Climate Models for Guiding Action: Adequacy, Inadequacy, and the Ethics of Downstream Use of CMIP Data

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| Eric B.Winsberg  Department of History and Philosophy of Science, University of Cambridge, Free School Lane, Cambridge, CB2 3RH, United Kingdom; Department of Philosophy, University of South Florida, 4202 E Fowler Ave, Tampa, FL 33620, United States |
| Monica Ainhorn Morrison  NSF NCAR, 1850 Table Mesa Dr, Boulder, CO 80305, United States |
| Stephanie Harvard  Division of Respiratory Medicine, University of British Columbia (UBC); Legacy for Airway Health, Gordon and Leslie Diamond Health Care Centre, 2775 Laurel Street,Vancouver, BC Canada V5Z 1M9 |

**Abstract**

As concern about climate change intensifies, there is increasing demand for ‘actionable’ information to help mitigate to effects of climate change through sustainable policy. As this demand has increased, so has the complexity and resolution of Earth System Models (ESMs) and Global Climate Models (GCMs), which play a central role in generating this information. However, the increased complexity and resolution of ESMs/GCMs does not guarantee that they will offer increased adequacy-for-purpose in applied domains. This article reviews numerous recent case studies that highlight specific research questions that ESMs/GCMs cannot reliably answer, due to features that these models possess as a result of their development history and what is described as the problem of “pseudo-detail”. These include case studies of modelling surface water availability in the Upper Colorado River Basin, regional changes to precipitation regimes surrounding the Great Lakes, and red tide patterns in the Gulf of Mexico. The inadequacy of ESMs/GCMs for certain applied purposes raises the risk of downstream harm, what philosophers of science and modelling have called ‘representational risk’. Strategies for managing representational risk include implementing both tailored and general strategies to better communicate models’ adequacies and inadequacies for different purposes and increasing awareness of the ethical significance of potential climate model misuses. In a review of literature from climate science and philosophy of modelling, this article establishes the adequacy of ESMs/GCMs for a range of applied purposes and underlines the connection between model inadequacy and emerging issues in the ethics of climate modelling.

# 1. Introduction

As concern about climate change intensifies, there is increasing demand for ‘actionable’ information about the future climate to help mitigate and adapt to adverse effects and inform sustainable policy. As this demand has increased, so has the complexity and resolution of Earth System Models (ESMs) and Global Climate Models (GCMs), which play a central role in generating this information. Indeed, these trends would appear to be related: as the demand for actionable climate information increases, development of ESMs/GCMs increases, and as ESMs/GCMs become more sophisticated and fine-grained, they generate demand for them to be used for applied purposes. However, this has given rise to an important current problem: the increased complexity and resolution of ESMs/GCMs does not guarantee that they will offer increased adequacy-for-purpose in applied domains. In fact, numerous recent case studies have highlighted specific research questions that ESMs/GCMs cannot reliably answer due to features that these models possess as a result of their development history (Briley et al., 2021; Lehner et al., 2019; Nissan et al., 2019). What is more worrying, ESMs/GCMs sometimes *appear* as though they will be capable of answering the very same questions for which they have been shown to be inadequate— and there continues to be explicit demand from policy-makers for researchers to use these models to answer these questions[[1]](#footnote-1). In a recent paper in the context of development economics, Nissan et al. (2019) drew attention to the problem, emphasizing that “Climate models are unable to represent future conditions at the degree of spatial, temporal, and probabilistic precision with which projections are often provided, which gives a false impression of confidence to users of climate change information.” In this context, there is a need to promote a better understanding of ESMs/GCMs adequacy *and inadequacy* for specific purposes, including among model developers (who make their models or their outputs widely accessible) and among researchers, policy-makers, and other users who are liable to apply these models for secondary purposes. What stakeholders must come to better understand is not just that current ESMs/GCMs are inadequate to provide reliable local knowledge, but also that these models routinely give the *illusion* of providing such knowledge. This illusion is a natural byproduct of a feature of models of large-scale complex phenomena. We call this feature “pseudo-detail”, and it plays a significant role in both climate models and models of other complex non-linear systems.

Policy-makers want actionable local climate knowledge and modellers aim to provide it. In light of this, and the limitations of ESMs/GCMs, there is a need to advance the conversation about the ethical significance of promoting and using climate models to answer questions they cannot reliably answer (Nissan et al., 2019). In this paper, we use case studies from the literature to assess the adequacy of ESMs/GCMs for actionable purposes, and discuss various models that contain pseudo-detail, which creates the appearance of actionable knowledge. We draw on the philosophical concept of ‘representational risk’ to explore the ethical significance of using these models (and making them available) for these purposes. Acknowledging that the demand for actionable information from climate models is likely to further increase, and building on the work of (Nissan et al., 2019) and others, we offer a way forward in the face of the technical and ethical challenges we describe.

# 2. ‘Actionable’ Climate Models: A Focus on Representational Adequacy

In our view, to count as ‘actionable’, a scientific product such as a climate model must be both *prima facie* relevant to a decision and adequate to inform that decision (Cash et al., 2002; Jebeile & Roussos, 2023). As an example, a model of future air quality is *prima facie* relevant to the decision whether to invest in health interventions to manage respiratory diseases that are exacerbated by air pollution. To be adequate to inform that decision, such a model must satisfy numerous other criteria: for example, it must be packaged in a way that facilitates its use, it must be perceived by decision-makers to be credible, salient, and legitimate, and it must be adequate to provide reliable information to inform the decision. Generally, this means that the forecasts, projections, or predictions it makes must fall within a margin of error that is not too large to be useful for the decision-maker. Our focus in this section is on the third criterion in particular, which we will call ‘representational adequacy’. Thus, to be ‘actionable’ a model must be, at least*,* *prima facie* relevant to a decision and representationally adequate to inform that decision.

