Overview

Earth system models: an overview

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Earth System models (ESMs) are global climate models with the added capability to explicitly represent biogeochemical processes that interact with the physical climate and so alter its response to forcing such as that associated with human-caused emissions of greenhouse gases. Representing the global carbon cycle allows for feedbacks between the physical climate and the biological and chemical processes in the ocean and on land that take up some of the emitted carbon dioxide and so act to reduce warming. The sulfur cycle is also important in that both natural and human emissions of sulfur contribute to the production of sulfate aerosols which reflect incoming solar radiation (a direct cooling effect) and alter cloud properties (an indirect cooling effect). Other components such as ozone are also being incorporated into some ESMs. Evaluating the physical component of an ESM is becoming increasingly comprehensive and sophisticated, but the evaluation of the biogeochemical components suffer somewhat from a lack of comprehensive global-scale observational data. Nevertheless, such models provide valuable insight into climate variability and change, and the role of human activities and possible mitigation actions on future climate change. Internationally coordinated experiments are increasingly important in providing a multimodel ensemble of climate simulations, thereby taking advantage of some 'cancellation of errors' and allowing better quantification of uncertainty. © 2011 John Wiley & Sons, Ltd.

How to cite this article:
WIREs Clim Change 2011. doi: 10.1002/wcc.148

INTRODUCTION

The term Earth System, as used here, refers to the interacting atmosphere, ocean, land surface, and sea ice which comprise the 'physical climate system', along with the biogeochemical processes that interact with this physical system. The latter include, for example, the carbon cycle and its connections to the terrestrial and oceanic ecosystems. Although, as we will see, many of the processes operate at very small scales, our focus is on those that are sufficiently pervasive as to be globally significant in terms of their role in climate. We will also restrict attention to time scales out to that of the multimillennial glacial/interglacial cycles (the 'ice ages')—that is, longer term changes in the Earth System involving geological processes and plate tectonics, for example, are not considered. Our interest is primarily in the interactions, processes and feedbacks that shape the Earth's climate and determine its response to natural and human forcings. It should be noted that others[1] have used a broader definition of Earth System, encompassing humans and their activities, however in contemporary usage, ESMs generally restrict themselves to the physical and bio-geophysical components, while explicitly modeling the human dimension is primarily in the realm of Integrated Assessment Models.[2] Earth System modeling is, by its very nature, an interdisciplinary enterprise requiring collaboration amongst atmospheric scientists, oceanographers, terrestrial ecologists, ocean chemists and biologists, and others. The development of an ESM therefore involves contributions from many scientists and many areas of science, and the output of such models provides information on how our climate system operates and will change in the future.

CLIMATE SCIENCE AND THE ROLE OF ESMs

The climate we experience—the averages and statistics of the ever-varying temperature and rainfall, wind

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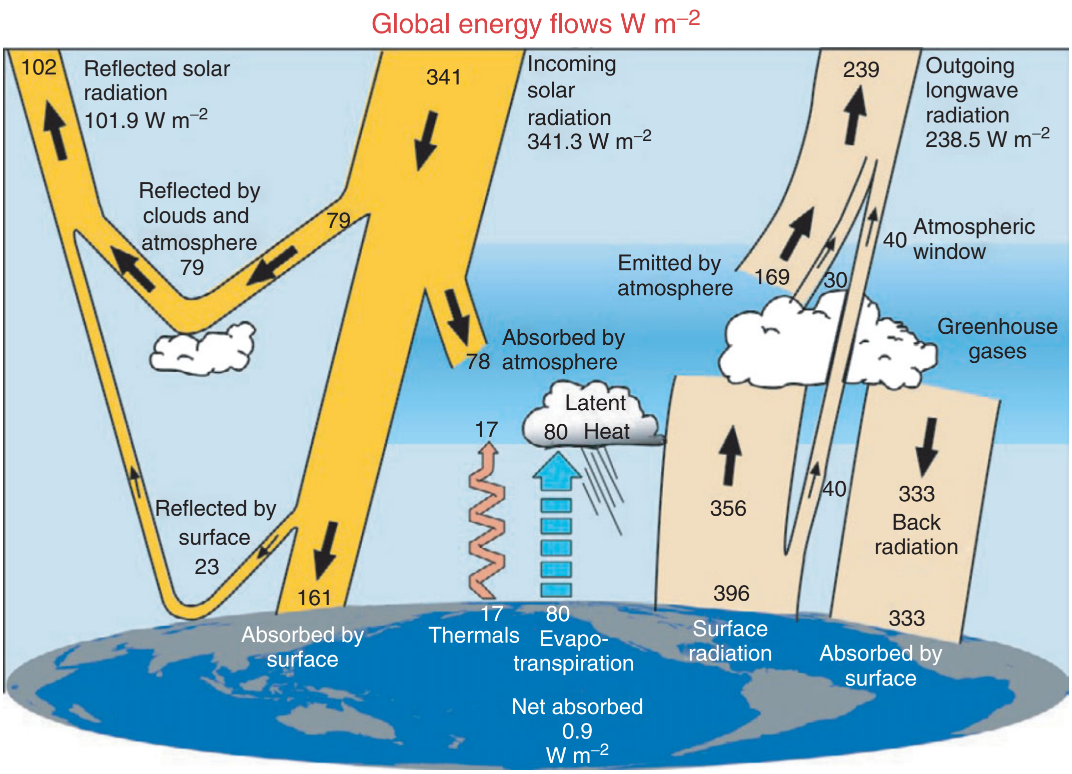

FIGURE 1 | Sketch of energy flows in the climate system, based on observations from March 2000 to May 2004. Units are W m^{-2}. (Reprinted with permission from Ref 6. Copyright 2009 American Meteorological Society)

and ocean currents, and all the other attributes of the Earth System in which we live—is a result of complex chain of interactions starting with the radiative energy provided by the Sun. Some of this energy, primarily in the form of visible light which we refer to as 'shortwave' radiation, is reflected back to space, whereas the remainder is absorbed in the atmosphere or at the land or ocean surface where it is converted to heat, and re-radiated in the form of infra-red or 'longwave' radiation. Some of this longwave radiation is absorbed and re-emitted by water vapor and other 'greenhouse gases[a]', increasing the temperature of the lower atmosphere—the so-called greenhouse effect. This flow of energy is illustrated schematically in Figure 1. Of course solar energy is not supplied uniformly. More is provided near the equator than at the poles (because of the spherical shape of the planet), there is a daily cycle of energy input, because of Earth's rotation, and a seasonal cycle because of Earth's orbit around the sun. This imbalance in solar heating leads to rising and sinking motion in the atmosphere which, when combined with the effects of Earth's rotation, lead to large-scale atmospheric circulation (winds and their associated transport of heat and moisture and trace gases). Evaporation from the land and ocean provides water vapor to the atmosphere, some of which condenses to form clouds which alter the absorption and reflection of solar radiation, and some of the condensed water vapor then falls as rain or snow, adding moisture to the soil and changing the surface reflectivity (albedo). These many, complicated, interacting processes all contribute to the state of the climate and its variability. In this article, we will not describe them in detail—there are many available sources for further information[3–5]—however, it is important to see that these processes connect the various components of the Earth System in such a way that they cannot really be considered in isolation. For example, the circulation set up in the atmosphere by non-uniform solar heating produces the surface winds that drive ocean currents, which in turn transport heat from the tropics to mid-latitude and polar regions, which in turn alters the temperature of the atmosphere, which alters its circulation. This is what is referred to as a 'feedback' in the climate system: a process in the system which affects another part of the system which in turn affects that process, either enhancing it (a positive feedback), or suppressing it (a negative feedback). The climate system is characterized by a complex web of physical feedbacks, and the broader Earth System extends this web to processes involving biology (e.g., terrestrial

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and oceanic ecosystems) and chemistry (e.g., sulfate aerosols, or the uptake and release of carbon dioxide).

