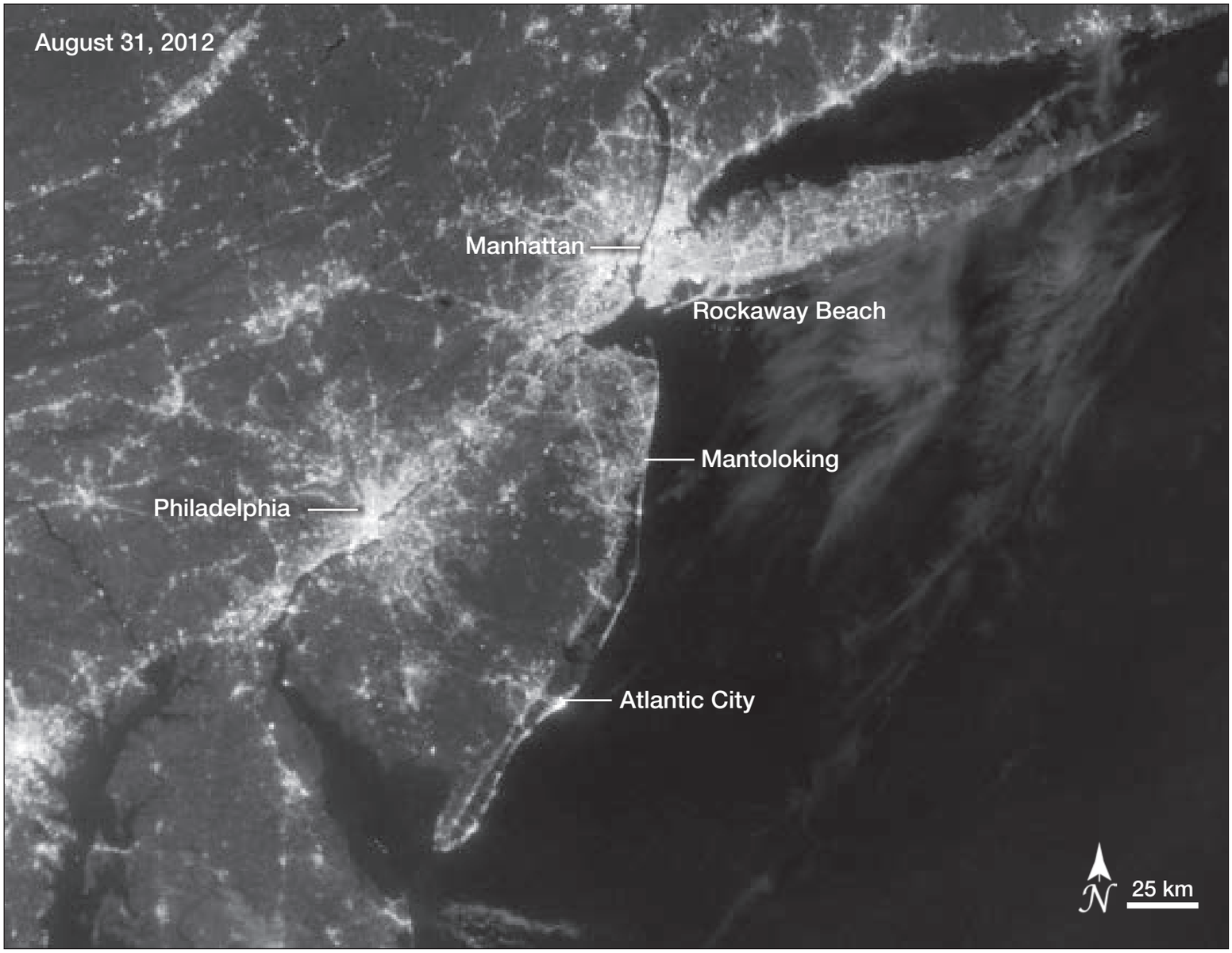
Overnight View of Hurricane Sandy—Eastern United States

This image of Hurricane Sandy was acquired by the VIIRS DNB on the Suomi NPP satellite at 2:42 a.m. Eastern Daylight Time on October 28, 2012. Cloud tops were lit by the nearly full Moon (full occurred on October 29). Some city lights in Florida and Georgia are visible through the clouds. At the time of the image, the United States National Hurricane Center estimated Sandy's location to be 31.5° North and 73.7° West, 275 miles (443 kilometers) south-southeast of Cape Hatteras, North Carolina, and moving northeast at 14 miles (22 kilometers) per hour. Maximum sustained winds were 75 miles (120 kilometers) per hour, and the minimum central barometric pressure was 960 millibars (28.35 inches).

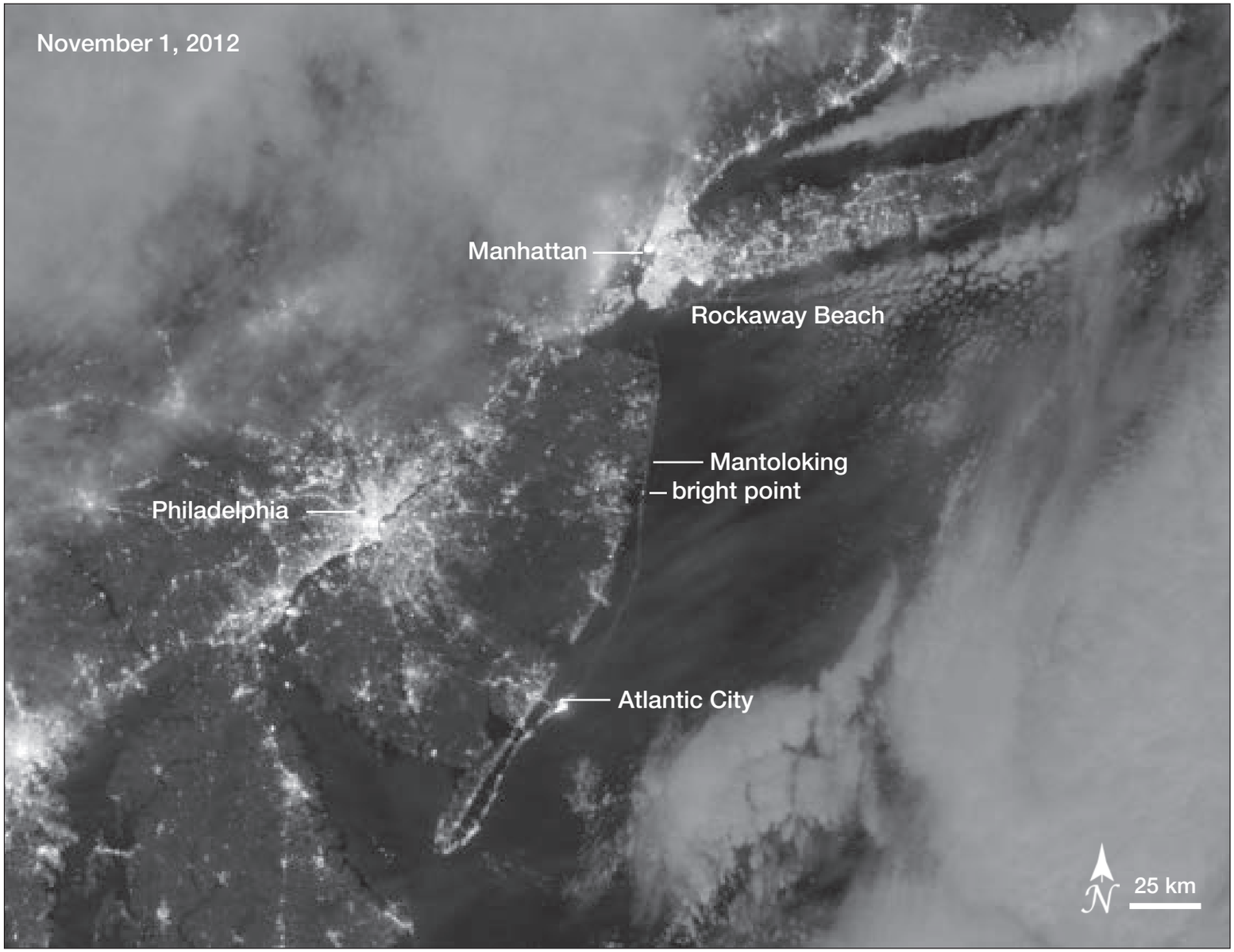

October 28, 2012
N
250 km

Blackout—New Jersey and New York

This pair of images shows New Jersey, New York, and eastern Pennsylvania as viewed at night by the VIIRS DNB on the Suomi NPP satellite. The "before" image (below) was taken at 2:14 a.m. Eastern Daylight Time on August 31, 2012, when conditions in the area were normal. The "after" image (right) was taken at 2:52 a.m. Eastern Daylight Time on November 1, 2012, after Hurricane Sandy had moved through. In the "after" image, lingering clouds from Sandy are lit by moonlight and obscure much of New York's Hudson Valley, northwestern New Jersey, and northeastern



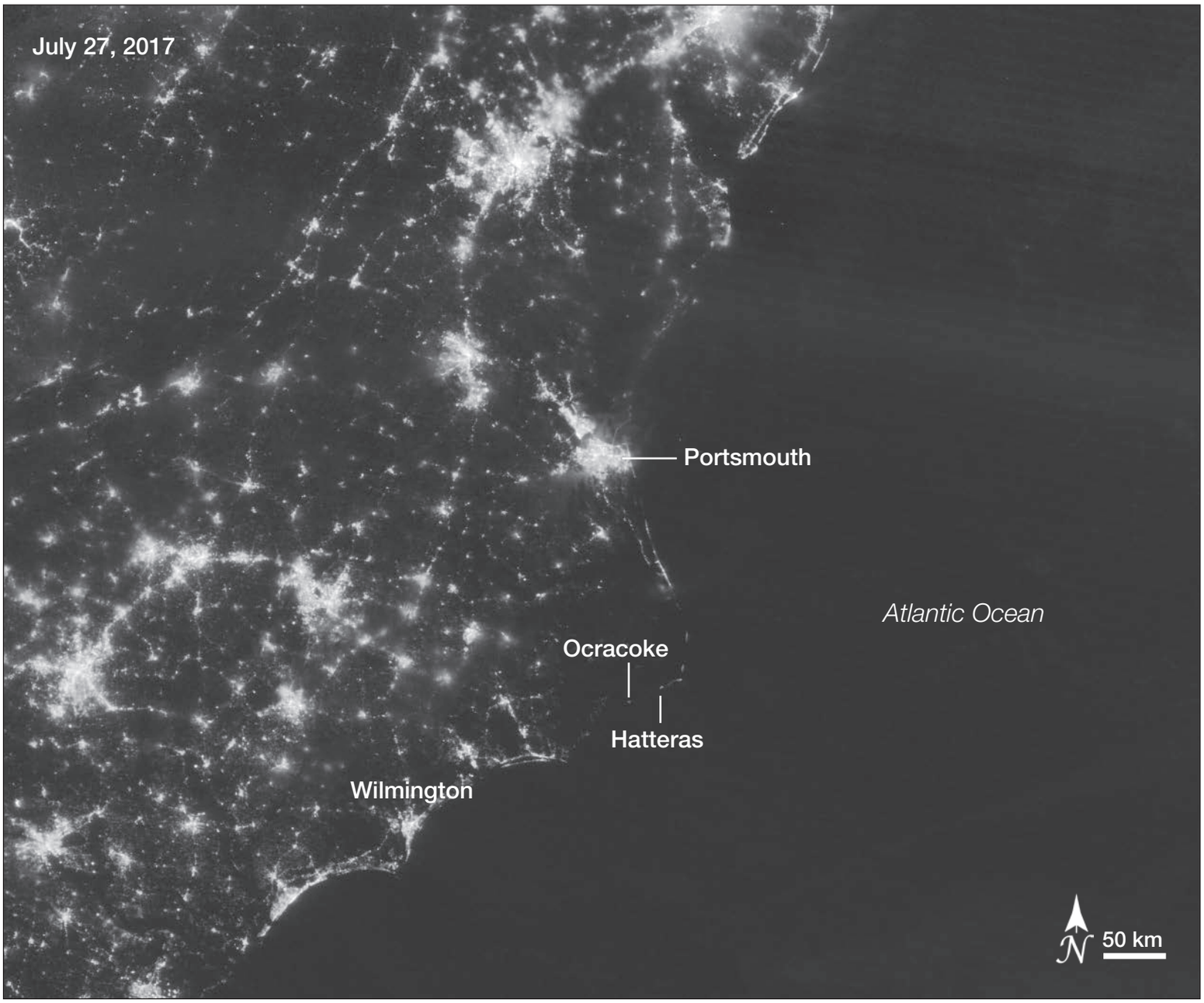
Pennsylvania. In Manhattan, the lower third of the island is dark on November 1, while Rockaway Beach, much of Long Island, and nearly all of central New Jersey are significantly dimmer. The barrier islands along the New Jersey coast, which are heavily developed with tourist businesses and year-round residents, are just barely visible in moonlight after the blackout. Along with the scattered electric lights, there is a bright point along the shore south of Mantoloking, New Jersey, that could be fires fueled by severed natural gas lines.



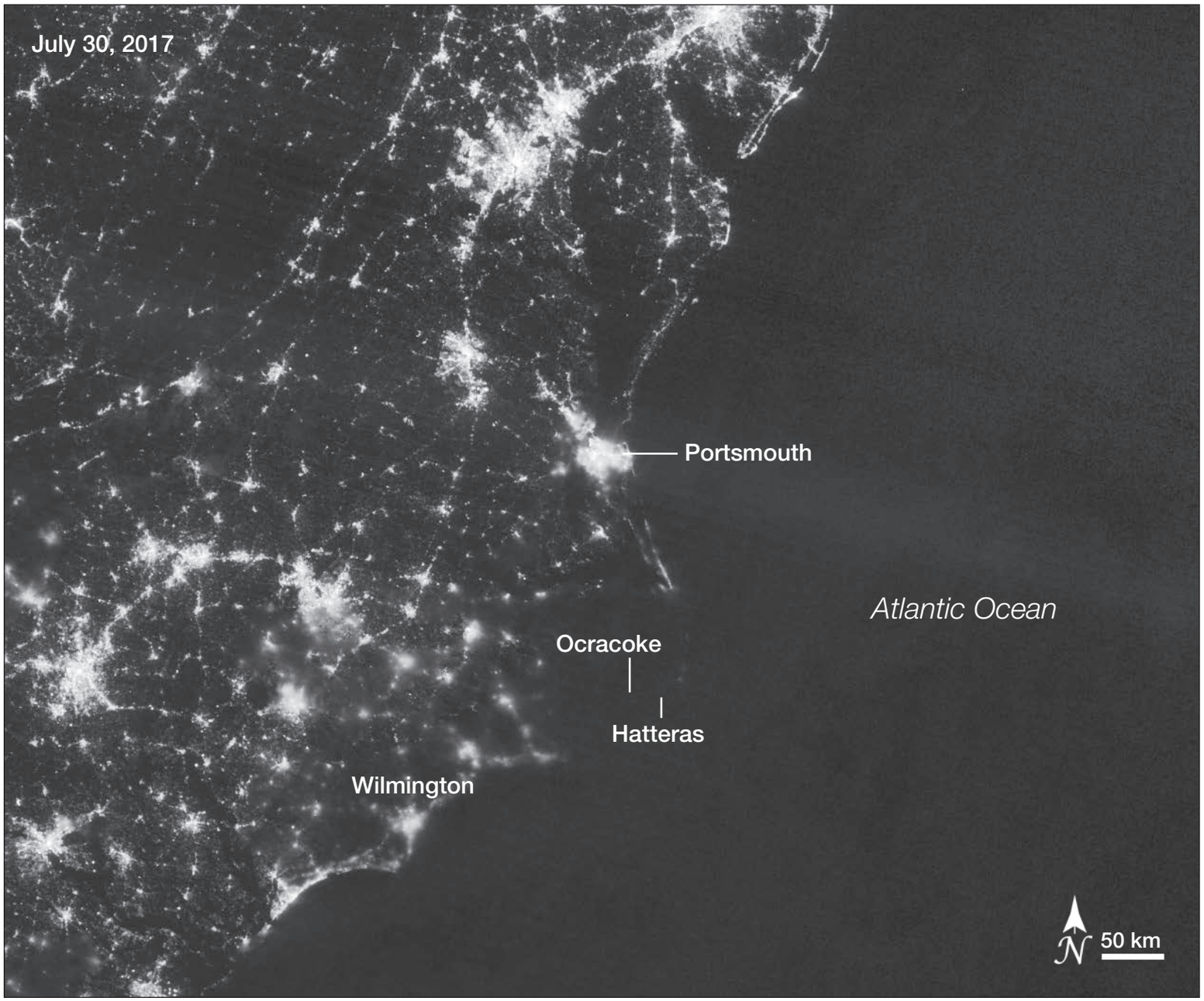
Other Power Outages

Lights Out in Hatteras—North Carolina

If a power outage spans a large area, there is the chance it can be seen from space. The outage pictured here shows the darkness that fell across parts of North Carolina's Outer Banks in late July 2017. The VIIRS DNB on the Suomi NPP satellite captured nighttime images of Hatteras and Ocracoke islands. They show the barrier

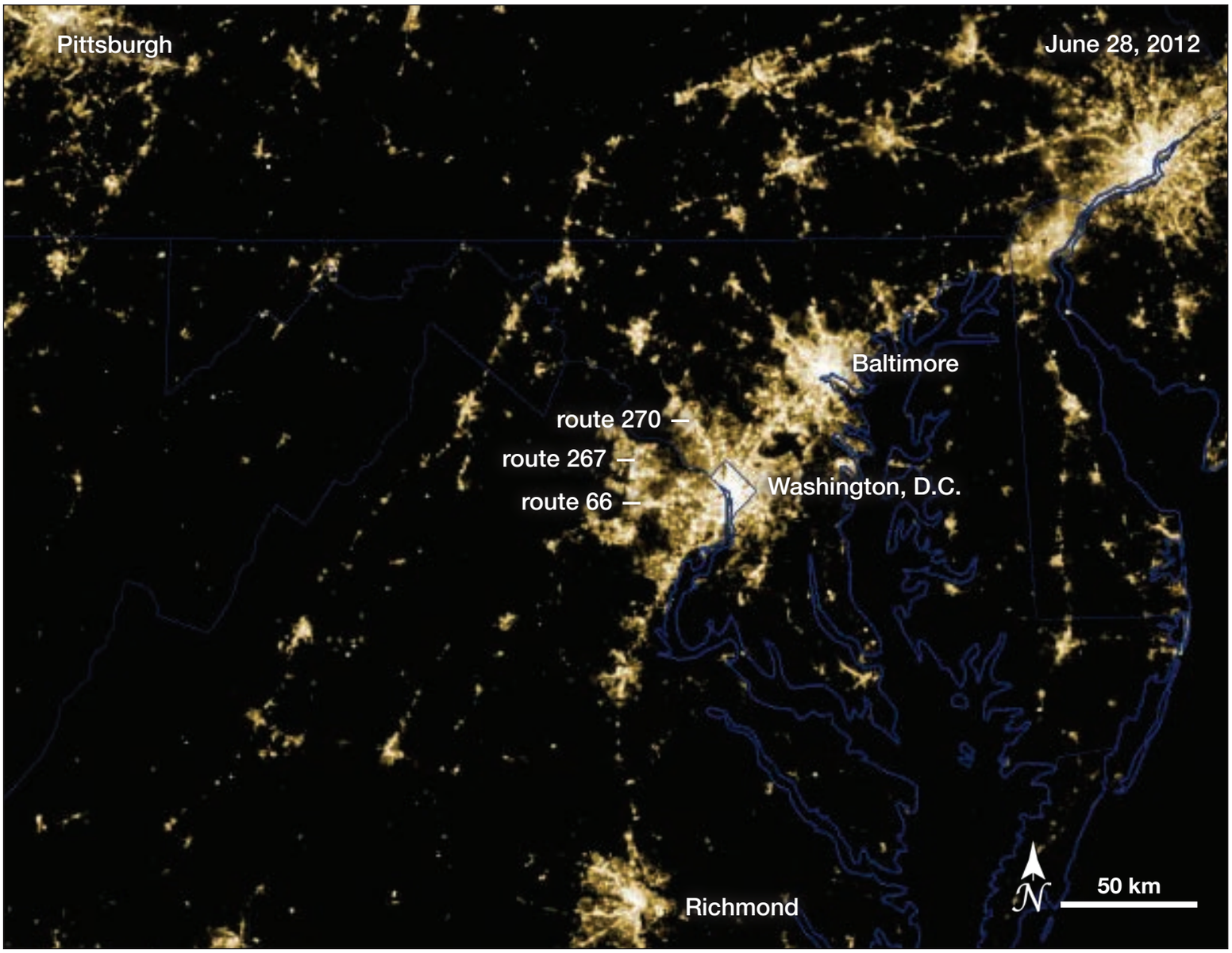


islands on July 27 (before the blackout) and on July 30, 2017. Storms are a common culprit for power outages, but the power outage pictured here had a more unusual cause—a construction accident that compromised buried transmission cables.

