Space-Based Earth Observations: Fundamental to Prosperity, Security, and Resilience on Our Changing Planet

Statement of

Waleed Abdalati
Director, Cooperative Institute for Research in Environmental Sciences
Professor, Department of Geography
University of Colorado, Boulder

before the

Senate Commerce, Science, and Transportation
Subcommittee on Space and Science

for the hearing

Landsat at 50 and the Future of U.S. Satellite-based Earth Observation

1 December, 2022

Chair Cantwell, Ranking Member Wicker, Chair Hickenlooper and Ranking Member Lummis and members of the subcommittee, thank you for the opportunity to testify today on the very important matter of the future of U.S. satellite-based Earth observations. I greatly appreciate the work of this committee and its bipartisan efforts to examine the importance, state, and prospects for Earth observations from space. In addition, it is a privilege to be here with representatives from civilian agencies and the private sector who develop, operate, and analyze these capabilities for the good of the American people, and for the good of the world.

As we continue to live in a world in which our relationship with the environment is critical to our success and prosperity, the value of knowledge about our environment has never been more consequential. Ours is a changing planet, and space-based observations of Earth not only provide us situational awareness that allows us to watch the story of that change unfold, but they provide us the information needed to understand the underlying causes, the evolution of their behaviors, and the implications for the future. They provide essential situational awareness and are a critical element of our national informational infrastructure that helps us thrive in the face of environmental changes and challenges.

Satellite observations are a fundamental component of our everyday lives (Figure 1), often in ways that many people don't realize, strengthening our national security, supporting effective resource management, advancing global health, and supporting our national prosperity. These benefits directly result from the fact that satellite observations provide the context, scale, and perspective needed to understand our Earth environment in ways that can inform our actions to optimize our relationship with the planet on which we live, by understanding how it functions, adapting to and managing changes, and capitalizing on opportunities.

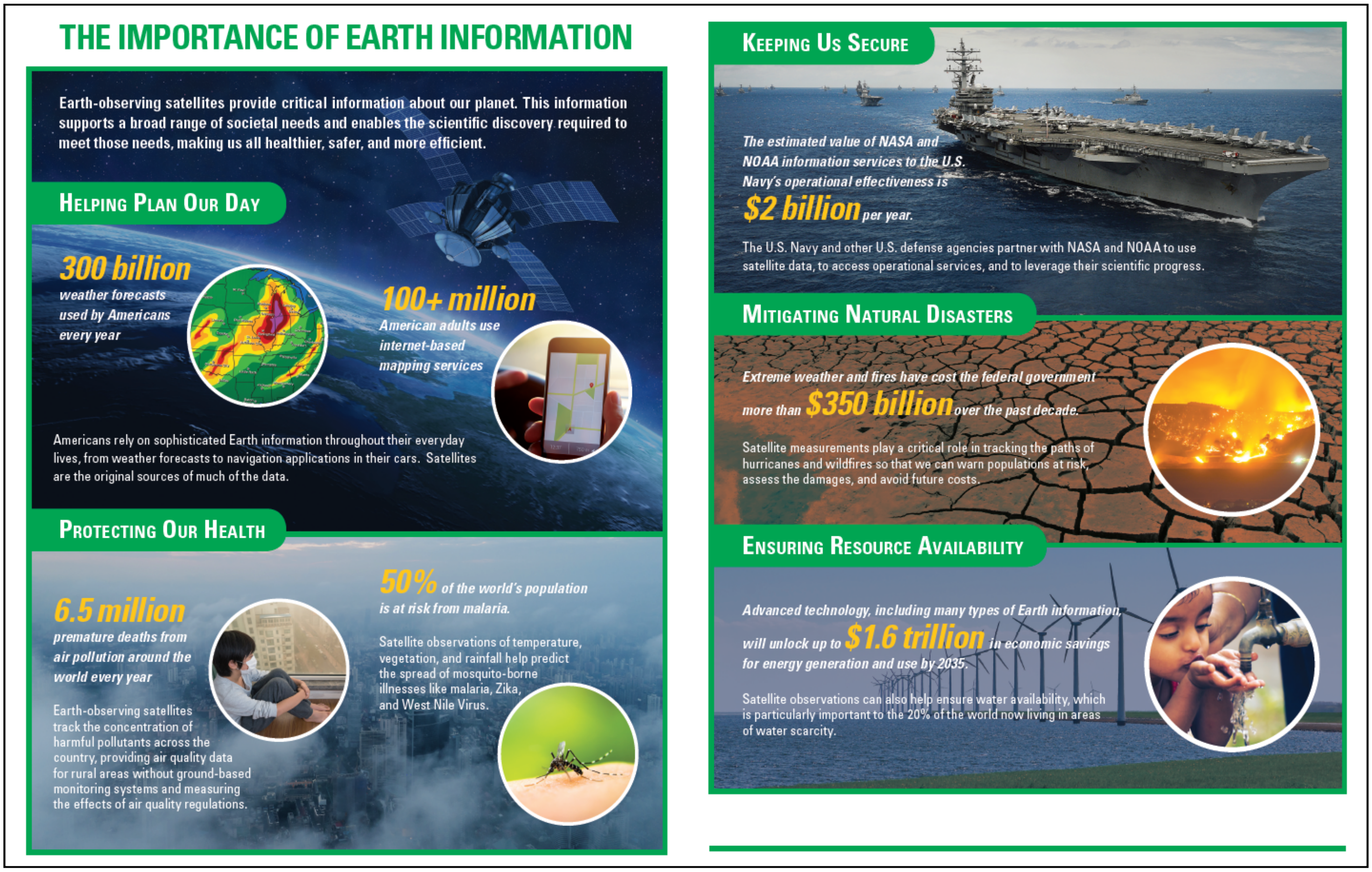

Figure 1: Many aspects of our individual and collective lives are positively impacted by data from space-based resources, often in ways that we do not recognize. SOURCES: Data available as follows: Helping Plan Our Day—Lazo et al., 2009; comScore, 2014. Protecting Our Health—WHO, 2016, 2017. Keeping Us Secure—Titley, 2016. Mitigating Natural Disasters—GAO Highlights, 2017. Ensuring Resource Availability—UN-Water, 2007; McKinsey Global Institute, 2017. Figure from National Academy of Sciences Earth Science and Applications from Space 2017 (NAS, 2018).

These capabilities are applicable to many domains of societal interest that directly affect our economic and social well-being and our strength as a nation. Here I will speak to just a few.

Water Resources

Water access and availability is perhaps the element that is most impactful to our societal well-being. With implications in the United States that go beyond simply access, into the domains of health, food production, recreation, and so much more. Globally, the access to water has further implications for migration and geopolitical stability (National Intelligence Council, 2021). Domestically the western United States is currently experiencing the worst drought in 1200 years (Williams et al., 2022), and comprehensive observations of the elements that contribute to water transport and storage are required in order to (a) fully appreciate the nature of this drought, (b) understand the driving factors, (c) recognize the implications of the stresses on our water resources, and (d) manage these resources most effectively. Such observations are needed on a scale that is only available from space.

