ENHANCING CLIMATE RESILIENCE AT NASA CENTERS

A Collaboration between Science and Stewardship

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NASA has developed a partnership between its Earth scientists and its institutional stewards to prepare for a changing climate and growing climate-related vulnerabilities.

National Aeronautics and Space Administration (NASA) scientists have been instrumental in discovering the nature of weather and climate hazards, yet their agency also has direct experience with their impacts. Power outages and electrical system damage from the tornado outbreak of 27–28 April 2011 closed Marshall Space Flight Center in Huntsville, Alabama, for 10 days. The Station Fire of August–October 2009, which burned a modern-record 250 sq. miles in Los Angeles County, reached within a mile of the Jet Propulsion Laboratory's (California) main campus adjacent to Pasadena (Fig. 1). Air quality concerns closed the Center, and employees, their families, and neighbors experienced evacuations and stress.

Coastal storms are another threat: Hurricane Isabel flooded portions of Langley Research Center (Virginia) in September 2003. Hurricane Frances in 2004 damaged Kennedy Space Center's (Florida)

FIG. 1. Recent climate extremes that have impacted NASA Centers. (a) Hurricane Frances, Sep 2004; (b) Damage to the Vehicle Assembly Building at the Kennedy Space Center from Hurricane Frances in Sep 2004; (c) Station Fire, Sep 2009; (d) Wildfires outside of the Jet Propulsion Laboratory in Sep 2009.

large Vehicle Assembly Building and other Center assets (Fig. 1). Hurricane Katrina in 2005 damaged buildings at Stennis Space Center (Mississippi) and the Michoud Assembly Facility (Louisiana) and displaced thousands of staff (some taking refuge at Stennis for several weeks). Hurricane Ike in 2008 caused flood and wind damage at the Johnson Space Center (Texas), with approximately three-quarters of all roofs sustaining at least minor damage (NASA 2008).

With $32 billion of constructed assets and about 60,000 employees, contractors, and partners, NASA's exposure to weather and climate hazards is not trivial. Its facilities include laboratories, launch sites, airfields, wind tunnels, data centers, and other structures that collectively occupy about 330 square miles, much of it also habitat for threatened and endangered species.

Changing climate alters, and in many cases compounds, the hazards to this infrastructure. The Intergovernmental Panel on Climate Change (IPCC; Field et al. 2012) reports that "it is virtually certain that increases (decreases) in the frequency and magnitude of warm (cold) daily temperature extremes will occur in the 21st century at the global scale." As sea levels, which have increased globally by 0.19 m over the past century (Church et al. 2013), continue to rise, coastal flooding is expected to increase as well (Wong et al. 2014). Two-thirds of NASA's constructed assets are within 5 m of sea level.

In light of such hazards NASA created an agency-wide partnership to better understand and respond to climate risks. In 2009, President Obama issued Executive Order 13514 entitled "Federal Leadership in Environmental, Energy and Economic Performance," which mandates that all U.S. agencies "evaluate agency climate-change risks and vulnerabilities to manage the effects of climate change on the agency's operations and mission in both the short and long term." NASA's program is thus part of the larger federal effort to provide scientific information to support decision-making around climate and weather-related issues (Melillo et al. 2014).

NASA's agency-wide partnership organizes management of climate risks and builds climate resilience at each Center through collaboration between Earth system scientists and institutional stewards (facilities managers, emergency management staff, natural resource managers, and human capital specialists). Thus far, local workshops have facilitated this management by covering planning for climate risks, analysis of climate data and projections for each Center, climate impact and adaptation toolsets, and Center-specific research and engagement. The collaboration between scientists and operations managers established in workshops is now fostering climate resiliency at NASA installations. The way NASA is enhancing resiliency puts its own science to work in a new, internally focused manner that could be a path other science-based agencies, companies, and institutions could implement to instigate their own climate adaptation measures.

Workshop observers from other federal agencies and local partners are now adopting elements of the NASA approach as well. For example, a General Services Administration (GSA)-led multipartner Greengov Spotlight Communities adaptation pilot in the National Capitol Region (www.epa.gov/fgc/spotlight/index.html) has been informed by NASA's adaptation process (Fig. 2) and the climate science information and communication approach developed for NASA's workshops (Ann Kosmal, GSA, 2013, personal communication). Agency neighbors also attend

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NASA workshops, since, as noted in a recent Government Accountability Office (GAO) report, "the climate-related challenges faced by these NASA centers are not unique . . . and can be instructive for other types of large federal facilities." One example is the joint coastal flood risk shared not only by NASA Langley and adjacent Langley Air Force Base, but also by the largest naval complex in the world, located in nearby Norfolk, Virginia (GAO 2013).

Fig. 2. The assessment framework used at the NASA resilience workshops (modified from Rosenzweig and Solecki 2010).

