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PLASIM-GENIE: a new intermediate complexity AOGCM

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Abstract

We describe the development, tuning and climate of PLASIM-GENIE, a new intermediate complexity Atmosphere–Ocean Global Climate Model (AOGCM), built by coupling the Planet Simulator to the GENIE earth system model. PLASIM-GENIE supersedes "GENIE-2", a coupling of GENIE to the Reading IGCM. It has been developed to join the limited number of models that bridge the gap between EMICS with simplified atmospheric dynamics and state of the art AOGCMs. A 1000 year simulation with PLASIM-GENIE requires approximately two weeks on a single node of a 2.1 GHz AMD 6172 CPU. An important motivation for intermediate complexity models is the evaluation of uncertainty. We here demonstrate the tractability of PLASIM-GENIE ensembles by deriving a "subjective" tuning of the model with a 50 member ensemble of 1000 year simulations.

1 Introduction

The Grid-ENabled Integrated Earth system model (GENIE, Lenton et al., 2007) has been developed as a modular framework that allows a spectrum of intermediate complexity Earth system models to be created by selecting different options for the various climate and carbon cycle components. Earth system models created within GENIE have been configured for published studies spanning a wide range of geological epochs across Paleozoic, Mesozoic and Cenozoic eras. GENIE framework models are normally capable of integration over multi-millennial timescales and several of the published studies have involved millions of years of simulation time combining long runs and large ensembles. The framework has been designed to be modular to facilitate the coupling of more complex component modules as available computing power increases.

Almost invariably, applications of GENIE have used configurations that represent the atmosphere with a computationally fast energy-moisture-balance-model (EMBM, Fan-

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ning and Weaver, 1996). These configurations are generically named “GENIE-1”. Although adequate for many purposes, especially in the context of global biogeochemical modelling, an EMBM introduces significant structural weaknesses to (or even rules out) a range of applications. Diffusive single-layer moisture transport leads to poor precipitation fields that cannot, for instance, represent convective precipitation or monsoon dynamics. The EMBM applies prescribed surface wind fields (Edwards and Marsh, 2005), defined either from climatology or from outputs of more complex models, so that dynamic ocean feedbacks are restricted to the thermohaline circulation. Clouds are represented through a prescribed albedo field (Lenton et al., 2006) and a spatially uniform adjustment to outgoing longwave radiation OLR (Holden et al., 2010), while uncertain cloud feedbacks on the radiative balance in a changing climate are represented through a globally uniform temperature dependent adjustment to OLR (Matthews and Caldeira, 2007; Holden et al., 2010).

In an effort to address these shortcomings, the Reading Intermediate General Circulation Model (IGCM3.1, de Forster et al., 2000), a 3-D dynamical model of the atmosphere, was coupled into GENIE (Annan et al., 2005; Lenton et al., 2007). Unfortunately this realization of the model “GENIE-2” proved problematic and has only been applied once since these early studies (Holden and Edwards, 2010). The coupling with the slab-ocean model was found to exhibit poor precipitation fields, apparently due to structural deficiencies in the convection routine (Annan et al., 2005). The coupling with the 3-D frictional geostrophic ocean model GOLDSTEIN displays a patchwork-instability and exhibits a low bias in precipitation over ocean. GENIE-2 requires a large flux correction (0.79 Sv, reversing the sign of the simulated flux) to reconcile freshwater transport from the Atlantic to the Pacific with reanalysis data (Lenton et al., 2007) and generate an Atlantic overturning circulation. A further shortcoming is that, on account of technical complications discussed in Sect. 3.3, the IGCM was not coupled to the dynamic sea–ice module GOLDSTEINSEAICE, but only to the slab sea–ice module.

GENIE-1 has been applied to a wide range of studies, including participation in the EMIC inter-comparisons that were performed for the two most recent IPCC reports

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(Plattner et al., 2008; Zickfeld et al., 2013). Although GENIE studies have generally addressed ocean physics, ocean biogeochemistry and the global carbon cycle, a more recent focus has been the development of emulators for climate impact assessment (e.g. Labriet et al., 2013; Mercure et al., 2014). This application is poorly suited to highly simplified atmospheric models such as the EMBM. Although the emulation techniques were developed from GENIE-2 simulations (Holden and Edwards, 2010), this first-generation emulator was not considered sufficiently robust for applications given the poor climatology of the underlying simulator. Instead, a second-generation emulator (Holden et al., 2014) was developed using the Planet Simulator PLASIM (Fraedrich, 2012).

PLASIM is a reduced complexity AGCM, with the 3-D primitive equation atmosphere model PUMA at its core (Fraedrich et al., 2005). Complementary to GENIE-1, it has been applied in a range of atmospheric studies, for instance investigating the global entropy budget (Fraedrich and Lunkeit, 2008), double ITCZ dynamics in an aquaplanet (Dahms et al., 2011), the Permian climate (Roscher et al., 2011) and a snowball Earth (Micheels and Montenari, 2008). However, although PLASIM simulates vastly better climatology than the EMBM of GENIE-1, it lacks dynamic representations of ocean and sea ice (and does not model the carbon cycle) so it too neglects important Earth system feedbacks.

We here describe the implementation of a coupling of PLASIM to the GENIE framework. The coupled model "PLASIM-GENIE" has been developed to join the limited number of models that that bridge the gap between EMICS with simplified atmospheric dynamics and state of the art AOGCMs. We are aware of three AOGCMs of comparable complexity with primitive equation atmospheric dynamics: FAMOUS, the reduced resolution implementation of HadCM3, which simulates 1000 years in approximately ten days on eight CPUs (Williams et al., 2013), SPEEDO, comprising a T30 spectral atmosphere with simplified parameterizations (Molteni, 2003) coupled to a primitive equation ocean model, which simulates 1000 years in approximately two weeks on a 3 GHz dual core Intel E6850 CPU (Severijns and Hazeleger, 2010) and OSU-

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Vic, a coupling of PLASIM to the UVic Earth system model (Schmittner et al., 2010). A 1000 year simulation with PLASIM-GENIE requires approximately two weeks on a single node of a 2.1 GHz AMD 6172 CPU.

State of the art climate models operate at the limit of available computing power, so that very few simulations can be performed with these models. An important motivation for intermediate complexity models is for the evaluation of uncertainty. We here demonstrate the tractability of PLASIM-GENIE ensembles by tuning the model with a 50 member ensemble of 1000 year simulations.