I recently had the opportunity to join Senators Michael Bennet and Mitt Romney on a short rafting trip down the Colorado River (Figure 2). The purpose of that bi-partisan trip was to provide a shared first-hand and up-close look at the water stresses in the Colorado river basin. Also on the trip were a rancher, a water manager, a native tribal leader, and others whose lives and livelihoods are tied to the water. What was most striking about that trip was how low the water level was and how slowly the water flowed. Our tour guides talked about how it "used to be," with the relatively still water in the picture standing in stark contrast to what used to be whitewater rapids. While those anecdotes are accurate, to truly understand the situation requires a broader view, one in which Landsat, along with other observing capabilities, has played an important role. Figure 3 shows a Landsat time sequence of the Colorado River near Lake Powell (a highly-stressed and depleting reservoir), which clearly shows a reduction in water flowing through the river over time, part of a longer trend. Our ability to monitor the river width and flow, here and in other water-stressed regions, help us understand the scope and scale of the reduced water and put them into a broader context – the kind of context needed to manage water effectively. The importance of this ability is underscored by the fact that the Colorado River System alone provides essential water resources to seven western states: Colorado, Wyoming, Utah, New Mexico, Arizona, Nevada and California.

Figure 2. Senators Romney (left) and Bennet (right) rafting on the Colorado River on September 27, 2021. Photo: Spenser Heaps, Deseret News

A key reason for the decreasing river flows is the fact that typical mountain snows that feed and recharge the rivers in the spring have been diminishing (Milly and Dunne, 2020). We know this too from satellite observations, combined with a sampling of ground-based measurements and hydrological models (informed by these observations), which make clear that the spatial extent of the snow cover and the associated water content are decreasing (Figure 4), and melt is occurring earlier and more rapidly (Musselman et al., 2021). The result is lower river levels, reduced soil moisture (Figure 5), fewer water resources, and significant threats to agriculture, ranching, and tourism.

Moving deeper, there is a space-based capability that allows us to go beyond the images of the surface (snow, timing of melt, river flow, and lake extent), and examine subsurface storage. The

Gravity Recovery and Climate Experiment (GRACE) satellite, and its successor (GRACE-Follow-on), have measured mass variations to provide an integrated assessment of overall ground and subsurface water storage and its evolution over time. It does so by measuring changes in the gravity field, which are directly tied to changes in the mass that lies beneath the satellites (Rodell et al., 2016). As shown in Figure 6, there has been a significant drying trend in the Colorado River Basin

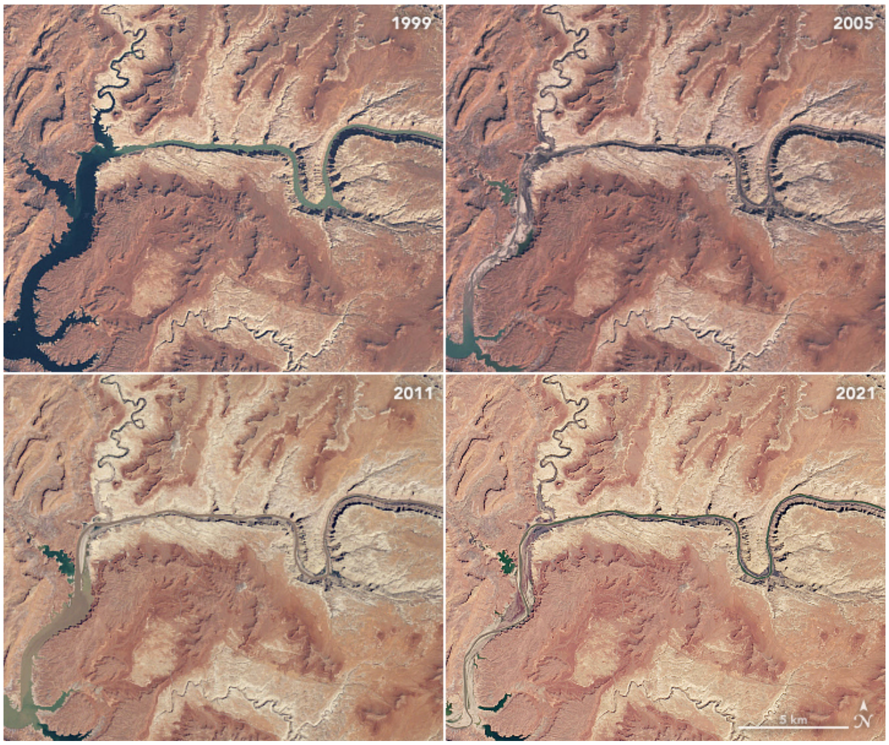

Figure 3: Colorado River upstream of Lake Powell. The natural-color images above were acquired in March 1999, April 2005, May 2011, and April 2021 by the Landsat 5, 7, and 8 satellites. Springtime typically marks the lowest water levels before mountaintop snow starts to melt and run down into the watershed. The images capture years with the two highest and lowest levels over the past 22 years.

(https://earthobservatory.nasa.gov/images/148861/lake-powell-reaches-new-low)

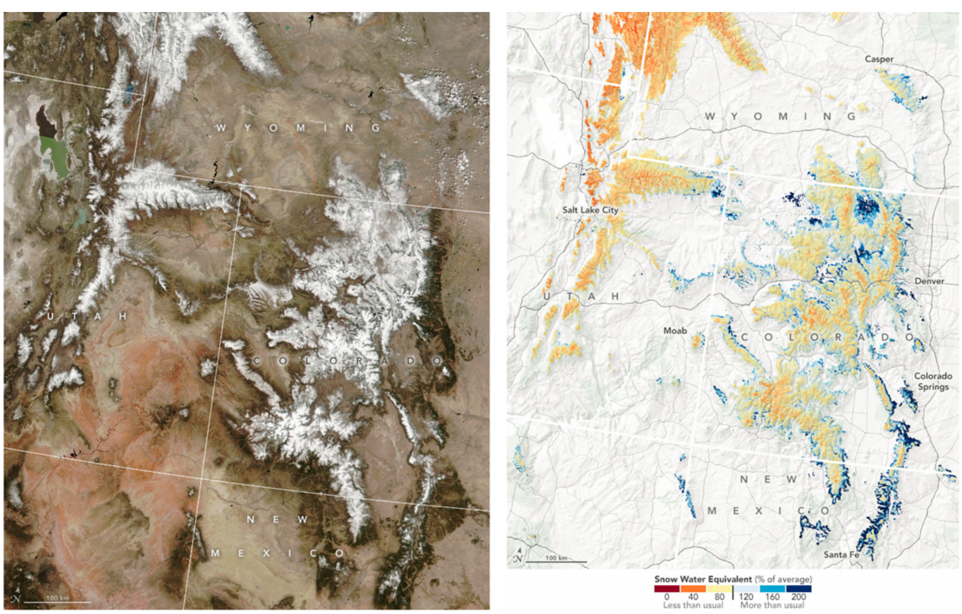

Figure 4: Visible Infrared Imaging Radiometer Suite (VIIRS) Image of Rocky Mountain snow cover on April 7, 2022 (left) and map of snow water equivalent (water stored as snow) in the Rocky Mountains on April 1, 2022, as compared to the 2000-2020 average.

