establishment of standards for different types of deliberative and analytic processes.

Research, case studies, and pilot projects are testing approaches to meet these challenges, and a useful next step is to organize evaluation and social learning to establish good practices and technical guidance. One option is to incorporate evaluation into assessments such as the Intergovernmental Panel on Climate Change and the US National Climate Assessment to establish a knowledge foundation for climate services. This would create standards for services delivered through international organizations, the private sector, academia, and public agencies (to ensure availability of services for underserved, low-income communities) (*15*). Another is an open-source wiki for climate solutions that would enable a more diverse range of knowledge holders to interact and curate guidance on good practices on an ongoing basis, emphasizing sources of credible information.

Another opportunity is to expand the use of intermediaries—individuals and institutions that facilitate interactions between stakeholders and experts (*8*). Many intermediary skillsets are necessary for the different stages of deliberative planning, financing, tactical implementation, and ex-post monitoring of relocation actions. Given the potential for contested needs and values, it is important that intermediaries be aware of how they can unintentionally affect power relationships or outcomes—for example, by using types of knowledge, analysis metrics, or visualizations that favor the perspectives of one group or another. A "critical pragmatic approach" highlights the importance of this awareness and of designing and critically evaluating deliberative processes where conflicts between parties are not reduced to simple consensus-driven debates (*11*). A variety of measures are needed to increase the number and efficacy of intermediaries, including professional certification; greater recognition, including in promotion and tenure processes; and increased funding.

Harness emerging innovations in community science and data analytics

Innovations in community science, sensing, and data analytics hold great promise in providing insights for planned relocation if privacy, equity, and other concerns such as maladaptive applications of generic algorithmic or sensing tools are addressed (*15*). Combining these innovations with monitoring investments in socioeconomic data offers the potential to better capture the interdependent evolution of human and natural systems that shape the experiences and prospects of populations facing relocation. For example, high-resolution models of flooding magnitude and extent might be available for an area, but data are missing on how inequities in agency and justice interact with exposure to hazards to shape the prospects of using planned relocation to improve people's lives.

These innovations will increase the utility of standard modes of multidisciplinary scientific research that combine hazard predictions, engineering, financial, and other analyses to inform technical solutions that contribute to physical transitions. Additional methodological advances that have not yet been fully exploited include improved projections of hazards at various spatial scales; research on coastal habitat loss and nature-based solutions; new data sources, indicator-based assessments, and demographic modeling to identify vulnerable populations; and practice standards for using global change risk analytics in engineering and other professions. This contextualized technical knowledge can provide insights for sequencing transitional risk reduction and protection measures.

REALIZING JUST RELOCATION

Revolutionizing the role of science to focus on conditions that will affect the ability of society to identify just relocation pathways, build agency, and implement strategies under uncertainty will require a "pluralistic and integrated approach to action-oriented knowledge" (*6*). Such an approach will increase confidence in the ability of communities to successfully navigate planned relocation on the massive scales at which it is likely to be required. It must build a more ethical and responsible approach that serves those affected. ■

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POLICY FORUM

Assessing human habitability and migration

Integrate global top-down and local bottom-up analyses

By **Radley M. Horton[1], Alex de Sherbinin[2], David Wrathall[3], Michael Oppenheimer[4]**

Habitability loss is increasingly recognized as an important dimension of climate risk assessment and one with complex linkages to migration. Most habitability assessments, like climate risk assessments more generally, are based on "top-down" approaches that apply quantitative models using uniform methodologies and generalizable assumptions at global and regional scales, privileging physical sciences over social science–informed understandings of local vulnerability and adaptive capacity. Many assessments have focused on a single climate hazard threshold (such as permanent inundation or the 1-in-100-year flood), and a subset have implied that outmigration may be one of the few viable adaptation responses (*1*). There is a risk that such climate determinism minimizes the potential for human agency to find creative, locally appropriate solutions. Although top-down modeling can serve a useful purpose in identifying potential future "hot spots" for habitability decline and potential outmigration, only by integrating "bottom-up" insights related to place-based physical systems and social contexts, including potential adaptive responses, will we arrive at a more nuanced understanding. This integrated framework would encourage development of policies that identify the most feasible and actionable local adaptation options across diverse geographies and groups, rather than options that are deterministic and one-size-fits-all and encourage binary "migrate or not" deci-

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sions. We propose a set of recommendations centered around building the research and assessment knowledge base most needed to inform policy responses around habitability loss and migration.

