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Near-term transition and longer-term physical climate risks of greenhouse gas emissions pathways

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Abstract (150 words)

Policy, business, finance and civil society stakeholders are increasingly looking to compare future emissions pathways across both their associated physical climate risks stemming from increasing temperatures, and their transition climate risks stemming from the shift to a low-carbon economy. Here we present an integrated framework to explore near term (to 2030) transition risks and longer term (to 2050) physical risks, globally and in specific regions, for a range of plausible greenhouse gas emissions and associated temperature pathways, spanning 1.5-4^{o}C levels of long-term warming. By 2050, physical risks deriving from major heatwaves, agricultural drought, heat stress and crop duration reductions depend greatly on the temperature pathway. By 2030, transition risks most sensitive to temperature pathways stem from economy-wide mitigation costs, carbon price increases, fossil fuel demand reductions and coal plant capacity reductions. Considering several pathways with a 2^{o}C target demonstrates that transition risks also depend on technological, policy and socio-economic factors.

Climate change scenarios are of increasing interest to a diverse range of stakeholders, including policy makers, civil society and businesses. There have already been calls for mitigation scenarios to cater to new users, including companies and financial institutions[1]. In the latter case, this stems from growing awareness that the consequences of and responses to climate change could pose significant financial risks[2], as highlighted by the Taskforce on Climate-related Financial Disclosures (TCFD)[3] and more recently US Federal Reserve Banks[4]. Such risks include transition risks stemming from policies and regulations that limit or price greenhouse gas emissions; climate-related damages; and liability risks associated with the legal responsibility for impacts of climate change[5] [6].

The recent (August 2021) publication of the Intergovernmental Panel on Climate Change's (IPCC's) Sixth Assessment Working Group I report on the physical science basis of climate change[7] paves the way for the Working Group II report on Impacts, Adaptation and Vulnerability (in 2022) and finally the Working Group III report on Mitigation of Climate Change (later in 2022). This sequencing, whilst logical, nevertheless separates analysis around physical implications of increased warming from the economic and societal implications of limiting warming. This makes it difficult for policy makers, corporations, financial institutions and other users to interpret in a holistic way the implications and risks of different pathways.

A truly integrated assessment of pathways is therefore warranted. Surprisingly, there is relatively little literature which simultaneously assesses both the transition and physical risks of different emissions pathways. A recent exception is the work of the Network for Greening the Financial System (NGFS)[8], whose scenarios explore both sides of the risk coin, using integrated assessment models to assess energy, agricultural and land systems changes, as well as associated temperature changes and climate-related impacts, from a set of reference and mitigation scenarios[9]. The physical risks draw from results from the ISIMIP[10] project.

However, future transitions can differ in myriad ways and the NGFS scenarios so far only cover a limited portion of the future possibility space around physical and transition risks, in terms of underlying socio-economics, technological options, timing of mitigation action, policy implementation in different world regions and the resulting temperature change and physical risk outcomes.

Here we present a fully integrated framework to undertake a self-consistent analysis of physical and transition risks stemming from scenarios spanning 1.5-4°C temperatures and encompassing a broad range of transition dynamics, that complements and expands on the NGFS scenarios (See Methods). We combine a technology-rich, regionally disaggregated IAM[11] representing energy system, agricultural and land-based greenhouse gas emissions, a reduced complexity climate model to simulate probabilistic global temperature changes over the 21st century[12], and a suite of impacts models to estimate regional climate-related physical hazards and impacts deriving from the temperature change pathways and their underlying socio-economics[13 14] (See Methods and Extended Data Figure 1). Our scenarios and their presentation of both physical and transition risk in a concise, integrated framework should be of significant utility to multiple stakeholders.

Our presentation of results is focused on the world as a whole and four key regions (China, USA, EU+UK and India), with additional results for additional major regions (Brazil, Japan, Middle East, Russia and Sub-Saharan Africa) presented in Extended Data and Supplementary Information (and referenced in the main manuscript where appropriate). In addition, we show the temporal evolution of transition risk indicators in Supplementary Figures S3.1-S3.25, and of physical risk indicators in Supplementary Figures S4.1-S4.10 to complement the single time snapshots presented in the main manuscript. The Methods contains a full description of modelling approach, indicator choices and rationale and scenario choices.

Temperature outcomes of the scenario set

We use 11 scenarios to explore a range of temperature outcomes as well as socio-economic and technological choices for a set of 2°C temperature target pathways (Table 1).

We show the emissions and associated temperature changes across the 21st century for two groups of the 11 scenarios (Figure 1): the first group of five scenarios spans long-term temperature targets of 1.5°C, 2°C, 2.5°C, 3°C (NDC Pledges) and 4°C (No Policy) with median likelihoods; the second set shows the different scenario variants targeted at meeting a 2°C level of 2100 warming with 50% likelihood. In all cases, the scenarios were not required to precisely meet these targets with this likelihood. The No Policy scenario, with coal, oil and gas demand growing by 72%, 58% and 143% respectively over the period 2020-2100, sees temperatures rise to 4.3°C by 2100. This is a purely hypothetical reference scenario to represent a world absent climate policy, as opposed to an estimate of where emissions are currently heading in light of current ambitions and policies[20]. The NDC Pledges scenario, by contrast, presents a more realistic picture of current ambitions, with median temperature projections rising to 3.1°C by 2100, on the basis of initial Paris pledges and maintaining a similar level of mitigation after 2030 in terms of a constant rate of reduction of GHG intensity of GDP[21].

