Demystifying Climate Scenario Analysis for Financial Stakeholders

Four Twenty Seven, December 2019

KEY TAKEAWAYS

- Quantifying climate risks under different scenarios is a key element in understanding how physical climate risks pose financial risks.
- Scenario analysis is often approached from the perspective of transition risk, where policy developments and greenhouse gas emission targets are the key drivers of risk pathways in the next 10 to 30 years. However, physical climate impacts over the coming decades are largely locked in, so physical risk requires a different approach.
- Even if we stopped emitting carbon dioxide tomorrow, many physical climate impacts, such as increasing temperatures, more severe droughts, and rising sea levels, would already be locked in because of the time carbon dioxide stays in the atmosphere and the time it takes the atmosphere to respond.
- The uncertainty in how physical climate risks may manifest in the next few decades is driven by model uncertainty, which should therefore be the focus of scenario analysis for physical climate risks in the near-term.
- Percentile-based analysis offers a flexible, data-driven approach, suitable for portfolio-level screenings, reporting, and in some cases, direct engagement with asset managers.

INTRODUCTION

As the effects of climate change increasingly threaten financial stability, investors and regulators are seeking to understand what impacts lie ahead, and calling for an increase in physical climate risk assessment and disclosure in line with the Task Force on Climate-related Financial Disclosures (TCFD).[1] It is important to quantify risks under different climate scenarios to assess the scale of financial risk posed by physical climate change. How will changes in extreme weather patterns, longer droughts and rising seas differ under various scenarios? Answering these questions through scenario analysis helps uncover the range of risks, allowing investors to identify assets and markets that are more likely to become stranded over time and to begin developing forward-looking resilience strategies.

However, science-driven, decision-useful scenario analysis poses many challenges for businesses and financial stakeholders today, due to complex feedback loops, varying timescales, and multiple interacting factors that ultimately determine how global climate change manifests. For investors, guidance is scant, and the resources can be difficult to distill and apply. Even businesses earnestly striving to understand their exposure across scenarios, face daunting challenges in accessing and understanding the climate science. The TCFD's latest Status Report noted that only 33% of the reporting companies included scenario analysis for physical risks, and even fewer described their assumptions and methods.[2] Regulators are cautious to offer guidance, perhaps because there is no one-size-fits-all approach. Yet scenario analysis is a critical component to planning and the best tool we have for identifying the range of possible outcomes associated with a warmer environment.

Scenario analysis is often approached from the perspective of transition risk, where policy developments and greenhouse gas (GHG) emission targets are the key drivers of risk pathways over the near-term, in the next 10 to 30 years. Physical risk, however, requires a different approach. Impacts over the coming decades are largely locked in, making the emissions scenarios less relevant. The sources of uncertainty also differ between physical risk and transition risk. Unlike transition risk, GHG emission pathways play a minimal role in the behavior of the near-term climate and GHG emission pathways only begin to meaningfully influence global temperatures near mid-century. The uncertainty in physical climate risks in the near-term is driven by uncertainty in physical processes, rather than in policy decisions. Indeed, as global temperatures rise, the distribution of impacts like heat waves or floods will be highly uneven, and the possible range of physical impacts can vary widely for any single location.

For organizations looking to construct physical climate risk scenarios for risk management and strategy purposes, it is critical to understand the scientific phenomena driving our plausible climate futures. Many financial stakeholders are looking to understand their range of risks under different scenarios in the near-term from the standpoint of climate science, which is considered around 10 to 30 years out in this report. This report explores which impacts are already locked in, identifies how Representative Concentration Pathway (RCP) scenarios fit into the conversation, and describes an approach to setting up scenario analysis for near-term physical climate risks.

[1]The Network for Greening the Financial System is a group of over 42 central banks and supervisors globally that is committed to supporting the goals of the Paris agreement and building a resilient financial system. https://www.banque-france.fr/en/financial-stability/international-role/network-greening-financial-system
[2]Task Force on Climate-Related Disclosures (TCFD). (2018). TCFD:2018 Status Report. *TCFD.* https://www.fsb-tcfd.org/publications/tcfd-2018-status-report/

THE SCIENCE BEHIND COMMITTED WARMING

This section explains several key scientific processes that influence the timing of when GHG emissions manifest in the global climate system through temperature, precipitation, and sea levels. The lag between emissions and impacts is essential to understand because it determines the key drivers of uncertainty in scenario analysis, and explains why RCPs are not a meaningful driver of uncertainty for the coming decades. Due to the locked-in impacts over the next few decades, near-term scenario analysis will look much different than scenario analysis for the long-term, which requires the incorporation of other large sources of uncertainties that become more relevant in long-term time scales, such as the ways we will respond to the climate crisis.

In the near-term, the effects of climate change are locked in as a result of a phenomenon known as *committed warming*, or the amount of future global warming that is already in the pipeline based on past emissions. We are already locked into substantial impacts because past emissions will continue to contribute to warming regardless of any emission reductions made today. As an analogy, the effect of significantly reducing GHG emissions is akin to applying the brakes on a rapidly moving truck. Warming won't stop instantaneously. Even if we were to stop emitting GHGs altogether tomorrow, the effects of climate change would persist. The atmosphere will continue to warm for many decades, and the oceans will continue to rise for millennia.[3] Droughts will intensify for several regions[4] and intense tropical cyclones will become more frequent and their range will expand poleward.[5]