PREPARING FOR CLIMATE CHANGE. A key to this collaborative response is the Climate Adaptation Science Investigator (CASI) Workgroup. Established in 2010, CASI consists of NASA scientists and applications developers (along with additional experts from academia, the private sector, and nongovernmental organizations) who research climate vulnerability at NASA Centers and develop the scientific and technical basis for adaptation (Rosenzweig et al. 2011a).

Like the large cadre of researchers within NASA as well as the broader global science community, CASI members utilize NASA products to understand Earth's climate system, variability and change, and impacts. For example, they use the NASA Goddard Institute for Space Studies (GISS) global climate model (GCM) (Model E; Schmidt et al. 2006) to understand the dynamics of the changing climate; data from the Moderate Resolution Imaging Spectroradiometer (MODIS) along with ecosystem process models to track the impact of land use changes on ecosystem services in the regions where NASA Centers are located (Nemani et al. 2009); and data from the Clouds and the Earth's Radiant Energy System (CERES) (Wielicki et al. 1996) to estimate solar irradiance for modeling energy use and production on NASA buildings.

Through CASI, NASA scientists not only put these products to use, but also learn how their products impact decision-making, which feeds back on their research. Facilities managers at Goddard Space Flight Center, facing more stringent regulation and more intense precipitation events (Horton et al. 2014), have become increasingly focused on stormwater management. CASI scientists have responded by augmenting traditional analysis of how mean precipitation is projected to change with research focused on 1) changes in precipitation intensity and 2) local hydrology, in order to inform the land cover and water flow decisions required to meet regulations.

CASI provides NASA's managers with immediate access to climate and impacts science relevant to their Centers and regions. CASI's partnership of scientists with institutional managers brings together NASA's Earth science expertise and its culture of risk management attained through years of experience in spaceflight and other core missions. NASA's exploration, science, and aerospace technology work necessarily involves risk. In response to both its successes and failures—some of which included a weather-related component—NASA's leadership culture focuses on program risk management. U.S. space vehicle programs and spaceport operations have managed risks by incorporating them into design specifications, mission planning, operations, and decision-making processes (Alcorn et al. 2008).

Olga Dominguez, former Associate Administrator for NASA's Office of Strategic Infrastructure, recounts her experience in learning to communicate stewardship issues with Agency leadership. "I chose the language of risk—the risk the institution bears to the Mission if not adequately managed. Aligning communications patterns with leadership's intent that the NASA Mission comes first, is helping NASA's institutional stewards to set their priorities and receive the consideration they merit."

Climate resilience workshops. Through site-specific climate resilience workshops at NASA Centers, CASI engages internal and external stakeholders in identifying and understanding past, present, and future climate hazards and opportunities, characterizing risks, exploring responses, and developing efficient, sustainable management strategies.

To date, these workshops have initiated climate adaptation for over half of NASA's on-site staff, four-fifths of its managed land, and two-thirds of its constructed assets (Table 1). About 80 internal and external stakeholders participate in each workshop, including Center leadership, Earth scientists, and the institutional stewards. Similarly, external stakeholders (utility providers, community planners, and other interested neighbors) share their climate assessment and adaptation experiences and perspectives.

Each workshop follows an eight-step adaptation assessment process (Fig. 2) with breakout groups focusing on built systems, natural resources, and human populations. Built systems include buildings, test facilities, infrastructure, and utilities, while natural resources encompass storm and surface water, wildlife, air quality, and land use. The human population issues—emergency preparedness, health and safety, and human capital management—are faced by those working on and living near the installation. This adaptation process was extended from an infrastructure-oriented adaptation assessment in New York City (Rosenzweig and Solecki 2010; Major and O'Grady 2010; Rosenzweig et al. 2011b; NRC 2011). While early NASA workshops devoted approximately equal time to each of the eight steps, most workshop breakout time is now devoted to steps 1–4, since these steps lend themselves to immediate climate risk and adaptation brainstorming by a diverse group of participants.

Workshops catalyze the incorporation of climate hazard information and adaptation solutions into post-workshop management plans and processes (steps 5–7). For example, post-workshop activities at Langley Research Center have included 1) storm-hardening projects (focused on protecting buildings and electrical substations, upgrading HVAC systems and utility tunnels, and building or enhancing perimeter flood barriers for facilities on the Center's vulnerable eastern wing; 2) designing and implementing a new 22-kilovolt (KV) redundant electrical loop distribution system to improve electrical system reliability and maintainability by gradually eliminating antiquated 2.4-KV and 6.9-KV infrastructure; and 3) improving understanding of flood vulnerability by performing a lidar-based topographic survey with new elevation measurements for Langley Research Center facilities, and refining a flood impact analysis and visualization tool. Because the climate change adaptation process is iterative, all adaptation strategies must be reevaluated through time, which makes the development of an effective indicators and monitoring system (step 8) critical. Iterations need to take into account how the climate system is changing, impacts being observed, and improved understanding of adaptation strategies and their effectiveness.

Table 1. NASA's climate resilience workshop coverage of on-site staff participation, land managed, and constructed assets.