The 2C Central scenario keeps median warming below 2°C throughout the century, whilst the 2.5C scenario peaks less than 0.1°C above 2.5°C in 2090, before returning to just below that level by 2100. The 1.5C scenario peaks at 1.7°C around 2050, before returning to below 1.5°C by 2080 and down to 1.3°C by 2100. This results from a complete phase out of liquids and natural gas from the transport sector after 2050, rapid technology improvement rates in the buildings and industry sectors, behaviour changes including reduced meat demand and goods consumption, and a phase out of F-gases. The 2C SSP3 scenario does not achieve a long-term temperature increase below 2°C with median likelihood. This results from a lack of land use policy, carbon and energy intensity improvements which are slower than recent historical rates, and supports other analysis on the challenges of meeting lower temperature targets in the SSP3 world[22].

Physical and transition climate risks of the scenarios

Several metrics of physical risk have been presented in the climate change literature, relating to major impacts from climate change, categorised as either gradual[3] and chronic[23], or acute[3] and extreme event-driven[23]. We utilise regional hazard and impact attributes of seven physical hazard indicators, measuring: heatwave, major heatwave, hydrological drought and river flooding annual likelihoods; agricultural drought and maize heat stress annual likelihood; and change in maize crop duration (see Methods and Table 2 for details and rationale). These indicators are calculated at the 0.5x0.5° resolution and averaged to the regional scale, and represent the regional average likelihood or change in duration at a point in the region. The indicators expressed as likelihoods can be interpreted as acute risks, since they characterise the chance of an extreme event happening each year, whilst the average annual change in crop growth duration is a chronic risk. Impacts deriving from these hazards, which we also report (Supplementary Figures S4.1-S4.10) are expressed as annual averages, so characterise chronic risks. For transition risks, we utilise readily-available metrics from IAMs to capture the most salient transition risk-related variables. We draw from a range of proposed low-carbon transition indicators[24] [25] [26] as well as those that track the feasibility of the transition[27] (see Methods and Table 2 for details and rationale). Attempts have been made to understand the specific "value-at-risk" of warming [28], as well as macroeconomy-wide estimates of economic damage stemming from warming, as presented in the NGFS scenarios[9], and based on IAMs' aggregate damage functions. Here we avoid such estimates owing to their aggregated nature and the recognised uncertainties and omissions of damage functions[29] [30].

Our framework allows the identification of the physical and transition risk metrics which vary most between the temperature scenarios (Figure 2). The metrics are all normalised by values in 2050 (physical risk) and 2030 (transition risk) with the 2C Central scenario, and the normalisation implicitly assumes that the significance of the change in metric is directly proportional to the change (in other words, a normalised indicator of 1.5 is 50% worse than the 2C Central scenario).

The physical risk metrics mostly show the change in likelihood of the specified acute event relative to the change with the 2C Central scenario. A value of 1.5, for example, means that the likelihood is 50% greater. The exception is the crop growth duration indicator which shows the change in yield relative to the change with the 2C Central scenario.

If the relationship between increase in temperature and physical risk metric is linear, then the risk in 2050 in the No Policy scenario would be 1.47 times the 2C Central scenario's risk and, at the other extreme, the 1.5C scenario's risk would be 0.9 times the 2C Central scenario's risk. This reflects the ratio of temperature increase above the 1981-2010 period used as a reference for physical climate impacts in this analysis (see Methods). Where the relationship between temperature and physical risk metric shows an increasing (decreasing) gradient with temperature, the differences in risk between the temperature scenarios increase (decrease).

Of the physical risk indicators considered here, the chance of experiencing a major heatwave and the three agricultural indicators have the most highly non-linear relationships with temperature, so show the greatest difference between the temperature scenarios. For example, there would be a 30-40% greater chance of a major heatwave in 2050 with the NDC Pledges scenario than the 2C Central scenario in most regions. The greatest differences between the NDC Pledges and 2C Central scenarios in the chance of river flooding are in India (18% increase, compared to 12% globally), and the greatest differences in agricultural drought frequency are in India (around a 25% increase), SubSaharan Africa (25% increase) and Middle East (50% increase) – see Extended Data Figure 2, for regions not shown in Figure 2. The frequency of periods with heat stress for maize would increase by over 50% in Russia and the EU+UK (slightly less in Brazil), and regional reductions in maize yield (resulting from reduced growth durations) could be consistently 20-30% greater with the NDC Pledges scenario than the 2C Central scenario.

Differences between the temperature scenarios in absolute terms are shown in Supplementary Figures S4.1-S4.10. The ratios of physical risk in each scenario compared to the 2C Central scenario, as shown in Figure 2, are calculated from median estimates of the indicators. There is an uncertainty range around these ratios, determined by uncertainty in the shape of the relationship between temperature and metric (a version of Figure 2 using maximum ratios is shown in Extended Data Figure 3).

Considering the transition risk indicators, at the global level the 1.5C scenario has notably higher values than the other scenarios for most metrics, with the exception being electricity and crop prices. These trends are also reflected for China and India. However, for the EU+UK and USA, the NDC pathway to 2030, as assumed in the NDC Pledges scenario, is actually more stringent than the 2C Central scenario in terms of emissions reductions by 2030. This results in higher transition risk metrics by 2030 as reflected in a colour intensity for the transition metrics which falls between the 1.5C and 2C Central scenario colours. This result is model-specific to GCAM, with other models showing more stringent 2^{o}C pathways to 2030, compared to the NDC case, for the EU+UK and USA[41]. But it importantly highlights that there is no set low-carbon transition pathway – and therefore no set degree of risk - to a given temperature pathway in each region. This point is elaborated below, when a range of 2^{o}C scenario variants' transition metrics are explored (see Figure 3).