It is increasingly clear that we cannot fully understand climate variability and change by studying or modeling only the physical climate system. In particular, the influence of humans on climate is in most cases intrinsically 'biogeochemical' rather than physical. The primary example here is the emission of carbon dioxide, CO_2, by fossil fuel combustion. In this case, CO_2 is added to the atmosphere, supplementing that which is in the atmosphere from natural sources, and then becomes part of the global carbon cycle. Some of this CO_2 is taken up by plants on land and in the ocean during photosynthesis, adding to plant biomass. The plants eventually die and the carbon is released back into the atmosphere or sequestered in the soil or the deep ocean. CO_2 is also dissolved directly in ocean water which, while storing carbon, also acts to acidify the ocean. As a result of processes like this, only about half of the CO_2 emitted from fossil fuel burning remains in the atmosphere, though what does remain contributes to climate warming via the greenhouse effect described very briefly above. In other words, the role of humans in warming the climate is mediated by a suite of biogeochemical processes which themselves are closely coupled to physical processes. As an example of the latter, the ability of plants on land to take up CO_2 depends, among other things, on the temperature and available precipitation (physical climate quantities); as the physical climate changes in response to increasing CO_2, the conditions in certain regions may become too hot or too dry for the plants that are there, slowing their growth and thus reducing the rate at which they take up CO_2. This in turn would leave more CO_2 in the atmosphere, leading to more warming—an example of a positive feedback. Another example is provided by changes in human land use, such as deforestation. This directly releases CO_2 to the atmosphere, but also alters the reflectivity and water-holding capacity of the surface, thereby altering the local physical climate.

In general then, the physical climate and the global biogeochemical cycles are intimately connected through various coupled processes and feedbacks, and human influences on climate are often mediated by biological or chemical processes. Therefore, in order to make quantitative projections of future climate such feedbacks must be considered. Feedbacks in the Earth System are clearly central to climate variability and change, and understanding them is key to separating natural from human effects on climate, and to quantifying the efficacy of emission reduction and mitigation policies aimed at reducing future climate change.

MODELING THE PHYSICAL CLIMATE SYSTEM

As described above, the Earth System is a complex interaction amongst various physical, biological and chemical processes, many of which operate at a microscopic scale, but which have global ramifications. Some of the individual processes are amenable to study in the laboratory, but the complicated whole is not. Nor do we have suitable analogues on which to undertake Earth System experiments—there is no equivalent to the lab mice or fruit flies used in other areas of science. And obviously we cannot undertake scientific experiments on the real Earth System (although mankind is in the process of a rather nonscientific one!). The alternative is to develop sufficiently realistic computer simulations that allow us to unravel some of the complex interactions and to study the behavior of the system (or at least an approximation of it) and its response to external forcings such as the addition of greenhouse gases. Such experimentation can improve our understanding of the Earth System and guide further observational or detailed laboratory studies on particular processes. In addition, such models can be used to make projections of future climate change when provided with scenarios of human emissions of greenhouse gases and land use change.

In many areas of science, a key tool for describing and consolidating our knowledge of a particular system or process is to construct a mathematical model—an equation or set of equations which describes the system and its behavior in mathematical terms. In some cases, such mathematical models are highly idealized approximations of a real system and are amenable to analytical solution (that is, one can write down an exact solution, also in mathematical terms). However, in many cases one must resort to approximate solutions obtained by numerical methods involving repetitive calculations on a computer. Such numerical models are widely used in many branches of science and engineering.

Numerical modeling of the climate system began in the 1960s with influential work by Budyko, Sellers, Manabe, Mintz and others (see, for example, Refs 3 and 4). Much of this work grew out of efforts to develop global numerical weather prediction models. Although the first coupled three-dimensional global atmosphere-ocean model was produced in the late 1960s by Manabe and Bryan,[7–9] most of the early climate models included only the atmosphere, or the atmosphere with a simple 'slab' ocean to represent, at least crudely, atmosphere-ocean feedbacks. (A slab ocean configuration involves a three-dimensional atmospheric model coupled to

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a two-dimensional, motionless ocean—a 'slab' of water—under which heat fluxes are specified to represent the assumed unchanging ocean transport. Such a model can represent some of the feedbacks between the atmosphere and upper ocean heat content.[10]) Although models with a slab ocean could not represent feedbacks involving changing ocean circulation, nor the time-evolving change in climate (which necessarily requires a three-dimensional ocean with its ability to store heat at depth), they were able to make the first quantitative projections of the spatial patterns of the equilibrium climate change associated with doubling of CO_2. Results from such models formed the core of the first IPCC Scientific Assessments.[11,12]

Advances in modeling the coupled physical system, along with access to increasingly powerful supercomputers, allowed more widespread use of fully coupled models and the capability to undertake transient (i.e., time-evolving) climate simulations, typically spanning the years 1850–2100. This progress is documented in the subsequent IPCC Assessments[5,13,14] wherein historical simulations, with observationally based changes in greenhouse gas concentrations,[a] are used to evaluate the models' ability to reproduce observed historical climate change, and then future scenarios of greenhouse gas concentrations (associated with plausible future emission scenarios[15]) are prescribed, allowing projections of future climate change. As modeling capability has advanced, the need to quantitatively evaluate these models has also grown. To address this, Working Group on Coupled Modeling (WGCM) of the World Climate Research Programme (WCRP) has initiated a series of coupled model intercomparison projects. In preparation for the IPCC Fourth Assessment, the third of these intercomparisons, CMIP3, was launched.[16] The resulting multimodel ensemble, in which each modeling group undertook the same suite of experiments using essentially the same specification of historical and future greenhouse gas concentrations, spawned a remarkable analysis and evaluation of these models (see Ref 17 for a synthesis). It also provided a means to estimate some aspects of the uncertainty involved in making future climate projections.[18]

One of the key findings from transient climate change experiments was that the ocean takes up a large portion of the heat associated with greenhouse gas forcing, sequestering this heat in the deep ocean, and thereby slowing the rate of warming relative to what one would get if the heat remained in the surface ocean. In fact the calculated warming at the time of CO_2 doubling (the so-called 'transient climate response') is only about half of the equilibrium warming.[14] This slow oceanic response has another consequence, and that is to 'commit' the climate system to additional warming even after the forcing has stabilized (as the deep ocean must 'catch up' to the new surface boundary conditions), a process that has a time scale of centuries.

Another result of undertaking transient climate simulations was to reveal the powerful cooling effect of sulfate aerosols in the climate system. In addition to natural sources such as volcanic emissions and the release of sulfur-bearing compounds from plants (notably dimethyl sulfide from phytoplankton in the ocean), the burning of fossil fuel produces sulfur dioxide which undergoes various chemical transformations in the atmosphere to produce small aerosol droplets which are eventually washed out by precipitation. While they are airborne, however, they play an important role in climate. Their 'direct' effect is to reflect shortwave radiation, reducing the amount that is absorbed near the surface and so imparting a cooling effect on the climate system. In addition, these sulfate aerosols add to the background cloud condensation nuclei, altering the size and lifetime of cloud droplets. These 'indirect' aerosol effects act to enhance the reflection of shortwave radiation by clouds—a further cooling effect. Although some aspects of these aerosol effects can be represented in physical climate models, by specifying aerosol amount, a comprehensive treatment necessarily involves aspects of atmospheric chemistry and ocean biology, along with the feedbacks to the physical climate.

It is important to note that in physical climate simulations of the sort described in this section, the greenhouse gas *concentrations* are, for the most part, prescribed and so feedbacks between the changing physical climate and the various biogeochemical cycles that determine these concentrations are essentially ignored. Including these feedbacks directly in the climate simulation is the objective of more comprehensive ESMs.

THE EMERGENCE OF EARTH SYSTEM MODELING

As noted above, there are several important feedbacks between the physical climate system and global-scale biogeochemistry that are not represented in a physical climate model with specified concentrations of greenhouse gases and aerosols. Of the 23 models summarized in the climate projections chapter of the most recent IPCC Assessment,[18] none included interactive stratospheric[b] ozone, only about 1/3

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included some aspects of the interactions between sulfate aerosols and clouds, and none included a representation of carbon cycle feedbacks (i.e., all used specified greenhouse gas concentrations). However, in a parallel activity, called the Coupled Climate-Carbon Cycle Model Intercomparison Project (C^4MIP[19]), 11 models that included a representation of the terrestrial and oceanic carbon cycle undertook simulations with a CO_2 *emission* scenario, rather than a concentration scenario. In this way, the models accounted for at least some of the feedbacks between the carbon cycle and the evolving physical climate. C^4MIP built upon the pioneering work of Cox et al.[20] and Friedlingstein et al.[21] Perhaps the most striking result was that future climate change reduces the ability of the terrestrial ecosystem and the ocean to remove CO_2 from the atmosphere. On land, as the climate changes in response to increasing CO_2 and other greenhouse gases, the combination of warming and drying in many regions reduces the productivity of plants (reducing CO_2 uptake) while at the same time increasing the rate at which carbon is released from soils by decomposition. In the ocean, the solubility of CO_2 in sea-water reduces as temperatures increase, and vertical mixing is also inhibited. The result is that, as climate changes, a larger fraction of anthropogenic CO_2 remains in the atmosphere, contributing to further warming: a positive feedback. An illustration of this positive feedback is provided in Figure 2. It compares the CO_2 concentration simulated by models with a coupled carbon cycle to that obtained when the carbon-cycle coupling is disabled. In all cases the CO_2 concentration is larger in the coupled case, indicating that the carbon-climate feedbacks act to reduce the system's ability to take up carbon as the climate changes, thereby leaving a larger fraction in the atmosphere. It is the inclusion of these carbon-cycle feedbacks that most clearly identifies the boundary between a physical climate model and an ESM.