Share of NASA's assets covered by climate resilience workshops (%)				
Installation	**Workshop**	**On-site staff (%)**	**Land managed (%)**	**Constructed assets (%)**
Agency-wide	**7/2009**	**58,000**	**330 mi²**	**$32 B**
Kennedy Space Center, FL	5/2010	12.1	66.4	18.5
Ames Research Center, CA	2/2011	7.8	1.0	15.1
Dryden Flight Research Center, CA*	8/2011	2.4	0.4	1.2
Langley Research Center, VA	9/2011	6.4	0.4	11.3
Johnson Space Center, TX	3/2012	12.7	0.8	7.0
Stennis Space Center, MS	10/2012	7.1	9.9	9.4
Wallops Flight Facility, VA	11/2012	1.7	2.9	2.8
Total through 2012**		***50.2***	***81.8***	***65.3***

* As of March 1, 2014, Dryden Flight Research Center has been renamed Armstrong Flight Research Center

** Total reflects the 7 Center workshops

Climate observations and projections. CASI's climate researchers analyze observed climate trends and make projections for all NASA Centers. Most Centers show statistically significant (99%) warming trends since the beginning of the twentieth century[1] and all coastal Centers show significant (99%) sea level rise trends (Tables 2 and 3), mirroring global and national trends (Stocker et al. 2013; Mellilo et al. 2014).

Because climate variability and change will impact each Center differently, CASI tailors climate projections to each location. These regional temperature and precipitation projections are based on dynamical and statistical downscaling of GCM outputs.[2] Sea level rise and coastal flooding projections are based on both a GCM approach similar to that in Solomon et al. (2007) and a rapid ice-melt scenario as described in Horton and Rosenzweig (2010).

Regional climate model (RCM) projections from the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al. 2009) indicate average annual temperatures will climb faster this century than last. Averaged across eight GCM-RCM pairings under the high greenhouse gas emissions A2 scenario (Nakicenovic et al. 2000), projected warming by the 2050s relative to the 1980s ranges from 1.9°C at Ames Research Center in Moffett Field, California, to 2.6°C at Glenn Research Center in Cleveland, Ohio, with a 10-Center average of 2.2°C warming (Fig. 3).

The RCMs also project that yearly maximum temperatures will increase more than the summer mean temperatures at all Centers except Ames[3] (Fig. 3). This suggests that for most Centers, increases in the frequency of extreme heat events could exceed projected levels based on a common approach that applies a uniform warming factor from climate models to historical data (Tables ES2).[4] Additionally, the coldest temperatures per year are projected to increase more

Table 2. Observed temperature trends at NASA Centers. Data are for the nearest climate stations going back to the beginning of the twentieth century; all temperature trends are for the 1901–2008 period.

Center	Weather station	Temperature trend (°C decade^{-1})
Ames Research Center	Livermore, CA	0.16*
Dryden Flight Research Center	Fairmont, CA	0.10*
Glenn Research Center	Oberlin, OH	0.03
Goddard Space Flight Center	Beltsville, MD	0.20*
Jet Propulsion Laboratory	Pasadena, CA	0.18*
Johnson Space Center	Liberty, TX	0.04
Kennedy Space Center	Titusville, FL	0.07*
Langley Research Center	Norfolk, VA	0.21*
Marshall Space Flight Center	Huntsville, AL	–0.03
Stennis Space Center	Waveland, MS	0.06*

* Trend that demonstrates 99% significance

Table 3. Observed sea level rise* trends at NASA Centers. Data are for the nearest tide gauges with the longest data record available through 2008. Length of data record: Ames Research Center (1901–2008), Johnson Space Center (1910–2008), Kennedy Space Center (1913–2008), Langley Research Center (1930–2008), and Stennis Space Center (1924–2008).

Center	Tide gauge	Sea level rise trend (mm decade^{-1})
Ames Research Center	San Francisco, CA	19.3**
Johnson Space Center	Galveston, TX	63.6**
Kennedy Space Center	Key West, FL	22.6**
Langley Research Center	Sewells Point, VA	45.2**
Stennis Space Center	Pensacola, FL	21.8**

* Sea level rise is driven by a range of factors, including land subsidence
** Trend that demonstrates 99% significance

[1] Marshall Space Flight Center is in the southeast, one of only a few land regions globally with long-term temperature records that do not show warming over the twentieth century (Hartmann et al. 2013).

[2] Regional climate models (RCMs) are from the North American Regional Climate Change Assessment Program (NARCCAP) (Mearns et al. 2007, 2009). Statistical downscaling is based on the bias corrected spatially disaggregated (BCSD; Maurer et al. 2007) Coupled Model Intercomparison Project phase 3 (CMIP3) dataset. See supplemental material for more information about methods, additional projections, and uncertainties.

[3] These regional climate model simulations are for the A2 emissions scenario for a 30-yr hindcast period and for a 30-yr future period centered on the 2050s.

[4] This approach is known as the delta method (e.g., Gleick 1986; Arnell 1996; Wilby et al. 2004).

than mean winter temperatures for all Centers except Johnson and Stennis on the Gulf Coast.