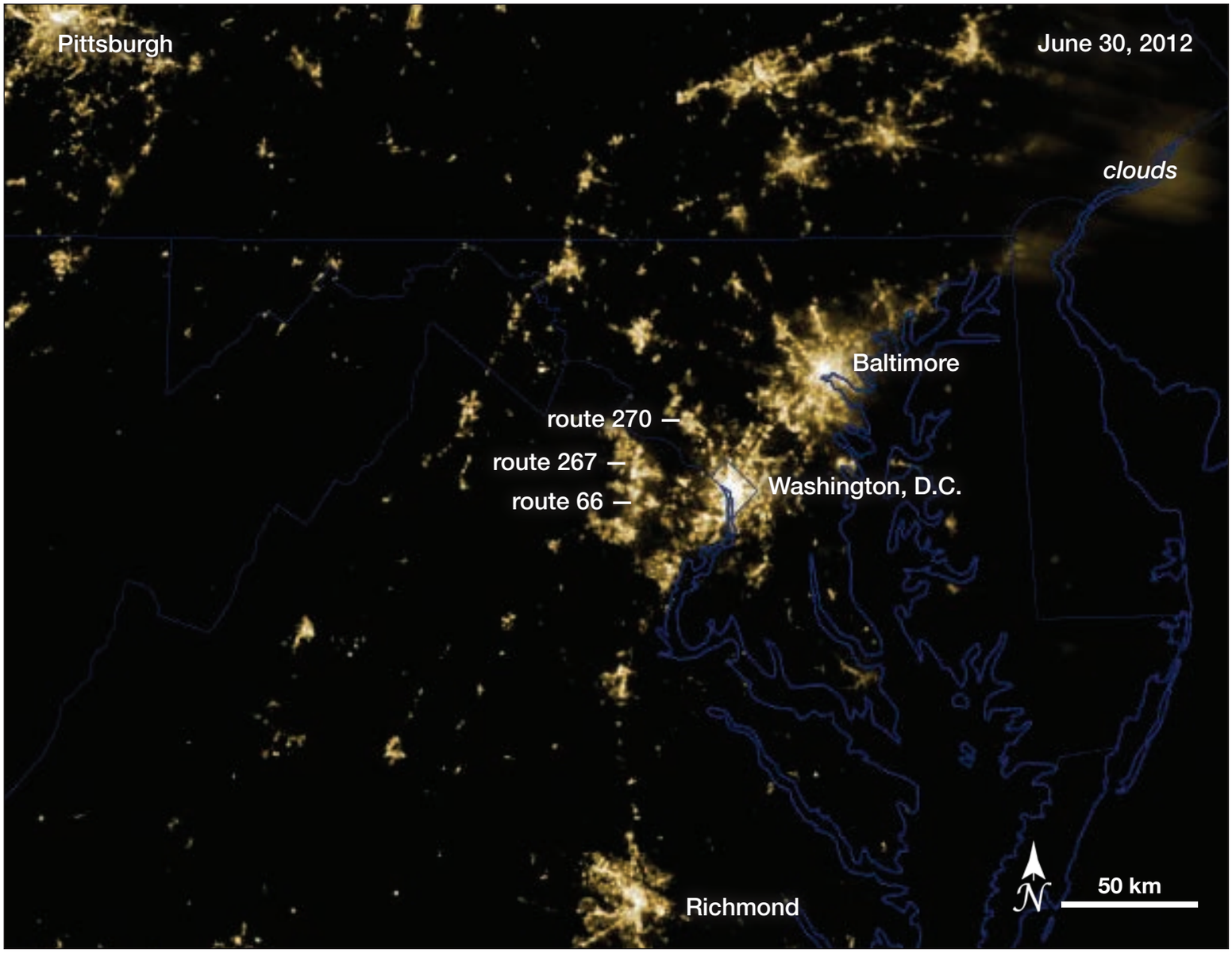


Rare Derecho Causes Power Outages—Washington, D.C.

These before-and-after images from the Suomi NPP VIIRS DNB show the severe impact that a rare, fast-moving thunderstorm system had on the Baltimore, Maryland–Washington, D.C. metropolitan area on June 29, 2012. The storm raced hundreds of miles from west of Chicago across Illinois, Indiana, Ohio, West Virginia, Virginia, Maryland, and Washington, D.C.; it combined intense lightning and rain with hurricane-force winds with speeds that were upwards of 60 miles (96 kilometers) per hour. It killed 22 people and caused some 4.3 million households to lose power for days. A

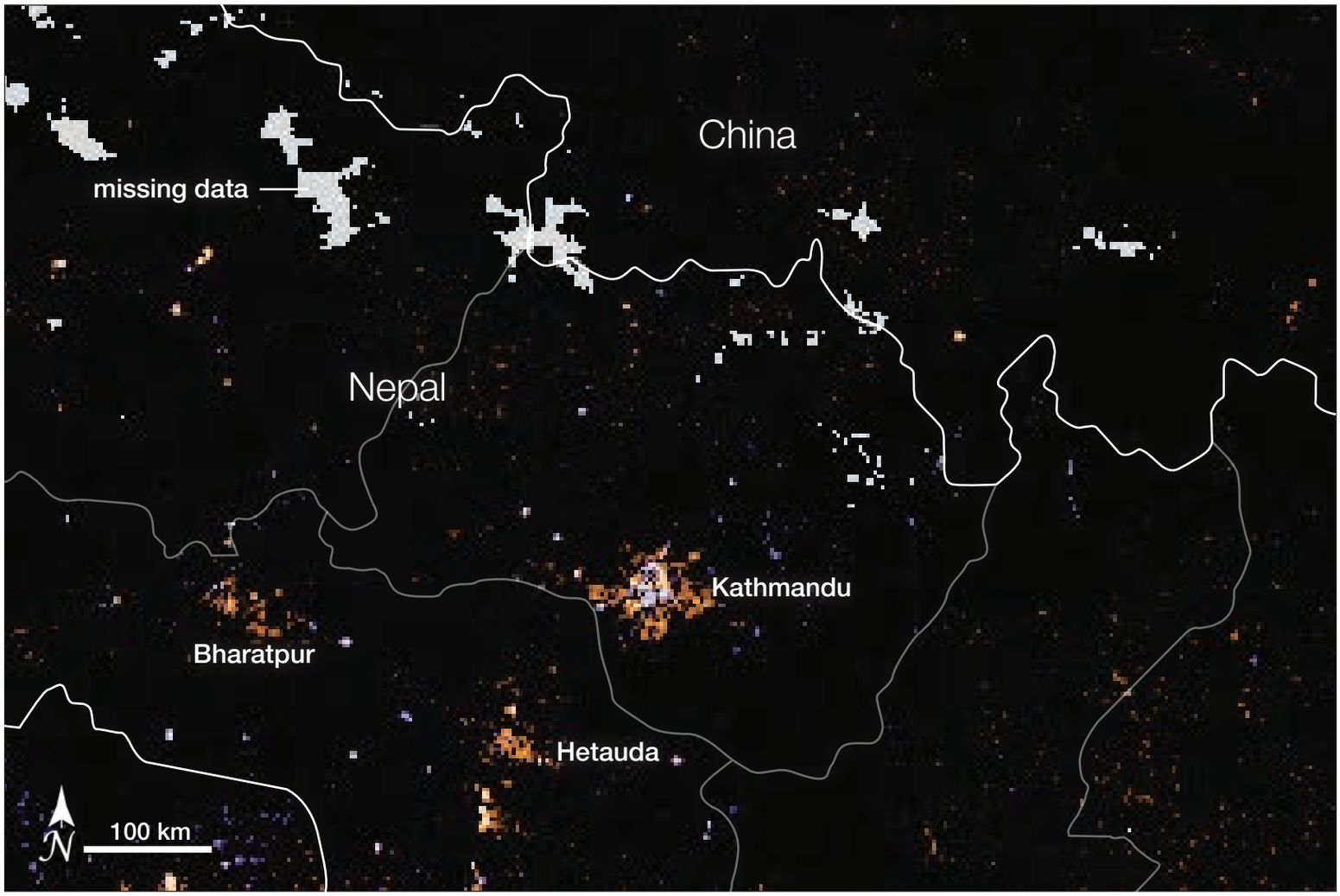


quick comparison between the June 28 and June 30 images reveals extensive power outages around Washington, D.C. and Baltimore. Clouds obscure the lights of Philadelphia and other areas north and east of Baltimore. Of particular interest is the loss of light to the north and west of Washington, D.C., along interstate highway Routes 270 and 66 and Maryland Route 267. Known as a "derecho," which is the Spanish word for "straight," the forceful winds can be as powerful as tornados, but the winds don't twist, instead driving in a straight line over long distances; hence the name.



Earthquake Aftermath—Nepal

Even before a powerful magnitude 7.8 earthquake jolted Nepal on April 25, 2015, continuous access to electricity was not something the Nepalese could take for granted. The country's rugged topography prevents Nepal's main electricity provider—the state-owned Nepal Electricity Authority—from providing service to many rural areas. And even in towns and cities where service is available, chronic power shortages mean the 30 million people of Nepal often face lengthy outages. In the aftermath of the earthquake, however, access to reliable electricity diminished even further. As shown by this map, made using VIIRS DNB data from the Suomi NPP satellite, both urban and rural areas face widespread outages after the earthquake. It compares the pre-earthquake period, using data from clear days between March 21–30, 2015, and the post-earthquake period, which includes observations from April 19–28, 2015. Combining data from several days makes the observations more meaningful and less prone to error. The map shows how the amount of light emitted by towns and cities in Nepal changed before and after the earthquake. Areas with less light output after the earthquake are shown in shades of orange; areas with the same output are black; areas with more light are purple. The satellite detected widespread power losses after the earthquake. The cities of Kathmandu, Bharatpur, and Hetauda were particularly hard hit. In rural areas, each pixel in the map appears to correspond with a different town or village.



Lighting Change

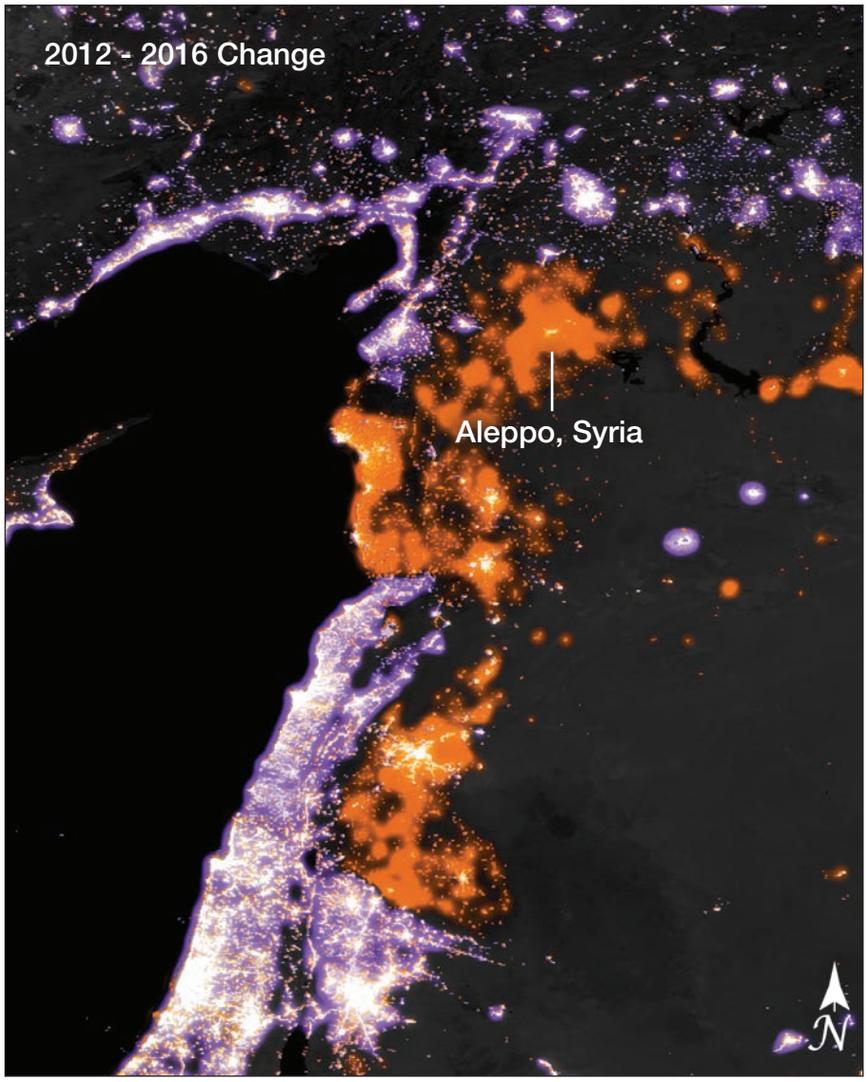
Less Same More

Effects of War

Conflict in the Middle East—Syria

Six years of war in Syria have had a devastating effect on millions of its people. One of the most catastrophic impacts has been on the country's electricity network. The left and middle images (below) were created using two separate nightlight datasets from the VIIRS DNB on the Suomi NPP satellite for 2012 and 2016, respectively. The image on the far right (below) shows the change in lighting intensity when the 2012

and 2016 images are combined. Orange shades indicate areas where lights have gone out over the years, leaving people to survive with little or no power. Syria was once one of the eastern Mediterranean's major power suppliers. It has 15 power stations, including 3 major hydroelectric dams. To view global changes in lighting intensity from 2012 to 2016, see page 26 of this volume.

