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Process Modeling of Global Soil Nitrous Oxide Emissions

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Eri Saikawa[*†], C. Adam Schlosser[*], and Ronald G. Prinn[*]

Abstract

Nitrous oxide is an important greenhouse gas and is a major ozone-depleting substance. To understand and quantify soil nitrous oxide emissions, we expanded the Community Land Model with prognostic Carbon and Nitrogen (CLM-CN) by inserting a module to estimate annually- and seasonally-varying nitrous oxide emissions between 1978 and 2000. We evaluate our soil N_2O emission estimates against existing emissions inventories, other process-based model estimates, and observations from two forest sites in the Amazon and one in the United States. The model reproduces soil temperature and soil moisture relatively well, and it reconfirms the important relationship between N_2O emissions and these parameters. The model also reproduces observations of N_2O emissions well in the Amazonian forests but not during the winter in the USA. Applying this model to estimate the past 23 years of global soil N_2O emissions, we find that there is a significant decrease in soil N_2O emissions associated with drought and El Niño years. More study is necessary to quantify the high-latitude winter activity in the model in order to better understand the impact of future climate on N_2O emissions and vice versa.

Contents

1. INTRODUCTION

Nitrous oxide (N_2O) is a major greenhouse gas with a Global Warming Potential of 300 in a 100-year time horizon (Forster *et al.*, 2007). Furthermore, its emissions weighted by ozone depletion potential currently dominate those of ozone-depleting substances after the decline of the chlorofluorocarbon (CFC) emissions (Ravishankara *et al.*, 2009). In addition, measurements of atmospheric N_2O mole fractions since the late 1970s show an increase (with a drop in 1992-1993) at a rate of 0.2-0.3% per year (Weiss, 1981; Prinn *et al.*, 1990; Nevison *et al.*, 1996). Despite a large number of studies in the last several decades examining the cause of this increase, large uncertainties still remain (Nevison *et al.*, 1996; Forster *et al.*, 2007; Huang *et al.*, 2008). Partially, this is due to diverse sources, both natural and anthropogenic. Recent increase in the atmospheric mole fractions has led to an estimation of the anthropogenic source to be approximately 1/3 of the

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total N_2O source (Khalil *et al.*, 2002; Hirsch *et al.*, 2006; Nevison *et al.*, 2007). However, microbial production in soils is still considered to be the largest producer of N_2O (Davidson, 2009). Understanding and quantifying N_2O fluxes from global soil in long time series is therefore an urgent task for predicting the future climate change and stratospheric ozone depletion (Forster *et al.*, 2007).

The bacterial processes of nitrification and denitrification are considered to be the most important source of N_2O emissions from soil. Microbial biomass decomposes in soil and creates ammonium ion (NH_4^+), which is converted to nitrate (NO_3^-) by the nitrification process in aerobic conditions. A small fraction of NO_3^- leaks to produce N_2O. In anaerobic conditions, NO_3^- is converted to N_2O and nitrogen gas (N_2) by denitrifying bacteria (Goreau *et al.*, 1980; Bremner and Blackmer, 1981; Poth and Focht, 1985; Nevison *et al.*, 1996). This nitrification and denitrification has been stimulated further by the increasing use of synthetic nitrogen fertilizers for food production (Davidson, 2009).

The mechanism of N_2O emissions from soil has been studied in several process models (Li *et al.*, 1992; Bouwman *et al.*, 1993; Potter *et al.*, 1996), but so far no model has been able to capture the long-term trend of soil N_2O emissions, including the details of seasonality and inter-annual variability at the global grid level. In this paper we present and evaluate a modified version of the Community Land Model version 3.5 (CLM v3.5), as explained by Oleson *et al.* (2008) and Stöckli *et al.* (2008), in order to better understand the seasonality and inter-annual variability of global natural soil N_2O emissions.

CLM v3.5 is the land component of the Community Earth System Model (CESM), which is designed to study inter-annual and inter-decadal variability, paleoclimate regimes, and projections of future climate change (Collins *et al.*, 2006; Oleson *et al.*, 2008). With a coupled carbon-nitrogen (CN) biogeochemical model (Thornton *et al.*, 2007; Randerson *et al.*, 2009; Thornton *et al.*, 2009) based on the terrestrial biogeochemistry Biome-BGC model (Thornton *et al.*, 2002; Thornton and Rosenbloom, 2005), the CLM-CN model represents land terrestrial water, carbon (C) and nitrogen (N) balances, and it is nominally run at an hourly time scale (Lawrence *et al.*, 2011).