DEFINING AND ASSESSING HABITABILITY

We define habitability as the environmental conditions in a particular setting that support healthy human life, productive livelihoods, and sustainable intergenerational development. Climate change may undermine one or more of the following associated, interacting, dimensions of habitability: basic human survival (*2*), livelihood security (*3*), and societies' capacity to manage environmental risks (*4*). Rapid rates of climate change and departures from historical variability ranges can increase risks, especially when coupled with nonclimate stressors. In such instances, threats to habitability may be evident in changing flows of human migration, whether forced or voluntary (*5*).

Most habitability assessments have relied on outputs from top-down models. This approach is conducive to system-level prediction, producing quantitative outputs that are globally comparable, such as single physical hazard thresholds that are either assumed or empirically based. Much recent work reflects a blend of long-term, high-resolution historical climate data where available, combined with projections across a large suite of global climate models driven by multiple representative concentration pathways (RCPs) representing trajectories of greenhouse gas concentrations. Another critical element is inclusion of extreme events, often expressed as a frequency of occurrence or a magnitude associated with a given recurrence period. In turn, top-down demographic and economic models, which form the basis for the shared socioeconomic pathways (SSPs) projecting global socioeconomic trajectories, provide a picture of future population and development that can also inform projections of people and assets at risk. Climate projections can also drive sectoral impact assessments—for example, empirically by extending historical statistical relationships between climate variability and the affected sector. More commonly, projections from standardized climate simulations drive sectoral impact models that dynamically simulate key features, such as crop growth. Top-down migration models use relative changes in sectoral impacts across regions along with other information as a means of projecting future population flows. Thus, these models project responses to habitability changes in regions where varying conditions may lead to outmigration, inmigration, or both.

The standardized nature of top-down methods facilitates comparisons—for example, of regions most at risk of crossing habitability thresholds associated with a climate hazard, and when. The top-down perspective can also reveal large-scale trends and interconnected features of global systems. However, there are several limitations. First, local and regional geophysical and sector-specific factors can drive hazards and risks at scales missed by global analyses. Second, less-modeled, place-specific characteristics of populations, such as health and socioeconomic status, shape both exposure and vulnerability. Third, adaptation choices and activities are embedded in historical context and culturally specific individual and community values and objectives that cannot easily be incorporated in models. Fourth, high-impact outcomes—associated, for example, with compound extreme events and abrupt changes in climate, ecological, and social systems—may be underestimated because of top-down model limitations such as the inability to credibly resolve evolving correlation structures across variables, space, and time, and key system sensitivities and feedbacks within and across systems (*6*). For example, climate phenomena teleconnected across great distances may lead to "breadbasket" failures in key food-producing regions and price shocks that can seriously reduce food security among vulnerable populations far away from the regions experiencing the climate stress.

Fortunately, top-down approaches are increasingly being paired with bottom-up approaches that offer a specificity that can help address these challenges. Bottom-up conceptual and/or computational modeling of complex adaptive systems can be designed to simulate the local experience of losing habitability over time. In the breadbasket case above, models of local responses can be paired with global models of international food trade that set boundary conditions. For example, agent-based models (ABMs) set up simulations with agents empirically calibrated to behaviorally respond to changing environmental conditions: the loss of assets and livelihood opportunities, threats to life, and changing structure of social networks. Modeling can be trained on local data to understand and predict important feedbacks at higher spatial and temporal resolution than is possible with global models. ABMs can be calibrated to examine a range of individual-actor preferences and test the effect of local decision-making to plausibly depict trade-offs among adaptation options, including migration (*7*). As another bottom-up example, qualitative information can be coproduced with diverse stakeholders, including subject matter experts, to explore high-impact scenarios and local solutions that will be missed by top-down approaches. Of course, bottom-up approaches have their limitations as well. For example, their specificity makes it difficult to compare across geographies and groups, and individual methodological decisions can appear arbitrary. Furthermore, bottom-up computational models such as ABMs are still limited by a lack of empirical data with which to calibrate model parameters.