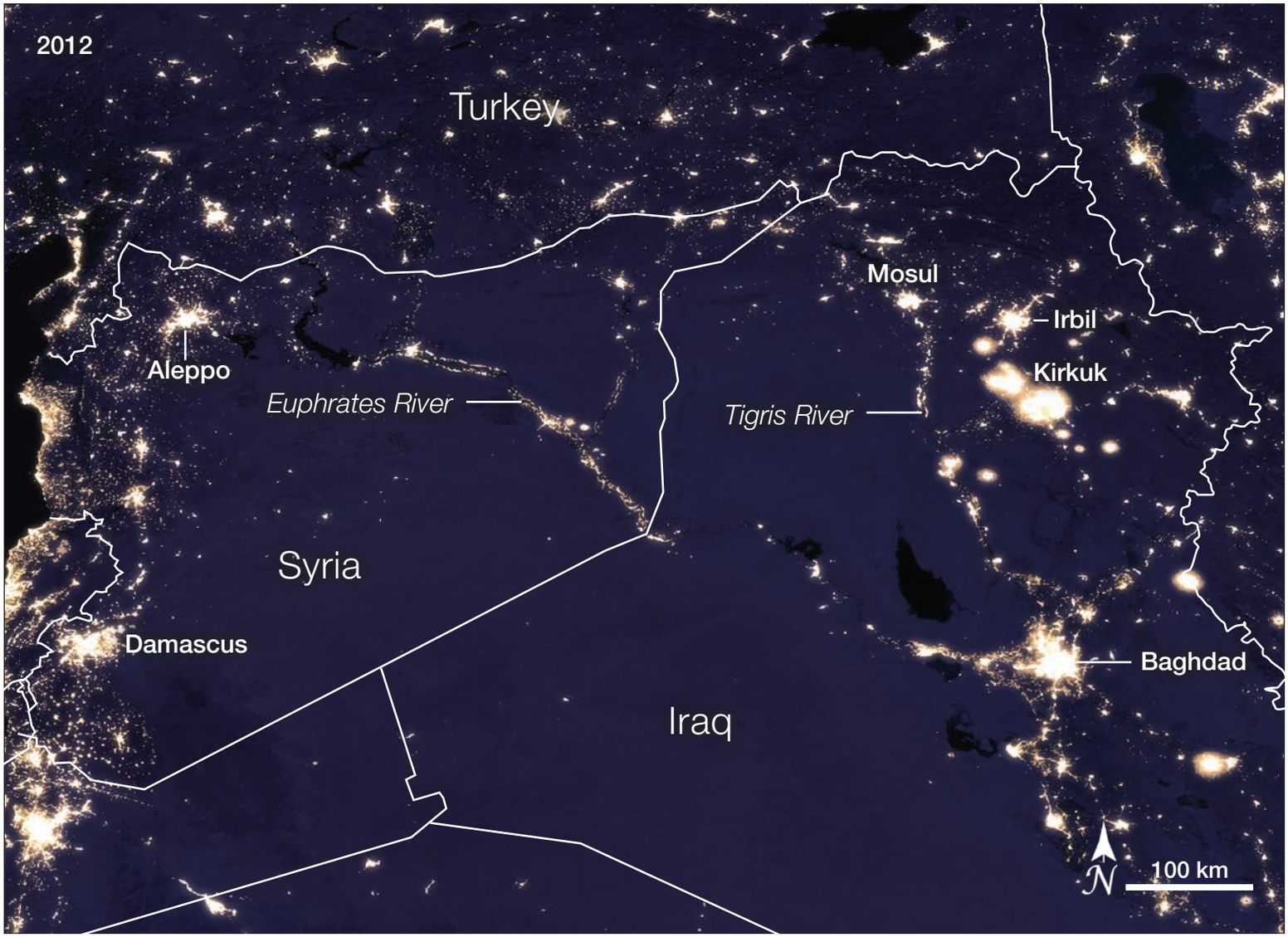


Change in Nightlights (2012-2016)

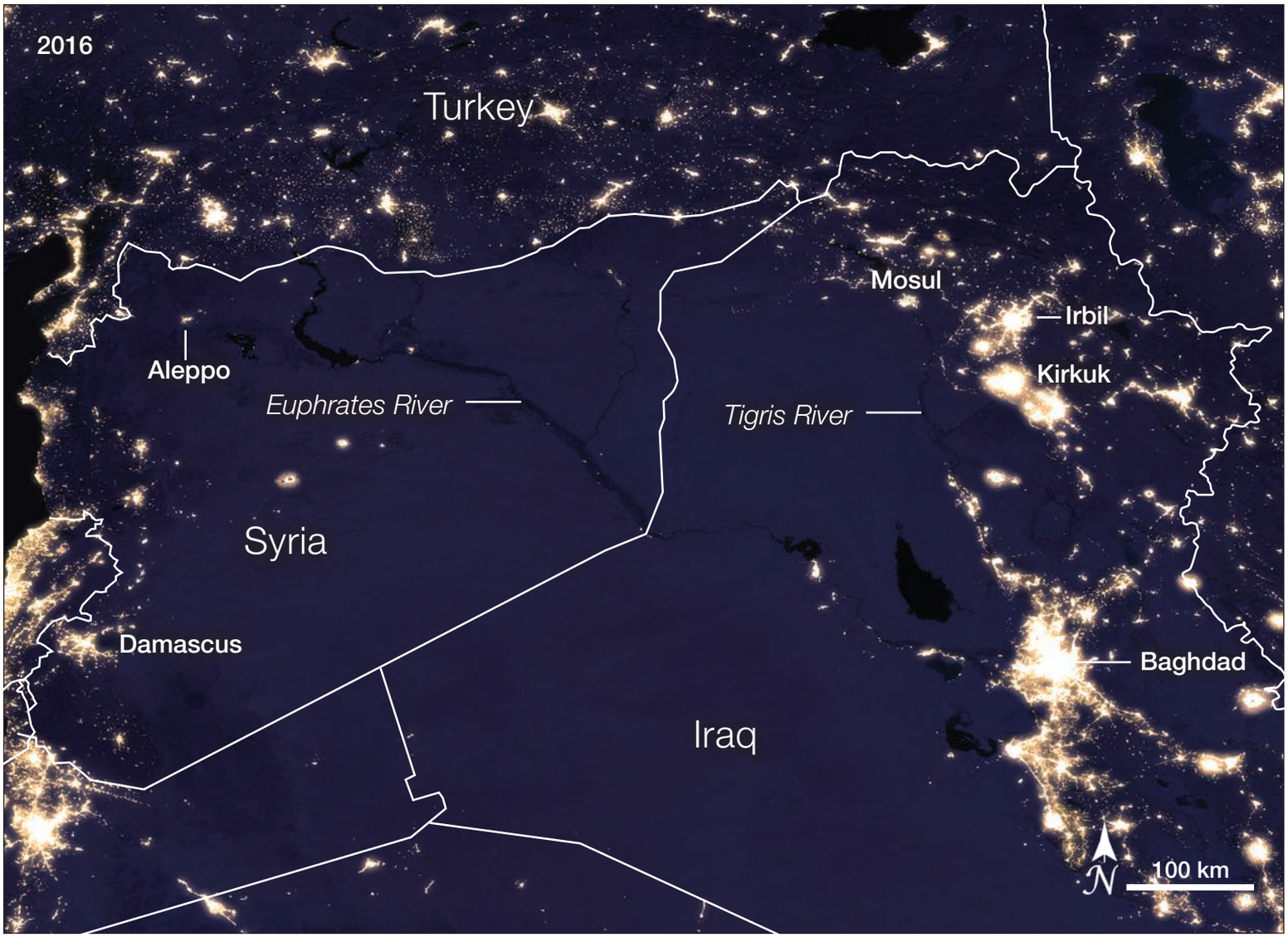
lights out — no change — new lights

Nightlights Change in the Middle East—Syria and Iraq

The images below show differences in nighttime lighting between 2012 (below) and 2016 (right) in Syria and Iraq, among several Middle Eastern countries. Each image is drawn from a global composite that was made by selecting the best cloud-free nights in each month over each land mass. The data come from the VIIRS DNB on the Suomi NPP satellite. The changes are most dramatic around Aleppo, but also extend through western Syria to Damascus. Over the four years shown, lighting increased in areas north of the Syrian border in Turkey and to the west in Lebanon. In Iraq, some northern sections near Mosul saw a decrease in light over the years, while areas



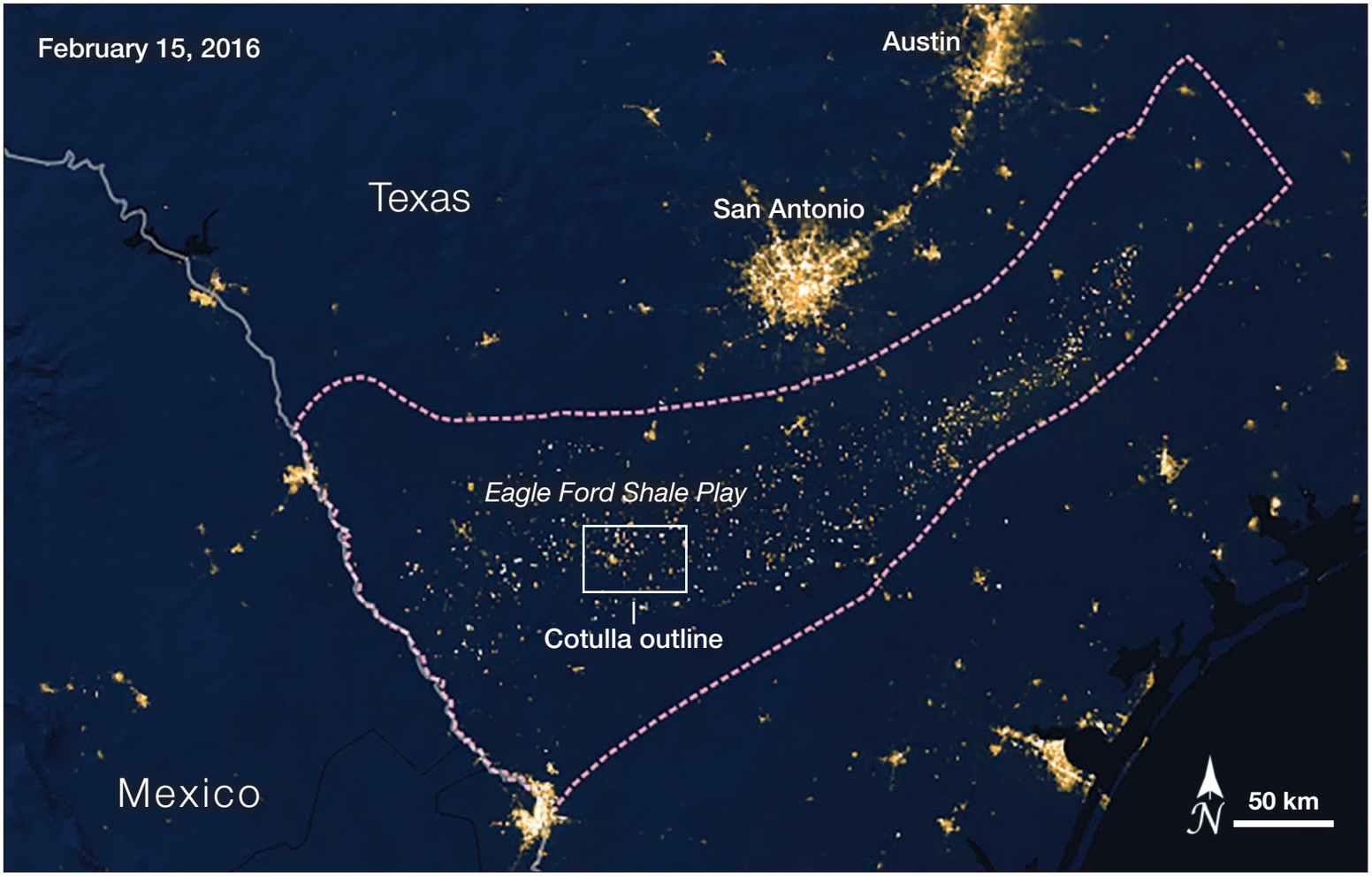
around Baghdad, Irbil, and Kirkuk saw increases. Note, too, the change in electric light patterns along the Tigris and Euphrates river basins. International agencies such as the United Nations Institute for Training and Research Operational Satellite Applications Programme (UNITAR-UNOSAT) have used such imagery in the past few years to support United Nations operations and activities in the areas of disaster response, humanitarian support, human security, and human rights. Nighttime imagery helps relief and peacekeeping groups identify areas that are most in need of aid and support.



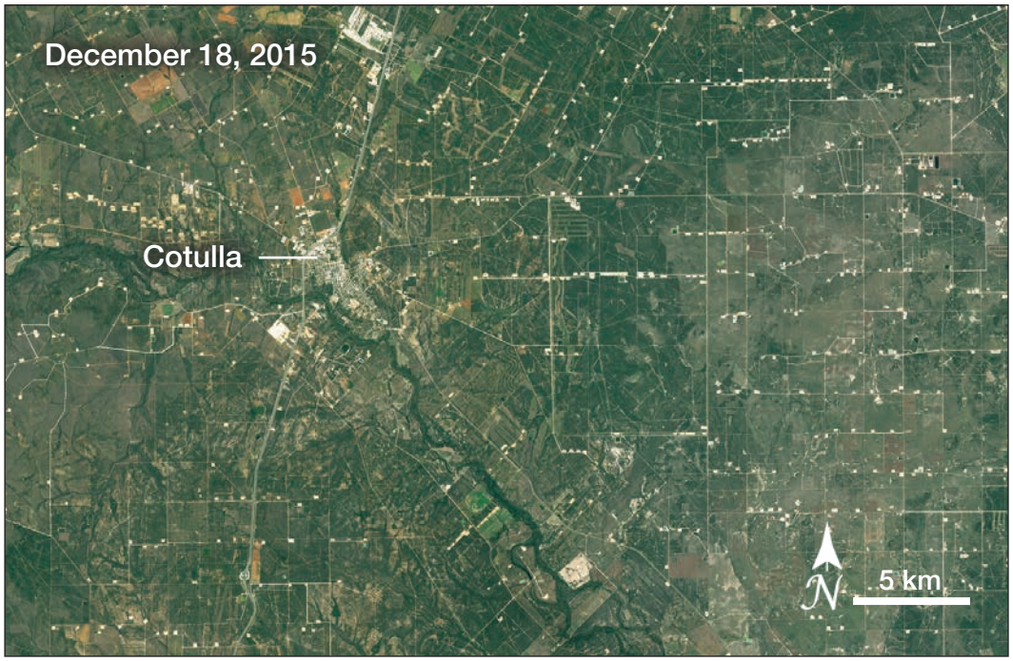
Mining

Shale Revolution: As Clear as Night and Day—South Texas

"Play" is a term used by petroleum geologists to describe a geological formation that has been targeted for exploration because it likely contains oil or gas. In nighttime satellite imagery, the light from the Eagle Ford Shale Play competes with the nearby cities of San Antonio and Austin, Texas. The electric glow of drilling equipment, worker camps, and other gas and oil infrastructure combine with flickering gas flares to create an unmistakable arc of light across southern Texas. On February 15, 2016, the VIIRS DNB on the Suomi NPP satellite captured this nighttime view of Eagle Ford (below). The Eagle Ford Shale, which is about 400 miles (600 kilometers) long and 50 miles (80 kilometers) wide, is a source of both oil and gas. Most of the oil-producing wells are located on the northern part of the play; the gas-producing wells are located along its southern edge. As shown in the two images (right) of Cotulla (outlined



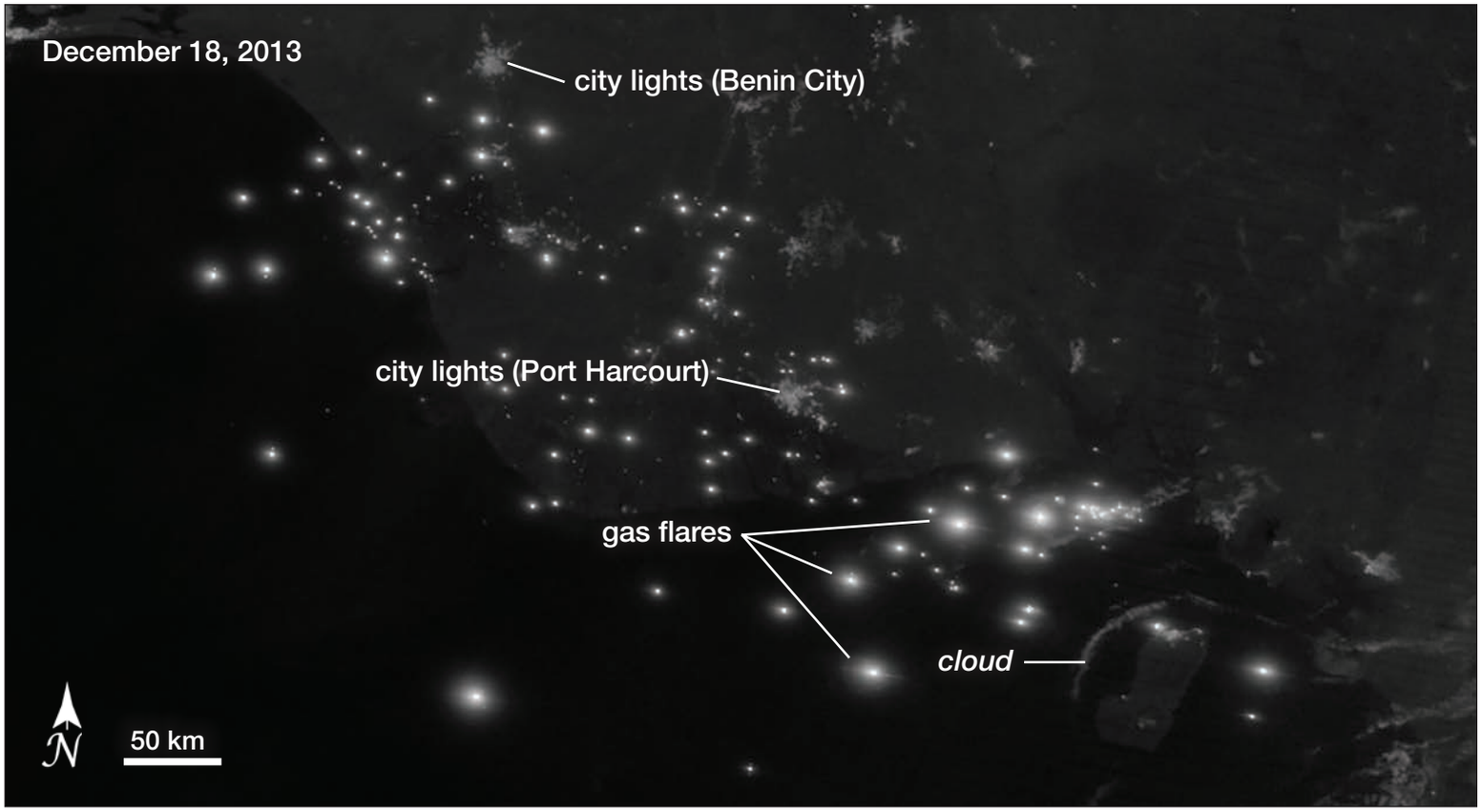
in white in the VIIRS DNB image, left), the view is also stunning during daylight. In the early 2000s, the area east of Cotulla, Texas, was dry, sleepy shrubland. By 2015 a bustling network of roads and rectangular drill pads had completely transformed the landscape. The pair of satellite images shows how much the landscape has changed. Landsat 5 acquired the December 17, 2000, image; Landsat 8 captured the December 18, 2015, image. According to a report from the *Texas Observer*, a nonprofit news organization based in Austin, Cotulla saw its population swell from about 4,000 to 10,000 people in just a few years due to an influx of oil and gas workers.

