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ABSTRACT

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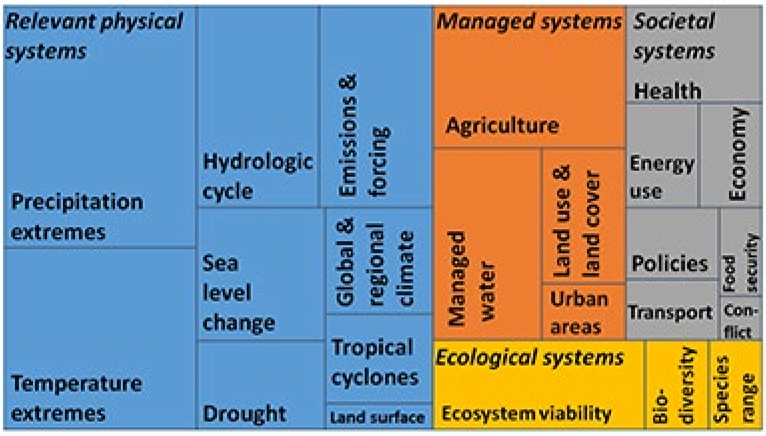
Earth system models (ESMs) are the primary tool used to understand and project changes to the climate system. ESM projections underpin analyses of human dimensions of the climate issue, yet little is known about how ESMs are used in human dimensions research. Such foundational information is necessary for future critical assessments of ESMs. We review applications of a leading ESM, the National Center for Atmospheric Research (NCAR) Community Earth System Model (CESM), to human dimensions topics since 2004. We find that this research has grown substantially over this period, twice as fast as CESM research overall. Although many studies have primarily addressed long-term impacts on physical systems with societal relevance, applications to managed, societal, and ecological systems have grown quickly and now make up more than half of CESM human dimensions work. CESM applications focused nearly equally on global and regional analyses, most often using multi-model ensembles, although the use of single simulations remains prevalent. Downscaling and bias correction of output was infrequent and most common for regional studies. U.S.-based, university-affiliated authors primarily drove human dimensions work using CESM, with only 12% of authors based at NCAR. Our findings identify important questions that warrant further investigation, such as reasons for the infrequent use of downscaling and bias correction techniques; motivations to continue to use older model versions after newer model versions have been released; and model development needs for improved human dimensions applications. Additionally, our synthesis provides a baseline and framework that enables continued tracking of CESM and other ESMs.

Graphical/Visual Abstract and Caption



The Community Earth System Model (CESM) has been applied to study a wide range of outcomes, with over half of published studies since 2004 focused on relevant physical systems; but applications to managed, societal, and ecological systems have been rapidly growing.

INTRODUCTION

Earth system models (ESMs) are fundamental to understanding the climate system and projecting how it may change in the future in response to anthropogenic forcing. In particular, ESM projections of future climate underpin analyses of climate change as it relates to human dimensions, which we define as research and applications whose results are directly relevant to improving understanding of how society contributes to climate change, is influenced by it, or takes action to respond to it. Studies focused on human dimensions topics are widely accepted as crucial to understanding the consequences of climate change and crafting responses to it. Furthermore, the development and application of ESMs is often justified at least in part by their relevance to human dimensions work. Yet, assessments of the ways in which ESMs are used in this research area are not available. Basic questions about this use remain unanswered, including:

- Is ESM use in human dimensions work substantial, and growing?
- To what types of human dimensions research questions are ESMs most frequently applied?
- Is the use of a particular ESM dominated by researchers from the same institution, or the same country, or is it more widespread?
- Are ESM simulations generally used as part of multi-model ensembles (such as CMIP—the Coupled Model Intercomparison Project), or does the human dimensions community also make substantial use of single simulations or smaller ensembles for specific studies?
- What resolution of ESM simulations is most often used, and is ESM output typically downscaled and/or bias corrected before being used in human dimensions work?
- Are applications typically global or regional, and do they mainly focus on shorter or longer timescales?

Answers to these fundamental, important questions are useful to the climate modeling and human dimensions research communities and are necessary in order to lay a foundation that would allow for future critical assessments of the strengths and weaknesses of ESMs used in human dimensions research, obstacles to such use, and lessons for future developments. However, no literature has provided such an assessment to date, so the landscape of ESM human dimensions research has, to this point, remained speculative or anecdotal. This paper explores this landscape by providing descriptive findings on the use of ESMs in human dimensions work and discussing questions elicited by these results that warrant further, in-depth exploration.

Human-dimensions focused climate research dates back to the 1970s, when such examinations were first applied to agricultural and biological research (Jones et al., 2017). In the 1990s, this work expanded more broadly, as continued increases in greenhouse gas emissions stimulated a growing emphasis on human dimensions elements, such as impacts and adaptation (Burkett et al, 2014). Vulnerability, impacts, and adaptation assessment by the Intergovernmental Panel on Climate Change (IPCC) evolved similarly over the years, progressing from primarily impacts-based assessments in the 1990s and early 2000s to assessments more focused on adaptation and vulnerability by the later 2000s (Ruane et al., 2016). Human dimensions research ultimately involves analysis of interactions between the physical climate system, society, and ecosystems, and therefore requires representation of the physical system. A hierarchy of models is available for use, from simple process-based models to models of intermediate complexity to ESMs, but as the most sophisticated representations of the system, ESMs often serve as the standard against which other models are measured.

The lack of assessment of the use of ESMs in human dimensions work represents a gap in the literature, which contains assessments of ESMs themselves, of impact and other human systems models, and of some types of integration between the two. For example, ESM evaluations are seen within that community as crucial to establishing confidence in climate projections (Masson & Knutti, 2011), and substantial effort has been invested in developing frameworks and metrics for the evaluation of model performance (Baker & Taylor, 2016; Zong-Ci, Yong, & Jian-Bin, 2013) and in comparing models, most prominently through CMIP (Knutti & Sedlacek, 2013). Eyring et al. (2016) noted a large demand for substantially more research in the area of ESM evaluation, calling in particular for expanded model evaluation to develop more downstream, user-oriented diagnostics and metrics.

In the impact modeling community, a number of large-scale intercomparison projects have also taken place, such as for agriculture, water, fisheries, and intersectoral analyses (Agricultural Model Intercomparison and Improvement Project (AgMIP, 2018); Water Model Intercomparsion Project (WaterMIP, Haddeland et al., 2013); Fisheries Model Intercomparison Project (FISH-MIP, Tittensor et al., 2018); Inter-Sectoral Impact Model Intercomparison Project (ISIMIP, 2018)). Larigauderie and Mooney (2010) detailed efforts to establish an “IPCC-like mechanism for biodiversity” through the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), calling for a broader range of models of global change impacts on biodiversity to improve global impacts work on biodiversity and ecosystem services.

There have also been efforts to evaluate the use and practicality of impact-relevant techniques, such as downscaling and bias correction (Maraun, 2016). Integrated assessment models (IAMs), often used for emissions and land use modeling but also increasingly for impacts assessment, have a long history of model comparisons (Weyant, 2017) and more recently have focused on aspects of model evaluation (Wilson et al., 2017). IAMs often employ simple climate models as emulators of ESM results to facilitate links between human and earth system representations, and the suitability of this approach has been evaluated (Van Vuuren et al., 2011).

We contribute to the body of model evaluation literature by developing a framework for collecting a set of baseline information to quantify the use of ESMs in human dimensions research and applications and applying it to one prominent ESM, the Community Earth System Model (CESM), and its predecessor, the Community Climate System Model (CCSM)[1]. The model is maintained by the National Center for Atmospheric Research (NCAR) in the United States, and has spanned numerous versions and capabilities since the release of CCSM 1.0 in 1996. Six versions of CCSM were released between 1996 and 2010, prior to the release of CESM 1.0 in mid-2010 (CESMa, 2017). CESM consists of five geophysical components—an atmosphere model (CAM), a sea-ice model (CICE), a land model (CLM), an ocean model (POP), and a land-ice model (CISM), plus a coupler, that together represent the full climate system (CESMb, 2017). Although it is generally known that CESM is used to investigate human dimensions outcomes related to climate, no explicit assessment to characterize that use has been carried out. We first describe the methodology that we use to identify and classify literature that uses CESM for human dimensions work in such a way that the assessment could answer the types of questions we pose above. We then discuss results relevant to those questions, and a final section presents a discussion of these results and related broader questions and synthesizes our conclusions.

METHODOLOGY

The methodology for identifying and classifying literature applying CESM to human dimensions questions consists of three main steps:

- Identify candidate literature (potentially relevant papers): draw on existing reference lists and carry out broader literature database searches;
- Identify relevant papers from the candidate literature: exclude papers not consistent with our definition of human dimensions research or applications (see above) or that did not use CESM or its components;
- Classify relevant papers according to our assessment framework.

We describe each of these steps in turn.

Identifying candidate literature

To assist in keeping the review manageable given the large number of publications using CESM, we established boundaries for the years and model versions considered. We chose to examine literature published from 2004 to 2016, since this timeframe covered two IPCC assessment report cycles. During this timeframe, three primary model versions were used: CCSM3, introduced in 2004, CCSM4, introduced in early 2010, and CESM1, introduced in mid-2010. No relevant publications

[1] NCAR's Community Climate Model (CCM) pre-dated CESM and CCSM (as did the related Parallel Climate Model (PCM)). CCM0 was first released in 1982 and continued through CCM3, which was released in 1996 (Kiehl et al., 1996). CCM (along with related ESMs) was used in early impacts work (see Lettenmaier & Sheer, 1991, for an example). Thus, human dimensions work with NCAR climate models did not begin with CCSM, and such work does exist before 2004. Our reasons for choosing to begin our literature review with CCSM in 2004 are presented in the Methodology section of this paper.

were found from 2004, so no results were reported for that year. To identify candidate literature within this time frame (see Table 1), we used two different approaches: identifying existing reference lists likely to contain relevant papers, and carrying out a broader search of general scientific literature databases.[2] We chose not to rely on a broader database search alone given the numerous challenges to such a search that would make it difficult to have confidence in generating a comprehensive list of candidate literature. For example, given the large number of themes relevant to human dimensions research and applications, it was difficult to determine a sufficiently broad list of keywords. In addition, climate models used in multi-model applications were often not specifically identified by name in a candidate paper except in supplementary material, which would not be captured in a keyword search. Furthermore, papers might only refer to a model component rather than to the overall ESM.