An important aspect of the terrestrial carbon cycle, particularly on longer time scales, is the changing amount and spatial extent of different vegetation types accompanying climate change. This can be represented to some extent in models with specified vegetation distributions, in which case the productivity and hence vegetation biomass can change as the physical climate changes. An example of this is provided in Figure 3, which shows changes in vegetation projected by the end of the 21st century in the Canadian Earth System Model (CanESM1, Ref 27). On century or longer time-scales, competition between plant types may be important in that one plant type may out-compete another in a given location, leading to the replacement of grassland by forest for example. This can be represented by so-called dynamical vegetation models which can be embedded within a climate model.[22–24] These changes in vegetation type introduce feedbacks to the physical climate by altering the surface characteristics (reflectivity, moisture exchange, etc.); they also play a role in altering the global carbon cycle (as some types of vegetation store more carbon than others—trees versus grass, for example). By way of an example, Betts[25] showed that for northern forests, the physical feedbacks can act such that expanding vegetation allows more absorption of solar radiation, warming the climate, and thereby offsetting some of the cooling associated with carbon taken out of the atmosphere by the forest biomass. In other areas, like the Amazon Basin, vegetation may die back as climate changes, thereby releasing stored carbon (from plant and soil biomass) and contributing to the positive carbon-climate feedback described earlier.[26]

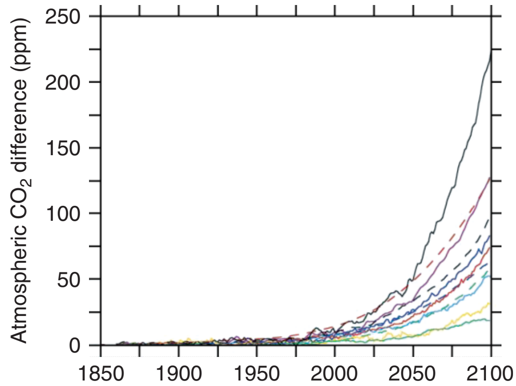

FIGURE 2 | Difference in atmospheric CO_2 concentration time series between 'coupled' and 'uncoupled' experiments with climate models that have a representation of the carbon cycle. Each curve represents the result of a different model having undertaken both the coupled and uncoupled experiments. In all cases the difference is positive, indicating that the carbon cycle feedback is positive (i.e., results in higher concentrations, and hence greater warming, for a given emission scenario). (Reprinted with permission from Ref 19. Copyright 2006 American Meteorological Society)

As noted above, modeling the physical climate system pushes the capabilities of even the largest supercomputers, and so the inclusion of biogeochemical processes has proceeded rather slowly. However, many of the basic consequences of carbon cycle—climate feedbacks were first explored in what are referred to as ESMs of intermediate complexity (EMICs). These models make rather profound simplifications to some aspect of the physical system, often reducing the atmosphere to a single vertical layer or to a two-dimensional (zonally averaged) cross-section. As a result, such models are typically not capable of representing many of the

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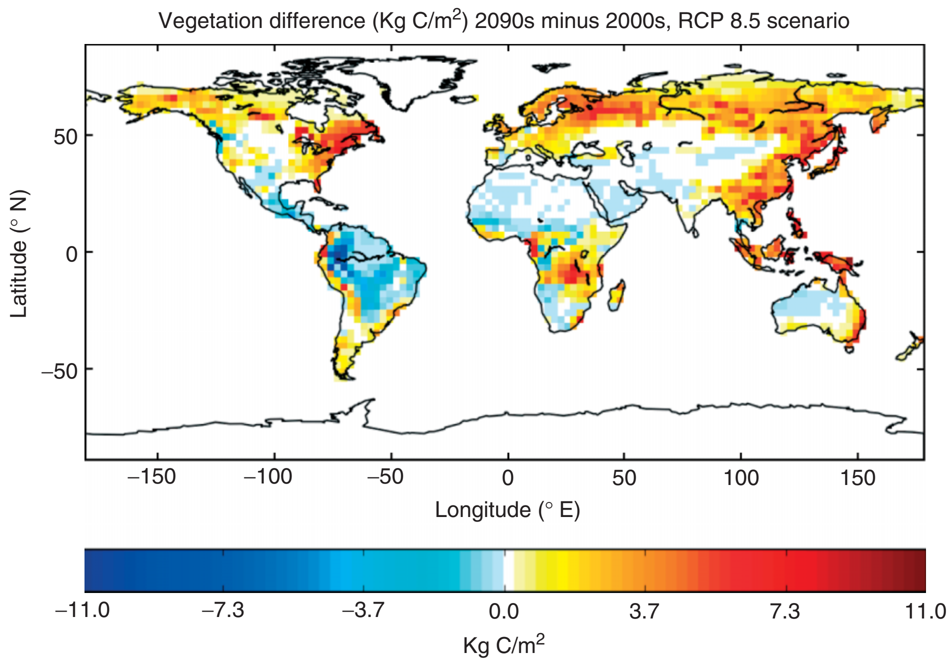

FIGURE 3 | Difference in vegetation, represented as the mass of stored carbon per unit area (kg C m^{-2}) between 2000 and 2090 as simulated by the Canadian Earth System Model (CanESM1[27]) for a particular CO_2 emission scenario. Red colors indicate increases in vegetation whereas blue colors indicate a decrease.

(fast) physical processes inherent in a fully three-dimensional general circulation model, but they retain some of the essential slow processes relevant to long-term climate change.[28,29] The simplifications in atmospheric (and oceanic) dynamics mean that an EMIC is much less computationally intensive, and so additional biogeochemical processes can be introduced and much longer integrations can be performed. This allows one to explore climate processes that occur on a very long time scale, such as the onset and decline of continental-scale ice sheets during ice ages.[30] They can also be used to look at the potential response of the climate system to human-caused greenhouse gas emissions many centuries into the future.[31–33] Such models have also been used to investigate specific processes involved in carbon cycle changes by conducting idealized experiments with wind and other changes prescribed from more comprehensive physical climate models.[34] However, the simplifications required to construct an EMIC inevitably leads to questions about the reliability of such models to simulate certain aspects of climate change, particularly those that are inherently connected to modes of variability or the transport of quantities in the atmosphere.

As an example of the latter, atmospheric aerosols are transported by the wind and are ultimately deposited or washed out of the atmosphere (by precipitation) in a matter of days or weeks. However, while they are airborne, they can have an important effect on radiative transfer and on the microphysical processes involved in cloud formation and precipitation. Sulfate aerosols were described in the previous section, but others include mineral dust, sea salt, and black and organic carbon. All of these have particular regional patterns owing to the location of their sources and the rate at which they are removed from the atmosphere. In order to model aerosol effects accurately, an ESM must represent wind patterns, mixing, cloud processes, and precipitation accurately. In addition, such models must represent the sources of these aerosols and their changes under changing climate. In some cases, these aerosols are specified directly as an emission (from fossil fuel burning or other human activities); in other cases they are computed by the model itself (examples here include natural aerosols such as mineral dust and sea-salt). Representing aerosols in this way allows feedbacks between climate change and aerosol sources and sinks (and hence their role in changing climate) to be included. In some cases, such interactions extend to the inclusion of forest fires in the terrestrial ecosystem component of the model and the resulting emission of both greenhouse gases and carbon aerosols.

Another area of research that builds upon the work in physical climate modeling, and is merging with Earth System modeling, is the simulation of ozone in the atmosphere and its historical and future change.