‘Representational adequacy’ is so-called because it depends on *representational decisions*, i.e., decisions about what aspects of the target system to represent and how to represent them (Harvard et al., 2021; Harvard & Winsberg, 2022). Such decisions are made not only by model developers in building a model from scratch, but by model users in choosing to use a particular model, or its outputs, off the shelf, either directly or following some adaptation. As a general rule, representational decisions made by model developers reflect the model’s intended purpose at the development stage, e.g., to project mean global surface temperature changes at the end of the century under different emissions scenarios, to project long-term local changes in surface water availability in the Upper Colorado River Basin (Lehner et al., 2019), etc. Depending on the model’s purpose at the development stage, model developers will make representational decisions such that the model will make salient the information that the modelers desire, and simplify, idealize, obscure, or omit the information that is not causally or informationally relevant to the purpose at hand. Thus, modelers will heavily idealize and simplify features of the target system that they determine to be insignificant to the emergence of the phenomenon that interests them, and more carefully resolve and represent those features that are thought to play a primary role (Winsberg, 2018). In climate modeling, examples of representational decisions at the development stage include selections of scale, causal processes, equations (along with a method of discretizing them), and sub-grid models that recover the effects that are not captured by the discretization. In general, climate models display many idealizations, simplifications, and obscurations, which are the product of representational decisions that reflect a multitude of background assumptions, including about what will best help achieve the model’s intended purpose.

Representational decisions are in large part what determines whether a model will provide reliable information *for a particular purpose* (Harvard et al., 2021; Winsberg & Harvard, 2022; Winsberg & Harvard 2024). It is crucial to emphasize not only that the adequacy of representational decisions (and of models themselves) is purpose-relative, but that purposes are routinely articulated at different levels (Winsberg& Harvard 2024). In this paper, we make a distinction between what we will call ‘primary’ versus ‘secondary’ model purposes: that is, the primary purposes by which model developers judge the adequacy of their representational decisions and the secondary purposes for which other agents use either the model or its outputs. We make this distinction in order to be clear that representational decisions (and thus models themselves) can be adequate for a primary purpose, but not adequate for one or more secondary purposes. This we will show by use of examples in Section 4.

A philosophical concept that is relevant to our discussion is that of ‘representational risk’, i.e., the risk of making a representational decision that is inadequate for purpose and this leading to downstream harm, whether it be a false inference, the obfuscation of crucial information, damage to public trust, etc. (Harvard & Winsberg, 2022). It is important to note that representational decisions made by model developers are always hazardous: first, because model developers can never be sure their representational decisions will be adequate for their own purposes, and second, because representational decisions in any form will inevitably mean the model will be adequate for some purposes but inadequate for others. Unless model developers intend to restrict access to the model, they will be releasing a tool into the world that could be used in a harmful way. As a result, model developers have a duty to be as explicit as possible about what purposes a model is and is not adequate for (Winsberg & Harvard, 2022). As for representational decisions made by model users, (i.e., decisions to use a particular model or its outputs, with or without adaptation) these are particularly hazardous when they correspond to a purpose for which the model was not originally intended. It follows that model users share the same responsibility to prevent downstream harms that they can reasonably foresee resulting from the inappropriate use of models, as do any individuals or entities (e.g., research funding agencies, private corporations, etc.) that aim to advance the use of models from a higher level position. We return to the significance of this in Section 7.

# 3. Determining the Representational Adequacy of Climate Models

The adequacy of a climate model is hinged to its purpose: it is impossible to assess the former without knowing the latter (Winsberg, 2018; Winsberg & Harvard 2024). Consider first GCMs and ESMs, whose primary purpose historically has been to estimate global features of the climate. This includes such global-scale tasks as estimating equilibrium climate sensitivity (ECS), transient climate sensitivity, or attributing observed temperature changes to anthropogenic activities. GCMs/ESMs contain numerous parameterizations of sub-scale processes, parameter values, and sub-models, which reflect representational decisions made by model developers, who, for a variety of reasons, took those idealizations to be adequate for the purposes they had in mind. To determine the adequacy of an ESM or GCM for their stated purposes, modelers will begin by evaluating the model’s consistency with global climate trends over the last century (a well-known practice referred to as ‘benchmarking’). An ESM or GCM’s ability to retrodict the past is a good indicator of its ability to predict the future, but it is not sufficient in itself— nor does it indicate that the model is adequate for projecting climate conditions under counterfactual scenarios. This means that benchmarking is not the only test that model developers aim for ESMs and GCMs to pass. Rather, model developers also aim to look at the *internal qualities* of these models, such as their fidelity to well-established theory and the mathematical arguments for the trustworthiness of the steps taken to articulate the basic model into its computational form. Modelers also perform sensitivity analyses, running the models under various inputs to determine the degree to which results vary when representational decisions (particularly those regarding parameters that are subject to substantial uncertainty) are changed. Finally, modelers use ensemble studies to determine the degree to which various climate models are consistent with each other. If all existing climate models agree that *x* will happen under counterfactual condition *y*, that is no guarantee that this is true, but it generally raises our degree of belief in this claim. Furthermore, if various models disagree substantially, and there is no consensus why, this is a good reason to be cautious about the results of any of these models (see Knutti, 2018a; Winsberg, 2018, chapter 12 for more details). In summary, the intended purpose of a model shapes the representational decisions that model developers make and, in turn, the way a model’s adequacy-for-purpose is evaluated (Parker, 2009; Winsberg & Harvard 2024). The latter includes how a model is benchmarked, how the internal characteristics of the model are evaluated (Winsberg & Harvard 2024), and the ways in which the variation in outputs of model ensembles will be weighed (Massoud et al., 2023). For example, a modeler who cares about an ESM’s ability to estimate ECS might in principle have no reason to benchmark the model’s skill against observations of the seasonal onset of lake freeze for the Laurentian Great Lakes, whereas researchers interested in understanding changes to regional precipitation regimes and water security in Michigan or Wisconsin would consider the model’s consistency with these observations to be critical. Similarly, the fact that ensembles of models (in the Climate Model Intercomparison Project (CMIP), for example) differ greatly with respect to the precipitation they forecast around the Laurentian Great lakes might, in principle, not be problematic if the purpose of the models is to estimate ECS. However, discordances of this kind would be deeply concerning if model users intended to make regional projections of precipitation in this area. Building on this general account of how the assessment of the representational adequacy of climate models is linked to the models’ purposes, we turn now to discussing cases of representational inadequacy in climate modeling.