The largest reference lists we used as candidate literature came from the IPCC Fourth and Fifth Assessment Reports for Working Groups I (IPCC, 2007b; IPCC, 2013b) and II (IPCC, 2007a; IPCC, 2014a; IPCC, 2014b). These lists (from each chapter in these reports) consisted of over 42,000 publications. Reference lists from Working Group III for each assessment report were not considered given our expectation that the use of ESMs appears less frequently in this literature. This decision was also influenced by the aim to be comprehensive enough to draw valid conclusions from our analysis but not necessarily exhaustive. In addition to the IPCC reference lists, we also examined reference lists maintained by NCAR for publications using CESM and separately for the Community Land Model (CLM) component (neither of which we assumed were complete), and publications from the NCAR project on the Benefits of Reduced Anthropogenic Uncertainty of Climate changE (BRACE), which made especially concentrated use of CESM simulations in human dimensions work (Oneill & Gettelman, 2018). In addition, we conducted a database-driven literature review (in January and February 2017) to identify any articles not present in the existing reference lists. This step was particularly helpful for identifying candidate literature from 2014-2016, which was published after the IPCC Fifth Assessment Report. We conducted this review using model name keyword searches of Web of Science, Google Scholar, and Thompson Reuters for 2004-2016. Simple Python code was used to build a basic reference file of papers already collected. This file was then used to match DOIs to eliminate duplicate papers. From this search, a list of 299 additional papers not already contained in existing reference lists was compiled.

Four-step process for identifying relevant papers from candidate literature

We employed a four-stage process for identifying relevant papers from candidate literature. This process was tracked in a database that began with all references from a given candidate literature list. The first stage used the paper's title to determine whether a publication clearly did not address human dimensions research or applications, and to exclude it from further consideration in that

[2] Although nearly all relevant literature was peer-reviewed, because we considered literature from existing reference lists, a dissertation and a handful of technical reports were included among the relevant papers.

case.[3] Otherwise, its abstract was then evaluated in a second stage, again excluding the paper from further consideration if the abstract indicated that the paper was clearly unrelated to human dimensions. During the third stage, we examined the full text of remaining papers and made a final decision on whether these papers were relevant (i.e., consistent with our definition of human dimensions research or applications). The first three review stages determined a paper's consistency with our definition of human dimensions research. In a fourth review stage, we confirmed whether the paper used one or more relevant model versions (CCSM3, CCSM4, or CESM1) or relevant model components (CAM, CLM, POP, CICE, or CISM, though we presumed that only CAM and CLM would be commonly used in human dimensions research). However, much of the time, this was already known from examination of the title, abstract, or full text, so a smaller number of papers passed through the fourth stage of the review.[4] Any papers not using a relevant model version were removed from the final list of relevant papers.

TABLE 1 | Total candidate and relevant papers considered by source[5]

Reference list	Total candidate publications considered	Relevant human dimensions publications
IPCC AR4 Working Groups I & II	14,512	23
IPCC AR5 Working Groups I & II	27,930	141
CESM Publications List	2,412	61
CLM Publications List	472	36
NCAR BRACE Project	20	16
Database literature search	299	61
Total	**45,645**	**338**

A framework for systematic classification of relevant papers

[3] This evaluation was carried out manually, with the exception of 299 references in the candidate list generated from the broader database searches. In that case, a list of keywords developed from experience with other candidate literature was used to aid in identifying potentially relevant titles.
[4] For the majority of papers, a review of at least the abstract was necessary to identify the model used. As such, we were able to record the model version used for most papers, whether they were ultimately deemed to be human dimensions-focused or not. This proved useful for later analysis of the broader, non-human dimensions set of papers using CESM, described further in the results section of our paper.
[5] Candidate literature was reviewed in the order listed in Table 1. Numerous publications appeared in multiple sources, but a relevant paper's source was recorded as the source in which we located it first.

We developed a framework with four key components, designed to allow us to address the research questions about the use of CESM discussed in the introduction. These components were: 1) Identifying information, 2) Model and study details, 3) Systems and outcomes, and 4) Research areas. We describe each of these below.

Identifying information

Identifying information described basic characteristics of a paper and included the title, all authors and their affiliations, year of publication, URL and DOI (if available), publication source, review source (i.e., which candidate literature list), as well as a list of human dimensions-focused keywords, a brief summary of the article's purpose, and any relevant notes.

Model and study details

Model details described distinguishing characteristics of the model version and associated methods. We recorded the model version(s) and specific model component(s) used, the resolution(s) of the model simulations, whether a component model (if the focus of the study) was run coupled to the rest of the model or offline (uncoupled), and the type of simulations run. We classified four types of simulations: 1) single simulations, 2) simulations as part of small multi-model ensembles consisting of fewer than 10 models, 3) simulations as part of large multi-model ensembles consisting of 10 or more models[6], and 4) initial condition ensembles, in which a single model was used but multiple ensemble members were generated by perturbing initial conditions. For study specifics, we recorded the time horizon of the study, the geographic scale of the analysis, and whether downscaling[7] or bias correction[8] of the CESM simulations were used. We distinguished three time horizons: 1) decadal, or pre-2050, 2) 50-100 year projections, or those between 2050 and 2100, and 3) projections beyond 2100. We aggregated scales of analysis into three categories: global, regional, or local. Global studies considered the entire world. Regional studies examined a sizable portion of the world, such as a continent, country, or a large related geographic area, such as the Arctic. Local studies examined small, contained geographic areas, such as individual lakes or cities.

Systems and outcomes

[6] Small and large multi-model ensembles consisted of CCSM and/or CESM as one or two of the models in the ensemble. The remaining models in the ensembles were comprised of comparable ESMs maintained by other institutions.

[7] "Downscaling" refers to methods used to process and refine ESM output with the end goal of producing output with finer spatial resolutions. This step can make ESM output more suitable for answering specific human dimensions research questions (GFDL, 2018). It is sometimes combined with bias correction (see next footnote). Downscaling as used for the purposes of our study can refer to either dynamical or statistical methods.

[8] "Bias correction" refers to the process of adjusting ESM output to better match observed climate conditions over a historical reference period, as described for example in Oleson et al. (2015). It is sometimes performed in combination with downscaling. Our use of this term covers any such corrections, including delta-change methods, as they relate to the use of CESM in our study.

To systematically define the substantive focus of research using CESM, and to understand which research communities were using the model, we classified papers according to three topic categories. The first two, systems and outcomes, were hierarchical descriptors of specific topics being investigated in the application (the third, research areas, is discussed in the following section). The first level classification (systems) indicates whether the paper focuses on societal, managed, ecological, or relevant physical systems, and the second level classification (outcomes) indicates which specific element of the system was of primary interest.

Four systems were defined:

- Societal systems are those that constitute an aspect of society or its activity, such as health, the economy, and energy use.
- Managed systems are those in which the conditions of biophysical environments, such as crops or managed water sources, are intentionally modified by human influence in order to control the system's characteristics for society's purposes.
- Ecological systems constitute distinct systems of living organisms and their interactions with the physical environment; these systems are dominated by natural influences.[9]
- Relevant physical systems encompass physical aspects of the earth system, such as extreme temperature and sea level rise, that are studied primarily to understand their implications for one or more of the other three systems, as opposed to primarily being aimed at improved understanding of climate system processes.[10]

Many studies focused on more than one system, or cut across multiple systems. To capture this feature of the literature, a primary and secondary system—defined as a lesser but still substantially discussed system—were recorded for each paper.

To capture the full span of human dimensions literature using CESM, a list of outcomes for each system was built throughout the review and expanded; thus, the final list is exhaustive of the outcomes we found during the review. In total, we identified 23 outcomes within the four types of systems (see Table 2 for definitions and example publications), including seven societal system outcomes, four managed system outcomes, three ecological system outcomes, and nine relevant physical system outcomes. To sufficiently distinguish outcome topics among papers, we typically only classified a primary outcome for each paper. However, many studies that focused on temperature or precipitation extremes had a primary focus on one of these outcomes and a secondary focus on the other outcome.

TABLE 2 | Outcome categorizations; their definitions; examples for societal, managed, ecological, and relevant physical systems; and the number of papers categorized for each outcome. Italicized

[9] This definition is taken, in part, from the IPCC's definition of "ecosystems" (IPCC, 2013a).
[10] Because the boundary for this definition can be particularly fuzzy, we devote several examples in the supplementary information to illustrating its application.

citations are discussed further as example papers in the supplementary information. Definitions with an asterisk draw on definitions from the IPCC Fifth Assessment Report Working Group I glossary (IPCC, 2013a).

Societal System Outcomes			
Outcome	*Definition*	*Example(s)*	*No. of papers*[11]
Health	Consequences for or impacts on human condition and well-being	Influences of climatic and population changes on heat-related mortality (Marsha, Sain, Heaton, Monaghan, & Wilhelmi, 2016) *Projected exposure to high-mortality heat waves (Anderson, Oleson, Jones, & Peng, 2016)*	14
Energy use	Production, distribution, or consumption of energy by humans for basic goods or services	Potential effect of climate change on heating and cooling demands (Zhou, Eom, & Clarke, 2013)	8
Economy	Distribution of wealth or monetary resources, or monetary consumption of goods and services	Estimated climate change impacts on economic activity (Backus, Lowry, & Warren, 2012) *Avoided economic impacts of climate change on agriculture (Ren et al., 2016)*	7

[11] These numbers indicate papers classified with each primary outcome. A secondary outcome was also classified for some papers but not indicated here, and this is further discussed in the results section.

