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The Climatic Impact-Driver Framework for Assessment of Risk-Relevant Climate Information

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Key Points:

- Deepens explanation of Climatic Impact-Driver (CID) Framework utilized in Intergovernmental Panel on Climate Change Sixth Assessment Reports
- Distinguishes practical CID types and categories that allows climate information to target conditions that affect the things we care about
- Neutral Framework does not pre-judge beneficial, detrimental or neutral outcomes which are system- and sector-dependent

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Abstract

The climate science and applications communities need a broad and demand-driven concept to assess physical climate conditions that are relevant for impacts on human and natural systems. Here, we augment the description of the "climatic impact-driver" (CID) approach adopted in the Working Group I (WGI) contribution to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report. CIDs are broadly defined as "physical climate system conditions (e.g., means, events, and extremes) that affect an element of society or ecosystems. Depending on system tolerance, CIDs and their changes can be detrimental, beneficial, neutral, or a mixture of each across interacting system elements and regions." We give background information on the IPCC Report process that led to the development of the 7 CID types (heat and cold, wet and dry, wind, snow and ice, coastal, open ocean, and other) and 33 distinct CID categories, each of which may be evaluated using a variety of CID indices. This inventory of CIDs was co-developed with WGII to provide a useful collaboration point between physical climate scientists and impacts/risk experts to assess the specific climatic phenomena driving sectoral responses and identify relevant CID indices within each sector. The CID Framework ensures that a comprehensive set of climatic conditions informs adaptation planning and risk management and may also help prioritize improvements in modeling sectoral dynamics that depend on climatic conditions. CIDs contribute to climate services by increasing coherence and neutrality when identifying and communicating relevant findings from physical climate research to risk assessment and planning activities.

Plain Language Summary

Climatic impact-drivers (CIDs) are climate conditions that affect the things we care about in nature and society. We deepen the motivation and definitions that allowed the Intergovernmental Panel on Climate Change to identify 33 distinct CID categories including extreme heat, hydrological drought, severe wind storm, permafrost, relative sea level, marine heatwaves, and air pollution weather. Each CID category may be analyzed with specific indices that inform adaptation, mitigation and risk management. The CID Framework allows us to avoid universally labeling a climate condition as a "hazard,"

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recognizing that the same physical condition may be detrimental for some and beneficial or inconsequential for others. This approach allows climate scientists to engage with impacts and risk experts to target specific tolerance thresholds that are system- and sector-dependent. This more comprehensive description of the CID Framework provides a practical foundation for climate research, climate and impact model development, risk assessments and climate service product creation.

1. Motivation

Continuing advances in climate change assessment have led to stronger interactions between the physical climate science community (with a focus on process understanding) and the climate impacts and risk communities (devoted to working with stakeholders to understand the implications of observed and future climate changes on affected systems). For the sake of efficient decision making, it is crucial that climate information is produced with a prior knowledge of its application through science and decision making interactions (Doblas-Reyes, et al., 2021; Lemos et al., 2012; Meinke et al., 2006; Ranasinghe et al., 2021). A process of "co-production" extending from these communities to stakeholders serves as a model to shift from a supply oriented (or "top-down") climate science assessment toward assessments driven by the demand for useful climate information (ISO, 2018; Jones & Preston, 2011; New et al., 2022; Pulkkinen et al., 2022). This process is cemented by sustained engagement and a recognition of context and values that shape diverse decision processes, including the identification, gathering, processing and delivery of climate information in a manner that complements stakeholders' perception of risk and motivation for action.

A common framework guiding climate information development has been a long-time challenge of the Intergovernmental Panel on Climate Change (IPCC) in creating coherent assessments across Working Groups. The IPCC has long fostered a neutral approach on climate information, for example, developing the "Reasons for Concern" framework in its Third Assessment Report (O'Neill et al., 2017; Smith et al., 2001). The IPCC adopted a cross-Working Group framework characterizing risk as an intersection of hazard, vulnerability and exposure in its Special Report on Climate Extremes (SREX; IPCC, 2012; see also Zscheischler et al., 2018). The Fifth Assessment Report (AR5) emphasized that good scientific and technical information is necessary but not sufficient for decision making given that actions are decided in particular contexts, with specific aims, and weighing multiple motivations under uncertainty (Jones et al., 2014; Kolstad et al., 2014; Kunreuther et al., 2014). In its most recent Sixth Assessment Report (AR6) the IPCC further recognized that societal actions can alter each component of risk (IPCC, 2019; Reisinger et al., 2020). The IPCC AR6 Working Group I (WGI) glossary definition of risk emphasized the potential for adverse climate outcomes even as the assessments also covered the potential for beneficial outcomes of climate change (IPCC, 2021b).

In this article, we describe the choices and methodological aspects underpinning a synergistic "Climatic Impact-Driver Framework" whereby physical climate science assessment can provide useful information for applications and decision making without pre-determining that changing climate phenomena are universally hazardous, beneficial, or inconsequential. The CID Framework therefore underscores that climate information is neutral even as it feeds into more complex risk and decision-making processes (Simpson et al., 2021). Application of this framework informs future IPCC assessments and additional climate services assessing specific regions, sectors or mitigation, adaptation and risk management responses.

The concept of a Climatic Impact-Driver (CID) was first proposed in response to review comments for the WGI Contribution to the IPCC AR6 First Order Draft. It was then noted in the IPCC Guidance Document on Risk (Reisinger et al., 2020), and the CID Framework was developed in consultation with WGII and utilized within the IPCC AR6 WGI (as described in Chapter 12; Ranasinghe et al., 2021) and carried into the Technical Summary (Arias et al., 2021), the Interactive Atlas (Gutiérrez et al., 2021) and the Summary for Policymakers (IPCC, 2021c). Here we augment the IPCC's utilization of the CID Framework by providing further context, deepening the Framework description, elucidating the process by which CID types and categories were distinguished, and describing how the Framework may be applied in co-developed vulnerability, impacts, adaptation and climate services applications (Burton et al., 2002; Ruane et al., 2016). We focus on the co-production of climate information but recognize that this is but one element of complex risk assessment and decision-making processes that merit further analysis beyond the purview of this paper (Simpson et al., 2021).