These projections strengthen the argument that NASA Centers and other institutions should focus on extreme events in their climate risk management. For example, more extreme heat events could have outsized impacts on employee health and safety, while less extreme cold events would reduce the frequency of cold weather-related operations delays and thus reduce damage to infrastructure caused by freeze/thaw cycles.

Sea level rise of between 13 and 69 cm by the 2050s is projected for NASA's five coastal Centers and facilities along the coast (Table ES1).[5,6] CASI applied these sea level rise projections to historical hourly tide gauge data (as in Horton et al. 2010) to determine

[5] Sea level projections are regionalized using the method described in Horton et al. (2011); this approach, which includes regional and global terms, produces lower GCM-based projections (Solomon et al. 2007) as well as a rapid ice-melt scenario that is consistent with recent higher projections (e.g., Pfeffer et al. 2008; NRC 2012; Parris et al. 2012; Perrette et al. 2013; Slangen et al. 2014).

[6] The large range reflects uncertainty related to future rates of melting of land-based ice, primarily the Greenland and West Antarctic Ice Sheets (Rignot et al. 2011, 2014; Vermeer and Rahmstorf 2009; Van den Broeke et al. 2011; Joughin et al. 2014). Variations in sea level rise projections across Centers are small, and relate primarily to changes in land elevation due to glacial isostatic adjustment (Peltier 2001); extraction of groundwater, tectonics, and sediment transport among other factors (Lambeck et al. 2010; González and Tornqvist 2006; Dokka 2011; Shinkle and Dokka 2004); and differences in relative ocean height caused by factors including changes in ocean currents such as the Gulf Stream (Yin et al. 2009, 2010; Horton et al. 2011; Sallenger et al. 2012). Possible gravitational/isostatic/rotational changes as ice sheet mass is reduced (Mitrovica et al. 2001, 2009) were not included.

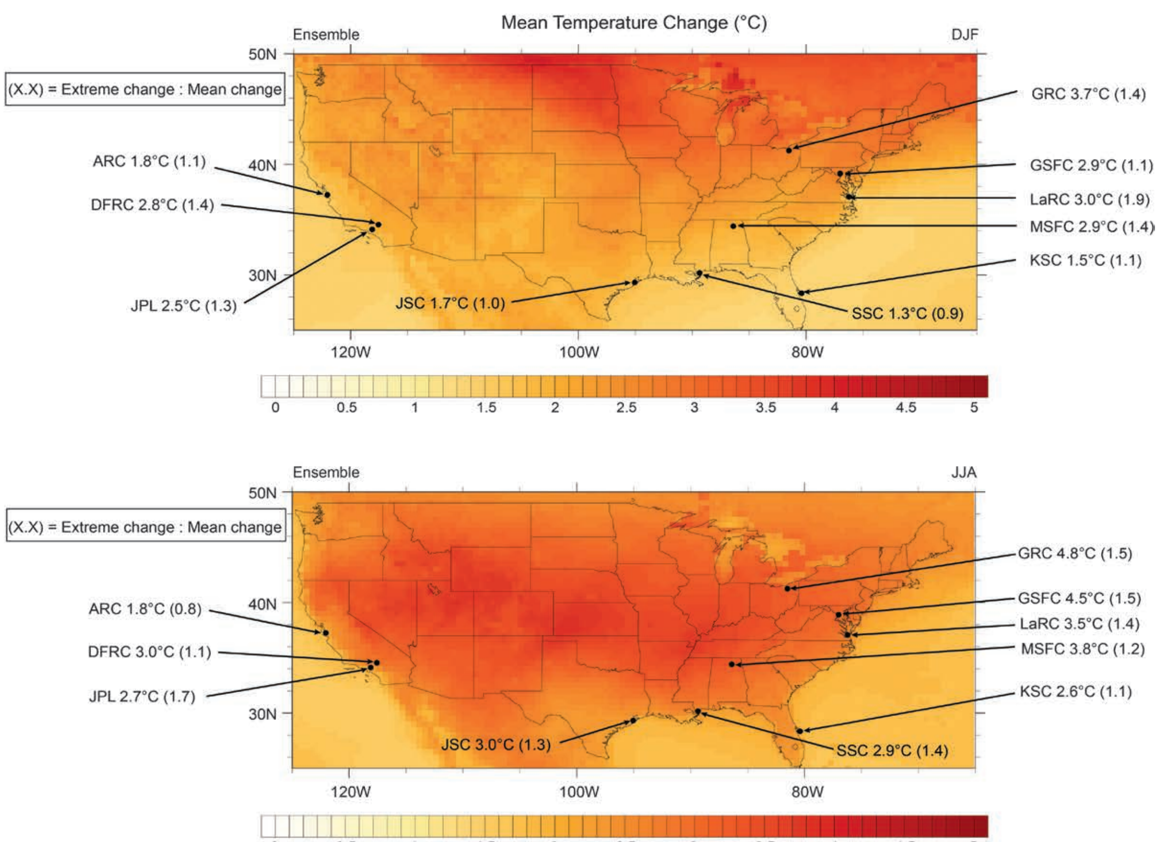

Fig. 3. Mean temperature changes (°C) for (top) winter (DJF) and (bottom) summer (JJA) for the 2050s A2 emissions scenario relative to the 1980s base period for an ensemble of eight GCM-RCM pairings from NARCCAP. For each NASA Center, the number to the right of the Center name is the projected temperature change (°C) in the coldest day per year (top) and hottest day per year (bottom). The number in parentheses is the ratio of the change in coldest (hottest) day relative to the mean changes for winter (summer).