Policies	Officially-directed course of action in response to climate change	Examination of emissions policies and climate change impacts (Arnell et al., 2013)	7
Transport	Movement of people or goods or the provision of services utilizing human-supported transport	Impacts of climate change impacts on transportation access in the Arctic (Stephenson & Smith, 2015)	6
Food security	Ability to procure reliable access to a sufficient quantity of food	Emerging threats of warming to global and regional food security (Funk & Brown, 2009)	4
Conflict and crime	Prolonged struggle between two or more parties with differing principles or interests	Impact of climate change on the prevalence of criminal activity in the U.S. (Ranson, 2014)	2
Managed System Outcomes			
Outcome	*Definition*	*Example*	*No. of papers*
Agriculture	Human-managed plants or animals grown or raised for food or energy	Estimated impacts of emission reductions on wheat and maize crops (Tebaldi & Lobell, 2015) *Impacts of elevated CO_2 on winter wheat yields (Özdoğan, 2011)*	29
Managed water	Water deliberately captured and/or stored for human uses	Evaluation of warming-driven impacts and adaptation issues for water resources (Fung,	22

		Lopez, & New, 2011)	
Land use/land cover	Arrangements, activities, and inputs directed by humans to use land or manipulate the land surface*	Impacts of climate change on land use in the rainforest (Lapola, et al., 2011)	12
Urban areas	Dense, developed, highly populated environments created and managed by humans	Contribution of urbanization to warming (Sun, Zhang, Ren, Zwiers, & Hu, 2016)	5
Ecological System Outcomes			
Outcome	*Definition*	*Example*	*No. of papers*
Ecosystem viability	Ability of a particular ecosystem to continue to thrive or survive	*Impacts of climate change on the world's most exceptional ecoregions (Beaumont, et al., 2011)*	*20*
Biodiversity	Naturally occurring and naturally influenced ecological diversity in a particular habitat or ecosystem	Impact of climate change on ecological diversity in Himalayan species, ecosystems, and mountain farming and pastoral systems (Zomer, 2014)	6
Species range	Area in which a particular species can be found during its lifetime	Projected geographic ranges of species under climate change (Lawler et al., 2009)	5
Relevant Physical System Outcomes			
Outcome	*Definition*	*Example*	*No. of papers*
Precipitation extremes	Changes to the	Projected changes in	49

	frequency, intensity, or duration of exceptionally high or low rainfall periods*	patterns of extremes (Meehl, Tebaldi, Teng, & Peterson, 2007)	
Temperature extremes	Changes to the frequency, intensity, or duration of exceptionally hot or cold spells*	Risk of record-breaking summer temperatures under warming (Lehner, Deser, & Sanderson, 2016) *Projected changes in extreme temperatures in East Asia and Korea (Ho et al., 2011)*	37
Hydrologic cycle	The complete lifecycle of water as it transitions among the atmosphere, oceans, and land surface.*	Implications of human-induced hydrology changes, on future water supply (Barnett et al., 2008)	26
Anthropogenic emissions and forcing	Greenhouse gas cycles, ozone and its precursors, and aerosols, and their effects on climate	Impact of anthropogenic aerosols on the Indian summer monsoon (Wang, Kim, Ekman, Barth, & Rasch, 2009)	24
Sea level change	Change in the shape of ocean basins or ocean volume as a result of a change in the mass or density of water in the ocean*	Projected sea ice changes in response to climate scenarios (Zhang & Walsh, 2006)	18
Drought	A period of abnormally dry weather long enough to cause a serious hydrological imbalance*	Effect of warming on drought patterns over Asia (Kim & Byun, 2009)	12

Global/regional climate	Large-scale, long-term changes in temperature, precipitation, or other climate characteristics relevant to societal, managed, or ecological systems	A new ensemble of GCM simulations to assess avoided impacts in a climate mitigation scenario (Sanderson, Oleson, Strand, Lehner, & O'Neill, 2015)	12
Tropical cyclones	Changes to the frequency or intensity or other characteristics of tropical cyclones	Projected changes in tropical cyclone activity under future warming scenarios (Bacmeister et al., 2016)	10
Land surface	Biophysical characteristics and processes related to the land surface and its interaction with the atmosphere, including soil characteristics, albedo, surface roughness, and exchanges of energy and water	*Implications of warming on permafrost thawing in Arctic tundra (Kitabata, Nishizawa, Yoshida, & Maruyama, 2006)*	3

Research areas

To more fully describe the fields in which CESM is used, we also assigned papers to one of five primary research area classifications independent of systems and outcomes (these definitions draw, in part, from the IPCC Fifth Assessment Report Working Group I glossary (IPCC, 2013a)), and recorded a secondary research area when applicable:

- Impacts: examines direct effects of climate change on an outcome;
- Emissions: examines the implications of the emissions of greenhouse gases, precursors, or other radiatively active substances on climate;
- Mitigation and geoengineering: examines human intervention either to reduce the sources or enhance the sinks of greenhouse gases or to intentionally modify the climate system directly;

- Adaptation: examines adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, in order to moderate harm or exploit beneficial opportunities;
- Paradigm: presents a new modeling framework, context, or methodology to facilitate the study of impacts, emissions, mitigation and geoengineering, or adaptation (e.g., the new 15-member "medium ensemble" described in Sanderson et al., 2015).

RESULTS

Publication trends for CESM use over time

We found that 338 publications used CESM for human dimensions research and applications from 2004-2016 (see Fig. 1 a)). Half of all human dimensions papers were found as part of the IPCC reference lists discussed earlier, while an additional third of papers came from NCAR-maintained reference lists. Remaining literature was found using the database-driven literature review. An average of 10% of all publications using CESM during our study period focused on human dimensions, though publication trends were heavily influenced by deadlines for the IPCC Fourth and Fifth Assessment Reports, in 2006 and 2013, respectively. Human dimensions papers peaked in 2013, with the number of publications generally increasing over time.[12] Publications decreased temporarily after IPCC deadlines, followed by substantial increases leading up to the next IPCC deadline, so we expect that the cycle of papers for the Sixth Assessment Report should be even larger.

Although the main aim of our study was to examine trends in human dimensions publications, we also wanted to compare trends in human dimensions publications using CESM to trends in all known publications using CESM during our study period. To approximate the total number of publications using CESM during this time[13], we counted all candidate papers using CESM from all sources, regardless of whether the publications were deemed relevant to our review. This was accomplished by using the full database of all possible candidate papers, described in the methodology section of this paper, which generally recorded the model used for all papers that underwent the abstract or full text review stages. We found a total of 3,554 articles using CESM (see Fig. 1 b)) from 2004-2016. It is likely that this is an underestimate, because the model version used was not recorded for papers that were excluded in the title review stage. However, we assume that this bias in the estimate remains relatively stable over time (the simplest assumption, given no reason to believe it should be

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[12] Because of the difference in methodology described previously for finding candidate papers for 2014-2016 compared with 2004-2013, it is likely the number of papers for 2014-2016 may be an underestimate and, thus, at least partially account for the drop in human dimensions publications after 2013.

[13] Because our review aimed to be comprehensive but not necessarily exhaustive, we assume that our total number of publications using CESM is a likely underestimate of the total number of publications using CESM from 2004-2016.

changing). In that case, although the absolute values of the relationship between all papers using CESM and human dimensions papers using CESM may not be accurate, the trends over time should be valid.

Like human dimensions publications, publications using CESM for any reason were strongly influenced by deadlines for the IPCC Fourth and Fifth Assessment Reports, declining temporarily after these deadlines and peaking in 2013. Between the two IPCC-driven peaks, the proportion of papers using CESM for human dimensions grew nearly twice as fast as the overall number of publications using CESM, increasing by a factor of 2.9 between 2006 and 2013 (see Fig. 1 a)) compared to a factor of 1.8 for all CESM publications (see Fig. 1 b)). The ratio of human dimensions papers to all CESM papers increased from generally below 5% before 2009 to 15% or more in 2014 or later (see Fig. 2). For the remainder of the paper, we report results only for papers describing human dimensions applications of CESM.

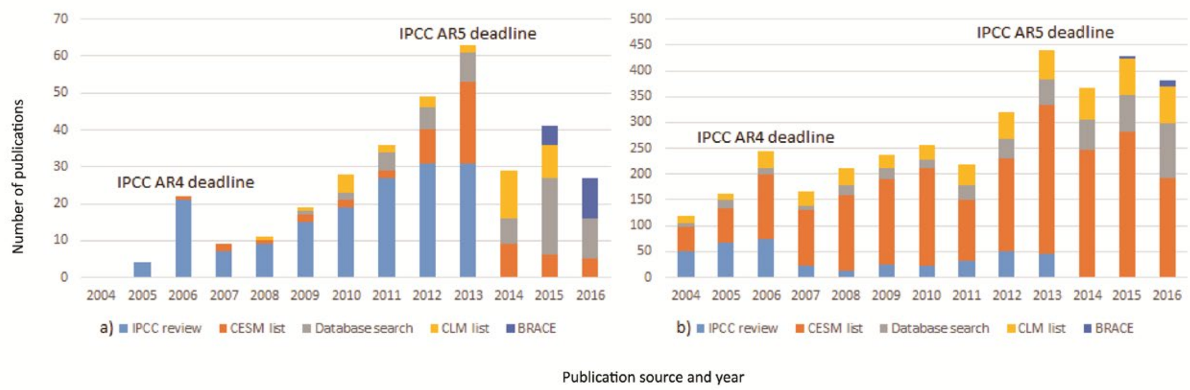

FIGURE 1 | Community Earth System Model (CESM) publication trends for human dimensions publications using CESM (a) and all publications using CESM for any purpose (b) by year.