2 Component modules

2.1 PLASIM-ENTS

PLASIM (Fraedrich, 2012) is a reduced complexity AGCM, with the 3-D primitive equation atmosphere model PUMA at its core (Fraedrich et al., 2005). The atmospheric dynamics are solved using the spectral transform method, formulated for temperature, log surface pressure, divergence and vorticity. Parameterized processes include shortwave and longwave radiative transport, interactive clouds, large-scale precipitation, moist and dry convection, boundary layer sensible heat and latent heat fluxes, and diffusive transport. The model accounts for the greenhouse gas effects of carbon dioxide, water vapour and ozone. Ozone concentration is prescribed with an analytic spatio-temporal distribution.

The land surface scheme was modified (Holden et al., 2014) to use GENIE's "efficient numerical terrestrial scheme" ENTS (Williamson et al., 2006), partly in anticipation of this coupling to GENIE. ENTS models vegetative and soil carbon densities, assuming a single plant functional type that has a doubled-peaked temperature response (representing boreal and tropical forest). In addition to temperature, the rate of photosynthesis depends upon the atmospheric CO_2 concentration and on soil moisture availability, and includes a parameterisation of self-shading. Land surface albedo, moisture bucket

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capacity and surface roughness are parameterised in terms of the simulated carbon pool densities.

PLASIM includes flux-corrected slab ocean and slab sea–ice models. The coupling described here (Sect. 3) replaces these simple models with the 3-D dynamical ocean model GOLDSTEIN and the thermodynamic-dynamical sea ice model GOLDSTEIN-SEAICE.

2.2 GOLDSTEIN

GOLDSTEIN is a 3-D frictional-geostrophic ocean model (Edwards and Marsh, 2005; Marsh et al., 2011). GOLDSTEIN is dynamically similar to classical GCMs, except that it neglects momentum advection and acceleration. Barotropic flow around Antarctica is derived from linear constraints that arise from integrating the depth-averaged momentum equations; we here neglect flow through other straits. Several modifications to the default GOLDSTEIN can be enabled; here we apply the modified equation of state that includes a parameterisation of thermobaricity (K. Oliver, personal communication, 2008) and the enhanced diapycnal mixing scheme (Oliver and Edwards, 2008).

2.3 GOLDSTEINSEAICE

GOLDSTEINSEAICE (Edwards and Marsh, 2005) solves for the fraction of the ocean surface covered by ice within a grid cell and for the average sea–ice height. A diagnostic equation is solved for the ice surface temperature. Growth or decay of sea ice depends on the net heat flux into the ice (Semtner, 1976; Hibler, 1979); sea–ice dynamics consists of advection by surface currents and diffusion. The thermodynamics of GOLDSTEINSEAICE are summarized in detail in Sect. 3.3.

3 Coupling methodology

A schematic of the PLASIM-ENTS/GOLDSTEIN/GOLDSTEINSEAICE "pl_go_gs" coupling is illustrated in Fig. 1.

In order to avoid the need for interpolation, the coupling was set up to require the three models have matched horizontal grids. PLASIM has previously been configured for T21, T31 and T42 resolutions. Here we restrict the coupling to T21 and use the matched 64×32 GOLDSTEIN grid (Lenton et al., 2007). PLASIM vertical resolution is 10 levels. GOLDSTEIN depth resolution is 32 levels, with bathymetry defined at the resolution of the 8 level configuration. Extension to other resolutions (horizontal or vertical) is straightforward in principle.

3.1 PLASIM-ENTS

The choice was made to preserve the coupled PLASIM-ENTS model in its entirety. The slab ocean and sea ice modules are retained only to provide boundary conditions; their state variables are over-written with GOLDSTEIN and GOLDSTEINSEAICE outputs, effectively negating the very simple dynamics of these models. This simplifies the coupling because the energy and moisture flux calculations are already made within PLASIM. The changes needed to PLASIM with this approach are therefore kept to a minimum, consisting of prescribing the slab ocean with GOLDSTEIN distributions of sea surface temperature and the slab sea–ice with GOLDSTEINSEAICE distributions of sea–ice fractional coverage, height, surface temperature and albedo. Furthermore, although GENIE contains a stand-alone version of the land surface module ENTS, the decision was taken to leave the existing PLASIM-ENTS coupling in place. Future work may separate the PLASIM and ENTS modules. The primary motivation for this would be modularity. Notably GENIEfied ENTS is coupled to the global carbon cycle (Lenton et al., 2006) and has been enabled to simulate the effects of anthropogenic land use change (Holden et al., 2013a).

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3.2 GOLDSTEIN

No changes were made to GOLDSTEIN. Surface wind stress, net energy and net moisture fluxes are supplied from PLASIM, modified by sea ice where relevant. We note that we use a PLASIM time step of 45 min and a GOLDSTEIN time step of 12 h, with coupling inputs averaged over the previous 16 PLASIM time steps (12 h). The computational demands of the coupled model, simulating 75 years day^{-1} on a single node of a 256 Gb 2.1 GHz AMD 6172 CPU, are dominated by PLASIM (98 %); the computational demands of PLASIM are dominated by diabatic processes (~ 76 %), in particular by radiation (~ 43 %) and precipitation (~ 16 %).

3.3 GOLDSTEINSEAICE

In GENIE-1 the thermodynamics of GOLDSTEINSEAICE are calculated within the EMBM, and coupling to alternative model atmospheres is not possible with this model structure. To enable a PLASIM-GOLDSTEINSEAICE coupling we have developed a stand-alone sea–ice thermodynamics routine.

Time-averaged incoming energy fluxes and atmospheric boundary conditions are supplied to the new surface flux (ICE-SURFLUX) routine from PLASIM. Sea surface temperature and salinity, sea–ice height and fractional sea–ice coverage are provided from the previous GOLDSTEIN/SEAICE time step.

ICE-SURFLUX closely follows the formulation of Edwards and Marsh (2005), where it is described in some detail. We summarize the approach here. Sea ice is assumed to have no heat capacity, so that the heat flux exchanged with the atmosphere equals the heat flux through the ice, thereby defining the vertical temperature gradient across the ice. The temperature at the sea–ice base is assumed equal to the salinity-dependent freezing point of the surface ocean, so that the ice-surface temperature is the remaining unknown. Now we need to derive the net heat flux from the atmosphere. Incoming radiative fluxes are provided by PLASIM; outgoing radiative fluxes, and sensible and latent heat fluxes are dependent upon the surface temperature of the sea ice, to-

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gether with atmospheric boundary conditions. These relationships together imply an ice-surface temperature (and the associated atmospheric heat flux) that balances the heat budget, which is solved for with a Newton–Raphson algorithm. The heat flux exchanged with the ocean is implied by the temperature differential between the sea–ice base (freezing point) and the surface ocean. The difference between the heat flux exchanged with the atmosphere and with the ocean is consumed by creating or melting ice.

