

GFDL CM2 with CO₂ transport

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Introduction.....	1
Design Goal	1
Methodology	2
Implementation	3
Technical Difficulties.....	4
Future Objectives	5
Performance	5
Conclusion	5
User's Guide	5
Appendix.....	6

Introduction

A fully coupled climate model with carbon dioxide transport among model components is desired to conduct scientific experiments on the feedback effect of CO₂ on a global spatial scale and over several hundred-year time scale. This project builds a high-resolution CO₂ transport model based on existing GFDL coupled model version 2 (CM2). The same technique is then applied to transport requirement of other gaseous tracers among component models. This paper summarizes the design goal, methodology, implementation, technical difficulties, future objectives, and performance assessment, etc, with the GFDL CM2 with CO₂ transport model development.

Design Goal

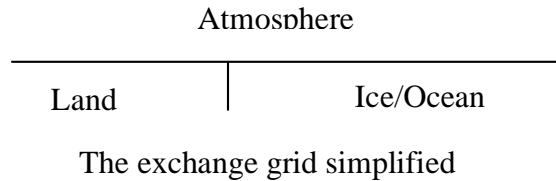
This project starts out with the following model components, the finite volume atmospheric model (fv), the land model version 3 (lm3), the ice model (sis), and ocean model version 4 (mom4). Based on this existing set of components, interface, and integration scheme, a coupled model is built. This newly built coupled model is used as a foundation to implement CO₂ transport among atmosphere, land, ice, and ocean. The atmospheric model accounts CO₂ as a tracer and exercises an implicit flux scheme in the atmosphere/exchange_grid transport interface. Due to the nature of the ocean/atmosphere CO₂ transport (a slower process therefore on a longer time step), an explicit scheme is used between the ocean/exchange_grid transport interfaces.

The goal is to seamlessly combine the different schemes of CO₂ transport calculation in the flux exchange grid interface, achieving the effect of full CO₂ transport in a high

resolution coupled model. The atmospheric CO₂ variation affects the model radiation balance. CO₂ feedback effect on overall global climate can be studied.

We have a model available at this point doing full carbon transport and we are planning on the integration of CO₂ feedback process in the atmosphere. The idea is to have a CO₂ transmission function applied all

The model first goes through an initialization phase where necessary physics fields obtain values from restart files. The ocean/ice boundary propagates quantities upward into the surface boundary layer exchange grid (xgrid) in step 1. Then the surface boundary layer maps these quantities through the xgrid interpolation scheme upward to the atmosphere in step 2. Given these quantities from the xgrid, the atmosphere goes through the vertical diffusion downward step to calculate matrix eigenvalue coefficients of these quantities using an implicit scheme in step 3 and 4. These coefficients and updated quantities are made available to land and ice through a downward atmospheric sweep. The reason for adopting such an implicit scheme is for stability. A more detailed description of this method is available in the flux exchange technical guide. With the corrected implicit coefficients at the bottom of the atmosphere by the land and ice in step 5, an upward sweep is made in the atmosphere to update the final atmosphere quantities in step 6 and 7. Then the land, ice/ocean quantities are updated accordingly before the next coupler iteration in steps 8 to 12.



In the surface boundary layer, explicit flux and flux derivative are computed on the xgrid. Due to the stability and time step characteristics of land and ocean, each has opted to its own scheme of computing the flux and flux derivatives. The land sees fast co2 concentration fluctuation and updates co2 concentration on a fast physics time step, while the ocean does not see dramatic co2 change over time. Therefore the land co2 is part of the surface flux scheme and surface flux computes co2 flux derivative (same as water vapor which is actually being computed) and co2 flux. The ocean, through the virtual ice cover, delivers flux directly to the surface boundary layer. The fluxes of land and ocean CO2 are then combined after the surface flux computation and are picked up by the atmosphere update process and join the downward sweep of the vertical diffusivity equation.

Implementation

Based on our understanding of the coupling mechanism, it's clear that the combination of land CO2 and ocean CO2 can be done right after the land/atmosphere surface flux calculation inside of surface boundary layer. We feel this scheme is flexible for future expansion of tracer transport in a coupled model. In the actual implementation, water vapor (we are not concerned with dry model at this point yet) flux derivative is computed in the surface flux process. Since all the tracer flux derivatives (a product of density, mixing length, and wind speed) are exactly the same, the same derivative is applied to the generalized atmosphere bottom tracer array. The fluxes from land and ocean are

combined into the exchange grid flux and averaged to the overlooking atmospheric cell. The land, ice, ocean mask is used to tell whether a particular xgrid cell is over land, over ice, or over ocean. Over ocean, flux derivatives are set to 0, fluxes go upward into xgrid cell; over ice, flux derivatives and fluxes are set to zero; finally over land, flux derivatives and fluxes are delivered upward into the atmosphere bottom layer for a downward sweep.