CLIMATE HAZARDS AND HABITABILITY

Here, we walk through the habitability challenges of two climate hazard examples, demonstrating the strengths and limitations of top-down approaches and how bottom-up perspectives lead to different policy-relevant insights.

Sea level rise and extreme sea level events

Recent years have seen growing complexity and nuance in assessments. Global assessments have supplemented climate model outputs by considering a broad range of sea level change components and including, for example, expert elicitation as a means of estimating low-probability, high-consequence outcomes (*8*). High-spatial-resolution digital elevation models and consideration of changes in the frequency and intensity of societally relevant metrics such as recurrence intervals and extreme values of coastal high water have been integrated into global products. Using many of the above advances, Kulp and Strauss estimated that the number of people exposed annually to coastal flooding under constant population could increase from 250 million people today to, by 2100, 310 million to 420 million under an intermediate scenario to 380 million to 630 million under a high-end scenario (*1*). Other studies have included changes in storms, hyper-local positive correlations between population density and subsidence, population projections consistent with SSP-RCP combinations, and assets at risk.

Additional refinements have focused on specific coastal locations, adding critical context at the expense of global information. For example, Storlazzi *et al.* framed their assessment of tipping-point risks to atolls around two metrics—annual overwash events that threaten infrastructure, and salinization of groundwater—that are specifically relevant for atolls given their small size, uniformly low elevation, and relative isolation and found that habitability is threatened in most atoll islands by the middle of the 21st century, far sooner than permanent-inundation–based studies would suggest (*9*). Some local studies have included dynamic interaction between coastal waters and adjacent landforms. Other local and regional studies have considered social dimensions of human vulnerability, as well as in situ adaptation, using empirically calibrated agent-based livelihood decision models that span multiple climate, RCP, and SSP scenarios (*7*).

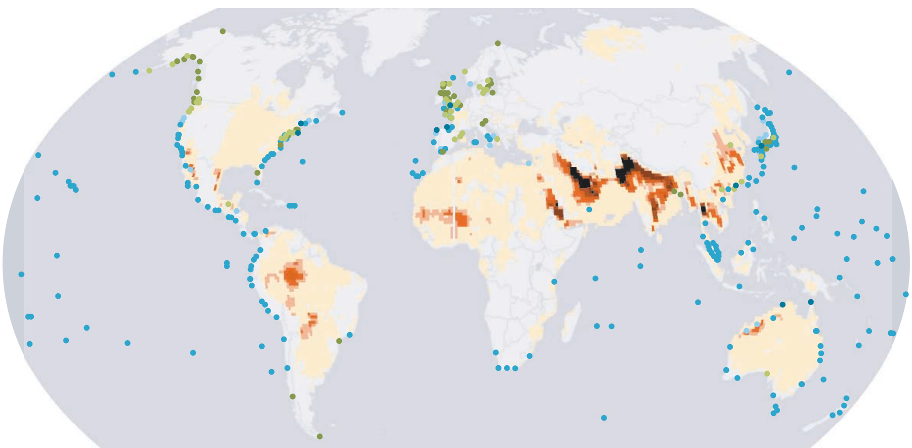
The three dimensions of habitability demonstrate why no single coastal flood metric threshold can be determined in a top-down way. For the direct survivability dimension, key factors include future flood control, feasibility of evacuation, and the stochasticity of individual storms. For livelihood, saline intrusion, for example, could benefit some sectors such as specialized aquaculture, even as it harms most sectors and people. And for the societal resilience dimension, large-scale factors such as levels of inequity, strength of governance and social networks, and quality of infrastructure will be critical. As sea levels rise and coastal flooding becomes more common, social, economic, and political factors in some locations will conspire to induce sudden loss of habitability far sooner than physical hazard–based thresholds such as permanent inundation would suggest, as risk perception and long-term economic viability shift. For example, increases in insurance premiums could negatively affect asset values and tax revenues, leading to deteriorating infrastructure and services. The timing of such threshold-crossing cannot be predicted on the basis of top-down models alone. In some instances, shocks can lead to rapid learning, adjustment, and in situ adaptation, at least temporarily.