# 4. Representational Inadequacy in Climate Modeling

## 4.1 General Sources

More and more, ESMs, GCMs and their products (i.e., CMIP experimental data and associated MIP outputs, translated to impacts timeseries, change distribution maps, regional projects, etc.) are being applied to answer questions that differ from the model developers’ primary purposes— that is, thosethat informed the initial assessments of the model’s adequacy-for-purpose. Such applications include forecasts concerning local climate adaptation and resilience questions (e.g., those requiring projections of high end estimates of regional sea level rise or changes to fire regimes in boreal forests (*NASA Sea Level Change Portal*, n.d.; *NOAA Climate, Ecosystems, and Fisheries Initiative | NOAA Fisheries*, n.d.; Public Health Agency of Canada, 2022). Among climate scientists, there is a general understanding that the raw output of ESMs/GCMs are not fit for such applied purposes (see, for example, Briley et al., 2021; Lehner et al., 2019; Nissan et al., 2019). One general source of representational inadequacy in ESMs/GCMs is that these models fail to represent many elements of their target systems, either at a sufficient level of detail for a given purpose, or at all. For example, estimating regional sea level rise requires representation of dynamical processes for ice sheets, both Greenland and Antarctic (Aschwanden et al., 2021; Smith et al., 2021; Vizcaino, 2014), as well as representation of relevant coastal physical features and processes (Ward et al., 2020), while estimating changes to fire regimes in boreal forests requires representation of ecosystem dynamics (Harris et al., 2016), soil structure and moisture (Fatichi et al., 2020), and projecting changes to marine ecosystems requires details of food supplies (Kearney et al., 2021). These features are largely omitted from the current generation of ESMs and GCMs. A more subtle problem is that small scale features of target systems (which are important for understanding emergent regional regimes) are often represented in ESMs and GCMs in the way we call *pseudo-detailed.* Representations contain pseudo-detail when some of the target system’s smallest-scale features are particularly distorted. Pseudo-detail allows the overall model to produce reliable output for certain purposes, but is not *itself* a reliable representation of those features at the smallest scale.

The role that pseudo-detail plays in helping to make simulation models (of which ESMs and GCMs are an example) has been discussed by Winsberg (2010) and Winsberg and Mirza (2017), who consider the example of so-called “artificial viscosity”. This method was pioneered by John von Neumann during his time in the Manhattan Project when his team used simulations to study the dynamics of shockwaves. They discovered that shock waves—highly compressed regions of fluid undergoing rapid yet still continuous pressure change—could not be modeled as genuine discontinuities. Their simulations were simply not fine-grained enough to allow the shock front to be resolved; to make the study of shock waves computationally tractable, they needed a more coarse-grained model. However, a more coarse-grained model created oscillations around the shockwave that that lead to unreliable predictions. To dampen the shock waves, von Neumann's team inserted a viscosity-like variable into the model. This variable, called "artificial viscosity," had a value far too high *to correspond to any real world feature*, yet it became indispensable for making a wide range of fluid dynamic computations. The reliability of many fluid dynamic models is parasitic on the use of artificial viscosity. Artificial viscosity is thus a pseudo-detail.

An example of pseudo-detail from climate science is the use of sub-grid cloud-physics parameter values to “tune” climate models viz their top-of-the-atmosphere (TOA) energy balance. A well-known structural problem with climate models is that they often get the TOA energy balance wrong; this is evident because this number is readily observable. Climate models are therefore “tuned”, primarily using adjustment of cloud physics parameter values, in order to correct the TOA value.

There are plenty of examples of pseudo-detail in climate models. Consider the case of the MG2 submodel of cloud microphysics in CSM1 (Morrison & Gettelman, 2008). The MG2 scheme sometimes produces more precipitation than water is available in the model, and it sometimes produces “unrealistic mean cloud and precipitation particle sizes”(Morrison & Gettelman, 2008, p. 3651). To rectify these problems, the modelers introduced pseudo-detail, including what they call a “particle breakup parameterization”.  However, the particle breakup is not a real physical process: it is a piece of pseudo-detail to reduce unrealistically large average particle size.

