Epitomic Data for Community Land Model Standalone Simulations for Prognostic Analyses of Tropical Mountain Glaciation and Lake Temperature in Pre-Industrial, Last Glacial Maximum, and Extreme Glacial Climates

Nicholas G. Heavens[1,*]

[1]Space Science Institute, Boulder, CO, USA

*Corresponding author; E-mail address: nheavens@spacescience.org

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Abstract

Global climate models typically simulate climate at much larger spatial scales than tropical mountain glaciers and many of the world's lakes. Yet some of the proxy data that can be used to validate models of past climate on land come from and are related to these geographic features. Validating global climate models using these proxies requires some method of downscaling global climate model output to the resolution of the relevant geographic feature. One possible downscaling technique is to use the global climate model to generate a time-evolving atmospheric state that can be used to force the model's own land component at much higher resolution than the global model to resolve the relevant geographic features and/or local topography as well as the processes of interest. This dataset contains the output from 50 experiments that use the Community Earth System Model version 2 (CESM2) and its land component, the Community Land Model (version 5) to downscale climate simulations of pre-industrial, Last Glacial Maximum, and an extreme glacial climate with gross similarities to hypothetical late Paleozoic conditions (but within a Last Glacial Maximum paleogeography) to better resolve tropical mountain glaciers in various parts of the world and in one case, a lake. These experiments largely interpolate the land properties assumed by the relevant global climate model simulation to a 100 point per degree grid in a domain that is 1° in longitude and 2° in latitude. Global, high-resolution topography, and sometimes lake distribution datasets are then used to provide information about topography and other properties on the 100 ppd grid. The experiments are then run for 30 or 60 years. The dataset also contains global climate model simulation output of the model experiments used to generate the atmospheric forcing, simple analyses of tropical mountain glacier stability and extent in the experiments, and the code necessary to reproduce these experiments or apply them to other spatial domains.

1. Introduction

While the horizontal resolution of global climate models (GCMs) continues to improve, horizontal resolution of most long-term experiments is only ~ 1° (~ 110 km at the Equator) (Hewitt et al., 2020). This horizontal resolution is much coarser than climate-sensitive landforms/bodies of water like tropical mountain glaciers (Heavens, 2021a), and lakes, and therefore GCMs may not adequate resolve the processes that control climatically-driven changes in these features. The problem is more pronounced for paleoclimate simulations, where it may be necessary to use lower resolution horizontal model grids to enable much different Earth system configurations to come to equilibrium in a computationally efficient manner (e.g., Yeager et al., 2006). Yet the proxy information provided by the extent and properties of past mountain glaciers and climate proxies dependent on the vertical stratification of lakes both may be valuable for validating the continental climates simulated by paleoclimate models. Paleoclimate model validation often depends heavily on proxies from marine climates (e.g., Tierney et al., 2020). Therefore, it would be ideal to have some way to downscale relatively low resolution GCM output to the scales relevant to continental climate proxies without significant computational expense.

Heavens (2021a) proposed and provided a good demonstration that pre-industrial mountain glaciation could be simulated within high-resolution, topography–resolving standalone land model simulations using version 5 of the Community Land Model (CLM5) forced by atmospheric output ultimately coming from fully coupled GCM simulations by the Community Earth System version 2 (CESM2) (whose land component is CLM5). The central argument of Heavens (2021) was that such a downscaling technique was a self-consistent tool to help validate the GCM as well as its land model component.

Because of interest in the sensitivity of tropical mountain glaciation to climates colder than that of the pre-industrial era as well as in the applicability of the technique to lakes, I have applied the technique of Heavens (2021) to lakes as well as to a broader range of climates and domains known to have had mountain glaciation in the present or in the past.

Here I report the existence of 50 archived standalone land model simulations using the Community Land Model version 5 (CLM5) (Lawrence et al., 2019) and the 3 fully coupled climate model simulations using the Community Earth System Model version 2 (CESM2) (Danabasoglu et al., 2020) that were used to make data atmospheres to drive the CLM5 simulations. These are archived in 53 separate datasets on Zenodo, one for each separate model simulation. In Section 2, I describe these datasets and their contents. In Section 3, I describe how they were made and how they may be reproduced.