Here, we add a new N_2O emissions flux module within CLM-CN v3.5 to create CLMCN-N_2O. CLMCN-N_2O includes the DeNitrification-DeComposition (DNDC) Biogeocheistry Model (Li *et al.*, 1992) to capture both the nitrification and denitrification processes that are important producers of N_2O. CLMCN-N_2O utilizes the soil C and N concentrations in soil as calculated by CLM-CN, but also estimates NH_4^+ produced by decomposition and calculates N_2O production through nitrification and denitrification depending on temperature and soil moisture.

The main objectives of this study were: (1) to build and validate the soil N_2O emissions module in CLM-CN; (2) to quantify global natural soil N_2O emissions between 1978 and 2000; and (3) to understand the effects of meteorology on seasonal and inter-annual natural soil N_2O emissions. We first estimate the global natural N_2O emissions from 1978 to 2000 and analyze the trend in annual and seasonal emissions in different regions. We use three separate forcing data sets (described in Section 2.2) to compare our N_2O emissions estimates due to given

meteorological conditions. Next, we evaluate CLMCN-N_2O by comparing our estimated N_2O emissions with observations from field measurements in forests in the Amazon and in the USA. Finally, we analyze the impact of meteorology on regional emissions by paying special attention to the role of El Niño and drought.

The paper is organized as follows. Section 2 describes the methodologies we use, including the model development and the observational data for this study. Section 3 explains the model simulation and the comparison with observations. Section 4 provides an analysis of the impact of El Niño and drought on soil N_2O emissions. We present a summary of results and conclude in Section 5.

2. METHODS

2.1 Model

CLMCN-N_2O is based on the CLM v3.5 model (Oleson *et al.*, 2008; Stöckli *et al.*, 2008) including the carbon-nitrogen (CN) biogeochemical model (Thornton *et al.*, 2007; Randerson *et al.*, 2009; Thornton *et al.*, 2009). CLM-CN simulates terrestrial water, C and N budgets for each plant functional types (PFTs) from hourly to decadal time series. The model can be run on any regular grid and here we run at a horizontal resolution of 1.9° latitude and 2.5° longitude. For each PFT and each spatial unit, CLM-CN balances soil C and N between four soil organic matter pools of differing decomposability (i.e., fast, medium, slow and slowest), three litter pools (i.e., labile, cellulose and lignin), and a soil mineral N pool. CLMCN-N_2O includes pools of N_2O, NO_3^-, NH_3 and NH_4^+, and treats N inputs from atmospheric deposition, biological N fixation, N losses to NH_4^+ and NO_3^- leaching. It simulates N_2O emissions due to nitrification and denitrification at an hourly time step.

NH_4^+ is produced via biomass decomposition. As both labile and resistant microbial biomass pools decompose, some new biomass is created, while others are transferred to resistant humads and the others produce CO_2. In this process of decomposition, NH_4^+ is also produced. Some of the produced NH_4^+ is dissolved into NH_3, a part of which then volatilizes. Nitrification is temperature and moisture dependent and it only takes place under the aerobic state. During the nitrification process, NO_3^- is produced from NH_4^+, and in between, N_2O is also released.

Denitrification, a process converting NO_3^- into N_2, is also temperature and soil moisture dependent and it takes place under the anaerobic state. The growth rate of denitrifiers, NO_3^-, nitrite (NO_2^-), and N_2O, is controlled by the ratio of the soluble C in saturated soil layer to the total soil C as well as the ratio of each denitrifier to the total soil N. The dynamics of the soil C pool are calculated in CLM-CN using the converging cascade structure (Thornton and Rosenbloom, 2005). The litter C are defined in three litter pools based on each PFT, and these litters go through either respiration or decomposition with specific rates assigned for each pool, depending on PFT. The dynamics of the soil N pool are calculated in CLM-CN based on the C:N ratio specified by PFT. Under the anaerobic condition, which is triggered in the model by the rain event and when soil moisture is greater than 50%, NO_3^- is first converted into NO_2^-, which is next converted to NO, then to N_2O and finally to N_2. The three denitrifier consumption is

controlled by the relative growth of denitrifiers, the amount of existing denitrifiers in soil, total soil N, soil pH, and soil temperature. Net increase in soil N_2O is thus determined from these denitrifier syntheses.