The primary reason these impacts are locked in is the long *residence time*[6] of carbon dioxide in the atmosphere combined with the time it takes the climate to fully respond to warming oceans.[7] The long residence time refers to the fact that carbon dioxide can remain in the atmosphere for hundreds to thousands of years after it's emitted.[8] The reason the atmosphere does not warm instantaneously after GHG are emitted is because of the time it takes for the ocean to heat up, otherwise known as *thermal inertia*.[9, 10, 11, 12] The mixing of heat into the deep ocean occurs over long time scales due to its isolation from the atmosphere and slow rate of overturning. As a result, heat will continue to transfer into the ocean long after emissions have subsided.[13] The ocean acts as a large reservoir for heat,[14] directly contributing to the warming of the planet. Warming oceans are also critical because, as they get warmer, they expand. Thermal expansion alone causes approximately 0.2-

[3] Clark, P. U., Shakun, J. D., Marcott, S. A., Mix, A. C., Eby, M., Kulp, S., ... & Schrag, D. P. (2016). Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. *Nature climate change*, *6*(4), 360

[4] Dai, A. (2011). Drought under global warming: a review. *Wiley Interdisciplinary Reviews: Climate Change,* 2(1), 45-65.

[5] Christensen, J. H., Kanikicharla, K.K., Aldrian, E., An, S.-I., Cavalcanti, I.F.A., de Castro, M., … & Zhou, T. (2013). Climate phenomena and their relevance for future regional climate change. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.*

[6] "Residence time" in this context refers to how long on average a gaseous compound, such as CO_2, remains in the atmosphere as a greenhouse gas.

[7] Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., … & Wehner, M.. (2013). Long-term Climate Change: Projections, Commitments and Irreversibility. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.*

[8] Archer, D., & Brovkin, V. (2008). The millennial atmospheric lifetime of anthropogenic CO 2. *Climatic Change*, *90*(3), 283-297.

[9] Stouffer, R. J., & Manabe, S. (2003). Equilibrium response of thermohaline circulation to large changes in atmospheric CO2 concentration. *Climate Dynamics*, *20*(7-8), 759-773.

[10] Wigley, T. M. (2005). The climate change commitment. *Science*, *307*(5716), 1766-1769.

[11] Archer & Brovkin, 2008

[12] Collins et al., 2013

[13] Solomon, S., Plattner, G. K., Knutti, R., & Friedlingstein, P. (2009). Irreversible climate change due to carbon dioxide emissions. *Proceedings of the national academy of sciences*, *106*(6), 1704-1709.

[14] Ibid

0.6 meters of sea level rise per degree of warming[15] and will continue, locking-in sea level rise for many centuries regardless of future emissions.

Furthermore, there are also several positive feedback loops that can affect the timing and severity of warming. A warmer atmosphere can lead to more GHG emissions, such as the release of methane when permafrost melts.[16] Increased ocean temperatures lead to more evaporation of water, which is itself a potent GHG, contributing to atmospheric warming. Changes to the land surface, in the form of melting glaciers and ice sheets (Fig. 1) or vegetation changes, can reduce how much energy is reflected back to space. Warming as a result of these feedback loops comes much later, largely due to the time it takes the oceans to respond and fully equilibrate to the long-term effect of anthropogenic GHG emissions.[17]

Figure 1. Melting glaciers contribute to feedback loops that decrease the amount of energy reflected back into space and thus accelerate warming. Source: Wing-Chi Poon via Wikimedia commons under CC BY-SA 2.5

The Effects of Committed Warming

The planet has already been warming as a result of anthropogenic GHG emissions, leading to impacts felt today, such as temperature increases, changing precipitation patterns, and sea level rise, among others. These are impacts with direct consequences for business operations, supply chains, real estate markets, labor productivity, and public health and these trends will continue because of committed warming.[18, 19]

Heat Stress

Due to anthropogenic climate change, heat extremes will become more frequent and more severe, particularly by the end of the century. Without concerted effort to reduce emissions, global mean temperature could be approximately 4°C above preindustrial levels by the end of the century,[20] with a significant portion of this warming expected regardless of whether mitigation action is taken. While natural variability differs by area, temperature changes will increasingly exceed the temperature ranges to which populations are acclimated. Regions with the highest relative change from the historical baseline will experience significant, unprecedented heat events, placing enormous stress on human health and infrastructure, impacting business operating costs and labor productivity for many decades.

Figure 2 illustrates the effect of anthropogenic warming, much of which is already locked in, on changes in temperature extremes by 2040, with the largest increases occurring in high elevations and northern latitudes. The most at risk regions, such as

[15]bid

[16]Unlike carbon dioxide, if emissions halted immediately, methane levels would return to pre-industrial levels in approximately 50 years and aerosols would be removed nearly instantly, though the warming potential of these greenhouse gases pale in comparison to the warming effects of committed carbon dioxide.

[17]Pierce, D. W., Barnett, T. P., & Gleckler, P. J. (2011). Ocean circulations, heat budgets, and future commitment to climate change. *Annual Review of Environment and Resources*, *36*, 27-43.

[18]Collins et al., 2013

[19]Seneviratne, S., Nicholls, N., Easterling, D., Goodess, C.M., Kanae, S., Kossin, J., … & Zhang, X. (2012). Changes in Climate Extremes and their Impacts on the 1 Natural Physical Environment 2. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation.*

[20]Collins et al., 2013

northern Canada and Russia and mountain ranges including the Himalayas, Andes, and Alps will experience temperatures that are up to 25% hotter than those previously experienced. While the multitude of disruptive heat waves across the United States, Japan and Europe in 2019 broke records by several degrees,[21] projections to mid-century show significantly more severe events.

