Integrated Climate Change Information for Resilient Adaptation Planning

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Awareness is growing that some air, water, and ecosystem impacts from climate change are inevitable due to the long residence times of key greenhouse gases (GHGs) (including CO_2, CH_4, N_2O) that are increasing in concentration as a result of human activities. Besides addressing the need to mitigate or reduce GHG concentrations in the atmosphere, efforts are now focusing on adaptation in order to minimize the impacts of climate change already underway, take advantage of any opportunities that may arise, and prepare for unavoidable future occurrences. While not directly attributable to climate change, extreme events in summer 2010 including the Pakistan flooding and Eurasian heatwave point to high background vulnerability and the great potential of adaptation strategies to reduce these vulnerabilities. To meet this need, transdisciplinary teams of scientists are working with stakeholders to provide the integrated knowledge base for the development of regional climate change adaptation plans. Regional-scale assessments are critical, since climate change impacts – on weather and associated air quality for example – will occur differently in different places.

Mitigation and adaptation need to proceed hand-in-hand. More than a quarter of the anthropogenic greenhouse gases currently in the atmosphere are due to human activities in the U.S., especially fossil fuel consumption (Marland et al., 2008). An important sink for CO_2 in the U.S. is natural vegetation, which scientists believe has been storing carbon through reforestation and longer growing seasons in the warming climate over recent decades; these vegetative carbon sinks in the U.S. are thought to have negated approximately 20 percent of U.S. carbon dioxide emissions (Pacala et al., 2007). A key question is how climate changes in the coming decades may affect natural ecosystems and the functioning of these sinks – will warming continue to cause vegetation to absorb further carbon or will a saturation point eventually be reached. Activities that strengthen ecosystems, such as preservation of forests may yield mitigation and adaptation co-benefits, by respectively preventing release of stored carbon dioxide to the atmosphere and reducing rainfall-induced soil erosion and flooding.

Uncertainties inherent in climate projections and physical, biological, and socioeconomic impacts pose challenges to U.S. decision-makers. Even though precise quantitative climate projections at the local scale continue to be characterized by high uncertainties, the existing local and scientific climate and adaptation knowledge summarized here can be instrumental in reducing vulnerability and building adaptive capacity. The way forward is robust decision-making under uncertainty (National Research Council (a), 2010). While some uncertainties are large, the science of climate change is clear and compelling (National Research Council (b), 2010; Gleick et al., 2010).

This article describes how regional climate projections may be used to identify key sector vulnerabilities and adaptation strategies, with a focus on health and ecosystems in the Northeast. It presents historical climate trends, methods for climate change assessments, future projections, and climate and air quality interactions in the U.S. Health impacts in a Northeast U.S. case study are described, along with approaches to vulnerability and adaptation assessment in New York City and Philadelphia. The integrated transdisciplinary approaches presented aim to provide decision-makers with relevant information as they develop adaptation plans, and to identify interactions between mitigation and adaptation that may lead to co-benefits as responses to climate change evolve.

Observed Climate Trends

Climate trends associated with human activity and natural variability have major implications for resource management.

Mean Temperature and Precipitation

Over the past 50 years, the U.S. has experienced a strong warming trend of more than 2ºF (USGCRP, 2009). As shown in Figure 1, observed precipitation in the continental U.S. has increased by approximately 5 percent over the past 50 years, although there is large regional variation (USGCRP, 2009). For example, most of the southeast has experienced decreasing trends, and portions of the extreme southwest have experienced large decreases in excess of 20 percent. Because natural variability is large at regional scales, distinguishing between climate 'noise' and the climate change signal associated with increasing anthropogenic greenhouse gas concentrations is not possible in many regions. However, as greenhouse gas concentrations continue to grow, the climate change signal is expected to become more prominent at regional scales.

Sea Level Rise

Over the past century, global sea level has risen by approximately 8 inches. In the US, sea level has risen in excess of 8 inches along the Atlantic Ocean and Gulf of Mexico coasts due to the added effect of land subsidence; portions of Alaska and the Pacific Northwest are unique in the U.S. in that uplift of land has exceeded sea level rise, leading to relative decreases in sea level.

Climate Extremes

Most of the U.S. has experienced an increase in warm extremes, and a decrease in cold extremes during recent decades (Meehl et al., 2009). In particular heat waves have become more common over the past 40 years (Kunkel et. al, 2008). As illustrated in Figure 2, the amount of precipitation falling in the heaviest 1 percent of rain events increased nearly 20 percent during the past 50 years (Kunkel et. al, 2008). During this time period, the greatest increases in heavy precipitation have occurred in the Northeast and the Midwest (USGCRP, 2009). Rising temperatures have also led to earlier melting of the snow pack in much of the country, especially the mountain west during the past three decades (Lemke et al 2007). This pattern, along with higher summer temperatures, has been linked to increases in forest fires since the mid 1980's as well (Westerling et al. 2006). There is some evidence of increases in recent decades in the frequency and intensity of the strongest tropical storms in some ocean basins, including the North Atlantic (Nyberg et al., 2007, Emanuel, 2005; Goldenberg et al., 2001) and the North Indian (Rao et al. 2008). While the robustness of these trends is limited, there is some indication that the mechanisms in the two basins may differ, with increasing upper-ocean heat content playing a key role in the North Atlantic (e.g. Emanuel, 2007) and decreasing vertical wind shear being a leading contributor in the Indian Ocean, with the latter also affecting Indian monsoon conditions (Rao et al. 2004, 2008).

Methods and Models for Climate Change Assessments

This section describes key resources and methods for climate change projections, with an emphasis on limitations that managers should consider as they incorporate climate change into their decision-making.

Global Climate Models

Global climate models (GCMs), the key tool for projecting future climate change, are mathematical representations of the behavior of the Earth's climate system through time. They simulate the movement and interactions of energy, moisture, and heat through the ocean, atmosphere, land, and ice. Representations of climate processes have become more complex as climate modelers have taken advantage of rapidly increasing computer power and greater physical understanding. When run in a 'hindcast' mode with accurate historical greenhouse gas concentrations, current-generation climate models are able to generally reproduce the warming that occurred over the 20th century at global and continental scales (Hegerl et al. 2007).