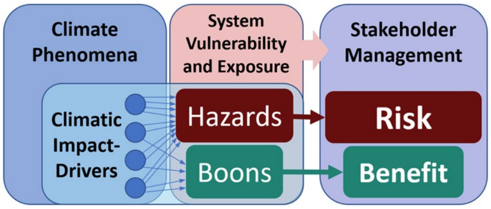

Figure 1. Climatic impact-drivers (CID) capture select characteristics of climate conditions (e.g., means, events, and extremes) that are relevant for impacts and risk management. CIDs emerge from the combination of climate phenomena with information on vulnerability and exposure determining assets' climatic responses, which allows translation of CIDs into hazards (associated with risk) or boons (associated with benefits or opportunities) for stakeholder management.

2. Defining Climatic Impact-Drivers

The term "impact-drivers" could essentially be used to describe a multitude of conditions that create impact in society and ecosystems (e.g., climate change, earthquakes, population growth, viral outbreaks, technological change, price spikes, natural resource extraction, and social conflict). Here we focus on distinguishing those impact-drivers that are directly related to the climate system, and thus IPCC AR6 defined "*climatic impact-drivers*" (CIDs) as "physical climate system conditions (e.g., means, events, extremes) that affect an element of society or ecosystems. Depending on system tolerance, CIDs and their changes can be detrimental, beneficial, neutral, or a mixture of each across interacting system elements and regions" (IPCC, 2021b; Ranasinghe et al., 2021). Note that the hyphen in *impact-driver* was added (since Reisinger et al., 2020) to establish this as a single term that could be modified to represent different varieties of impact-drivers (climatic, tectonic, technological, etc.).

The true extent of a CID's consequence cannot be understood by gauging a CID alone, as climate information must be combined with vulnerability and exposure information to determine realized impact or the profile of risk or benefit (Figure 1). Universally labeling a given climatic condition as a "hazard" or "boon" is very rarely possible, given that it may have detrimental impacts on one sectoral element and beneficial impacts on another leading to a continuum of impacts. Climatic impact-drivers form a subset of all climate information given that many aspects of the climate system do not directly affect natural and societal system assets in a manner practical to decision making. Likewise only a subset of vulnerability and exposure information determines an asset's physical climate responses. Although previous IPCC assessments have documented an overall imbalance between detrimental and beneficial sectoral outcomes of climate change (Field et al., 2012; IPCC, 2014), that result is not inherent in the physical climate condition itself (and thus the CID changes); rather it is a reflection of the impacts and risk assessment that directly follow.

The CID Framework is designed to help climate scientists deliver climate information contextualized at a scale for decision making by stakeholders and policymakers concerned with risk to a particular aspect of society or ecosystems (assets which may have economic, cultural, or intrinsic value). Relevant CIDs are identified by recognizing climate means, events and extremes that drive a system response, encouraging evaluation that extends beyond the most obvious climate connections. CIDs operate from the perspective of the affected system or sectoral asset, which tends to be substantially more localized than the climate phenomena that may cause CID changes. Assessments using the CID Framework therefore aim to evaluate shifts in CID characteristics (intensity, frequency, duration, timing, and spatial extent) caused by a variety of interacting large- and local-scale thermodynamic, dynamical and chemical processes in order to provide stakeholders with a more focused and comprehensive picture of changing conditions likely to challenge their system.

3. Determining Practical CID Types and Categories for Assessment

Climate hazard lists have long formed the basis for climate assessments and disaster risk management frameworks (e.g., IPCC, 2021b; Seneviratne et al., 2012; UNEP, 2021; UNISDR, 2015). However, in many assessments the decision process that led to a given framework or the inclusion or exclusion of specific climate factors is not always explicitly justified.

Here we describe the formal approach to categorize climatic impact-drivers according to specific connections between physical climate conditions and affected natural and societal assets (adopted in Ranasinghe et al., 2021). Our goal is to identify a limited set of practical CID categories that capture generalizable regional responses that may be useful across multiple sectoral applications (e.g., for research and applications within the domain of IPCC Working Group II). Figure 2 illustrates the iterative process utilized to determine CIDs and practical CID categories for assessment, as described below.

Determination of robust CID categories begins with an examination of documented impacts and sectoral response plans by public and private stakeholders as well as associated climate impacts and risk management literature. We

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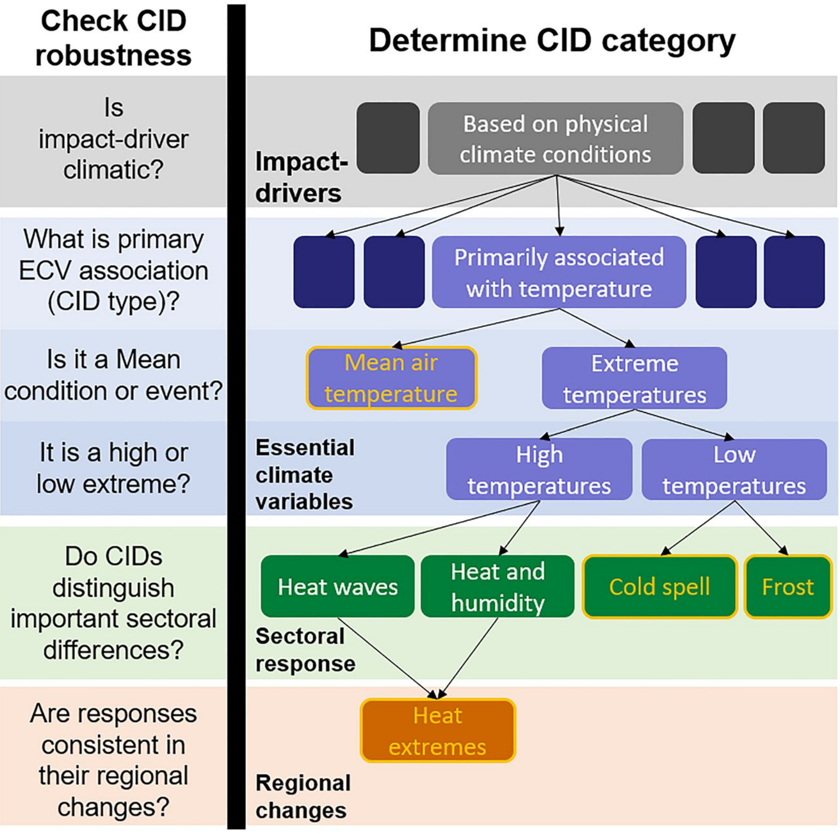