Global abatement costs in 2030, which affect overall macroeconomic performance of each region and the world as a whole, are 1.6% of global GDP in the 1.5C scenario, compared to 0.6% in the 2C Central scenario, whilst the 2C Central scenario's abatement cost is about 40% higher than that of the NDC Pledges scenario (at 0.4% of global GDP), as shown in Supplementary Figure S3.1. By comparison, a previous study[42] found 2030 global abatement costs of 0.8% of GDP in a 1.5^{o}C scenario, compared to 0.5% in a 2^{o}C scenario and 0.2% in the (Conditional) NDC scenario. It is important to note that, whilst an insightful measure of the overall additional resource cost of decarbonising by 2030, the abatement cost alone does not capture all macro-economic consequences, if for example it results in a net investment, innovation and growth stimulus to the economy. Further macro-modelling analysis would be required to substantiate this, taking into account the extent to which resources (including investment capital) are fully or under-employed in the region in question[43].

Fossil fuel demand reductions and coal plant reductions are also notable in their inter-scenario intensity variation, indicating specific risks for fossil fuel supply and coal-dependent utility sectors stemming from the temperature pathway followed. Finally, carbon prices are around twice as high in the 1.5C scenario than in the 2C Central scenario, but only a quarter as large in the 2.5C scenario (Supplementary Figure S3.3), with GHG emissions intensity reductions following a similar range in many regions

A more in-depth exploration of transition dynamics across the range of 2^{o}C-targeted scenarios, using a wider range of indicators to assess the transitions, allows a more detailed examination of the differences between these scenarios (Figure 3). Even scenarios aimed at the same temperature goal (thus resulting in similar mid-century physical climate risks) can have considerably different transition risks by 2030. For example, at both the global and regional level, the 2C SSP1 and 2C RES scenarios have higher solar and wind capacity than the other scenarios, owing to the emphasis on these technologies as per their design (Supplementary Figure S3.13). By contrast, the less renewables-focused 2C SSP3 and 2C NUC CCS scenarios have a greater role for nuclear (Supplementary Figure S3.15) and a smaller role for solar and wind. The 2C NDC and 2C Fragmented scenarios have less coal demand reduction (compared to the No Policy scenario) in China and India (Supplementary Figure S3.5), with correspondingly lower reduction in fossil fuel capacity and fossil electricity generation (without carbon capture and storage), reflecting the slower accession to a global 2^{o}C-targeted regime in these scenarios in these regions. By contrast, the 2C NDC scenario has a much higher reduction in unabated fossil fuel capacity and generation in the EU+UK and USA, reflecting the assumed more ambitious pathway in this scenario by 2030, when compared to the 2C Central scenario in these two regions. At a global level and across the regions shown, the 2C SSP3 scenario shows the greatest energy system transition risks, resulting from a lack of land policy, requiring more drastic decarbonisation efforts in the energy system to try to meet the 2^{o}C long-term temperature target. The key point unifying all of these observations is that the technology and sector-specific dynamics governing any 2^{o}C-targeted pathway (and indeed any other given temperature pathway) are by no means a given, but rather depend on the particular scenario features. It will therefore be imperative for any risk assessment to consider these nuances. This point has already been demonstrated to some extent through inter-model diversity of results from the NGFS scenarios[32], so our analysis, using broad scenario sensitivity within a single model, reinforces this finding.

In addition, and as shown in Supplementary Figures S2.1, S2.2 and Supplementary Table S2.1, the range of 2030 transition indicator values represented by our non-delayed action 2^{o}C-targeted scenarios (2C Central, 2C SSP1, 2C SSP3, 2C RES, 2C NUC CCS) also overlaps with the NGFS scenarios targeting a below 2^{o}C long term temperature outcome, with for most indicators comparable median values. However, as also demonstrated in Figure 3 and discussed above, the regionally uncoordinated socio-economics of the 2C SSP3 scenario provides a source of significant 2030 transition risk variation in our scenarios. It is useful to be able to isolate these differing socio-economics (as well as the different technological assumptions around renewables and CCS and nuclear) to uncertainties in future outcomes, over and above the inter-model variations around the same socio-economics (in this case SSP2) as used in the NGFS scenarios.

Indeed, this single-model analysis can be situated within the broader ensemble of mitigation pathways from recent years. Our illustrative 1.5^{o}C pathway sits within the range of the IPCC's SR1.5 database of 1.5^{o}C-consistent scenarios (considering no-, low- and high-overshoot scenarios) across a number of transition indicators (Supplementary Figure S2.1), whilst our 2^{o}C-targeted pathway ensemble mostly overlaps with the possibility space as represented in the database (Supplementary Figure S2.2).

A consideration of uncertainty and more extreme values is likely to be critical to comprehensive risk assessments. Furthermore, it could be highly beneficial to consider futures analysis approaches beyond systems modelling such as that undertaken here, to better populate the future possibility space[44], as well as considering extremes and traditionally under-represented disruptions[45].

In sum, though not a comprehensive assessment of all future possibilities and uncertainties, this analysis serves as a critical framework for comparing physical and transition risks. It can viably be built upon to encompass a wider range of scenarios and metrics as desired.