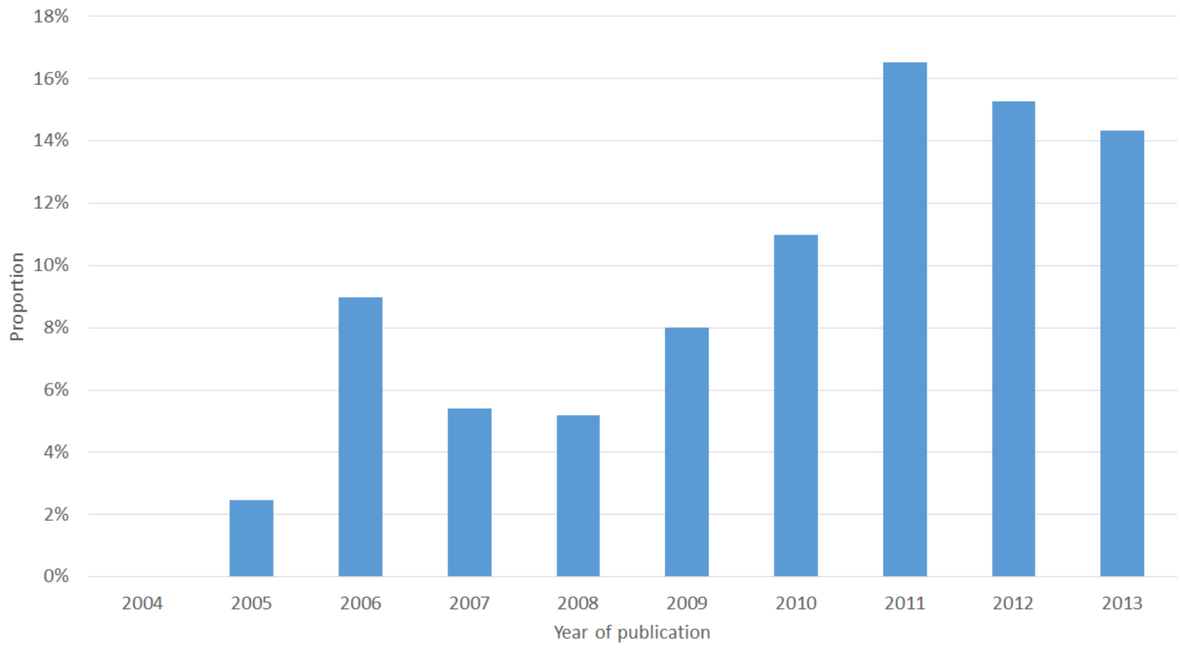

FIGURE 2 | Proportion of human dimensions publications compared to all publications using CESM. This figure does not include proportions for 2014-2016, since the methodology for finding candidate literature for these years is not sufficiently comparable to the methodology for all preceding years.

Primary and secondary systems, outcomes, and research areas

Over half of all papers focused on relevant physical systems (see Fig. 3 a)). Just over 20% of papers addressed managed systems, while 14% addressed societal systems. Ecological systems papers accounted for fewer than 10% of papers. Most papers only addressed one system, but around 12% of papers also focused on a secondary system. Managed and societal systems made up two-thirds of these secondary systems. Relevant physical systems publications dominated human dimensions work until 2009 (see Fig. 3 b)), after which the proportion of papers on other systems began to increase, a trend that generally continued throughout the study period until papers on physical systems fell to less than half of all applications in 2014 and beyond. The non-physical system papers were dominated by growing numbers of studies on managed and societal systems, whereas papers on ecological systems remained relatively small over time, indicating that CESM has been used infrequently to address ecological topics.

One quarter of physical system applications focused on outcomes for either precipitation or temperature extremes (see Fig. 4). Agricultural outcomes accounted for nearly 10% of outcomes studied. Ecosystem viability was the most common ecological system outcome, while health outcomes were the most studied societal system outcome. Secondary outcomes were recorded for 12% of all papers. Agricultural outcomes were the most common secondary outcome, followed by temperature extremes. These outcomes were often secondary outcomes for a paper examining a societal system outcome, such as mortality related to heat events or food security.

Taken as a whole, these results indicate that during our study period (2004-2016), CESM was predominantly used to examine physical system outcomes relevant to human dimensions, but they also highlight growing work in important areas for societal and managed systems. The frequency of agricultural outcomes studied suggests the importance of CESM's Community Land Model in human dimensions research and applications. We expect that similar implications exist for the use of single components in other ESMs.

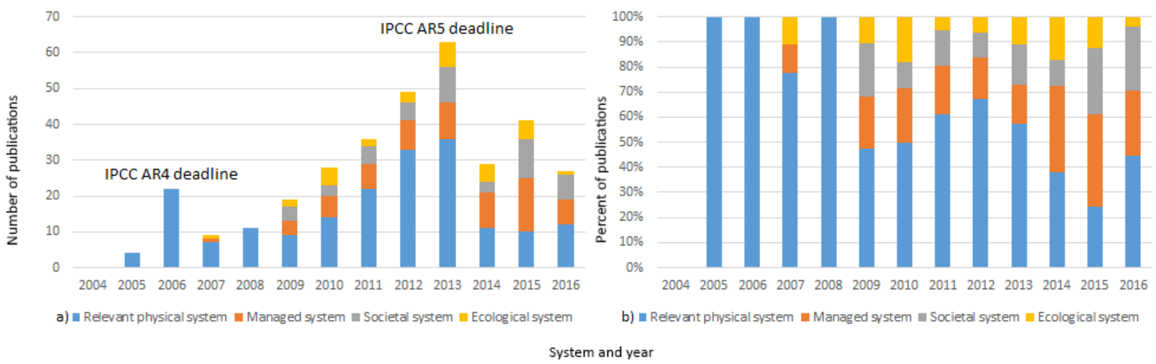

FIGURE 3 | Number (a) and share (b) of CESM publications per year by primary system.

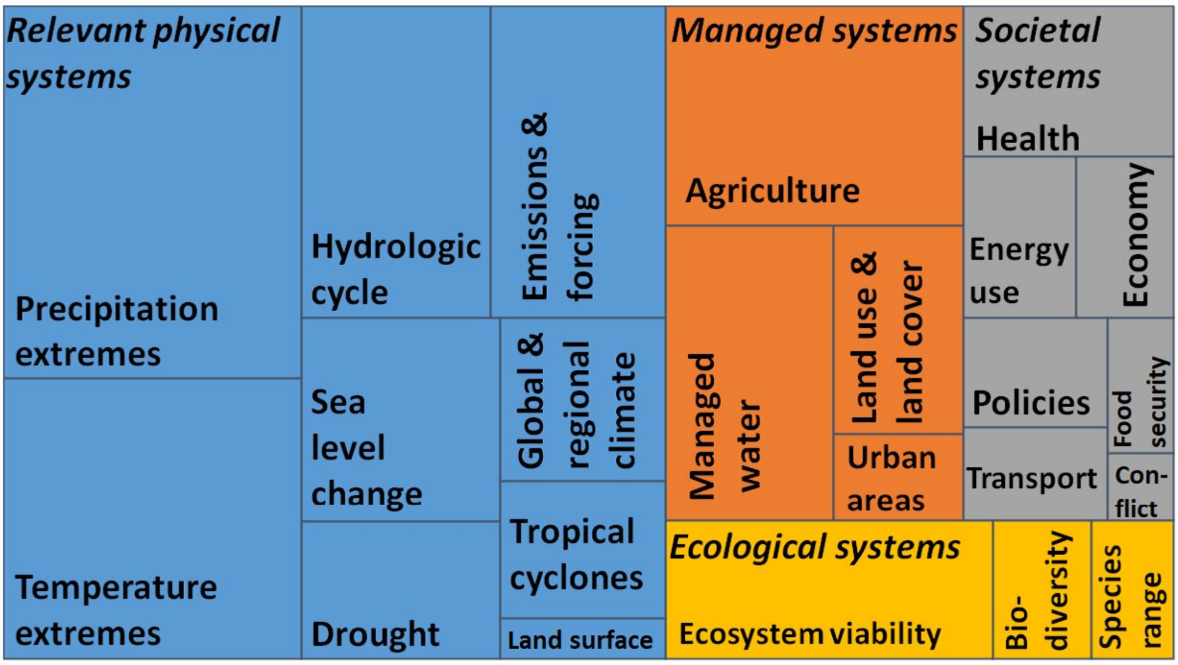

FIGURE 4 | Papers on human dimensions applications of CESM by primary system and outcome. The area of each rectangle is proportional to the number of papers in that category. Table 1 in the supplementary information provides a list of absolute values and percentages for each category.

Primary research area

For human dimensions, CESM was most commonly used in impacts work, with nearly 70% of papers primarily addressing climate impacts (see Fig. 5). This was consistent with our expectations, given that detailed climate model outcomes are more useful to impact studies than to other research areas, such as emissions or mitigation. Paradigm papers accounted for 16% of all papers, while emissions papers accounted for around 7% of primary research areas. Adaptation, mitigation, and geoengineering research areas were less commonly focused on, with only six papers addressing adaptation as the primary research area. However, adaptation was a common secondary research area, accounting for a third of the 30% of papers for which a secondary research area was recorded. The proportion of research areas remained fairly constant over time, with minor deviations. Paradigm papers were more prevalent around the time of IPCC deadlines. Emissions-focused papers appeared throughout the study, while papers focused primarily on adaptation, mitigation, and geoengineering research areas didn't appear in our study sample until about halfway through our study period, indicating that the application of the CESM models in our study to these research areas is more recent.

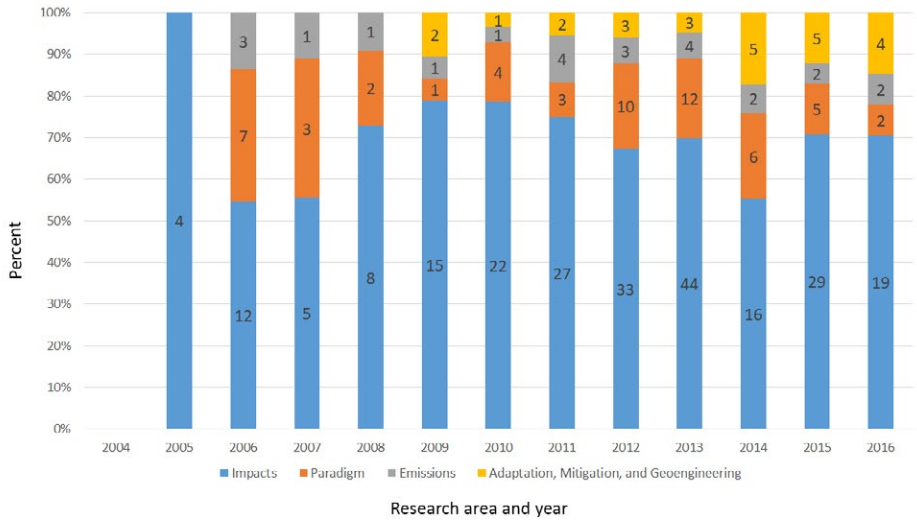

FIGURE 5 | Share of CESM publications per year by primary research area, with numbers of publications in each category labeled on each bar[14].