Frequent exceedance by 2100 of historically rare climate thresholds

Under the high-emissions scenario RCP8.5, at most coastal locations extreme sea level events historically defined as 1-in-100-year events are projected to range in frequency from once per year to more than 10 times per year due to the effects of sea level rise alone. Only point locations where historical event data are available are shown. Projected number of days per year by 2100 exceeding a 33°C wet bulb globe temperature (WBGT) in a high-emissions scenario are also depicted. Under standard assumptions of wind and solar radiation, a WBGT of 33°C corresponds to a wet bulb temperature of roughly 31.5°C. [Sea level data are from figure 4.12 in (*8*); WBGT data are from figure 3 in (*12*).]

Extreme sea level (occurrences per year) 1–3 | >3–6 | >6–9 | >9–12 | >12

WBGT return periods (occurrences per year) >50 | >40–50 | >30–40 | >20–30 | >10–20 | >5–10 | >0–5



GRAPHIC: N. DESAI/*SCIENCE* BASED ON HORTON *ET AL.*

Extreme heat

Most assessments of future heat hazards have considered temperature only, although recent efforts are increasingly adopting a compound events framework—for example, considering how co-occurring extremes of high temperature and high humidity can modulate threats to habitability. Humid heat is particularly harmful to human health and the ability to engage in outdoor activities. Sherwood and Huber described a wet bulb temperature of 35°C as a threshold above which humans could not survive beyond approximately 6 hours owing to physiological and thermodynamic limits on the ability to cool through perspiration (*2*). Model-based studies have projected that this threshold could be crossed in the Persian Gulf and South Asia during the second half of the 21st Century under a high-emissions scenario (*10*). However, a finer-scale study found that this threshold has already been briefly crossed multiple times in populous cities.

Although an absolute habitability threshold exists for the survivability dimension of extreme humid heat, some people will lose their ability to thermoregulate at much lower wet bulb temperatures. Mortality rates of the elderly, those with chronic health conditions, and those involved in strenuous activity rise dramatically well below the 35°C wet bulb threshold. In terms of the livelihood dimension, at ~3.5°C of global warming above preindustrial levels, de Lima *et al.* project that in Sub-Saharan Africa and Southeast Asia increases in humid heat may decrease agricultural labor productivity by 30 to 50%, leading to larger agricultural sector impacts than are associated with direct temperature and CO_2 effects on crops (*11*). However, air conditioning and other adaptations will enable—indeed, have enabled—some people to continue to live in places that exceed the 35°C threshold. Such an outcome increases inequity because those with no option but to work outdoors, or no access to affordable air conditioning, would be forced to migrate. And even for those with air conditioning, the third dimension of habitability—society's capacity to manage environmental risks—will be tested in unforeseen ways because it will be critical that air conditioning not fail.

Sea level rise and extreme humid heat are far from the only climate hazards that have been assessed in the literature for potential habitability thresholds. For example, changes in surface moisture fluxes as mean precipitation and temperature shift are projected to have large impacts on dryland agriculture, fire regimes in forests, and water availability downstream from snow and glacier reservoirs. These and other hazards and impacts may overlap and interact across scales to affect habitability in complex ways, such as by potentially increasing the risk of conflict.

Areas where current-day rare extreme sea level and humid heat events will occur with high frequency by the end of the century under a high emissions scenario of sea level rise and warming are identified in the figure (*8*, *12*). The two metrics, corresponding to the current 1-in-100-year extreme sea level event and a wet bulb globe temperature of 33°C, respectively, are emblematic of top-down approaches. They thus represent an important point of entry for engagement with the bottom-up insights described above, as a step toward more nuanced habitability and migration assessments.