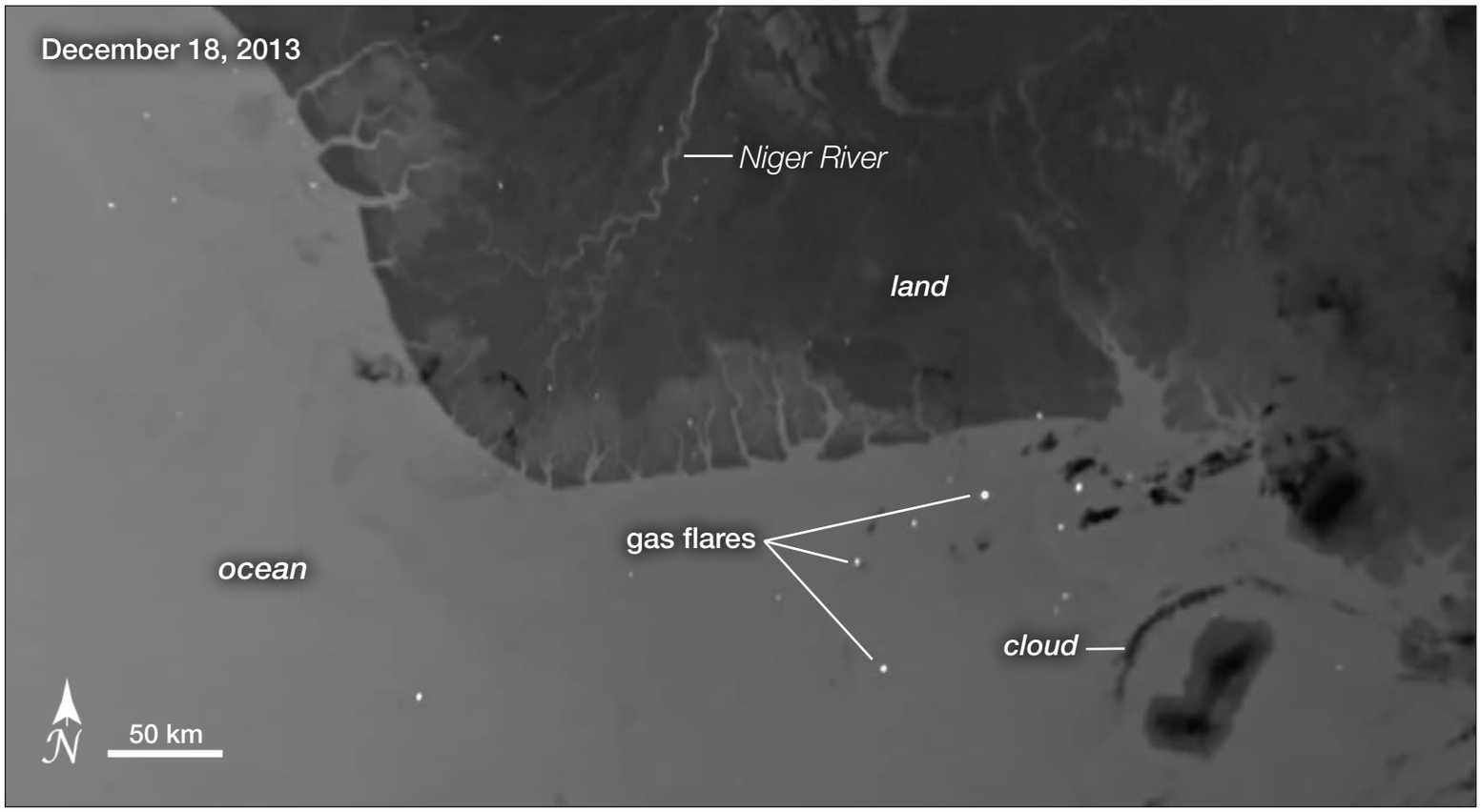


Ten Percent of the World's Gas Flares in One Spot—Nigeria

At night, gas flares—used to remove unwanted natural gas found in crude oil—outshine everything else in the Niger River Delta. In this image of Nigeria taken on December 18, 2013, by the VIIRS DNB on the Suomi NPP satellite (top right), the lights of Port Harcourt and Benin City are dim compared to the flares. The image illustrates two facts from a U.S. Energy Information Administration assessment: Nigeria contains more gas flares than any other country except Russia, and Nigeria has one of the lowest per capita electricity generation rates in the world. About ten percent of the world's gas flares are located in Nigeria, and most of them are concentrated in the Delta region. The flares and oil production occur both on land and offshore. It is hard to see where the land ends and the ocean begins in the nightlights image, which shows the Delta region in visible light as it might appear to the human eye. But viewing the scene in infrared light reveals the distribution of the flares.

The VIIRS image (bottom right) shows the same area on the same night in midwave infrared light, a portion of the electromagnetic spectrum often used to study emitted thermal radiation at night. In this view, warm ocean waters are brighter than the cool land and cold clouds, making it possible to see the boundary between land and water. The flares shine brightly in both views.

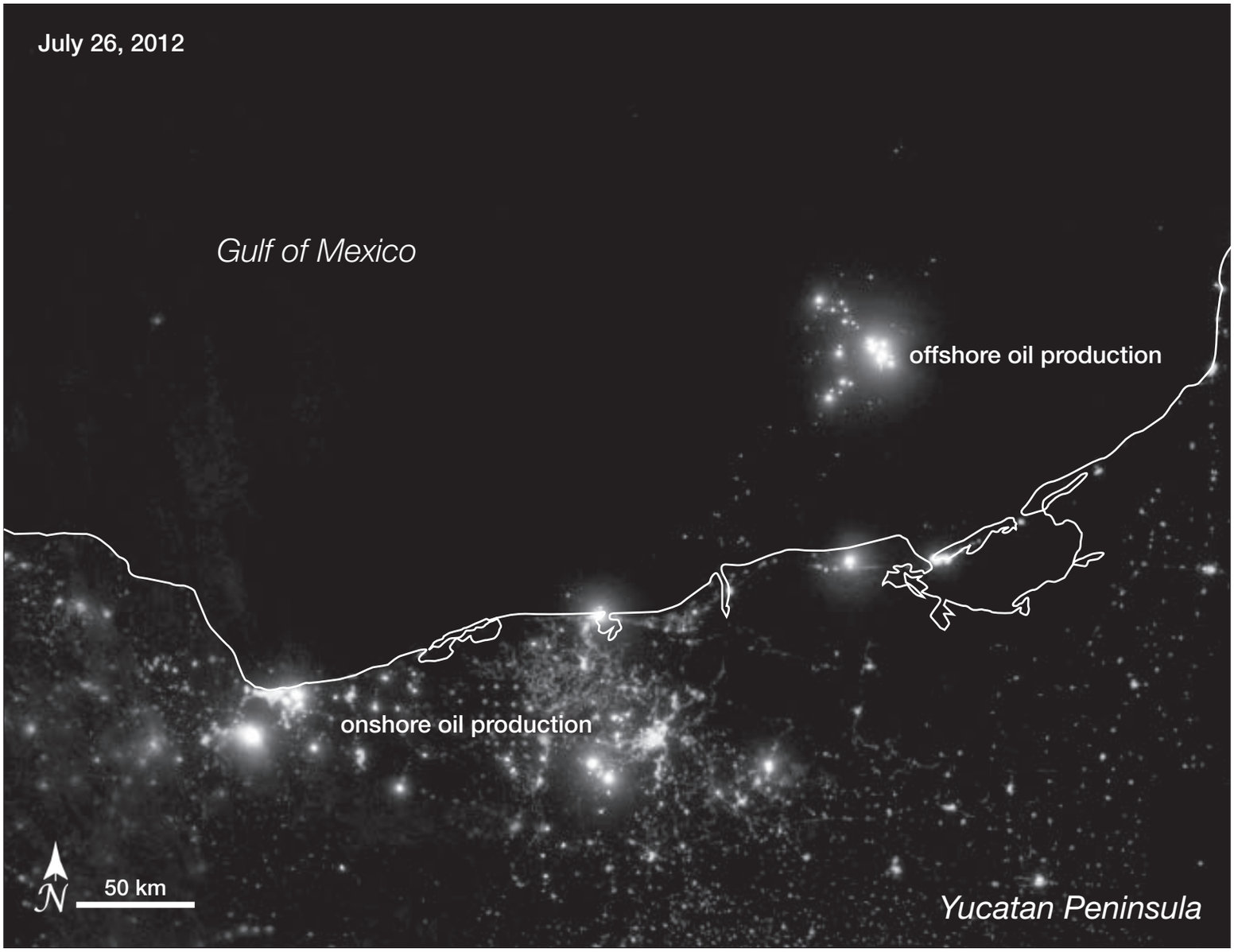

December 18, 2013
city lights (Benin City)
city lights (Port Harcourt)
gas flares
cloud
N
50 km


December 18, 2013
Niger River
land
gas flares
ocean
cloud
N
50 km

Gas Flares in Bahía de Campeche—Gulf of Mexico

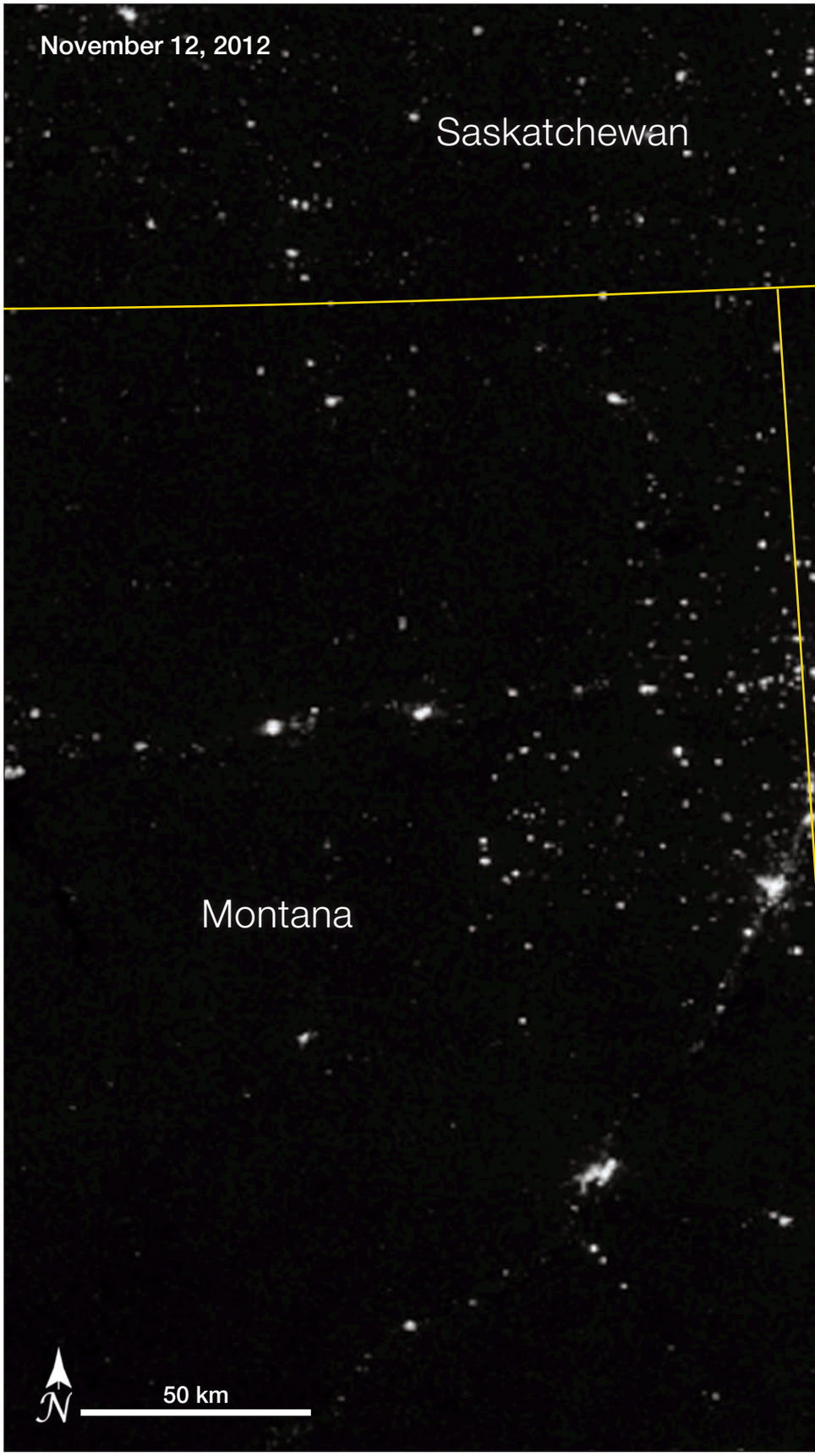
In the early 1970s, oil exploration turned up vast reservoirs of oil and gas under the Bahia de Campeche (Bay of Campeche), located along the southern margin of the Gulf of Mexico, just west of Mexico's Yucatán Peninsula. Offshore oil drilling continues in that region today, and signs of the activity are visible from space as crude oil often contains natural gas, which is disposed of by flaring, as noted earlier. On September 13, 2009, the Advanced Land Imager (ALI) on NASA's Earth Observing-1 (EO-1) satellite captured a natural-color image of gas flares and an oil slick in the Bahia de Campeche (below).

Sunglint—sunlight reflecting off the ocean surface and back to the satellite—gives the ocean a silver-gray appearance and also illuminates the oil slick, which smoothed the ocean surface. Nearly three years later (July 26, 2012), the VIIRS DNB on the Suomi NPP satellite captured a nighttime image (below) of city lights and oil production. Gas flares appear as extremely bright central spots surrounded by a circular halo. Electric lights in cities and oil production sites vary in brightness, and do not have a halo.



Gas Drilling—North Dakota

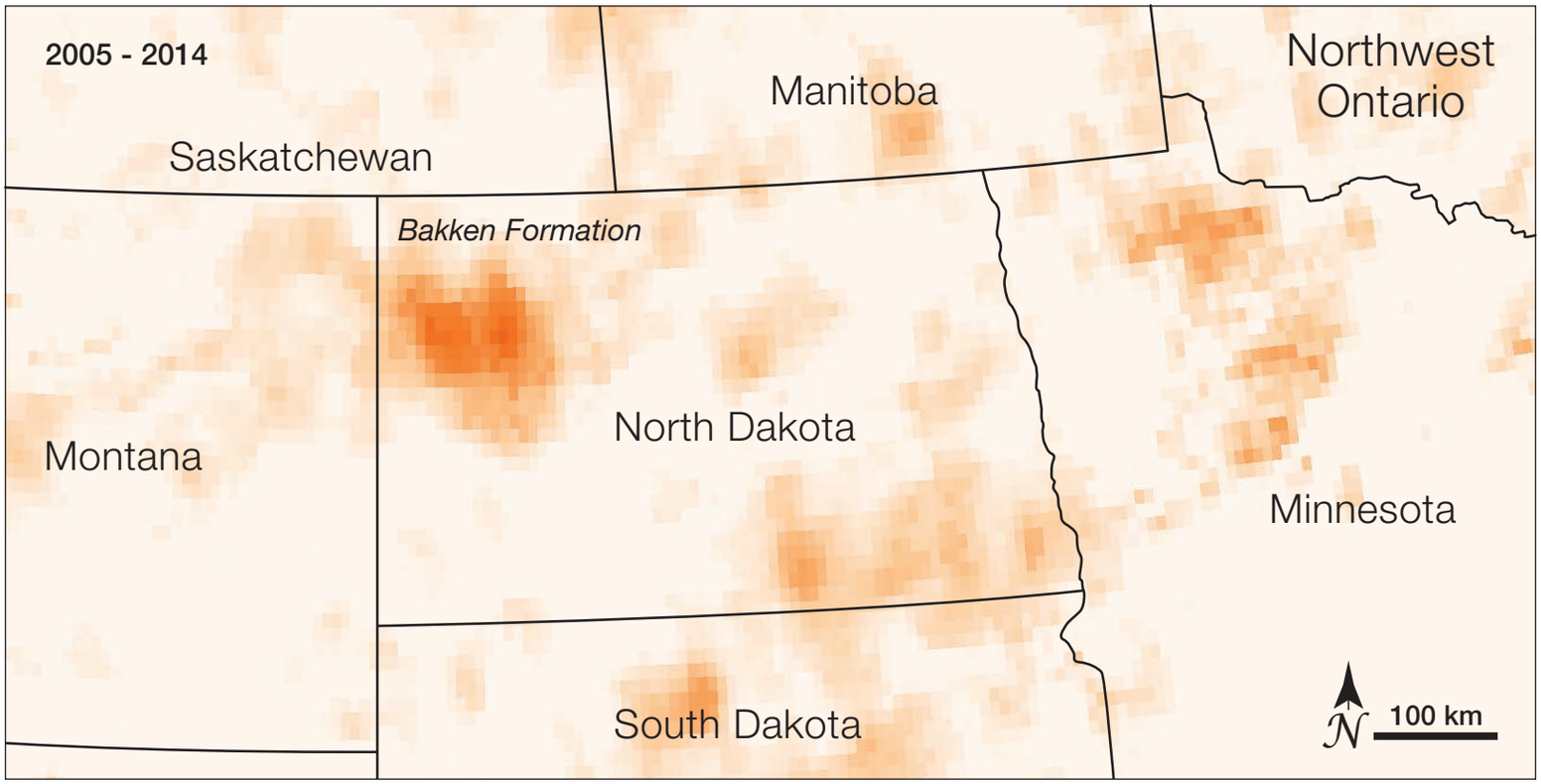
Northwestern North Dakota is one of the least-densely populated parts of the United States. Cities and people are scarce, but satellite imagery shows the area has been aglow at night in recent years. The reason: the area is home to the Bakken shale formation, a site where gas and oil production are booming. On November 12, 2012, the VIIRS DNB on the Suomi NPP satellite captured this nighttime view of widespread drilling throughout the area. Most of the bright specks are lights associated with drilling equipment and temporary housing near drilling sites, although a few are evidence of gas flaring. Some of the brighter areas correspond to towns and cities including Williston, Minot, and Dickinson. When VIIRS acquired the image, the Moon was in its waning crescent phase, so the landscape reflected only a small amount of its light.



