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PORT, a CESM tool for the diagnosis of radiative forcing

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Abstract

The Parallel Offline Radiative Transfer (PORT) model is a tool for diagnosing radiative forcing. It isolates the radiation code from the Community Atmosphere Model (CAM4) in the Community Earth System Model (CESM1). The computation of radiative forcing from doubling of carbon dioxide and from the change of ozone concentration from year 1850 to 2000 illustrates the use of PORT.

1 Introduction

In the IPCC Third Assessment Report, Ramaswamy et al. (2001), defined radiative forcing, "*The radiative forcing of the surface-troposphere system due to the perturbation in or the introduction of an agent (say, a change in greenhouse gas concentrations) is the change in net (down minus up) irradiance (solar plus long-wave; in* $W\,m^{-2}$*) at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values*". This definition of radiative forcing includes the stratosphere adjustment under the assumption of fixed dynamical heating (FDH) as discussed in Kiehl and Boville (1988) or Fels et al. (1980). Radiative forcing is distinguished from instantaneous radiative forcing, in which the stratospheric temperatures are not allowed to readjust to radiative equilibrium.

The Community Earth System Model, (CESM1) and the Community Atmosphere Model version 4 (CAM4, Gent et al., 2011), use a radiation parameterization developed by Briegleb (1992), Collins et al. (2002), and Collins (1998). This parameterization computes the scattering and absorption of shortwave (solar) radiation by the atmosphere and surface, as well as the absorption and emission of longwave radiation by the atmosphere and surface. This parameterization applies to atmospheres from about 1mb (because of the lack of non-local thermal equilibrium parameterization and additional absorption) to 1000 mb. It includes optical effects of water vapor, methane,

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ozone, chlorofluorocarbons, sulfuric acid aerosols, ammonium sulfate aerosols, dust aerosols, carbonaceous aerosols, sea salt aerosols, nitrous oxide, carbon dioxide, water and ice clouds, and molecular oxygen. It also includes optical characterizations of the surface and time-dependent spectral characteristics of the solar irradiance, including solar cycle variability and sun-earth geometry.

A Parallel Offline Radiation Tool (PORT) is distributed with CESM1. PORT isolates the radiation computation in CESM1/CAM4 so that radiative fluxes and heating rates can be computed without feedbacks on surface, subsurface, and atmospheric states. PORT has been used extensively with CAM4 generated data (Lamarque et al., 2011; Meehl et al., 2012; Shindell et al., 2012; Stevenson et al., 2012). Extensions for use with updated physics (CAM5) and radiation (RRTMG, Clough et al., 2005; Iacono et al., 2008), are ongoing. From CESM, PORT inherits the parallel processing capabilities and data ingest and export methods. It also inherits the namelist specifications and netcdf file types. Users of CAM should find most aspects of running PORT familiar. This paper describes PORT's implementation of both instantaneous radiative forcing and radiative forcing including fixed dynamical heating.

Computation of the radiative forcing due to (1) the doubling of CO_2 (from 380 ppbv to 760 ppbv) and (2) the ozone changes from 1850 to 2000 illustrate how to use PORT, and allow for comparison with a previous study.

2 Implementation of radiative forcing, including FDH

As defined in the introduction, running PORT on two different atmospheric compositions (keeping the thermodynamic specifications the same) and then differencing the net radiative fluxes provides the instantaneous radiative forcing, Fig. 1. The instantaneous radiative flux is typically reported at the top of the atmosphere, top of the atmospheric model, tropopause or at the surface. For all calculations below, we sampled CAM4 instantaneous radiative fluxes and atmospheric states from a 16-month (1 September to 31 December of the following year) present-day simulation of CAM4

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with a carbon dioxide volume mixing ratio of 380 ppbv. We first checked that the calculation using PORT led to bit-for-bit identical results to the CAM4 simulation. We then doubled the carbon dioxide (as illustrated in Fig. 1) and ran PORT. Differencing the net fluxes at the top and surface gave us the instantaneous radiative forcings listed in Table 1. Sampling issues are discussed in Sect. 3.

