GFDL CM2 with CO_2 transport

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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

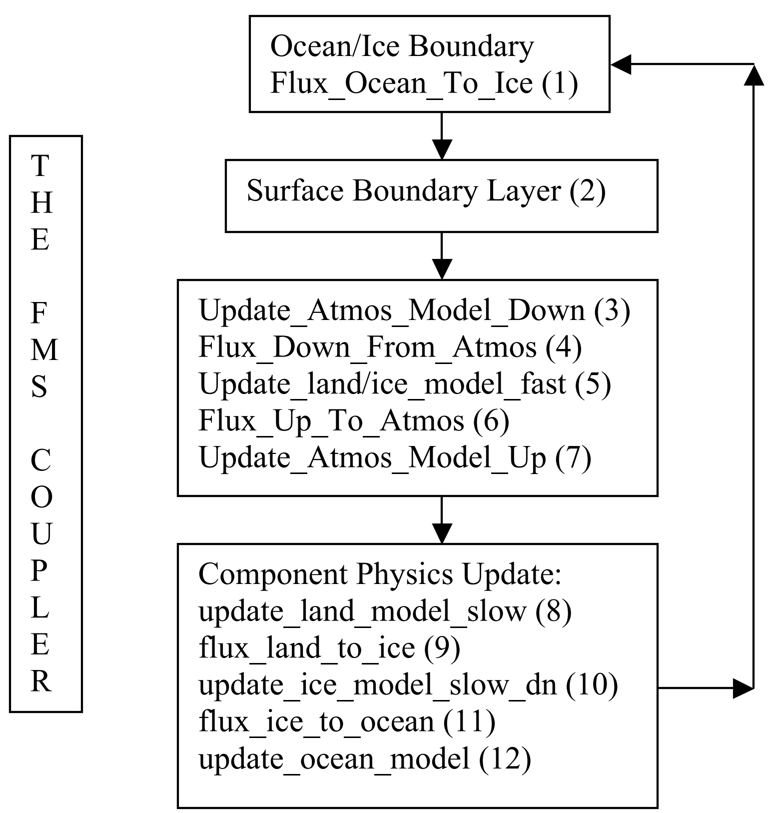
This project starts out with the following model components, the finite volume atmospheric model (fv), the land model version 3 (lm3), the ice model (sis), and ocean model version 4 (mom4). Based on this existing set of components, interface, and integration scheme, a coupled model is built. This newly 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.

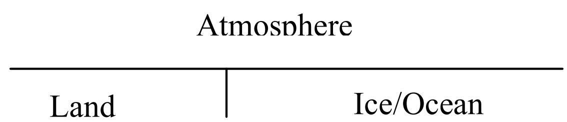
We have a model available at this point doing full carbon transport and we are planning on the integration of CO2 feedback process in the atmosphere. The idea is to have a co2 transmission function update every month based on a globally averaged co2 concentration in the atmosphere.

Methodology

The FMS infrastructure provides a readily available platform for the integration of model components. The coupler iterate through the ocean/ice boundary, the surface boundary layer, the land/ice boundary, and the atmosphere, land, ice, and ocean physics update. Physics quantities including tracer concentrations are communicated in the surface boundary layer. Therefore we concentrate our discussion on how flux_exchange handles the surface boundary layer update. (Surface boundary layer calculation resides in flux_exchange module and temporary fluxes and derivatives are calculated in surface_flux. These terms surface boundary layer, flux_exchange, surface_flux are sometimes used interchangeably in this document)



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.



The exchange grid simplified

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, etc in the future. The current model has full co2 transport among atmosphere, land, ice and ocean.

I would also like to thank all the people who are involved in this project for their effort and contribution.

User's Guide

The tracer transport scheme is transparent to the user, the only thing required is the addition of tracer 'sphum' in land model if it's not there already, such as:

```
"TRACER", "land_mod", "sphum"
        "longname",    "specific humidity"
        "units",       "kg/kg" /
```

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