Discussion

Significant near-term transition risks to specific business sectors could result from carbon prices, potential stranding of carbon-intensive assets such as coal-fired power stations, and demand reductions for fossil fuels and the technologies that use them, as well as changes to electricity and food prices resulting from the transitions. In the latter two cases, however, our analysis indicates relatively little inter-scenario variation in the near-term. In addition, higher economy-wide abatement costs could affect assets across the business and household sectors, depending on both the resource cost and investment stimulus consequences of these additional incurred costs. As demonstrated in this analysis and elswehere[46 47], the more stringent the mitigation action, the higher the abatement costs and sector-specific transition risks. Such risks are of particular relevance to the government and finance sectors that will foot the bill, in the former case in terms of greater fiscal expenditure to support the economy, and in the latter case in terms of lower returns on aggregate investments across the economy. However, such scenarios result in lower physical climate hazards throughout the century. For some hazards (major heatwave likelihood, change in maize crop duration) there are considerable differences between the higher and lower temperature pathways.

Our physical risk analysis, whilst focused on mid-century, is salient for policy, corporate, household and financing decisions today. For example, anticipated long-term physical climate-related damages have been found to lead to present-term asset devaluations[48 49], which include 25-40 year mortgage books, as well as long-term investments in pension funds[48]. The multiple 2°C pathways explored demonstrate that scenarios with similar longer-term physical risks could have very different near-term transition risks. As such, “a single scenario will not answer all questions”[50].

Our integrated scenario analysis framework can be built upon by interested stakeholders across business, finance, household and government sectors, as shown in Figure 4, which indicates sample implications for a range of key economic sectors. For example, the framework serves as a first step towards a full “scenario expansion” towards financial risk estimates[50], which would involve quantitatively downscaling sector-level and economy-wide outputs from IAMs to firm- and household-level financial risks. There is already a wide range of tools available to help do this[51], for example through calculating firm level input cost increases as a result of carbon intensity and carbon pricing, as well as calculating loss of incomes of fossil fuel companies as a result of reduced demand[52], leading to changes in returns, probability of default, credit risk and credit ratings[51]. A critical consideration in undertaking such financial risk analysis is systemic risk, deriving not just from first-round exposure of investors to carbon-intensive sectors, but also to second-round effects from financial firms’ investment in each-other, creating networks of exposure to losses[53], as well as the extent of insurance against losses[54]. More detailed analysis is therefore required to understand the full financial system and wider economic risks. In addition, we do not explicitly account for adaptation measures in our analysis, but recognise that it is clearly of critical importance that the translation of risks to economic impacts takes into account the storyline of each region’s adaptation and risk resilience frameworks.

Nevertheless, the insights gleaned from comparing physical and transition risks in a consistent scenario framework provides a clear basis for building such analysis, including identifying underlying drivers of economic changes that result from them. In essence, we provide the first chapter in this storyline of global and regional physical and transition consequences of different plausible emissions pathways.

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Author contributions

A.G. and S.Mo. conceived the study. A.G., D.B., J.L., H.M., J.R., M.G., N.W.A. and S.Mo. designed the scenarios and modelling protocol. H.M. and M.G. ran GCAM. D.B. ran MAGICC. N.W.A. ran the climate impact models. S.Mi. undertook all scenario data analysis and visualisation. A.C.K. advised on financial risk analysis and literature. A.G. wrote the manuscript, with input from all authors.

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Competing Interests

The authors declare no competing interests.

Table 1: Scenario details

No.	Name	Details	Rationale
1	No Policy	No new policies from 2010.	This mirrors the NGFS[9] and Bank of England (BoE)[15] scenarios with no new policies, and reaches ~4°C of median warming by 2100.
2	NDC Pledges	NDCs to 2030.	Assumes NDCs met under the Paris Agreement from 2015 to 2030 and then a continuing trend of reduction of regional GHG intensities, leading to ~3°C of median warming by 2100.
3	2C Central	Paris Agreement compliant transition from 2025. Socio-economics based on second shared socio-economic pathway (SSP2[16]). Full technology portfolio.	A central reference case for a 2°C-compliant transition stemming from a ratchet against current policies over the current decade (i.e. 2020-2030). Socio-economics represent a continuation of historical socio-economical dynamics, whereas all other SSPs represent shifts away from this (in different directions).
4	2C NDCs	NDCs to 2030, then rapid mitigation towards a 2°C target.	Assumes NDC action to 2030 as with scenario 2, then rapid rise in carbon price as part of a disorderly transition. This scenario reflects one dimension of disorderliness.
5	2C Fragmented	Different start dates of 2°C-consistent action, with some countries going early e.g. EU+UK, USA, and others going later e.g. China, Russia, Brazil, India.	Showcases fragmented regional approach to mitigation based on capacity (GDP/capita). The High-Income Countries (HICs) start mitigation efforts from 2021, with Middle-Income Countries (MICs) joining in 2025 with half the effort of the HICs and gradually ramping up to match them by 2035. The Low-Income Countries (LICs) start with full mitigation effort in 2040.
6	2C SSP1	Alternative underlying socio-economics to 2C Central (i.e. scenario number 3), focusing on greater resource efficiency and energy efficiency, utilising the SSP1[17] dynamics.	Underlying socio-economic and technological variation, focus on renewables and energy efficiency, and high levels of international cooperation and governance offers a different view to historical socio-economic trend continuation dynamics in 2C Central scenario.
7	2C SSP3	Alternative underlying socio-economics to 2C Central (i.e. scenario number 3), consistent with a more challenging mitigation scenario (utilising the SSP3[18] dynamics) that may require greater disruption and transition risk.	SSP3 in particular has resurgent nationalism which leads to domestic focus on policy, and virtually no land use protection policy, since growth is material-intensive and international governance weak.
8	2C RES	As 2C Central (i.e. scenario number 3), but with higher renewables (wind and solar).	Included to understand the sensitivity of transitions to underlying technological preferences – in this case renewables (wind, solar and geothermal energy) being cheaper and preferred options.
9	2C NUC CCS	As 2C Central (i.e. scenario number 3), but with higher nuclear and CCS.	As scenario 8, but this time with focus deliberately away from renewables and on nuclear and carbon capture.
10	2.5C	As 2C Central (i.e. scenario number 3), but orderly, coordinated transition to higher temperature outcome (2.5°C).	A deliberate exploration of a case between the NGFS[9] higher temperature, lower transition risk cases and 1.5-2°C cases with higher transition risks.
11	1.5C	As 2C Central (i.e. scenario number 3), but orderly though ambitious coordinated transition to lower long-term temperature (1.5°C).	Lowest temperature scenario provides a critical contrast to others in terms of full-century physical risk. Includes demand reduction through behaviour changes, higher energy efficiency, rapid electrification, reduction in non-CO_2 GHGs, limits on bioenergy use, and gradual afforestation. Results in peak in median warming of ~1.7°C around mid-century and a return to below 1.5°C by 2100. Further details available in Ref[19].