The calculation radiative forcing is more complicated than the calculation of instantaneous radiative forcing. The complication arises from the inclusion of the effect of stratospheric temperature adjustment. PORT implements radiative forcing similarly to Kiehl and Boville (1988) or Fels et al. (1980). In the definition of radiative forcing in Ramaswamy et al. (2001), the stratospheric temperatures are allowed to adjust to radiative equilibrium in the forced system above the tropopause, under the assumption that the dynamical heating of the stratosphere does not change. PORT prognoses the stratospheric temperature adjustment at every time step using an explicit Euler method as discussed below.

The total heating, H above the tropopause is assumed to be the sum of radiative heating, Q and dynamical heating D, where T is the temperature and c is the atmospheric composition.

$$H(T,c) = Q(T,c) + D(T,c) \quad (1)$$

The radiative heating rate, $Q(T,c)$ is total of the shortwave and longwave heating at atmospheric temperature, T, by an atmosphere with composition, c. Under the assumption of fixed dynamical heating, when the composition is perturbed c_p, and the consequent adjusted temperature in the stratosphere is T_p, the dynamical heating is assumed to be unchanged $D(T,c) = D(T_\mathrm{p}, c_\mathrm{p})$, but the radiative heating rates, $Q(T_\mathrm{p}, c_\mathrm{p})$, and total heating rates $H(T_\mathrm{p}, c_\mathrm{p})$ in the forced system change.

$$H(T_\mathrm{p}, c_\mathrm{p}) = Q(T_\mathrm{p}, c_\mathrm{p}) + D(T,c) \quad (2)$$

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The time evolution of the temperature in the unperturbed and perturbed system is given by the equations,

$$\frac{dT}{\mathrm{d}t} = H(T,c) = Q(T,c) + D(T,c) \tag{3}$$

$$\frac{dT_m}{\mathrm{d}t} = H(T_\mathrm{p},c_\mathrm{p}) = Q(T_\mathrm{p},c_\mathrm{p}) + D(T,c) \tag{4}$$

Differencing the previous equations leads to the resulting prognostic equations for stratospheric temperature adjustment, $T_\mathrm{sa} = T - T_\mathrm{p}$ in the forced system,

$$\frac{dT_\mathrm{sa}}{\mathrm{d}t} = H(T,c) - H(T_\mathrm{p},c_\mathrm{p}) \tag{5}$$

$$= Q(T,c) - Q(T_\mathrm{p},c_\mathrm{p}) \tag{6}$$

The temperature adjustment is only computed above the tropopause. The tropopause is defined as the WMO lapse rate tropopause and is found using the technique of Reichler et al. (2003). This technique compensates for the coarse vertical resolution present in many GCMs. Other definitions of the troposphere can be implemented by way of the namelist.

To be precise in our definition of stratospheric temperature adjustment, we define a mask, M, which is 1 for all vertical levels for which the midpoint pressure is less than the tropopause pressure and 0 elsewhere, and the diagnosis of the tropopause is based on the unadjusted temperature. In the case of doubling carbon dioxide, the stratospheric temperatures cool as can be seen in Fig. 2. As a result of the fixed dynamical heating assumption, the change in stratospheric heating (due to doubling of the carbon dioxide and the stratospheric temperature adjustment) has been driven close to zero, but the tropospheric heating rates change as can be seen in Fig. 3.

$$\frac{dT_\mathrm{sa}}{\mathrm{d}t} = M \cdot (Q(T,c) - Q(T - M \cdot T_\mathrm{sa}, c_\mathrm{p})) \tag{7}$$

Equation (7) is solved using the Euler time step method. The adjustment to the stratospheric temperature in the tropics (−20° to 20°) equilibrates over a period of about

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2–3 months as can be seen in Fig. 2. Running the model for 4 months prior to the 12 month period of the average is recommended, so that the stratospheric temperatures are in steady state before the time for a full-year (1 January–31 December) computation begins.

