Atmospheric Chemistry Impacts on the Land Biosphere

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The terrestrial biosphere interacts with the atmosphere to impact climate through impacts on albedo, the hydrological cycle, atmospheric chemistry & aerosols, and carbon dioxide fluxes. The terrestrial biosphere fluxes of carbon dioxide are large, and small changes in those fluxes over time impact the overall atmospheric carbon dioxide concentrations. In return, changes in climate plus atmospheric chemistry & aerosols impact the terrestrial biosphere, and therefore food and other resource production upon which humans rely.

There are many ways that biological systems can respond to impacts from atmospheric chemistry. Sometimes the effects of atmospheric chemistry and aerosols will be to increase stresses (reducing growth), but sometimes atmospheric chemistry and aerosols may *reduce* existing stresses, leading to greater growth (e.g. Nitrogen fertilization and increases in diffuse radiation).

Below is a list of important stresses on the land biosphere. The stresses atmospheric chemistry and aerosols can impact are noted, and subdivided into the stresses directly impacted, and those affected indirectly through the impact of atmospheric chemistry and aerosols on climate.

1. [AC-direct] Ozone Damage (a strong oxidant, it can damage leaves),
2. [AC-direct] Nitrogen Deposition (fertilizes soils with nitrogen),
3. [AC-direct] Increase in Diffuse Radiation (aerosols scatter solar radiation, increasing the proportion of diffuse to direct light at the surface),
4. [AC-direct] Acid Rain (leaches nutrients out of soils),
5. [AC-indirect] Precipitation (quantity, frequency, timing, & state of precipitation are all important),
6. [AC-indirect] Temperature (the radiative impact of reactive GHGs and aerosols have an effect on global warming),
7. [AC-indirect] CO_2 Fertilization (*in situ* oxidation of carbon monoxide, methane, and higher hydrocarbons is equal to 25% of anthropogenic CO_2 emissions),

Note: The order of the listed stresses is not an indication of the relative importance of each stress.

Scientific advances to be accomplished within this project

First: Estimate the importance of each of the land biosphere stresses affected by atmospheric chemistry and aerosols.

Second: Incorporate the important feedbacks into CCSM as appropriate.

Third: Estimate whether online chemistry is required in order to correctly incorporate the interactions within the system.

Necessary model capability (general)

The requirements for the four land biosphere stresses directly impacted by atmospheric chemistry on atmospheric chemistry, land biogeochemistry, and other components of CCSM are:

	Atmospheric Chemistry	Land Biogeochemistry	Other
Ozone Damage	Ozone surface concentration and deposition are both readily available in both the full and fast mechanisms, and just need to be passed through the coupler	Should be straight forward to implement.	Ozone through coupler
Nitrogen Deposition	Nitrogen deposition (wet & dry) is readily available for all nitrogen species in each mechanism. It would be good to add ammonia to the fast (28-specie) ozone-sulfate mechanism.	Requires nitrogen cycle in land biogeochemistry. Already present in CN model.	Nitrogen species through coupler
Increase in Diffuse Radiation	Radiation already includes the direct effect of aerosols from atmospheric chemistry.	Already in CLM.	Send diffuse radiation and VOC emissions through coupler.
Acid Rain	Sulfuric acid and nitric acid are already calculated in both atmospheric chemistry mechanisms, although the degree of neutralization may need some work, especially for the fast mechanism, which lacks ammonia	Significant development still required.	Sulfuric acid and nitric acid through coupler

For the three stresses which atmospheric chemistry and aerosols can indirectly affect through physical climate change, we need all the mechanisms through which atmospheric chemistry & aerosols can affect climate: GHGs, plus aerosol direct and indirect effects. The coupling of GHGs and the aerosol direct effect are already available. The aerosol indirect effect is still being developed.

It would also be good to get volatile organic emissions (VOCs) from the land biogeochemical model for the chemistry. This capability is already available in CLM, and just needs to be connected up to the specific leaf area from each land BGC model.

Current status of models / model development. Key scientific personnel needed.