https://earthobservatory.nasa.gov/images/149779/taking-stock-of-rocky-mountain-snowpack

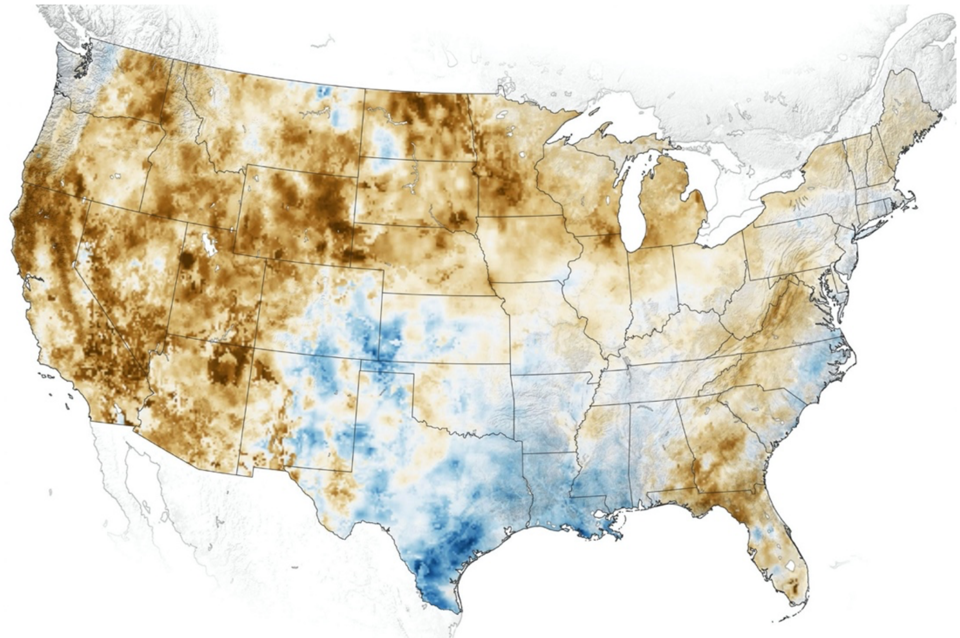

Figure 5: Soil moisture anomalies in the top meter of soil based in part on measurements NASA's Soil Moisture Active Passive (SMAP) satellite and vegetation indices from the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on NASA's Terra and Aqua satellites.

https://scitechdaily.com/long-term-drought-grips-the-western-u-s-soils-and-plants-are-parched/

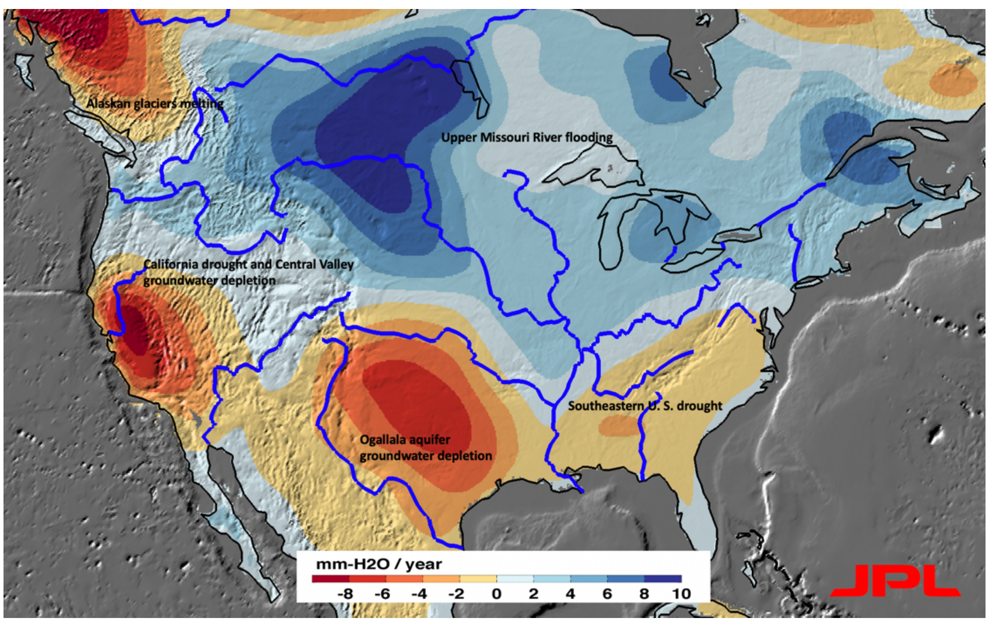

Figure 6: Changing Freshwater Availability from GRACE, 2002-2015, (Rodell et al., 2016)

In the immediate term, these observations and how they are used enable us to manage challenges associated with water access. In the longer term, their value is further amplified through their ability to inform practices related to farming, ranching, land use and more. As we observe and understand trends in our environment, we are better positioned to anticipate what the future holds in terms of water stresses and water availability. This advanced knowledge is critical to successfully positioning ourselves as a nation to manage the emerging challenges and capitalize on potential opportunities.

Fires and other Hazards and Extreme Events

The costs associated with natural hazards and extreme events has been increasing significantly over the last 40 years (Figure 7). All of these types of events listed below are those that can be observed, predicted, understood, and most importantly prepared for and managed, with the aid of space-based observations.