The diagnosed energy and moisture fluxes are not passed to PLASIM. Instead, in order to achieve energy and moisture conservation, PLASIM transfer coefficients are used in the calculation of sensible heat and sublimation during the Newton–Raphson step. This ensures that net fluxes calculated in PLASIM (which use the sea–ice temperature and albedo derived in ICE-SURFLUX) will be consistent with those calculated in ICE-SURFLUX, but does not guarantee perfect conservation. Conservation errors arise through time-step gearing (the averaging of non-linear flux terms over 16 PLASIM time steps) and also because PLASIM does not explicitly account for sea–ice leads; ICE-SURFLUX separately accounts for ocean and sea–ice in a partially covered gridcell, but PLASIM fluxes are derived from weighted average surface properties. To evaluate the magnitude of the conservation errors, we consider all of the sea–ice covered grid cells at each time step across a year of the spun-up model. The energy conservation error across these 152 495 data points is $0.1 \pm 1.0\,\mathrm{W\,m^{-2}}$ (1σ). We note that the PLASIM atmosphere does not precisely conserve energy because the conversion from potential to kinetic energy cannot be formulated in a conservative manner in a spectral model; the top-of-atmosphere energy balance converges to $-0.7\,\mathrm{W\,m^{-2}}$ in both the coupled and stand-alone versions of PLASIM, dominating over the conservation errors of ICE-SURFLUX.

Sea–ice growth rates are provided to GOLDSTEINSEAICE, which derives updated sea–ice distributions, considering both thermodynamics and dynamics (advection and diffusion). The updated sea–ice distribution is provided to PLASIM and the associated freshwater exchange with the ocean is provided to GOLDSTEIN.

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4 Tuning methodology

Our approach for the selection of a tuned set of parameter values was to retain the existing tunings of models where possible (for exceptions see Sect. 4.1) and to only consider the parametric uncertainty of GOLDSTEIN. The motivation was that both PLASIM (Lunkeit et al., 2007) and ENTS (Williamson et al., 2006) have already been tuned to reproduce observations when forced with climatology[1]. In contrast, existing GOLDSTEIN tunings have been developed within a coupled atmosphere–ocean model, usually the EMBM atmosphere. We anticipated that a tuning of GOLDSTEIN that reproduces the main features of global ocean circulation when coupled to climatologically tuned PLASIM-ENTS would likely provide a good representation of observed climatology in general.

We performed a 50 member ensemble of 1000 year preindustrial spin-up simulations varying six GOLDSTEIN parameters, in the expectation that some subset of ensemble members would produce reasonable climate states from which we could select a tuned model. (Failure in this regard would have necessitated the application of more sophisticated statistical techniques for searching parameter input space).

4.1 Ensemble design

Parameters from modules besides GOLDSTEIN were all fixed. However, some were changed from their default values on the basis of exploratory simulations:

i. The PLASIM parameter acllwr controls the effect of clouds on outgoing longwave radiation and was found to exert the strongest control on surface air temperature in PLASIM-ENTS ensembles (Holden et al., 2014). The acllwr parameter was increased from 0.1 to 0.2 $m^{-2} g^{-1}$, a value estimated to yield a simulated global

[1]The diurnal cycle is switched off in these simulations, reflecting the default assumption for both the PLASIM and ENTS tunings.

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average surface air temperature of approximately 14 °C in conjunction with parameter choices (ii) to (v) below.

ii. The PLASIM parameter albseamax defines the latitudinal variation of ocean albedo (Holden et al., 2014), applied to both direct and scattered radiation. A high value (0.4) was favoured, leading to cooler high latitude ocean and favouring increased Southern Ocean sea–ice and deep-water formation, which both tended to be too low with default parameters.

iii. Sea ice diffusivity (SID) influences AABW formation by controlling the strength of brine rejection (Holden et al., 2013b). A high value was favoured, again to strengthen deep-water formation, but values greater that 15 000 $m^2 s^{-1}$ were found to lead to numerical instabilities in this model and SID was fixed at this value.

iv. The standard PLASIM expression for the dependence of sea ice albedo α_i on surface air temperature was used, but a minimum value α_{min} was introduced, viz.

$$\alpha_i = \max\left[\alpha_{min}, \min\left(\alpha_{max}, 0.5 - 0.025\, T_{air}\right)\right]$$

where T_{air} is the surface air temperature (°C). Values of 0.5 and 0.7 were applied for α_{min} and α_{max} respectively.

v. The PLASIM-ENTS parameter qthresh was set to 0.1, allowing the development of vegetation in semi-arid regions (Holden et al., 2014).

The ensemble was generated using a 50 × 6 maximin latin hypercube design, varying the six GOLDSTEIN parameters tabulated in Table 1. The ranges are considered to reflect the plausible range for each parameter (Holden et al., 2013b, and references therein). Two parameters merit particular discussion here:

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4.1.1 APM

APM is a flux correction that transports moisture from the Atlantic to the Pacific, originally developed for the EMBM coupling (Edwards and Marsh, 2005). The default flux correction (0.32 Sv) is subdivided into three latitude bands reflecting the observed Atlantic–Pacific moisture transport (Oort, 1983): −0.03 Sv south of 20° S, 0.17 Sv in the tropical zone 20° S to 24° N, and 0.18 Sv north of 24° N. Exploratory simulations suggested that PLASIM-GENIE would likely require a moisture flux correction and APM was introduced as an ensemble variable. APM is varied across ensemble members by a linear scaling across the latitude bands.

An exploratory simulation with a flux correction of 0.32 Sv was performed and integrated net freshwater fluxes (precipitation, evaporation, runoff and the flux correction) were diagnosed for the Arctic/Atlantic and the Pacific. In both basins, grid cells north of 32° S were included, following the observational estimates of Talley (2008). Values of −0.5 and +0.1 Sv respectively were diagnosed, compared to observations of -0.28 ± 0.04 and $+0.04 \pm 0.09$ Sv (Talley, 2008). Informed by this result, we allowed APM to vary in the range 0 to 0.32 Sv.