Manitoba
Bakken Formation
Minot
Williston
North Dakota
Dickinson

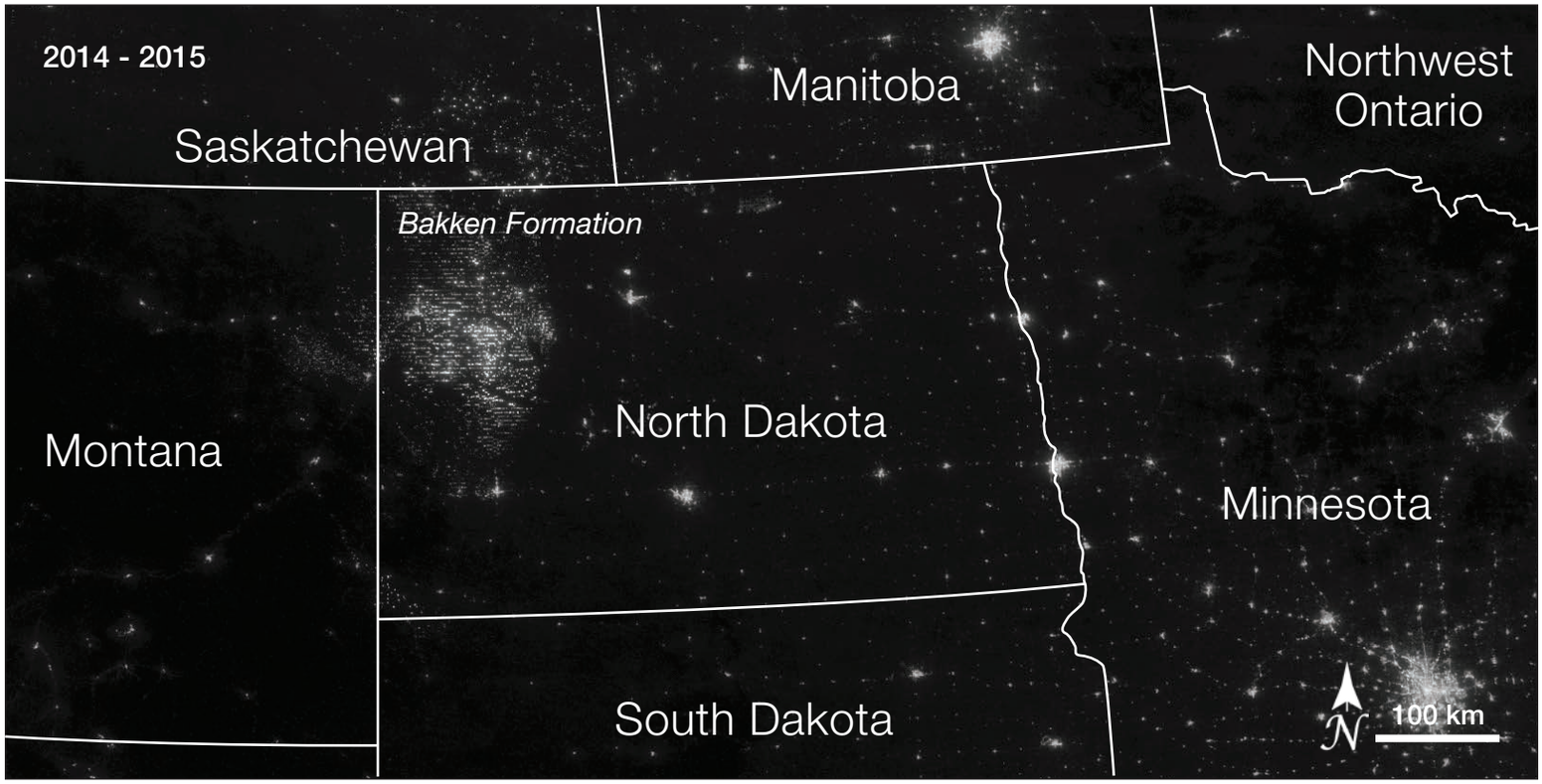
Connection Between Gas Flaring and Arctic Pollution—North Dakota

Previous research has suggested that gas flares from oil and natural gas extraction in the Northern Hemisphere could be a key source of black carbon pollution in the Arctic. But since international inventories of industrial emissions have gaps in observations and reporting, they often over- or underestimate the amount of pollutants. Gas flares are an often-overlooked subset in that incomplete dataset. Data from the VIIRS DNB on the Suomi NPP satellite were used to examine gas flare signals from nightlights (bottom right) and the nitrogen dioxide retrievals (top right) for four regions around the planet; only the Bakken Formation in North Dakota is shown here. Levels of atmospheric nitrogen dioxide were found to rise about 1.5 percent per year at Bakken. This means the concentration of black carbon produced by those flares was also likely on the rise. Such local or regional nightlight data as are described here clearly show the potential for global consequences.



NO_2 Column Density Change, 2005-2014 ($x10^{14}$ molecules/cm^2)

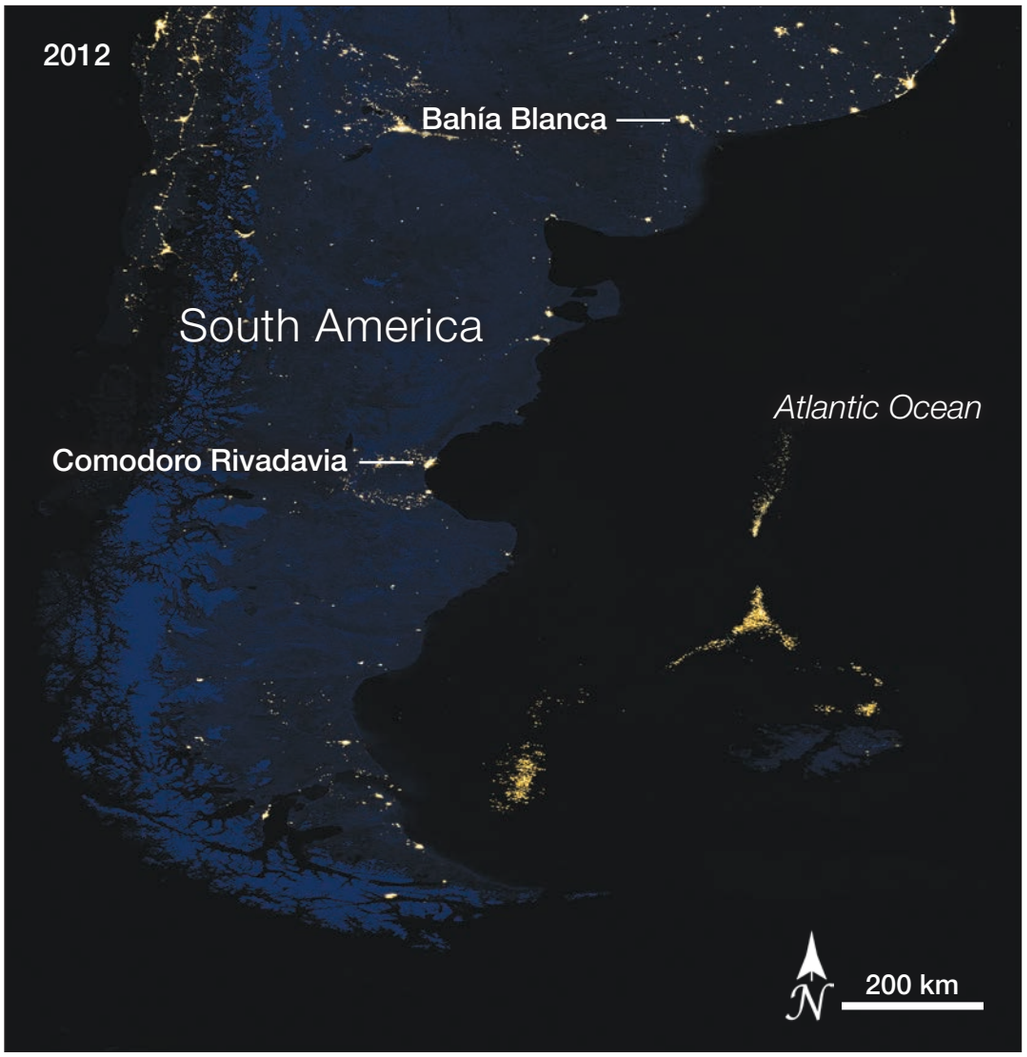
≤0 3.75 ≥7.5

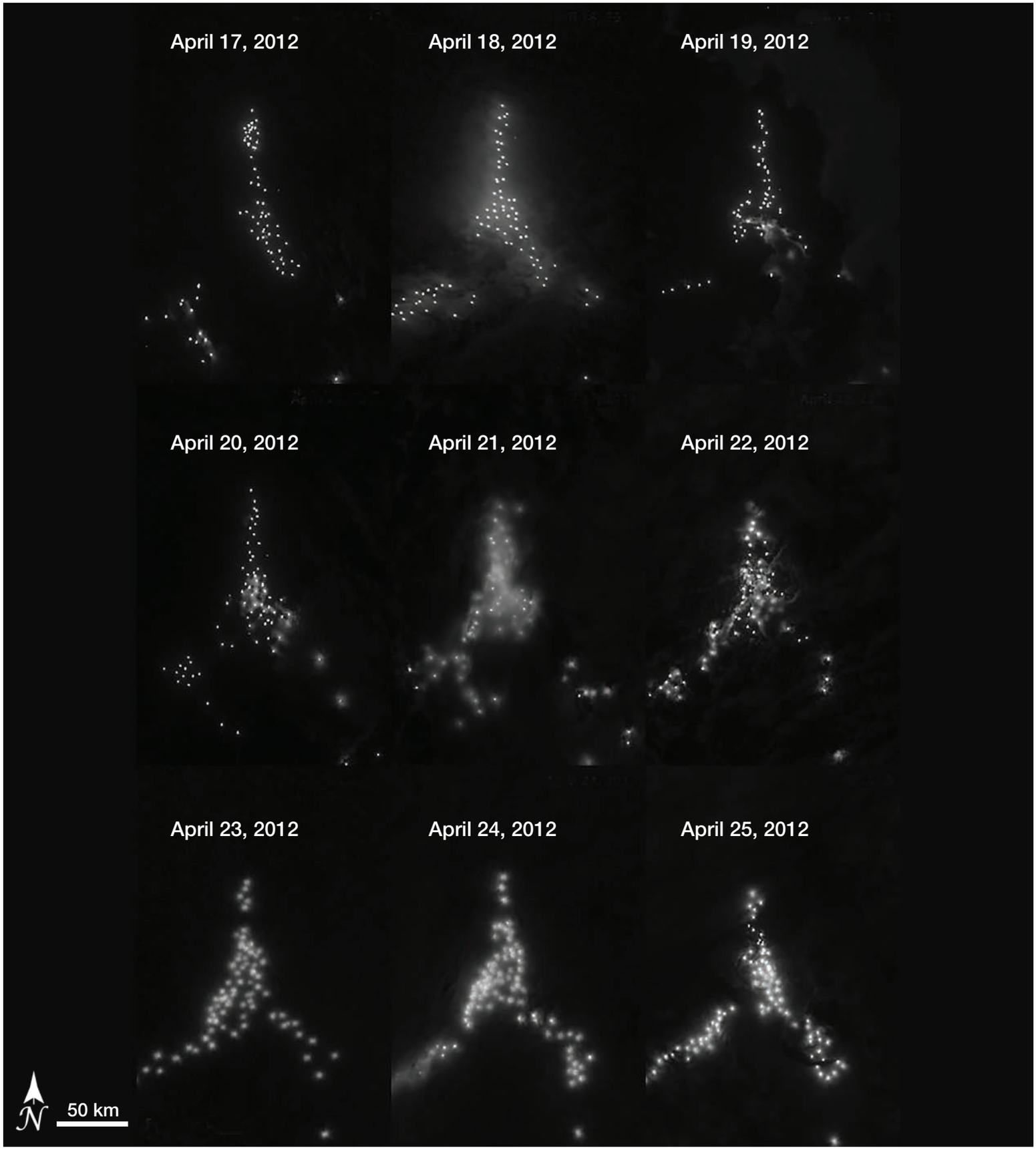


Sea-Going Vessels

Something Fishy in the Atlantic Night—South Atlantic Ocean

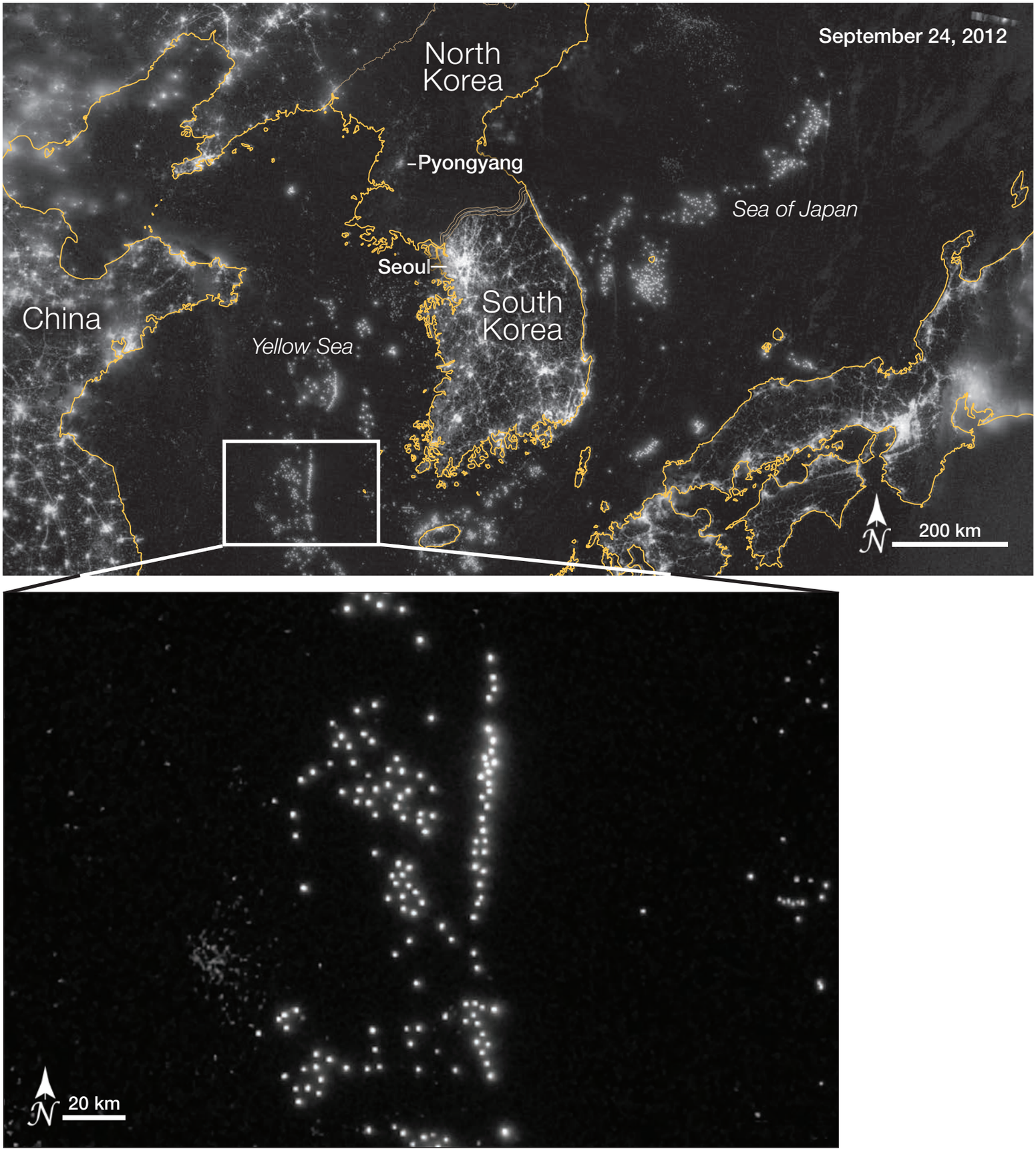
First noted in the late 1970s and early 1980s, about 200 to 300 miles (322 to 483 kilometers) off the coast of Argentina, a city of light routinely appears in the middle of the South Atlantic Ocean as shown in the 2012 composite image below, created with data from the VIIRS sensor on the Suomi NPP satellite. There are no human settlements there, nor fires or gas wells. But there are lots of fishing boats. Squid fishermen adorn their boats with bright lights for night fishing to draw prey into their nets. The boats cluster offshore along invisible lines: the underwater edge of the continental shelf, the nutrient-rich Malvinas Current, and the boundaries of the exclusive economic zones of Argentina and the Falkland Islands. The maps on the right show the locations of fishing boats on nine consecutive nights from April 17 to 25, 2012, also obtained with VIIRS on Suomi NPP. Note that lights appear sharper on some nights and more diffuse on others due to the presence or absence of cloud cover and fog. While not shown specifically here, other vessels are involved: In addition to the fishing boats, large refrigeration and refueling ships keep the long-distance operators working without having to go back to a port. Satellite images like these allow scientists to better understand and manage fisheries in international waters; for example, they can estimate the weekly captures of different species.




April 17, 2012
April 18, 2012
April 19, 2012
April 20, 2012
April 21, 2012
April 22, 2012
April 23, 2012
April 24, 2012
April 25, 2012
N
50 km

Korea and the Yellow Sea—Korean Peninsula

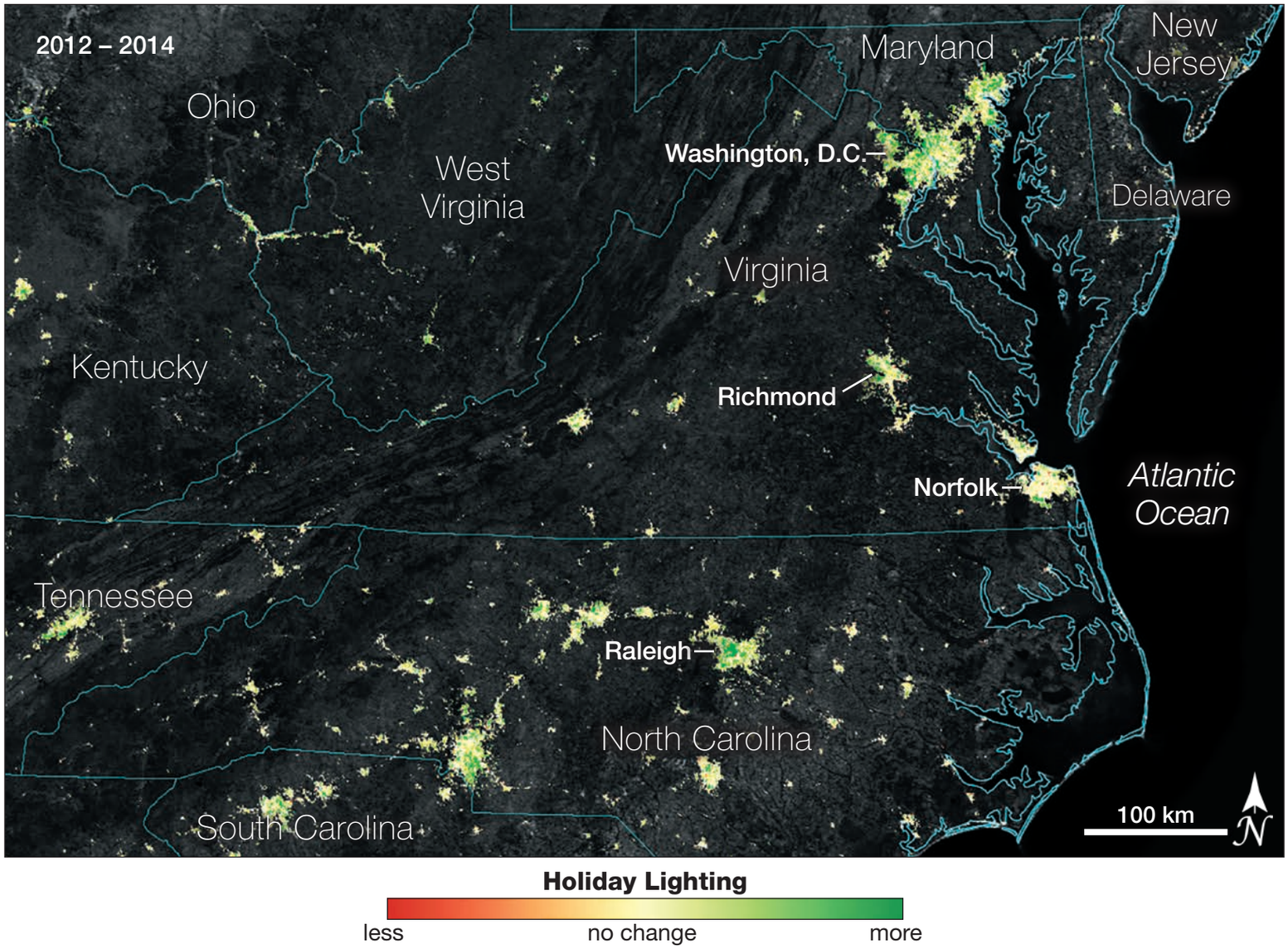
On September 24, 2012, the VIIRS DNB on the Suomi NPP satellite captured this nighttime view of the Korean Peninsula. The wide-area image shows the Korean Peninsula, parts of China and Japan, the Yellow Sea, and the Sea of Japan (also known as the East Sea). The white inset box, magnified in the image on the bottom right, shows the lights of fishing boats in the Yellow Sea; many of the boats appear to form a line, as if marking a watery boundary between nations.