Table 2: Physical and transition indicators included in this analysis

Indicator	Rationale	Example of use
Physical hazard indicators (2050)		
Annual likelihood of a heatwave (% chance))	Heatwaves adversely impact upon human health and wellbeing: the heatwave definition here currently occurs in around 35% of years.	Reported in literature on global and regional impacts of climate change under different temperature change pathways, considering different underlying socio-economic development scenarios[13].
Annual likelihood of a major heatwave (% chance)	Heatwaves adversely impact upon human health and wellbeing: the heatwave definition here currently occurs in around 5% of years.	
Annual likelihood of a river flood (current 50-year event) (% chance)	River flooding causes direct and indirect losses to health, livelihoods and economic assets: the flood here currently occurs in 2% of years.	
Annual likelihood of hydrological drought (% chance)	Water resources droughts affect supplies of water to people and industry. The drought defined here currently occurs in around 6% of years.	
Annual likelihood of agricultural drought (% chance)	Agricultural droughts affect crop yields, farmer livelihoods and food security. The drought defined here currently occurs in around 10-12% of years.	
Annual likelihood of heat stress for maize (% chance)	High temperatures at critical points in the growing season can adversely affect crop yields. The current chance varies considerably between regions, with a global average of around 5%.	
Change in maize crop growth duration (days)	Reduction in time to maturity due to higher temperatures would result in lower yields.	
Transition risk indicators (2030)		
Economy-wide abatement cost ($billion, % of GDP) – relative to No Policy scenario	Measure of macro-economic risk affecting all production / consumption activities.	Reported in IPCC scenario databases[31] and NGFS results database[32].
Carbon price ($/t$CO_2$)	High carbon price will place additional production cost on carbon-intensive industries, reducing profits / margins.	Used to assess the risk of carbon leakage of sectors, when combined with production carbon intensity and trade intensity[33].
GHG emissions intensity of GDP reductions (tCO_2e/$000) – reductions measured relative to No Policy scenario	Rapid reduction in emissions intensity indicates potentially disruptive transition.	Transition Pathways Initiative includes sectoral emissions intensity benchmarks for low-carbon scenarios[34].
Fossil fuel demand (EJ/year) reductions measured relative to No Policy scenario	If this decreases rapidly, it signals a disruptive shift away from established industries.	Common metric in IPCC scenario database analysis[25,35] and specific analysis of low-carbon technology disruptions[36].
Coal plant capacity reductions (GW) – reductions measured relative to No Policy scenario	Indicator of lost capital and lost jobs in coal power and upstream (i.e. mining, distribution) sectors.	Used in mitigation feasibility and stranded asset analysis[37,38].
Electricity prices ($/kWh)	Rapid increase in electricity price could be associated with rising business and household energy bills and disruption.	Key indicator to compare transitions to 1.5°C in different shared socio-economic pathways[26] and to 2°C scenarios[39].
Crop prices ($/Mcal)	Rising household food prices indicates lower ability to service debt.	Previous use in impact of bioenergy use in mitigation scenarios on wheat prices[40].

Figure 1 – Scenario emissions and temperature outcomes across 21st Century. *In the main figure, the left panels show aggregate GHG emissions (using GWP100) whilst the right panels show median temperature increases (on 1850-1900) as solid lines and 10th to 90th percentile range as plumes. On the side figure the 10th to 90th percentile range in 2100 is shown by the bar with circles indicating the median. Two groups of scenarios are shown, for clarity of presentation: the upper panels show a range of scenarios spanning approximate 1.5-4°C long-term temperature outcomes; the bottom panels show the set of scenarios targeted at a 2°C long-term temperature rise.*

Figure 2 – Physical and transition risk metrics for world and four major regions*. Each heat map shows 7 physical hazard metrics on the left-hand panel and 7 transition risk metrics on the right-hand panel. The metrics are expressed as a ratio of each scenario's value and the value for the 2C Central scenario. For the physical hazard metrics, this is the median ratio across the uncertainty range. Each transition risk metric is for the year 2030, whereas each physical risk metric is for the year 2050. Circle size indicates 2100 median temperature increase on pre-industrial (1850-1900) levels in each temperature scenario.*