2. The Datasets and Their Contents

2.1 The Datasets:

The datasets are titled in two ways: (1) CLM Standalone Simulation xxxsector_yy_exper22a or (2) CESM Simulation zzzzzzzzzzzz (Epitomic Data).

The simulation name for the CLM experiments (Table 1) is used in the title of the dataset and is in the form xxxsector_yyyy_exper22a. The xxx is a 3 letter code indicating the geographic region covered by the simulation domain (named after a nearby mountain or lake), as listed in Table 2. The yyyy (2–4 letter code) indicates the background climate/data atmosphere used to force the CLM simulations: pi for pre-industrial; 21ka for Last Glacial Maximum, and cold for an extreme glacial climate simulation.

The simulation names for the datasets corresponding to the fully coupled climate model simulations titled CESM simulation are non-standard: pi_b1850_paleocab is the pre-industrial simulation; lpia_21ka_c211105 is the Last Glacial Maximum simulation; and prestdlpia_stdins_c220126 is the extreme glacial simulation.

The datasets can be accessed on Zenodo using the Deposit ID numbers, as detailed in Table 1.

Table 1: List of archived simulations on Zenodo. The simulation name is the leading string for model output files. The Deposit ID can be used to access the dataset, for example, by using its Digital Object Identifier (DOI) in the form dx.doi.org/10.5281/zenodo.<Deposit ID> (The brackets should not be typed.)

Simulation Name	Deposit ID
badsector_pi_exper22a	7086021
ccrsector_pi_exper22a	7096016
chisector_pi_exper22a	7096038
gilsector_pi_exper22a	7096085
huasector_pi_exper22a	7096089
illsector_pi_exper22a	7096097
iztsector_pi_exper22a	7096105
kilsector_pi_exper22a	7096119
kinsector_pi_exper22a	7096123
knysector_pi_exper22a	7096144
mausector_pi_exper22a	7096138
ngasector_pi_exper22a	7096159
nsisector_pi_exper22a	7096153
nspsector_pi_exper22a	7096165
pujsector_pi_exper22a	7096181
rassector_pi_exper22a	7096187
lpisector_pi_exper22a	7096199
badsector_21ka_exper22a	7096227

ccrsector_21ka_exper22a	7096241
chisector_21ka_exper22a	7096245
gilsector_21ka_exper22a	7096263
huasector_21ka_exper22a	7096274
illsector_21ka_exper22a	7096278
iztsector_21ka_exper22a	7096282
kilsector_21ka_exper22a	7096308
kinsector_21ka_exper22a	7096317
knysector_21ka_exper22a	7096321
mausector_21ka_exper22a	7096335
ngasector_21ka_exper22a	7096329
nsisector_21ka_exper22a	7096339
nspsector_21ka_exper22a	7096342
pujsector_21ka_exper22a	7096346
rassector_21ka_exper22a	7096352
lpisector_21ka_exper22a	7096358
badsector_cold_exper22a	7118511
ccrsector_cold_exper22a	7096372
chisector_cold_exper22a	7096376
gilsector_cold_exper22a	7096386
huasector_cold_exper22a	7096394
illsector_cold_exper22a	7096400
iztsector_cold_exper22a	7096415
kilsector_cold_exper22a	7096421
kinsector_cold_exper22a	7096425
knysector_cold_exper22a	7096429
mausector_cold_exper22a	7096434
ngasector_cold_exper22a	7096438
nsisector_cold_exper22a	7096445
nspsector_cold_exper22a	7096447
pujsector_cold_exper22a	7096451
rassector_cold_exper22a	7096463
pi_b1850_paleocab	7096491
lpia_21ka_c211105	7096473
prestdlpia_stdins_c220126	7096499

Table 2: Sector names, their domain bounds, and key features within the domains.