Model version and resolution

CCSM3 was the most common model version during our study period (see Fig. 6a)), used in over half of all papers. CCSM4 was used in nearly a quarter of papers, while CESM1 was used in about 20% of papers. The greater use of CCSM3 can be explained, in part, by the fact that CCSM3 was available during the entire study period, as opposed to the other two model versions, which were released at different times in 2010. CCSM3 was also one of the CMIP3 models heavily used in the IPCC Assessment Reports, from which much of our literature was obtained. Significant use of CCSM3 continued through the IPCC Fifth Assessment Report literature deadline in 2013. CCSM4 was first used in human dimensions papers published in 2011, and its use peaked in 2013 and then declined predictably in favor of CESM1, which was the predominant model used in 2014, 2015, and 2016. We expect to see a similar introduction and upward trend with CESM2 given its recent release (CESM, 2018).

Three quarters of studies used the models' default resolution of 1° (see Fig. 6 b)), while 19% ran simulations at coarser resolutions of 2° or 3°. The latter resolutions were generally associated with the use of CESM components, such as CLM and CAM, and were likely utilized to save time and complete runs more quickly. The models and their components were used infrequently at finer resolutions (0.5°, 0.25°, 0.125°); the use of these resolutions generally involved offline runs of CESM components commonly utilized for human dimensions research—CAM or CLM—or the use of downscaling. CAM and CLM have recently introduced the capability to run variable-resolution grids that allow the specification of a high resolution in a particular area of the globe with a coarse resolution elsewhere (Zarzycki & Jablonowski, 2014), and the newly released CESM2 has additional capacity to perform simulations at grid spacings akin to regional climate models (CESM, 2018). Therefore, we expect that future human dimensions studies may use CESM2 (and future model versions) at finer resolutions.

[14] Adaptation, mitigation, and geoengineering research areas were recorded separately, but results for these three categories were combined for the purposes of reporting this result because of the very small number of papers in each of these categories.

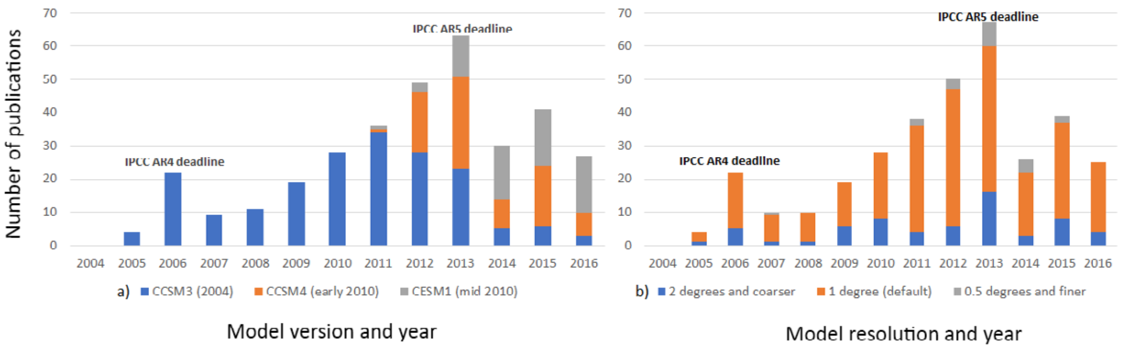

FIGURE 6 | Number of CESM publications per year by model version (a) and model resolution (b). Results for model and resolution counts include all model versions and resolutions used in all studies, so cumulative totals account for more than the number of papers in our study.

Types of simulations

Nearly half of all studies used CESM as part of large multi-model ensembles, which we defined as ensembles with members from 10 or more models (see Fig. 7). Just over a quarter of studies used CESM single simulations, while just under a quarter of studies used CESM as part of small multi-model ensembles, defined as having members from 9 or fewer models. Initial condition ensembles were the least common way in which CESM was used, utilized less than 6% of the time. As with trends in other model aspects we considered, the use of large multi-model ensembles, which were most often used to examine research questions related to extremes and the hydrologic cycle, increased with both IPCC cycles. However, an examination of the proportion of output type over time showed a decline in the use of large-multi model ensembles, in favor of increased use of single model projections, frequently in the form of a single simulation. This may be of concern since large multi-model ensembles are thought to do a better job of representing uncertainty than single simulations (Knutti et al., 2010), but also may point to the fact that IPCC deadline-driven assessments are more likely to use large multi-model ensembles, while other papers are more likely to use single model approaches; single model approaches were more common for societal and managed system applications. The use of small multi-model ensembles also tended to decrease over our study period, and this may indicate that such ensembles that adequately span uncertainty are not yet well developed.

Although the use of initial condition ensembles to explore the effect of internal variability in impact studies can be documented in European studies as early as the late 1990s (e.g., Hulme et al., 1999), we first detected the use of initial condition ensembles for human dimensions studies using CESM in 2012. That use increased during the remainder of the study period, although much of that increase was observed in studies done as part of NCAR's BRACE project. Initial condition ensembles have been performed through ESM experiments for some time, including well before our study period, but because of computational constraints, such ensembles were limited to a small number of members. With the increase in computational capacity, large ensembles began to be performed, and the magnitude of natural variability became better appreciated (Deser, Knutti, Solomon, & Phillips, 2012), spurring additional experiments and studies (Kay et al., 2015, Sanderson et al. 2015, Sanderson et al., 2017). The focus on the importance of natural variability and its confounding role in future projections, thus, also became apparent for applications to impact studies. This could further explain the increasing use of CESM as part of (large) initial condition ensembles for human dimension studies.

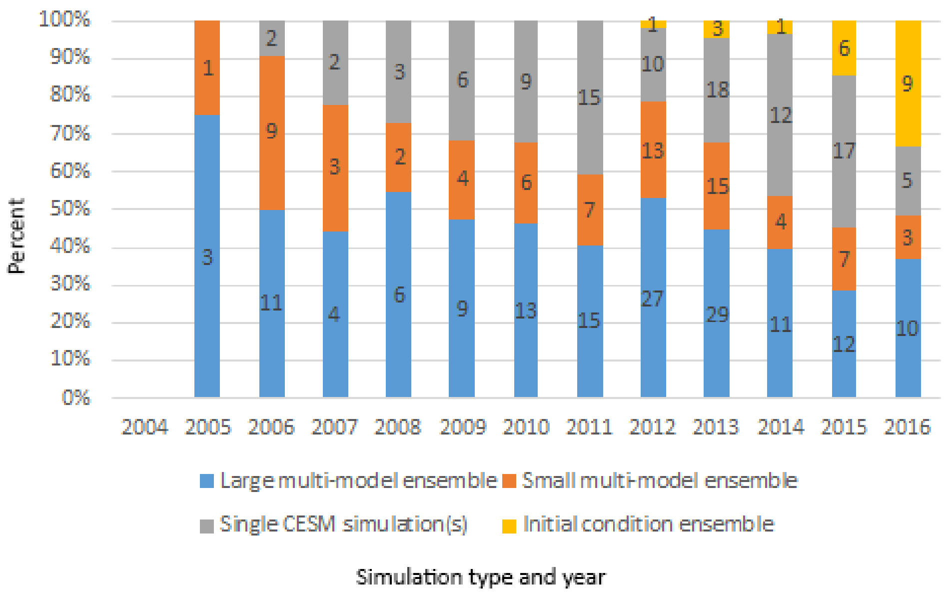

FIGURE 7 | Share of CESM publications per year by type of simulations employed, with numbers of publications in each category labeled on each bar.

Scale of analysis

Just over half of all papers used CESM primarily for regional analyses, while just under half of papers focused on global analyses (papers conducting both global and regional analyses were classified as global). The proportion of global and regional studies was fairly even and consistent over time (see Fig. 8). Studies at the local scale were uncommon, suggesting that CESM is used infrequently for localized human dimensions examinations. Because CESM2 possesses enhanced capabilities for conducting research at finer resolutions, we expect that the use of CESM in studies at smaller scales will grow as the adoption of CESM2 increases.

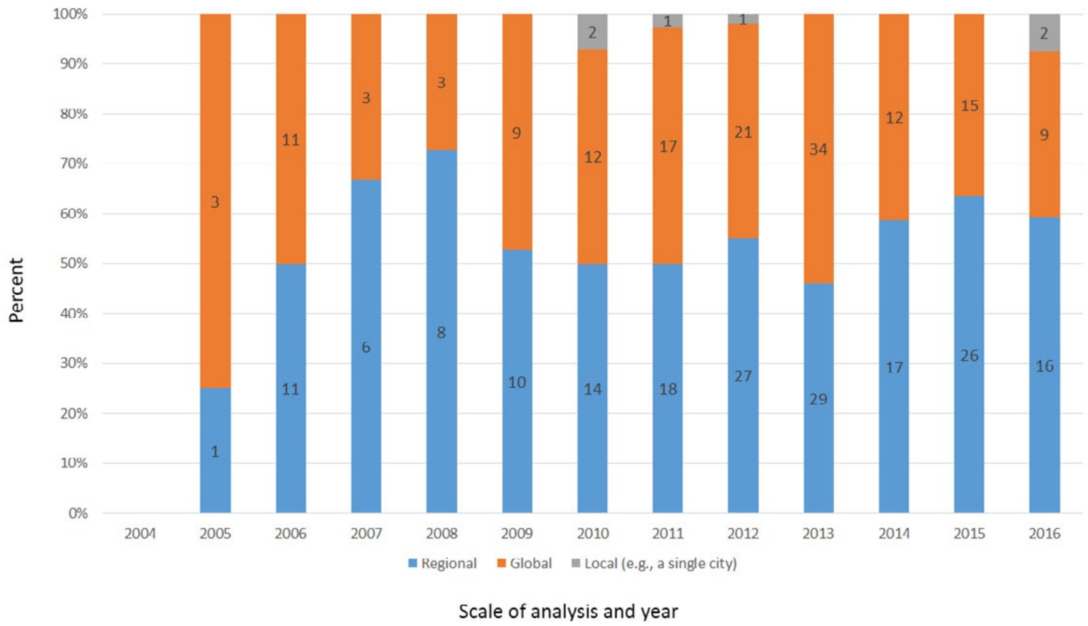

FIGURE 8 | Share of CESM publications per year by scale of analysis, with numbers of publications in each category labeled on each bar.