how much sea level rise alone would modify the frequency of future coastal flooding events. Even under lower sea level rise scenarios, the coastal flood event that currently occurs on average once every 10 years is projected to occur approximately 50% more often by the 2050s in the Galveston/Johnson Space Center area; 2 to 3 times as often near Langley Research Center and Kennedy Space Center; and 10 times more frequently in the San Francisco Bay/Ames Research Center area. NASA coastal Centers that are already at risk of flooding are virtually certain to become more vulnerable in the future.

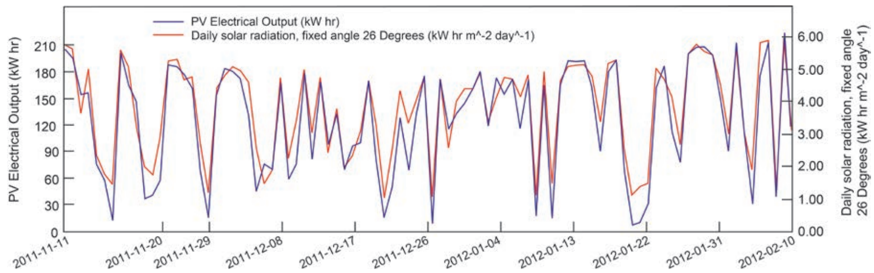

FIG. 4. Output from the RETScreen Plus software system showing the agreement between CERES FLASHFlux daily averaged surface solar flux (adjusted to the solar panel tilt angle) vs Solar Panel Electrical Output for a solar photovoltaic (PV) system attached to a building at the Langley Research Center. The RETScreen Plus tool is designed to provide monitoring, targeting, and verification analysis for renewable energy and energy-efficient technologies. (Figure courtesy of Gregory J. Leng and Urban Ziegler, RETScreen International.)

Climate impact and adaptation toolsets. CASI scientists are developing climate impact and adaptation tools to support Center decision-making related to energy, hydrology, and ecosystems.

CASI energy specialists are collaborating with Natural Resources Canada's RETScreen International team to model energy balance at NASA buildings, including production (e.g., solar power generation) and demand. Using NASA satellite and modeling data products as input, the newly developed RETScreen Plus energy management software monitors current systems, targets future energy efficiency goals using new technologies for existing or new structures, and verifies the result of any system change. CASI and RETScreen assessed the performance of a 39.5 kilowatt (kW) building-level solar panel system at NASA Langley Research Center. Analysis showed high correlation between solar irradiance[7] and the solar panel system electrical output (see Fig. 4). This energy assessment helped to refine system specifications, linked fluctuations in building energy use to atmospheric aerosols from a nearby forest fire, and related system performance to average solar conditions. CASI is incorporating climate projections into the analysis to assess the efficacy of mitigation and adaptation strategies for Langley Research Center buildings, such as solar power and building retrofits for energy efficiency. It also plans to use RETScreen Plus at other Centers to contribute to the development of their own energy-related climate change mitigation and adaptation strategies.

CASI hydrologists and ecologists are using NASA's Terrestrial Observation and Prediction System (TOPS; Nemani et al. 2009) model to analyze projected changes in hydrology and vegetation productivity at the Ames Research Center. TOPS integrates ground observations of climate and physical land cover conditions with NASA satellite observations and climate model projections. Downscaled climate projections from CASI are being combined in TOPS with land-use change scenarios of projected urban growth for two California watersheds: the Coyote Watershed, in which Ames is located, and the Upper Tuolumne Watershed, which contains the Center's water-supply reservoir (the Hetch Hetchy Reservoir) (Fig. 5a). In the Coyote Watershed, where up to a 60% increase in impervious surface area is projected by 2100 under a high-development urban growth scenario (Bierwagen et al. 2010), an increase in winter runoff is projected, and hence an increase in flood risk. In the Upper Tuolumne Watershed, located in the Sierra Nevada of California, projected warming as well as decreasing spring precipitation may cause earlier snowmelt and lead to runoff peaking up to two months earlier by the end of the century. This results in a shorter projected growing season (measured in terms of gross primary production, or GPP, an indicator of vegetation growth) and implies reduced water availability for Ames and an increase in energy costs (given the importance of hydropower) for the region (Fig. 5b).