Number	Abbreviation	Latitude Bounds (°N)	Longitude Bounds (°E)	Mountains/Features
1	izt	18.5, 20.5	-99.5, -98.5	Iztaccihuatl+ Ajusco Mexico
2	ccr	8.5, 10.5	-84,-83	Cherro Chirripo, Costa Rica
3	nsi	4,6	-76,-75	Los Nevados de Santa Isabel y del Ruiz, Colombia
4	chi	-2, 0	-79,-78	Chimborazo+ Antisana, Ecuador
5	hua	-10,-8	-78,-77	Huascaran, Peru
6	nsp	-18.5,-16.5	-69.85,-68.85	Nevado Sajama, Bolivia; Parinacota, Chile
7	ill	-17.5,-15.5	-68.5,-67.5	Illimani, Bolivia
8	kny	-1,1	37,38	Mt. Kenya, Kenya
9	kil	-4,-2	37,38	Mt. Kilimanjaro (Kibo and Mawenzi peaks)
10	nga	-1,1	29.5,30.5	Mt. Ngaliema, Uganda

11	ras	12.5,14.5	38,39	Ras Dejen, Ethiopia
12	bad	7,9	39,40	Mount Badda, Ethiopia
13	gil	-5,-7	143.5,144.5	Mount Giluwe, Papua New Guinea
14	kin	5,7	116,117	Kinabalu, Malaysia
15	puj	-4.9, -2.9	136.7, 137.7	Puncak Jaya, Indonesia
16	mau	19,21	-155,-156	Mauna Kea, Hawaii
17	lpi	16,18	-89.5,-90.5	Lago Petén Itzá, Guatemala

2.2 Contents of the Datasets:

A. The CLM Standalone Simulation datasets contain: (1) monthly mean output from 30 years of CLM simulations at 100 points per degree (~1.1 km at the Equator) resolution named in the form: xxxsector_yyyy_exper22a.clm2.h0.aaaa-bb.nc, where xxx and yyyy are defined as in the name of the dataset, aaaa is the simulation year, and bb is the month of the simulation year; (2) one of the land information input files necessary for the simulation named in the form: domain.lnd.xxxsector_yyyy.fv1.9x2.5_gx1v7.nc; (3) the other land information input file necessary for the simulation named in the form: surfdata.xxxsector_yyyy.fv1.9x2.5_gx1v7.nc; and (4) the code used to create the land input files: landfilemaker_yyyy2deg_c<date>.py, where <date> is the date of creation. In experiments number 1–16 in Table 2, the dataset also includes (5): a .MAT binary file with a name in the form of xxxsector_yyyy_exper22a_c220629.mat that is an analysis of parameters related to glaciation in the experiment. (Note that files of this form can be opened and manipulated by non-proprietary software such as octave or scipy.

In Experiment 17 (lpisector), file type (5) is omitted, file types (2), (3), and (4) have the string "_hodell" in their name. The difference is that this experiment is trying to resolve lakes within the model domain rather than mountain glaciers. The domain chosen resolves Lago Petén Itzá for comparison with the results of Hodell et al. (2012).

The variables of file type (5), where it is present, are:

lat_grid: Latitude grid of simulation in degrees North.

lon_grid: Longitude grid of simulation in degrees East (0-360)

TOPO_GLC: High-resolution topography (m) grid used in the simulation

SNOWDP_ICE_FINAL: Snow depth (m) in the last month of the simulation over glaciers.

SMB_SUM_FINAL: Net surface mass balance (m) on glaciers after 30 years of simulation.

SMB_SF_EST: If defined, the first number is the minimum elevation (m) at which surface mass balance>0, and the second number is the maximum elevation (m) at which surface mass balance<0.

SDP_EST: If defined, the first number is the minimum elevation (m) at which snow depth > 0, and the second number is the maximum elevation (m) at which snow depth=0.

SDP1m_EST: If defined, the first number is the minimum elevation (m) at which snow depth > 1 m, and the second number is the maximum elevation (m) at which snow depth < 1 m.

EXTRTMO_list_peaktopo: If the simulation is divided into regions where surface mass balance > 0, this is the list of the maximum elevation of each region (m).

EXTRTMO_list: If the simulation is divided into regions where surface mass balance > 0, this is the list of the estimated minimum elevation of terminal moraines associated with the region.

EXTRTMO_EST: This is the minimum elevation (m) of a terminal moraine for any region in the domain.