LINKING HABITABILITY TO CLIMATE MIGRATION

Migration may result from threats to survival, upended livelihoods, or the breakdown in the collective capacity to adapt (*5*). However, research on climate change and migration makes clear that an even broader set of factors undergird migration decision-making. A decision to move is ultimately a personal or household judgment on factors that include local habitability. Involuntary migration occurs when people lack agency about the key dimensions of mobility, including the timing, destination, or duration of mobility or whether to migrate at all. Where agency is extremely low, involuntary migration may take different forms, including temporary or permanent displacement and distress migration. Distress migration—mass migration or displacement related to rapid deterioration in local circumstances—is a humanitarian concern because of the need for emergency interventions to avoid poor outcomes. Distress migration has been a common phenomenon throughout history but has risen and fallen on the global policy agenda largely as a function of whether or not wealthy industrialized countries are destinations. Also of humanitarian concern is the phenomenon of involuntary immobility, in which people are unable to move without help—the population most likely to require assistance relocating under managed retreat programs. Avoiding distress migration and involuntary immobility in favor of safe and orderly migration, as advanced by the Global Compact on Migration, is now a global policy priority, and the Compact calls on governments to "strengthen joint analysis and sharing of information to better map, understand, predict, and address migration movements" as a result of climate change impacts—all of which are essential aspects of habitability assessment.

Many assessments posit some form of forced migration as an inevitable outcome of declining habitability. Yet, environmental stress rarely directly results in migration but works through a complex array of economic, demographic, social, and political proximate determinants that both initiate and sustain or modify flows. In any given population exposed to climate risks, different segments of the population respond to hazards differently and at different points in time, and as such, migration evolves with habitability through time. Whereas some may be able to migrate from deteriorating conditions without assistance, others may become immobile owing to limited options and insufficient resources, suffering progressive impoverishment and vulnerability unless social protection or planned relocation efforts are implemented (*5*). In situ adaptation, facilitated migration, and improving reception of migrants in (largely urban) destination areas are often more appropriate policies in these regions. Managed retreat has been proposed as a strategy for regions with declining habitability, but as a largely technical package of responses that includes buyouts, incentives, and planned relocation, among others, it does not currently translate well to most developing-world circumstances.

The relationship between habitability and migration may be counterintuitive, as illustrated by the lack of evidence for migration away from low-lying delta areas despite acute risks (*7*). Migration itself affects habitability for those who are unable or unwilling to leave increasingly vulnerable circumstances, either positively, such as through incoming remittances, or negatively, such as through outmigration of the working-age demographic stratum and subsequent changes in economic dynamism and livelihood options. Flows may begin owing to entrenched poverty and environmental risks and then be sustained as migrant social networks lower barriers for those who initially remained behind.