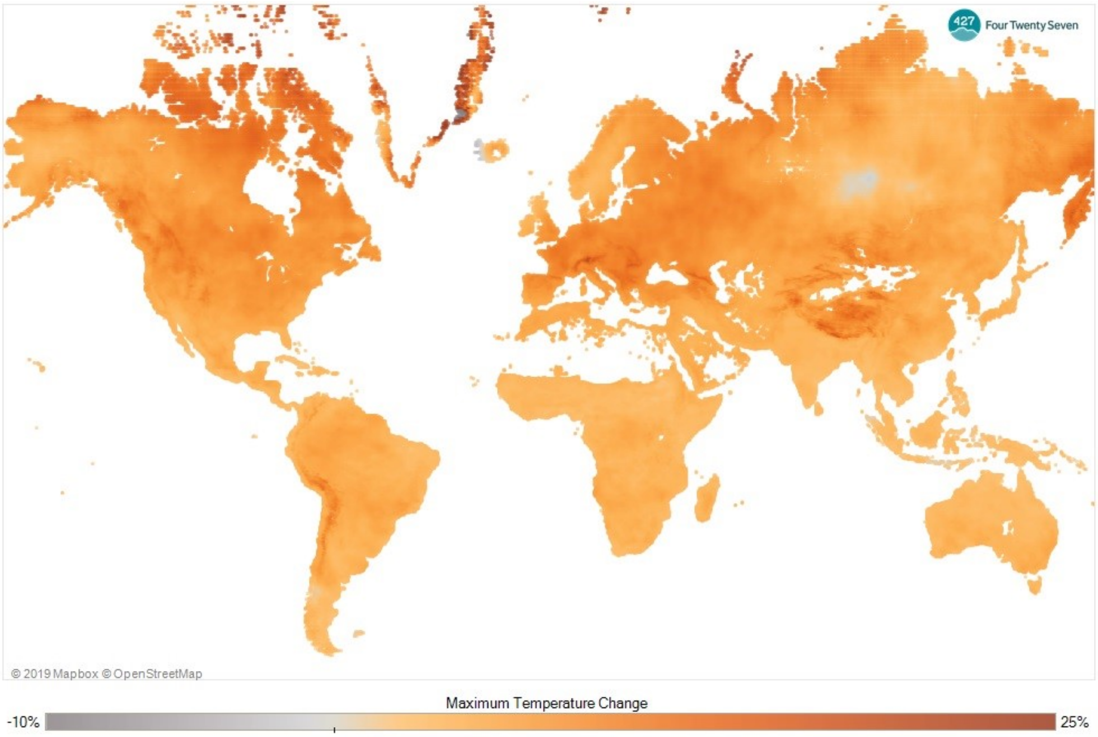

Figure 2. Distribution of daily extreme temperature changes in 2030-2040, expressed as a percent change, relative to a baseline of 1975-2005 under RCP 8.5. This map shows statistically downscaled global climate models averaged together, for this time frame and scenario. NASA Earth Exchange Global Daily Downscaled Projections statistically downscales climate model outputs to a ~25 kilometer resolution (see full details here) White areas are excluded because they lack potential for significant economic activity.

Water Stress

Many regions have already experienced changing precipitation patterns, leading to impacts such as drought.[22] Broad patterns of drying and increased drought in the subtropics have been linked to changes in large-scale atmospheric circulation in both hemispheres, interacting with systems which also govern the behavior of trade winds around the equator.[23, 24] Poleward expansion of these circulation patterns is leading to increased drying over already dry subtropical regions such as the southern United States, northern Africa, and Australia, which has dire implications for food security, water availability, and wildfire risk.[25]

[21] Stylianou, N and Guibourg, C. (2019). "Hundreds of temperature records broken over summer." *BBC News.* https://www.bbc.com/news/science-environment-49753680
[22] Solomon et al., *2009*
[23] Lu, J., Vecchi, G. A., & Reichler, T. (2007). Expansion of the Hadley cell under global warming. *Geophysical Research Letters*, *34*(6).
[24] Hu, Y., Tao, L., & Liu, J. (2013). Poleward expansion of the Hadley circulation in CMIP5 simulations. *Advances in Atmospheric Sciences, 30* (3), 790-795.
[25] Solomon et al., 2009

Figure 3 illustrates levels of water stress across the globe, when considering both current and near-term imbalances between water supply and demand, affected by both climate change and population growth patterns. Greater demand for freshwater coupled with climate-induced water shortages is leading to more severe and widespread water stress across the globe. The most stressed areas, such as southern Europe and the Mediterranean, the southwest United States, and southern Africa, are anticipated to experience 10 to 20% reductions in dry season rainfall,[26] reductions equivalent to the two decades surrounding the American "dust bowl." This trend is expected to continue as committed warming increases global temperatures in the near-term.[27, 28]