PLASIM has also been coupled to the UVic Earth system model, creating the OSUVic model (Schmittner et al., 2010). At T21 resolution the integrated Atlantic surface moisture balance simulated by OSUVic (−0.33 Sv) is in good agreement with observations without any flux correction. However, OSUVic nevertheless simulates a weak (9 Sv) Atlantic overturning circulation at T21 resolution. This was attributed in part to errors in the latitudinal distribution of the simulated moisture flux, which create low surface ocean salinities at high latitudes in the Atlantic (balanced by high salinity at low latitudes). We note that an exploratory PLASIM-GENIE simulation with a uniformly distributed 0.32 Sv moisture flux correction also exhibited low Atlantic salinity at high latitudes and weak overturning.

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4.1.2 SCF

SCF scales the surface wind stresses that are applied to GOLDSTEIN. The scaling is needed because the frictional-geostrophic ocean dissipates wind energy so that increased surface wind strengths are required to compensate and drive a reasonable circulation. The conventional ensemble range for the SCF parameter in GENIE-1 (forced by observed climatological wind stress) is 1 to 3 (Edwards and Marsh, 2005).

In the OSUVic model (Schmittner et al., 2010), the weak overturning circulation at T21 resolution discussed in Sect. 4.1.1 was, in addition to errors in the surface salinity distribution, partly attributed to low zonal wind-stress in the Southern Ocean, likely due to inadequate meridional resolution (cf. Held and Phillipps, 1993). In anticipation of systematically understated zonal wind stress in our T21 coupling, we here allowed SCF to vary in the range 2 to 4.

4.2 Ensemble outputs

Thirty-seven of the 50 ensemble members successfully completed the 1000 year preindustrial spin up simulations. These simulations exhibited a global average surface air temperature of $12.1 \pm 1.2\,^{\circ}\mathrm{C}$ (1σ). Simulation-failure was invariably associated with low frictional drag (high ADRAG); low frictional drag leads to unrealistically strong flow near the Equator and topographic features (Edwards and Marsh, 2005). Three successfully completed simulations (with inverse frictional drag 4.01, 3.21 and 3.98 days^{-1}) were excluded from the ensemble on account of unreasonably strong Pacific overturning (277, −174 and 633 Sv respectively). We briefly summarise some of the characteristics of the remaining thirty-four simulations in terms of their response to APM, SCF and ADRAG, the three parameters that dominate the ensemble variability.

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4.2.1 APM

The Atlantic overturning cell collapsed in all 20 simulations with APM less than 0.16 Sv. It collapsed in only five of the 14 simulations with APM greater than 0.16 Sv.

A regression of ensemble outputs suggests that the observed integrated Atlantic freshwater balance (correlation −0.88) is best reproduced for APM of approximately 0.13 Sv, while the integrated Pacific freshwater balance (correlation +0.57) is best reproduced for APM of approximately 0.28 Sv. Values between these limits (∼ 0.13 to 0.28 Sv) are therefore favoured to optimise the surface ocean inter-basin salinity distribution.

It is worth noting that these conclusions only pertain to the specific model setup considered (i.e. the vector of all fixed parameters). We cannot rule out the possibility that alternative model parameterisations can reproduce observed salinity and circulation fields without a moisture flux correction.

4.2.2 SCF and ADRAG

Wind stress scaling and inverse frictional drag affect the simulations in similar ways, as expected because the role of wind-stress scaling is to compensate for frictional dissipation. Many clear relationships between these parameters and simulated outputs are apparent, for instance high values of either tend to strengthen overturning circulation and decrease sea–ice coverage in both hemispheres. It is interesting to note a strong negative correlation (−0.62) between ADRAG and the integrated surface Pacific freshwater flux, opposing a positive correlation (+0.77) with the integrated freshwater flux of the Indian Ocean. (Similar, though weaker, relationships exist with SCF).

4.3 Selection of a "subjectively" tuned parameter set

Three of the 37 completed 1000 year simulations have already been ruled out for unreasonably strong Pacific overturning and a further twenty-five because the Atlantic

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overturning circulation had collapsed. Two further simulations were ruled out for unacceptably low (and still cooling) global surface air temperature (< 10 °C) and two for an excessively evaporative Atlantic basin (~ 0.5 Sv, forced by APM ~ 0.3 Sv). The remaining five simulations were spun on for an additional 1000 years. After this spin on, two of these simulations were ruled out under a stricter global surface air temperature constraint (requiring > 12 °C), a third simulation did not exhibit penetration of Antarctic Bottom Water into the Atlantic and a fourth simulation displayed a positive Pacific overturning cell that penetrated to the ocean floor north of 15° N. The remaining simulation was clearly preferable on the basis of these simple large-scale constraints, testing for reasonable surface–ocean forcing and circulation. This "subjective" parameter set (see Table 1) is therefore taken as our preferred tuning[2].

5 Simulated climate of the subjective tuning

The simulated climate metrics of the subjective tuning are global average surface air temperature 12.9 °C, surface Atlantic freshwater balance −0.34 Sv (including the −0.21 Sv moisture flux correction), maximum Atlantic overturning (below 500 m) 15.5 Sv, minimum Atlantic overturning −3.4 Sv, and maximum Pacific overturning 8.8 Sv (restricted to high latitudes and intermediate depths, see Fig. 6). We now evaluate the climate in some detail.

Table 2 compares the subjectively tuned PLASIM-ENTS preindustrial global energy balance against a range of observationally constrained (present day) estimates presented in Trenberth et al. (2009). Simulated fluxes are generally within the ranges of these estimates besides reflecting the simulated cold bias that is most clearly appar-

[2]We note that after the tuning ensemble was performed, the "surfstep" PLASIM subroutine was moved to the start of the diabatic time step (in the stand-alone model, PLASIM surface conditions are updated after the calculation of diabatic processes). This change was made so that boundary conditions are immediately updated after a call to GOLDSTEIN. Differences in simulated outputs were not distinguishable from internal variability.

ent in OLR (and only partially attributable to anthropogenic forcing). Although within ranges, these data suggest that too little solar radiation is absorbed within the atmosphere and too much is reflected by the surface (likely due to the high ocean albedo, Sect. 4.1).

Table 3 compares the simulated surface ocean net moisture fluxes in each basin with the estimates of Talley (2008). The good agreement in the Atlantic is imposed by the moisture flux correction. We emphasise that the requirement for a flux correction in this parameterisation does not necessarily indicate an inherent structural weakness in the model, pending a full exploration of parameter-space (cf. Williamson et al., 2015). The largest disagreement between these observations and the subjective tuning is the moisture flux differential between the Indian and Pacific Oceans. The global aggregates of precipitation, evaporation and runoff are in good agreement with the observationally constrained estimates of Trenberth et al. (2007), with a modest low bias that is consistent with the simulated cold bias.