Time horizon of analysis

Nearly two thirds of studies were conducted at time horizons of 50- to 100- year projections through 2100, while one third of studies were conducted on decadal, pre-2050 time horizons (see Fig. 9). This trend remained consistent throughout our study period. The predominance of 50- to 100-year projections is consistent with our expectations, given that the majority of studies were focused on impacts. We found very little use of CESM for projections past 2100, which is reflective of the general focus of current impacts literature on outcomes through 2100. In addition, projections beyond 2100 were not widely available before CMIP5 (Taylor, Stouffer, & Meehl, 2012). The use of projections beyond 2100 first appeared in our human dimensions literature in 2011, and the proportion of these papers remained similar throughout the remainder of the study period. The proportion of physical and societal systems examined were similar for all three timeframes. Ecological systems were rarely examined using decadal timeframes, while managed systems were rarely examined for timeframes beyond 2100[15].

[15] Because there were only 11 papers for timeframes past 2100 (see Fig. 9), these results should be interpreted with caution.

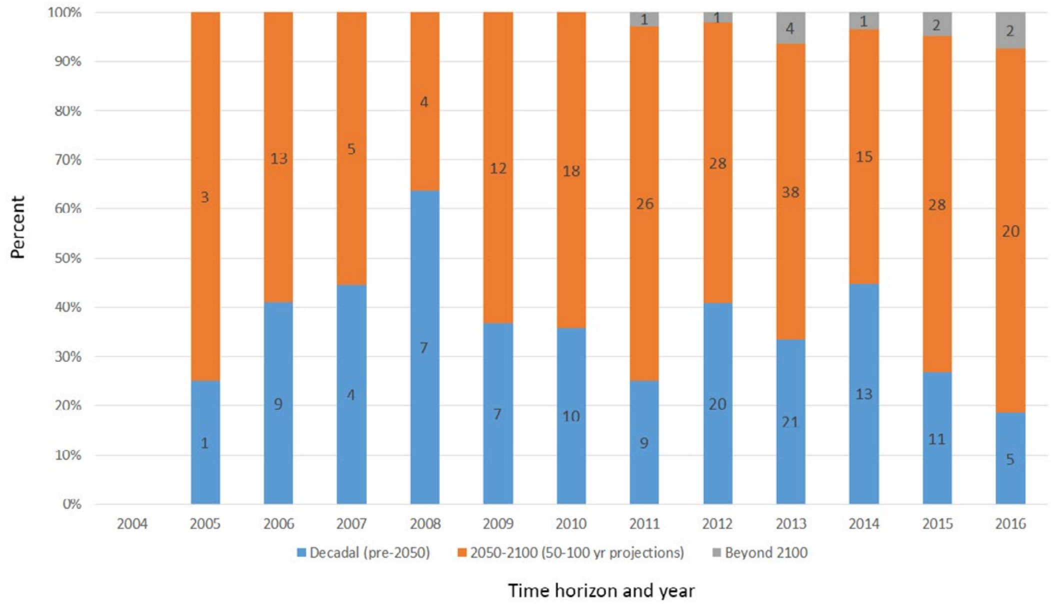

FIGURE 9 | Share of CESM publications per year by time horizon of analysis, with numbers of publications in each category labeled on each bar.

Downscaling and bias correction

Approximately 41% of papers used CESM projections that had been either downscaled or bias corrected, with about 15% of papers applying both techniques. Papers with a regional focus were more likely to use downscaled or bias corrected results, with nearly one quarter applying at least one of these techniques, compared with 15% of global studies. All papers at the local scale used at least one of these techniques, with one third of these papers applying both techniques. The use of both downscaling and bias correction was most common for papers examining managed systems, particularly for managed water and agriculture outcomes. Papers on extremes (temperature and precipitation) and health outcomes were also frequently bias corrected, which was expected since bias correction should typically be done for studies in which absolute values (as opposed to changes or relative values) in climate variables are important, such as those corresponding to extreme heat or precipitation thresholds.

Authorship

To determine whether author affiliation with NCAR or geographic location of authors disproportionately impacted the choice to use CESM, we analyzed the affiliations of all authors at the time of publication for the 338 papers in our review. Most authors are not from NCAR; NCAR authors comprised only 12% of all authors. Just over half of all authors were U.S.-based (see Fig. 10). Another quarter were based in Europe, while nearly 13% of authors were based in Asia. Authors from other areas of the world comprised the remaining 12% of authors. Half of all authors were affiliated with universities (see Fig. 11). Just over one quarter of authors were affiliated with research institutes, while just under one quarter worked for government institutions. Fewer than 3% of authors were affiliated with miscellaneous organizations, including consulting companies and non-governmental organizations.

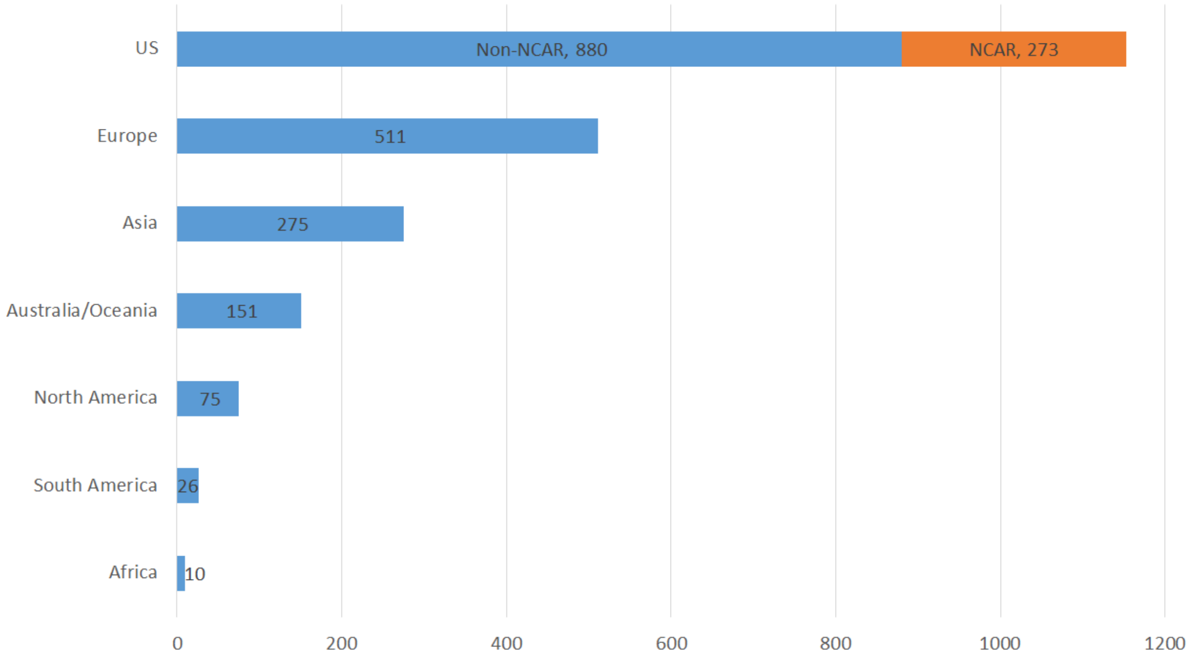

FIGURE 10 | Authorship by geographic area for all author affiliations for human dimensions publications using CESM (n=2148).

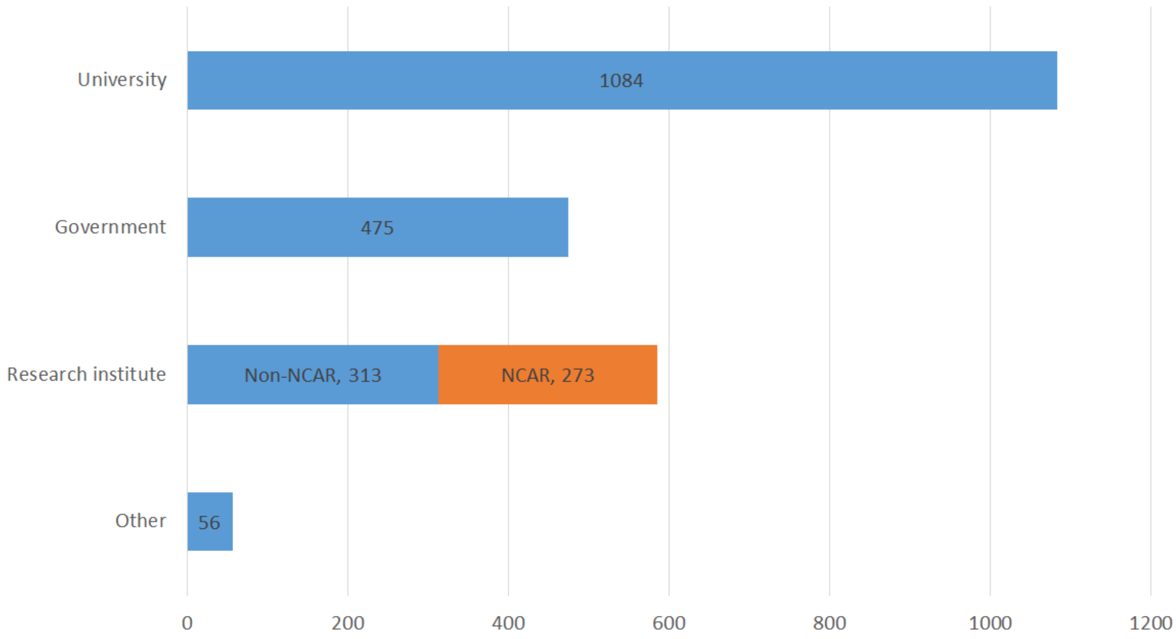

FIGURE 11 | Authorship by institution type for all author affiliations for human dimensions publications using CESM (n=2148).

We compared the results from the analysis of all authors to results for first authors only and found that percentages for geographic area and institution type were similar. NCAR authors comprised 15% of all first authors, and U.S. authors (including NCAR) accounted for over half of first authors. European authors accounted for just under 20% of first authors, compared with 12% of first authors based in Asia. Nearly half of first authors were affiliated with universities. Over one quarter were affiliated with research institutes, while fewer than one quarter were affiliated with government organizations. Only 1% of first authors were affiliated with miscellaneous organizations, including consulting companies and non-governmental organizations.