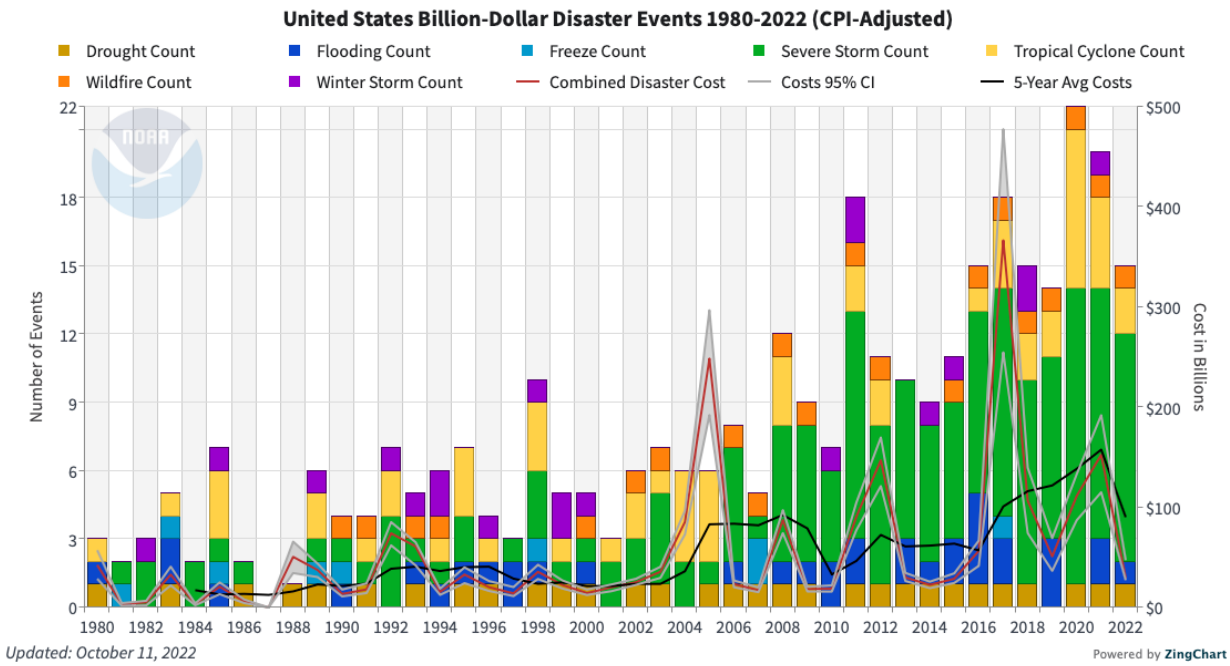

Figure 7: Number of billion-dollar disasters in the United States from 1980 to 2021. Each bar is colored to show the different types of billion-dollar disasters with the number of events (left vertical axis) and the associated costs (right vertical axis.). During the first nine months of 2022 there have been fifteen separate billion-dollar weather and climate disaster events. Figure is from NOAA National Centers for Environmental Information (NCEI) at https://www.ncei.noaa.gov/access/billions/time-series)

The parameters that drive or contribute to each of these disasters is derivable from satellites, and their prediction depends critically on space-based observations, integrated with ground-based measurements and modeling capabilities. A very familiar example is the weather-related events, which are managed through weather forecasts that integrate satellite observations with sophisticated weather forecasting models.

Closely coupled to the above discussion on drought and water trends is the prevalence and impact of fires in the United States. This is a matter that literally hits close to home for me, as my town was devastated by the loss of 1100 homes in Colorado's Marshall Fire in December 2021. My family and I were forced to evacuate, and we returned the next day to a severely smoke-damaged home, neighborhoods that were destroyed, and neighbors who were devastated.

As with water resources, satellite observations allow us to go beyond the local impacts to directly assess the presence and extent of fires, the nature of their burn scars, the time of recovery, and the trends in fires and their severity over the years. Moreover, topographic maps, as well as population and residential distribution maps, also supported by satellite images, complemented by weather and wind forecasting, help us understand the vulnerability of communities to fires. When coupled with drought information (such as the soil moisture and vegetation information described above), the susceptibility to fire can be assessed, both in real-time and in terms of longer-term vulnerability.

An analysis of the Monitoring Trends in Burn Severity (MTBS) data set, which integrates Landsat observations with federal and state fire reports (described in Eidenshink et al., 2007), has revealed a significant increase in wildfires, particularly in the western U.S. (Figures 8 and 9). When combined with population and development data, the human and economic vulnerability of these regions can be determined. With this increasing risk of fires and other natural hazards, understanding the vulnerability is critical to informing development and management strategies to limit the damage and manage its threats to lives and property. The satellite observations are critical tools in doing so.

In the case of fires, an added capability to support health and disaster management is the modeling of smoke movement in the atmosphere. NOAA's High Resolution Rapid Refresh Smoke (HRRR Smoke) model combined satellite observations of atmospheric composition and meteorological conditions to predict, with great accuracy, the propagation of smoke during and after the Marshall Fire, enabling an understanding of where health-risks were high. HRRR Smoke was previously used to do the same for the Camp Fire, California's most destructive fire in its history (Chow et al., 2022). On a larger scale, it is possible to observe and model not just smoke's migration and impact on air quality, but also the movement of pollution and its implications for visibility, temperature, air quality, and wind.

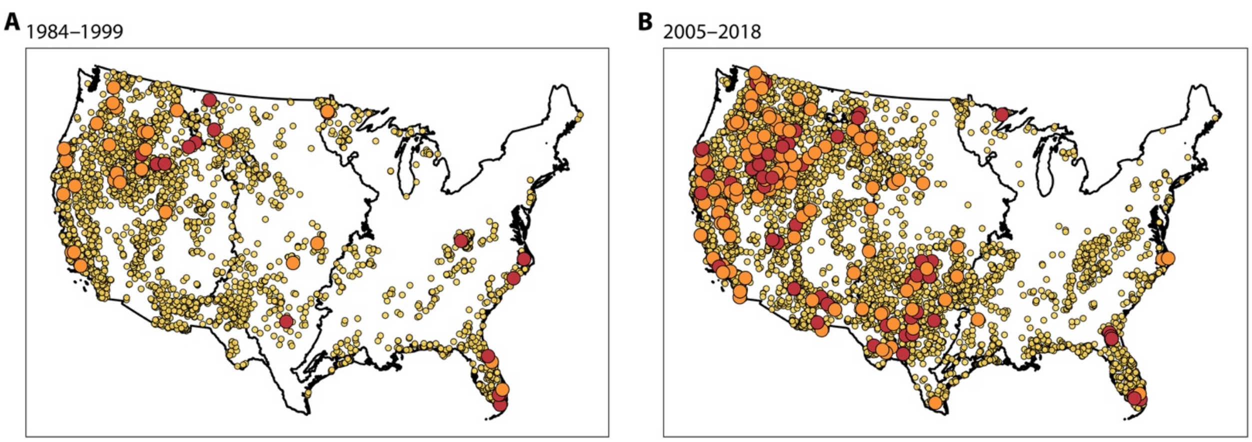

Figure 8: U.S. fires during the period 1984–1999 (Panel A) and 2005–2018 (Panel B). Small dots indicate nonextreme fires while extreme fires are represented with larger orange (area burned >99th percentile in 1984–1999) or red bubbles (area burned >99th percentile in 2005–2018)." The history of the aggregate fires and burned land, and their associated trends, are shown in Figure 9 below.
https://www.science.org/doi/10.1126/sciadv.abc0020