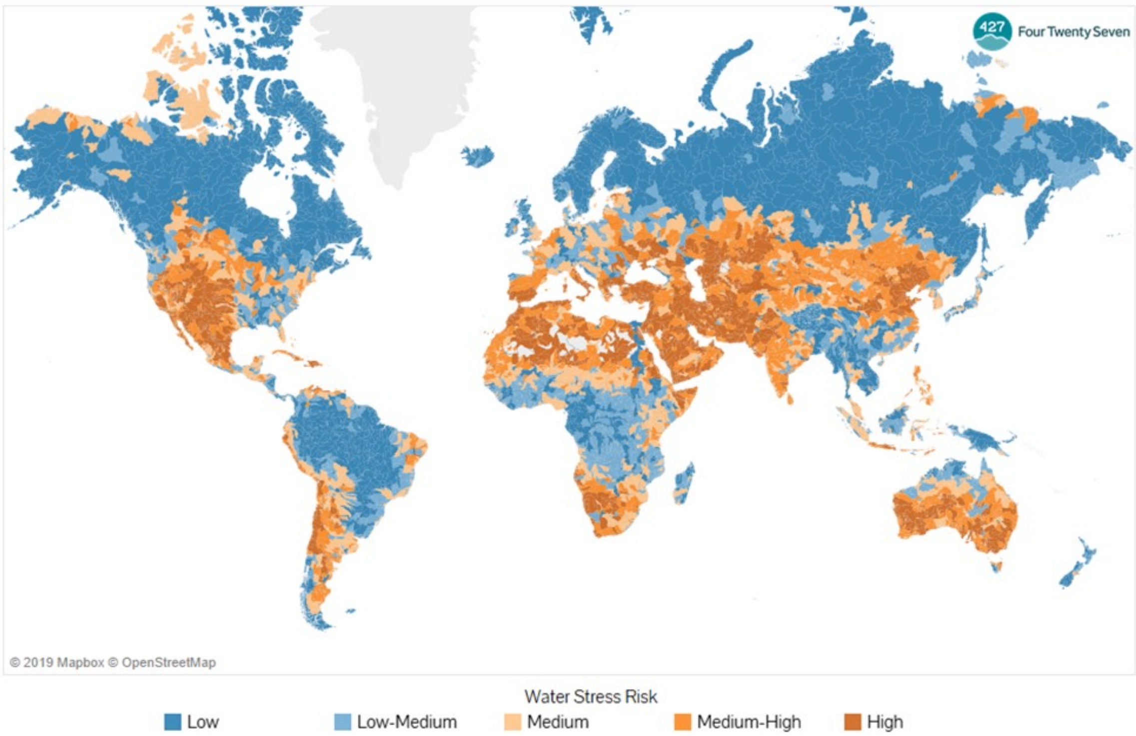

Figure 3. Distribution of water-stress levels, comprised of six indicators that measure current water stress, water availability, and projected changes in water availability in volume and in relative terms in 2040. Data derived from Aqueduct Global Maps 2.1 and Aqueduct Water Stress Projections, and processed by Four Twenty Seven.

Sea Level Rise

Sea level rise, unlike temperature extremes and changing precipitation patterns, is locked in for many millennia, rather than just several decades, but impacts may manifest more slowly due to the time it takes oceans to fully respond to GHGs in the atmosphere. While the direction and magnitude of change is well-known, some uncertainties persist, particularly the extent of severe impacts. For example, ice mass loss is a potentially large source of additional sea level rise that has not been realized,[29, 30] and the timing and amount is still quite uncertain. Like oceans, ice sheet and glacier melt have delayed responses to GHG emissions.[31] Thus, there is the possi-

[26] Ibid.
[27] Collins et al., 2013
[28] Mauristen & Pincus, 2017
[29] Wigley, 2005
[30] Solomon et al., 2009
[31] Archer & Brovkin, 2008

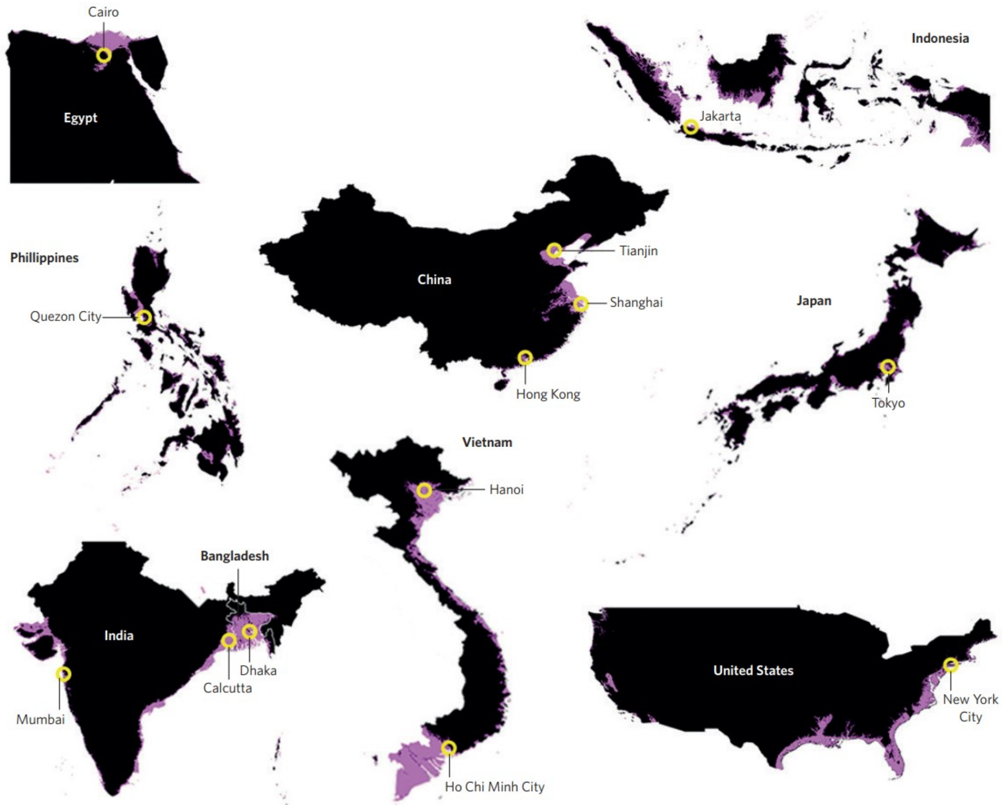

Figure 4. Geographic extent of sea level rise flooding in 2300 for countries with at least 50 million people living on land affected by long-term sea-level projection based on the 1,280 Pg C emission scenario. The purple represents areas that are projected to be "chronically inundated" in 2300 under this scenario. Image source: Clark et al., 2016.

bility that certain levels of warming could lead to tipping points, causing seemingly sudden drastic ice melt and irreversible abrupt sea level rise.[32] As a result, sea level rise overall takes longer to respond to changes in GHG emissions than even global average temperature.[33]

Figure 4 illustrates the geographic extent of sea level rise flooding in 2300. However, at our current emission levels, and on top of committed emissions, we could ostensibly emit enough carbon dioxide to lock-in the full extent of these sea level rise effects within the next 120 years. Sea level rise has wide-ranging impacts, including stranding coastal assets and reshaping coastal real estate markets, inundating key transportation nodes, disrupting trade routes, and potentially leading to the relocation of entire populations. While 2300 is very long-term, the impacts of rising seas are already being felt in vulnerable coastal cities, such as Miami,[34] Mumbai,[35] and Venice,[36] and losses will continue as sea levels continue to rise. Scenario analysis that explores degrees of varying impacts can enable businesses and investors to prepare today for the impacts that will continue to manifest with increasing severity over time.