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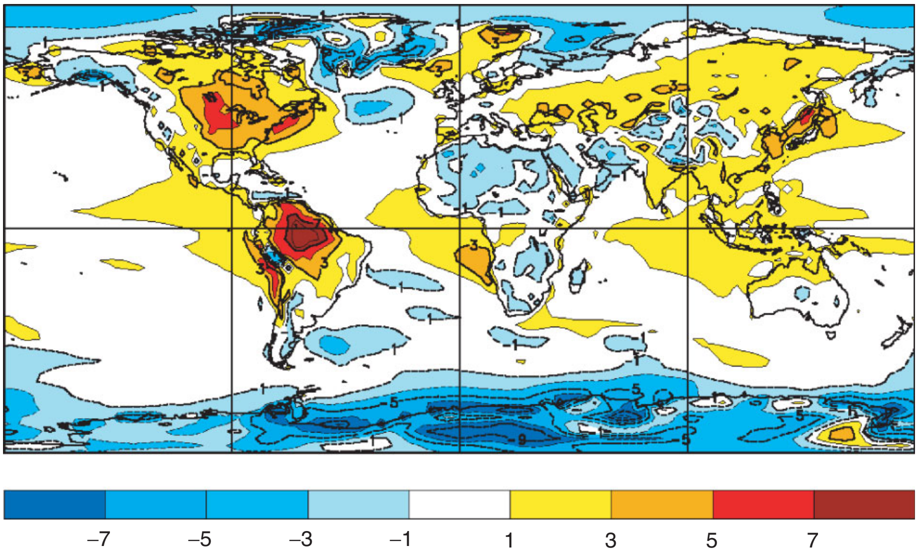

FIGURE 4 | Near surface air temperature error (model minus observations) in °C for the control integration of the Canadian Earth System Model (CanESM2[43]). Red colors indicate areas where the model is warmer than observed, blue colors where the model is colder than observed.

Ozone is produced naturally in the stratosphere[b] by photochemical processes and is destroyed by other chemicals, notably chlorine and bromine from industrial compounds like chloroflourocarbons (CFCs) which are now controlled by the Montreal Protocol. The chemical reactions involved in ozone depletion are very sensitive to temperature and the presence of polar stratospheric clouds (made up of tiny ice crystals). The amount of stratospheric ozone is therefore closely related to stratospheric climate and, as for other greenhouse gases, simply specifying its concentration eliminates the possibility of feedbacks between ozone and climate. Models that include stratospheric ozone chemistry and transport have been developed and used to simulate the deepening and future recovery of the so-called 'ozone hole' in the polar regions (e.g., CCMVal[35] and WMO/UNEP Ozone assessment[36]). Such models are essentially upwardly extended versions of physical climate models with ozone chemistry included. However, until recently[35] such models have not been coupled to three-dimensional ocean models and therefore have not included the full range of physical climate feedbacks on ozone depletion and recovery.

EVALUATING ESMs

Confidence in a model's ability to make future climate projections is certainly enhanced if one can first demonstrate that it does a credible job at reproducing the past. Evaluating physical climate models has a long history and has become increasingly sophisticated—the body of available observational data continues to grow, and the way in which models are confronted with this data is increasingly comprehensive.[17,37–40] The bulk of the evaluation effort so far has been aimed at evaluating physical climate models, and of course an ESM should be built upon a credible and reliable physical model. Model evaluation essentially involves comparing model results to observations of a particular quantity. The most basic of such comparisons involves simple differences between the long-term average (or climatological) value of quantities like near-surface air temperature, precipitation or surface pressure–meteorological variables for which there is a long history of observations. One can of course compute various statistics from such a comparison, such as the global mean or zonal mean bias, one can produce global maps of the difference, such as shown in Figure 4, or one can compute other kinds of error statistics. As an example, Figure 5, shows the root mean square (RMS) error (for precipitation and surface pressure) computed as the difference at each grid point between the model and observations—this difference is squared, and then the square root of the global sum of these squared errors is taken to provide a measure whose value would be zero for perfect agreement. In this figure, errors have been computed for each of 21 models submitted to the CMIP3 intercomparison project described earlier. Some general remarks can be made about such comparisons. First, it is almost universally true that the ensemble mean of a collection of models has smaller errors (i.e., performs better) than any of the individual models.[39,41] This is the case for the quantities illustrated in Figure 5 in which both

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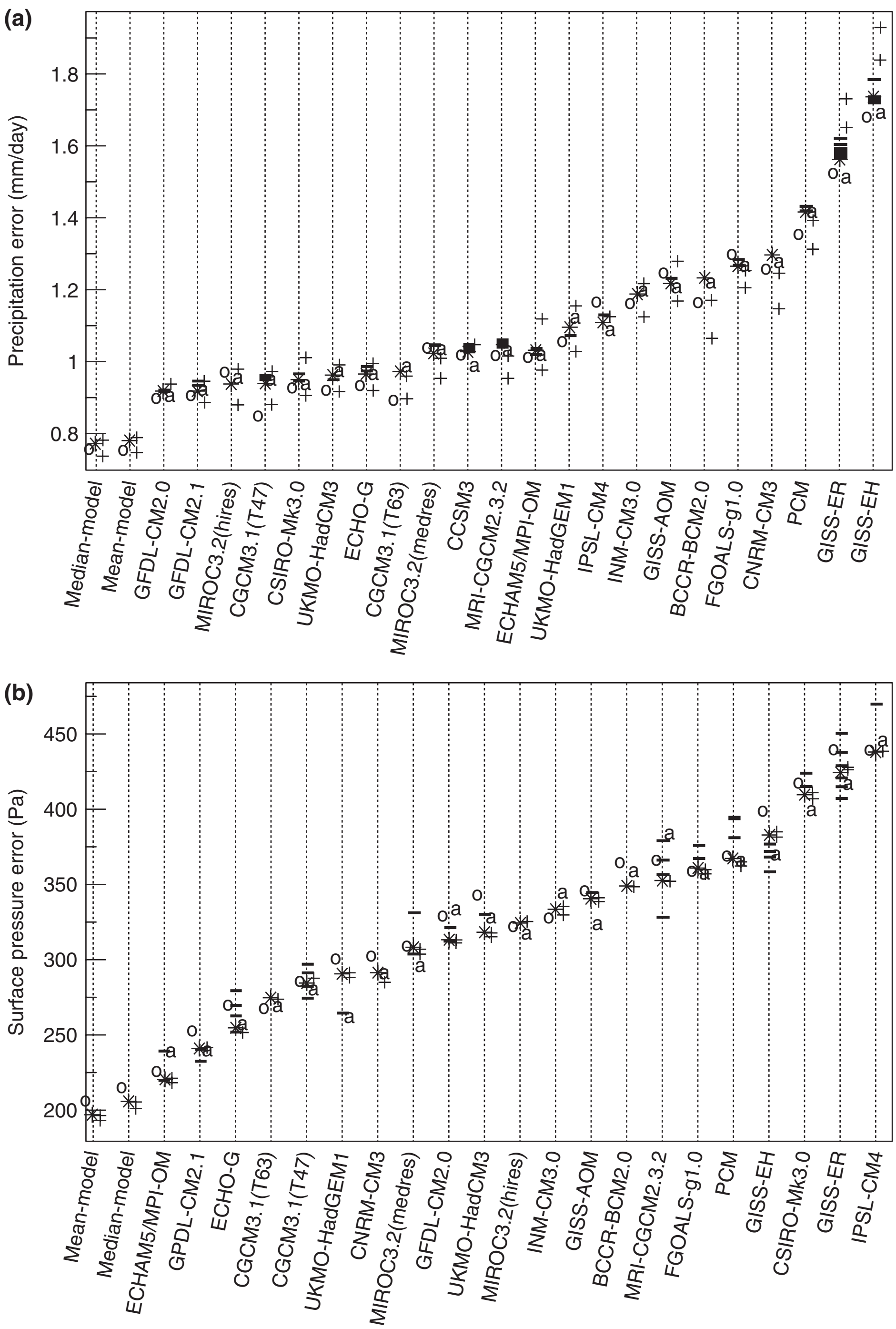

FIGURE 5 | Root mean square (RMS) errors for precipitation (upper panel) and surface pressure (lower panel) computed for 21 different global climate models participating in the CMIP3 intercomparison project. Also shown is the RMS error for the ensemble mean and median. The different symbols illustrate the sensitivity to different analysis choices, with (*) indicating the standard analysis, (o) representing the result when using an alternate reference data set, (a) indicates an alternate averaging period, (+) indicates different target grid resolution and (–) indicates different ensemble members. From Gleckler et al.[38]

the multimodel mean and median outperform any of the individual models. This is to some extent a consequence of the cancellation of errors that occurs when different models are averaged together and it provides ongoing motivation for the need to have multiple, more-or-less independently developed models. A second remark is that there is no 'universally' best individual model; that is, the model that has the smallest