ELA_regions_noflow: If the simulation is divided into regions where surface mass balance > 0, this is the minimum elevation of each region.

ELA_flow: An estimate of ELA if ice is allowed to flow to an extreme degree in a one grid cell valley that balances all accumulation for a region in the domain and the accumulation area + glacial valley are assumed to be one glacier to which the accumulation area ratio method for calculating ELA is applied. A ratio of 0.65 is assumed.

PRECIP_ANN_MEAN: Annual mean precipitation for the domain coming from the data atmosphere

T2M_ANN_MEAN: Annual mean 2 m air temperature for the domain

The calculation of these fields is described in Heavens (2021a,b).

B. The contents of the CESM Simulation datasets are: (1) averages over a 30 year period of monthly mean output from the atmospheric component of the fully coupled simulation in files with names of the form <leading string of the simulation> .cam.h0_clim_cccc_dddd-bb.nc, where cccc and dddd are the start and end date of the average and bb is the month; (2) .mat files with an analysis of the mean tropospheric lapse rate for the simulation with names of the form <leading string of the simulation>_lapserate.mat.

   In the case of the cold simulation, other file types are added. Restart files necessary to start the simulation at the point the data atmosphere was generated are named in a form like: prestdlpia_stdins_c220126.eeeee.0981-01-01-00000, where eeeee is a string indicating the model component and type of restart file. Restart pointer files are named with the leading string: rpointer.

   Files named prestdlpia_stdins_c220126_analysis_cccc_dddd.mat contain information used to assess the radiative balance of the fully coupled simulation and its surface temperature drift.

The variables of this file type where it is present, are global annual means:

A_tot is the shortwave albedo, Ac_tot is the cloud-cleared shortwave albedo, E_tot is the longwave emissivity, FLNT_tot is the top of the atmosphere net longwave flux, FSNT_tot is the top of the atmosphere net shortwave flux, FSNTc_tot is the cloud-cleared top of the atmosphere net shortwave flux, and TS_tot is the surface temperature.

3. Steps to Reproduce

The CLM standalone simulations were created in a similar way to what was outlined in Heavens (2021a,b), but the resolution and other aspects of the fully coupled simulations and the lake-focused simulations are different, as outlined below.

Step 1: We first generated suitable fully coupled model simulations. In this case, these simulations are described in Zhu (2021) and Zhu et al. (2022) or derived from them. These simulations are 1.9°x2.5° resolution in the atmospheric finite volume core and gx1v7 (384 latitude x 320 longitude points) resolution in the ocean. They have a modified microphysics that generates a pre-industrial control and Last Glacial Maximum simulation within the range of uncertainty of extant paleoclimate proxy observations (Zhu et al., 2022). The process of setting up these simulations is described and the necessary files needed to set up these simulations are archived in Zhu (2021). The pre-industrial simulation pi_b1850_paleocab is directly taken from Zhu (2021).

The Last Glacial Maximum Simulation (whose data atmosphere simulation is archived as datatm21ka_c211123) branches off the Last Glacial Maximum simulation of Zhu (2021) and Zhu et al. (2022) but changes no settings and is run another 105 model years to verify equilibrium. It has a radiative imbalance over the last 30 years of simulation of -0.4020 Wm^{-2} and decreases in surface temperature at a rate of -0.51 K/century.

The extreme glacial simulation (whose data atmosphere simulation is archived as datatmcold_c220426) is a branch off the Last Glacial Maximum simulation of Zhu (2021) and Zhu et al. (2022) with pCO$_2$ lowered from 190 ppmv to 142.35 ppmv, i.e. 0.5x pre-industrial. It was run for 1075 model years, but it remained significantly transient. So model years 981–1010 were chosen to generate the model atmosphere. Radiative imbalance during this period averages -0.375 Wm^{-2}, while the surface temperature drift is 0.22 K/century.

Step 2: Branch simulations were run off each fully coupled model simulation from Step 1, following the procedure outlined in Zhu (2021). Data atmosphere history files were created by adding these settings to user_nl_cpl:

```
histaux_a2x1hri = .true.
histaux_a2x3hr = .true.
histaux_a2x1hr = .true.
histaux_a2x24hr = .true.
histaux_l2x1yrg = .true.
```

The simulation then was run for 30 model years, whose averages are archived in the CESM Simulation files.