We use N deposition data as estimated by Community Atmosphere Model (CAM) for year 2000. Mineral N deposition is one of the pathways for N addition in the model. The flux is prescribed as an annual rate and is kept constant over the duration of the model run. It is applied daily to the soil mineral N pool. Our N deposition data would include the indirect effect of fertilizer use in agricultural lands, but we consider this to be a negligible effect based on Mosier *et al.* (1998) that the mean estimated emissions of N_2O from atmospheric deposition is 0.3 (0.06-0.6) Tg N_2O-N yr^{-1}.

2.2 Measurement Data

Several N_2O emissions flux measurements were used to verify the CLMCN-N_2O model. One is taken at the Tapajós National Forest in east central Amazonia (2.90°S, 54.95°W), as described in Davidson *et al.* (2004, 2008). Precipitation, volumetric water content (VWC) of the top 2m of soil and N_2O emissions flux under normal as well as the drought experimental condition were available at this site between 1999 and 2005. For the drought experiment, throughfall was excluded from the measurement site during the rainy seasons from January to June. The experiment lasted for 5 years between 2000 and 2004 in a large area (1ha) within a 20ha forest.

Another measurements were taken monthly at Fazenda Vitoriá from 1995 February to 1996 May. The Fazenda Vitoriá forest is located in eastern Amazonia, near Paragominas (2.98°S, 47.52°W) as described in Verchot *et al.* (1999). Precipitation and soil water content in the top 30cm of the soil for primary forest and active pasture were available at the site as well as the N_2O emissions flux in four different ecosystems - primary forest, secondary forest, degraded pasture and active pasture. Primary forest is the forest stand that has not gone through major disturbance (e.g. clearing or fire) during the last couple of centuries. The secondary forest refers to the naturally regenerated forest from a pasture, which was abandoned in 1976. Degraded pasture is mainly covered with shrubby regeneration as a result of the clearing in 1969. The pasture was abandoned in 1990 after having been heavily grazed until the early 1980s and then intermittently for a while after that. Active pasture has undergone similar land use history as the degraded pasture until 1987, but it was since "reformed" by having been cleared, burned, disked, fertilized, and planted.

Third, we used measurements from the White Mountain National Forest in New Hampshire, USA (43.93°S, 71.75°W), as described in Groffman *et al.* (2006). Soil temperature and volumetric soil moisture as well as N_2O emissions flux were available from fall 1997 to spring 2000. The forest is dominated by American beech (*Fagus grandiflora*), sugar maple (*Acer saccharum*), and yellow birch (*Betula alleghanieusis*). The main objective of their study was to conduct snow manipulation to understand the relationships between snow depth, soil freezing and forest biogeochemistry. They took measurements in four stands, and created two 10m x 10m plots at each - with and without snow manipulation. In this paper, we only use their reference data that

has not gone through any snow manipulation.

2.3 Emissions Inventory Data

We also compare the model results with two existing emissions inventory for global natural soil emissions. One is GEIA v1 in which an estimate of global N_2O emissions from soils under natural vegetation and arable lands (without the effects of anthropogenic N inputs) are calculated using the model by Bouwman *et al.* (1993), as described in Bouwman *et al.* (1995). Bouwman *et al.* (1993) uses the "process pipe" or "hole in the pipe" concept (Firestone and Davidson, 1989; Davidson, 1991), and calculates the soil NO and N_2O emissions flux simultaneously. In the model, total soil N availability determines the total N gas production, and the soil water content determines the ratio of N_2O to NO emitted to the atmosphere. GEIA v1 provides annual global soil N_2O emissions with 1° x 1° resolution for the year 1990.

Another inventory we compare our results with is the Carnegie-Ames-Stanford (CASA) Biosphere model (Potter *et al.*, 1996). CASA simulates natural soil N_2O emissions as well as daily and seasonal patterns in C fixation, nutrient allocation, litterfall, soil N mineralization and CO_2 exchange, similar to CLMCN-N_2O. This model provides a monthly global soil N_2O emissions with 1° x 1° resolution for the year 1990.

3. SIMULATIONS AND EVALUATIONS

In order to estimate annual and monthly global soil N_2O emissions flux from 1978 to 2000, the CLMCN-N_2O was run with three climate data sets: 1) NCEP Corrected by CRU (NCC): a 53-year data set based on the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Ngo-Duc *et al.*, 2005); 2) Climate Analysis Section (CAS): a 54-year data set also based on the NCEP/NCAR reanalysis (Qian *et al.*, 2006); and 3) Global Offline Land-Surface Dataset (GOLD): a 21-year data set which combines the reanalysis with monthly observations (Dirmeyer and Tan, 2001). Each data set provides air temperature, humidity, wind speed, surface pressure, precipitation and solar radiation to run CLM.