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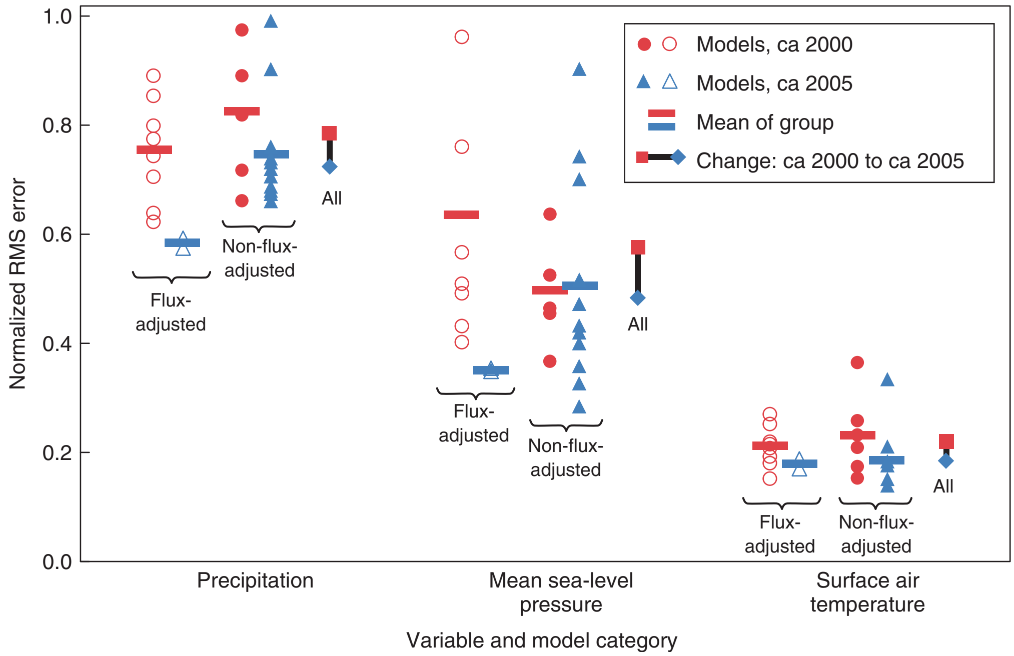

FIGURE 6 | Model errors in precipitation, sea-level pressure and surface air temperature for models participating in the CMIP2 intercomparison (ca 2000) and the CMIP3 intercomparison (ca 2005). Models are segregated into two groups: those that employ 'flux adjustment' and those that do not (see text for details). From Gleckler et al.[38]

error for one climate variable (like precipitation) is not necessarily the model that performs best for other variables (like pressure). A recent paper by Hazeleger et al.[42] nicely illustrates the process of model evaluation and improvement. In this case a new model, based on a numerical weather forecast model, was coupled to an ocean and metrics such as those described above were evaluated and used to guide model refinements.

Although there is clearly a range in model performance, illustrated for example in Figure 5, and clearly room for ongoing model improvement, it must be said that models are indeed getting better in many respects, although perhaps not as rapidly as one would like. Figure 6 shows RMS error in precipitation, surface pressure and surface air temperature for models participating in CMIP2 (ca 2000) and CMIP3 (ca 2005). The models are partitioned into those that employed some form of 'flux adjustment' (a means of accounting for biases in the models' exchange of heat, moisture and momentum between the atmosphere and ocean—an adjustment that is increasingly not required as models improve), and those that do not. What can be seen is that the errors for all three quantities have reduced when going from the earlier to the later model versions, although it must be said that the improvements are not dramatic, and that as the errors reduce, further improvement obviously gets more and more difficult. It must also be said that, despite the evident improvements in model 'comprehensiveness' and the quantitative improvements in model fidelity, the range of model projections of future climate change remains essentially as large now as it was a decade ago.[18] The connection between model resolution and model fidelity, and the tradeoffs between resolution and complexity, are discussed later.

For the physical climate system, there is a large and growing body of observational data that can be used to evaluate a model. In addition to meteorological variables, there is a growing body of oceanographic data that can be used to assess the ocean component of a model—over the past decade a particular revolution has been the availability of three-dimensional ocean temperature and salinity data from the ARGO profiling floats deployed throughout the global ocean.[44] There is also an ever-expanding suite of satellite-based observations available to evaluate the ability of models to simulate clouds and aerosols, and many other important climate variables (e.g., Cloudsat[45] and other satellite systems). There is also a wealth of detailed process data available from field campaigns aimed at providing detailed measurements of specific processes such as radiative transfer, cloud microphysics, ocean mixing, turbulent transfer over land, etc. In order to promote and sustain such observations, organizations like the Global Climate Observing System[46] (GCOS) and the

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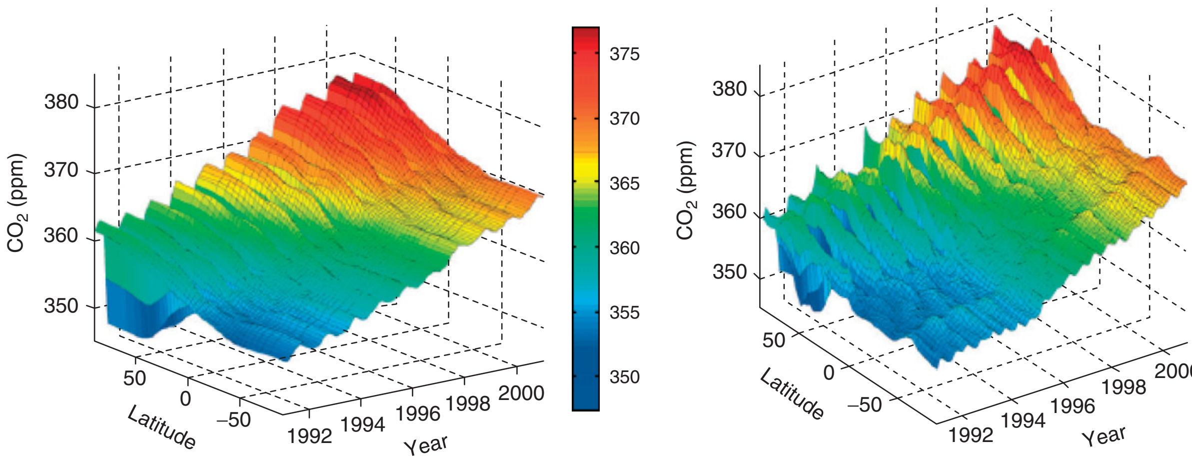

FIGURE 7 | Zonal mean CO_2 concentration from 1991 to 2000 from observations (left) and from the Canadian Earth System Model (CanESM1). (Reprinted with permission from Ref 27. Copyright 2009 American Meteorological Society). The annual cycle, larger in the northern hemisphere and smaller in the southern hemisphere is clearly visible, as is the background human-forced increase in CO_2 concentration.

Global Earth Observing System of Systems[47] (GEOSS) have evolved.

Assessing the ability of models to simulate longer time scale climate processes and variability requires the use of paleoclimate 'proxy' data—inferences about climate that can be drawn from natural records such as tree-ring width, sediment layers, air bubbles in glacial ice, and the like. Coordinated assessment has been undertaken via the Paleoclimate Modeling Intercomparison Project (PMIP[48,49]). Ongoing work involves incorporation of geochemical tracers in models (e.g., isotopes of carbon or nitrogen) to allow alternate means of assessing the ability of models to simulate paleoclimate and contemporary processes.[50]