Figures 2–4 compare a selection of PLASIM-GENIE outputs against NCEP/NCAR reanalysis fields (Kalnay et al., 1996). The selected variables were chosen to highlight feedbacks neglected by the EMBM. In each case we compare fifty-year averages of southern summer (JJA) and northern summer (DJF) with the long-term monthly means (July and January 1981–2010) of the reanalysis data.

Surface air temperature and precipitation fields are plotted in Fig. 2. The cold bias of the subjective tuning is especially apparent in the high Arctic. Despite the global cold bias, surface air temperatures are warm-biased over the Southern Ocean, consistent with an underestimation of southern sea–ice coverage that was apparent over the entire ensemble.

PLASIM precipitation fields are reasonable given our low resolution. Distinct arid regions are captured, as is the seasonal migration of the Inter-Tropical Convergence Zone and associated monsoon systems. Precipitation over the eastern Pacific Ocean is generally understated, while it is overstated over the eastern Atlantic Ocean, consistent

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with the need for an Atlantic–Pacific moisture-flux correction to generate reasonable salinity distributions and an Atlantic overturning circulation.

Figure 3 compares the surface wind fields of the subjective tuning with 10 m reanalysis winds. The simulated spatiotemporal distributions are in good agreement with reanalysis, although Antarctic circumpolar wind speed is somewhat understated (cf. Schmittner et al., 2010). We note that simulated wind speeds are at the 0.983 sigma pressure level, typically $\sim$ 136 m above the surface, so that boundary layer damping is weaker than the 10 m reanalysis winds. Therefore we expect greater wind speeds in the PLASIM-GENIE plots, as is generally the case.

Figure 4 compares incoming solar and thermal radiation fields with the reanalysis data. These fields are also chosen to reflect dynamics that are absent from GENIE-1, which applies prescribed planetary albedo fields and a globally uniform OLR adjustment to represent the effect of clouds on the radiation balance. Although the representation of clouds in PLASIM is of low complexity, the ability of the model to represent dynamic cloud feedbacks represents a substantial improvement upon GENIE-1.

The PLASIM coupling improves simulated vegetative carbon (Fig. 5a) with respect to GENIE-1. In GENIE-1, deserts are poorly resolved and boreal forest does not penetrate far into the continental interior of Eurasia, both shortcomings that arise from diffusive moisture transport (Lenton et al., 2006). Although the deserts of the Southern Hemisphere are not well resolved in either model, the larger deserts of the Northern Hemisphere are distinct in PLASIM-GENIE, while simulated boreal forest penetrates the Eurasian interior. Global terrestrial carbon storage in the subjective tuning of PLASIM-GENIE is 604 GTC (vegetation) and 1971 GTC (soil). These compare to 491–574 GTC and 1367–1416 GTC respectively in GENIE-1 (Lenton et al., 2006). The significantly higher soil carbon values in PLASIM-GENIE primarily reflect the increased area of Eurasian boreal forest, where soil carbon is respired slowly due to the low temperatures. The global terrestrial carbon pools are consistent with ranges of 460–660 GTC (vegetation) and 850–2400 GTC (soil) derived from a range of observational and modelling studies and summarised in Bondeau et al. (2007).

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Budyko's (1974) framework of climate analysis is based on the climate mean dryness ratio D or aridity index (mean energy supply or net radiation N to mean water supply or precipitation P). It provides quantitative geobotanically relevant thresholds for land surface climate regimes that are related to vegetation structures (Fig. 5c): Tundra, $D < 1/3$, and forests, $1/3 < D < 1$, are energy limited ($D < 1$), because available energy N is low, so that runoff exceeds evaporation for given precipitation, $E \sim N$. Steppe and savanna, $1 < D < 2$; semi-desert, $2 < D < 3$; and desert $3 > D$, are water-limited climates ($D > 1$), where the available energy is so high that water supplied by precipitation evaporates, which then exceeds runoff, $E - P$. This analysis highlights the Tibetan Plateau and North American Arctic climates and demonstrates consistency with the simulated vegetation carbon (Fig. 5a). The similarity with ERA-interim based analysis (Cai et al., 2014; Fig. 1a) is notable. Similarly, a bucket model interpretation of the land surface climate (Fraedrich et al., 2015) is possible using the soil moisture fraction, $S = s/s^* = E/N$, and is plotted in Fig. 5d.

Sea–ice distributions (not illustrated) exhibit a systematic bias towards low southern sea–ice area across the ensemble, with an annual average of 2.8 million km^2 in the subjective tuning; this compares to observational estimates of 11.5 million km^2 (Cavalieri et al., 2003). Surface air temperature over the southern ocean is warm biased with respect to the reanalysis data, despite a modest cold bias in the global temperature (Fig. 2). While this may in part be a consequence of reduced sea–ice (through the albedo feedback), the continued presence of the warm bias in southern summer suggests the possibility that the bias arises in the atmosphere. The decision to control the global temperature with acllwr (Sect. 4.1) preferentially warms cloudy regions and may have contributed. A thorough investigation of the source of this bias is beyond the scope of this study, requiring consideration of uncertainties in atmospheric and ocean energy transport, and in solar and thermal radiative transfer, considering clouds, water vapour, and surface processes.

Figure 6 illustrates the simulated ocean state. These plots each reflect the constraints imposed upon the subjective parameter set and require little further discussion.

It is worth emphasising again that the simulation of realistic salinity fields and ocean circulation required an Atlantic–Pacific moisture flux adjustment in this parameterisation (Sect. 4.1.1 and 4.2.1).

6 Summary and conclusions

We have presented a new intermediate complexity AOGCM PLASIM-GENIE, which reproduces the main features of the climate system well and represents a substantial upgrade to GENIE-1 through the representation of important atmospheric dynamical feedbacks that are absent in an EMBM. PLASIM-GENIE has been developed to join the limited number of intermediate complexity models with primitive equation atmospheric dynamics. It supersedes an earlier coupling with the IGCM ("GENIE-2"), which was contaminated with spurious numerically generated features, limiting its usefulness.

The simple "subjective" tuning approach applied here considered only six ocean parameters, seeking a reasonable ocean circulation when coupled to PLASIM-ENTS (both PLASIM and ENTS have previously been tuned with climatological forcing). This limited tuning approach required approximately 2 CPU years, demanding but readily tractable, representing approximately two weeks of computation on 50 cluster nodes.