[32]Solomon et al., 2009
[33]Collins et al., 2013
[34]Cappucci, M. (2019). Sea level rise is combining with other factors to regularly flood Miami. *The Washington Post.* https://www.washingtonpost.com/weather/2019/08/08/analysis-sea-level-rise-is-combining-with-other-factors-regularly-flood-miami/
[35]Kumar, H. (2019). 32 Dead as Worst Flooding in a Decade Hits Booming Mumbai. *The New York Times.* https://www.nytimes.com/2019/07/02/world/asia/32-dead-as-worst-flooding-in-a-decade-hits-booming-mumbai.html
[36]Chow, D. (2019). Venice's devastating floods are the 'canary in the coal mine' for coastal cities worldwide. *NBC News.* https://www.nbcnews.com/science/environment/venice-s-devastating-floods-are-canary-coal-mine-coastal-cities-n1084031

WHAT ABOUT RCPS?

It is often assumed that emission scenarios, commonly referred to as Representative Concentration Pathways (RCPs), are applicable for scenario analysis of physical risks in the near-term. The 2017 TCFD technical supplement suggests utilizing these publicly available scenarios from the Intergovernmental Panel on Climate Change (IPCC) 5th assessment report, to "reflect a range of GHG emissions and concentration pathways and consequent temperature outcomes."[37] These RCPs "describe four different 21st century pathways of greenhouse gas (GHG) emissions and atmospheric concentrations, air pollutants emissions and land use."[38] The pathways underpin climate model simulations, and their assumptions ultimately drive the projected changes in climate and subsequent impacts. RCPs allow us to better understand what climate impacts would manifest in the long-term under different hypothetical futures in which various mitigation actions are undertaken.

However, most businesses and financial stakeholders are interested in understanding the range of outcomes in the next several decades and global temperature and other physical hazards do not show meaningful differences across different RCPs until approximately mid-century. At a regional level, differences between RCPs can appear larger than the global level, but differences remain relatively small compared to differences between individual models (Figure 5). Figure 5 shows how temperature projections vary between models and different scenarios. Temperature change is shown on the y-axis, while the colored lines show the climate models colored based on their associated RCP. For example, red lines show projections under the high-emissions

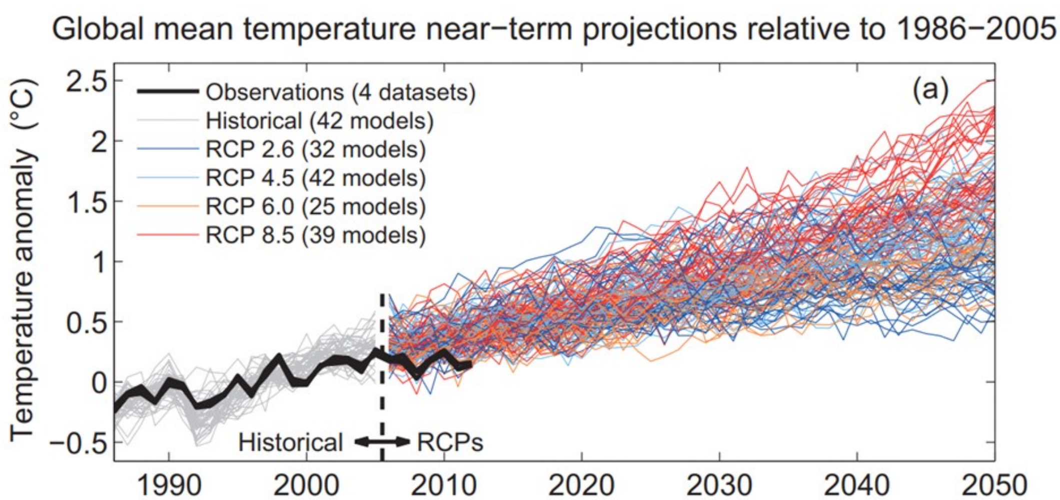

Figure 5. Global mean surface temperatures from CMIP5 models under all RCPs. Each line represents the projected difference in global temperature relative to the 1986-2005 baseline by an individual model. Through the early part of the century, RCP scenarios do not have a significant influence over global temperature anomaly, as there is little correlation between temperature anomaly and RCP. During this timeframe other factors, such as differences in model construction, are the leading drivers of differences between projections. Closer to mid-century, model runs begin to diverge slightly by RCP, e.g. the models indicating more warming tend to be associated with RCP8.5. However, even is 2050, there is still considerable overlap in model projections between the separate RCPs. Image source: IPCC Fifth Assessment Report.