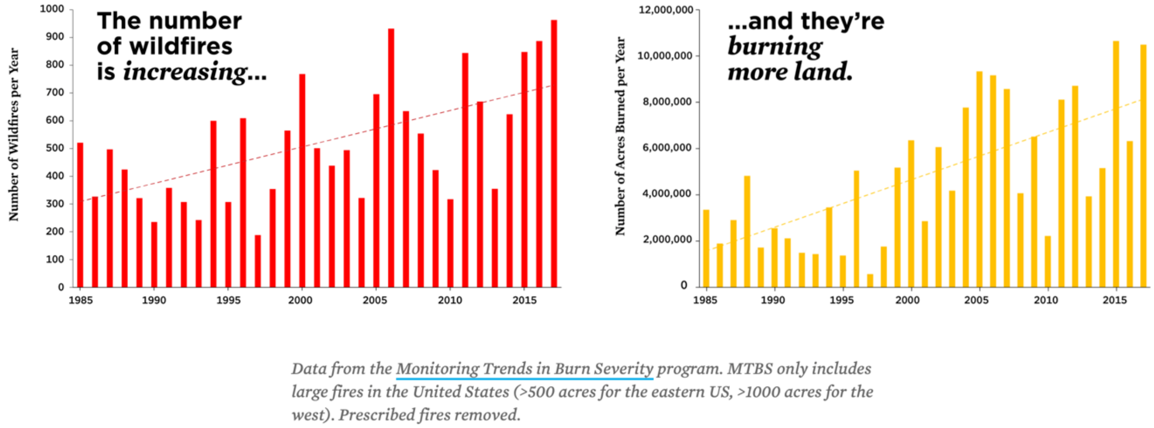

Figure 9: Number of wildfires in the U.S. (left) and area burned (right) from 1985 to 2015. The graphs are from https://www.ucsusa.org/resources/infographic-wildfires-and-climate-change, and the underlying data are from https://www.mtbs.gov.

While I have focused on drought and fires here, the similar satellite utility applies to other types of disasters. In the case of flooding, for example, these observations inform assessments of precipitation amounts and location, storm trajectories, vulnerability to storm surges in coastal areas, river stages, landslide potential, and threats to people.

The fundamental role of satellites goes beyond understanding the level of risk and how it evolves over time (with Figure 8 providing a clear example of information to inform such an assessment). They also contribute to understanding the vulnerability to such risks in part through observations of infrastructure and population distribution, providing important information on how many people are in harm's way and what the potential impacts of such disasters may be. And finally, satellites play a key role in managing the aftermath of such disasters to inform recovery responses and priorities, by providing observations of the nature, location, and amount of damage, as well as the state of access routes to enable effective response. (Le Cozannet et al., 2020).

Sea Level Rise

In a more global sense, but with direct ties to our nation's shores, oceans have been rising since the late 1800's (Church and White, 2011). While the rise in seas prior to the satellite era was observed with tide gauges, it was difficult to accurately determine overall rate of global sea level rise and impossible to determine its regional character. It was not until the satellites provided global coverage that scientists were able to derive such information. Since the first routine observations, beginning with the Topex mission in 1993, the data have shown the global trends in sea level rise of 3.3 mm/yr (which is higher than that of the previous century), as well as an increase in the rate of sea level rise over the nearly 30-year record (Figure 10).

More important than the global sea level rise, however is its spatial distribution, as some areas are rising more rapidly than the global mean, and some are rising more slowly, even lowering in some places (Figure 11). The nature of this distribution has to do with where heat is stored in the oceans, the sources of sea level rise, and the movement of the land in relation to forces acting on it (mainly the isostatic adjustment in response to land ice changes). Satellite observations allow us to monitor the surface temperature and water movement, which combined with models allows us to understand the heat distribution and transport throughout the world's oceans. They also provide information on the behavior of the Earth's glaciers and ice sheets, the shrinking of which has been adding fresh water to high-latitude regions of the Earth, while at the same time resulting in an upward movement of high-latitude land masses as the solid earth responds to the lightening of the load near its polar regions.

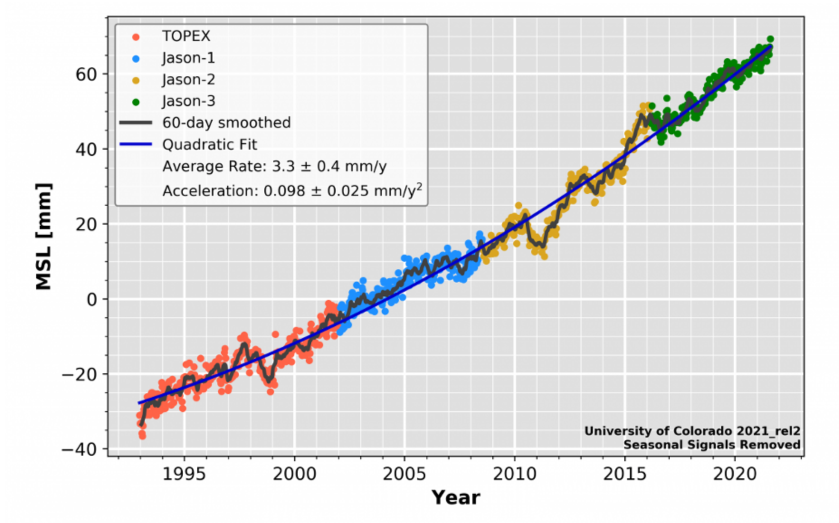

Figure 10: Global mean sea level rise from 1993-2022 derived from a sequence of satellite altimeters. (https://sealevel.colorado.edu)

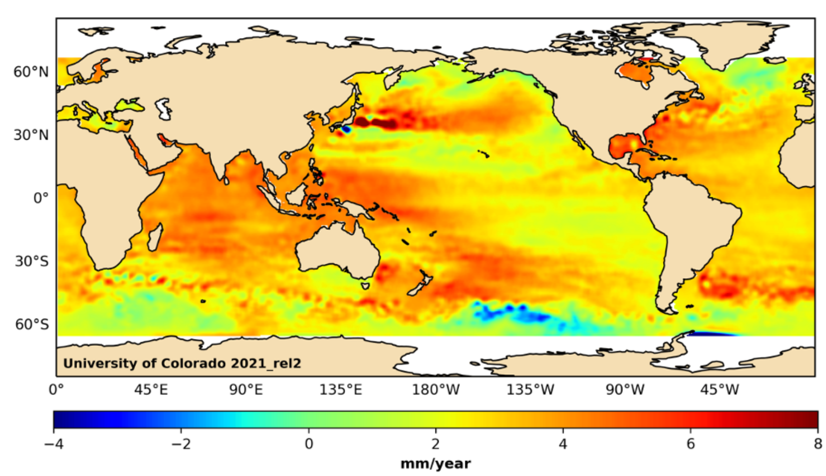

Figure 11: Regional trends in sea level rise for the 1993-2021 period. (https://sealevel.colorado.edu)

All of these factors, observable and quantifiable from space, provide a picture of the rate of sea level rise, its causes, its regional distribution, and coastal vulnerability to storm surges. These storm-surge events are also observable from space, predicted by operational satellites, and the damage assessed by commercial and other satellite observations.