To implement the CLMCN-N_2O simulation, we conducted the equilibrium run, followed up by a transient run. For the equilibrium run, we used a 26-year repeating climate of 1949-1974 to drive the model to reach an equilibrium state. After running the model for 1300 years, we have determined that the model was at an equilibrium by confirming that an annual carbon storage change less than 1gC m^{-2} $year^{-1}$ was reached and the imbalance in the plant N cycle was approximately 1%, as specified in McGuire *et al.* (1992) and Lin *et al.* (2000), respectively. From the equilibrated state, we ran the model for 26 years (1975-2000) for NCC, CAS and GOLD, using the respective forcing data of matching years. We used the first 3 years (1975-1977) of the transient run to be a spin-up and only analyzed years between 1978 and 2000. Annually-varying meteorology with a constant N deposition for the year 2000 was used for all simulations.

3.1 Model-Observation Comparison

In order to evaluate our model, we first compare several forcing parameters for both model results and observations. There are three important parameters to estimate soil N_2O emissions,

which are: precipitation, VWC, and soil temperature. Precipitation is essential to achieve anaerobic condition for denitrification to start in the model. VWC determines anaerobic condition for denitrification. Soil temperature affects the amount of soil N_2O emissions emitted to the atmosphere in both nitrification and denitrification processes.

We first conduct comparisons with two Amazon measurements. One is from the Tapajós National Forest in east central Amazonia between 1999 and 2000 (Davidson *et al.*, 2004, 2008), and the other is from Fazenda Vitoriá between 1995 February and 1996 May (Verchot *et al.*, 1999). **Figure 1** illustrates that our meteorological forcing agrees with the observed precipitation values quite well, although there are some visible underestimations in winter in the Tapajós National Forest and in spring in Fazenda Vitoriá. Correlation coefficients are 0.80 and 0.90, and

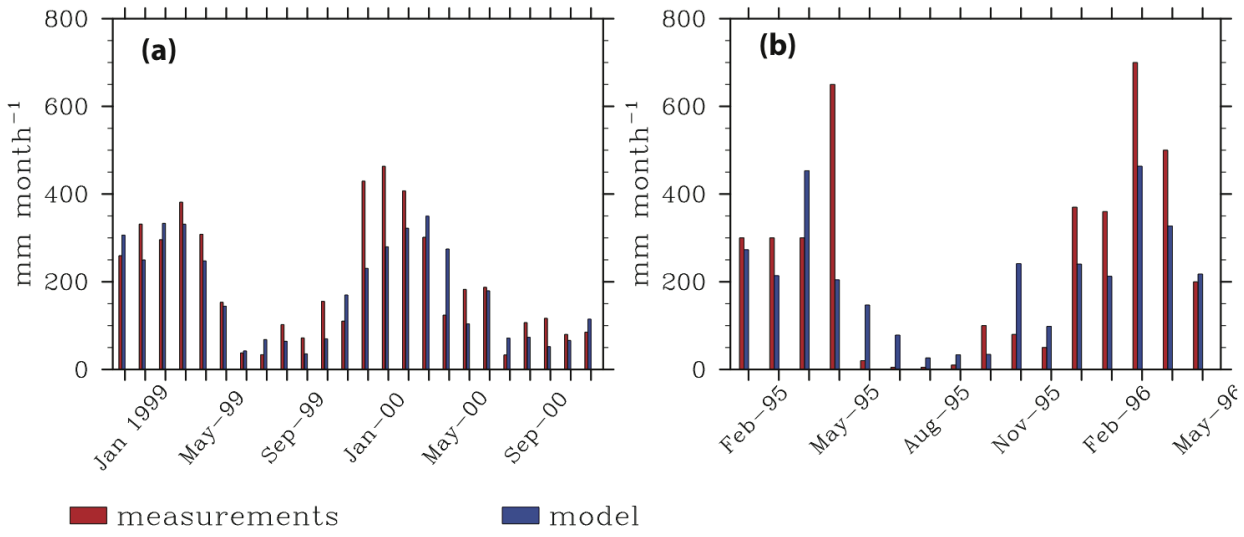

Figure 1. Comparison of precipitation between (a) observations in the Tapajós National Forest and model and (b) observations in the Fazenda Vitoriá and model in mm month^{-1}.

root mean squared errors (RMSE) are 82mm and 101mm at the former and latter sites, respectively. The precipitation from the reanalyses tends to capture the seasonality of precipitation at these sites, as confirmed by high correlation coefficients.