A similar issue arises when assigning the distribution of surface grid cells in an ESM as land, ocean, ice, etc. (this is called “masking”), as coastlines and inland water bodies are especially complex (Jones, 1999). The Baltic and Caspian Seas, islands, and coastal areas with considerable amounts of sea ice are problematic cases (Gröger et al., 2021; Koriche et al., 2021; Taylor & Doutriaux, 2000). In some models, the ambiguous treatment of land-water gridding in masks can be treated with regridding (Taylor & Doutriaux, 2000), but many iterations are required for the remapping as islands, lake and inland seas are still sometimes omitted. For coastlines an even simpler fix is to assign a fraction of the grid box as land and the remainder as ocean, but many of these schemes will default fractions over 50 percent to full making for the grid box, i.e., 50 percent and over of land, the entire grid box is assumed to be land (ECMWF). In some cases, values less than 50 percent will default to full ocean grid cell coverage. Some models have improvised and treat boundaries between ocean masks and land masks as wetlands (Lawrence forthcoming). In fact, *there are no wetlands in these areas.* This is simply a pseudo-detail to help solve a coupling problem[[2]](#footnote-2). The coupling problem can involve the atmosphere in some cases, where if there is considerable mismatch in the land-ocean masking, one gets inaccurate vertical fluxes, for example with evapotranspiration. The various pseudo-details are adequate for certain purposes, and inadequate for others.

In their recent article on the modeling of the Great Lakes, Briley et al. (2021) come close to describing the concept of pseudo-detail by distinguishing between entities that are “represented” and those that are “resolved”. Following this distinction, to say that the Great Lakes are represented in a model is merely to say that if one inspects the model, one will find things that look like the Great Lakes. In contrast, to say that the Great Lakes are resolved is to say that the model gives a reliable picture of how the Great Lakes actually affect the local environment— a much more complicated task. As Briley et al. (2021) describe, including a three-dimensional representation of the Great Lakes in a model is crucial for using the model to project regional changes to precipitation regimes, as capturing the interactions between the lake surface, land surface, and atmosphere are key. However, for estimating global ECS, capturing the details of the lake-land-atmosphere interactions is not critical: having a one-dimensional lake surface in the land model (or even ocean grid cells where large lakes exist) could be considered adequate for simulating the emergent features of the regional system that matter for estimating ECS. In short, one can have an ESM in which small-scale features must be *represented* to make the model adequate for large scale purposes, but where it is is unnecessary for them be *resolved* (and, indeed, they are not). In many models, pseudo-detail is good enough (and is in many ways *needed*) to reproduce global effects, but the fact that small scale features are represented in only pseudo-detail means the model will be inadequate for making useful local projections.

Another general source of representational inadequacy is the differential behavior of ESMs and GCMs at different scales. While ESMs and GCMs generally produce epistemically robust information at larger spatial scales and longer temporal scales, they have questionable behavior at smaller spatial scales and provide less-reliable predictions at shorter, annual to sub-annual temporal scales. This reflects the fact that scientist have historically been limited in their knowledge of fine-scale climate processes, which (especially when combined with limited computational resources) has resulted in low-resolution models with non-realistic representation of the relevant sub-grid processes in the form of parameterizations. Consequently, ESM and GCM performance is scale dependent, i.e., they might operate reliably at one scale but quite poorly at another. In particular, these models face significant challenges in performing well at certain scales of human experience and interest—especially the local scales where climate impacts are experienced by decision-making communities, and where adaptation and resilience decisions are made.

## 4.2 Case Studies

### 4.2.1 Briley et al. (2021): Laurentian Great Lakes

Briley et al. (2021) looked at the adequacy of ESMs and GCMs for providing credible information about future climate changes in the Laurentian Great Lakes region. They found that a number of the CMIP models, and therefore their output, are unable to simulate the effects of the Great Lakes on the regional climate because they represent the lakes in highly oversimplified ways. To capture, for example, the precipitation trends in the region there is a need to represent the processes governing the interactions of the lake surface, the land cover and land surface, and the atmosphere. A three-dimensional lake model—one that can resolve the hydrodynamics of large lakes—is crucial for simulating the interactions between the lake surface and atmosphere. If it is done well, it can greatly improve the model’s ability to accurately represent lake surface temperatures and ice coverage, which are key determinants of precipitation trends for the region. However, Briley et al. (2021) found that only a third of the models in CMIP5 represented the processes that are necessary for reliable simulations of lake temperature and ice coverage, and therefore two thirds of the models are missing key processes for projections of the future regional climate. In the case Briley et al. (2021) describe, representational inadequacy stems from pseudo-detail. That is, the representation of lakes in the Laurentian region in most ESMs and GCMs help make the models adequate for estimating ECS, and other such global tasks. At the same time, the way the lakes are represented means these models are not adequate for model users who care to know what the local effects of climate change will be on the Great Lakes themselves.