Figure 2. Example of the decision tree used to map climate means, events, or extremes into robust and practical climatic impact-driver (CID) categories (denoted with gold frames) that are relevant for regional sectoral assets. Here we have elaborated the 'heat and cold" type of CIDs that are primarily associated with the air temperature essential climate variable, but this process formed the basis for determining CID categories for each CID type (unlabeled dark blue boxes). A similar process could be used for impact-drivers beyond the climatic realm (unlabeled gray boxes). ECV = Essential climate variable.

encourage the co-production process to recognize that value judgments of scientists and stakeholders may affect adaptation and risk priorities and thus it is important to extend beyond initial perceptions of risk (Doblas-Reyes, et al., 2021; Pulkkinen et al., 2022). We first assess whether current and future impact-drivers are "climatic" as opposed to socioeconomic, geopolitical, or connected with geophysical processes beyond the climate system, using as our starting point the classification from the Sendai Framework (UNISDR, 2015) and completing it with impacts literature. Here, "climatic" includes the atmosphere, oceans, cryosphere, and land surface. The best evidence of a climatic condition driving sectoral impact is historical evidence of such impacts, which may be documented in observations or shared as local or Indigenous knowledge (Ford et al., 2019). This evidence is bolstered by physical understanding of the dynamics or chemistry causing the climatic condition as well as the biophysical, structural, or biogeochemical response that climatic condition causes.

Most CIDs are strongly associated with a major climatic variable, sometimes referred to as an Essential Climate Variable (ECV; Bojinski et al., 2014). We further distinguish CIDs depending on whether they capture the mean state climatic condition (and its typical variation over the course of a day or seasonal cycle) or an event that may be episodic or extreme, as these often motivate different types of proactive or reactive adaptations. For instance, the mean air temperature category example in Figure 2 includes the annual and summertime mean temperature. Event-based CIDs separate according to whether they are on the high or low tails of the expected distribution given that these can often lead to distinct strain and responses by affected systems (e.g., farm technologies designed to accommodate wet vs. dry extremes). However, in some cases events are the result of a tipping point in direction with no opposite outcome (e.g., there is no opposite extreme event equivalent to a snow avalanche).

CIDs may be further distinguished by sectoral responses due to interaction with additional ECVs or physical thresholds. For example, high temperatures may prove lethal to some crop species while high temperatures compounded by high humidity challenge people's ability to regulate body temperatures (Schwingshackl et al., 2021). CIDs are also distinguished when a given threshold leads to a prominent step-change behavior relevant to impacts, such as cold temperatures leading to cycles of freezing and thawing at 0°C. CID categories motivated by strong sectoral responses also include the particular set of conditions favorable to fire spread, different types of water supply and demand balances that distinguish drought conditions, hailstorms as a unique type of precipitation event, and the interactions across spatial and temporal scales that can differentiate river and localized flooding (e.g., in urban settings). Likewise, a climatic condition that does not lead to direct sectoral impacts is likely not an appropriate CID (e.g., changes in upper atmosphere temperatures).

The complexity of the climate system and asset responses could result in a rapidly expanding set of CID distinctions that may overwhelm climate information assessment. A practical categorization is therefore imperative and possible through the lens of regional CID change assessment. CID categories that are closely related to each other from an ECV standpoint and are highly similar in terms of regional changes may be combined into a broader category. For example, heat waves and heat/humidity events are both strongly associated with the temperature ECV and most regions experiencing increases in heat waves also have increases in heat/humidity extremes (Russo et al., 2017). This suggests that we can group both phenomena into the same CID category ("heat extremes") even as we may track specific CID indices connected to distinct types of impact (Figure 2). Similar groupings based on regional change patterns include heavy precipitation and pluvial flooding; lake, river and sea ice; snow, glacier, and ice sheet; and severe wind storms.

Expert-judgment analysis of sectoral stakeholder resilience plans, impacts and risk management literature and the application of the CID categorization process (Figure 2) resulted in 7 CID types and 33 CID categories (Table 1). CID types are generally associated with a prominent ECV, including "heat and cold" (primarily associated with air temperature), "wet and dry" (associated with precipitation or lack thereof), "wind" (associated with atmospheric circulation and storms), "snow and ice" (associated with many aspects of the cryosphere), "coastal" (associated with the land/sea interface), "open ocean" (associated with ocean thermal structure and chemistry) and an "other" category that captures additional CIDs related to atmospheric chemistry and radiation.