The key missing element for the atmospheric chemistry is ammonia in the fast mechanism for nitrogen deposition. This will be implemented by LLNL under existing funds (Philip Cameron-Smith). The fast mechanism also currently lacks handling for VOCs. This project could also be done using the full mechanism which currently includes both ammonia and VOCs, if sufficient resources were available.

Modifications to the land model will require collaboration with the developers of the land biogeochemical models used (eg, CN, CASA', IBIS). We need to ascertain the interest of the different developers. Peter Thornton at NCAR (C/N code) is very interested in collaborating on the first three topics (ozone impacts, nitrogen deposition, and diffuse radiation).

Passing tracers through the coupler has recently been made easier, and we can seek the aid of the coupler developers at ANL and NCAR.

Implementation of the aerosol indirect of the first kind is currently being worked on by Phil Rasch, Steve Ghan, Cathy Chuang, and others.

Significant model development is still required in order to study the impact of acid rain.

CCSM simulations are needed

We propose an incremental process to evaluate the importance for climate and biospheric productivity of each direct stress from atmospheric chemistry & aerosols on the land biogeochemistry. We propose to do this first with the CN developer (Peter Thornton) followed by the other two land BGC models that are part of the current BGCWG intercomparison of land BGC models (CASA', and IBIS), resources permitting. We will not consider acid rain at this time, since it is not yet represented in the land BGC models.

There are two questions we want to ask for each interaction:

A. Are the interactions important enough that they should be included in climate simulations?
B. Do the interactions require online chemistry in order for them to be simulated accurately?

The key variables (from the land BGC models) whose response we want to determine are 2D maps and global means of:

I. Net Primary Productivity (NPP = CO_2 uptake by biosphere),
II. Respiration (CO2 flux to the atmosphere)
III. Albedo,
IV. Surface latent heat flux,
V. Surface sensible heat flux,
VI. Volatile organic compound (VOC) emissions.

In order to determine the importance of these interactions, we will focus on the differences between current climate and 2050 using the IPCC A2 scenarios. These two emission fields are well defined by IPCC groups and include large differences. An alternate would be to look at preindustrial vs. current, but preindustrial emissions are also quite uncertain.

Summary of simulation tasks:

Task 1: Get initial CAM/CLM-CN simulations with atmospheric chemistry: Two 10-year simulations with atmospheric chemistry (+ spin-up of up to 5 years), saving the high temporal resolution driving fields for running the standalone land model.

a. 2000 emissions
b. 2050 emissions (A2 scenario)

Task 2: Impacts on land model: Conduct offline land model simulations (up to 500 years), to get land model into equilibrium with chemistry perturbations and see if impacts are significant. The following runs will be required:

	ozone	**nitrogen**	**dir/indir**
a		2000	2000
b	2000	2000	2000
c	2000	2050	2000
d	2000	2000	2050
e	2050	2000	2000
f	2050	2050	2050
g	MM(2000)	MM(2000)	MM(2000)
h	MM(2050)	MM(2050)	MM(2050)

NOTE: The table entries refer to the 1a and 1b simulations, and MM stands for "monthly-mean".

Task 3: Physical system equilibrium: If land response is significant, obtain the equilibrium physical climate for the cases in which the land response is significant. Conduct up to 50 year simulations of CAM/CLM-CN simulations. The main feedback from the land onto the climate is expected to be through leaf area index (LAI) changes altering the surface energy budget.

Task 4: Chemical/physical equilibrium: Obtain physical/chemical equilibrium, using 10 year simulation of CAM/CLM-CN/CHEM. If necessary, repeat land model and physical climate spinup in order to reach steady state (probably only necessary if changes in land emissions of VOCs are very large and cause large change in chemistry).

Task 5: If changes in climate and chemistry between runs done in 1 and 4 are large, and the differences between cases g and b compared to h and f is large, we need to assess whether the impact of atmospheric chemistry & aerosols can be represented by reading data from a file or needs to be done synchronously. To do this, start with equilibrated physical system in Task 4, and include chemical forcing on the land model by reading in the chemical fields written out by Task 4. See if physical/chemical system drifts from that seen in Task 4.