A reasonable ocean circulation state and salinity distribution required the application of an Atlantic–Pacific moisture flux correction. We do not rule out the possibility that a full investigation of PLASIM-GENIE parametric uncertainty could generate a plausible ocean circulation without a flux correction, and may additionally resolve the understated southern sea ice. However, a comprehensive tuning will demand the application of more complex statistical approaches designed to deal with computationally demanding simulators. For instance, the use of emulators to inform a sequential ensemble design process has been demonstrated to yield a ~ 100 fold reduction in computational demand (Holden et al., 2015).

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Code availability

The code base is provided as Supplement. We recommend setting up a root directory (e.g. PLASIM-GENIE) containing the subdirectories genie_output and genie. The subdirectory genie will be the code base that you download from the Supplement. This code base contains the entire GENIE model, except that input data files required for modules other than pl_go_gs have been removed in order to satisfy the data limits for *Geoscientific Model Development* supplementary material. The full code base is available on request from the authors.

In addition to the source code, PLASIM-GENIE makes use of several applications and packages. You must have the following list of prerequisites installed on your computer before you can run the model: Python, Perl, GNU make, the BASH shell, a C++ compiler, a Fortran compiler that supports Fortran90, and NetCDF libraries (compiled on the same computer using the same compilers that you will use to compile PLASIM-GENIE).

Before you compile the model you must provide information about (i) where you have installed the source code, (ii) which compilers you are using, and (iii) the location of the netCDF libraries that you have created; this is achieved by editing the files user.mak and user.sh in the directory genie-main. Comments in those files explain which lines need to be edited.

The code base includes configuration file needed to perform a 1000 year spin-up with the subjective parameter set. To run this simulation, enter the genie/genie-main directory and type:

```
make cleanall
genie.job –f configs/pl_go_gs_GMD.xml
```

The Supplement related to this article is available online at doi:10.5194/gmdd-8-10677-2015-supplement.

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Table 1. Ensemble varied parameters.

Parameter	Description	Range	Subjective tuning
APM (Sv)	Atlantic–Pacific moisture flux correction	0 to 0.32	0.2132
OVD ($m^{-2} s^{-1}$)	Reference diapycnal diffusivity	2×10^{-5} to 2×10^{-4}	1.583×10^{-4}
OHD ($m^{-2} s^{-1}$)	Isopycnal diffusivity	500 to 5000	1937
(dimensionless)	Wind stress scaling	2 to 4	3.788
ADRAG (days)	Inverse ocean drag	0.5 to 5.0	2.069
OP1 (dimensionless)	Power law for diapycnal diffusivity depth profile	0.5 to 1.5	0.8200

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Table 2. The global energy balance of subjectively-tuned PLASIM-GENIE in the preindustrial state compared against estimates derived from the "Earth Radiation Budget Experiment" ERBE (1985–1989), when the Earth's radiation balance was in approximate equilibrium, and the "Clouds and Earth's Radiant Energy System" CERES data (2000–2004). The observational uncertainties reflect a range of analyses summarised in Trenberth et al. (2009).

	Solar radiation ($W m^{-2}$)				
	Incoming TOA	Reflected by atmosphere	Absorbed by atmosphere	Reflected by surface	Absorbed by surface
PLASIM-GENIE	341	75	66	39	161
ERBE (1985–1989)	339–343	70–83	64–81	23–45	156–169
CERES (2000–2004)	339–342	69–82	64–78	23–45	161–170
	Planetary radiation and heat fluxes ($W m^{-2}$)				
	Sensible heat	Latent heat	Back radiation	Upward surface radiation	Outgoing radiation OLR
PLASIM-GENIE	20	78	323	386	228
ERBE (1985–1989)	15–24	78–85	324–345	390–396	235–254
CERES (2000–2004)	15–19	83–90	324–345	394–397	236–254

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Table 3. Simulated surface ocean moisture fluxes of the subjective tuning and observationally constrained estimates. The definition of ocean basin boundaries follows Talley (2008) viz. Atlantic and Indian Oceans north of 32° S, Pacific Ocean north of 28° S.

	Surface ocean moisture fluxes (Sv)					
	Atlantic/Arctic Ocean	Pacific Ocean	Indian Ocean	Southern Ocean	Total Ocean	Trenberth et al. (2007)
Precipitation	1.96	4.76	1.67	2.89	11.28	11.8
Evaporation	−2.68	−5.48	−1.98	−2.52	−12.66	−13.1
Run off	0.59	0.36	0.23	0.18	1.37	1.3
Flux correction	−0.21	0.21	0.00	0.00	0.00	
Net	−0.34	−0.14	−0.07	0.56	0.00	
Talley (2008)	−0.28 ± 0.04	0.04 ± 0.09	−0.37 ± 0.10	0.61 ± 0.13		

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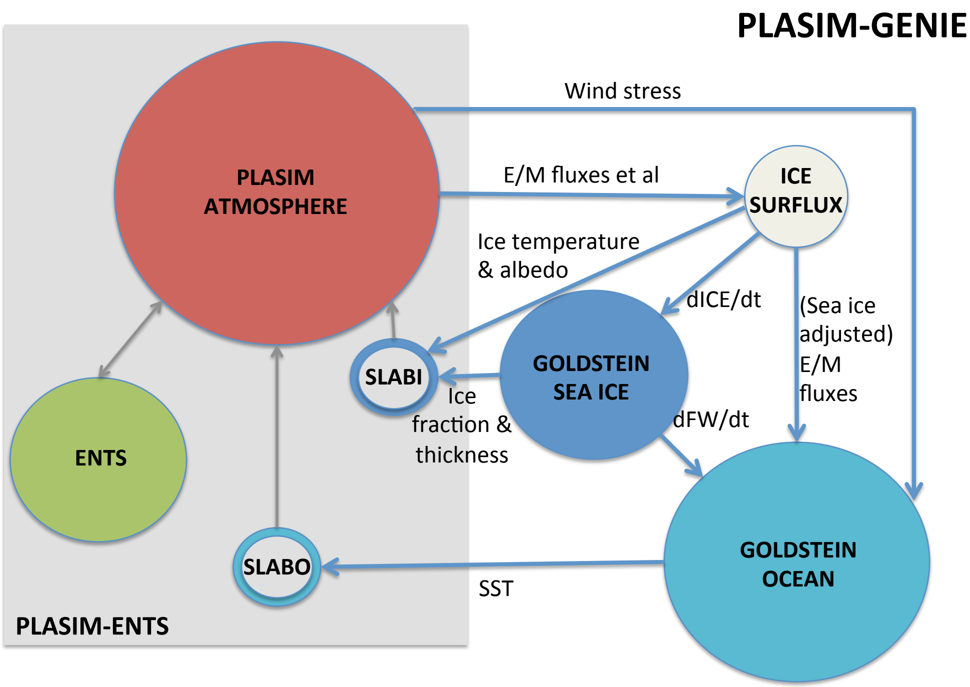

Figure 1. A schematic of the PLASIM-GENIE coupling. The circles represent the component modules, with sizes indicative of their relative complexity. The grey box defines the PLASIM-ENTS model, which has been retained in its entirety; hollow circles (SLABO and SLABI) are dummy PLASIM modules, retained only to specify ocean and sea–ice boundary conditions from GOLDSTEIN outputs; grey lines are energy and moisture fluxes that are calculated within the pre-existing PLASIM-ENTS coupling. Blue arrows are variables passed in the PLASIM-GENIE coupling. ICE-SURFLUX is the new surface flux routine that was developed for the coupling (see Sect. 3.3).