As the number of GCMs in use at research institutes around the world grows, assessment of future climate projections has factored in a range of model climate sensitivities[1]. The outputs of recent simulations have been collected and made publicly available by the World Climate Research Program (WCRP) and the Program for Climate Model Diagnosis and Intercomparison (PCMDI; Meehl et al. 2007a) (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php).

Although GCMs are the primary tools for long-range climate prediction, they do have limitations. For example, they simplify some complex physical processes, such as cloud physics and land-atmosphere processes. GCMs, with their spatial and temporal resolution constrained by

[1] Climate sensitivity is defined as the mean equilibrium temperature response of a global climate model to doubling carbon dioxide (CO_2), relative to pre-industrial levels.

limits to computational power, also have gaps in comprehensively representing some of the relevant climate forcings e.g., in the treatment of black carbon and aerosol-cloud interactions, land-use and land-cover changes, urban heat island effects, and solar variability.[2] For these and other reasons, local climate may change in ways not captured by the GCMs, leading possibly to temperature, precipitation, and sea level changes outside the range suggested by the Intergovernmental Panel on Climate Change (IPCC, 2007) projections described in Section 4.

Emissions Scenarios

To produce future climate scenarios, many GCM simulations have been made with projected GHG emissions/concentrations scenarios[3]. Figure 3 shows three GHG emissions scenarios (A2, A1B, and B2; see figure caption for definitions), available from WCRP/PCMDI, force the GCMs with greenhouse gas concentrations and other radiatively important agents associated with particular developmental storylines. Each represents a blend of demographic, social, economic, technological, and environmental assumptions about how the global and regional societies will progress in the future (Nakicenovic, 2000).

Downscaling of Global Climate Models

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[2] Changes in these additional factors are expected to have a smaller influence on climate change than increases in greenhouse gases during the 21st century.

[3] Many of the simulations being conducted for the IPCC Fifth Assessment Report will couple climate models with carbon cycle and other models in ‘Earth System Models’, which will incorporate more feedbacks among the main components of the climate system.

Despite the uncertainties associated with climate models, there is a need for climate information at the urban and watershed scales, for example, so that scientists and regional decision-makers can conduct impact and adaptation assessments and prepare adaptation plans. The spatial scale of cities and many watersheds is finer than the highest spatial resolution in current-generation GCMs, which do not resolve areas smaller than approximately 10,000 km^2. Regional climate models and statistical downscaling can help to address issues of scale.

Regional Climate Models

Regional climate models (RCMs) are similar to the models used for global modeling, except run at higher spatial resolution over a limited portion of the globe and with different representations of some fine-scale physical processes. The higher resolution helps to improve the depiction of land and water surfaces, as well as elevation, in the RCMs. Another advantage is that they do not depend on 'stationary' relationships because they are based on physical processes. Such stationary relationships may not be valid as the climate moves further from its present state. For example, regional climate models may be able to provide improved information about how changes in land-sea temperature gradients may modify coastal breezes in the future. Regional climate models can also play a key role in impact assessments, such as forecasting of air quality under changing climate conditions (Hogrefe et al., 2004)., although even RCM resolutions are sometimes too coarse to resolve important meteorological phenomena.

Because RCM simulations rely on high-quality global climate model boundary conditions or drivers, biases in GCMs are transferred to the RCMs, a problem that can be exacerbated by lack of feedbacks between the regional and global models. Furthermore, because regional climate modeling is computationally expensive, historically there have been few of the multidecadal simulations driven by multiple regional climate models needed for a robust assessment of model-based probabilities. The ongoing North American Regional Climate Change Assessment Program (NARCCAP) is designed to address this need for multi-ensemble high-resolution climate projections (Mearns, 2009).

STATISTICAL METHODS

Statistical downscaling is a low-cost downscaling approach that lends itself to multi-ensemble, multidecadal scenarios. Statistical downscaling links observed historical relationships between large-scale predictors (with the assumption that these are realistically simulated by bias-corrected GCMs) to small-scale predictands (the local information needed for impact analysis, which GCMs cannot simulate due primarily to their coarse spatial resolution). Projection skill of statistical downscaling depends on the continuance of these historical relationships, which may be modified by regional climate change, as well as the quality of the GCM predictors (Wilby et al. 2004). Statistical downscaling has been used extensively for impact assessment in the U.S. (e.g. Wood et al., 2004, and Hayhoe et al., 2007 and 2008). A useful set of statistically downscaled projected for the continental US is the Bias-corrected and Spatially-Downscaled (BCSD) Climate Projections at 1/8 degree resolution derived from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-model dataset. The BCSD projections are available at: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/ (Maurer et al., 2007).

UNCERTAINTIES IN DOWNSCALING

While these downscaling methods are useful, major scientific uncertainties remain related to lack of complete understanding of key basic processes (e.g., convection and clouds) and how regional climatic effects of land-sea contrasts, complex topography, and large-scale patterns of climate variability such as the El Nino Southern Oscillation may be modified by increases in greenhouse gases and other radiatively-important agents. While finer resolution is desirable, downscaling is not a cure-all for climate projection challenges.

Future Projections

In general, the rate of climate change during the 21st century is expected to exceed what has been experienced in the past few decades (IPCC, 2007); while this information can inform decision-making it is also important that uncertainties are incorporated into managers' decision-making processes.

Mean Temperature and Precipitation

The entire U.S. is expected to warm during this century, generally with the largest warming in the North (Figure 4a). Precipitation changes by contrast are likely to be mixed spatially and are characterized by larger uncertainty; increases are generally expected in the North while decreases are expected in the South (Figure 4b). The IPCC Fourth Assessment generated projections for the west, central, and eastern regions of the continental US[4] (Christensen, 2007). Projections were made for the 2080-2099 period relative to 1980-1999 based on 21 GCMs and the A1B emissions scenario. The middle 50 percent of values (i.e., the 25%-75% range of the distribution) for temperature and precipitation are presented here (this is

[4] Note that portions of Canada are also included in these domains.

the middle 50 percent of the model-based distribution; the true probabilities differ from the model results due to the uncertainties described above). In the west (30-75ºN, 50-100ºE), warming of 2.9 to 4.1 ºC is projected for the 2080s-2090s, with peak warming in summer and less warming in spring. Annual precipitation is projected to increase by 0 to 9 percent for the same period. In the central U.S. (30-50ºN, 103W-85ºW), warming of 3.0 to 4.4 ºC is projected for the 2080s-2090s, with a peak in summer of 3.1 to 5.1 ºC; precipitation projections cannot be distinguished from natural variability in the region. In the eastern U.S. (25-50ºN, 85-50ºW), warming of 2.8 to 4.3 ºC is projected for the 2080s-2090s, with high consistency across the four seasons. Precipitation in the East is projected to increase by 5 to 10 percent; the projected increase exceeds natural variability in the winter, spring, and fall, but not the summer.