Despite this growing body of climate observations, evaluating an ESM remains very challenging. In the first place, many quantities related to global biogeochemical cycles are difficult to observe, or have not been systematically observed over a long period of time or over large spatial scales (something that is required in order to evaluate a model's 'climate'). Another difficulty, which is not unique to ESM evaluation, is that many of the important processes occur on small spatial scales or exhibit significant small-scale spatial variability. For example, vegetation and underlying soil conditions vary remarkably even over distances of a few tens of meters, and this makes it difficult to assemble representative regional and global data sets. As a result, for many biogeochemical variables, only rough estimates are available, and one must often resort to comparing one model against another or making use of inferences obtained by rather indirect means. Nevertheless, there are some quantities that are amenable to direct comparison, one obvious example being simulated and observed concentration of atmospheric carbon dioxide (CO_2). Figure 7 shows an example of such a comparison from Arora et al.[27] in which the zonal mean CO_2 concentration estimated from some 40 observing sites is compared to that obtained from the Canadian Earth System Model (CanESM1). This so-called 'flying carpet' plot shows the seasonal cycle of CO_2 along with the secular increase over the period 1991–2000—models are generally able to reproduce many aspects of the carbon cycle, including the north–south gradient in CO_2 concentration, the larger seasonal cycle in the Northern Hemisphere (owing to the predominance of terrestrial vegetation as compared to the Southern Hemisphere). Longer time-scale evolution of CO_2 concentration can also be compared to direct atmospheric measurements, such as those available from Mauna Loa in Hawaii since 1958, and to estimates obtained from ice core analyses extending back for many centuries. One would of course also like to evaluate other aspects of the carbon cycle such as soil carbon, biomass on land an in the ocean, and the uptake and release of carbon by soil and plants. Unfortunately, observationally based estimates of such quantities are either highly uncertain or lacking altogether and so one can often make only qualitative comparisons to observational estimates or resort to comparisons to other models (ideally models that are constrained by observations in some way). In Figure 8 we show a comparison of the latter sort, in this case an evaluation of net primary productivity (NPP—a measure of the carbon taken up by vegetation). The upper two panels of this figure show results from CanESM1, on the left from the freely running model, and on the right from the terrestrial ecosystem model driven by observationally based meteorological conditions. This allows an assessment

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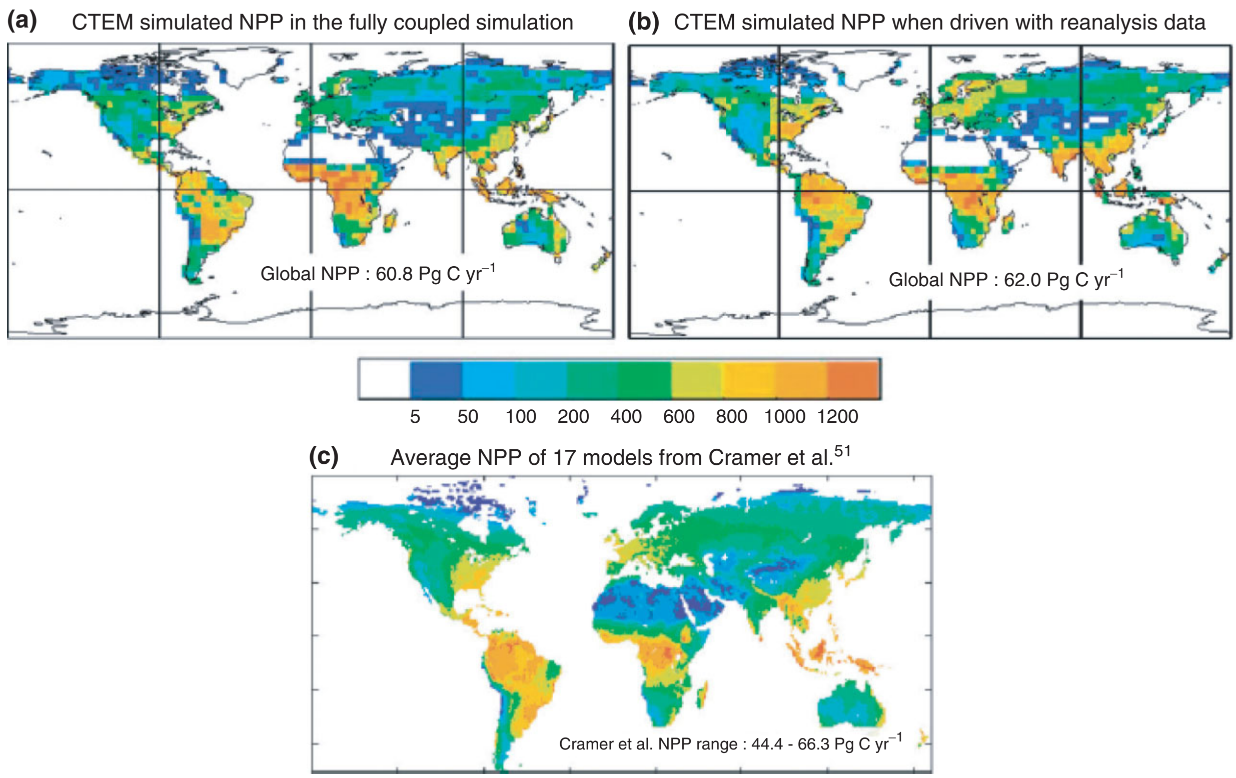

FIGURE 8 | Net primary productivity (NPP) for the terrestrial ecosystem as simulated by the Canadian Earth System Model (CanESM1—upper left), by an off-line version of the CanESM1 terrestrial ecosystem model driven by observationally based meteorology (upper right) and the average from 17 different dynamic vegetation models.[51] (Reprinted with permission from Ref 27. Copyright 2009 American Meteorological Society)

of the errors in the carbon cycle that arise from errors in the model's physical climate because the results on the right have essentially the 'right' physical climate (from observations). Although direct observations of NPP are unavailable, the bottom panel in this figure shows the average of a 17 dynamic vegetation models all driven by observationally based meteorology, typically at much higher spatial resolution than is possible in a fully coupled model. In general, one can see overall agreement, although there are certain areas, such as the northern Amazon, in the coupled model (upper left) where NPP is lower than expected and this can be traced to a bias in the coupled model's physical climate (not enough precipitation in this region).

Evaluation of the ocean component of an ESM is likewise difficult. Observationally constrained estimates of the atmosphere–ocean CO_2 flux are available, though uncertain particularly in the sparsely observed Southern Ocean, as are estimates of ocean 'productivity' (as on land, this refers to the carbon uptake via photosynthesis). In the latter case, satellite-based observations of chlorophyll concentration provide input to derive an estimate of productivity. An example comparison, again from CanESM1 is provided in Figure 9, and it is apparent that there are significant discrepancies. Some possible reasons for this are given in Arora et al.[27] One of the challenges in modeling future ocean productivity (and hence carbon uptake) is the role of ocean mixing in transporting carbon and nutrients, along with the phytoplankton, the role of zooplankton grazing on phytoplankton, and the role of micronutrients such as iron which limit the ability of phytoplankton to photosynthesize in some areas.

Other ocean biogeochemical datasets such as dissolved carbon, nutrients, oxygen and other chemicals are also available for use in evaluating the ocean component of an ESM. An interesting recent example of this is provided by Schmittner et al.[52] in which a range of physical and chemical tracers are used to constrain model-parameterized diffusivity and hence heat and carbon uptake in climate change simulations.

In summary, the evaluation of the physical aspects of an ESM is increasingly comprehensive and relatively well constrained by a growing body of observational data. However, the evaluation of biogeochemical aspects of an ESM is hampered to a large extent by the lack of global, high-quality data sets. There are also shortcomings in the data required

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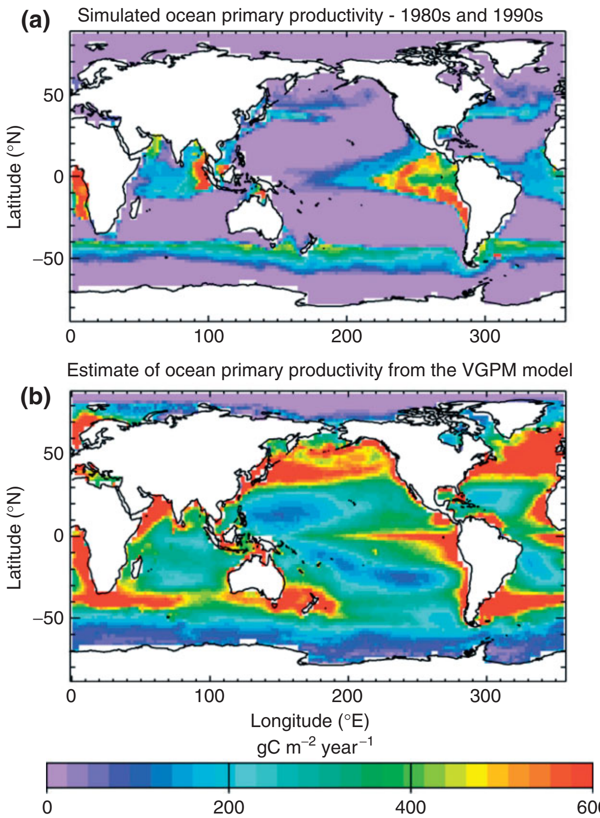

FIGURE 9 | Comparison of simulated ocean primary productivity and an estimate made using a model constrained by satellite-based chlorophyll observations. (Reprinted with permission from Ref 27. Copyright 2009 American Meteorological Society)

to set up and run such models; data such as vegetation type and historical land use, soil type and texture and carbon content, micronutrient distribution in the ocean, etc. All of these contribute to uncertainty in our ability to simulate the biogeochemical processes that shape the response of the climate system to greenhouse gas emissions and other climate forcings.