The model results are also able to reproduce the VWC well at the Tapajós site (**Figure 2**(a)). Davidson *et al.* (2008) has conducted a 5-year throughfall exclusion experiment (drought) as well as no exclusion (reference) as mentioned in Section 2.2, so we compare our model results with both. Correlation coefficients are 0.70 and 0.83, and root mean squared errors (RMSE) are 139mm and 96mm when model results are compared with drought and reference, respectively. Our model overestimates the value compared to observations, but is consistent with the range of modeled uncertainty seen in previous multi-model comparisons (Dirmeyer *et al.*, 2006). Soil temperature was not available at these sites to compare with our results.

We also conduct comparisons with measurements at the White Mountain National Forest in New Hampshire, USA (Groffman *et al.*, 2006). In their study, Groffman *et al.* (2006) manipulated

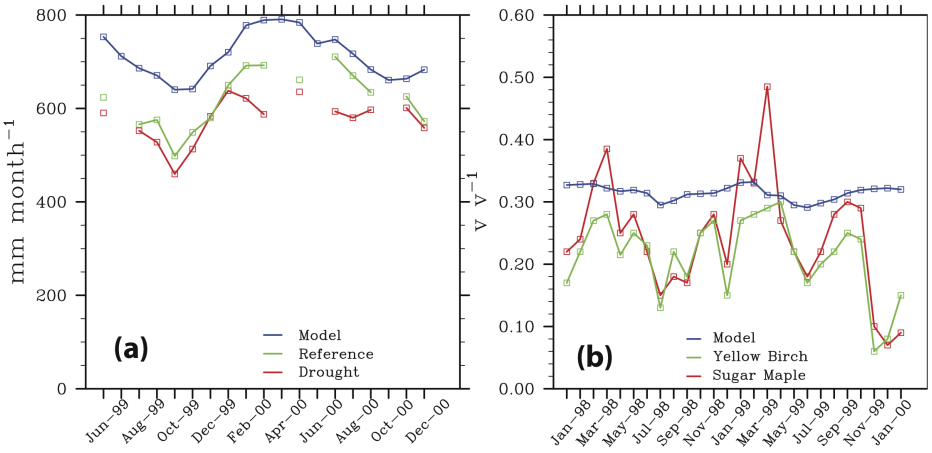

Figure 2. Comparison of volumetric water content of (a) top 2m of soil between observations in the Tapajós National Forest and model in mm month^{-1} and (b) top 10cm between observations in the White Mountain National Forest and model in v v^{-1}.

snow depth to induce soil freezing in order to understand the impact of frozen soil on soil N_2O emissions flux. In this paper, we compare their reference VWC measurements at sugar maple and yellow birch stands without the snow manipulation. These are different northern hardwood forest vegetation, and the soils are shallow (75-100cm) and acidic (pH 3.9) for both types of stands.

As Figure 2(b) illustrates, the model results do not represent the observations very well. Correlation coefficients are 0.23 and 0.13, and root mean squared errors (RMSE) are 0.11 v v^{-1} and 0.12 v v^{-1} when model results are compared with soils planted with sugar maple and yellow birch, respectively. The model constantly overestimates the volumetric soil water content compared to the observations of the soil with yellow birch, and it is not able to trace the seasonality that is visible at this site. This discrepancy is, in large part, due to the shallow depth of the soil-moisture considered (10 cm) and the fact that CLM tracks the macro-scale variations of the soil hydrothermal profile - allowing for multiple vegetation types to compete with the same soil-column water.

The model, however, represents the soil temperature well at the White Mountain National Forest, as seen in **Figure 3**. Correlation coefficients are 0.91 and 0.93, and root mean squared errors (RMSE) are 3.53°C and 3.63°C when model results are compared with sugar maple and yellow birch branches, respectively. The model slightly overestimates the temperature, but it is able to reproduce the seasonal cycle quite well.