3 Errors from time sub-sampling

Typically, radiative forcing is reported as an annual global average value. Computing the radiation for every CAM4 time step (30 min) with an offline model requires the specification of the atmosphere, surface, solar spectrum, and earth-sun geometry at that frequency, leading to a data storage of nearly 1.3 TB. Sub-sampling the CAM4 model every 73 time steps (1.5 days plus 1 time step) balances a number of different concerns, in particular, having a reasonable file size (18 GB), sampling evenly all seasons, and sampling numerous solar angles of the direct beam at the surface. The sub-sampling relative error in net fluxes is less than 0.1 %, as seen in Table 1. The sub-sampling error in the net longwave flux correction due to the stratospheric temperature adjustment is also less than 0.01 % as seen in Fig. 4. Additional analysis (not shown) have indicated the low biases associated with our chosen 73-step sampling. Less frequent output leads to increasing deterioration of the PORT results against high-frequency output.

4 Basic usage of PORT

A radiative forcing calculation is the difference in radiative fluxes due to a change in atmospheric composition. Figure 1 shows the steps required to perform a radiative forcing calculation using PORT. Here we describe in more details those specific steps:

1. Sample the baseline atmospheric and surface states from a run of CAM4 simulation (at least 1 September–31 December of the following year is needed if FDH is

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being used). Creating the samples requires adding three CAM namelist options specifying (1) that the data should be output, (2) in which history file to place the data, and (3) to place instantaneous samples in that file. Alternately, the user may wish to simply use the baseline state samples (cam4_base.nc) that are distributed with the code. These baseline state samples include data from a little more than a year of data from CAM4.

2. Create two files to be processed by PORT. The files should only differ in the composition for which the forcing is to be computed. For example one may wish to create a file containing ozone from 1850 by overwriting the ozone levels in the baseline file with values appropriate to 1850. Similarly, create a second file containing ozone concentrations appropriate for 2100. The file for 1850 and the file for 2100 should be identical except for the ozone concentrations, if one is interested in ozone forcing only.

3. Compile and run PORT twice, once for each file from the second step. Configuring PORT is as simple as adding a configuration flag to the CAM configuration specification. Running PORT requires (1) specifying the file containing samples of the atmosphere and surface (created in the second step) and (2) specifying the case name for the output results. The user may use the namelist to output additional radiation diagnostics, such as heating rates for clear sky, or fluxes at the surface or tropopause.

4. Radiative forcing is the difference between fluxes computed in the third step as seen in Fig. (1).

Computational time and disk space can be a concern for some wanting to run PORT. PORT can be run on a typical Linux cluster. As an example, using the distribution baseline data (cam4_base.nc), sampled from an atmosphere simulation with 26 vertical levels (up to 2.3 hPa) and horizontal grid ($1.9^{\circ} \times 2.5^{\circ}$) every 73rd time step, leads to 17 520 columns for each of 240 time samples from the year (about 17 GB). PORT, when

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compiled using the Portland Group fortran compiler processes this 16-month data slice in 28 minutes on 8 Intel Xeon processors running at 2.67 GHz. Note that a typical PORT run will require processing 2 files of 16 months if stratospheric temperature adjustments (FDH) are included in the radiative forcing.

5 Application: ozone radiative forcing

As an application, we compare multi-model radiative forcing calculations, in this case from tropospheric and stratospheric ozone separately or together. In particular, we focus on the recent Atmospheric Chemistry and Climate Model Intercomparison (ACCMIP; Lamarque et al., 2012) model simulations for 1850 and 2000.

From those simulations, we extract from each model the monthly ozone distribution average over the period of simulation (which ranges between 1 and 10 yr). These files are then interpolated to the vertical (26 levels up to 2.3 hPa) and horizontal grid ($1.9^{\circ} \times 2.5^{\circ}$) used in the distributed base-state file, cam4_base.nc. Using those interpolated monthly fields, we overwrite the tropospheric, stratospheric or total ozone distributed cam4_base.nc file at each corresponding month in the base-state file, doing this separately for each model.

Note that in the present calculations, the tropopause is defined by the 150 ppbv ozone distribution in the 1850 simulation (following Young et al., 2012). Note that the monthly average field is used for all timestamps contained in the respective month (i.e. no time interpolation on the ozone field is performed). In this computation there are (11 models) × (2 timeslices, one for each year, 1850 and 2000) × (3 targets) = 66 PORT simulations. In this case, we included the stratospheric temperature adjustment (FDH) to compute the radiative forcing.