Quantifying sea level rise, understanding its spatial variability, determining vulnerability, predicting coastal flooding, assessing the damage, and informing recovery are critical to our national interests, particularly considering that the effects of sea level rise on the order of 1 meter by 2100 is conservatively predicted to result in costs of hundreds of billions of dollars to the U.S. alone (Neuman et al., 2015). Our understanding of vulnerability in this area and the likely implications is all made possible by satellite observations, not just of sea level rise itself, but of the factors that contribute to it, and the factors that ultimately result in the water from these rising seas invading our shores.

Sea ice

While much of what I have addressed to this point is tied to phenomena that we see or feel directly in our country and on its shores, there is another area, seemingly far removed from our everyday lives, in which satellites have been critical in observing changes that have direct environmental, economic, and strategic impact. That is the disappearance of Arctic sea ice. The layer of ice that blankets the Arctic Ocean is a driver in the weather and climate of this nation, and has direct ties to economic and strategic interests. Since 1978, we have been able to track the extent and concentration of sea ice cover (Figure 12), using both civilian satellites and non-classified data from defense satellites, and since 2003, we have also been able to track its thickness (Figure 13). Both the extent and thickness are changing in ways that will have a profound impact on how we live and function.

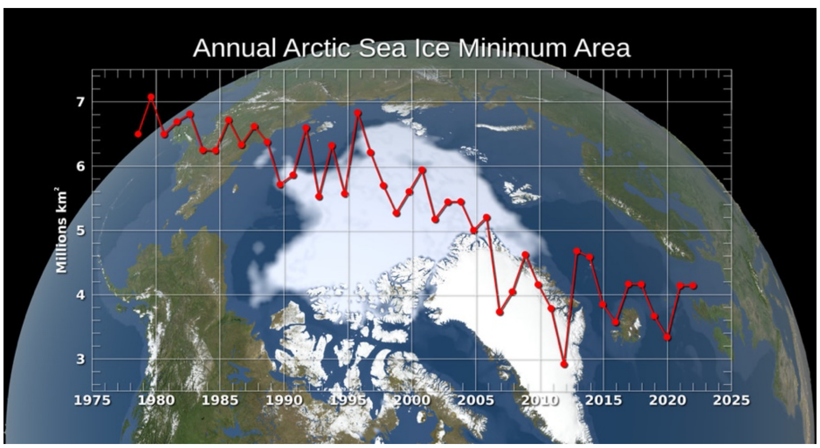

Figure 12: Annual extent of Arctic sea ice, at its minimum extent each year (late September) for the period 1978-2022. Minimum extent is indicative of the overall state, since it includes the ice that survives the summer melt season https://svs.gsfc.nasa.gov/5036

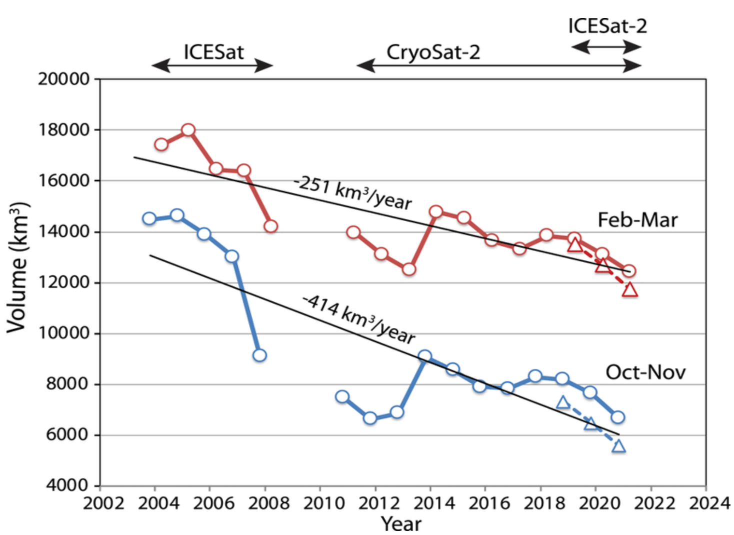

Figure 13: Arctic sea ice volume calculated from ICESat, CryoSat-2 and ICESat-2 ice thickness fields, for February–March (in red) and October–November (in blue). The Linear trends are calculated using estimates from longer time series of ICESat and CryoSat-2. (Kacimi and Kwok, 2022)

From a weather and climate perspective, modern civilization has never known an ice-free Arctic in the summertime, yet we are likely headed to such a state in the coming decades (Liu et al., 2022). The implications range from a disruption in the Earth's radiation balance, as the darker ice-free water absorbs more sunlight than is the case in its ice-covered state, to changes in ocean circulation and associated weather and climate phenomena, as the melting ice freshens the Arctic waters. The impacts for North America of these changes could be felt on time scales of days (weather), to months (seasonal climate), to years and decades. Successfully managing these changes requires information on where and how they are occurring, as well as information on the associated changes in the atmosphere and ocean – all of which are supported by space-based observations.

From an economic standpoint, an ice-free Arctic can offer tremendous commercial and trade opportunities as the Arctic Ocean becomes seasonally navigable, greatly reducing the transport costs between North America and Asia. Understanding the navigability, and planning out the most cost-effective routes, however, requires situational awareness, which requires observations that only satellites can provide. One of the challenges in observing the Arctic is that it is frequently cloud-covered. Many of our Arctic-observing satellites operate in the microwave portion of the electromagnetic spectrum, which allows them to "see" through clouds, enabling the tracking of sea ice, and assessment of its thickness, and navigability. As the shrinking trend of Arctic sea ice continues, an understanding of that trend can inform investments into Arctic navigation capabilities that could ultimately have tremendous economic payoff.

From a strategic sense, an ice-free Arctic and increased economic activity, creates an exposed marine border and vulnerable operations in the Arctic that will require the kind of security considerations and management that has not been necessary in the past. Such management will require situational awareness on scales that are best achieved through satellite coverage.

It is important to recognize that the behavior of sea ice, as is the case with sea level rise, occurs on scales that require observations that span hundreds, even thousands, of miles. Such observations are far beyond the capability of any sea-faring vessel. The satellites provide the scale of observation, and the context and perspective of change against a broader Earth system backdrop, to truly understand the nature, causes, and implications of such changes. It is also worth noting, with regard to the monitoring of Arctic sea ice and the shrinking high-latitude ice, the orbits of polar-orbiting or near-polar-orbiting satellites converge in the polar regions, offering far more frequent coverage then they do at lower latitudes, thus from a sampling perspective, polar regions are well-suited to satellite monitoring.