The difference between runs from the different tasks will begin to answer the following questions for each interaction:

A. Interaction important for land BGC model?
    a. Ozone damage = 2b - 2a and 2e - 2b
    b. Nitrogen fertilization = 2c - 2b
    c. Direct/indirect sunlight = 2d - 2b
B. Climate change effects significant? = 2f - 2b
C. Effects of interactions add linearly? = (2f - 2b) - (2e - 2b) - (2d - 2b) - (2c - 2b)
D. Is temporal variability of interaction important? = 2g - 2b and 2h – 2f
E. Amplification by fully interactive model? = 4 - 2
F. Must atmos. chem. & aerosols be synchronous? = 5 - 4

These answers will then allow us to answer the two key questions we posed above: (1) are these interactions important for climate?, and (2) do they require on-line chemistry?.

We propose to do these simulations at low (4x5) or moderate resolution (2x2.5 degrees), depending on compute resources.

The simulations in step 2 will be done with the land running in stand-alone mode, with the relevant atmosphere and chemistry driving fields generated from the 10-year CAM runs in step 1 at high temporal resolution (3 hourly), which can then be cycled. Since the standalone land model is inexpensive to run, we will spin-up each case to steady-state to get see the effect on the long-lived carbon pools (50-500 years) and vegetation distributions. These changes in vegetation will then impact the physical climate system, which will be tested in Task 3, and the chemical system (Task 4).

The base case offline CLM-CN model will use (i) no ozone damage, (ii) existing nitrogen deposition inputs, (iii) existing diffuse/direct radiation inputs, and (iv) no acid rain effect.

Thus, these will be the defaults for the interactions that are not being studied in a particular run.

The main purpose to the runs in Tasks 3 and 4, is to determine the impact of full feedback on:

i. The land output fields,
ii. The atmospheric chemistry & aerosol fields,
iii. The physical fields (e.g., surface temperature).

Our intention is to be just semi-quantitative, ie just to get some idea of how big the effects are. If the feedback effects are large, further study will be required.

We expect that changes in aerosol radiative forcing will require only 5years to get in equilibrium, while changes in land surface properties will require longer time for the physical climate to respond. These statements are qualitative and based on non-tested personal experience.

Since each fully-interactive runs will be computationally expensive, we will only select the cases from the initial tests which merit attention, ie cases for which the interaction produced a statistically significant response. If several cases prove to be statistically significant, and compute resources are limited, then we will combine changes to several of the interactions into single runs.

Time frame

Apart from acid-rain, there is relatively little development work to be done, and the development which is required is already underway. It is therefore reasonable to start doing these simulations in 2006.

Computing resources needed

The full and fast chemical mechanisms are approximately 6 and 3 times as expensive as basic CAM respectively (including the CAM runtime).

The land BGC models are just 2% more expensive than basic CAM.

If FV with 2x2.5 degree resolution is used:

Years for task:	**1**	**2**	**3**	**4**	**5**	**GAU / yr**	**Total GAU**
CLM/CN		4,000				4	16,000
CAM/CLM/CN			200			30	6,000
CAM/CLM/CN/CHEM (full)	30			40	??	180	12,600

CAM/CLM/CN/CHEM (fast)	30			40	??	90	6,300

If FV with 4x5 degree resolution is used:

Years for task:	**1**	**2**	**3**	**4**	**5**	**GAU / yr**	**Total GAU**
CLM/CN		4,000				1	4,000
CAM/CLM/CN			200			10	2,000
CAM/CLM/CN/CHEM (full)	30			40	??	60	4,200
CAM/CLM/CN/CHEM (fast)	30			40	??	30	2,100

In summary, the total GAUs for each choice of resolution and chemistry is:

	Full chemistry	**Fast chemistry**
FV 2x2.5	34,600	28,300
FV 4x5	10,200	8,100

Assumptions used in calculating computing resources:

1) The spin-up for task 1 is 5 years for each scenario.
2) The offline-BGC runs for task 2 will require 500 years each.
3) There will be 4 simulations performed for tasks 3 & 4.
4) The need for task 5 is speculative, so no time is included here.