CID category names were selected to be compelling to stakeholders and easily understood by non-scientists. While many CID category names are self-explanatory, here we emphasize a few CID category names to elucidate distinctions and avoid potential misinterpretations:

- "*River flood*" versus "*Heavy precipitation and pluvial flood*": The "river flood" CID category is affected by the supply of precipitation (both mean and extreme) and meltwater as well as the basin land surface dynamics that may cause a lagged response in downstream river levels. The "heavy precipitation and pluvial flood" CID category captures the direct effects of heavy precipitation (e.g., leading to crop damage) and localized surface water flooding events caused by associated runoff rates exceeding drainage capacity.
- "*Hydrological drought*" versus "A*gricultural and ecological drought*": These two drought categories are distinguished by the aspects of water balance they represent. The "hydrological drought" CID category looks at the availability of surface and groundwater resources governed by episodic changes in precipitation (*P*) supply, evaporation (*E*) loss (negative anomalies of *P*-*E*) and runoff leading to low river flows and lack of aquifer water (Van Loon, 2015; Wang et al., 2016). The "agricultural and ecological drought" CID category looks instead at the episodic combination of water supply and atmospheric demand that determines whether plants will be able to meet their biophysical needs through available soil moisture (negative anomalies of *P*-[reference evapotranspiration ET_0]) (Douville et al., 2021; Seneviratne et al., 2021). Crausbay et al. (2017) similarly defined climatic conditions associated with "ecological drought" rooted in water availability, but their definition requires ecosystem impacts and thus extends beyond the physical climate domain. Many agricultural studies call the latter drought category simply "agricultural drought"; however, we use "agricultural and ecological drought" to emphasize that the same climatic conditions drive plant responses in both agricultural lands and natural ecosystems. Note that water resources, agriculture and ecosystems respond to multiple CID categories in addition to these strongly associated drought categories (Ranasinghe et al., 2021).
- "*Aridity*" versus "*Hydrological drought*" *or* "*Agricultural and ecological drought*": The "aridity" CID category is distinct from the drought CID categories in that aridity examines long-term mean dry conditions over the course of the expected seasonal cycle rather than the episodic events covered by the drought CID categories (Sherwood & Fu, 2014).

Table 1
The Practical Set of Climatic Impact-Driver (CID) Types and Categories for Regional Climate Assessment

CID Type	CID Category	Brief description	Example CID index *(Relevant to sector)*
Heat and cold	Mean air temperature	Mean surface air temperature and its diurnal and seasonal cycles	Mean growing degree days *(Agriculture)*
	Extreme heat	Episodic high air temperature events potentially exacerbated by humidity	NOAA heat index HI > 41°C *(Health)*[a]
	Cold spell	Episodic cold air temperature events potentially exacerbated by wind	Annual minimum temperature *(Ecosystems)*
	Frost	Freeze and thaw events near the land surface and their seasonality	Julian day of last spring frost *(Ecosystems)*
Wet and dry	Mean precipitation	Mean precipitation and its diurnal and seasonal cycles.	Total monsoon-season rainfall *(Water resources)*
	River flood	Episodic high water levels in streams and rivers driven by basin runoff and the expected seasonal cycle of flooding	1-in-100 years flood discharge *(Infrastructure)*
	Heavy precipitation and pluvial flood	Episodic high rates of precipitation and resulting localized flooding of streams and flat lands	99th percentile daily precipitation total *(Cities)*
	Landslide	Ground and atmospheric conditions that lead to geological mass movements, including landslide, mudslide and rockfall	Frequency of slope failure *(Transportation)*
	Aridity	Mean conditions of precipitation and evapotranspiration compared to potential atmospheric and surface water demand, resulting in low mean surface water, low soil moisture and/or low relative humidity	Water table depth (Water resources)
	Hydrological drought	Episodic combination of runoff deficit and evaporative demand that affects surface water or groundwater availability.	1-in-100 years low streamflow levels *(Ecosystems)*
	Agricultural and ecological drought	Episodic combination of soil moisture supply deficit and atmospheric demand requirements that challenge the vegetation's ability to meet its water needs for transpiration and growth. *Note: "agricultural"* versus *"ecological" term depends on affected biome*	Ratio of actual/potential evapotranspiration *(Agriculture)*
	Fire weather	Weather conditions conducive to triggering and sustaining wildfires, usually based on a set of indicators and combinations of indicators including temperature, soil moisture, humidity and wind. Fire weather does not include the presence or absence of fuel load. *Note: distinct from wildfire occurrence and area burned*	Forest Fire Danger Index *(forestry)*
Wind	Mean wind speed	Mean wind speeds and transport patterns and their diurnal and seasonal cycles	Wind power potential *(Energy)*
	Severe wind storm	Episodic severe storms including extratropical cyclones, thunderstorms, wind gusts, derechos, and tornados.	Average number of tornadoes per outbreak day *(Infrastructure)*
	Tropical cyclone	Strong, rotating storm originating over tropical oceans with high winds, rainfall, and storm surges	Frequency of Category 3 or higher cyclones *(Infrastructure)*
	Sand and dust storm	Storms causing the transport of soil and fine dust particles	Dust storm hours per dust storm year *(Health)*
Snow and ice	Snow, glacier, and ice sheet	Snowpack seasonality and characteristics of glaciers and ice sheets including calving events and meltwater	Duration of season with snow water equivalent >10 cm *(Recreation)*
	Permafrost	Permanently frozen deep soil layers, their ice characteristics, and the characteristics of seasonally frozen soils above.	Active layer thickness *(Infrastructure)*
	Lake, river and sea ice	The characteristics and seasonality of ice formations on the ocean and freshwater bodies of water.	Seasonal landfast ice duration *(Indigenous communities)*
	Heavy snowfall and ice storm	High snowfall and ice storm events including freezing rain and rain-on-snow conditions	Frequency of ice accumulation > 0 mm *(Transportation)*