### 4.2.2 Lehner et al. 2019: Upper Colorado River Basin

In another case study, Lehner et al. (2019) demonstrate that ESMs do a poor job of capturing surface-water runoff sensitivities that are regionally specific. This causes problems for data fields that are causally related to these features of the system. What is important to know is that changes in surface water availability are extraordinarily difficult to simulate at decision-relevant scales, and runoff sensitivity has been notoriously hard to capture in ESMs. These models have regionally specific biases (e.g., systematic over- or underestimations of relevant variables) related to atmospheric circulation, microphysics, lack of representation of orographic processes, and local hydrological processes which impact runoff estimates. Despite this, there is direct use of ESM hydrological fields when studying regional or local water security by regional water managers responsible for adapting or developing resilience for their basins, such as in the United States Rocky Mountain and Pacific Northwest areas.

One particularly interesting case of this is what Lehner et al. (2019) refer to as model 9—IPSL-CM5A-MR, which for the Upper Colorado river basin appears to provide good data for runoff change (based on its agreement with the rest of the CMIP model distribution). In fact, however, this is the result of a balancing of gross errors in runoff sensitivities to precipitation and temperature during the calculation of average runoff. The runoff sensitivities are not realistically reproduced (and in the case of temperature sensitivity, physically unrealistic in their representation of the relationship between temperature and runoff) because of the rudimentary assumptions made (e.g., about how to treat vegetation processes, plant responses to forcings, canopy light use, interception loss and root water uptake) and land surface models lack the sophistication in their representation of land and vegetation processes to capture processes that impact runoff. The sensitivities are also influenced by local temperature and precipitation changes that cannot be reliably produced even in high resolution models. The decisions to simplify and obscure the representations of these processes, and to embed various assumptions about homogeneity, are adequate for capturing the impact of these small-scale processes on larger climatic features that were of interest to the model developers, but are not adequate for the purposes of answering questions about regional runoff.

# 5. fIXING REPRESENTATIONAL INADEQUACY WITH DOWNSCALING?

It is tempting to think that some sources of representational inadequacy in climate models might be successfully eliminated with a strategy called ‘downscaling’ (see Barsugli et al., 2013; Dixon et al., 2016). Downscaling is the process of using a global scale model to forecast the coarse-grained features of the climate in some region, and then to use either statistical or dynamical models to recover the local/regional detail lost in the large grid size of the global model. However, there are reasons to think downscaling will not solve the problem of representational inadequacy (Nissan et al. 2019; Barsguli et al. 2013). Drawing on Barsugli et al.’s (2013) work, Nissan et al. (2019) argue that regional models inherit the problems of the global climate models and the risk of error can be multiplied by regional downscaling, as it will introduce additional assumptions and approximations with each step. As Barsugli et al. (2013) describe, the goal of downscaling is to enhance the accuracy of climate forecasts by capturing detailed features like temperature and precipitation variations near coastal areas and mountainous regions. These structural features significantly affect the behavior of the climate system in ways that often escape the resolution of global scale ESMs. There are two types of downscaling: statistical/empirical methods and dynamical methods. The former are fine-tuned with historical data: the method tries to explicitly represent high-resolution details by modifying the output of ESMs in accordance with historically observed patterns and thereby lessen the inaccuracies found in GCM simulations for past periods. However, statistical downscaling methods assume that historical data-based relationships (the ones used to adjust for GCM inaccuracies) will remain valid in the future. Dynamical downscaling, on the other hand, tries to couple a more fine-scaled Regional Climate Model (RCM) to the GCM or ESM. The RCM will attempt to accurately depict the coastlines, water bodies, mountain-related processes, and interactions between the land and atmosphere that are too coarse-grained in the GCM or ESM to be reliable. However, this is no panacea. Downscaling using RCMs will only be as good as the boundary conditions fed to the RCMs by the larger model. The downscaling will also be only as good as the choice of coupling of the two models at that boundary. Downscaling also ignores two-way interactions between the larger and the smaller model. Finally, even RCMs are frequently not fine-grained enough to resolve all the physical details that are salient to the physical problem being modeled.

# 6. ANTICIPATING REPRESENTATIONAL INADEQUACY

There are significant difficulties with using ESMs/GCMs and CMIP data to produce actionable scientific products, as we have demonstrated above by describing general sources of representational inadequacy in these models and specific case studies. Nonetheless, in the current science-to-policy landscape, there is a palpable expectation to use these products to inform decision-making.

**6.1 Red Tide**

One priority for environmental policy-makers is to manage harmful algae (Ralston & Moore, 2020) (specifically *dinoﬂagellate Karenia brevis*) blooms in the Gulf of Mexico knows as “red tide” (Elshall et al., 2022a, 2022b). In this context, researchers are hopeful that CMIP data could be useful in helping to understand the causal processes that environmental policy-makers would need to understand in order to effectively manage red tide. The reason is simple: red tides are initiated by something called the ‘Loop Current’, a warm ocean current in the Gulf, and the Loop Current is well resolved in CMIP data. This means that anyone with access to CMIP data would have a representation that is adequate for the purpose of predicting when red tides are going to begin. This has led environmental policy-makers to believe that CMIP data is adequate for their higher-level purposes, i.e., managing red tide via environmental policy (Elshall et al., 2022a, 2022b).

However, environmental management is not, first and foremost, about predicting red tides. It is about managing conditions that lead to their severity, which is a task that is far more complex than simpy predicting the Loop Current. To be adequate for the task of managing red tide severity, a model or data product would need to represent various drivers of the algae bloom, which include regional warm ocean currents, local and deep-ocean upwelling, river flow and sediment transport in rivers and ocean currents, nutrient source location and dispersion. Nutrient dispersion includes, among other things, sources from atmospheric deposition and aerosol transport, which itself can require representation of interactive organic aerosols from dust, such as African Sahara dust. Being able to resolve the features that drive red tide severity requires that a model adequately represent all of these physical system features and processes in addition to adequately representing the Loop Current.