Sea Level Rise

Sea level rise is expected to accelerate globally throughout the 21st century. IPCC-based approaches (Meehl et al. 2007b) indicate an increase in mean sea level of up to 2 feet in most coastal locations by 2100. Dynamical changes in polar ice sheets, not captured by GCMs, may accelerate melting beyond that level (Horton et al., 2008). A Rapid Ice-Melt Sea Level Rise scenario developed for New York City's Climate Change Adaptation Task Force addresses this possibility, based on extrapolation of recent accelerating rates of ice melt from the Greenland and West Antarctic Ice sheets and on paleoclimate studies that suggest sea level rise of up to 2 meters may be possible in the Northeast over the course of the 21st century (Horton and Rosenzweig 2010).

As noted in section 2, regional variation in sea level rise results from differential land motion throughout the U.S. Furthermore, relative ocean height may change with climate change.

For example, many studies suggest that a weakening of the Gulf Stream this century (Meehl et al. 2007b) may lead to higher ocean height increase along the east coast than is experienced globally (Yin et al. 2009; Horton and Rosenzweig 2010).

Climate Extremes

Resource managers in the U.S. will likely be dealing in the future with changes in the frequency, duration, and intensity of heat waves, cold events, intense precipitation, drought, and coastal flooding. The mean shifts in temperature, precipitation, and sea level described above are expected to have a large impact on these climate extremes, even if variability remains unchanged. Furthermore, it is climate extremes, not mean values, which produce the largest societal impacts (Meehl et al., 2007b).

EXTREME HEAT AND COLD EVENTS

By the end of this century, heat indices, which combine temperature and humidity, are very likely to increase over most of the country, both directly due to higher temperatures and because warmer air can hold more moisture. The combination of high temperatures and high moisture content in the air can produce severe additive health effects by restricting the human body’s ability to cool itself while placing strain on the electric grid when it is most critical to provide cooling for public safety. Because extreme cold events are expected to become less frequent, cold-related mortality may decrease.

INTENSE PRECIPITATION AND DROUGHT

Increases in the percentage of total precipitation associated with intense precipitation are expected (Meehl et al. 2007b), consistent with what is already being observed nationally (Karl and Knight 1998; Kunkel et al 2008).

At the same time, more evaporation is expected due to higher temperatures, leading to higher drought risk. Drought in many regions of the U.S. has been associated with local and remote modes of interannual ocean-atmosphere variability (see e.g. Namias 1966; Ropelewski and Halpert 1986; Gershunov and Barnett 1998; Dettinger et al. 1998). These major climate variability systems are currently unpredictable at multi-year timescales and may change with climate change. Changes in the distribution of precipitation throughout the year, and the timing of snowmelt, could potentially contribute to more frequent droughts as well. The length of the snow pack season is expected to decrease, leading to earlier spring peak river flows and flooding and heightened summer and fall drought risk over much of the U.S. More frequent and intense droughts are expected to result in increased risk of forest fires, with implications on regional climate and air quality, as discussed in Section 5.

Storms and Coastal Flooding

As sea levels rise, coastal flooding associated with storms will very likely increase in intensity, frequency, and duration. Any increase in the frequency or intensity of coastal storms themselves, which is highly uncertain, would result in even more frequent future flood occurrences. By the end of the 21st century, sea level rise alone suggests that coastal flood levels that currently occur on average once per decade in the Northeast may occur roughly once every one-to-three years (Horton and Rosenzweig, 2010).

Because future changes in critical factors for tropical cyclones are highly uncertain (Vecchi and Soden 2007; Gray 1984), regional impacts of future changes in hurricane behavior are difficult to assess given current understanding. Currently, it appears that intense hurricanes and associated extreme wind events will more likely than not become more frequent (Bender et al. 2010) due largely to expected warming of the upper ocean in the tropical cyclone genesis regions (Meehl et al. 2007b; Emanuel 2008). Intense mid-latitude cold-season storms are projected to become more frequent and shift further north (Kunkel et al. 2008).

Uncertainties in Future Projections

Because precipitation variability is large, there is a distinct possibility that regions will experience multi-decadal periods in which precipitation anomalies are of opposite sign to what is expected due to GHG forcing alone. In some regions, even the sign of the precipitation change associated with increasing greenhouse gases is not known. Because they tend to be local in time and space, changes in extreme events are generally characterized by high uncertainty as well.

For all variables, uncertainties generally increase with the length of the projection time from the present (i.e., the ranges of outcomes become larger through time) due primarily to uncertainties in the climate system (such as ice-albedo feedbacks, an example of a positive feedback that, if powerful, could lead to larger climate changes than those described above) and the differing possible pathways of the greenhouse gas emission scenarios (such as carbon cycle feedbacks). For the next 2-3 decades, the different emissions scenarios produce similar climate projections, which creates a policy challenge since some of the benefits of mitigation activities are deferred until later in the century.

Climate Change and Air Quality Interactions

One of the key challenges associated with climate change is the prospect of serious changes in air quality, from the global to the regional and local scales (IPCC AR4, 2007). While climate change is expected to exacerbate air quality degradation, many air pollutants can also affect climate in multiple ways. Changes in species due to climate change can result in either increases in other climate-active species or decreases, which, in turn, would represent positive and negative feedbacks, respectively, on the climate system.

Ozone – A Positive Feedback

A warmer future climate, featuring more of the greenhouse gas methane (CH_4), is expected to increase mean summertime ozone concentrations with larger increases during peak pollution events (Hogrefe et al. 2004, Weaver et al. 2009, Nolte et al. 2008). This is critical, since ozone in the lower troposphere is both a greenhouse gas and leads to respiratory problems. Furthermore, many chemical reaction rates as well as evaporative and biogenic emissions of volatile organic compounds (VOC) increase with increasing temperature. Possible changes in solar insolation (which is inversely related to cloudiness), air mass patterns and mixing heights associated with stagnation events further complicate projections of ozone and other pollutants.