September 24, 2012
North Korea
Pyongyang
Sea of Japan
Seoul
South Korea
China
Yellow Sea
200 km
N
20 km
N

Holiday Lights

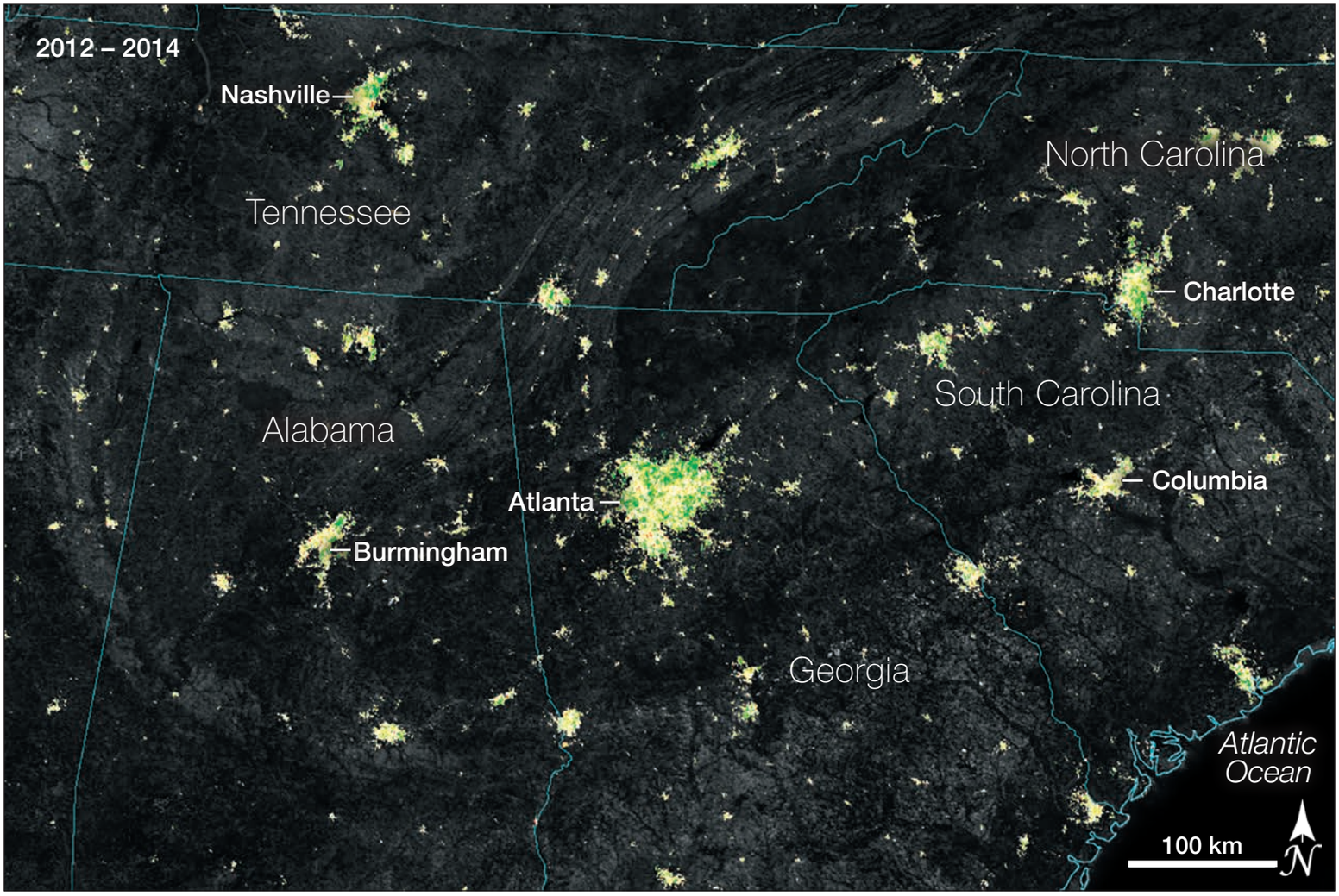
Bursting with Holiday Energy—United States

NASA researchers found that nighttime lights in the United States shine 20 to 50 percent brighter in December due to holiday light displays and other activities during Christmas and New Year's when compared to light output during the rest of the year. The next five maps (see also pages 161–163), created using data from the VIIRS DNB on the Suomi NPP satellite, show changes in lighting intensity and location around many major cities, comparing the nighttime light signals from December 2012 and



2013 to the average light output for the rest of 2012 to 2014. On any given night, the signal is subtle; however, averaged over days and weeks, it is more perceptible. Green shading marks areas where light usage increased in December; yellow marks areas with little change; and red marks areas where less light was used.

The light output from 70 U.S. cities was examined as a first step toward determining patterns in urban energy use. They found that light intensity increased by 30 to 50



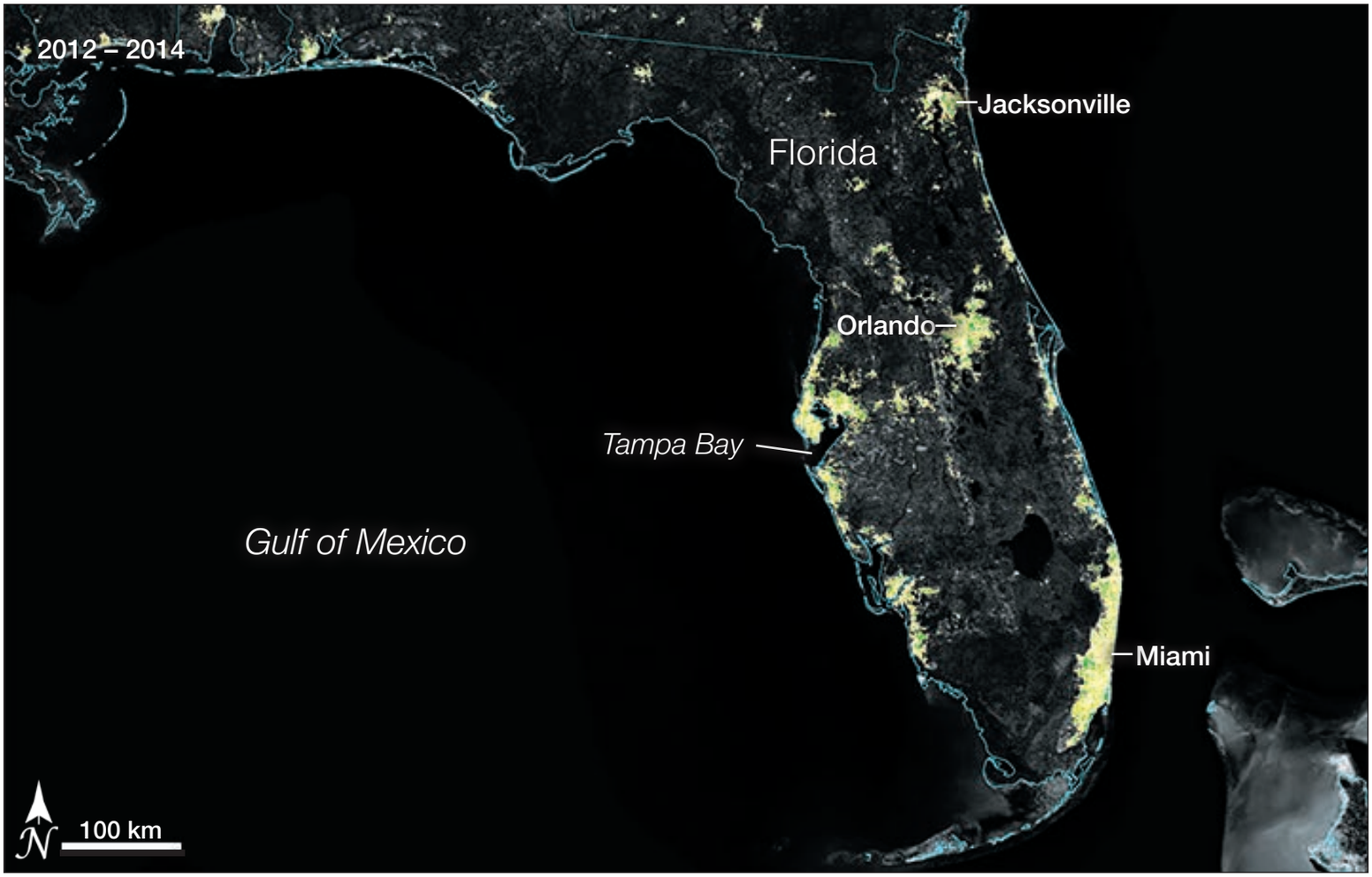
Holiday Lighting

less — no change — more

percent in the suburbs and outskirts of major cities where there is more yard space and more single-family homes. Lights in the central urban areas did not increase as much as in the suburbs but still brightened by 20 to 30 percent. Despite being ethnically and religiously diverse, the U.S. experiences a holiday increase across most urban communities—tracking a national, shared tradition.

While the trend says some interesting things about culture, it also tells us something important about energy use. A daily global dynamic dataset of nighttime lights provides a new way to understand the broad societal forces impacting energy decisions. As noted by the Intergovernmental Panel on Climate Change, improvements in energy efficiency and conservation are critical for making greenhouse gas reductions. Daily nightlight data provide a new way of looking at how people use cities and the forces and patterns driving energy use.

(images continue on pages 161–163)



Holiday Lighting

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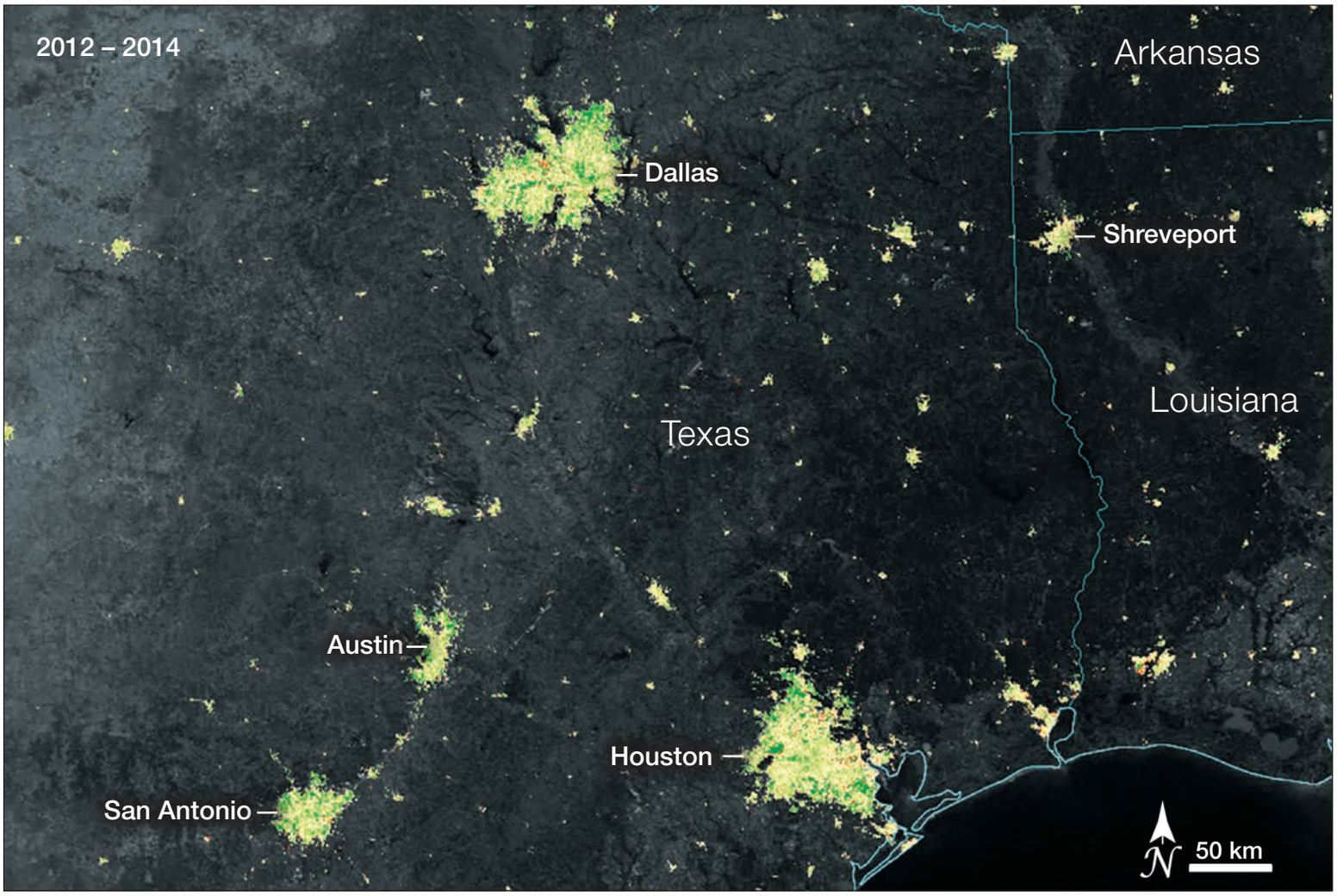

Holiday Lighting

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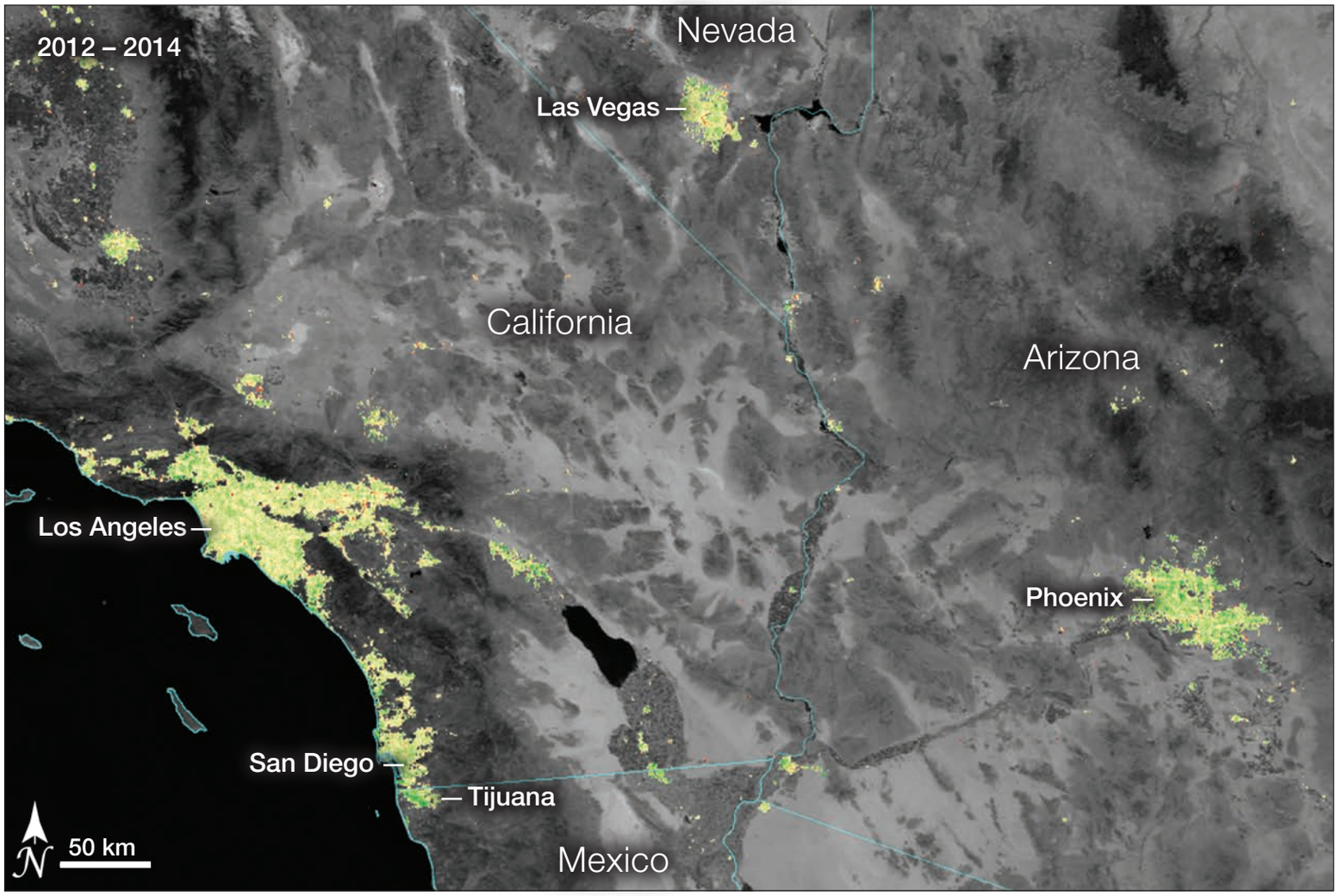