Then, for each PORT simulation, we compute the annual/global average fluxes at the top of the model for shortwave and longwave fluxes (labeled in the netcdf output files as FLNT and FSNT respectively). The difference for each model of the 2000 fluxes with the 1850 fluxes leads to the results in Table 2.

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We see that, similar to results published in Ramaswamy et al. (2001), we find a multi-model mean tropospheric ozone RF (shortwave and longwave combined) of 0.34 $W m^{-2}$, a stratospheric ozone RF of $-0.05 W m^{-2}$. Interestingly, we also find that the RF from ozone over the entire column is very close to the sum of the tropospheric and stratospheric contributions, adding to the overall understanding that we are mostly dealing with perturbations in the linear regime.

6 Conclusions

PORT isolates the radiation code from CESM1 and provides a method for computing radiative forcing. It can be used both for radiative forcing and instantaneous radiative forcing.

Testing PORT on another computational platform can be performed by verifying that PORT run on the base state file (distributed with PORT) produces the same fluxes as in the distributed file.

Running PORT on a sub-sample of the data gives very similar global annual averages as when run on samples from every time step of the model.

We find that the forcing due to ozone is nearly linear in a study of radiative forcing between 1870 to 2000 for ozone. The ozone forcing computed using PORT is similar to the results from Ramaswamy et al. (2001).

The source code for PORT is included in the CESM distribution releases 1.0.1 through 1.0.4 (see http://www.cesm.ucar.edu/models/cesm1.0/). The code for the PORT driver is located in models/atm/cam/tools/rad_driver sub-directory. Input data is provided via a public subversion repository located at https://svn-ccsm-inputdata.cgd.ucar.edu. PORT may use the same input data in addition to the radiation control data that is generated by the baseline run, as described above in Sect. 4.

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Table 1. Global annual average instantaneous radiative forcing (in $W m^{-2}$) due to doubling CO_2 when computed with every time sample and with every 73rd time sample. Errors due to sub-sampling are small for both longwave (LW) and shortwave (SW) at both the surface and top.

	every sample	every 73rd sample
LW Top	2.53904	2.53916
SW Top	−0.01718	−0.01718
LW Surface	1.38071	1.38092
SW Surface	−0.04832	−0.04843

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Table 2. Radiative forcing due to changes in ozone between year 1850 and 2000 in the troposphere, stratosphere, and total (combined stratosphere and troposphere) when analyzed with PORT using fixed dynamical heating. Radiative forcing is the sum of the longwave (LW) and shortwave (SW). See Lamarque et al. (2011) for a discussion of the simulation protocol and models used.

	Troposphere		Stratosphere		Total	
RF = LW + SW	SW	LW	SW	LW	SW	LW
CESM-CAM-Superfast	0.09	0.32	0.20	−0.23	0.29	0.09
CMAM	0.08	0.24	0.09	−0.10	0.16	0.13
GEOSCOM	0.09	0.28	0.10	−0.11	0.19	0.16
GFDL-AM3	0.10	0.30	0.07	−0.07	0.17	0.23
GISS-E2-R	0.08	0.22	0.10	−0.23	0.18	−0.01
HadGEM2	0.07	0.21	0.19	−0.24	0.26	−0.06
LMDzORNICA	0.09	0.26	−0.01	0.02	0.08	0.27
MIROC-CHEM	0.09	0.29	0.09	−0.08	0.18	0.20
MOCAGE	0.04	0.16	0.46	−0.79	0.50	−0.64
NCAR-CAM3.5	0.10	0.32	0.11	−0.08	0.20	0.24
UM-CAM	0.09	0.27	0.14	−0.20	0.22	0.05
Multi-model						
mean	0.08	0.26	0.14	−0.19	0.22	0.06
σ	0.02	0.05	0.12	0.21	0.11	0.25