Sulfate Aerosols – A Negative Feedback

In the Industrial era (i.e., since ~1860), fossil fuel combustion has led to an increase of sulfur gases emitted into the atmosphere. The oxidation and the condensation-hydration processes lead to the formation of sulfate aerosols (IPCC 2001). These particles are suspended in the troposphere and have typically lifetimes of a few days. Aerosols can enhance reflection of solar radiation both directly by scattering light in clear air and indirectly by increasing the reflectivity of clouds. On the other hand, dust and soot associated with fossil fuel combustion and other factors absorb radiation, thus warming the atmosphere. Anthropogenic aerosols act as cloud condensation nuclei and can affect precipitation.

The links among aerosols, radiation, clouds, and precipitation are topics of great importance in climate change research (e.g., Ramanathan et al., 2001; Levin and Cotton, 2009). Current global model studies using the best available estimates of aerosol forcing suggest that the sum of direct and indirect forcing by anthropogenic aerosols is negative (a cooling influence), on a global basis, offsetting a fraction of the warming influences of greenhouse gases. However, current global estimates of aerosol radiative forcing are quite uncertain (IPCC AR4 (2007)).

Unlike greenhouse gases, aerosol radiative forcing is spatially heterogeneous (Figure 5) and estimated to play a significant role in regional climate trends. The figure shows the direct effects of atmospheric aerosols and accompanying circulation changes on solar (shortwave; 'SW') radiation at the ground (solar dimming) and air temperature at 2-m throughout the day, as simulated by a coupled hemispheric meteorological and atmospheric chemistry model (WRF-CMAQ) (Mathur et al, 2010). Such coupled meteorological and atmospheric chemistry models are needed to characterize the spatial heterogeneity in the radiative forcing associated with short-lived aerosol and gases, and, consequently, to better understand their influence on regional climate and the radiation budget.

Win-wins and Win-losses

Curbs in human-induced methane emissions would likely improve health by reducing tropospheric ozone concentrations (West et al. 2006). While there are considerable uncertainties and complexities to be accounted for (e.g., Shindell et al. 2007) reduction in the linked chain of methane, tropospheric ozone, and health hazards is a potential "win-win-win" circumstance, with gains to be accrued in climate, air quality, and health hazard improvements.

Policy actions are being undertaken to reduce sulfur emissions since they degrade visibility and are a respiratory health hazard, especially in metropolitan areas. Sulfur-reduction technology has advanced considerably, in the form of scrubbers that can remove the plumes containing sulfur gases coming out of power plants. The short lifetime of these particulates implies that the consequences of emissions reductions can be discerned and measured immediately. This will have a climate impact that, unlike the methane/tropospheric ozone example, represents a "win-loss" situation – there is potential for rapid warming when the sulfates are removed (CCSP3.2). This amplified warming occurs because CO_2 and the other greenhouse gases have much longer lifetimes than the short-lived sulfate aerosols, and because their emissions and atmospheric concentrations are projected to continue to increase. Owing to the effects of atmospheric circulation wherein effects of forcing in one continent can be 'felt' at remote distances, the removal of sulfur in Asia over the next few decades can have a 'downstream' effect of higher warming over the North American continent[5] (Levy et al., 2008).

Health Impacts in the Northeast

While an analysis of the full suite of climate impacts throughout the U.S. is beyond the scope of this article (see for example USCGRP, 2009 for a more comprehensive survey of U.S.

[5] Note that for black carbon the net effect of removal would be one of potential downstream cooling, since black carbon is thought to cause net warming.

impacts), impacts on one sector and region are described to show how linkages between climate, impacts, vulnerability, and adaptation.

Several health risks in the Northeast will be more challenging to manage in a changing climate featuring increases in the frequency, intensity, and duration of some extreme events. Death and disease can result from episodic heat and air quality events, sea level rise-enhanced coastal flooding, and compromised water quality due to more extreme precipitation. Northeastern cities also share several unique vulnerability factors, including a geographic location that is downwind of major air pollution source regions from Ohio eastward, a dense network of urban infrastructure and residences near sea level, reliance on surface water supply for a substantial proportion of water needs, and widespread use of combined sewers that mix residential and storm effluents together. Further, the region's cities share a highly diverse distribution of population vulnerabilities across scales of age, economic position, and pre-existing diseases such as asthma.

Heat Waves and Air Quality

Extreme heat has a direct effect on mortality. Review of National Weather Service reports has shown inadequate warning systems to be an important mortality risk factor (French et al., 1983). A closely-related issue is urban smog events due to tropospheric ozone and fine particulate matter, which in the Northeast are often associated with high temperatures and regional air stagnation (Kinney, 2008). During heat events, peak load on electrical systems increases with greater use of air conditioning, leading to a heightened risk of brownouts or blackouts when the population is most in need of electricity[6]. Furthermore, during extended

[6] Heat can damage transformers and power lines by driving energy demand beyond their capacity (Miller et al. 2008). Heat can also directly cause power lines to fail or sag to dangerous levels (Hewer 2006).

periods of high energy demand associated with heat waves, there is often increased reliance on more-polluting back-up energy sources that contribute to air pollution.

Coastal Storms and Intense Precipitation Events

The degree of health and mortality impacts from heavy rains and coastal flooding events depends on the interactions between hazard exposure and the characteristics of the affected communities (Keim, 2008). Low-lying infrastructure and dense population introduce additional susceptibilities for communications, healthcare delivery continuity, evacuation, and thus affect community resilience.

Analyses of historical storm events have established the range of direct (e.g., death, injury and property damage) and indirect (e.g. psychological stress) long-term potential impacts of extreme weather on health (Greenough et al., 2001). Studies have demonstrated strong associations between extreme precipitation events and outbreaks of water-borne infectious diseases (Curriero et al., 2001; Fisman et al, 2005). Infectious disease impacts from flooding include creation of breeding sites for vectors (Ivers et al., 2006) and bacterial transmission through inadequately treated (for example due to turbidity in reservoirs) or untreated (for example due to combined sewer overflow events) water sources causing gastrointestinal outcomes. Chemical toxins (e.g., heavy metals, asbestos) can be mobilized from industrial or contaminated sites creating exposure pathways through standing water and recreation/green spaces (Euripidou, 2004). Elevated indoor mold levels associated with flooding of buildings and standing water have been identified as risk factors for cough, wheeze and childhood asthma (Jaakkola, et al., 2005; Bornehag, et al., 2001). Outdoor molds in high concentrations have been registered following flood events and are associated with allergy and asthma, with particular risks to children (Solomon, 2006). Mental health impacts have been among the most common and long-lasting post-disaster impacts. Stress of evacuation, property damage, economic loss, and household disruption are some of the triggers that have identified through recent work with populations in the Gulf Coast after Hurricane Katrina and the Midwest region after the recent floods.