There is some evidence that high resolution ESMs (and the CMIP data based on them) are adequate for the task of resolving timing of red tide events and identifying the location of the phenomena at different points in its temporal oscillation in the region (Elshall et al., 2022a). If adequacy-for-purpose were defined in terms of these tasks alone, then we might say that many ESMs behave adequately. However, ESMs’ ability to simulate many other features of the relevant phenomena is still in question. Environmental managers, it would at least seem, are interested in understanding the spread, initiation, magnitude and severity of red tide events. If that is the case, then they need to be able to resolve the composition, and not just the temperature, of the water—and water composition is driven by river and current nutrient transportation, as well as sea level rise and coastal inundation. And as Elshall et al. (2022a) describe in detail, ESMs omit features of the earth system that are key to being able to resolve all of these components.

**6.2 The NOAA Climate, Ecosystems, and Fisheries Initiative**

As the National Oceanic and Atmospheric Administration (NOAA) website (*NOAA Climate, Ecosystems, and Fisheries Initiative | NOAA Fisheries*, n.d.) emphasizes, climate change is significantly impacting marine and Great Lakes ecosystems and fisheries, as well as the people, businesses, and economies that depend upon them. The NOAA Climate, Ecosystems, and Fisheries Initiative therefore intends to “build the end-to-end, operational modeling, and decision support system needed to provide the information and capacity resource managers and stakeholders need to reduce impacts and increase resilience in a changing climate.”

This invites the question: are ESMs and their outputs adequate for their purposes? The answer seems to be no[[3]](#footnote-3). Kearney et al. (2021 p.1) highlight the fact that “projections of LMR[[4]](#footnote-4)-relevant metrics such as net primary production can vary widely between ESMs, even under identical climate scenarios.” The reasons for this tension between the goals of those who would use climate information for managing LMRs and the poor adequacy for purpose of the models are familiar ones. On the one hand, starting with CMIP-5, many modelling centres have included an ESM variant that includes ocean biochemistry— and those released under CMIP-6 have expanded to include biogeochemical models and lower-trophic-level processes that inspire confidence that the models will provide accurate LMR-relevant metrics. On the other hand, the reality is that ESMs often fail to represent the taxonomic diversity of phytoplankton and zooplankton, resulting in omission of certain characteristics that are important to higher-order consumers (e.g., energy density, lipid content of various zooplankton sources, the effects of acidification on zooplankton growth, etc.). Furthermore, their spatial and temporal resolution is too coarse to link “life stage-specific, highly localized responses of higher-trophic-level LMRs to their biophysical environment” (Kearney et al. 2021, p.2). Finally, different ESMs use different theoretical frameworks, objectives, and modeling structures—with tremendous uncertainty about which of these frameworks is most reliable, particularly as objectives shift from model-builder to model (or model output)-user.

**6.3 Generating Knowledge to Inform Public Health Action on Climate Change**

In a document titled “Generating Knowledge to Inform Public Health Action on Climate Change in Canada”, the Public Health Agency of Canada details what public health research “opportunities” exist related to climate change (Public Health Agency of Canada, 2022). One natural way to interpret this is as a set of research priorities, which are advantageous to address in applications for funding for public health research in Canada. Among other things, the document encourages researchers to consider “Health impacts and vulnerabilities to neglected climate hazards, such as droughts, coastal erosion, flooding, wildfires, landslides, reduced sea ice, thawing permafrost and other landscape hazards, as well as the impacts of mitigation strategies” (Public Health Agency of Canada, p. 6).

Here, we will focus on the interest in projecting wildfire activity. This interest is widespread (Bowman et al., 2020; Hanan et al., 2022; Kloster & Lasslop, 2017; Liu et al., 2016; Sarangi et al., 2023; Turco et al., 2018), in part given the impact of wildfire smoke on respiratory and cardiovascular diseases (Chen et al., 2021; Liu et al., 2015; Public Health Agency of Canada, 2022; Rice et al., 2021). How adequate are ESMs and CMIP data for the purpose of projecting wildfires in Canada?

Kloster and Lasslop (2017) note that ESMs in CMIP5 performed poorly both at simulating historical fire occurrence and with respect to incomparison regarding the future. Ceteris paribus, higher temperatures will result in conditions that are more favorable to wildfire, as reflected in the fire risk metrics used in forest management which are based on temperature, wind, moisture and fuel availability (Hanan et al., 2022; Kirchmeier-Young et al., 2017; Sanderson & Fisher, 2020).[[5]](#footnote-5) However, Sanderson and Fisher (2020), citing Clarke and Evans (2019), caution that these metrics are calculated using historical datasets and it is uncertain whether these relationships will hold in the future. Uncertainty in simulating and understanding fire smoke arise from uncertainties regarding production, transport, and chemical aging of the smoke. No matter what fuel is being burned, fuel moisture content (FMC) is especially important to forecasting the amount and composition of smoke produced. Higher fuel moisture directs more energy to evaporation rather than combustion. So moist fuels burn less intensely, but also generate more smoke and more volatile organic compounds (Ichoku & Kaufman, 2005; Popovicheva et al., 2015). The problem is that FMC is nearly impossible to extract from ESMs at sufficiently small scales of space and time, and FMC is also extremely sensitive to soil moisture and humidity, which are equally hard to forecast (Fatichi et al., 2020; Lund et al., 2023; Simpson et al., 2024). Ultimately, there is a significant possibility that fires will behave in unseen patterns as climate conditions change and interact with changes in human activities.