At the above-mentioned three sites, we compare soil N_2O emissions with our modeled estimates. As explained in Section 4, because model results applying NCC forcing dataset represent the average estimates of the three simulations, we use them for further analysis. At the Tapajós National Forest, we also compare the relationship between VWC and soil N_2O emissions flux between the observations and the model. **Figure 4**(a) illustrates the comparison of the relationship between VWC and soil N_2O emissions for model results (green) and observations (reference in blue and drought experiment in red). The lines show the best fit of the data for

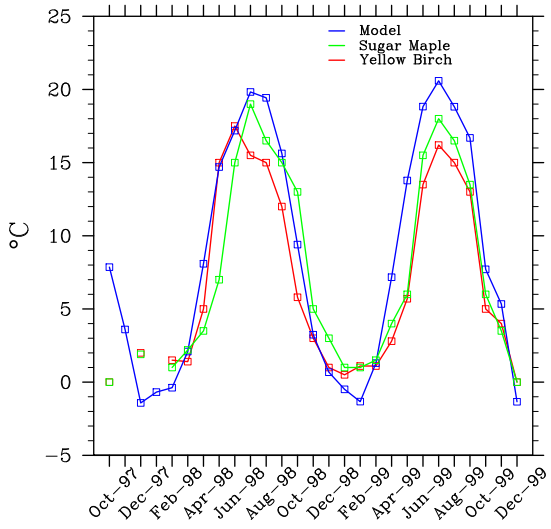

Figure 3. Comparison of soil temperature at 10cm depth between observations (sugar maple and yellow birch branches) and model in White Mountain National Forest in °C.

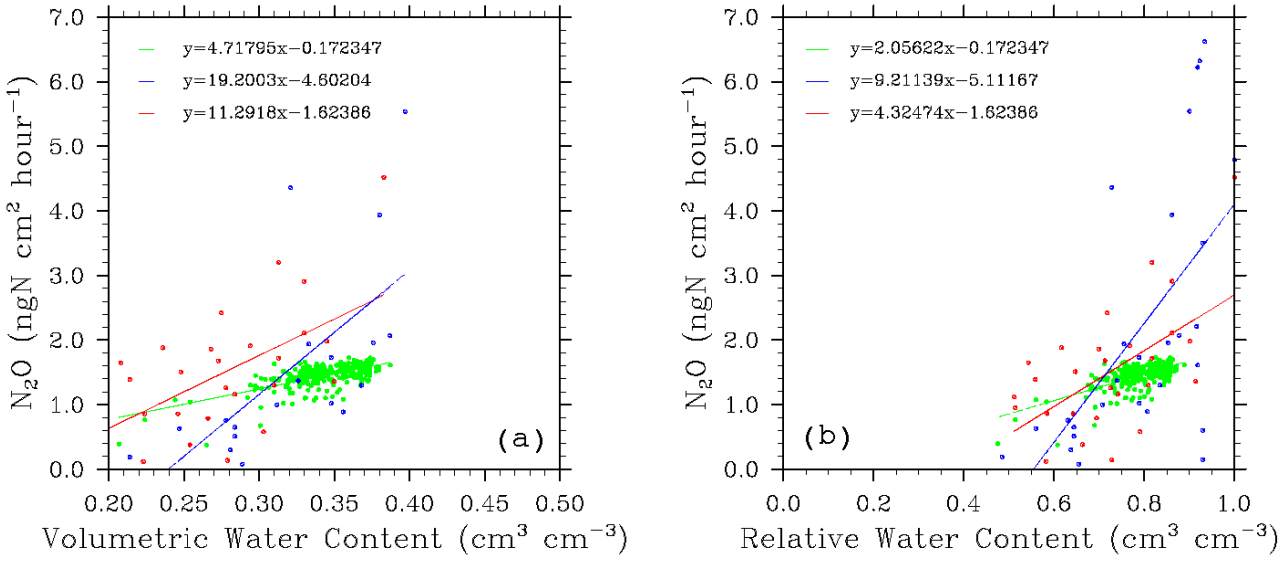

Figure 4. Comparison of the relationship between N_2O fluxes (model (green) and observations (drought (red) and reference (blue))) in ngN cm^{-2} $hour^{-1}$ and (a) volumetric water content of the top 30 cm soil with nitrous oxide in cm^3 cm^{-3} and (b) relative water content of the top 30 cm soil with nitrous oxide in the Tapajós National Forest in cm^3 cm^{-3}.

modeled estimates, reference and drought experiment, respectively, shown in the same colors as the data. The model results are clustered around VWC between 0.29 and 0.38, whereas the observations are more scattered, and as for the reference case, there are VWC values over 0.407 - the model maximum value in this grid cell. Observed soil N_2O emissions vary from less than 0.2 to more than 6.6 when VWC is approximately 0.41. However, the model is not able to reproduce these observations close to saturation, and it shows a much stronger control of soil moisture on N_2O flux.