[37]Task Force on Climate-Related Disclosures (TCFD). (2017). Technical Supplement: The Use of Scenario Analysis in Disclosure of Climate-Related Risks and Opportunities. *TCFD.* https://www.fsb-tcfd.org/wp-content/uploads/2017/06/FINAL-TCFD-Technical-Supplement-062917.pdf

[38]Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., ... & Dubash, N. K. (2014). Climate change 2014: Synthesis Report. *Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.*

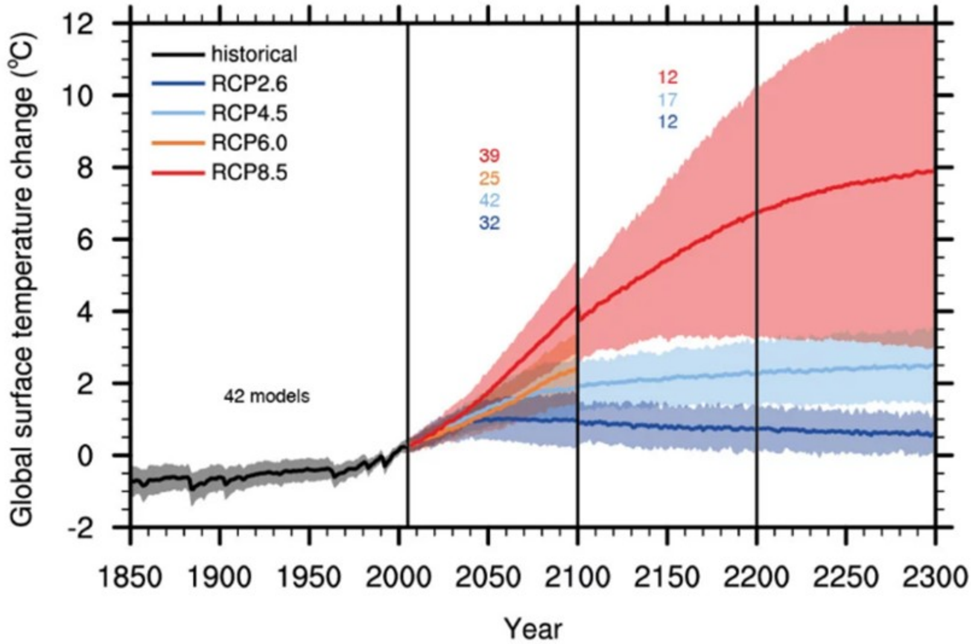

Figure 6. Global annual mean surface air temperature anomalies (relative to 1986-2005) by RCP over time. The solid lines represent the CMIP5 multi-model mean, while the 5-95% across the distribution of individual models is represented by the shaded region. Image source: IPCC Fifth Assessment Report.

scenario while blue lines show projections for RCP 4.5 and 2.6, which assume drastic reductions in GHG emissions globally. The significant overlap between individual model projections, regardless of RCP, illustrates the fact that there is not a meaningful difference in global temperatures between the RCP scenarios through mid-century.

The Current Trajectory

While global actions have not precisely followed one RCP, they are on a trajectory in-line with the higher-end emission scenarios. The IPCC's Fifth Assessment report states that "without additional efforts to constrain emissions," this would "lead to pathways ranging between RCP 6.0 and RCP 8.5."[39] Over the last twenty-five years of half-hearted mitigation initiatives, emission reduction efforts have not materialized, and we are already advancing towards 3.5 ˚C[40] and up to 4.5 ˚C[41] of warming by 2100, depending on the modeling assumptions applied (Fig. 6). This has set us on a trajectory that would require an immediate and complete cessation of GHG emissions by mid-century to have a 50% chance of staying below 1.5 ˚C of warming by the end of the century, a threshold that the scientific community has warned has significant ecological implications.[42] Without immediate and substantial mitigation, there is little chance of keeping global temperatures from rising less than 2°C by 2100 compared to pre-industrial levels.[43] Despite the efforts of the Paris Agreement, emissions have not slowed; rather, GHG emissions increased yet again in 2018.[44]

In the absence of substantial GHG mitigation, it is our recommendation to use the high-emissions scenario, RCP 8.5, to guide climate risk assessments, at least in the mid-century timeframe. Since variations in physical climate outcomes in the mid-century are

[39] Pachauri et al., 2014
[40] Mauritsen, T., & Pincus, R. (2017). Committed warming inferred from observations. *Nature Climate Change*, *7*(9), 652.
[41] Ramanathan, V., & Feng, Y. A. N. (2008). On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead. *Proceedings of the National Academy of Sciences*, *105*(38), 14245-14250.
[42] Mauristen & Pincus, 2017
[43] Jackson, R. B., Friedlingstein, P., Canadell, J. G., & Andrew, R. M. (2015). Two or three degrees CO2 emissions and global temperature impacts. *The Bridge, 45*(2), 16-21
[44] Figueres, C., Le Quéré, C., Mahindra, A., Bäte, O., Whiteman, G., Peters, G., & Guan, D. (2018). Emissions are still rising: ramp up the cuts. *Nature.* https://www.nature.com/articles/d41586-018-07585-6/

more largely driven by uncertainties in global climate models, rather than uncertainties in mitigation policy, scenario analysis in this timeframe should focus on those scientific uncertainties. Exploring those uncertainties within RCP 8.5 models provides a feasible and realistic scope given our current trajectory.

SCENARIO ANALYSIS FOR THE SHORT-TERM

Scenario analysis is an important tool to explore the uncertainties in how physical climate risks may manifest in the coming decades. As noted above, global temperature and other physical hazards do not show meaningful differences across different RCPs until approximately mid-century. In contrast, differences between climate models can be quite large, even within a single RCP. Take extreme temperature as an example. The direction of change is well-known and trending upward for the entire globe, yet the magnitude and rate of change are not as precisely known, particularly at a regional level. To estimate the magnitude of extreme temperature change, it is possible to develop a range of future heat extremes by exploring the differences between global climate models within a single RCP.