Step 3: Land input files were made for each CLM Standalone Simulation. In most cases, the land input files used for the fully coupled simulation were interpolated to a 100 point per degree grid by nearest neighbor interpolation in the domains listed in Table 2.

For Experiments 1–16 in Table 2, high-resolution topography, standard deviation of elevation, and slope data were then added using 30 arc-second resolution data from GMTED2010 (Danielson and Gesch, n.d.). The topography was used to assign each grid point to one of 10 possible elevation classes and set its elevation. Glaciation then was set to 1% everywhere and vegetation cover was lowered by 1% everywhere.

For Experiment 17, no glaciation is added, though high-resolution topography, standard deviation of elevation, and slope data are added, as in Experiments 1–16. The main difference is that any high-resolution grid point within a the polygonally defined bounds of a lake included in the HydroLAKES database (Messager et al., 2016) is made into a lake with a lake depth equivalent to the mean depth of that lake in HydroLAKES and all other land units are removed.

Step 4: CLM Standalone Simulations then were run using the data atmospheres from Step 2 and the land input files from Step 3. The method for doing so and examples are provided in Heavens (2021a,b).

But the basic routine is this:

a. Set up a directory called xxxsectordata.
b. Copy into it the land domain files for xxxsector.
c. Set up a file called shell_commands with this text:

```
./xmlchange ATM_DOMAIN_PATH <full address of xxxsectordata>
./xmlchange LND_DOMAIN_PATH <full address of xxxsectordata>
./xmlchange ATM_DOMAIN_FILE  domain.lnd.xxxsector_yy.fv1.9x2.5_gx1v7.nc
./xmlchange LND_DOMAIN_FILE  domain.lnd.xxxsector_yy.fv1.9x2.5_gx1v7.nc
```

d. Set up a file called user_nl_clm with this text:

```
fsurdat=<full address of surfdata.xxxsector_yy.fv1.9x2.5_gx1v7.nc>
lapse_rate= <The annual mean of the lapse rate in the domain, as calculated from the
fully coupled model simulation and listed in Table 3>

hist_fincl1=’TSA_ICE’,’RAIN_ICE’,’SNOW_ICE’,’QFLX_SUB_SNOW_ICE’
```

e. Set up a file called user_nl_datm with this text:

```
 domainfile = <full address of domain.lnd.xxxsector_yy.fv1.9x2.5_gx1v7.nc>
 dtlimit = 3.0, 3.0, 3.0, 3.0, 3.0, 3.0
 fillalgo = "nn", "nn", "nn", "nn", "nn", "nn"
 fillmask = "nomask", "nomask", "nomask", "nomask", "nomask", "nomask"
 fillread = "NOT_SET", "NOT_SET", "NOT_SET", "NOT_SET", "NOT_SET",
"NOT_SET"
 fillwrite = "NOT_SET", "NOT_SET", "NOT_SET", "NOT_SET", "NOT_SET",
"NOT_SET"
 mapalgo = "bilinear", "bilinear", "bilinear", "bilinear", "bilinear",
     "bilinear"
 mapmask = "nomask", "nomask", "nomask", "nomask", "nomask", "nomask"
 mapread = "NOT_SET", "NOT_SET", "NOT_SET", "NOT_SET", "NOT_SET",
```

```
"NOT_SET"
 mapwrite = "NOT_SET", "NOT_SET", "NOT_SET", "NOT_SET", "NOT_SET",
"NOT_SET"
 readmode = "single", "single", "single", "single", "single", "single"
 streams = "datm.streams.txt.CPLHISTForcing.Solar yearstart yearstart yearend",
    "datm.streams.txt.CPLHISTForcing.nonSolarFlux yearstart yearstart yearend ",
    "datm.streams.txt.CPLHISTForcing.State3hr yearstart yearstart yearend
    "datm.streams.txt.CPLHISTForcing.State1hr yearstart yearstart yearend ",
    "datm.streams.txt.presaero.cplhist yearstart yearstart yearend ",
    "datm.streams.txt.topo.cplhist yearstart yearstart yearend"
 taxmode = "cycle", "cycle", "cycle", "cycle", "cycle", "cycle"
 tintalgo = "nearest", "nearest", "linear", "linear", "nearest", "nearest"
 vectors = "null"
```

where yearstart and yearend are the starting and ending year of the simulation.