Climate change impacts are often magnified in regions, sectors, and populations with high background vulnerability to hazards. For example, low-income communities may suffer high rates of pre-existing health conditions that increase the impact of climate stressors such as heat waves, air pollution, flooding, and water pollution. Because existing adaptation options may be particularly limited for the vulnerable, proactive and ambitious adaptation strategies should target vulnerable populations and sectors.

Developing Adaptation Strategies for the Health Sector in the Northeast

This section includes both practical examples of adaptation strategies, and more general guidance on best practices in the adaptation assessment process.

Specific Adaptations

The following are representative examples of health-relevant adaptations to a specific climate hazard—heat waves. Many of the adaptations are applicable to other sectors and hazards and require a regionally coordinated multi-sectoral response:

1. Stakeholder-inclusive research to map heat-wave vulnerability at fine geographic scales to target proactive interventions that build resilience, such as:

2. Emergency preparedness, warnings, and response
3. Provision of air conditioners,
4. Cooling centers
5. Redesign of buildings and open spaces to improve ventilation and reflectance
6. Reducing peak load and increasing clean energy supply,
7. Communication messages, and
8. Health literacy programs

The Need for Integration to Overcome Barriers to Adaptation in the Health Sector

More generally, there is a need for coordinated research identifying geographic, infrastructural and population-based vulnerability factors. To be successful, barriers related to data sharing and standardization and jurisdictional responsibility will need to be overcome. Furthermore, the ability of health stakeholders to effectively incorporate climate information into decision-making has often been hampered by inadequate communication channels for informing stakeholders about emerging climate science and impacts, as well as by a lack of capacity within agencies to understand and incorporate emerging science.

Partnerships between health, emergency management and the weather service offices in New York City and Philadelphia have led to innovative measures to anticipate and prevent heat-related impacts. The New York State Department of Environmental Conservation has developed sophisticated air quality forecast tools that are now being used routinely to announce bad air days. NOAA and EPA provide air quality forecasts over the entire continental United States; it has been demonstrated that these forecasts can be improved by applying bias corrections operationally (Kang et al. 2008, 2010).

Just as vulnerability reflects a blend of climatic and non-climatic factors, health-related climate change adaptation strategies must go beyond consideration of climate hazards. In one of the most comprehensive and coordinated adaptation efforts to date, the New York City Panel on Climate Change (NPCC) developed for New York City's Climate Change Adaptation Task Force an eight-step adaptation assessment process (see Figure 6) (NPCC, 2010). It was found that a process-based approach to developing climate resiliency that monitors and readdresses climate challenges through time is more likely to succeed than 'one-off' technical solutions. Another key finding was that analysis of historical extreme events can point to system vulnerabilities and illuminate which adaptation strategies are most likely to be effective in the future.

Summary and Recommendations

Climate change is expected to bring warmer temperatures and more frequent and intense heat waves to the U.S. Total annual precipitation may decrease in much of the southern U.S., and increase in much of the northern U.S. Rising sea levels are expected to increase the frequency and intensity of coastal flooding, and intense precipitation events are expected to become more frequent. Drought is also expected to become more frequent in many regions, due in large part to a combination of higher temperatures and earlier snow melt.

Climate hazards are likely to produce a range of health impacts in the coming decades. There are many types of risk-management adaptation strategies designed to reduce future impacts. Some adaptation strategies are also likely to produce benefits today, since they will help to lessen impacts of climate extremes that currently cause health effects, mortality, and damages.

Managers should note that regional climate and impact projections are only one part of successful impact and adaptation assessment. A policy challenge is presented by the fact that remote climate changes and impacts may rival the importance of local climate changes; for example drought-driven forest fires can influence downstream air quality and ecosystem and human health. Furthermore, impacts such as droughts are often regional phenomena, with policy implications (such as water-sharing) among jurisdictions that extend beyond state boundaries. Finally, since climate vulnerability depends on many factors in addition to climate (such as poverty and health), some adaptation strategies can be adopted in the absence of region-specific climate change projections.

Given the existing uncertainties regarding the timing and magnitude of climate change and impacts, monitoring and reassessment are critical. For example, expanded observation networks will improve understanding of the relationship between air quality and microclimate, facilitating short-term impact forecasting. Monitoring also plays a critical role in refining long-term projections and reducing uncertainties. Uncertainties of timing and magnitude point to the need for flexible adaptation strategies that optimize outcomes by recursively revisiting climate, impacts, and adaptation science rather than committing to static adaptations. Frequent science updates will help to reduce these uncertainties. Future projections can also be refined with greater coupling of models, including high-resolution regional climate models and energy models.

In terms of greenhouse gas mitigation, transdisciplinary integrated science and policy assessments at the local-scale are needed to determine sustainable solutions. Key elements will include technological innovation and economic investments in the fossil fuel and energy sectors, as well as improved understanding of carbon cycle and atmospheric chemistry feedbacks. The fact that greenhouse gases are well mixed, and inter-continental transport of pollutants is a widespread problem within and outside US borders, poses additional challenges in the nation's efforts to meet current and future air quality standards while minimizing climate risk and maximizing sustainability and quality of life.

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FIGURES

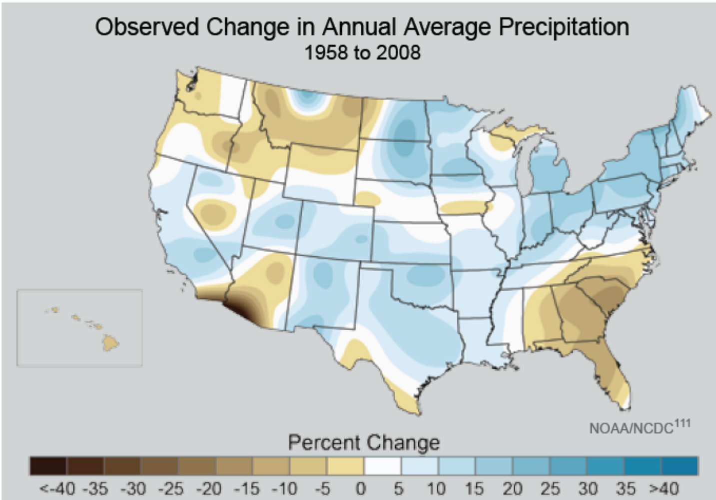


Figure 1. Source: NOAA/NCDC in USGCRP, 2009.