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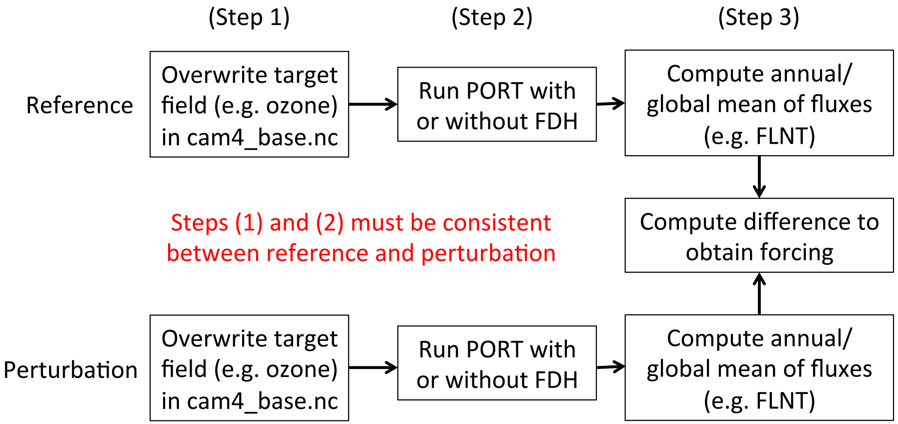

Fig. 1. Typical usage of PORT to compute radiative forcing.

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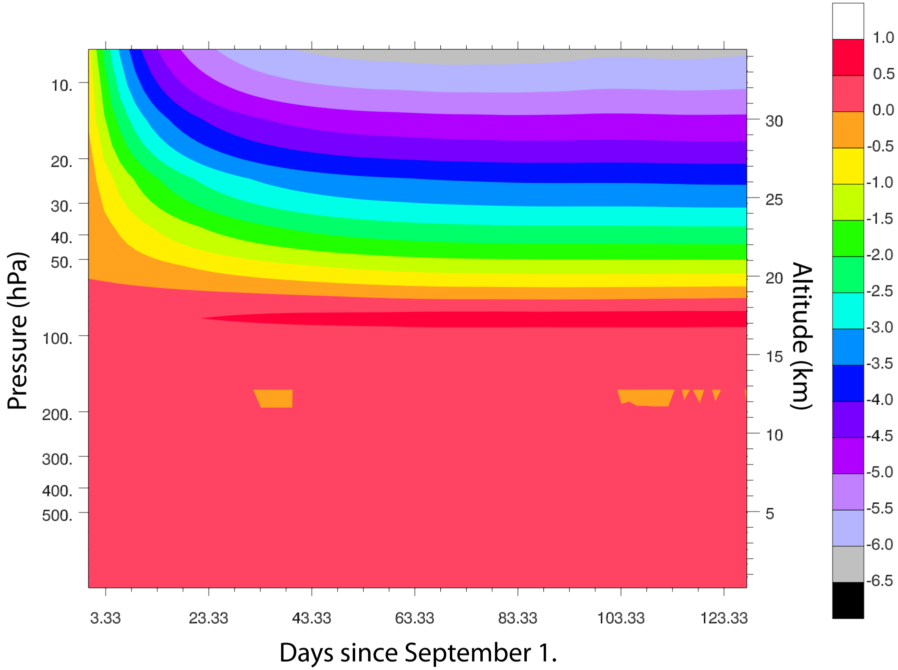

Fig. 2. Tropical (–20° to 20°) average stratospheric temperature adjustment due to doubling CO_2 as a function of time. Relaxation is fastest nearest the tropopause and slower in the upper layers of the model. The temperature adjustment seems to be complete after 2 to 3 months since the beginning of the calculations (1 September). Temperature corrections sometimes appear beneath the average tropopause height due to detection of tropopause heights lower than the average tropopause height.