f. Change directory to the CESM2 code directory

```
./create_newcase --case ~/xxxsector_yy_exper22a --res CLM_USRDAT --compset 1850_DATM%CPLHIST_CLM50%BGC-CROP_SICE_SOCN_MOSART_SGLC_SWAV --project <project number redacted> --run-unsupported --user-mods-dir  ~/xxxsectordata --queue economy
```

```
cd ~/xxxsector_pi_exper22a
```

```
cp ~/chisector_fldstest1/SourceMods/src.clm/* SourceMods/src.clm
```

[this is a small code change described in Heavens (2021a,b) to reduce downwelling longwave radiation with altitude

```
./xmlchange NTASKS=360
```

```
./case.setup
```

`./xmlchange STOP_OPTION=nmonths,STOP_N=60` [the run was then restarted after 5 years to run 25 more years]

```
./xmlchange DATM_CPLHIST_DIR=<location of data atmosphere>
",DATM_CPLHIST_CASE=<name of data atmosphere>
./xmlchange
DATM_CPLHIST_YR_START='yearstart',DATM_CPLHIST_YR_END='yearend'
```

```
./xmlchange CLM_FORCE_COLDSTART=on
```

`cp ~/streamfiles_yy_c220516/datm.streams.txt* .` [data atmosphere streamfiles were copied as described and with formatted examples in Heavens (2021b).

```
./xmlchange RUN_STARTDATE="yearstart-01-01"
```

```
qcmd -- ./case.build
```

```
./case.submit
```

For 21ka and cold experiments,

user_nl_cpl was modified before building the case to add:

```
orb_iyear   = -19050
orb_mode    = 'fixed_year'
```

user_nl_clm was modified to add:

```
urban_hac='OFF'
calc_human_stress_indices='NONE'
!stream_fldfilename_popdens='/glade/work/erik/Data/clmforc.no_anthro_zero_hdm_1x1_simyr1925_181113.nc'
!pot_hmn_ign_counts_alpha=0.0
do_harvest=.false.
stream_year_first_urbantv=1850
stream_year_last_urbantv=1850
!stream_year_first_ndep=1850
```

```
!stream_year_last_ndep=1850
irrigate=.false.
!cropfire_a1=0.0
popdensmapalgo = 'nn'
!stream_year_first_popdens = 1925
!stream_year_last_popdens = 1925
```

For experiment 17, the simulation was run 60 years and the last 30 years have been archived to ensure equilibration of the 1-d lake model within CLM.

Table 3: Lapse rate settings for the CLM Standalone Simulations

Number	**Abbreviation**	**Lapse rate for Pre-industrial (pi) simulation (K/km)**	**Lapse rate for Last Glacial Maximum (21ka) simulation (K/km)**	**Lapse rate for extreme glacial (cold) simulation (K/km)**
1	izt	-6.5345833	-6.863401	-6.863401
2	ccr	-6.6540159	-6.997803	-6.997803
3	nsi	-6.7336335	-7.071638	-7.071638
4	chi	-6.6993308	-7.09633	-7.09633
5	hua	-6.8385518	-7.191112	-7.191112

6	nsp	-7.017757	-7.382404	-7.382404
7	ill	-6.7956522	-7.214337	-7.214337
8	kny	-6.6596509	-7.057313	-7.057313
9	kil	-6.5717795	-6.977162	-6.977162
10	nga	-6.8624304	-7.192029	-7.192029
11	ras	-6.9150642	-7.238328	-7.238328
12	bad	-6.8497046	-7.194491	-7.194491
13	gil	-6.8318304	-7.281467	-7.281467
14	kin	-6.823007	-7.274063	-7.274063
15	puj	-6.8644846	-7.261823	-7.261823
16	mau	-6.3513172	-6.697149	-6.697149
17	lpi	-6.5771	-6.8661	N/A

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