The Approach: Percentile-based Analysis

Global climate models are simulations of the future state of the Earth, which use physical equations to represent complex and interconnected Earth processes.[45] These models are developed, run, and made publicly available by government agencies and research institutions around the world. They incorporate cutting-edge climate science and their outputs are treated as plausible future climates from which to assess risk and impacts. For its 2012 Fifth Assessment report, the IPCC relied on an ensemble of over 40 such climate models which were coordinated under the Coupled Model Intercomparison Project Phase 5 (CMIP5). The next generation of global climate models, part of the forthcoming CMIP6 initiative, will integrate the latest science and computing resources to iterate and improve upon previous modelling efforts. The outputs from these models are beginning to be released and will soon be fully available to inform the IPCC's Sixth Assessment report.

Each climate model is constructed with a slightly different set of initial conditions, parameters, and assumptions, and therefore represents the effects of climate forcings differently, even within an RCP. Each model subsequently produces different levels of warming or rainfall based on its construction and its own unique set of initial conditions. To illustrate the full range of future impacts, i.e. the **scenarios** for physical climate change in the near-term, it is essential to utilize known differences between models and identify potential alternative outcomes based on the outputs from several models. One such method, often referred to as **percentile-based analysis**, addresses a wide range of projections for one or more climatological variables by calculating percentiles based on the distribution of outcomes from the pool of available models within a single emission scenario, such as RCP 8.5.

Heat Stress

Using percentile-based analysis to explore heat stress results in **high**, **medium**, and **low tiers**[46] based on the range of projections in extreme heat, which represent possible climatic futures within this time period and RCP scenario, based on individual climate model outputs. Take for example the incidence of additional heat days in Los Angeles over the next thirty years. For illustrative purposes only, in this example, we define an "extreme heat day" as a single day where maximum temperature exceeds 95°F (35°C).[47]

[45] Gannon, C, Steinberg, N. (2018). Using Climate Data. (N. Ambrosio, Ed). *Four Twenty Seven.* http://427mt.com/wp-content/uploads/2018/04/Using-Climate-Data-4.25.2018.pdf

[46] In this example, low = bottom 33rd percentile; medium = 34-66th percentile; and high = 67-99th percentile

[47] This threshold has been utilized for illustrative purposes only, and meaningful extreme heat thresholds should, in applied cases, be further defined according to sector, season, and historical acclimation levels.

Figure 6 shows nine models estimating the annual occurrence of extreme heat days across three time periods: 2020-2029, 2030-2039, and 2040-2049. When ranking the additional number of extreme heat days annually, we can construct a low, medium, and high scenario based on the averages of the individual climate model outputs within each tier and decade. Figure 5 shows that the outputs from the group of climate models that fall in the 2020-2029 high percentile tier of the distribution, range from 4.5 to 8 additional extreme heat days per year. In this case, each tier presents a single estimate of additional extreme heat days, but is itself comprised of a range of possible outcomes, averaged together.

In other words, we can develop three scenarios for extreme heat in Downtown Los Angeles. These scenarios are not dependent on GHG emissions, but on scientific uncertainty as to how hot Los Angeles will get, with a significant portion of the impacts attributable to the locked-in effect of GHG emissions already in the atmosphere. We use the range of available climate models to create a distribution from high to low, and group the highest, lowest, and mid-range projections into three tiers that can be used for planning or analysis around energy costs, infrastructure failure, and health impacts for example.

Additional Days (individual model outputs)

Model	2020-2029		2030-2039		2040-2049	
CanESM2	High	8.00	High	8.00	High	11.80
GFDL-CM3	High	5.00	High	8.80	High	17.10
HadGEM2-CC	High	4.50	Medium	3.00	Medium	5.10
HadGEM2-ES	Medium	2.70	High	4.60	Low	4.60
CMCC-CMS	Medium	1.90	Low	1.20	High	8.80
CESM1-BGC	Medium	1.90	Low	2.90	Low	4.90
ACCESS1-0	Low	1.40	Medium	4.10	Medium	6.40
CNRM-CM5	Low	-0.20	Low	1.00	Low	2.00
CCSM4	Low	-0.30	Medium	3.50	Medium	6.40

Low Medium High

Figure 6. Example of percentile-based analysis for constructing scenarios for future extreme heat (days in a year) in downtown Los Angeles, California under RCP 8.5. This is based on a spatial resolution of approximately 6 km and records provided on a daily timescale. Data is derived from daily climate projections which have been downscaled from global climate models from the CMIP5 archive, using the Localized Constructed Analogs (LOCA) statistical technique developed by Scripps Institution of Oceanography.

Sea Level Rise

The uncertainties of projecting near-term climate changes also vary by hazard. Constructing scenarios for more dynamic events, such as inland floods and sea level rise, requires other input variables in addition to differences between models. Climate models do not provide sufficient information about many of the physical processes influencing flood characteristics, such as inundation levels.

Coastal flooding at a given location, for example, is determined by a combination of physical processes including vertical land movement (i.e., coastal subsidence), tides, storm surge heights, and lastly, regional sea level rise. Sea levels set a baseline for storm surge. As sea level rise continues to accelerate through the century, so does this baseline, pushing coastal water further inland.

RCP scenarios do not begin to show a meaningful difference in global sea levels until around 2060.[49] Despite several key uncertainties in modelling future sea level rise, including the rate and dynamics of ice sheet melt discussed above, the physical processes governing change over the next half century are mostly locked in and independent from today's policy decisions and emission pathways. It is therefore similarly possible to construct low, medium, and high tiers based on the distribution of regional sea level rise outcomes within a single RCP, alongside a probabilistic understanding of local storm surge (Table 1).