Figure 4(b) illustrates the comparison of the relationship between N_2O emissions and relative water content for model results and observations. These compare better than the relationship between N_2O emissions and VWC, as we are able to put soil moisture from model and observations on the same scale by taking porosity into account. The model reproduces the soil N_2O emissions under water-stress condition (i.e. drought) better than the reference case. Some other environmental conditions (e.g. temperature, precipitation frequency, soil-carbon content, etc.) apart from soil moisture may be playing a role for such diverse soil N_2O emissions that we see for the reference case close to saturation. However, it is most likely that this discrepancy is due to comparing a global model estimates against instantaneous measurements. There are large differences between the two in terms of a grid scale and time - while the model estimates a value within a horizontal grid scale of 1.9° latitude and 2.5° longitude every hour, instantaneous measurements are conducted either monthly or bimonthly within eight 10m x 10m plots. There are also errors associated with measurements, and it is not surprising that the results do not match perfectly.

Figure 5 compares the modeled and observed (primary forest and secondary forest) soil N_2O emissions in Fazenda Vitoriá. The model reproduces the observations at the secondary forest quite well, and the correlation coefficient for the latter is 0.52 with an RMSE of 0.67 ngN cm^{-2} $hour^{-1}$. Slight overestimation is found between June and August, but the model reproduces the values well even compared with the primary forest site between May and December. There are several reasons why the model is unable to reproduce high N_2O emissions from the primary forest. The first is the same as the reason mentioned above, and it is due to the difference in grid scale and time. The second is due to the PFT considered at this specific grid cell. We have four PFT types on the grid cell that we analyze on Figure 5, and they include C4 grass, broadleaf evergreen tropical tree, broadleaf deciduous tropical tree, and corn. Primary forest is the forest that has never gone through human intervention, whereas secondary forest has, and thus it is closer to the PFT types specified for the grid cell. It is therefore very possible that, under these PFT types, we are unable to resolve the high emissions as estimated from the measurement.

Figure 6 illustrates the modeled and observed (sugar maple and yellow birch branches) soil N_2O emissions flux in the White Mountain National Forest. In our model, there is a clear seasonality, with maximum in the growing season and negligible emissions in winter. The measurements in the White Mountain National Forest focused on emissions in winter, so the only comparison available here is during December through April from 1998 to 2000. For the observations, a large variation in emissions in the winter months are seen. Groffman *et al.* (2006)

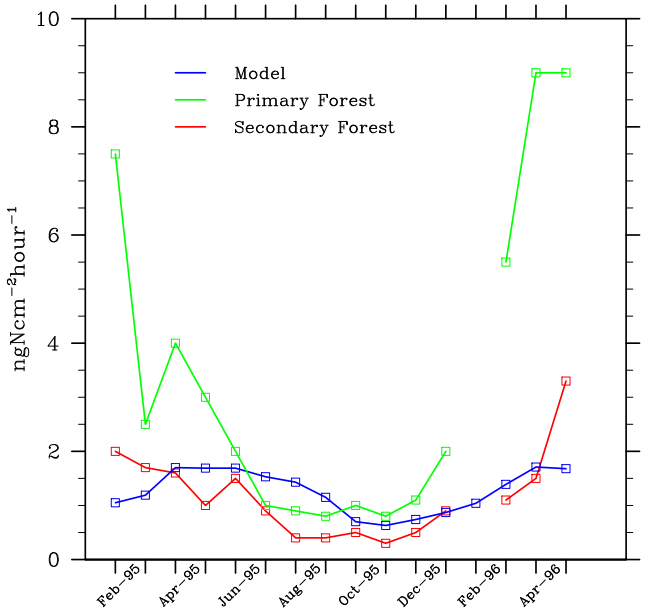

Figure 5. Comparison of soil N_2O emissions flux between observations (primary forest and secondary forest) and model in Fazenda Fazenda Vitoriá in ngN cm^{-2} hour^{-1}.