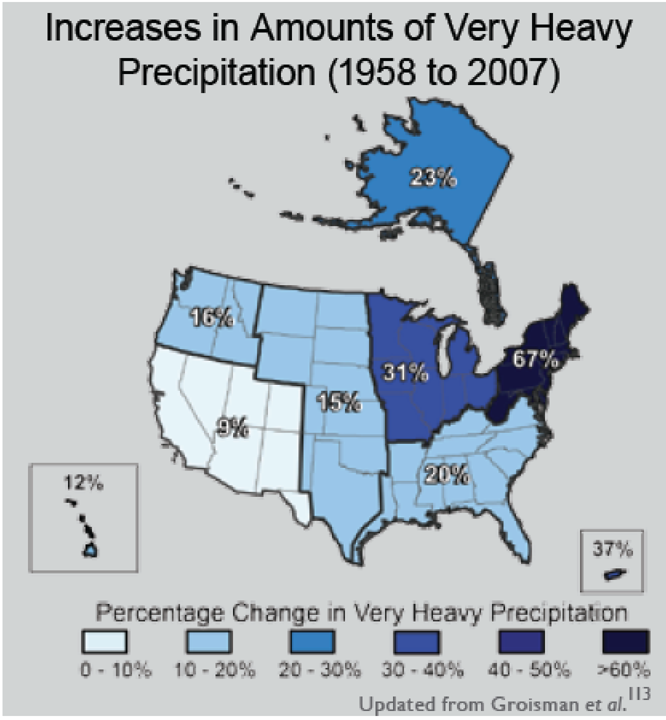


Figure 2. Source: Groisman et al. and USGCRP, 2009.

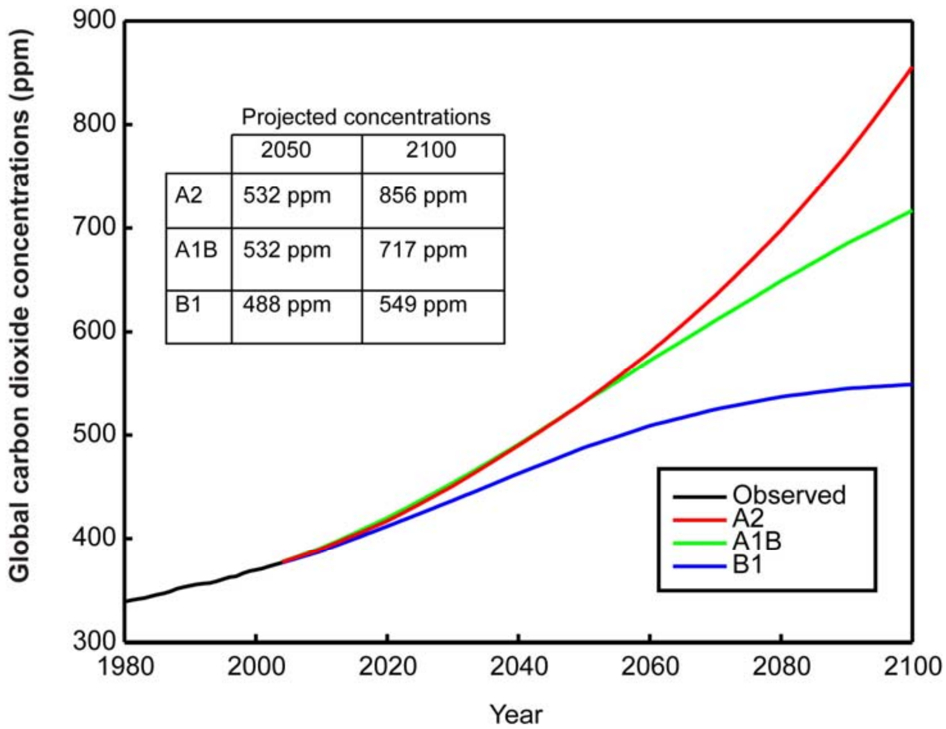


Figure 3. SRES Emissions Scenarios. Source: Columbia University/ CCSR.

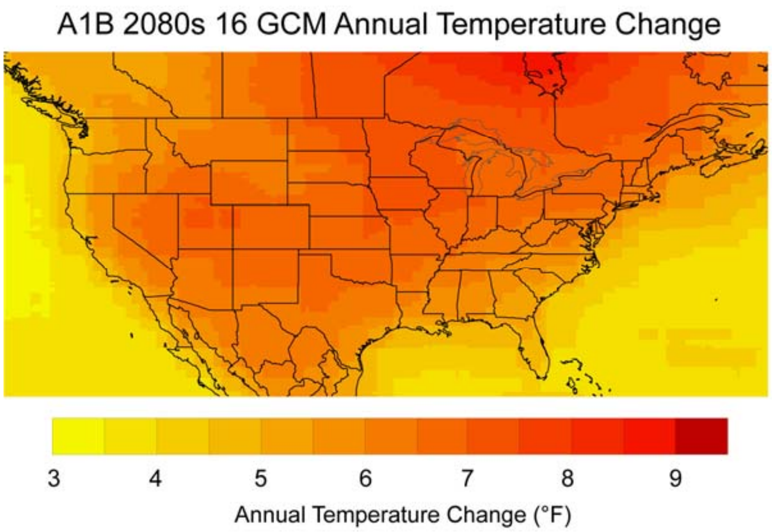
A2: *Relatively rapid population growth and limited sharing of technological change combine to produce high greenhouse gas levels by the end of the 21st century.*

A1B: *Effects of economic growth are partially offset by new technologies and decreases in population after 2050. This trajectory features rapid increases in GHG emissions for the first half of the 21st century, followed by a gradual decrease in emissions after 2050.*