Center-specific research and engagement. One of NASA's strengths is the diversity of skills across its

[7] Based on NASA CERES Fast Longwave and Shortwave Radiative Fluxes (FLASHFlux) data.

field installations. By conducting coordinated climate risk and adaptation research and engagement at its many facilities, NASA is able to address both unique and shared vulnerabilities. The sidebar titled "Kennedy Space Center and Space Coast Case Study" highlights ongoing activities at Kennedy Space Center and the surrounding region in Florida in recognition of the Center's importance to NASA and its vulnerability to climate hazards.

ADAPTATION AT NASA CENTERS. By developing climate adaptation strategies for local risks and impacts, NASA Center managers are able to reduce the negative effects of climate extremes and climate change. The following examples highlight specific adaptation strategies underway.

At Goddard Space Flight Center in Greenbelt, Maryland, situated in the Chesapeake Bay watershed, extreme precipitation, flooding, and stormwater management are major concerns. In response, grassy areas that previously required mowing are being replaced with natural vegetation and trees to reduce water flows into storm drains during high-intensity rainstorms. Additionally, rain gardens at key drainage points lower stormwater runoff from parking lots and filter the water that flows into storm drains. Together, these efforts will reduce the amount of polluted water that flows from the Center into Chesapeake Bay. Integrating projections of climate change into planning will help ensure that new projects will comply with stormwater regulations in the future.

Ames Research Center is responding to the risk of decreasing water availability by reducing overall water use and maximizing local water sources. Groundwater recovered as part of site-remediation efforts is recycled for cooling some research facilities, such as the Arc Jet and Unitary Wind Tunnel. Reclaimed water from a local wastewater treatment facility is used to irrigate grassy areas, while other landscapes have been converted to native, drought-tolerant plants. The Center has also transitioned to low-flow fixtures through a Utility Energy Services Contract. In response to the prospects of higher energy prices due to increased demand (in part for air conditioning as summer temperatures rise) and reduced hydropower availability, Ames has constructed a top-level (Platinum) Leadership in Energy and Environmental Design

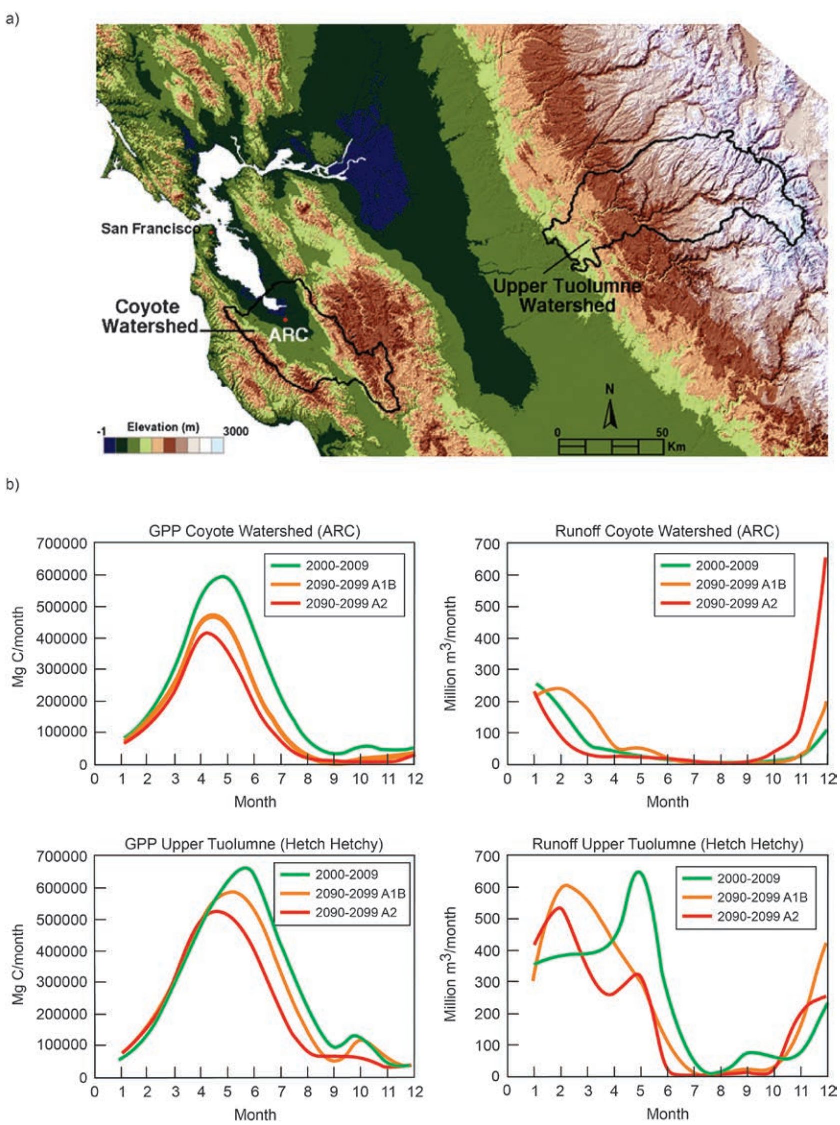

Fig. 5. (a) NASA Terrestrial Observation and Prediction System (TOPS) simulations for Coyote and Tuolumne (Hetch-Hetchy) watersheds. (b) In the Coyote watershed, as the biomass [gross primary productivity (GPP)] decreases, surface runoff increases. In the Upper Tuolumne watershed, warming is associated with a large decrease in biomass (GPP) and an earlier growing season. With earlier snowmelt, earlier runoff is projected, thus exacerbating summer drought risk.