Table 1
Continued

CID Type	CID Category	Brief description	Example CID index (*Relevant to sector*)
	Hail	Storms producing solid hailstones	Hailstone size distribution *(Agriculture)*
	Snow avalanche	Cryospheric mass movements and the conditions of collapsing snowpack.	Seasonality of wet snow avalanche *(Transportation)*
Coastal	Relative sea level	The local mean sea surface height relative to the local solid surface	Local elevation of astronomical high tide *(Cities)*
	Coastal flood	Flooding driven by episodic high coastal water levels that result from a combination of relative sea level rise, tides, storm surge and wave setup.	1-in-100 years extreme total water level *(Infrastructure)*
	Coastal erosion	Long term or episodic change in shoreline position caused by relative sea level rise, nearshore currents, waves and storm surge.	Shoreline position change by 2100 relative to present-day *(Infrastructure)*
Open Ocean	Mean ocean temperature	Mean temperature profile of ocean through the seasons, including heat content at different depths and associated stratification	Depth of mixed layer (*Ecosystems*)
	Marine heatwave	Episodic extreme ocean temperatures	Degree heating weeks *(Ecosystems)*
	Ocean acidity	Profile of ocean water pH levels and accompanying concentrations of carbonate and bicarbonate ions	Depth of saturation level *(Fisheries)*
	Ocean salinity	Profile of ocean salinity and associated seasonal stratification. *Note: distinct from salinization of freshwater resources.*	Mean ocean salinity *(Ecosystems)*
	Dissolved oxygen	Profile of ocean water dissolved oxygen and episodic low oxygen events	Areal extent of anoxic zones *(Ecosystems)*
Other	Air pollution weather	Atmospheric conditions that increase the likelihood of high particulate matter or ozone concentrations or chemical processes generating air pollutants. *Note: distinct from aerosol emissions or air pollution concentrations themselves*	Frequency of stagnant air days *(Health)*
	Atmospheric CO_2 at surface	Concentration of atmospheric carbon dioxide (CO_2) at the surface. *Note: distinct from overall radiative effect of* CO_2 *as greenhouse gas*	Annual mean CO_2 concentration *(Agriculture)*
	Radiation at surface	Balance of net shortwave, longwave and ultraviolet radiation at the Earth's surface and their diurnal and seasonal patterns	Growing season total incident shortwave radiation *(Ecosystems)*

Note. An example sector-relevant CID index is provided for each CID category, which is one of many that could be identified and tailored through stakeholder engagement (adapted from Table 12.1 of Ranasinghe et al., 2021).
[a]NOAA, National Oceanographic and Atmospheric Administration (see Schwingshackl et al., 2021).

- "*Fire weather*" versus *fire*: The "fire weather" CID category looks strictly at climatic conditions conducive to fire outbreaks and spread but does not directly assess the actual number of fires or the area burned given that these are strongly affected by non-climatic influences such as campfires, forest management, monitoring capacity and firefighting efforts (Abatzoglou et al., 2019). "Fire weather" is affected by changes in many other CIDs (e.g., aridity, extreme heat, hydrological and agricultural and ecological drought, mean wind, snow), but is distinguished due to the compound nature of related physical processes and prominent stakeholder interest.
- "*Severe wind storm*" versus "*tropical cyclone*": The "severe wind storm" CID category includes thunderstorms, wind gusts, derechos, tornados, and extratropical cyclones. "Tropical cyclones" are distinguished from this more general group given that they are prominent and prolonged compound hazards combining high winds, heavy precipitation, and storm surge across a large area.
- "*Relative sea level*" versus *mean sea level or* "*coastal flooding*": The "relative sea level" CID category emphasizes that most coastal assets move with land uplift or subsidence in addition to being affected by changes in mean sea level. The "coastal flooding" CID refers to the episodic combination of relative sea level, tides, storm surge and high wave setup at the shoreline (Fox-Kemper et al., 2021).
- "*Ocean salinity*" versus *salinization of freshwater resources*: The ocean salinity CID category is restricted to shifts in seawater salinity and its impacts on the water column, with processes related to the salinization of

coastal freshwater resources captured by the relative sea level and coastal flood CID categories. Inland salinization of soil and freshwater resources is often a result of non-climatic factors such as irrigation applications and soil management.

- "*Air pollution weather*" versus *air pollution*: The "air pollution weather" CID category focuses strictly on climatic conditions that favor high concentrations of air pollution or processes that create or remove air pollutants. These conditions affect the overall concentration of air pollutants; however, climate influence is often small compared to the overall level of societal emissions largely governed by pollutant emissions policy (Naik et al., 2021).
- "*Atmospheric CO_2 at surface*" versus *greenhouse gas concentration*: The "atmospheric CO_2 at surface" CID category looks explicitly at near-surface CO_2 concentrations as related to physiological forcing (e.g., gas exchanges related to photosynthesis). This CID category does not cover the broader radiative influence of CO_2 and other greenhouse gases in the atmospheric column and the resulting warming at the root of anthropogenic climate change.

CID categories described in Table 1 serve as a practical starting point for regional climate information assessment and provision. Additional candidate CIDs that were not included in our final list include:

- *Fog, dewfall canopy water*: The presence of near-surface cloud droplets can reduce visibility with substantial impacts for transportation and can also be an important aspect of ecosystem or agricultural microclimates. Likewise, the presence of liquid water on plant canopies can serve as an important supply of ecosystem freshwater and alter plant susceptibility to pests and diseases. These CIDs are currently linked to the "aridity" CID category that includes associated soil moisture and humidity conditions (reduced aridity associated with more of these events) but some assessments may wish to assess these conditions more prominently.
- *Meteorological drought:* A deficit of precipitation is an important atmospheric quantity and "meteorological drought," which refers to periods associated with lack of precipitation, is a climate metric that is often assessed in the physical climate literature and is also considered in the IPCC AR6 WGI assessment (Seneviratne et al., 2021). However, contrary to the effects of "agricultural and ecological droughts" as well as "hydrological droughts" (see above), we could not identify prominent sectoral assets that respond solely to meteorological drought other than direct rainwater harvesting. Therefore, even though meteorological drought is an important factor driving the other drought types, it is not a CID as such. In the vast majority of applications meteorological drought indices must be further contextualized by the evaporative losses and evapotranspiration demand that completes those CIDs' assessment of specific forms of water availability. Meteorological drought indices remain an appealing partial indicator of hydrological or agricultural and ecological drought when these additional data or model parameters are not available to decision makers.
- *Lightning*: Lightning can lead directly to sectoral impacts such as electrical grid interference, human or animal strikes and fire initiation (Romps et al., 2014). Rather than standing as its own CID category, the lightning CID often follows aspects of the "severe wind storm" CID category and is an element of "fire weather" CIDs.
- *Ocean circulation*: Similar to atmospheric winds, circulation patterns such as currents, eddies and upwelling in the ocean have strong implications for nutrient and species movement (Hicke et al., 2022). Changes in surface winds and the three-dimensional structure of ocean temperature and ocean salinity are primary drivers of ocean circulation changes, so this information is grouped into those CID categories even as some assessments may wish to explore the topic more comprehensively.
- *Biogeochemical cycling*: Biogeochemical properties such as primary productivity, the availability of nutrients, biodiversity, or carbon fluxes are important aspects of the earth's biogeochemical cycling and are thus considered conditions of the climate system in some applications. These also fall within the domain of ecosystem function or water quality, so we consider these reflections of an impact sector rather than CIDs.
- *Connected CIDs*: Compound, sequential, or simultaneous climate conditions can affect sectors in combined ways that extend beyond the individual CID components (Raymond et al., 2020; Zscheischler et al., 2020). Examples include a region being affected by an overlapping coastal flood (due to storm surge) and a fluvial flood (due to rainfall) [*compound event*], killer frosts when a region experiences a warm early season that encourages growth followed by a late frost [*sequential event*], and concurrent extreme events affecting different locations with similar assets (e.g., large crop production regions) [*simultaneous event*]. In most cases, these connections are an element of systemic vulnerability and exposure (other impact-drivers) rather than the climate system CIDs themselves (Gaupp et al., 2019; Ranasinghe et al., 2021; Sillmann et al., 2022). In several cases connected events may be considered as potential CIDs depending upon whether they: (a) feature

established physical phenomena within the climate system, (b) act in concert as an external local pressure on affected systems (rather than separately affecting complex systems which then have to deal with simultaneous challenges), and (c) are widely recognized as connected conditions meriting comprehensive adaptation or risk management by stakeholders (e.g., a tropical cyclone response team). Changes in compound events are also assessed in the IPCC AR6 WGI report (Seneviratne et al., 2021).

4. Identifying Sector-Relevant CID Indices

What CID indices measure: CID indices capture specific attributes of the climatic condition that natural and human systems respond to, including key thresholds, safe limits and coping ranges. For example, the seasonal thermal environment that is suitable for plant growth is a climatic condition under the mean air temperature CID category, and this condition is commonly captured via a suitable range of growing degree days (GDD; the cumulative growing season exceedance of daily mean temperatures above a generalized threshold such as 5°C; IPCC, 2021a). Practical considerations and stakeholder demand for assessments may suggest more tailored CID index specification according to the responses of specific assets, for example, GDD indices featuring different threshold temperature for maize and wheat or defined over different sub-seasonal periods (e.g., vegetative vs. reproductive growth stages; McMaster & Wilhelm, 1997). While it may be beneficial to isolate a large number of unique CID indices within a given category, the CID Framework considers whether additional distinctions in these indices (a) isolate decision-relevant insights and/or (b) diverge in a manner that justifies their specific assessment. Likewise, evaluation of a single CID index may not be sufficient to assess regional CID changes. Ideally, a middle ground is found where a small number of CID indices capture a core sectoral condition, reveal coherent change patterns, and are indicative of important changes across a range of sectoral assets.

How CIDs represent change: Stakeholders and climate impacts scientists examine CID indices as indicators of sector-relevant changes, which can take the form of shifts in:

- *intensity* or *magnitude* (the extreme nature of a condition above or below average),
- *frequency* (the number of times that a condition occurs),
- *duration* (the time over which a condition persists),
- *timing* (the seasonality or speed of a condition's onset or termination), or
- *spatial extent* (the area affected by a condition). (see also FAQ12.3 in Ranasinghe et al. (2021)).

Connections between CID indices and change characteristics: Most CID indices are strongly associated with a threshold determined by sector response to one of these aspects, and we assess different ways that the climate can change in one or more of the other dimensions relative to this threshold. For example, lake ice exceeding a given thickness may be a useful CID index that helps determine the safety of activities such as ice fishing (Knoll et al., 2019). Changes in that CID index (which is defined by ice thickness magnitude) could then indicate the number of days each year when the ice is sufficiently thick (frequency), the longest coherent period of sufficiently thick ice (duration), the date when the ice is first thick enough (timing), or the fraction of a given lake that would be thick enough (spatial extent). Likewise, an index defined according to frequency can be examined according to its magnitude (such as a 1-in-10 years flood level). Timing, in particular, is the subject of increased focus in recent years given its substantial interactions with the time evolution of vulnerability and exposure such as that in a growing crop (Mäkinen et al., 2018). In many circumstances these dimensions of change are correlated, with increasing intensity or magnitude associated with increased frequency, longer duration, earlier seasonal initiation and later cessation, and an extended spatial extent (the opposite changes are associated with decreasing intensity or magnitude) (Ranasinghe et al., 2021; Seneviratne et al., 2021).

The final column of Table 1 provides an example CID index for each CID category (among many possible CID indices). Some CID categories are very difficult to observe or simulate directly. For example, the supply and demand comparison that determines agricultural and ecological drought is hampered by a lack of in situ or remotely sensed observations of soil moisture and evapotranspiration across diverse settings. In such cases we may develop proxy indices that capture aspects of the supply or demand changes, which in turn shed light on the CID itself (Seneviratne et al., 2021; Svoboda & Fuchs, 2017). Tornadoes, hail, ice storms, landslides, and snow avalanches are likewise difficult to observe or simulate but each may be estimated according to proxy indices of larger-scale conditions that are indicative of a CID event (e.g., Diffenbaugh et al., 2013).