Holiday Lighting

less — no change — more

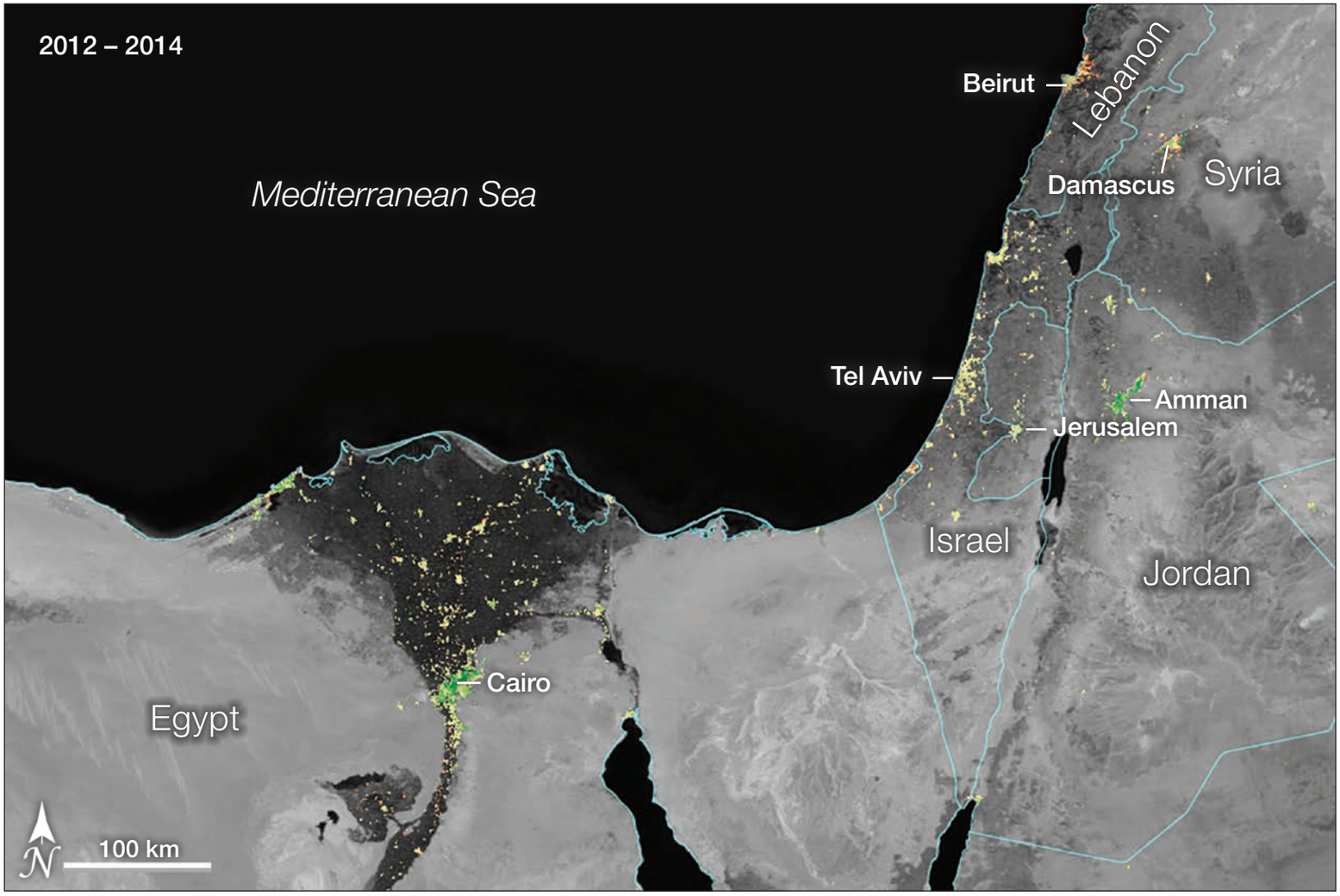
The Lights of Ramadan and Eid al-Fitr—Middle East

In December 2014, NASA researchers announced that they had detected significant changes in the amount and distribution of nighttime lighting during the holy month of Ramadan in the Middle East.

The maps on pages 165 and 166 show changes in lighting intensity and location on the Arabian Peninsula and in the countries along the eastern Mediterranean coast. They are based on data from the VIIRS DNB on the Suomi NPP satellite. These maps compare the nightlight signals from the months of Ramadan in 2012–2014 (parts of July and August in those years) to the average light output for the rest of 2012 to 2014. Green shading marks areas where light usage increased during the holy days; yellow marks areas with little change; and red marks areas where less light was used.

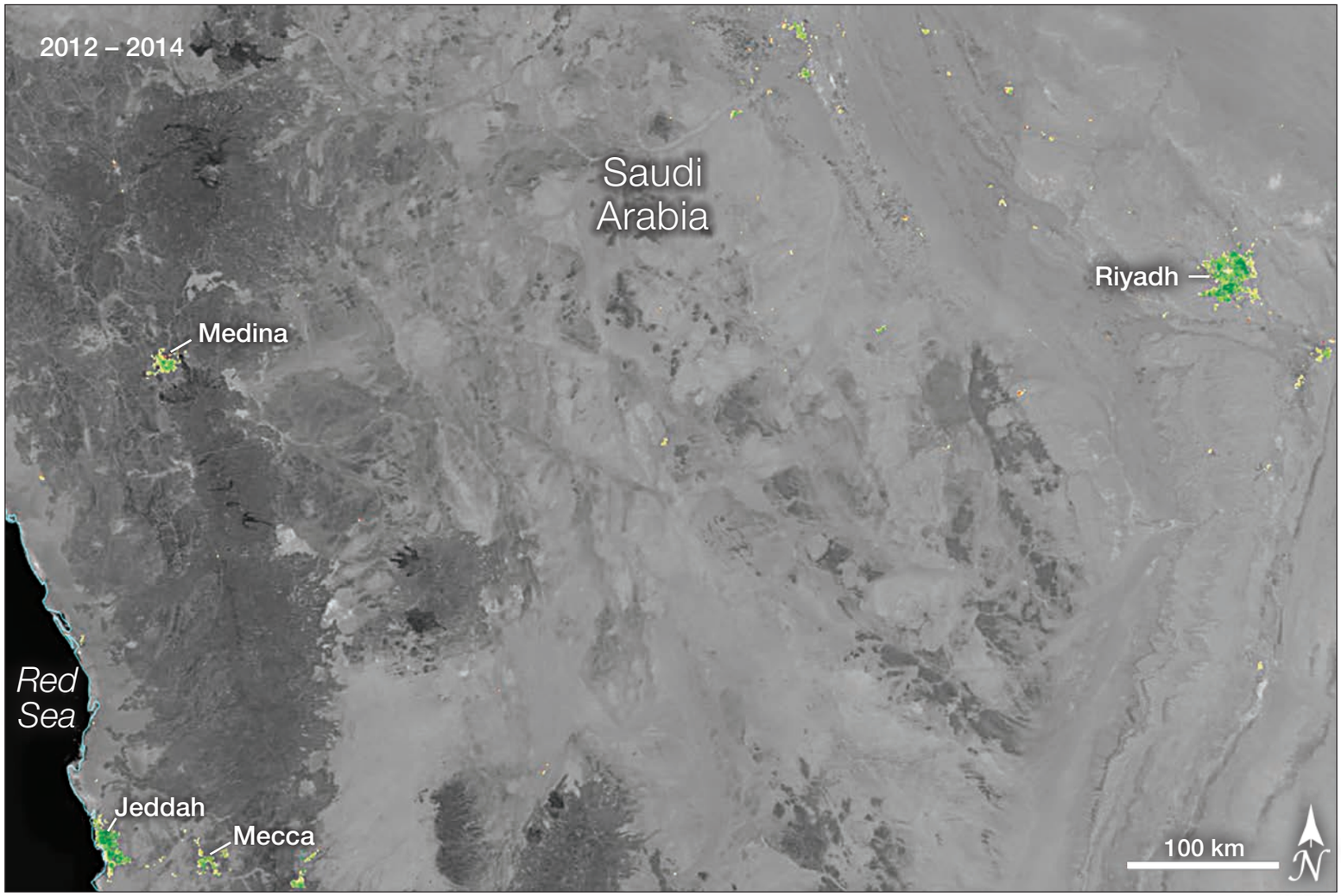
A large increase in light output around the Egyptian capital Cairo corresponded with the holy month of Ramadan. The change made sense because Muslims fast during daylight in Ramadan, pushing meals, social gatherings, commerce, and other activities into nighttime hours. Peaks in light use closely tracked the Islamic calendar, as Ramadan shifted earlier in the summer each year.

(cont'd on page 167)



Holiday Lighting

less — no change — more



Holiday Lighting

less — no change — more

(cont'd from page 164)

Light use in Saudi Arabian cities, such as Riyadh and Jeddah, increased by 60 to 100 percent throughout the month of Ramadan. Light use in Turkish cities, however, increased far less. Some regions in Syria, Iraq, and Lebanon did not have an increase in light output—and some even demonstrated a moderate decrease, possibly due to unstable electrical grids and conflict in the region. Even within majority Muslim populations, there are a lot of variations. Lighting patterns track cultural variation within the Middle East.

These variations appear even at the neighborhood level. Some of the poorest and most devout areas observed Ramadan without significant increases in light use throughout the month, choosing—whether for cultural or financial reasons—to leave their lights off at night.

However, during the Eid al-Fitr celebration that marks the end of Ramadan, light use soared across all study groups, as all the neighborhoods appeared to join in the festivities. Energy use patterns seem to reflect social and cultural identities, as well as the habits of city dwellers, and not just price or other commercial factors.

Epilogue

Over the last 50 years of the space program we have had the opportunity to view planet Earth not only during the day but also at night. As so many astronauts have remarked, seeing the day-lit Earth from space changes our perspective. We move away from feeling like local or regional creatures, living in countries, states, and towns, towards a new perspective of becoming citizens of the whole world. This shift in awareness is because the day-lit Earth shows no artificial boundaries created by humans to separate different societies and political systems. But this perspective changes at night, when we see the places on Earth where progress has produced vivid displays of lights.

Earth evolves through a process of dynamical change. This evolution surely includes human inhabitants, since we live, work, multiply, and migrate within Earth's biosphere on a continual basis. Throughout human history on Earth, civilizations have come and gone due to natural disasters, long-term climate change, and the consequences of large meteorite impacts.

What will Earth at night look like from space in the next 50 years? Will there be new and sprawling cities where today there are none? Will natural disasters destroy densely populated areas we see today, turning them into dark, forbidden areas at night? Surely all these things will happen to some extent.

Chances are Earth at night will only get brighter with more complex webs of lights strung all over the planet. This shows progress and is important for sustaining life, but my hope is that there will still be places where the darkness is treasured, and where we can continue to look outward to the planets, stars, and beyond.

James L. Green

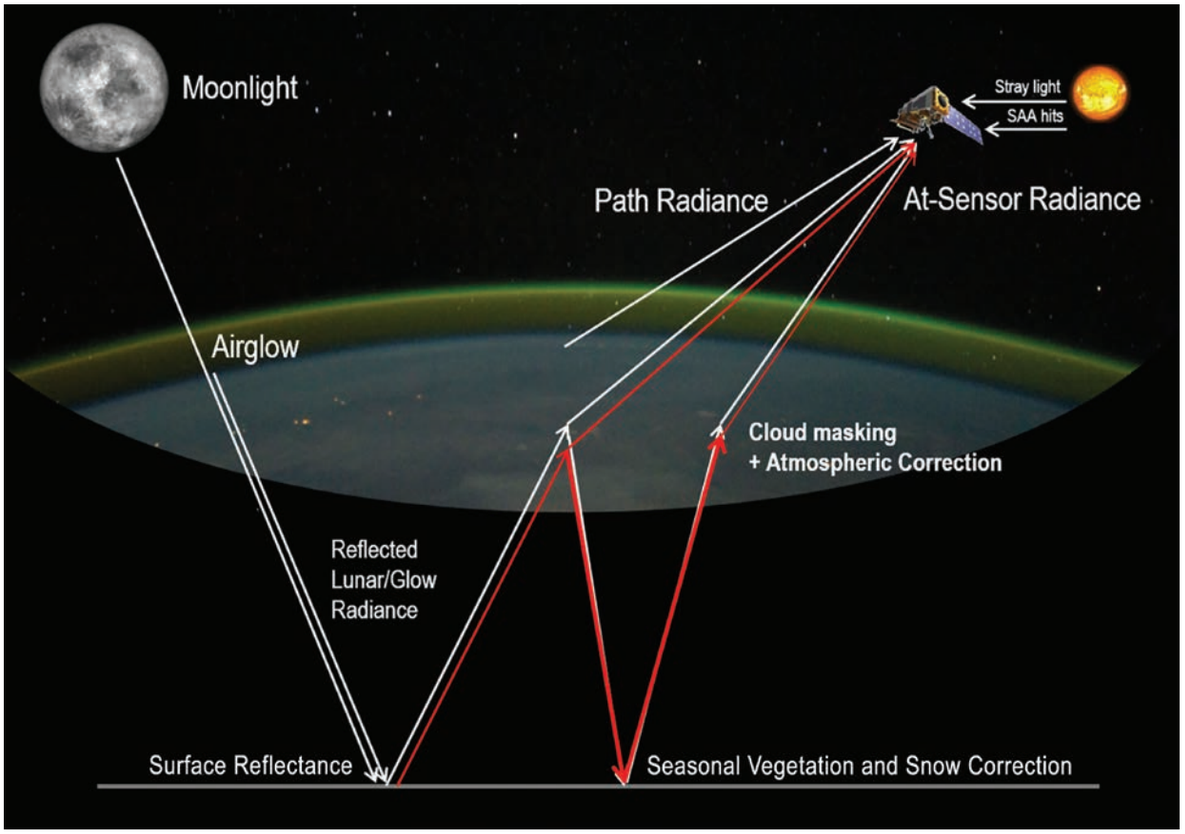
NASA Chief Scientist

Appendix A

NASA's Black Marble Product Suite

NASA's Black Marble product suite provides estimates of daily nighttime lights and other intrinsic surface optical properties of Earth at night. The product is based on the Day/Night Band (DNB) sensor of the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument onboard the Suomi National Polar-orbiting Partnership (NPP) satellite. The VIIRS DNB is a highly sensitive, low-light sensor capable of measuring daily global nighttime light emissions and reflections, allowing users to identify sources and intensities of these artificial lights, and monitor changes over a period of time. Like any optical sensor, the principal challenge in using VIIRS DNB data is to account for variations in light captured by the sensor. Certainly, there are variations in the sources and intensity of anthropogenic light due to changing human processes like urbanization, oil and gas production, nighttime commercial fishing, and infrastructure development. However, these processes can only be studied when other naturally-occurring factors that influence nighttime lights are removed. For example, variations in lunar lighting due to consistent changes in Moon phase cause fluctuations in the amount of light shining on Earth. Similarly, land-cover dynamics (e.g., seasonal vegetation, snow and ice cover), as well as atmospheric conditions (e.g., clouds, aerosols, airglow, and auroras), influence the intensity of the light captured by the sensor as it travels over various parts of the world.

To realize the full potential of the VIIRS DNB time series record for nighttime lights applications, NASA's Black Marble product suite was developed, building on a history of 20 years of research on how light changes when it reflects off of surfaces with different angular and spectral properties. Through complex modeling, scientists can now predict how moonlight, snow, vegetation, terrain, and clouds impact the lights we



[Left] *Overview of NASA's Black Marble product retrieval process*. During the portion of the lunar cycle when moonlight is present at the time of satellite observation, the surface upward radiance from artificial light emissions (shown in red) can be extracted from at-sensor radiance (white lines with arrows towards satellite). The Black Marble product suite removes several natural sources that influence the at-sensor radiance, including airglow, moonlight, snow and seasonal vegetation, stray light, and clouds.

see. The Black Marble product suite removes these extraneous effects and creates consistent daily records of man-made lighting (see figure above). The product ingests multiple sources of ancillary data to output the highest-quality, pixel-based estimates of nighttime lights.

With these corrections in nighttime radiances, we get a superior view of nighttime lights with frequent observations and reduction in background noise, enabling various quantitative analyses of daily, seasonal, and annual changes, in an analysis-ready file format. Products are calibrated across time, validated against ground measurements, and include quality indicators so that they can be used effectively and accurately in science and applications studies.

The product is routinely made available from NASA's Level 1 and Atmosphere Archive and Distribution System (LAADS) Distributed Active Archive Center (DAAC), and can be freely accessed through NASA's EarthData portal: *https://urs.earthdata.nasa.gov/home*. The standard product is available at 500-meter spatial resolution since

January 2012 and is being processed on a daily basis within 3-5 hours after acquisition, enabling both near-real-time uses and long-term monitoring applications. Detailed information on product generation, applications, and documentations can be found at the product's website (*https://blackmarble.gsfc.nasa.gov*).

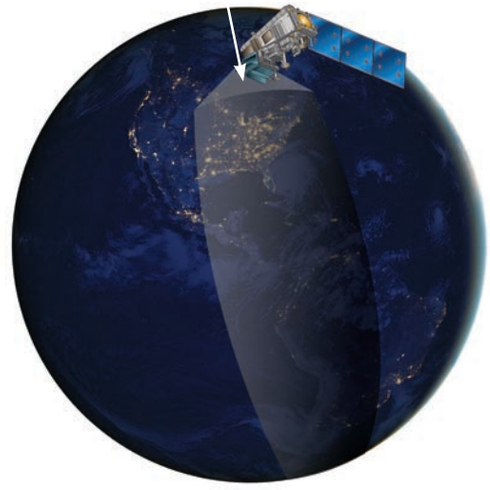
These products are not just pretty maps of Earth at night. They provide a global nighttime, environmental-science-quality product needed for all major disciplines that focus on the nocturnal environment, with emphasis on targeted studies of phenomena related to, for example, light pollution, urbanization science, disaster response, clouds and aerosols, and the ocean at night, as well as various applications like energy access, disaster risk reductions, and resilience. These daily records are invaluable to city planners, ecologists, economists, and emergency responders assessing damage after major storms like Hurricane Maria (discussed on pages 118–121 of this volume). Since light at night is a primarily human-created phenomenon, these products will improve our understanding of human processes that take place on the land and ocean, and interactions between human systems and the environment.