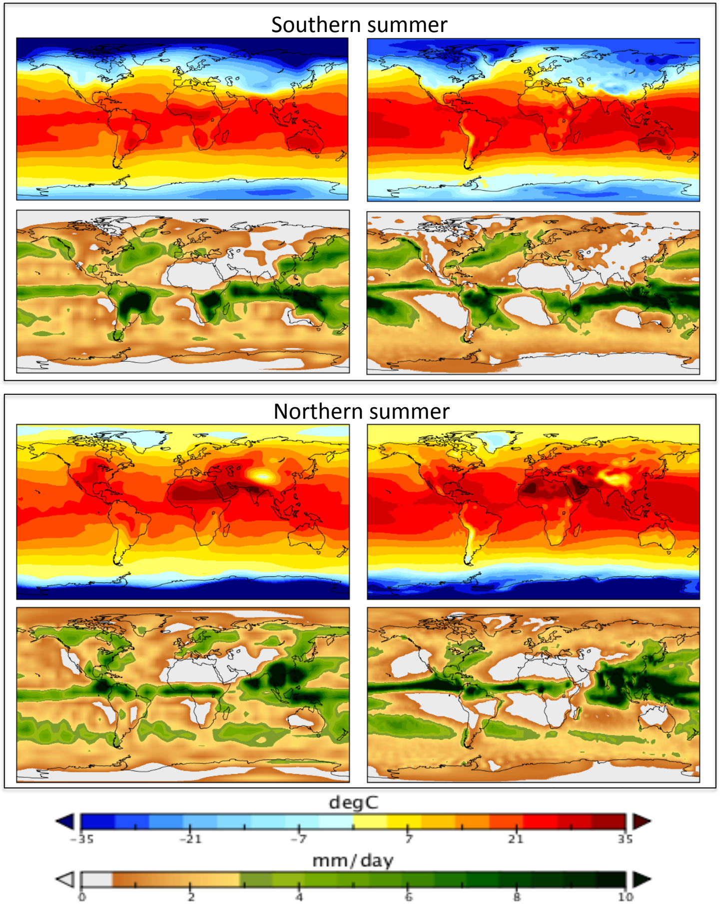

Figure 2. Seasonal surface air temperature and precipitation. PLASIM-GENIE outputs (left) are compared with NCEP/NCAR reanalysis fields (right, Kalnay et al., 1996).

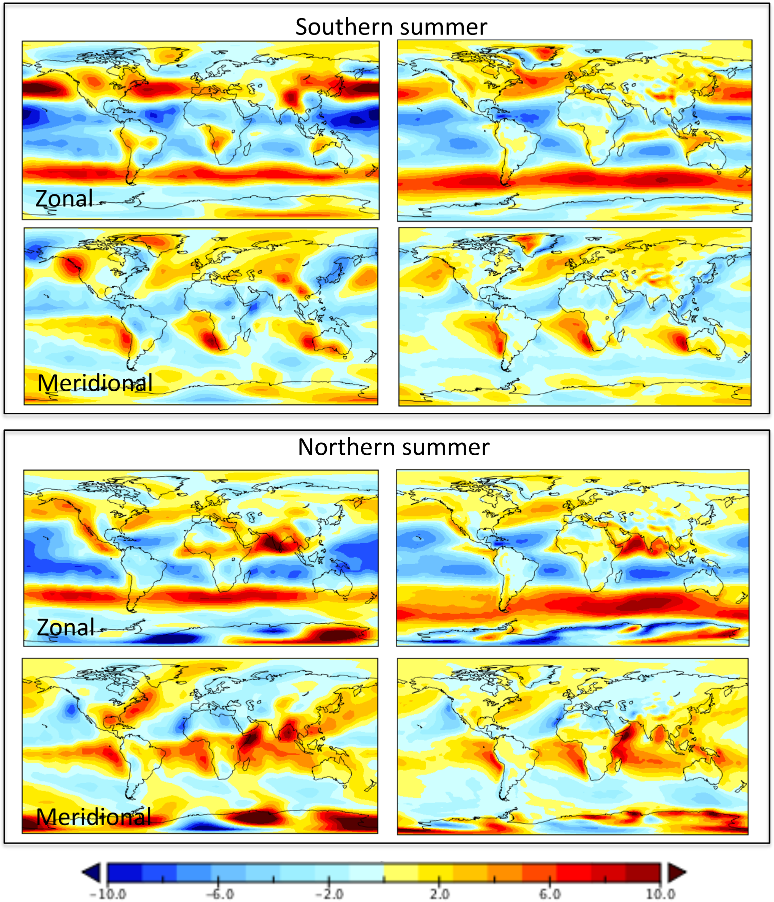

Figure 3. Seasonal surface zonal and meridional wind speeds ($m\,s^{-1}$). PLASIM-GENIE outputs (left) are compared with NCEP/NCAR reanalysis fields (right, Kalnay et al., 1996).