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Although CID assessment is best performed at the scale of the affected asset and decision context, we recommend that assessments limited to larger scales describe overall patterns of CID change relevant to multiple sectors and assets (e.g., direction of change, change relative to other regions, temporal evolution and statistical emergence of the change signal, scenario dependence). In practice, this was not possible for all CIDs at the scale of the Iturbide et al. (2020) regions assessed within the IPCC AR6 WGI report. At this scale it is practical to quantify changes to emblematic CID indices and note strong regional heterogeneities or characteristics that change counter to the broader assessment (as exemplified by the table footnotes in Ranasinghe et al., 2021). This information also provides a broader scale perspective that motivates more detailed sub-regional and sector-specific assessments tailored toward specific stakeholder decision contexts.

5. Implications and Limitations of the CID Framework for Climate Modeling, Impact Assessment and Climate Services

The CID Framework facilitates the construction of actionable climate information based on multiple lines of evidence connecting the understanding of physical processes to practical, regional and contextual information bolstered by confidence levels (Cash & Belloy, 2020; Coppola et al., 2021). As an outcome of a bottom-up co-production process, stakeholders can weigh CID assessments with information about other non-climatic impact-drivers to make an overall decision that balances competing motivations and values (e.g., legal, organizational, fiduciary, social and environmental (Begum et al., 2022; New et al., 2022).

The goal of CID assessment is to convey climate system changes that will either provide opportunities or drive challenges for sectors, even if their resilience or adaptive capacity is high. CID assessment for systems that are strongly controlled by humans further emphasizes that CID changes indicate pressure on systems but cannot be directly translated to impacts. For example, river engineering strongly affects the likely impact of floods on floodplain farms and infrastructure; however, changes to the river flood CIDs indicate shifts in discharge amount that this engineering would need to withstand. Stakeholders working with climate experts would therefore benefit from assessments of CID index thresholds tailored to the tolerance levels of the flood control systems. The co-production process is helpful to determine the appropriate level of detail in system response thresholds, safe limits and coping ranges needed by the stakeholder utilizing this climate information.

The IPCC and many national and sectoral assessments have utilized these indices in published assessments, but we are aware of few attempts to systematically identify and generalize CID indices across climate phenomena and sectors. The Expert Team on Climate Change Detection and Indices (ETCCDI; Zhang et al., 2011) created a number of extreme event indices, but it is their connection to sectors that would make a CID index. The World Meteorological Organization (WMO) Expert Team on Sector-specific Climate Indices (ET-SCI) has assembled a list of many indices that could appropriately be called CID indices (https://climpact-sci.org/indices/), and further CID index connections have been documented as hazard indices (Mora et al., 2018) and risk connections (ICOMOS, 2019; UNDRR, 2020; Yokohata et al., 2019).

Figure 3 summarizes how the CID Framework translates physical climate data and process understanding into salient impact- and risk-relevant climate information on practical temporal and spatial scales with threshold information requested by sectoral experts and stakeholders. The simultaneous and interacting left- and right-side activities emphasize the importance of co-production and response orientation as this guides the processing of climate data into salient climate information. The left side of this Framework illustration shows the determination of CID types, categories and sectoral indices relevant to a given application, as described in Sections 3 and 4. The right side shows the parallel effort to provide robust regional climate change evidence so that CIDs may be assessed on scales relevant for sectoral decision making. This begins with an evaluation of specific sectors and stakeholder decision-making processes that CIDs are meant to inform. Multiple lines of evidence form the foundation of this process, including physical understanding of anthropogenic influences on the climate phenomena at the heart of each CID, coherent findings in past observations, attribution of changes to anthropogenic influences, and future projections (Coppola et al., 2021). Selection of downscaling and bias-adjustment methods benefits from consideration of the variables, scales, uncertainties and attributes associated with each CID index, particularly for those indices based on true rather than relative quantities (Casanueva et al., 2020; Doblas-Reyes et al., 2021). Finally, a clear indication of confidence in CID changes and their evolution over time across scenarios and global warming levels provides stakeholders with an indication of uncertainty and temporal pressure as a component of the risk they will manage (e.g., Chen et al., 2021; Tebaldi et al., 2021).