National Security

Finally, another extremely important dimension of U.S. interests, in which satellite observations are essential is in the national security domain. Understanding threats to military infrastructure requires knowledge of the kind described above. As one example, the Norfolk Naval Station is the largest in the world, and because of its situation in coastal Virginia, the risks associated with sea level rise are of great importance. The assets that observe sea level rise and inform predictions, as well as observations that enable weather forecasting and climate projections have direct implications for this base and its operations, particularly given its vulnerability to sea level rise. Other facilities are similarly subject to a range of environmental exposure for which knowledge of risks is essential for effective operations. Another domain in which satellite observations are very important is with respect to the theater of operations in conflicts involving U.S. forces. Knowledge in this domain requires intelligence on conditions on the ground and in the air and how they will evolve throughout the operations period.

In addition, the risks of conflict, which are driven by such matters as drought, resources, food access, etc., are informed by the access and information provided by satellite observations. Our understanding population migration and strategic actions of parties of interest benefit significantly from space-based observations. Many of these are acquired in the domain of the intelligence community and Department of Defense, but there are capabilities, such as weather forecasts, that are enabled by observations in the civil space domain that either fill gaps in or complement those in the classified domain.

This year the Office of the Director of National Intelligence (ODNI) released *The Annual Threat Assessment of the U.S. Intelligence Committee* (ODNI, 2022) in which it categorizes threats to National Security interests into eight topic areas:

- China,
- Russia,
- Iran,
- North Korea,
- Health Security,
- Climate Change and Environmental Degradation,
- Additional Transnational Issues, and
- Conflicts and Instability.

While the management of each of these threats benefit to some degree from space-based observations, Health Security and Climate Change and Environmental Degradation stand out as relying heavily on civilian satellite observations to enable their understanding and support predictions of future conditions and future threats. Similarly, as described above, assessing and anticipating conflicts and instability are supported substantially by such observations as well. With regard to climate change specifically, the 2021 National Intelligence Estimate (National Intelligence Council, 2021) further supports the importance of understanding climate change in a national security context.

Sustaining Important Observations

The capabilities in space-based Earth observations have advanced tremendously over the last two decades, with companies such as Maxar, Tomorrow.io, IceEye, Planet, Capella, and others developing capabilities with direct applications for commercial and government markets. These capabilities do – or will – provide robust and timely monitoring of fundamental Earth system parameters that include visible and thermal imaging, precipitation monitoring, all-weather surface conditions, surface deformation, etc. These efforts are quite impressive and represent a significant advance in the nation's capabilities to make cost-effective, economically valuable observations of the state of the Earth for various applications. There remain challenges however for securing important Earth observations for which there is great societal need but no viable commercial business model. While the economic value of visible imagery, for example, is intuitive, there are some variables needed to advance science, and that have a less direct benefit to specific applications of the sort that would generate paying customers.

While it may seem that such observations could be sustained by operational agencies, this is often not the case. Once NASA-sponsored efforts have demonstrated success in such observations, the resource-limited operational agency investments are, appropriately, targeted at fulfilling their operational functions, such as weather forecasting, in the case of NOAA, or land surface change and land-resource management in the case of USGS. There are variables that are vitally important to our success as a nation and society in planning for an evolving future state, but that don't have an operational benefit that directly aligns with these agencies' core mission and that don't lend themselves to commercial viability. Some examples of the most critical include:

- carbon monitoring to understand the evolution of carbon, its sources and sinks and its implications for atmospheric warming,
- precipitation amount and type, to better understand precipitation processes, which are critical for assessing drought, flooding, and water availability,
- mass change to track the movement of water throughout the Earth, including aquifer depletion and replenishment, as well as ice sheet and glacier changes and their impacts on sea level rise,
- the monitoring of incoming and outgoing radiation to assess the Earth's energy balance, and the degree of warming and cooling and how it varies with time and space,
- stratospheric ozone, to assess exposure potential to harmful ultraviolet radiation,
- tropospheric ozone, to understand the health risks associated with increases,
- soil moisture to assess water availability (and its evolution) for plant growth and drought conditions, and
- ocean salinity, to improve understanding of ocean circulation characteristics and the movement of heat by and through the ocean, in particular between the equator and the poles.

There are other variables of interest, and in some cases the military satellite observations provide data for civilian purposes (such as ocean winds). In other cases, private foundations provide support for very specific applications (e.g. methane and carbon dioxide monitoring). We also rely on international partners for some measurements that are not part of the US portfolio, as has historically been the case for synthetic aperture radar for example and will be the case for upcoming atmospheric composition observations.

U.S. Leadership

The United States has pioneered many space-based Earth observations and has also effectively partnered with international agencies to advance Earth observation and understanding. NASA has invested in and developed various technologies and capabilities that have pushed technological and scientific boundaries. Some of these sensors have transitioned to the operational communities; some have been taken on by the private sector, and some have been carried forward by international organizations. In this way, U.S. leadership in space-based observations has produced tremendous benefits for our nation and humankind. Success in the future requires a continued innovation on the technical and scientific fronts, as well as on the programmatic front. This is where the broader space-based Earth observing enterprise requires investments in the research and development (primarily NASA), development and operational use (agencies such as NOAA and the USGS), and the innovation of the private sector, bringing low-cost approaches to critical observational needs. The challenge is that, while each of these entities does its part and does it well, there are significant gaps in the broader Earth observing enterprise that will impair our ability to anticipate and prepare for environmental challenges and opportunities that lie ahead.

In addition, U.S. leadership is challenged by the limited degree of domestic talent to work on such capabilities. There is currently a great deal of competition for the appropriate skilled workforce across all related disciplines in science and engineering, with some of the various smaller start-up companies providing significant competition for the larger more established entities (such as NASA centers or the larger contractors). On the one hand, this is very good, as these start-ups introduce novelty and ingenuity into the pursuits, but at the same time, a robust workforce that supports a diverse set of capabilities is essential for U.S. leadership in this arena.

The needs are primarily in basic engineering - aerospace, mechanical, electrical, computer, etc., which includes robotics and autonomy, and the universities remain the key source for entry-level engineers. The limiting factor, however, is at the mid-career level engineers who, in addition to their domain expertise, have strong capabilities in systems engineering, in other words, people who are able to put all the components together to deliver a successful project. In addition, it is important that these systems engineers have a basic understanding of the science and applications for which these systems are being developed, so trade-offs can be assessed. Talent in this area is in high demand and of limited supply. They are aggressively sought by all types of organizations (small start-ups, large contractors, NASA centers, etc.), and competition is high. In some cases, the domestic labor workforce is not sufficient to meet these needs, and international talent is brought in. For the U.S. space-based Earth observation enterprise, the challenges are not so much at the entry level, but in the availability of seasoned mentors, to help these entry-level engineers evolve into project leadership roles.