WHERE ARE WE NOW, AND A LOOK TO THE FUTURE

At present, many climate modeling centers are moving rapidly toward Earth System Modeling, with fully coupled models including the carbon and sulfur cycles, and in some cases ozone chemistry as well. In parallel, a shift has taken place in the design of climate change experiments undertaken with such models. An influential meeting in Aspen, USA, took place in 2006 at which a new approach was proposed[53,54] as illustrated in Figure 10. In the traditional approach to climate modeling, a socioeconomic scenario (or 'storyline') was proposed and a compatible scenario for emissions of future greenhouse gases, land use change and other climate forcings was produced.[15] These emissions could then be used to drive either an ESM or an off-line carbon cycle model to produce a time series of greenhouse gas concentrations. In the case of an ESM, these concentrations and the associate climate change (represented in the figure by surface temperature) are computed simultaneously; whereas in the case of an off-line carbon cycle model, the concentrations are computed and then used to drive a physical climate model. In either case, the uncertainty in climate response is added to the uncertainty in carbon cycle response (i.e., the uncertainty in going from emissions to concentrations). Although the total uncertainty (represented by the width of the line in the figure) is certainly relevant, in that it represents the cumulative uncertainty in the climate consequences of a particular socioeconomic scenario, this approach makes it very difficult to separate the uncertainties due to *physical climate* processes from those due to *carbon cycle* processes. The alternative 'reverse' approach outlined in the figure specifies a greenhouse gas concentration scenario from which the ESM computes climate change and also computes the emissions required to produce these concentrations (including all the carbon cycle feedbacks). This approach is appealing because the uncertainties in representing the physical climate are confined to the simulated climate change, whereas the uncertainties in representing carbon cycle processes are confined to the simulated emissions. The extent to which this will provide optimal information for policy- and decision-makers remains to be seen, but it is the experimental design adopted by the latest Coupled Model Intercomparison Project (CMIP5[55]) which in turn will provide the bulk of climate model results to be assessed in the upcoming IPCC Fifth Assessment. It should be pointed out that this experimental design has the added advantage that both physical-only climate models and ESMs can be directly compared—the physical models producing climate change projections given a time series of greenhouse gas concentrations, but obviously without the ability to do the 'reverse' calculation of associated emissions.

The new ESM experiments being coordinated under CMIP5 will produce a new multimodel ensemble of historical and future climate simulations that will improve our understanding of past climate variability and change, and provide quantitative projections of future change. In addition, there are a suite of idealized experiments proposed that will help isolate the role of various processes and the climate system feedbacks they participate in. Examples include the role of aerosols and cloud feedbacks in

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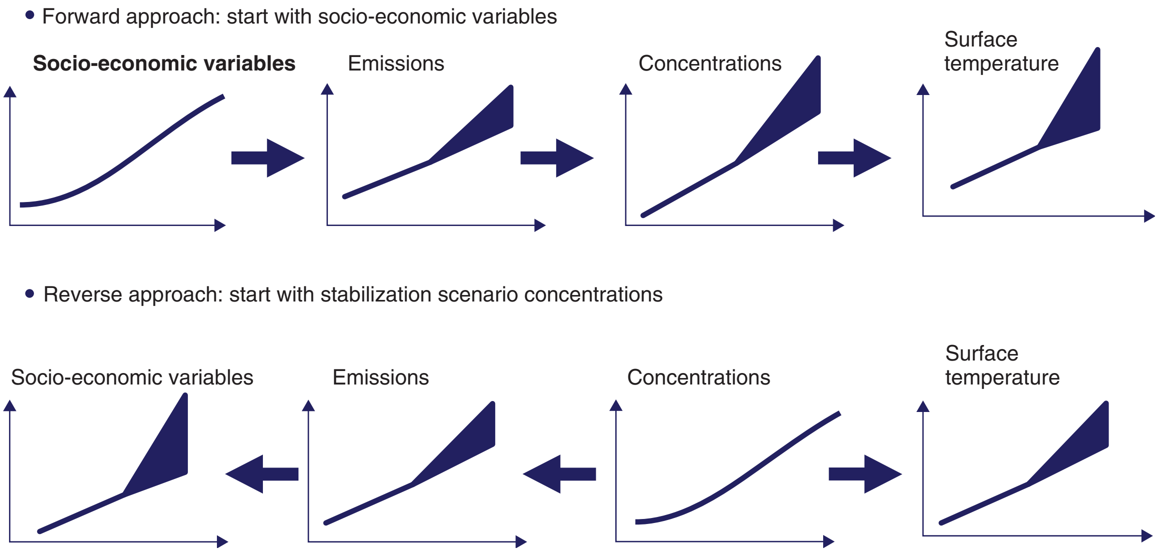

FIGURE 10 | Schematic of traditional approach to climate projection, in which socioeconomic assumptions lead to emissions estimates, to concentration scenarios, which are used to drive physical climate models (upper set of diagrams), and the new strategy in which concentrations are prescribed and an ESM simulates climate change and the corresponding emissions, the latter of which are interpreted to infer corresponding socioeconomic changes. (Reprinted with permission from Ref 54. Copyright 2007 World Climate Research Programme)

determining climate sensitivity. ESMs also allow, at least in principle, experiments aimed at evaluating various climate change mitigation strategies such as forest and other land use management, along with so-called 'geoengineering' approaches such as the deliberate injection of aerosols into the upper atmosphere (in an attempt to increase planetary reflectivity and hence offset some of the greenhouse gas warming) or the fertilization of areas of the ocean with micronutrients like iron that currently limit phytoplankton productivity and hence oceanic carbon uptake. A particular advantage of using an ESM, rather than a more idealized model, in such studies is that a broader range of feedbacks and 'unintended consequences' may be revealed. For example, attention is increasingly drawn to the acidification of the ocean as CO_2 is dissolved into sea water (one of the mechanisms that extracts atmospheric CO_2 emitted by human activities) which in turn impacts on the ability of certain marine organisms such as corals and plankton to maintain their carbonate skeletons.[56] This is relevant in the context of geoengineering in that approaches which offset warming without reducing CO_2 emissions will not slow ocean acidification. ESMs can, by construction, address some of these very policy relevant issues.

Looking further into the future, modeling groups are grappling with a number of model development issues in the ongoing attempt to improve the realism of climate simulations. Some of the key issues are as follows.

Resolution Versus Complexity

ESMs are computationally expensive, with typical experiments (e.g., an ensemble of simulations spanning the historical and future period from 1850 to 2100) taking weeks or even months on a supercomputer. Even with this level of computational effort the spatial resolution of contemporary ESMs is on the order of 100–300 km and perhaps 40 vertical levels in both the atmosphere and ocean component. Obviously at this resolution, many important processes are not explicitly resolved and must be parameterized (approximated based on the resolved, large-scale model variables), and even processes that are resolved may not be well-represented at this resolution. In the numerical weather prediction field, increased model resolution has played an important role in improving the skill of weather forecasts, and some argue that climate prediction (and longer term climate projection) should be done with models of similar resolution (the so-called 'seamless' approach to weather and climate modeling[57]). As a result, there is constant pressure to move toward higher resolution climate models, and indeed there have been some attempts at significantly higher resolution global climate models.[58] However, the computational cost of a numerical model increases, in principle, by a factor of 16 for every doubling of spatial resolution (a factor of two for each of the three spatial dimensions, and another factor of two for the concomitant reduction in time step length). This means that increasing climate model resolution from say 200 to 20 km (roughly

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the difference between contemporary global climate and weather prediction models respectively) requires about 10,000 times more computing capacity! (of course the reason high resolution is feasible in weather prediction is because such models are only run for a few days at a time, as opposed to the decades to centuries run by a climate model). On the other hand, the range of processes and variables that one would like to include in an ESM is also much broader than what is currently done—that is, there is a corresponding pressure to increase model 'complexity' in order to capture as many of the interactions and feedbacks as possible. Such complexity is also computationally expensive, and so model developers must constantly weigh the costs and benefits of increasing resolution or complexity. Ideally, both are desired and strategies to achieve this continue to be discussed.[59] An impending roadblock however has to do with changes in computing technology. In the past, improvements in the speed of large supercomputing facilities have largely come from improvements made to the speed of the individual processors (i.e., the clock speed and hence number of operations per second that can be executed on an individual computer processor). Power demands and other limitations have essentially halted the increase in processor speed, and current gains in overall computing speed are primarily achieved by expanding the number of processors, and this in turn has profound implications on the way in which models are developed and used. A much more extensive discussion of these technical challenges is available in Washington et al.,[60] but it is clear that there will be some profound changes required in the numerical methods and the structure employed in ESMs being developed over the coming decade, largely to accommodate the inevitable shift to computers with thousands or tens of thousands of processors.