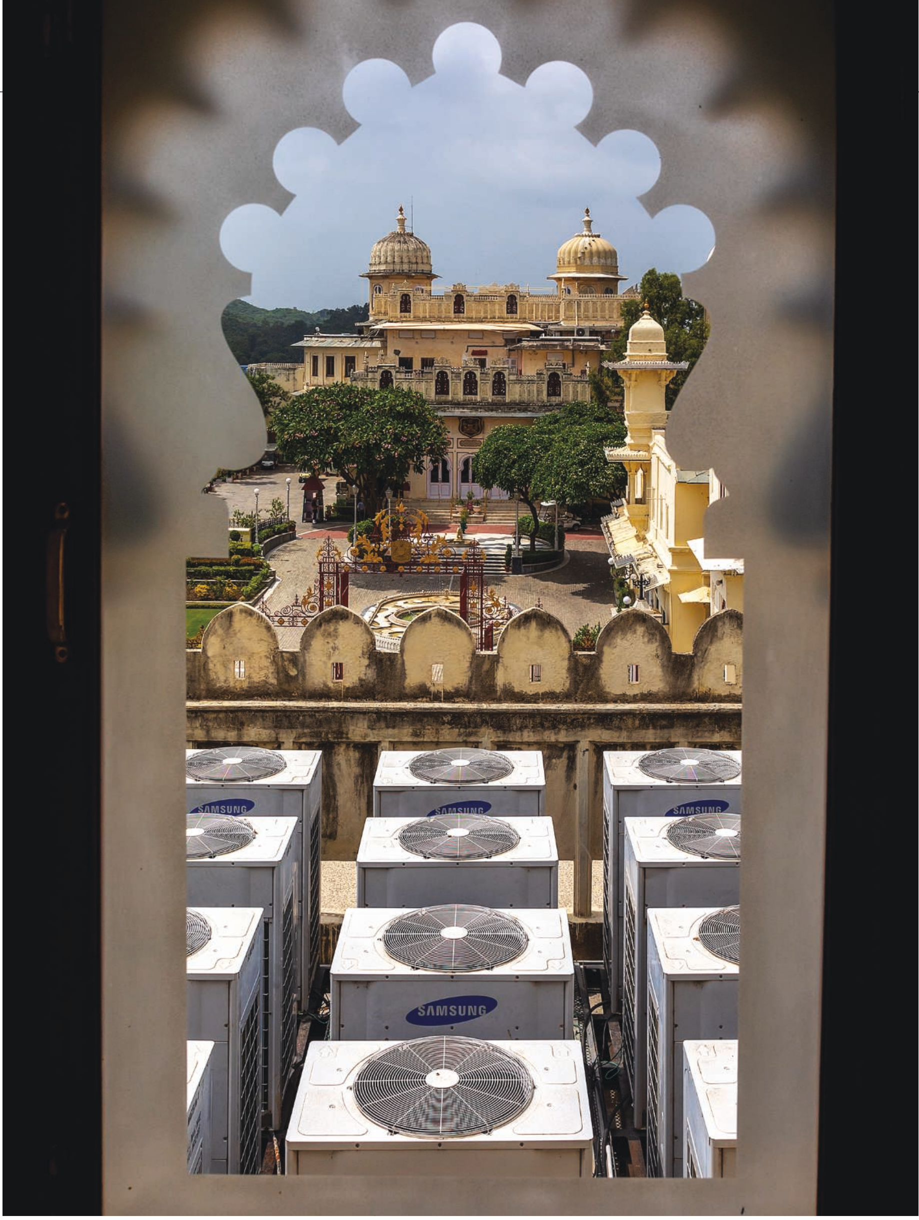
Although migration offers possibilities for advancing human well-being, as multiple dimensions of habitability are compromised, resulting forced migration will negatively affect human well-being. Migrants risk new constraints in urban informal settlements, and displaced persons may become permanently disconnected from their original communities and livelihoods in resettlement communities or refugee camps (*13*). Although top-down assessments oversimplify likely migratory responses to habitability declines, this does not necessarily imply that migration flows are overestimated. Multiple factors are driving migration in developing regions to varying degrees, including poor governance, perceived lack of opportunities, conflict, individual extreme events, and in some cases, climate-catastrophic discourses that add to a sense of hopelessness (*14*). Deeper and more contextualized understandings of migration dynamics aid in policy design, but the threats that result from declining habitability in combination with other drivers are real and may lead to substantial displacement of populations across a range of spatial scales.

A PATH FORWARD

Top-down, threshold-based habitability assessments can serve a critical role in helping to identify priority regions and groups for integrated bottom-up work while revealing interactions in global systems that cannot be gleaned from the bottom-up work alone. Integration not only leads to better predictions of when and where habitability may diminish but also can be used to inform adaptation responses that themselves help preserve or restore habitability. Bottom-up assessments by definition provide finer, local resolution, and their richness of detail means that they require diverse participation and methods. To date, most locales have not been subject to such integrated habitability assessment. We thus encourage transdisciplinary, long-term coupled top-down and bottom-up habitability assessment [for example, (*15*)] to complement and augment efforts such as the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP), which has contributed so much to our understanding of potential future climate impacts on sectors such as agriculture, water, ecosystems, and health. Initial model intercomparison could focus on what regions and groups face diminishing habitability under different model configurations. Particularly where models agree on potential habitability hot spots, bottom-up modeling experiments could be conducted and compared on specified challenges to human survival, livelihoods, and capacity to manage risk, although standardization would be needed. The Intergovernmental Panel on Climate Change (IPCC) and national efforts can also help to develop this still inchoate middle space between top-down and bottom-up approaches to habitability and migration. Migration is emerging as a cross-cutting theme throughout the current IPCC assessment, and a special report on habitability and migration would both advance the knowledge base and showcase emerging methodologies. As one example, a climate change detection and attribution dimension would help inform dialogues about loss and damage under the Paris Agreement. Likewise, a discussion on migration across the Reasons for Concern commonly used in IPCC assessments (*5*) would allow us to distinguish how climate-induced migration, distress or otherwise, is distinct from other forms of migration.