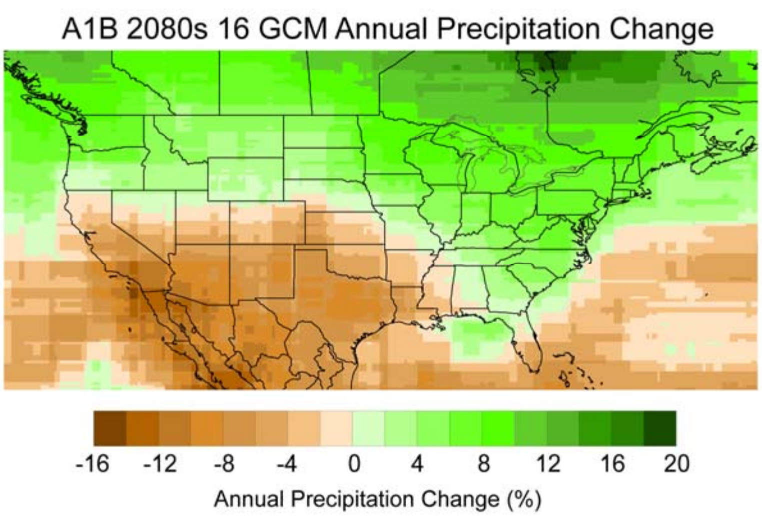
B1: *This scenario encompasses societal changes that reduce greenhouse gas emissions growth. The result is low GHG emissions, with emissions decreasing around 2040.*

Figure 4. a) Temperature change (°C) and b) precipitation change (%) for the 2080s timeslice relative to the 1970-1999 baseline, A1B emissions scenario and 16 GCM ensemble mean. Source: Columbia University/CCSR.

a)



b)



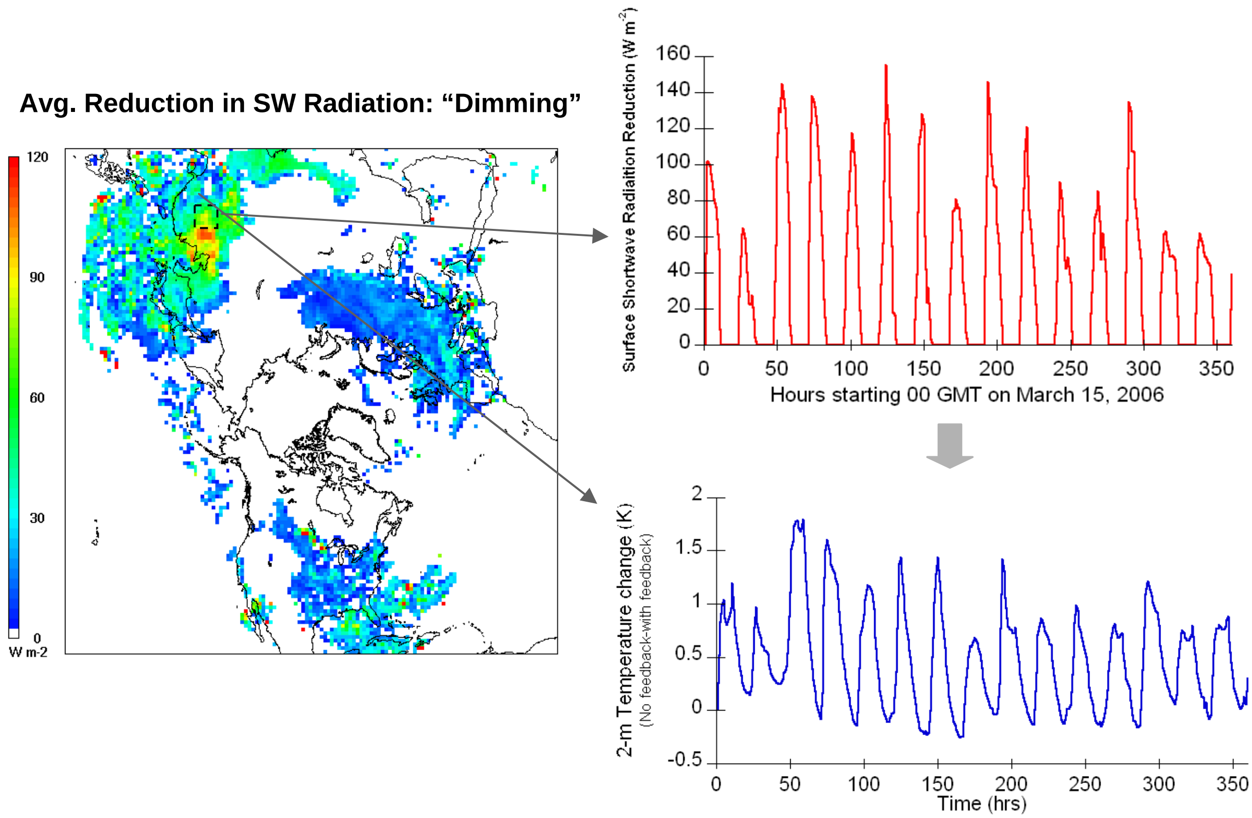


Figure 5: Spatial Heterogeneity in Dimming and Cooling Effects. These plots show differences between model runs without direct aerosol feedback and model runs with direct aerosol feedback.