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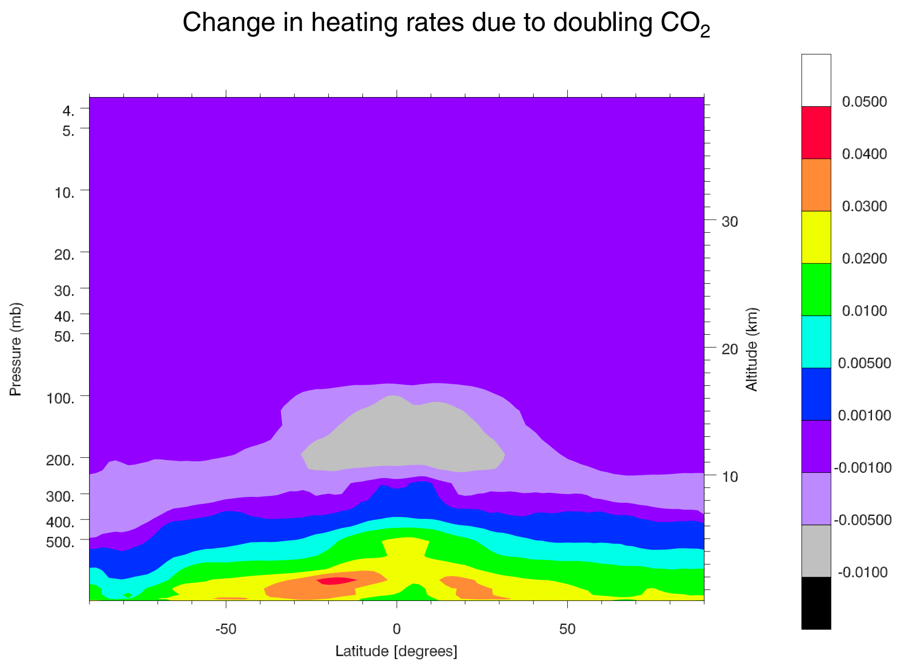

Fig. 3. Change in total (shortwave plus longwave) instantaneous annual average zonal average radiative heating rate due to doubling CO_2 (K day^{-1}). Fixed dynamical heating was assumed in the stratosphere. Note that the predominant changes in radiative heating are in the lower troposphere.

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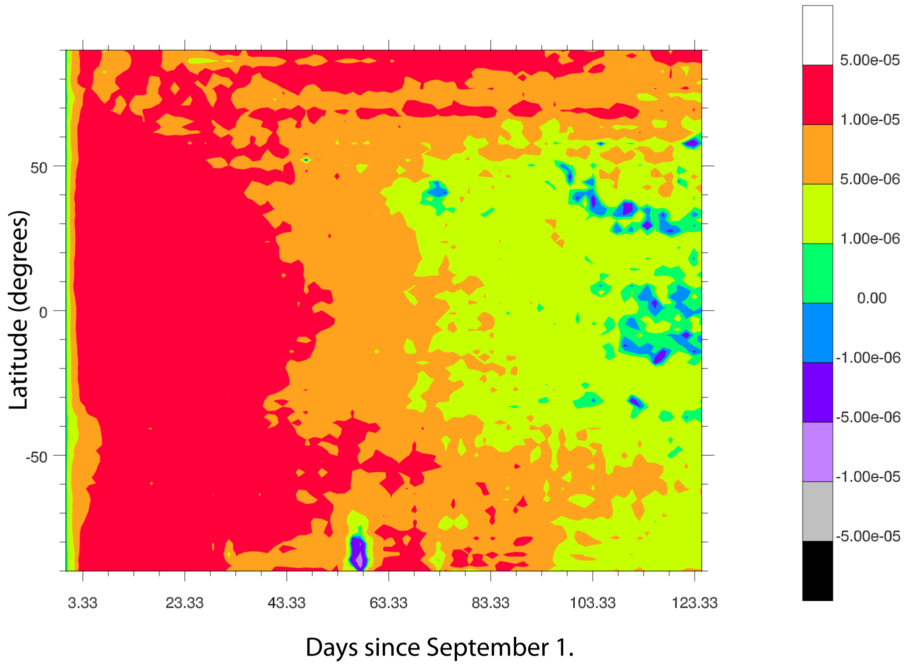

Fig. 4. Plot of relative error in net longwave flux due to sub-sampling as a function of latitude and days. When CO_2 is doubled, the temperatures in the stratosphere relax over a period of 2 to 3 months. Relative error of the net longwave flux between sampling every time step and every 73rd time step in zonal average net flux at the tropopause is less than 0.005 % everywhere during this relaxation period.

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