Figure 3 – Transition metrics for world and four major regions*. Each heat map shows 10 transition metrics for 2030. These are all transition risk indicators, apart from nuclear capacity and solar and wind capacity expansion, which capture a transition opportunity for low-carbon technologies and industries, rather than a reduction in carbon-intensive technologies and industries. The metrics are normalised to a value of 1 for the 2C Central scenario and then ranked based on the value of the metric. Thus, for any given scenario, a higher value of the rank means a higher the value of transition indicator compared to other scenarios, for any given region. Building, Industry and Transport* CO_2 *intensity expressed per unit final energy.*

Figure 4: From an integrated scenario risk framework to sectoral and financial risk analysis*. Left-hand side of figure ("Scenario Analysis") shows a selection of key transition and physical risks and typical outputs from integrated assessment and physical impacts models that reflect them. Right-hand side ("Sectoral implications") shows examples of how each risk could impact on different sectors, including corporate and financial sectors.*

Extended Data Figure 1 - Model set-up to produce physical and transition risk-related output indicators for each scenario*.*

Extended Data Figure 2 – Physical and transition risk metrics for five additional regions*.*

Extended Data Figure 3 – High (a) and Median (b) physical risk metrics for world and four regions*.*

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Methods

Integrated assessment modelling approach

The scenarios in this study use GCAM (Global Change Analysis Model), an Integrated Assessment Model (IAM) developed by the Joint Global Change Research Institute (JGCRI) of the University of Maryland and the Pacific Northwest National Laboratory. GCAM is an open-source, technology-rich model of the energy, economy, agriculture and land use, water, atmosphere, and climate systems[55]. GCAM is a five-year time step, dynamic-recursive market equilibrium model which represents the global economy by disaggregating the world into 32 geopolitical regions, 235 river basins and 384 agro-ecological land-use regions. GCAM has been used extensively for a wide range of applications to explore the implications of changes in key driving forces such as technology and economic growth on national and international policies and pathways[56 57 58 59].

GCAM version 5.1, as used in this study, is calibrated to a historic base year (2010), with trajectories to different temperatures in these scenarios specified using fossil fuel and industry CO_2 constraints (and GHG constraints, in case of the NDCs). All emission constraints are assumed to begin in 2025 (except for the NDCs, which begin in 2020). GCAM uses assumptions about population growth and changes in labour productivity, along with representations of resources, technologies, and policies, and solves for the equilibrium prices and quantities of various energy, agricultural, and CO_2/GHG markets in each five-year model period from 2010 (the calibration year) to 2100 at different spatial resolutions. Primary energy (i.e., coal and other fossil fuels), agricultural products, and biomass are traded globally. GCAM calculates the CO_2 prices required to meet the emissions constraint imposed in each model period. Land-use change emissions are in addition to the constraint, and their price is determined as an exogenously specified proportion of the fossil emissions price. This is done because, whereas fossil fuels are largely a market commodity, much of the land use and agriculture occurs outside of regulatory frameworks in many countries[60]. To represent long-term improvements in institutions for implementing land-use policy, land-use change emissions are priced here as a linearly increasing proportion of fossil and industrial emissions price, based on the respective SSP assumptions.

GCAM tracks emissions of 24 GHGs, aerosols, and short-lived species endogenously based on the resulting energy, agriculture, and land systems activity. Emissions can then be passed to the climate carbon-cycle module and converted to concentrations, radiative forcing, temperature, and other responses to the climate system, although in this study, a separate climate module and impacts models are used for these subsequent steps (see Extended Data Figure 1). Further descriptions of other GCAM version 5.1 model specifications (and prior releases) can be found in the online GCAM documentation[61].

Transition metrics choices

Transition risks derive from the rapid shift from carbon-intensive to low-carbon energy sources and technologies, as well as associated structural changes in economies from carbon-intensive industries (such as industrial manufacturing using fossil fuel combustion for high temperature heat) to low-carbon sectors (such as digital services utilising low-carbon electricity).

Existing climate scenario databases (e.g. refs [31 62 32]) consist of hundreds of output variables describing transitions in the energy system as well as (where covered by participating models) agricultural and land systems. Each of these variables provides a degree of information of potential relevance to transition risks, though it is unclear which are the most directly useful or applicable to value-at-risk calculations. There is as yet no established set of transition risk indicators, even though several indicators have been identified as relevant to transition risk considerations.

Here we focus on a subset of integrated assessment model (IAM) outputs to capture the most salient transition risk-related variables. We first draw from a set of indicators to track progress towards the Paris Agreement goals[24], which uses a Kaya identity to highlight the importance of emissions intensity of the economy, as well as share of fossil fuels in energy and the energy technology mix. On the latter, we focus particularly on coal-plant capacity, owing to the considerable literature on the potential for stranding of this asset class, with widespread implications for job losses and coal community decline [38 63]. Emissions intensity at sectoral levels has become a central metric to benchmark company performance against transition scenarios, in for example the Transition Pathways Initiative project[34], so we extend our economy-wide intensity metric to a sectoral intensity metric (in Figure 3). We additionally draw from IAM-based indicators of feasibility of the transition[25] which emphasise the importance of abatement costs and carbon prices, as well as reaffirming the importance of coal plant idling and capacity reductions[26]. Carbon price levels are central to considerations of energy portfolio default likelihoods[64], whilst abatement costs directly impact economic output. Critically however, we do not consider the potential stimulus effect of low-carbon investment on economic growth. Finally, we include electricity and food price indicators, as these relate directly to household energy costs and therefore loan defaults, and (in the case of electricity prices) feature as key indicators in assessments of energy system transitions in deep mitigation scenarios [39].