Conclusion

These are just a few examples of the critical importance that space-based observations play in our lives and how they contribute to our livelihoods, safety, and prosperity. There are too many to comprehensively address for this hearing, but these examples make the point that such observations can positively impact how we live in a day-to-day sense, how we thrive as a nation, and how we succeed as a society on a changing planet. The benefits from such observations are realized in many sectors. Among them are:

- everyday citizens, who rely on forecasts in such areas as weather and air quality to plan their daily and weekly activities and make health risk exposure choices,
- the insurance industry, which relies on observations of risk, damage, and vulnerability to effectively insure the properties of people subject to potential environmental threats,

- land resource managers, who require intelligence on resource availability, risks and trends,
- water managers, who require information on current and predicted water availability, drought, usage, and related resources,
- coastal managers, who require information on sea level rise, land subsidence or uplift, coastal erosion, and storm forecasts,
- urban planners, who need to understand vulnerability of populations and structures to weather and climate related events, so they can plan accordingly,
- the transportation sector such as aviation and shipping (on land, sea, and via rivers), who need to understand and manage the navigability of rivers, the skies, and the oceans, all of which have tremendous impacts on supplies and costs of goods,
- farmers, who need to know the degree to which factors affecting crop health, crop yield and optimum times for planting and harvesting,
- ranchers, who similarly need to know the health of lands for grazing,
- the recreation industry (e.g. skiing, rafting, etc.), which relies on information about snowpack, river flow, vegetation health, etc. to plan their operations,
- those managing disaster response, who need to know avenues for evacuation and access;
- the military and national security communities, which need to understand threats to their resources, potential areas of resource-driven environmental conflict, conditions in theaters of operations, and potential vulnerability of U.S. assets, and
- elected officials and other policymakers who rely on credible information for policies such as resource management, federal flood insurance, rebuild vs. relocate decisions.

It is clear that space-based observations of Earth improve lives, enable us to manage environmental challenges, and provide great economic benefit. They do so by providing the context, scale, and perspective needed to characterize, understand, anticipate, manage, and respond to change. In so doing, they enable – and empower - individual, national, and societal success.

Thank you for the opportunity to testify and for your commitment to this important topic, and I look forward to your questions.

References

Chow, F. K., Yu, K. A., Young, A., James, E., Grell, G. A., Csiszar, I., Tsidulko, M., Freitas, S., Pereira, G., Giglio, L., Friberg, M., and Ahmadov, R., (2022). High-Resolution, Smoke Forecasting for the 2018 Camp Fire in California, *Bulletin of the American Meteorological Society* 103, 6; 10.1175/BAMS-D-20-0329.1

Church, J.A., White, (2011). N.J. Sea-Level Rise from the Late 19th to the Early 21st Century. *Surv Geophys* 32, 585–602. https://doi.org/10.1007/s10712-011-9119-1

Eidenshink, J., Schwind, B., Brewer, K. *et al.* (2007). A Project for Monitoring Trends in Burn Severity. *fire ecol* 3, 3–21. https://doi.org/10.4996/fireecology.0301003 comScore, Inc. (2014). "The U.S. Mobile App Report." August 14. https://www.comscore.com/Insights/Presentations-and-Whitepapers/2014/The-US-Mobile-App-Report.

Kacimi, S. and R. Kwok, (2022). Arctic Snow Depth, Ice Thickness, and Volume From ICESat-2 and CryoSat-2: 2018–2021, *Geophysical Research Letters*, DOI 10.1029/2021GL097448.

Lazo, J.K., R.E. Morss, and J.L. Demuth. (2009). 300 billion served—Sources, perceptions, uses, and values of weather forecasts. *Bulletin of the American Meteorological Society* 90(6):785-798.

Le Cozannet, G., Kervyn, M., Russo, S. *et al.* (2020) Space-Based Earth Observations for Disaster Risk Management. *Surv Geophys* **41**, 1209–1235. https://doi.org/10.1007/s10712-020-09586-5

Liu, J., Song, M., Zhu, Z. *et al.* (2022). Arctic sea-ice loss is projected to lead to more frequent strong El Niño events. *Nat Commun* **13**, 4952. https://doi.org/10.1038/s41467-022-32705-2

McKinsey Global Institute. (2017). *How Technology Is Reshaping Supply and Demand for Natural Resources*. February. https://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/how-technology-is-reshaping-supply-anddemand-for-natural-resources.

Milly, P. C. D. and Dunne, K. A., (2020), Colorado River flow dwindles as warming-driven loss of reflective snow energizes evaporation, *Science*, Vol. 367, No. 6483, pp. 1252-1255, DOI: 10.1126/science.aay9187

Musselman, K.N., Addor, N., Vano, J.A. *et al.* (2021) Winter melt trends portend widespread declines in snow water resources. *Nat. Clim. Chang.* 11, 418–424. https://doi.org/10.1038/s41558-021-01014-9

National Academies of Sciences, Engineering, and Medicine, (2018). *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space.* Washington, DC: The National Academies Press. https://doi.org/10.17226/24938.

National Intelligence Council (2021). *Global Trends 2040: A More Contested World*. ISBN 978-1-929667-33-8. NIC 2021-02339.

Neumann, J.E., Emanuel, K., Ravela, S. *et al.* (2015). Joint effects of storm surge and sea-level rise on US Coasts: new economic estimates of impacts, adaptation, and benefits of mitigation policy. *Climatic Change* **129**, 337–349. https://doi.org/10.1007/s10584-014-1304-z

NOAA National Centers for Environmental Information (2021). U.S. Billion-Dollar Weather and Climate Disasters. https://www.doi.org/10.25921/stkw-7w73

NOAA National Centers for Environmental Information, Climate at a Glance: Global Time Series, published March 2021, retrieved in April 2021 from https://www.ncdc.noaa.gov/cag/

Office of the Director of National Intelligence (2022), *Annual Threat Assessment of the U.S. Intelligence Community*. 31 pages.

Rodell, M., Famiglietti, J.S., Wiese, D.N. et al. (2018). Emerging trends in global freshwater availability. *Nature* (557)651 https://doi.org/10.1038/s41586-018-0123-1

Titley, D. (2016). "Cutting NASA Earth Observations Would Be a Costly Mistake," *Defense One*. December 2. http://www.defenseone.com/technology/2016/12/cutting-nasa-earth-observations-would-be-costly-mistake/133586/.

UN-Water. (2007). *Coping with Water Scarcity: Challenge of the Twenty-First Century*. http://www.fao.org/3/a-aq444e.pdf.

WHO (World Health Organization). (2016). *Burden of Disease from the Joint Effects of Household and Ambient Air Pollution* for 2012. http://www.who.int/airpollution/data/AP_jointeffect_ BoD_results_Nov2016.pdf.

WHO. (2017). "Malaria Fact Sheet," http://www.who.int/mediacentre/factsheets/fs094/en/.

Williams, A.P., Cook, B.I. & Smerdon, J.E. (2022). Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. *Nat. Clim. Chang.* 12, 232–234. https://doi.org/10.1038/s41558-022-01290-z