KENNEDY SPACE CENTER AND SPACE COAST CASE STUDY

NASA began its climate adaptation work at the Kennedy Space Center (KSC) for several reasons. Its launch responsibilities are not broadly duplicated elsewhere, and its constructed assets would cost more to replace than at any other NASA site. Furthermore, extreme weather events have demonstrated its vulnerability to climate hazards since sand dunes that both protect KSC's launch pad sites and provide nesting sites for endangered sea turtles are periodically breached by nor'easters and hurricanes.

Assets at stake. Kennedy Space Center (which includes the Merritt Island National Wildlife Refuge) is adjacent to both the Cape Canaveral Air Force Station and the Canaveral National Sea Shore along Florida's east coast. The region has high biodiversity, rich ecosystem services, and national assets for assured access to space valued at roughly $10.9 billion (Breininger et al. 1998; T. Carlson 2012, personal communication; D. George 2012, personal communication). These structures include space vehicle launch and landing facilities, numerous vehicle and payload-processing facilities, fuel-handling systems, and industrial and office complexes. Tourism and recreation in the area, associated with KSC and the abundant natural resources of the Indian River Lagoon, have been valued at more than $3.7 billion annually (Hazen and Sawyer 2008). Using CASI sea level rise projections (Fig. SB1), NASA has identified a broad range of vulnerabilities, including facilities and structures, transportation, communications, energy, drinking water, wastewater, and solid waste systems, as well as protected species habitats and archaeological sites (Dewberry 2009; NASA 2010; Industrial Economics 2011).

Priority research activities. CASI is embarking on studies at KSC based on research and data needs identified in partnership with its management personnel. Topics include changes in extreme events and their impacts on launch hardware processing activities; heat indices and impacts on workforce and work scheduling; and effects of sea level rise and changing hydrological conditions on water table depth, a factor that influences plant community distributions, protected species wildlife habitats, and potential redistribution of chemical contaminants. Additionally, NASA-funded academic and private-sector teams are now working with CASI at KSC to investigate climate impacts on local mangrove populations, launch criteria, and sea level rise.

Interactions with area stakeholders. Recognizing the importance of information-sharing and regional coordination, CASI scientists and Kennedy Space Center managers have engaged with land managers from the U.S. Air Force, U.S. Fish and Wildlife Service, St. Johns River Water Management District, and the Environmental Protection Agency (EPA) Indian River Lagoon National Estuaries Program to discuss issues associated with wetlands and protected species habitats in the region. For example, after attending KSC's climate resilience workshop, Air Force staff of the 45th Space Wing began expanding evaluations of climate change risks and projected sea level rise impacts along the Space Coast as part of their management and planning responsibilities at both Patrick Air Force Base and the Cape Canaveral Air Force Station, adjacent to Kennedy Space Center. These evaluations include consideration of new facility designs that protect electronics and computers from storm surge, and land use plans that would site new construction away from the beach and dune area along the coast (D. George 2012, personal communication).