Our results indicate that for human dimensions research, NCAR authors are not disproportionately leading or contributing to analyses, since most studies are led and conducted by non-NCAR authors.

DISCUSSION AND CONCLUSIONS

The use of CESM for human dimensions research has grown substantially since 2004, with strong variations in use tied to the IPCC assessment cycle. Between 2004 and 2016, the proportion of papers using CESM for human dimensions work grew nearly twice as fast as all publications using CESM, suggesting that societally-focused users of CESM—and possibly other ESMs—are a growing and important research community. Although human dimensions applications of CESM have been dominated by studies focused on physical system outcomes relevant to impacts, particularly related to temperature and precipitation extremes, a substantial and growing proportion of studies have focused on managed and societal systems, indicating the potential for continued future growth of this type of work.

Although CESM is housed and maintained by NCAR, human dimensions research using CESM is predominantly led and carried out by non-NCAR authors, which suggests that the trends we've observed likely extend beyond the CESM community. U.S.-based, university researchers comprise the largest group of authors using CESM, with substantial participation by researchers from Europe and Asia, and from government agencies and other research institutions. In addition, the predominance of non-NCAR authors using CESM in human dimensions research and applications underscores the importance of effective connections between the CESM community and the human dimensions community, in order to maintain the observed growth in such work over time.

Our descriptive analysis has identified questions about the strengths and weaknesses of ESMs that should be addressed more critically in future analyses. For example, more often than not, output from CESM was not downscaled or bias corrected when used in human dimensions research; we found that more than half of all applications applied neither technique. Studies that did downscale and bias correct were more likely to be regional in scale (as opposed to global) and focused on outcomes for which absolute values of climate variables were important. The reasons for the lack of downscaling and bias correction are not mentioned in the literature. It might be the case that some authors were unaware of the need to bias correct or downscale in their work, that bias correction or downscaling were not available due to technical or resource constraints, or that the authors had substantive reasons for not using such approaches. Follow up research using a variety of techniques, such as surveys and in-depth CESM user interviews, could examine why such approaches were (or were not) used, assess whether these practices were appropriate or not, and suggest remedies if necessary.

In addition, we found that CESM was typically used as part of large multi-model ensembles, such as CMIP, or as single simulations. There was little but growing use of small multi-model ensembles, and infrequent use of initial condition ensembles. It is unclear whether the emphasis we found in human dimensions applications literature on the use of either large multi-model ensembles or single simulations is an appropriate approach to the topics under study, or whether it simply reflects availability. A reliance on single simulations may underestimate climate uncertainty or fail to distinguish forced response from internal variability. Conversely, large multi-model ensembles may provide more climate information than is necessary, the use of which may reflect insufficient development of methods for selecting small multi-model ensembles that adequately span uncertainty (Ruane & McDermid (2017) provide an example of such methods). Similarly, the benefits of initial condition ensembles for investigating particular issues related to extreme events and natural variability may be under-appreciated, and such ensembles not widely available. The rationale for the particular types of climate simulations used was rarely included in the studies reviewed. Follow up research is needed to understand the considerations users make when selecting the type of simulations to run in their studies and to what extent these choices are appropriate or not.

Another question raised by our findings concerns the continued use of older model versions long after newer model versions have been released. For example, the use of CCSM3 continued throughout the study period, even after two newer model versions were released. This is partially due to the availability of output from CMIP3 archives, but more investigation is needed to understand this practice, which we assume likely extends to other ESMs as well. Similarly, while the majority of studies (75%) used CESM at the default result of 1°, studies using CESM components sometimes utilized coarser resolutions. Anecdotal evidence indicates that coarser resolutions were often used to save computing time and to allow for quicker completion of model runs. However, the exact reasons for choices about model versions and resolutions are rarely discussed in the papers. Additional research involving direct correspondence with the authors would allow for an understanding of these choices. In addition, although we focus on spatial resolution in this review, time resolution (e.g., the time step of model outputs) is also an important consideration for model applications. Future reviews may want to examine issues related to which applications require information at various time resolutions (e.g., sub-daily, daily, seasonal, or annual time steps) and the related implications.

We found that human dimensions research and applications have focused primarily on examining climate change impacts over the 50-100 year time horizon at both global and regional scales, with smaller numbers of studies at shorter (or longer) time horizons and finer geographic scales. Additional research could investigate user needs related to the use of CESM for projections past 2100 and could examine whether evolving model capabilities are allowing for increased use of CESM in studies at local or city scales as expected. Similarly, we found that CESM was used much less frequently in emissions, mitigation, adaptation, and geoengineering work. Given the increased emphasis on this type of work generally by researchers and the IPCC, an examination into the reasons for the infrequent use of CESM in these areas and related research needs could help contribute meaningfully to future model development. In particular, the fact that adaptation is a frequent secondary (if not primary) focus may signal an evolving need.

Additional research could expand the scope of the metrics we studied, examining issues such as the origin of outputs used in human dimensions work (e.g., from the PCMDI—Program for Climate Model Diagnosis and Intercomparison—data portal, versus a downscaling repository, such as that provided by NARCCAP—the North American Regional Climate Change Assessment Program), whether specific socioeconomic scenarios (e.g., Shared Socioeconomic Pathways) were used, and whether there were analyses of current/paleoclimate conditions in addition to the pre-2050 time horizon. Such research could also better examine cross-sectional results, such as downscaling, bias correction, model version, and resolution choices by outcomes.

Our findings suggest that model development efforts should recognize the disproportionately growing human dimensions user communities for CESM—and possibly for other ESMs—particularly in regard to model design, output availability, and interactions across communities. Within this overall trend, there has also been a shift in interest from relevant physical system outcomes to managed and societal system applications. If these trends continue, the fastest growing user base for CESM will be research communities seeking climate model simulations and output that are most relevant to societal applications. Understanding these needs will be increasingly important.

Finally, we consider this synthesis of past use of CESM to be a baseline that will allow continued tracking of the model's use for CESM2 and beyond. We also present our framework in hopes that it can be adapted for similar use in assessments of other ESMs for human dimensions research and applications, in an effort improve understanding of the applications of the ESM field more broadly to human dimensions questions.

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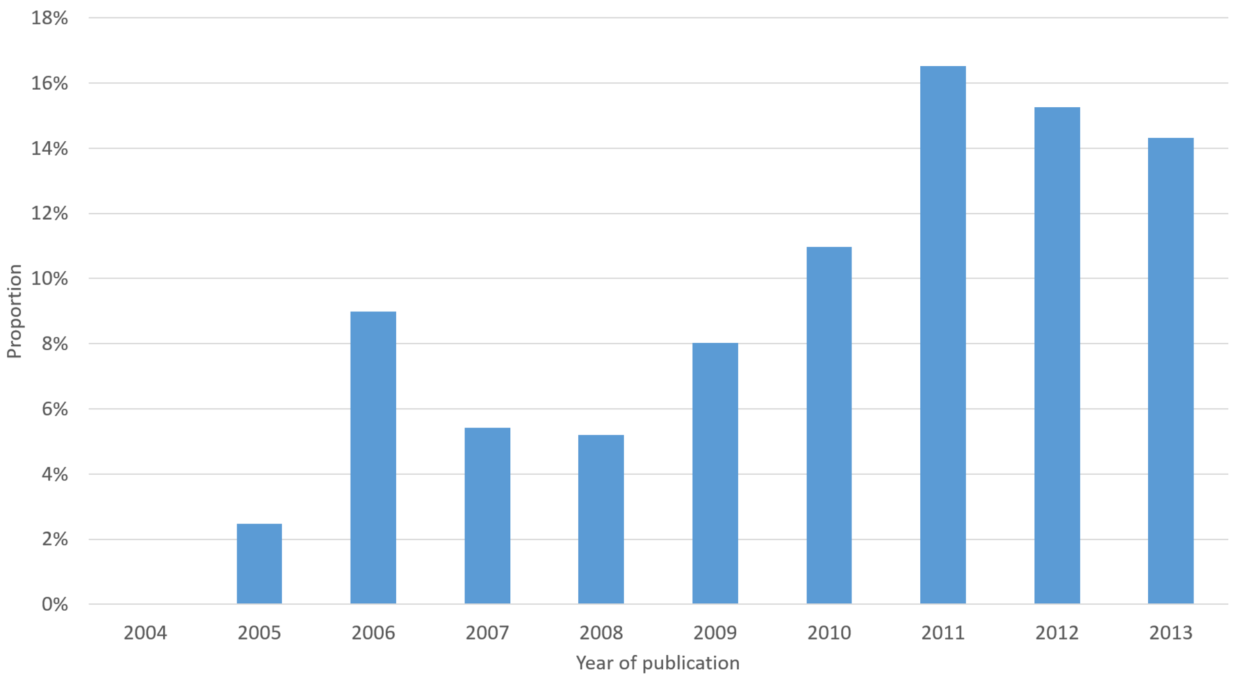

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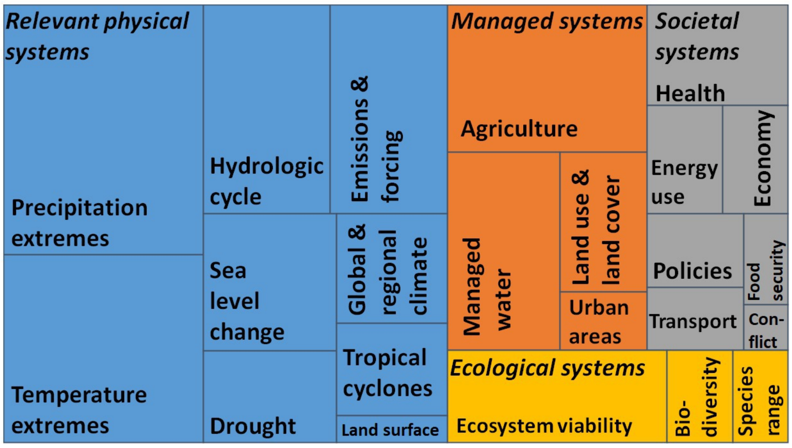