We added CO₂ feedback process in the atmosphere. CO₂ longwave transmission function is updated every month based on a globally averaged CO₂ concentration. Due to the fact that co₂ transmission function computation is a CPU expensive task, it is unlikely that instantaneous 3D CO₂ concentration will be used in longwave radiation calculation. It's a compromise to have co₂ transmission function updated on a monthly basis and used in the longwave radiation calculation. The shortwave radiation, on the other hand, can compute instantaneous 3D CO₂ absorption without paying significant performance price.

We ensured that individual model components, i.e. atmosphere, land, ocean, ice can run with or without CO₂ transport in standalone mode without dependence on the presence of other component. The latest LM3 has taken this into account and will be able to run standalone mode with or without CO₂ transport. All other component model driver were updated.

Technical Difficulties

Because of conservation requirement, gas flux computations cannot be performed in the ocean model and it has to be done in the coupler. This complicates the overall design of the tracer transport scheme. In the case of land-atmosphere interaction, the land model only needs a few coefficients from the boundary layer to perform necessary flux computation. This is not the case for the ocean, tracer flux has to be explicitly computed inside the coupler. This required an addition of a data structure and associated algorithm to exchange information between ocean and coupler through ice.

Initially we were not clear how the ocean explicit flux should be incorporated into the scheme of things. Because ocean fluxes are computed from quantities obtainable only from the bottom of the atmosphere, in the case of co₂, namely the surface pressure, the mixed layer surface wind, and the atmosphere co₂ concentration. Of particular difficulty is the mixed layer surface wind that is updated later on in the surface boundary layer before diagnostic output. We have decided to perform monin-obukhov boundary layer update twice to solve this problem, one right after the surface flux calculation to compute ocean co₂ flux, the other one before diagnostic output. The effect of doing so on the model physics is yet to be assessed.

Another difficulty is to enable concurrent mode co₂ transport calculation. Because of synchronization issues in the data initialization sequence and the coupling steps, the coupled model couldn't run in concurrent model. We added necessary code to enable this very important feature of the coupled model.

An overall difficulty encountered during the model construction is the lack of testing of the pristine version of the model (without co2), the fv_lm3_sis_mom4 combination. Two pieces of the model are only recently introduced to GFDL. So far, we have fixed numerous bugs involving platform compiler issues, xgrid u* bug, broadband land albedo, fv I/O restart, etc. Results from this particular model combination could use more attention from the scientists in GFDL.

Future Objectives

We need to add dry tracer deposition through the ice model for future ESM research.

Performance

The coupled model performance is 6.5 year / RealLife day on Altix with 120 PE concurrent mode.

Conclusion

Right now we have a solid model infrastructure available for tracer coupling. This infrastructure can easily be extended to include interesting tracers such as nitrogen, methane

There is also a special requirement for the land model. To use the generic tracer scheme, land model must be compiled with `-DLAND_BND_TRACERS`.

Appendix

Current working rts script: `~fil/ESM/rds.170105.xml` (`~fil/ESM/rds.170105.ia64.xml` on Altix)

Experiment name: `CM2.1U_co2_test_concurrent`

A non co2 model rts script is available: `~fil/ESM/fil.050208.xml` (`~fil/ESM/fil.050208.ia64.xml` on Altix)

Experiment name: `CM2.1U_co2_base_concurrent`

We have modified the following files to carbonize the model:

Coupler:

`coupler/coupler_main.f90`
`coupler/coupler_types.F90` ← new
`coupler/flux_exchange.f90`
`coupler/surface_flux.f90`

Ice:

`ice_sis/ice_model.f90`
`ice_sis/ice_type.f90`

Ocean:

`mom4/ocean_core/ocean_model.F90`
`mom4/ocean_core/ocean_sbc.F90`
`mom4/ocean_core/ocean_tpm_util.F90`
`mom4/ocean_core/ocean_tracer.F90`
`mom4/ocean_core/ocean_types.F90`
`mom4/ocean_tracers/ocean_age_tracer.F90`
`mom4/ocean_tracers/ocean_bgc_phyto.F90`
`mom4/ocean_tracers/ocean_bgc_restore.F90`
`mom4/ocean_tracers/ocean_gas_fluxes.F90`
`mom4/ocean_tracers/ocean_tpm.F90`
`mom4/ocean_tracers/ocmip2_biotic.F90`
`mom4/ocean_tracers/ocmip2_cfc.F90`
`mom4/ocean_tracers/ocmip2_co2calc.F90`

Atmosphere:

`atmos_coupled/atmos_model.f90`
`atmos_fv_dynamics/driver/coupled/atmosphere.f90`
`atmos_param/physics_driver/physics_driver.f90`
`atmos_param/vert_diff/vert_diff.f90`

atmos_param/vert_diff_driver/vert_diff_driver.f90
atmos_shared/tracer_driver/atmos_co2.f90
atmos_shared/tracer_driver/atmos_tracer_driver.f90 ← new

Land:

land_she/driver/land_model.F90
land_she/driver/she_land_tile.f90
land_she/driver/she_land_types.f90
land_she/vegetation/she_site.h
land_she/vegetation/she_veg_tile.f90
land_she/vegetation/she_vegetation.F90

Shared:

shared/tracer_manager/tracer_manager.F90
shared/field_manager/field_manager.F90