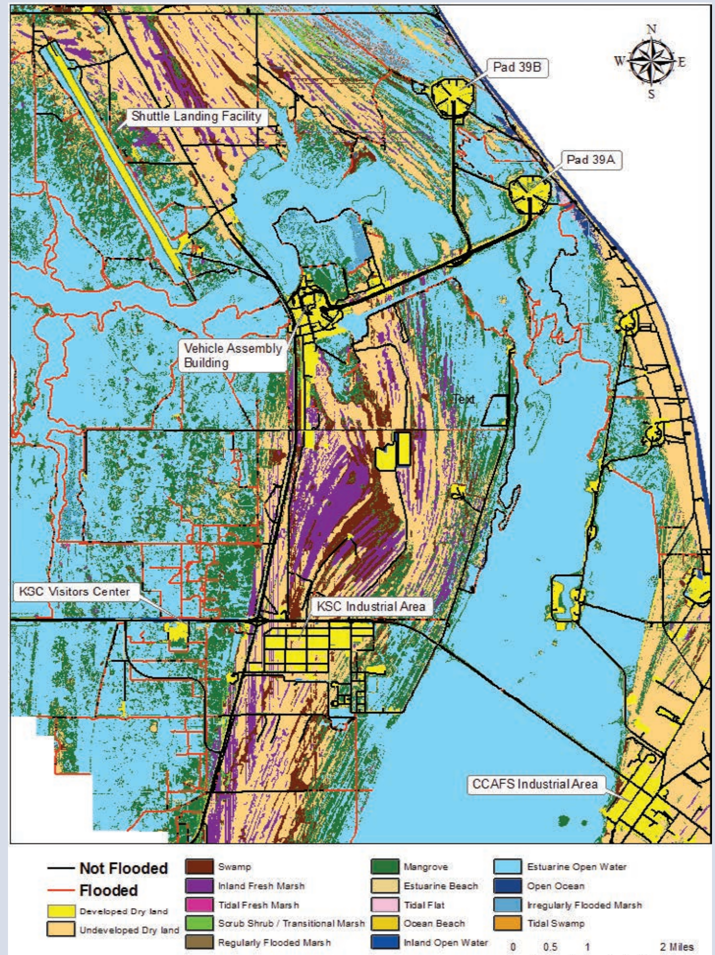

Fig. SB1. Potential flooding in the KSC environs based on the Sea Level Affecting Marshes Model (SLAMM) under a 1.2-m (NAVD88) sea level rise scenario. SLAMM output was developed in conjunction with the EPA Indian River Lagoon National Estuaries Program and Industrial Economics, Inc. (2011) utilizing CASI-developed climate change scenarios for KSC. In this scenario, most current wetlands in the region convert to open water and mangrove forest. Road inundation, during the annual fall period of maximum monthly mean sea levels, includes 11.5%, 30.5%, and 60% of primary (main arteries), secondary (paved), and tertiary (unpaved) roads, respectively. These roads are at or below 1.2-m elevation, so any combination of sea level rise, storm surge, wave-induced runup, and wind-driven seiches (standing waves) that raise the lagoon level to 1.2 m will inundate these areas. Duration of inundation will depend on magnitude and duration of individual events. These event-based inundations are projected to increase in frequency and magnitude as sea level rises from current elevation.

(LEED) building that provides both climate change adaptation and mitigation benefits. The CASI Ames team now coordinates with local agencies including the Fish and Wildlife Service, U.S. Geological Survey (USGS), Army Corps of Engineers, and Santa Clara County Water District.

At the Kennedy Space Center, coastal storms have been an ever-present hazard since NASA purchased 200 square miles of land in 1961, north and west of the Air Force launch pads at Cape Canaveral. Now, a Dune Vulnerability Team is addressing potential sea level rise and future storm-surge impacts to coastal facilities and infrastructure at Kennedy Space Center, especially Launch Pads 39A and 39B, which have played a critical role in space flight programs (NASA 1978, 2010). The Dune Vulnerability Team is designing an engineering approach to managing coastal erosion and preparing an environmental assessment under the National Environmental Policy Act (NEPA). Options to provide long-term protection of the launch sites include construction of a three-mile secondary inland dune, and dune and beach nourishment (NASA 2012). Climate risks have also been factored into the master planning process for ongoing twenty-first century spaceport facilities modifications and upgrades and the Kennedy Space Center 2012–2031 Future Development Concept (available online at http://kscpartnerships.ksc.nasa.gov/documents/KSC_FDC_Brochure.pdf). Finally, the Kennedy Space Center Sustainability Program is incorporating climate risk information in the planning process for facilities designs to address energy efficiency (NASA 2012).

CONCLUSIONS AND NEXT STEPS. While building climate resiliency at NASA is a long-term process, early CASI interactions and results hold promise. CASI strengthens the science community's commitment to understanding climate impacts, targets research to the needs of NASA institutional stewards, and equips those stewards through workshops and ongoing knowledge-sharing with a basis for proactive risk management.

The Agency's scientist–steward partnership reflects its commitment to deliver value to local communities as well as nationally and globally. NASA shares common resources including water and infrastructure with these communities. Sharing of climate risk information and coordinated planning in the broader areas where NASA Centers are located contribute to the development of regional climate resilience over the long term. Supporting a productive workforce depends on the well-being and climate preparedness of families, neighbors, homes, schools, and services.

Next steps for CASI involve both scientists and stewards. Scientists are integrating the newer global climate model [phase 5 of the Coupled Model Intercomparison Project (CMIP5)] results into the existing [phase 3 (CMIP3)] projection framework. It is also critical to advance understanding of why extreme climate events are projected to change. For example, how are extreme temperature projections influenced by changes in atmospheric dynamics (Liu et al. 2012) and the land surface (Seneviratne et al. 2010)? Researchers are also investigating how impacts of extreme events may change due to nonclimatic factors (e.g., population growth and land management). Next-generation sea level rise and storm surge projections are integrating advances in geodesy (Nerem et al. 2010), improved understanding of ice sheets and glaciers (Bamber and Aspinall 2013; Radic et al. 2014), and the global impacts of land water storage (Pokhrel et al. 2012).

On the stewardship side, site-specific workshops are helping the agency integrate efforts across its workforce, its natural systems, and its constructed assets with an emphasis on involving stakeholders from beyond NASA's fencelines. Future workshops may also focus on specific climate hazards and impacts. Additional management efforts include integrating climate risk and resilience into each Center's master plan. These initiatives catalyze integration of climate risk management into ongoing short- and long-term decision-making at NASA.

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