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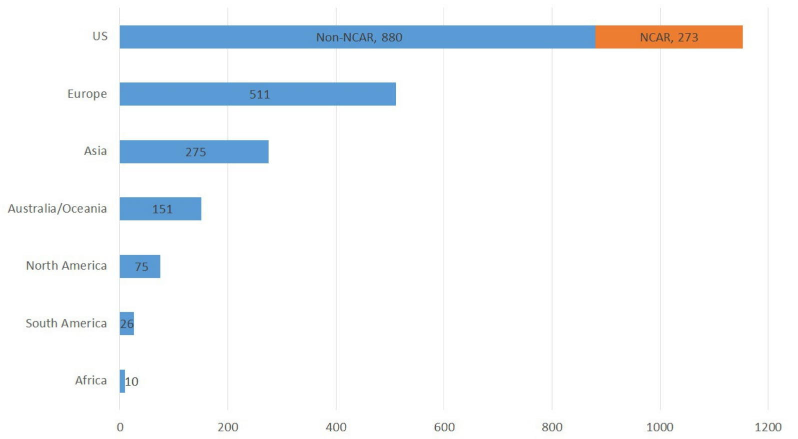

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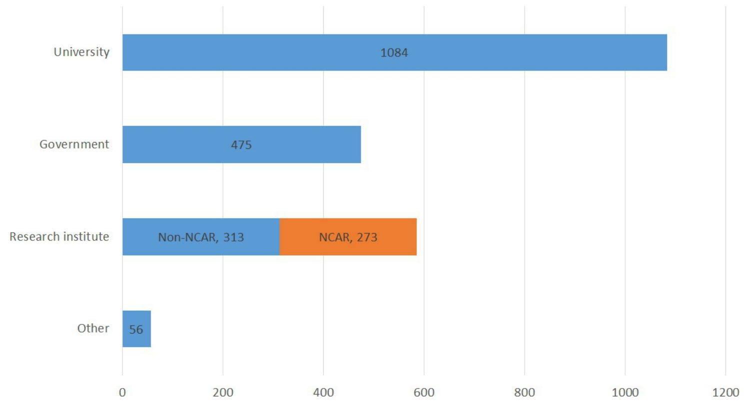

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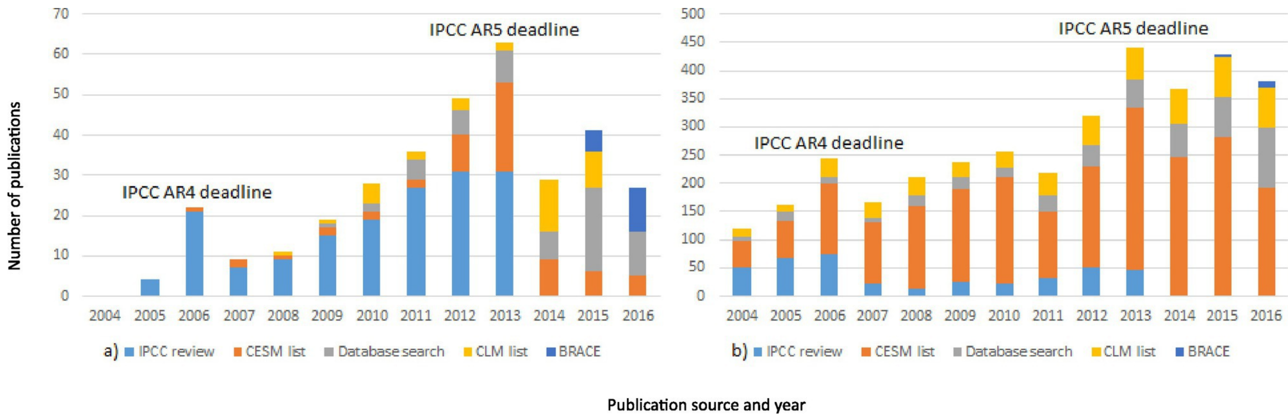

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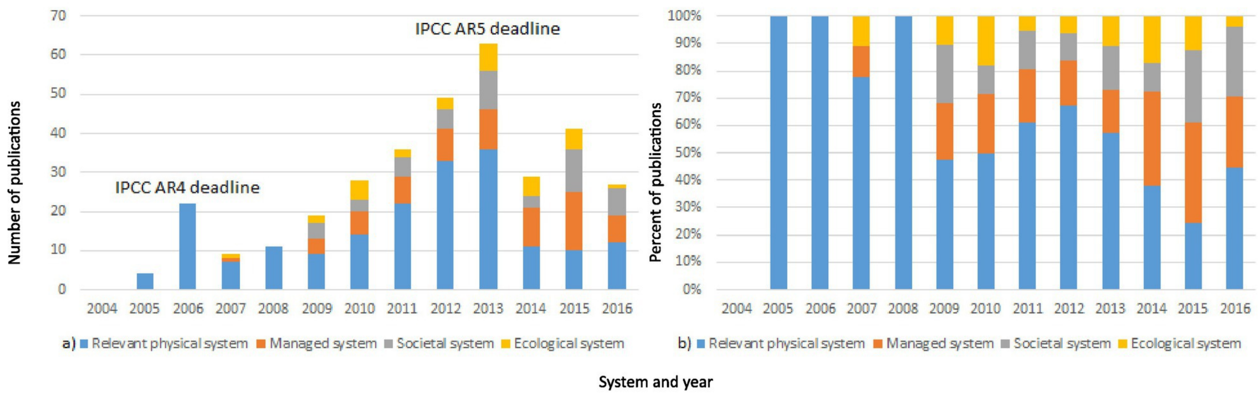

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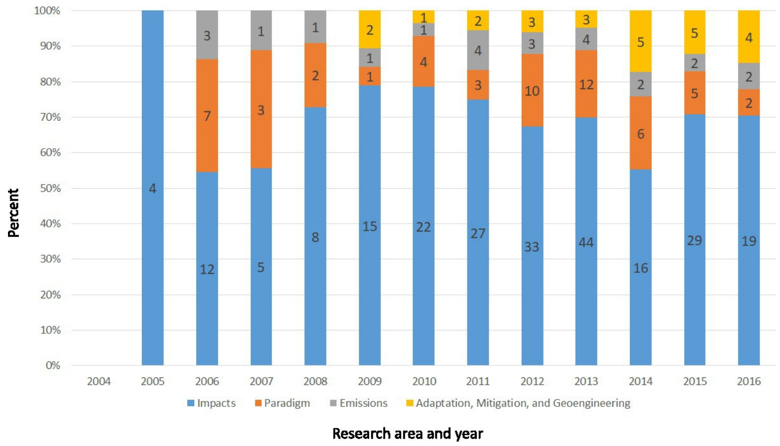

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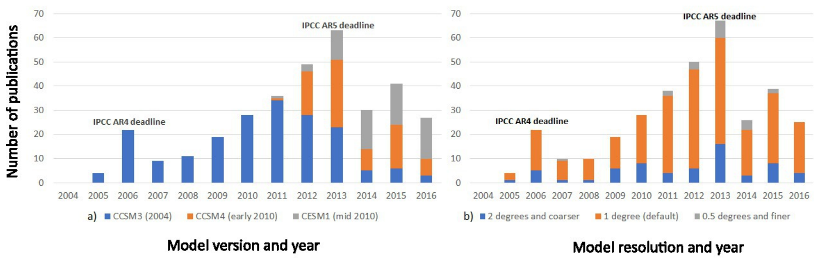

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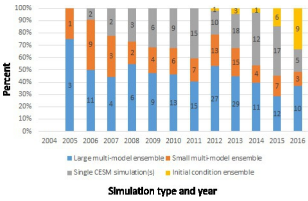

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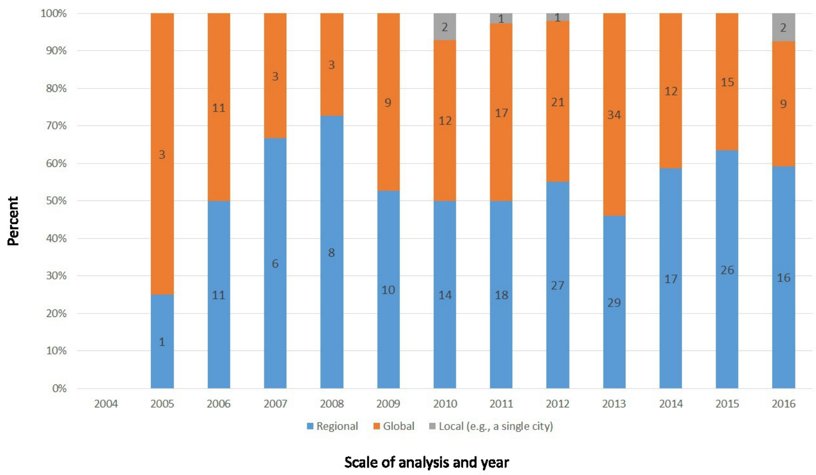

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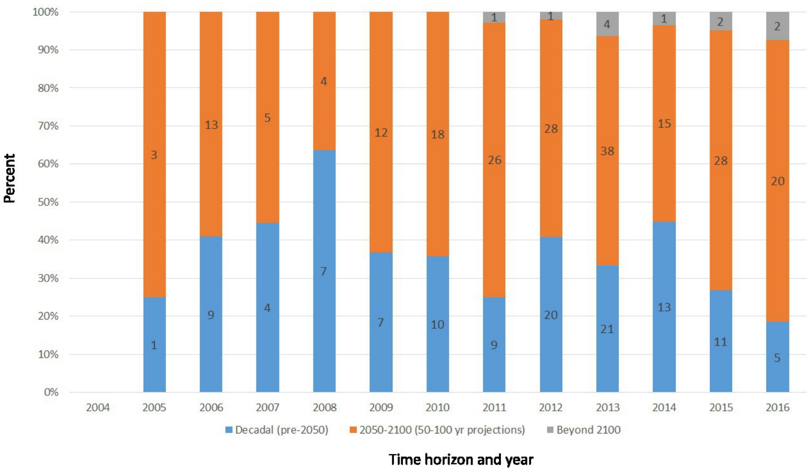

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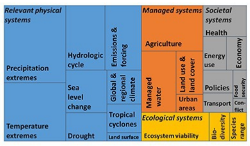

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