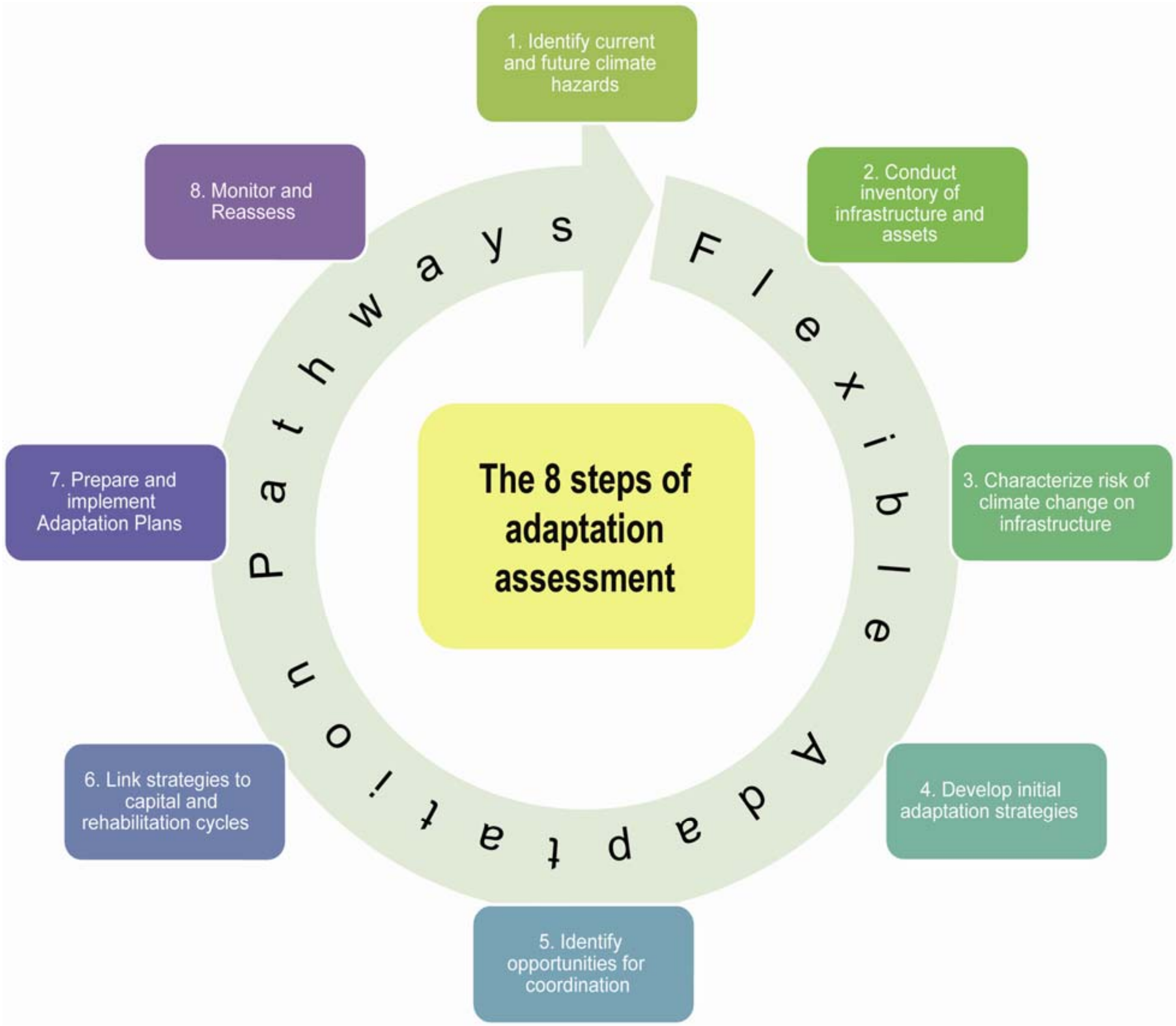


Figure 6: Adaptation Assessment Steps Developed by the New York City Panel on Climate Change (Source: NPCC, 2010)

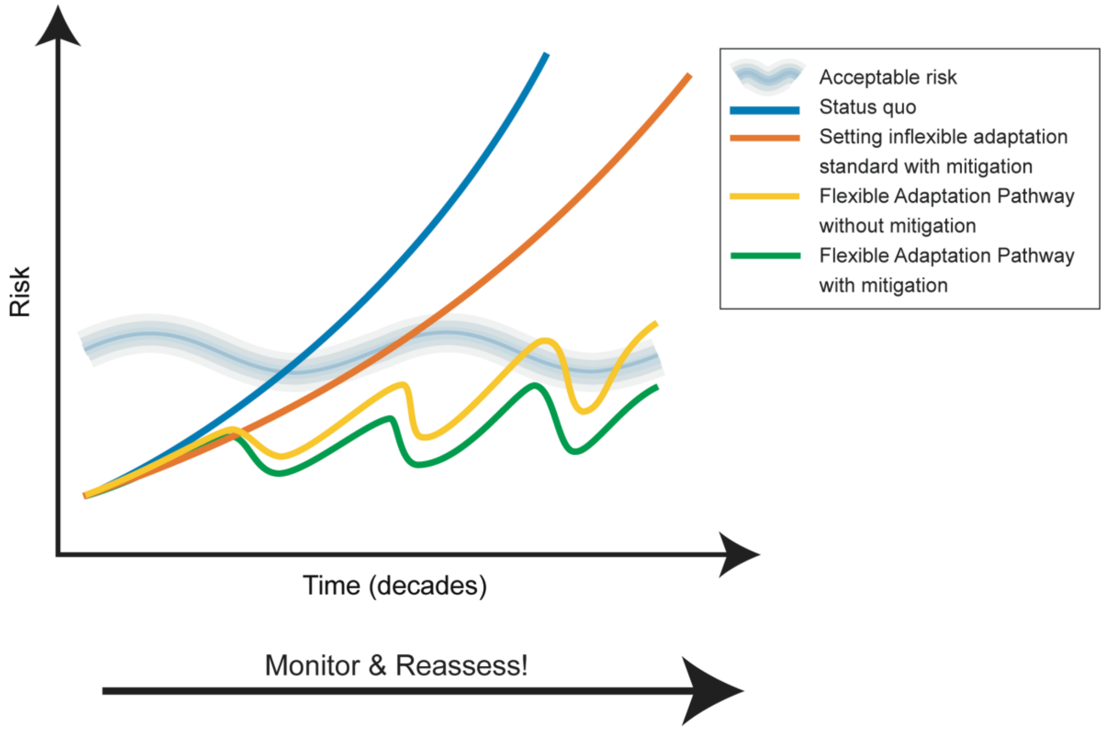


Figure 7. Flexible Adaptation and Mitigation Schematic. Source Columbia University/CCSR. Graphic adapted from: Lowe, J., T. Reeder, K. Horsburgh, and V. Bell. "Using the new TE2100 science scenarios." UK Environment Agency.

Societies and institutions have "acceptable level of risk" (represented by the light blue wavy line in Figure 2) that are likely to change over time. The royal blue line depicts a status quo trajectory for emissions and adaptation. The orange line represents risk reduction associated with a one-time static adaptation. The yellow and green lines depict Flexible Adaptation Pathways. The green line is an ideal in terms of risk management, creating Flexible Adaptation Pathways to adaptation alongside emission mitigation. This trajectory allows policymakers, stakeholders, and experts to develop and implement strategies that evolve over time.