Improved Representation of Processes

The 'complexity' issue discussed briefly above essentially relates to the scope of physical, chemical, and biological processes represented in a model, and the level of detail or comprehensiveness assigned to each—that is, the parameterization of these processes (see Box 1). Many processes that are involved in potentially important climate feedbacks are still incompletely understood and rather crudely represented in current climate and ESMs, and this contributes directly to uncertainty in the future climate projections. Feedbacks involving clouds, their role in radiative forcing, and the connection between cloud processes and aerosols (particularly sulfate aerosols) remain areas of large uncertainty,[61] and therefore an area of intensive research. New satellite systems are providing information on clouds, aerosols and the Earth's radiation budget that will help, along with ongoing aircraft and surface based observational campaigns.[62] Other processes that contribute to important climate uncertainties include plant photosynthesis and its dependence on both CO_2 and nutrient availability, decomposition of soil carbon and its dependence on soil temperature and moisture, wetlands and their emission of methane (a much more powerful greenhouse gas), forest fires and their role in the global carbon budget, coastal ocean processes, mixing and stirring in the ocean, and so on. These are but a few examples, and even a cursory discussion of each would be beyond the scope of this article. However, all of these require dedicated research, built upon careful observations, and subsequent integration into ESM development efforts. Some of the key issues currently being pursued include explicit representation of the nitrogen cycle so as to better model the uptake of carbon by plants, the more widespread inclusion of dynamical vegetation, fire and land-use change in ESMs, expanding the number of phytoplankton and zooplankton types in the ocean ecosystem component of such models[63] (so as to represent the potentially important effects of ecosystem shifts—some species replacing others—particularly as a response to ocean acidification), and inclusion of ice shelf and ice sheet processes so as to explicitly represent aspects of sea-level rise that must now be computed in an 'off-line' way.

BOX 1 PARAMETERIZATION OF PHYSICAL PROCESSES

A numerical model represents physical processes by first expressing them in mathematical terms and then solving the resulting mathematical equations using numerical methods (a means of approximating a mathematical equation so that it can be solved using a computer). This involves the 'discretization' of the domain into a collection of grid cells—the smallest units of calculation. For a contemporary climate model these grid cells are typically 100–300 km on a side and tens or hundreds of meters deep. A complex system (like the Earth's climate) requires a large set of mathematical equations to describe it, and each of these equations necessarily involves some approximations. Generally speaking, the equations express the spatial and temporal variation of variables that describe the system, such as temperature and humidity and wind speed in the atmosphere (referred to

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as 'prognostic variables'). The change in these variables from one time step to the next (typically 15 minutes or so) depends on both the large-scale or 'resolved' processes and small scale 'unresolved' processes. Resolved processes in the atmosphere include the propagation of planetary (Rossby) waves which manifest themselves as the moving high and low pressure systems seen on a weather map. Unresolved processes include things like the nucleation of cloud droplets, their growth and ultimate descent as precipitation. These unresolved processes must be represented in terms of the prognostic variables and additional physical parameters (such as the density of water, the nucleation temperature, etc.). This step is referred to as 'parameterization' of an unresolved process—it is essentially the construction of a 'submodel' that represents some physical process in terms of a few large-scale quantities. Parameterizations are often evaluated by comparison against detailed field or experimental data, or very detailed process models, and the quality of these parameterizations that directly affects the quality of the overall numerical model.[64]

CONCLUSION

An ESM is in some way a synthesis of our knowledge of how the planet operates; how the physical climate system interacts with the terrestrial and oceanic ecosystem, how energy is exchanged, how radiatively active chemical species are transported and transformed and feedback on the physical climate. Of course not everything that is known, nor all the detailed knowledge that is available about each or the individual processes involved, can be included in such a model. Compromises and approximations must be made in order to yield a model that is simple enough to be run on available supercomputers, yet is comprehensive enough, and of high enough resolution, to provide useful and reliable results. The choices regarding just what compromises to make, what processes will be included, which will be neglected, the complexity to be retained ... these constitute the 'art' of climate modeling and they rely on the scientific judgement of an interdisciplinary team of researchers. Different modeling groups will necessarily make different choices, based on their experience and expertise, and the result is some diversity amongst ESMs. This diversity has benefits in that the spread amongst model results provides some ability to quantify uncertainty in future climate change. It is also the case that the average of such a collection of model results outperforms any individual model when compared against historical observations, and so one expects the average model projection of the future to be more reliable than any individual projection (in much the same way that ensemble weather prediction improves forecast skill).

The development of ESMs is ongoing, driven primarily by the constant confrontation of model results to a growing body of observational data. This highlights model shortcomings and spurs improvements in process parameterization, numerical methods, and coupling schemes. Model evaluation of this kind points toward limitations associated with neglected processes and so motivates increases in model complexity. Model resolution—the ability to represent small-scale structure in the climate system—is inevitably a limitation, and will always be so. Many important processes fundamentally occur on the scale of microns (e.g., cloud microphysics) and so will never be explicitly resolved in a climate model, but there are many processes such as atmospheric convection or eddy mixing in the ocean that occur on scales of a few kilometers and should ideally be explicitly resolved. However, the roughly 16-fold increase in computing power necessary to accommodate a doubling of model resolution means that kilometer-scale climate modeling will not happen in the near future. Changes in supercomputing technology, particularly the trend toward massively parallel multiprocessor machines, will ultimately provide the kind of computing capacity required, but this poses a number of technical challenges to model developers (and another interdisciplinary opportunity to work more closely with computer scientists!).

The need to explicitly represent the feedbacks between the carbon cycle and the physical climate system has spurred the development of ESMs—first with models of intermediate complexity and now fully three-dimensional comprehensive models. Such models are able to represent at least the leading order interactions between biology, chemistry and the physical climate system, but as in many fields of science, each step forward reveals many more paths to follow. In particular, modeling groups are increasingly incorporating dynamic vegetation to allow competition amongst plant types as climate changes, incorporating aspects of the nitrogen cycle and its important connections to the carbon cycle. The sulfur cycle is being represented in ever growing detail so as to better constrain the role of sulfate aerosols in cooling the climate both directly and indirectly via altering cloud properties. In addition to drawing in a broader segment of the Earth Sciences community, this

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expansion in model complexity is allowing new areas of research into the changes that are a consequence of ongoing emission of greenhouse gases and other human activities. Such models provide the quantitative climate change information that feeds into impact assessments and adaptation plans, and will allow exploration of the efficacy and perhaps unintended consequences of various 'geoengineering' schemes currently being discussed. The current generation of ESMs are running now, producing results that will ultimately inform the next IPCC Scientific Assessment, and, in parallel, new and innovative approaches to modeling the Earth System are being developed. Plans to explicitly incorporate human activities, economies, and decision-making into such models are also being pursued in several centers, perhaps leading ultimately to the 'revolution' described by Schellenhuber.[1]

NOTES

[a]Greenhouse gases here refer to all trace gases that absorb and re-emit longwave radiation, and therefore participate in the greenhouse effect. Water vapor is also a greenhouse gas (in fact the most important in Earth's climate), but it is included as a prognostic variable in climate model; therefore when we refer to greenhouse gases in this paper, we are referring to all the other trace gases such as carbon dioxide, methane, nitrous oxide, etc.—an extensive list and discussion of their radiative properties can be found in Chapter 2 of the Working Group 1 report of the IPCC Fourth Assessment.[5]

[b]The atmosphere is generally described in terms of layers. The lowest being the troposphere which contains about 75% of the atmosphere's mass and extends up to about 17 km altitude at mid latitudes (higher at the equator and lower at the poles). Temperatures in the troposphere decrease with increasing altitude. The next layer is the stratosphere which extends upward from the top of the troposphere to about 50 km altitude. In the stratosphere, temperatures increase with height.

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