Table 1. Total water heights under three sea level scenarios across storm levels for a hypothetical property in Alameda, California. Table derived from data in Climate, Drought, and Sea Level Rise Scenarios for California's Fourth Climate Change Assessment

Sea Level Rise (SLR) Scenario (2020-2050)	+SLR (m)	Local Storm Surge (+Tides, Waves)			
		a	b	c	d
		1-yr	5-yr	50-yr	100-yr
[1] Existing conditions	0	0.4 m	0.6 m	0.9 m	1.1 m
[2] 50th percentile	0.08	0.4 m	0.6 m	< 1m	< 1.2 m
[3] 99th percentile	0.20	0.5 m	0.8 m	1 m	1.2 m

For example, in Alameda, an island city in the San Francisco Bay, sea levels are expected to rise between 0.08 meters (3.1 inches) (50th percentile) and 0.20 meters (7.9 inches) (99th percentile) by 2030, with no discernable difference between RCP 4.5 and 8.5.[50] If an asset under consideration is buttressed by a shoreline barrier that is approximately one meter in height, the asset owner could use Table 1 to identify when the asset will be inundated. By adding projected sea level rise in the left-hand column, with recorded storm surge during different severities of storm (columns a-d), an asset owner could identify when the barrier is likely to be breached. For example, water levels could reach 1 meter even under a moderate flooding event (1-in-5-year storm in column b) if sea level rise is within the higher range of estimates (row 3). This type of analysis provides guidance around minimum trigger points for inundation, informing asset owners' strategies for flood mitigation strategies.

[49] Pierce, D. W., J. F. Kalansky, and D. R. Cayan. (2018). Climate, Drought, and Sea Level Rise Scenarios for the Fourth California Climate Assessment. *California's Fourth Climate Change Assessment, California Energy Commission.* Publication Number: CNRA-CEC-2018-006.
[50] Ibid.

Applying Percentile-based Scenario Analysis for Decision-making

When evaluating the many near-term climate futures, percentile-based analysis can inform concrete decisions regarding a single asset, allowing managers to work directly with the asset operators to develop appropriate forward-looking preparedness measures. For example, asset-owners could determine whether and what flood protections to put in place, identify insurance requirements, or consider relocation efforts. For heat stress, asset-owners can calculate potential increases in operational costs from increasing energy demands under low, medium, and high temperature scenarios.

Real asset investors can evaluate a portfolio of properties using multiple near-term futures to understand their range of potential physical risks, or they can focus on a few high-value, or high-risk assets to gain a better understanding of the range of risk levels. Similarly, real asset portfolio managers can identify potential stranded assets over time or identify markets likely to experience loss in value due to climate change.

At the site-level, municipalities and utilities can explore the range of potential risks in the near-term and evaluate operational resilience of existing infrastructure against those risks. Together, percentile-based analysis offers a flexible, data-driven approach, suitable for portfolio-level screenings, reporting, and in some cases, direct engagement with asset managers.

CONCLUSION

Scenario analysis for physical climate risks is an important element of forward-looking climate risk assessments. When exploring the range of risks posed to individual assets or portfolios in the near-term, it's critical to first understand that the magnitude of certain climate hazards is locked in. As such, percentile-based analysis provides a way to understand the range of potential climate outcomes in the near-term.

One of the largest sources of uncertainty when projecting outcomes in the climate lies in modeling human behavior, and the ways we will respond to the climate crisis. Over time, publicly available emission and socioeconomic pathways such as the RCPs, can inform analysis of physical risk of longer-term climate change impacts. When focusing on the shorter term, the warming and related impacts we have already committed to calls for scenarios that are decoupled from economic and policy activities and instead focus on the impacts that are already locked in. Four Twenty Seven is working to develop standardized scenario analysis at scale for several climate hazards by first leveraging percentile-based scenario analysis in the near term.

AUTHORS

Authors: Nik C. Steinberg • nsteinberg@427mt.com, Colin Gannon • cgannon@427mt.com, Josh C. Turner • jturner@427mt.com

Editors: Natalie Ambrosio • nambrosio@427mt.com, Emilie Mazzacurati • emazzacurati@427mt.com

ABOUT FOUR TWENTY SEVEN

Four Twenty Seven (427mt.com), an affiliate of Moody's, is a publisher and provider of data, market intelligence and analysis related to physical climate and environmental risks. We tackle physical risk head on by identifying the locations of corporate production and retail sites around the world and their exposure to climate change hazards such as sea level rise, droughts, floods and tropical storms, which pose an immediate threat to investment portfolios.

Four Twenty Seven's ever-growing database now includes one million corporate sites and covers over 2000 publicly-traded companies. We offer subscription products and on-demand analytics to access this unique dataset. Options include data licenses, an interactive analytics platform, and company scorecards, as well as reporting services, data for scenario analysis, and real asset portfolio risk assessments.

Four Twenty Seven has won multiple awards for its innovative work on climate risk and resilience and its work has been featured by Bloomberg, the Financial Times and the UNFCCC. Four Twenty Seven was founded in 2012 and is headquartered in Berkeley, California with offices in Washington, DC, Paris, France and Tokyo, Japan.

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CONTACT INFORMATION

San Francisco Bay Area, CA
2000 Hearst Ave, Ste 304
Berkeley, CA 94709
Tel: +1.415.930.9090

Washington, D.C.
1875 K Street NW
Washington, D.C. 20006
Tel: +1. 202.897.4020

Paris, France
2, rue du Helder
75009 Paris, France
Tel: +33. 01.53.34.11.87

Tokyo, Japan
Minamomirai 3 Chome-7-1
Nishi Ward, Yokohama, Kanagawa
220-0012, Japan
Tel: +81.80.5426.4980