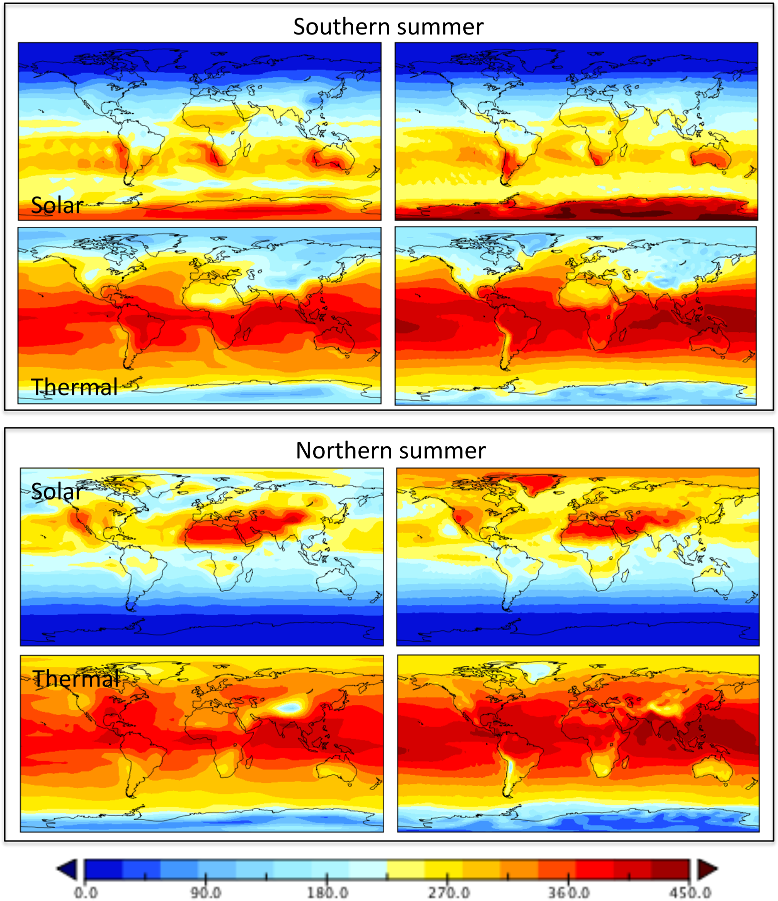

Figure 4. Seasonal incoming surface solar and thermal radiation ($W\,m^{-2}$). PLASIM-GENIE outputs (left) are compared with NCEP/NCAR reanalysis fields (right, Kalnay et al., 1996).

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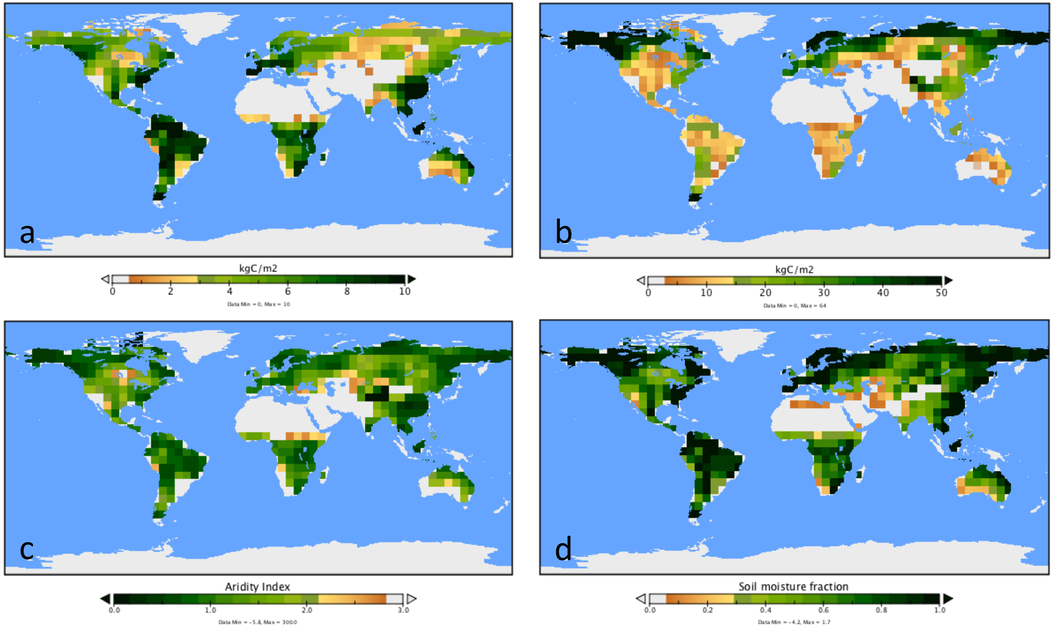

Figure 5. Land surface. **(a)** ENTS vegetation carbon density, **(b)** ENTS soil carbon density, **(c)** Budyko aridity index N/P and **(d)** soil moisture fraction E/N.

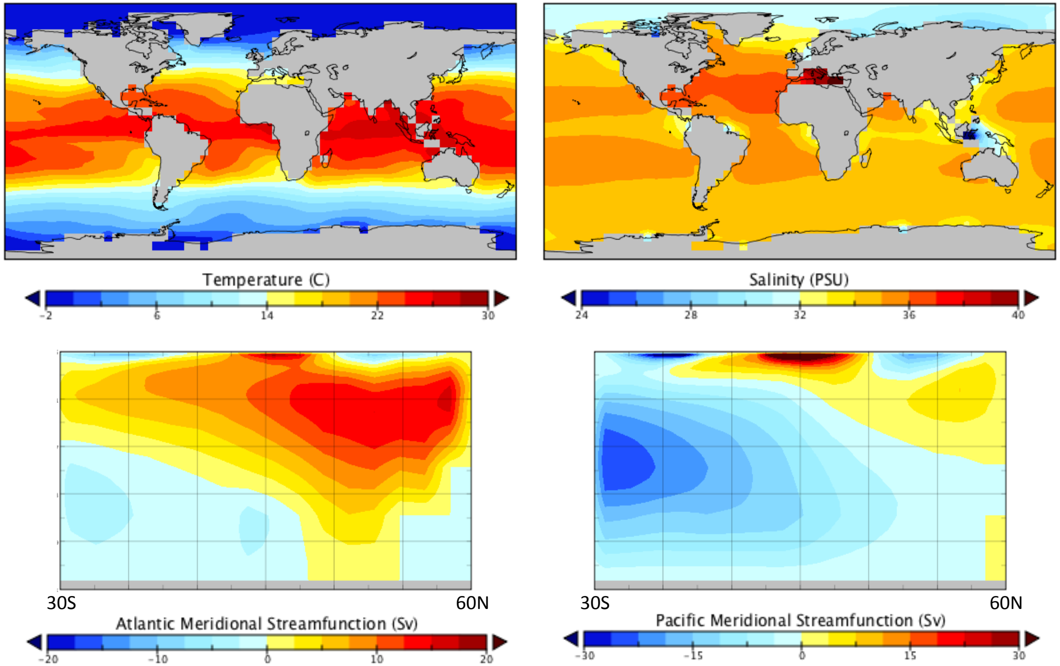

Figure 6. Ocean. Upper panels: PLASIM-GENIE simulated surface ocean temperature and salinity. Lower panels: PLASIM-GENIE simulated Atlantic and Pacific meridional stream functions.

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