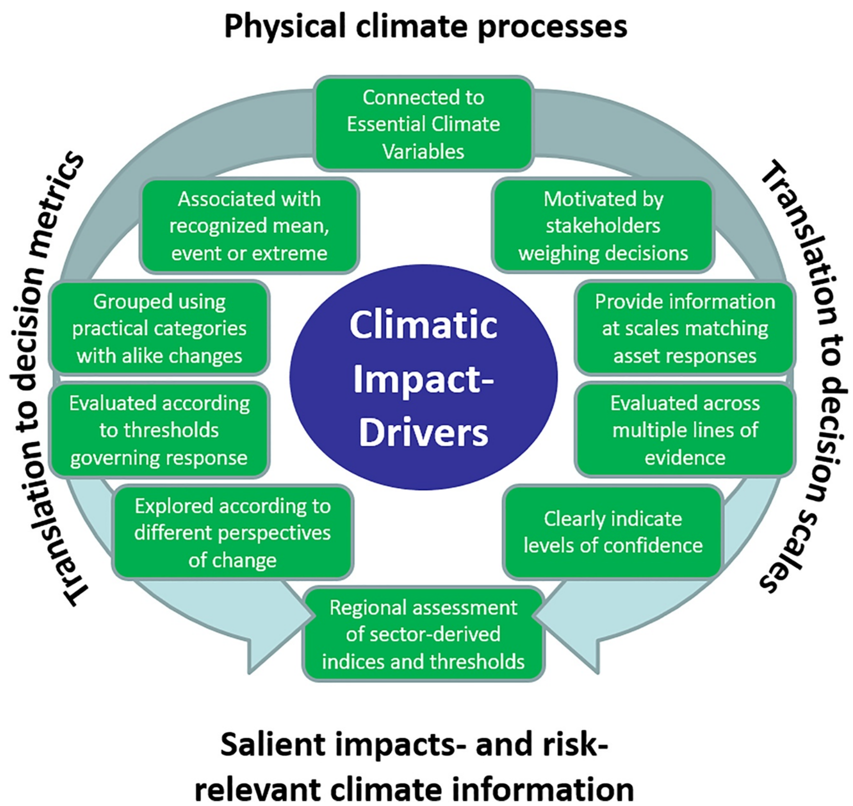

Figure 3. Schematic of the Climatic Impact-Driver (CID) Framework processing of climate data into climate information that is salient for decision-making processes. CID assessment is the result of coordinated efforts to translate physical climate process understanding into impacts- and risk-relevant information through a translation to decision support metrics and scales. The result is a more practical and standardized set of regional climate information to inform risk management, resilience investments, and strategies for adaptation and mitigation.

The utility of the CID Framework depends on strong engagement between climate scientists, stakeholders, and experts in impacts and risk management in order to create salient, legitimate and credible climate information (Cash & Belloy, 2020; Hewitt & Golding, 2018; Ranasinghe et al., 2021; Steynor et al., 2020). Climate services provide a useful forum for such engagement, building CID understanding by:

- engaging sectoral experts, stakeholders, and decision makers to determine climate conditions that influence the current assets in each region and climate events that have historically driven sectoral impacts (*CID types and categories*),
- ascertaining common indices and specific rules of thumb, established thresholds, safe limits and coping ranges used in sectoral decision making (*CID indices*),
- evaluating how climatic conditions will change in the future at the scale decisions are made (depending on local and global scenarios) (*regional CID assessment*),
- collaborating with sectoral experts, stakeholders, and decision makers to provide information about changing regional and sector-relevant climatic conditions along with related levels of confidence (*climate services utilizing CID Framework*).
- Tracking the ramifications of these climatic changes in assessments of impacts to inform adaptation and risk management actions (*CID information driving impacts assessment*).

The CID Framework has great potential to help prioritize improvement of both earth system and impacts models. Evaluation of CID indices provides a stakeholder-oriented and applications-relevant lens on earth system model performance. Most CID indices rely on variables already provided by earth system models through community projects like the Coupled Model Intercomparison Project (CMIP; Eyring et al., 2016) and CORDEX project (Giorgi et al., 2009); however, some CID indices require additional diagnostics and may require less common temporal and spatial attributes (Ruane et al., 2016). Accurate simulation of the profile of regional CIDs and their

Table 2
Suggested Translations of the "Climatic Impact-Driver" Term for Example Languages

Language	Recommended term
English	Climatic impact-driver (CID)
Arabic[a]	العوامل المناخية المحركة للتأثير
Chinese[a]	产生影响的气候因子
Dutch	Klimaatafhankelijke invloedsfactoren
Farsi	محرک های اثرگذار اقلیمی
Filipino	Kalagayan ng klima na nagdudulot ng matinding epekto
French[a]	Facteur climatique générateur d'impact
German	Klimatische einflussfaktoren
Italian	Condizioni climatiche responsabili di impatti
Korean	기후영향인자
Portuguese	Fenômenos climáticos que geram impactos
Russian[a]	Климатические факторы воздействия
Spanish[a]	Fuerzas impulsoras de los impactos climáticos

[a]= Terms used in translations of the IPCC glossary to UN official languages.

changes requires a combination of many climate system processes, and CID evaluation may provide unique perspective on model improvement priorities.

Process-based impacts models may be compared against the inventory of CIDs to highlight where model improvement is needed to capture climate responses. For example, process-based crop models commonly respond to agricultural and ecological drought but rarely include process responses to hail, severe wind storms or river floods (Ruane et al., 2021). Analysis by CID elucidates the likely biases introduced when CID responses are not well captured in either the driving climate scenario or the impacts model. Empirical impact models are often built around responses to specific CID indices within their statistical predictands (e.g., killing degree days representing extreme heat in Butler & Huybers, 2015), and may therefore be examined structurally to determine which CID responses are likely to be captured or to identify potential new CID indices via machine learning. Impacts models also benefit when they combine changing CIDs with risks affected by alterations to a system's vulnerability (e.g., socioeconomic change, health status, and forest management) or shifts in exposure (e.g., population growth, land use change, resource investment, and infrastructure construction). Impacts and systems models are uniquely positioned to track the compounding and carry-over effects of multiple CIDs potentially interacting in impacted systems over the course of a scenario (Raymond et al., 2020; Sillmann et al., 2022; Yokohata et al., 2019).

The "climatic impact-driver" term was constructed using the English language, and translation to other languages can be challenging especially because "driver" does not have a clear equivalent in many languages. Table 2 includes a set of translations for the six United Nations languages as well as other languages.

The co-production of CID change information across 33 CID categories expands stakeholder considerations of climatic impact pathways but does not indicate that all CID changes are equal in importance. Some CIDs have more widespread relevance than others, although each may be the most important piece of information for a given system or decision process at a given time. A lack of confident change assessment (owing to any line of evidence) is also an important result that should be factored into risk management rather than ignored (Coppola et al., 2021; IPCC, 2021c; Ranasinghe et al., 2021). Providing this information forms a marker in time such that successive assessments can indicate progress related to each CID's assessment. The CID Framework has further applications beyond anthropogenic climate change applications, as CID changes can also be imposed by localized land-use change, short-term climate variability and natural events such as major volcanic eruptions. O'Neill et al. (2022; Figure 16.12) also demonstrated how assessments may support holistic actions by connecting the dots between changes in CIDs, regions, Representative Key Risks (RKRs) and Sustainable Development Goals (SDGs).

Data Availability Statement

No specific data were created for this manuscript.

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