Appendix B

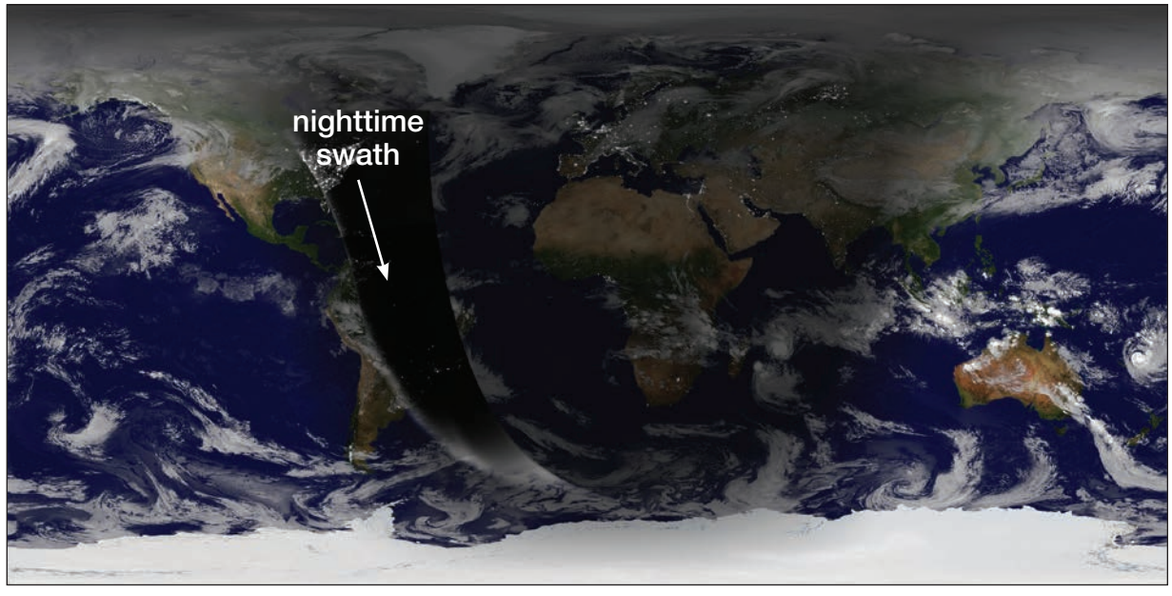
Making a Cloud-Free, Global, Earth-at-Night Image Using NASA's Black Marble Product Suite

1

In its orbit, the Suomi National Polar-orbiting Partnership (NPP) satellite platform flies 512 miles (824 kilometers) above Earth, crossing the equator at roughly 1:30 a.m. and 1:30 p.m. local time, while circling the planet from pole to pole about 14 times a day. A key instrument on Suomi NPP is the Visible Infrared Imaging Radiometer Suite (VIIRS), which is a multispectral instrument that scans 1889-mile- (3040-kilometer-) wide swaths of data.

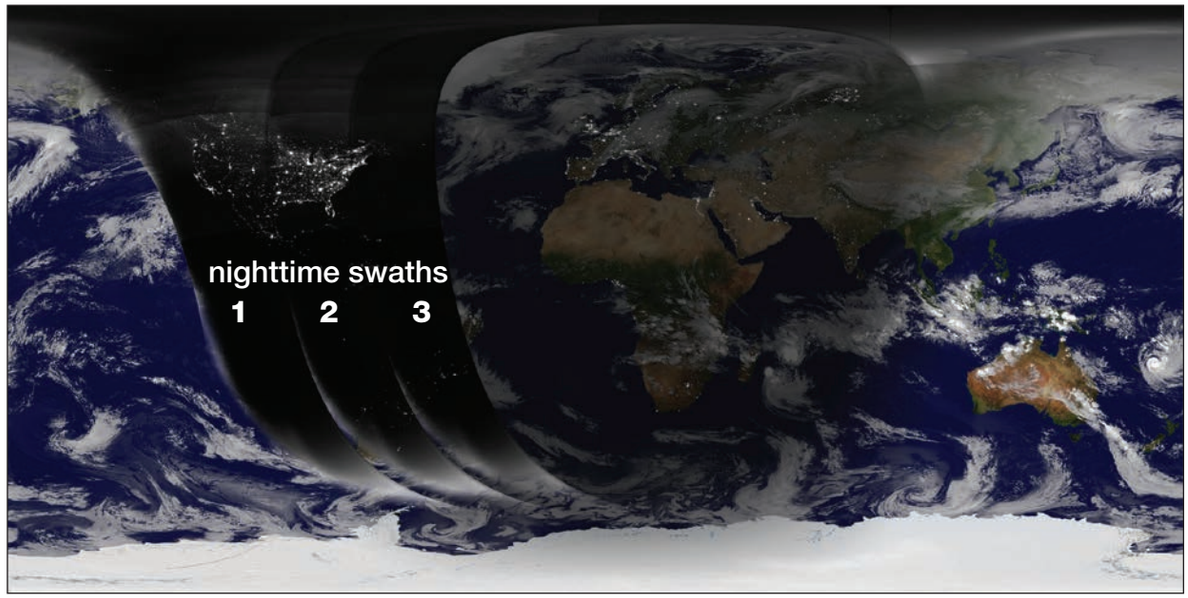


2



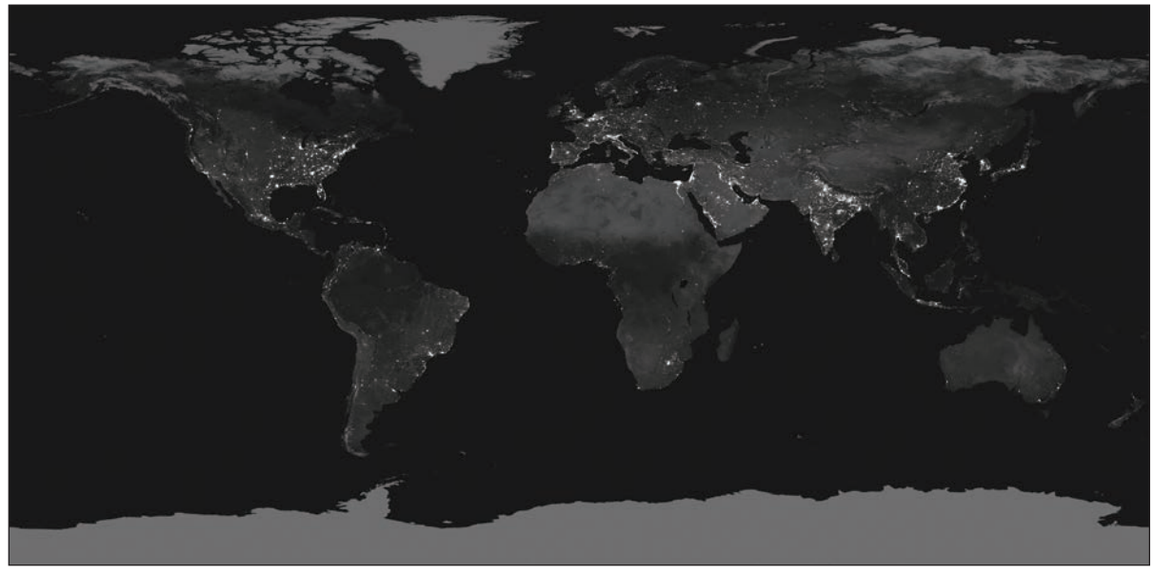
The Suomi NPP satellite observes Earth's surface throughout the day—and at night. The Day/Night Band (DNB) of the VIIRS instrument detects light in a range of wavelengths from green (500 nanometers) to near-infrared (900 nanometers) and uses filtering techniques to observe dim signals such as city lights—down to the scale of an isolated highway lamp—wildfires, gas flares, auroras, and reflected moonlight at night. In this example (above), the satellite acquired a swath of data during nighttime hours over portions of South America, the Atlantic Ocean, and the Eastern United States.

3



Every day, swaths of data—acquired during day and night hours—can be stitched together to create daytime and nighttime images of Earth. In the example above, three nighttime swaths show lights at night over much of North and South America.

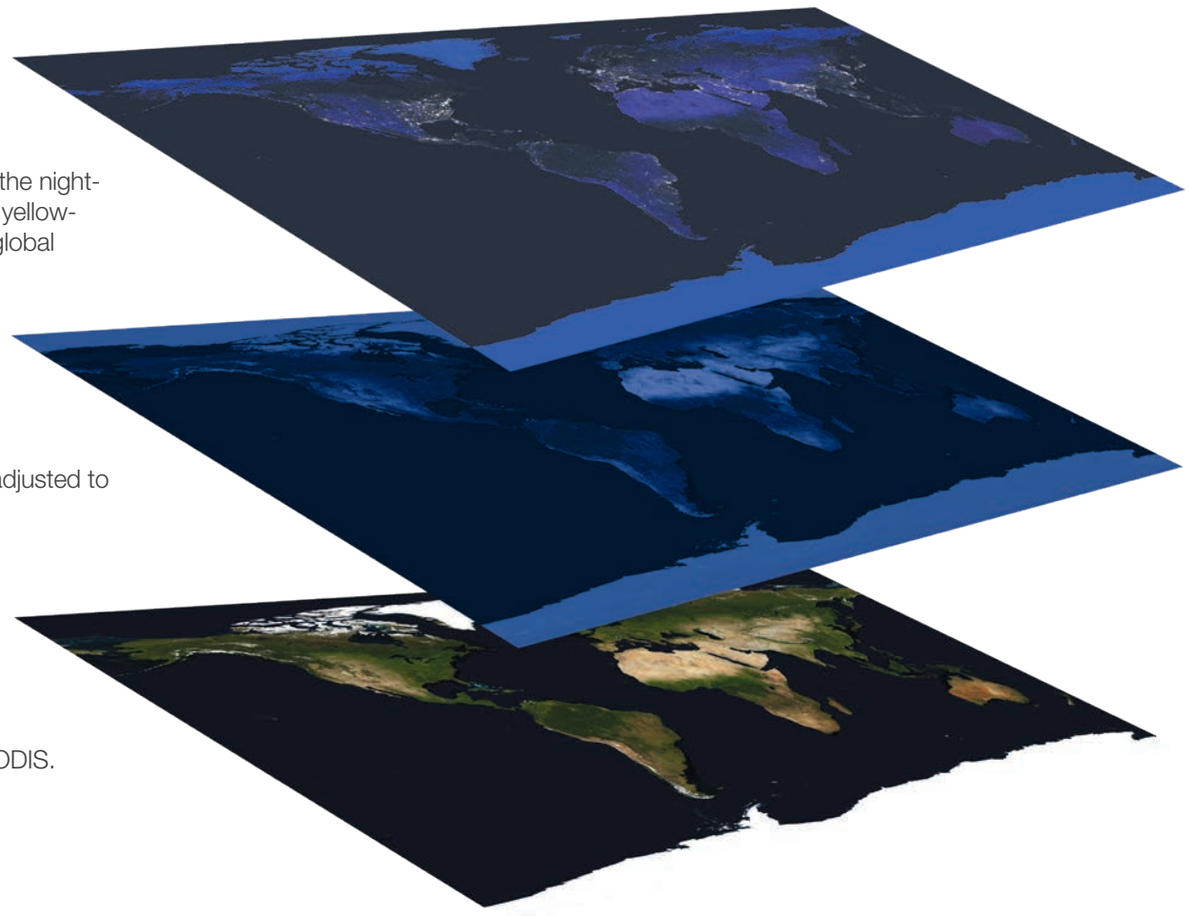
4



Daily images of Earth at night, available via NASA's Black Marble product suite (see *Appendix A*), were then stitched together to create the Black Marble global composite image (above). Away from the cities, much of the light observed by Suomi NPP during nighttime is from wildfires. In other places, fishing boats, gas flares, oil drilling, or mining operations show up as points of light.

5

The final step in making an image of Earth at night involves combining a background Earth image with the Black Marble global composite image to give context to dark areas. Any background image could have been used—in this case, a global true-color image called the Blue Marble: Next Generation, or BMNG, was used, made with data from the Moderate Resolution Imaging Spectroradiometer (MODIS), which flies on NASA's Terra and Aqua platforms. The BMNG was then modified to appear more "night-like" to highlight Earth's land surfaces. The land appears in shades of dark blue and the ocean appears black. The Black Marble global composite image was tinted yellow to closely match the actual appearance of lights from space. The night-like background and Black Marble global composite images were then combined to produce this image of Earth at night.



Final combination of the night-like background and yellow-tinted Black Marble global composite images.

Background image adjusted to appear night-like.

Background image - BMNG true-color MODIS.

Appendix C

OLS and VIIRS Technical Details

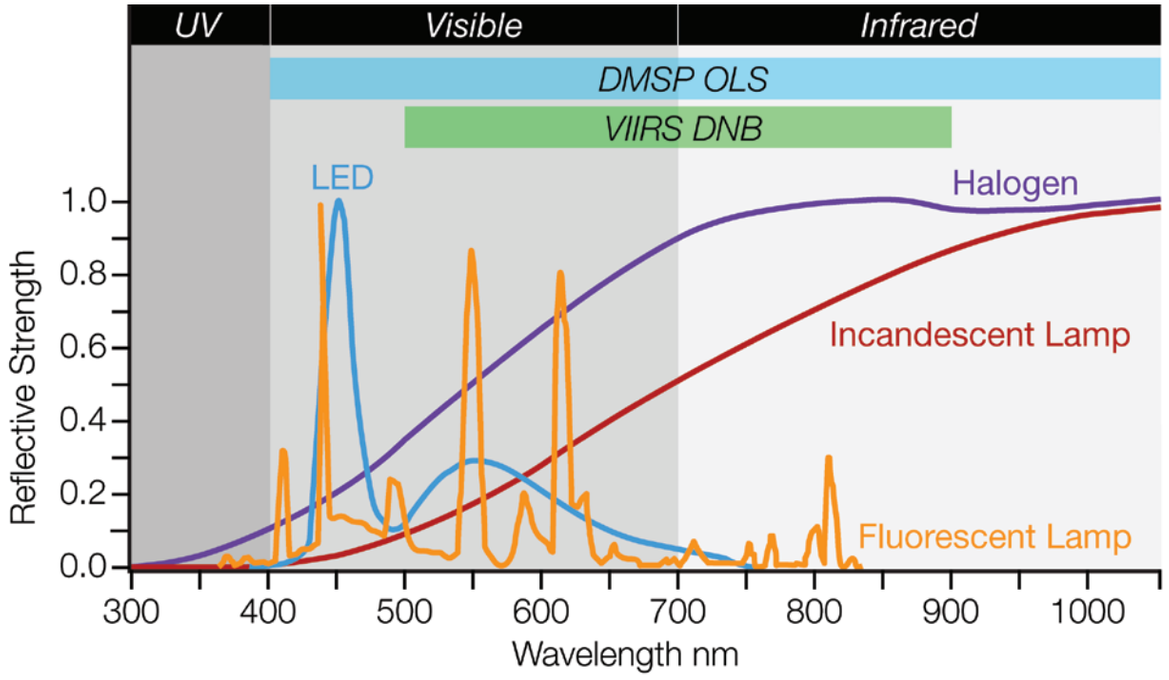
The beautiful, evocative, and informative images that make up the bulk of this volume are the result of advances in technology, science, and computation—the details of which would form an entire volume of their own. For those who are interested delving deeper, we provide a bit more information, primarily about the technical details of the sensors that enable such images.

Credit: U.S. Airforce

[Right] An artist's concept depicting a DMSP satellite, which series includes DMSP-8, DMSP-9, DMSP-10, DMSP-11, DMSP-12, DMSP-13, and DMSP-14.

The Operational Linescan System (OLS) onboard the Defense Meteorological Satellite Program (DMSP) satellites, one of which is depicted above, provides global coverage in both visible (Band 1) and infrared (Band 2) modes. An earlier, popularized version of Earth at night was created using DMSP OLS data from October 1, 1994 to March 31, 1995. DMSP OLS has been a highly successful sensor, but it is dependent on older technology with lower resolution than scientific research now demands.

The Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi National Polar-orbiting Partnership (NPP) satellite has 22 channels, with responses ranging from 412 to 12,010 nanometers. Five of these channels are high-resolution imagery bands or "I-bands," as they are commonly referred to, and sixteen are designed as moderate-resolution bands or "M-bands." One of these M-bands is the Day/Night Band, or DNB, that is a panchromatic band sensitive to visible and near-infrared wavelengths. (See *Appendix B* to learn how the DNB is used to create nighttime imagery.)



[Left] The range for visible light is about 400 (blue light) to 700 (red light) nanometers, while the VIIRS DNB's sensitivity is 500 to 900 nanometers and the DMSP OLS's sensitivity is 400 to 1100 nanometers.

Specifically, the range for visible light is about 400 (blue light) to 700 (red light) nanometers, while the VIIRS DNB's sensitivity is from 500 to 900 nanometers. The various ranges and a comparison of VIIRS's spectral capabilities with those of OLS is found in the graphic on this page; the table (next page) provides more technical detail about these two instruments. Because of these capabilities, the VIIRS DNB can easily "see" most common light sources such as incandescent and fluorescent light bulbs,

Table. Parameters of VIIRS and OLS

Parameter	VIIRS	OLS
Orbit	Polar	Polar
Overpass time	1:30 p.m. and 1:30 a.m., local	8:30 – 9:30 a.m. and 8:30 – 9:30 p.m., local
Swath width	3040 km (~1889 mi)	3000 km (~1864 mi)
Temporal resolution	12 h	12 h
Spatial resolution	742 m (~2434 ft)	2.7 km (~1.7 mi)
Wavelength range	500 – 900 nanometers	400 – 1,100 nanometers

as their spectral ranges significantly overlap with the VIIRS DNB spectral range. The only anthropogenic visible light source that is not always easily detected by the VIIRS DNB is light from LED bulbs. For example, white LED bulbs peak near 450 nanometers, and therefore return dimmer signals. Despite this limitation, VIIRS DNB is highly sensitive to very low amounts of light; it can sense light 100,000 times fainter than conventional visible-light sensors.

Unlike cameras that many use every day to capture a scene in one complete exposure, VIIRS produces an image by repeatedly scanning a scene (increasing exposure time) and resolving it as millions of individual picture elements, or pixels. The DNB goes a step further, determining on the fly whether to use its low-, medium-, or high-gain mode. If a pixel is very bright, the low-gain mode on the sensor prevents the pixel from oversaturating. If the pixel is dark, the signal will be amplified.

Appendix D

Additional Credits and Information

Black Marble: front and back covers, endpapers, ii, iii, ix, 2, 3, 5, 13, 26, 27, 114, 115, 120, 121, 128, 129, 139, 140–143, 158, 159, 161–163, 165, 166, 170–172, 174

NASA's Earth Observatory: 9, 14–25, 30–43, 46–119, 122–167

International Space Station (ISS): xvi, 1, 14, 15, 16, 17, 18, 19, 20, 21, 28, 29, 50, 55, 60–66, 72, 73, 78–81, 85, 87, 89–95, 97, 98, 100–103, 111–113, 116, 117

For more information

Black Marble

https://blackmarble.gsfc.nasa.gov

https://earthobservatory.nasa.gov/features/NightLights

Black Marble Science Team

https://blackmarble.gsfc.nasa.gov/#people

NASA's Earth Observatory

https://earthobservatory.nasa.gov

The Electromagnetic Spectrum

https://science.nasa.gov/ems/01_intro

https://imagine.gsfc.nasa.gov/science/toolbox/emspectrum1.html

National Aeronautics and Space Administration

www.nasa.gov

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