Whilst considering the different metrics that IAMs produce as outputs, a key set stems from the diagnostic exercises that have been undertaken to compare major IAM characteristics[65 66]. These include: a relative abatement index (measuring the share of baseline emissions reduced in a policy case); an emissions reduction type index (showing the share of the relative abatement index that can be attributed to supply side measures); marginal abatement cost curves showing emissions reductions against carbon prices; energy intensity and carbon intensity; measures of fuel shares of major primary fuels such as fossil and non-fossil sources; mitigation costs; and the mitigation cost achieved per unit of carbon pricing. Many of these metrics are directly useful for measuring transition risks and have been included in our transition indicator analysis (mitigation costs, emissions intensity; fuel shares). We deem the others to be useful for diagnosing model characteristics and responses to carbon pricing at a macro level, but not easily translatable to sectoral or company-level transition risk.

This is not intended to be a comprehensive or exhaustive set of transition risk indicators, but rather highlights the high-level dynamics of the transition that have clear transmission channels to business and household asset values, as well as other economy-wide risks. It is important to note that here we do not attempt to convert these metrics into value-at-risk or value losses.

Climate modelling approach

The temperature outputs from GCAM version 5.1 are deterministic, without representation of climate system uncertainties. In this study we include leading order uncertainties into the climate simulations by running each emissions scenario through a probabilistic variant of the MAGICC4.2 simple climate model. This is an upwelling-diffusion ocean coupled to an atmosphere layer and a globally averaged carbon cycle model which has demonstrated skill in reproducing the surface temperature response of a wide range of more complex models.

In the configuration used here[12], the uncertainty in temperature response is sampled by perturbing the equilibrium climate sensitivity, the ocean mixing rate (which determines how quickly the warming at the surface is diffused throughout the ocean) and a measure of the climate-carbon cycle feedback strength (regulating how much carbon is emitted and absorbed naturally in response to climate change).

Uncertain parameter distributions are taken from the climate modelling literature. Equilibrium climate sensitivity is based on that of the Fifth Coupled Model Intercomparison Project (CMIP5)[67], which tends to give higher temperature changes and a tighter allowable carbon budget for a given warming target than alternative distributions of equilibrium sensitivity. Carbon cycle uncertainty is based on C4MIP[68] for which the carbon cycle response is broadly similar to that in CMIP5.

Uncertainty in ocean mixing is based on model results from the IPCC fourth assessment as more recent updates were not available at the time of performing the calculations, but the range of transient responses from the simple model in this configuration suggests the distribution remains acceptable.

Physical hazards and impacts modelling approach and metrics

Seven indicators of hazard and related impact across different sectors were calculated for each emissions scenario. All are based on spatially-explicit global-scale impacts models. The indicators represent exposure to drought, river flooding, heatwaves, and reductions in potential crop yield. All impacts are calculated over a 30-year period. Each indicator is characterised by damage functions relating indicator to increase in global mean surface temperature, calculated separately from climate scenarios constructed from 23 CMIP5 climate models[14]. The damage functions are combined with the probability distributions of change in temperature for a given emissions scenario to produce distributions of hazard and impact indicator in each year[13]. The distributions combine uncertainty in the magnitude of temperature increase with uncertainty in the spatial pattern of change in rainfall and temperature represented by the different damage functions, and therefore represent scientific uncertainty in how a given emissions scenario translates into change in local climate. We compare the distributions of risk at a place for a given scenario with the risks under the 2C Central scenario, and characterise physical risks by the median ratio between the scenarios (and show also the 90th percentile ratio in Extended Data Figure 3 as a 'worst case').

Damage functions are constructed separately for five SSP socio-economic scenarios[69] and at 10-year increments.

The damage functions were constructed by applying spatially-explicit global-scale impacts models operating at a scale of 0.5x0.5° [14]. Each model operates on a daily time step and applies climate scenarios corresponding to specific increases in global mean surface temperature to observed climate time series[70] spanning the period 1981-2010: this period is used to define the current reference climate. The scaled climate scenarios were constructed using pattern-scaling[71]. It is assumed that each damage function is equally plausible.

Two heatwave indicators represent different magnitude heatwaves: one defines a heatwave as occurring when at least two days exceed the 95th percentile of daily temperatures over the 3-month warm season during the 1981-2010 reference period (this occurs in around 35% of years on average), and the other requires at least four days exceeding the 99th percentile (this occurs in less than 5% of years). Hazard is expressed as an annual likelihood (therefore acute risk), and regional average likelihood at a point is calculated by averaging over all grid cells with more than 1000 people. The average annual number of people exposed to heatwave (a chronic risk) for a given year and SSP is determined by multiplying heatwave frequency in a 0.5x0.5° grid cell by population.

River flood and water resources drought are both based on river flows simulated using the Mac-PDM.09 global hydrological model[72]. River flood risk[73] is characterised by the frequency of the reference period 50-year flood (2% annual likelihood), and the average annual number of people exposed to flooding is determined by multiplying frequency by the number of people living in major river floodplains (estimated at approximately 700 million in 2010). Note that this does not include the numbers living in smaller floodplains, but the proportional change should be consistent. The regional average likelihood at a place is averaged over all the floodplain grid cells. Water resources drought risk is represented by the Standardised Runoff Index (SRI)[74], calculated here from runoff accumulated over 12 months. A drought is defined as an SRI of less than -1.5, which occurs by definition 6.8% of the time during the 1981-2010 reference period, and a 'significant' drought is a period with at least six months with an SRI_{12} of less than -1.5 (which has a global average likelihood of around 6% in 1981-2010). The regional average annual likelihood of a 'significant' drought at a place is averaged over all the cells with more than 1000 people. Impact is characterised as the average annual number of people affected by a 'significant' drought.