# 7. Representational Risk: ethical Significance and Management in Future Climate Modeling

**7.1 Ethical Significance**

For the reasons discussed above, the inclusion of certain features of the system within ESMs/GCMs should not be taken as an indication that the model is adequate for the purposes of answering adaptation, resilience, or vulnerability questions for the local and regional impacts of climate change. It is crucial to recognize that when a model is developed to be adequate for one set of purposes, using that model for any other purpose increases *representational risk* (Harvard & Winsberg, 2022). Representational risk refers to the potential for climate models to be used to inform decision-making in ways that could lead to downstream harms. As a result of this risk, Winsberg and Harvard (2022) have argued that modelers have the “moral-epistemic duties” to clarify the intended purposes of a model and to continually assess its adequacy for those purposes, thereby establishing “the scope of their responsibility” (p.515). Winsberg and Harvard (2022) use the term ‘duties’ in the general ethical sense: they are explicit that they use the term “moral epistemic duties” in order to underline that modelling tasks “have moral significance” (p. 515) and draw on the work of Douglas (2009) to make the point that scientists have the same moral responsibility we all do to avoid foreseeable harms.

Although Winsberg and Harvard (2022) provide only a limited account of scientists’ moral epistemic duties, we can expand their account here with further connection to Douglas (2014). Douglas (2014) argues that scientists have three bases of responsibility, including responsibility to good reasoning practices, responsibility to the epistemic community of science, and responsibility to broader society. For Douglas (2014), responsibility to good reasoning practices “rests on the aim of science, to produce reliable empirical knowledge”, while responsibility to the epistemic community refers to the responsibility to create “robust intellectual community”, e.g., to foster discussions that ensure the robustness of science and to make other scientists aware of their blind spots (p.964)*.* On these two bases in particular, Douglas’ (2014) account is consistent with Winsberg and Harvard’s (2022) suggestion that modellers have a responsibility to clarify what purposes a model can reliably serve before they release it and its outputs into the wild, where it will potentially be used by other researchers or policy-makers; indeed, Douglas’ (2014) account suggests anyone who makes use of existing models and their outputs will share the same responsibility. Douglas (2014) further argues that scientists’ responsibilities can be understood both in terms of general responsibilities (i.e., responsibilities we all share) and role responsibilities (i.e., responsibilities “we take on when we adopt a particular role” (p.968)), though Douglas emphasizes that one’s role responsibilities do not diminish one’s general responsibilities (p. 969). Thus, following Douglas (2014), scientists’ duties or responsibilities include both what is required of them as moral agents generally and what is required of them as scientists (see also Douglas, 2003). While Winsberg and Harvard (2022) emphasize that the duty to clarify model adequacy-for-purpose falls under the general responsibility to avoid foreseeable harms, there are reasons to think this duty should be counted equally among scientists’ role responsibilities. In particular, it is widely agreed that a well-functioning society needs to have some degree of *trust* in science (e.g., Brown, 2020; John, 2018; Schroeder, 2017) and being *trustworthy* is arguably constitutive of scientists’ social role, i.e., their special authority in public policy, education, technology, and culture (Brown 2020, p.71). There are numerous philosophical accounts of trustworthiness, but trustworthiness is widely taken to consist in reliability plus some other factor (McLeod, 2023), (e.g., commitment (Hawley, 2014)). Following such accounts, maintaining trustworthiness arguably requires scientists to avoid epistemic practices that are known to be unreliable. Both releasing a model into the wild, or making available a model’s output, without investigating when and where the model is adequate for purpose, or without informing the community of those possible deficiencies, are examples of engaging in unreliable practices.

In a different sort of account, Hills (2023) argues that trustworthiness is better characterized as *responsibility,* given that many tasks that we trust other agents to perform are too complex and unpredictable to be able to articulate in precise terms and therefore require trustees to exercise their judgment and negotiate different values. Arguably, modelling tasks have the very features that Hills (2023) highlights: modellers routinely encounter challenges they could not have predicted in precise terms and are generally required to exercise their judgment and make value-laden trade-offs, e.g., in identifying the representational decisions that will best serve the model’s purpose (Harvard et al., 2020; Winsberg, 2012). Following Hills’ account, trustworthy scientists would have the disposition to take responsibility for what is appropriately entrusted to them (i.e., an epistemic project) and have the “right kind of values, motivations and judgements” (p. 758). Importantly, Hills (2023) argues that trustworthiness-as-responsibility meets the conditions of moral virtues, consistent with Winsberg and Harvard’s (2022) assertion that ensuring model adequacy for purpose is a moral-epistemic duty, i.e., a responsibility with moral significance. Drawing on Hills’ account, we can use the example of being a trustworthy catsitter. A trustworthy catsitter is one that can exercise good judgment under an open-ended set of circumstances that could arise while caring for a cat. Now imagine someone who advertises themselves as a trustworthy cat-sitter who also tends to faint at the sight of blood. Such a person would be neglecting their moral duties if they neglected to disclose this tendency to their potential clients, since fainting at the sight of blood is something that could foreseeably affect one’s ability to care for a cat. Similarly, imagine someone who presents themselves as a trustworthy scientist and who makes available models or model outputs that *appear* to be useful for forecasting wildfire smoke in the Pacific Northwest, but are not actually adequate for this purpose. Such a scientist would be violating their moral-epistemic duties if they were to neglect to issue a warning like “this model and its outputs are not adequate for forecasting wildfire smoke in the Pacific Northwest”.