The complexity of the assessment challenge calls for a holistic, people-centric approach in which models, data aggregation, and ethnographic work are all advanced. Sectors such as engineering, hydrology, and reinsurance, that have historically been overreliant on physical models and hazard thresholds, operate at a scale that is ripe for habitability-relevant innovations at the interface between top down and bottom up. In this middle space, models could be used to examine policy scenarios instead of learning occurring exclusively from costly, time-consuming, real-world policy interventions that may put vulnerable people at risk. Greater communication among modelers will be key, and models must be validated with on-the-ground local research. To support migration and habitability modeling specifically, this would include data on when, where, and why people have moved or considered moving, how they define habitability, and the policy conditions that determine mobility outcomes (*14*). Furthermore, bottom-up research must account for the place-specific characteristics of populations—such as assets, livelihood opportunities, and social networks—that shape both exposure and adaptation. Investments in place-based social science thus help address data gaps, providing ground-truthing that will strengthen simulations of the outcomes of interventions. Investments in early-warning systems could help to anticipate where distress migration may happen, a key step in informing policy.

The shortcomings of adaptation planning and policy at current risk levels in wealthy countries hint at the global challenges ahead in a changing climate. In the United States,



Air conditioning, such as in Rajasthan, Udaipur, India, will enable some people to continue to live in places that exceed the 35°C threshold. Those with no access to affordable air conditioning could have little choice but to migrate.

PHOTO: ERIC LAFFORGUE/ART IN ALL OF US/CORBIS/GETTY IMAGES

for example, federal and local risk assessments—let alone policies—are not presently centrally coordinated or comparable. There is woefully insufficient funding available for bottom-up adaptation efforts from the better-financed federal level. Policies toward population mobility—whether planned, internal responses or immigration from other countries—vary from inconsistent over time to incoherent and sometimes inhumane. Coproduction of knowledge across diverse groups will be a precondition for any breakthroughs. In some instances, a starting point may be to bring preexisting top-down habitability and migration assessments to communities, provided that community feedback is collected and integrated iteratively and before key policy decisions are made. In other instances, stakeholder engagement may begin with fewer top-down, nonprobabilistic approaches that can be developed with communities, such as storylines and scenarios. Storylines and scenarios lend themselves to exploration of the uncertainties that most influence habitability locally (for example, the potential for changing correlation structures in models) and which adaptation strategies should be explored for which groups. Deeper stakeholder engagement, coupled with the other recommendations above, thus provides a foundation for colearning, iteration, and developing flexible approaches to the challenge of diminishing habitability.

To the extent that top-down, threshold-based approaches are used to define habitability universally, there is a risk of assuming a high likelihood of uniform outmigration or concluding with blanket policy recommendations around managed retreat. Basing assessments on nuanced definitions of habitability and integrating top-down with bottom-up approaches could encourage a broader range of policies tailored to specific locations and groups, including regions that have been put forth as likely receiving areas. A focus on the dimensions of habitability presented here, and bottom-up approaches, will invariably alter top-down projections of migration. Under wetbulb temperatures exceeding 35°C, high levels of outmigration from the Persian Gulf may be avoided if air conditioning is widely available and alternative livelihood options develop for those who would otherwise work outdoors. However, there will be regions where social tipping points and a sense of prevailing pessimism about the future—for example, owing to evolving risk perception or disinvestment by the private or public sectors—could contribute to outmigration far sooner and more suddenly than top-down habitability threshold–based methods would suggest. Global, regional, and national migration policies themselves will also play an important role in facilitating or impeding migration.

What is already clear is that climate change will result in shifting population distributions and that this process will overall be harmful to the most vulnerable, including those who may be "trapped" in deteriorating circumstances. For the reasons described here, and as a matter of climate justice, many semi-arid regions, much of the tropics, and some low-lying deltas and islands should be high priorities for integrated transdisciplinary work on habitability risks and major investments in adaptation. But only by taking into account the complexities described here will we avoid climate determinism and instead implement proactive policies on adaptation and migration that in particular will address the needs of the most vulnerable. ■

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