Agricultural impacts are represented by three indicators. Agricultural drought is calculated using the Standardised Precipitation Evaporation Index (SPEI)[75], accumulated over 6 months. A 'significant' drought occurs when there are at least three months with an $SPEI_6$ of less than -1.5, and drought likelihood is the annual chance of experiencing such an event. The regional average likelihood at a point is averaged over cells with cropland (the global average likelihood is around 9-10%). Drought impact is characterised as the average annual area of cropland affected by 'significant' drought. Change in crop yield potential is represented by change in the time taken for maize to accumulate a specific number of growing degree-days (actually the reference period (1981-2010) mean). A shorter growing period means less time for grain to fill and, as a first approximation, potential yield reduces in proportion to the percentage reduction in growing period (note that in water-limited regions the effects of changes in drought are likely to be more significant for yields than the effect of higher temperatures on potential yield). The impact indicator here is the average annual area of maize cropland with a reduction in crop growth duration of at least 10 days, which corresponds to a reduction in potential yield of approximately 8%. The third agricultural indicator is the likelihood of experiencing at least five days with damaging temperatures (above 36^{o}C) during the maize reproductive phase. The regional average likelihood at a point is calculated by weighting by maize cropland area (the global average likelihood is around 5%, but there is considerable variability between regions), and impact is calculated as the regional annual average area of maize cropland affected. It is assumed here that the area of cropland remains unchanged over time.

Scenario choices

We reviewed a range of scenarios proposed by the Network for Greening the Financial System (NGFS)[976] as well as the UK Bank of England's proposed Biennial Exploratory Scenario consultation document to explore climate risks[15]. Each points to three "archetypes" of future emissions pathway, with associated warming impacts. The first archetype, around no additional mitigation policy action, involves little transition away from recent trends of energy usage, thereby entailing relatively low transition risks. However, associated temperature changes of between 3°C and 4°C by 2100 could result in significant physical risks. Two mitigation scenario archetypes, the first entailing a relatively rapid but orderly coordinated transition to low-carbon starting from 2020, and the second seeing weak mitigation action through the 2020s and then rapid, "disorderly" action thereafter, both keep warming to below 2°C, avoiding or reducing physical risks. However, both cases entail transition risks, though the second, disorderly transition is designed to explore more significant transition risks. The NGFS scenarios explore variants within these archetypes, including around limitations on carbon dioxide removal (CDR) as well as both below 2°C and below 1.5°C targets. Alternative scenario frameworks have also been explored. For example, De Nederlandsche Bank (DNB) explores four different potential shocks, stemming from technological (rapid penetration of renewables), policy (e.g. rapid carbon price increase) and confidence shocks (delaying investments in the face of uncertainty around technology and policy)[77].

Here we complement and expand the scope of the NGFS scenarios in four ways. First, we explore variations around underlying socio-economic trends. Whereas the NGFS scenarios are all driven by "middle of the road" assumptions on population and economic growth (specifically, the "SSP2" socio-economics[16]), we include key variations that explore very different socio-economic paradigms – a green growth paradigm (SSP1[17]), and a much more challenging paradigm with increasing nationalism, higher material consumption and lower educational and technological development (SSP3[18]). Second, we explore disorderly scenarios through regional fragmentation and staged accession to a long-term temperature mitigation strategy. This adds to the NGFS's "disorderly" scenarios which assume rapid mitigation from 2030, as well as a "divergent" net-zero scenario which achieves this goal with immediate but divergent policy implementation. Third, we explicitly explore what we deem plausible technology variations in the transition pathway to 2°C – focusing on either a high renewables pathway, or one with a greater role for non-renewables (nuclear and carbon capture) technologies. Fourth, we explore plausible transition pathways which, owing to their slower rate of mitigation, do not achieve the below 2°C goal, but rather a higher (~2.5°C) level of warming, in line with several experts' scepticism around the achievability of a 2°C or below temperature goal even under a scenario where the Paris Agreement temperature goal is aimed for[78], as well as reflecting a world somewhere between current pledged NDCs and envisaged mid-century net-zero targets[79]. We note that the updated NGFS NDC scenarios in Phase II[76] now show a similar temperature increase (around 2.5°C) resulting from the assumption of increased climate policy commitments. We include a specific 1.5°C scenario developed by ClimateWorks Foundation (in partnership with the Pacific Northwest National Laboratory GCAM modelling team). This scenario, by design, emphasises rapid electricity decarbonisation (with a focus on high non-bioenergy renewables, low nuclear and CCS, and low bioenergy) and rapid electrification of end use sectors. It also assumes lower industrial manufacture demand (e.g. for cement), smaller and more efficient new buildings and a range of transport behaviour changes including ridesharing and reduced aviation and shipping demand. Land use and agricultural sector assumptions include limited meat consumption, improved crop practices that enhance yields, and gradual afforestation. Full details of this 1.5°C scenario are available in Ref[19].

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request. The GCAM data system is publicly available at https://gitbhub.com/JGCRI/gcamdata.

Code availability

All code used for data analysis and creating the figures is available from the corresponding author on reasonable request.

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