**7.2 Management in Future Climate Modeling**

As the demand for actionable climate information is increasing, it is becoming especially important to recognize the significance of representational risk, the duties it presents, and strategies to manage it in climate modeling. One strategy to manage representational risk would be tailored assessment of the representational adequacy of key features of the system that are related to user purposes. Especially important would be tailored assessments of features that are adequate or inadequate for user purposes. For example, work conducted by Bukovsky et al. (2017) assessed the representational adequacy of RCMs by engaging in process level studies of the causal determinants of monsoon in the North American Great Plains. In addition to determining that the models adequately represented key processes, they also assessed the behavior of the emergent dynamics that results from process-level interactions, determining that the model can capture dynamical changes to the system through time. Kawamleh (2022) has called this “dynamical adequacy” of models, and argued that a model’s ability to meet this criteria in terms of its representational features means the model is sufficient for use in decision-making.

Tailored assessments, however, might be untenable when scaled to meet the demands of users of climate model output. A different, more passive, and thus less demanding, response to the problem might be to provide general, explicit guidance on the adequacies of models, and more importantly, their significant limitations. General guidance could be provided by those institutions like CMIP and the communities responsible for postprocessing of CMIP data. An example that might serve as a template is the “model guidance sheets” produced in the form of a consumer report, which allows users to make informed decisions about which models might be “best” in relation to their use purposes (Briley et al., 2020). Another possible parallel strategy might be an interactive website similar to the National Center for Atmospheric Research (NCAR) data guide (*Data Discovery Guided by Experts | Climate Data Guide*, n.d.). This, of course, would also require an increase in transparency around model development decisions—especially when there is pseudo-detail or representational simplications that are known to produce inadequacies in regional outputs. Ultimately, it is critical to maintain transparency about model development and to communicate the models’ known inadequacies, as well as the features of the models that might lead to unreliable or deficient information about impacts. This is especially important when they play a central role in societal decision making in vulnerable regions (Nissan 2019).

Both the tailored and general strategies for clearly communicating model adequacy and inadequacy for purpose are reasonable and worthwhile approaches to reducing representational risk in climate modelling. However, one might worry that effective communication alone would not prevent any cases of *knowing* misuse of climate models (i.e., to answer questions we know the models cannot answer). Indeed, for this reason, there is a separate need to recognize the ethical significance of knowingly using climate models for purposes for they are known to be adequate, as well as to avoid *incentivizing* this type of model misuse through research funding (or other types of structural) initiatives that would reward modellers for generating unreliable results. As we noted, the responsibility to prevent foreseeable downstream harms from climate model misuse lies not just with modellers and model users, but all individuals and higher-level organizations that aim to advance the use of climate models. Accordingly, all research communities and stakeholders who are invested in climate science, and potentially ‘actionable’ local climate knowledge, have a role to play in setting and reinforcing ethical norms and attitudes around climate model misuse. A key message for climate research communities and stakeholders is that misusing models can have harmful social effects, including distorting policy deliberations and decisions (Nissan et al. 2019). It follows that using models appropriately is a moral-epistemic duty (Winsberg & Harvard 2021), which raises the need for rigorous model assessment, effective communication, and future conversations on the ethics of climate modelling.

# 8. CONCLUSION

Caution is warranted when using ESMs, GCMs and their products to answer questions about local and regional impacts of climate change. Given their increased resolution and complexity, these models can *appear* to represent elements of climate systems that are determinants of local and regional effects. However, this representation is often only at the level of ‘pseudo-detail’: the representation of lower-level processes and physical features of the system at local and regional scales is only for the sake of capturing the emergent, large-scale (global) features of the system and the representation is inadequate for predicting smaller-scale processes. In Briley et al.’s (2021) terms, the small scale feature are ‘represented,’ but not ‘resolved’. The current inadequacy of ESMs/GCMs for applied purposes raises the need to advance the conversation, initiated by Nissan et al. (2019), about the ethical significance of climate model misuse and strategies to prevent it.

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**Notes**

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**Further Reading**

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1. See (Nissan et al., 2019) and references therein, especially (Environment, 2011, 2011; *Fact Sheet*, 2015; Frankel-Reed et al., 2017; Tom Mitchell & Maxwell, 2010) [↑](#footnote-ref-1)
2. This is remarkably like the example of “silogen” atoms, a fictional atom with some of the properties of hydrogen and some of silicon, that is similarly created to solve a coupling problem in simulations of nanostructures (Winsberg, 2010, p. 87). [↑](#footnote-ref-2)
3. At least not generally so. There may be significant species, especially in the tropics and sub-tropics, that can be adequately represented by ecosystem models coupled to the ESM, FEISTY being a nice example (Petrik et al., 2019). [↑](#footnote-ref-3)
4. “Living Marine Resources”. [↑](#footnote-ref-4)
5. What follows in our discussion of wildfire is informed by unpublished material by Jason Knievel [↑](#footnote-ref-5)