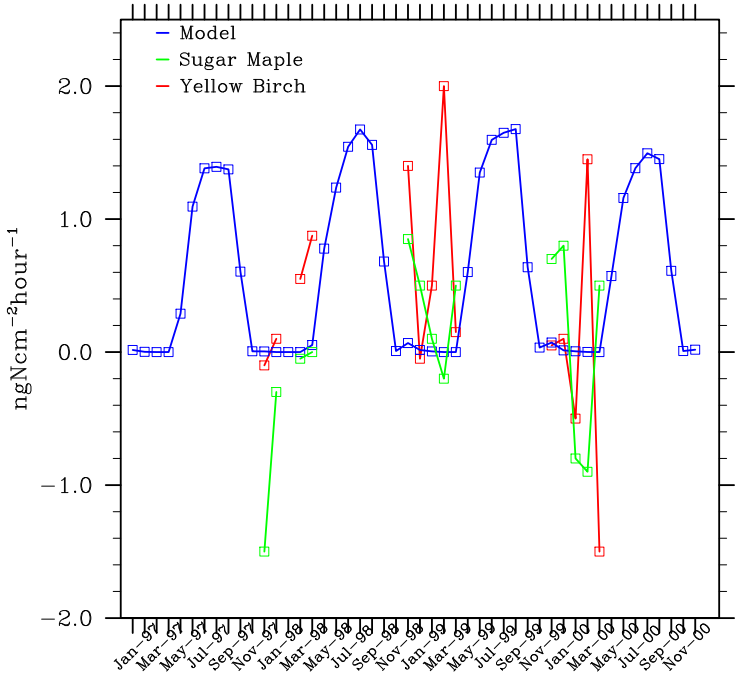

Figure 6. Comparison of soil N_2O emissions flux between observations (sugar maple and yellow birch) and model in White Mountain, USA in ngN cm^{-2} hour^{-1}.

finds that increasing soil freezing enhances soil N_2O emissions flux, and that winter fluxes are important. In our current model setup, there are no soil N_2O emissions when soil temperature is below 0°C, based on the DNDC model. However, as Kielland *et al.* (2006) has suggested, labile substrate production might be more important than temperature for soil N_2O production, which

needs to be explored in the future. Moreover, the observations also indicate that there are conditions resulting in N_2O uptake, which most N_2O emission models would be unable to capture. More research is needed to enhance our understanding of the winter fluxes, as this might be an important emission source of N_2O exchange.

4. SOIL N_2O EMISSIONS FLUX ESTIMATE

4.1 Seasonal Emissions Variation

Figure 7 shows the estimated global natural soil N_2O emissions flux for the year 2000. The global spatial distribution of monthly N_2O emissions flux from the CLMCN-N_2O model suggests that high emissions flux originate in South America, Southern Africa, and Southeast Asia in the northern hemisphere spring and winter, whereas high emissions originate in equatorial regions and Northesatern America, Europe as well as South Eastern Asia in the northern hemisphere summer and fall. There is a clear seasonality especially in the Northern Hemisphere, where there are only little emissions in winter, whereas high emissions of more than 1 Gg/month are visible in the summer.

We compare our model estimates using NCC forcing dataset for 1990 with GEIA v1 (**Figure 8**) and with CASA (**Figure 9**) emissions. From Figure 8, we notice that our model has lower emissions than GEIA over most equatorial land areas. However, in Figure 9, a different pattern is found. Here, our model produces higher emission rates in sub-Saharan Africa, Northeastern China, and South Asia from July to November, with respect to the CASA estimates.

Considering that we see higher simulated emissions mainly in agricultural regions and the down wind areas including the eastern U.S. in August and September, we have conducted a sensitivity study by reducing our N deposition data in the eastern U.S. by 35% to assess the impact of indirect fertilizer emissions. The reduction in N deposition, however, did not affect model simulation results, confirming that the indirect effect of fertilizer emissions is indeed small. Comparing the two figures (Figures 8 and 9), we do not see a systematic bias in our model results, and it is not too surprising that we see the largest discrepancies to other model estimates in Africa. As Bouwman *et al.* (1995) notes, there is a lack of measurements in Africa, and it remains difficult to calibrate model results for the region.

4.2 Inter-annual Flux Estimate

The CLMCN-N_2O model estimates global average soil N_2O emissions flux for years between 1978 and 2000 to be 8.15, 8.90, and 7.49 Tg N_2O-N year^{-1}, when using NCC, CAS and GOLD forcing datasets, respectively. **Figure 10** shows the inter-annual variability of global total natural soil N_2O emissions flux as estimated by the model using the three different forcing datasets. When we calculate the regional distribution based on **Figure 11** for year 2000, more than 20% and 35% of the global emissions originate in Africa and Asia, respectively (**Table 1**). The trend of inter-annual variability and spatial distribution of the emissions are similar among the results using the different forcing datasets.

The estimated global total soil N_2O emissions (7.49-8.90 Tg N_2O-N year^{-1}) matches with the

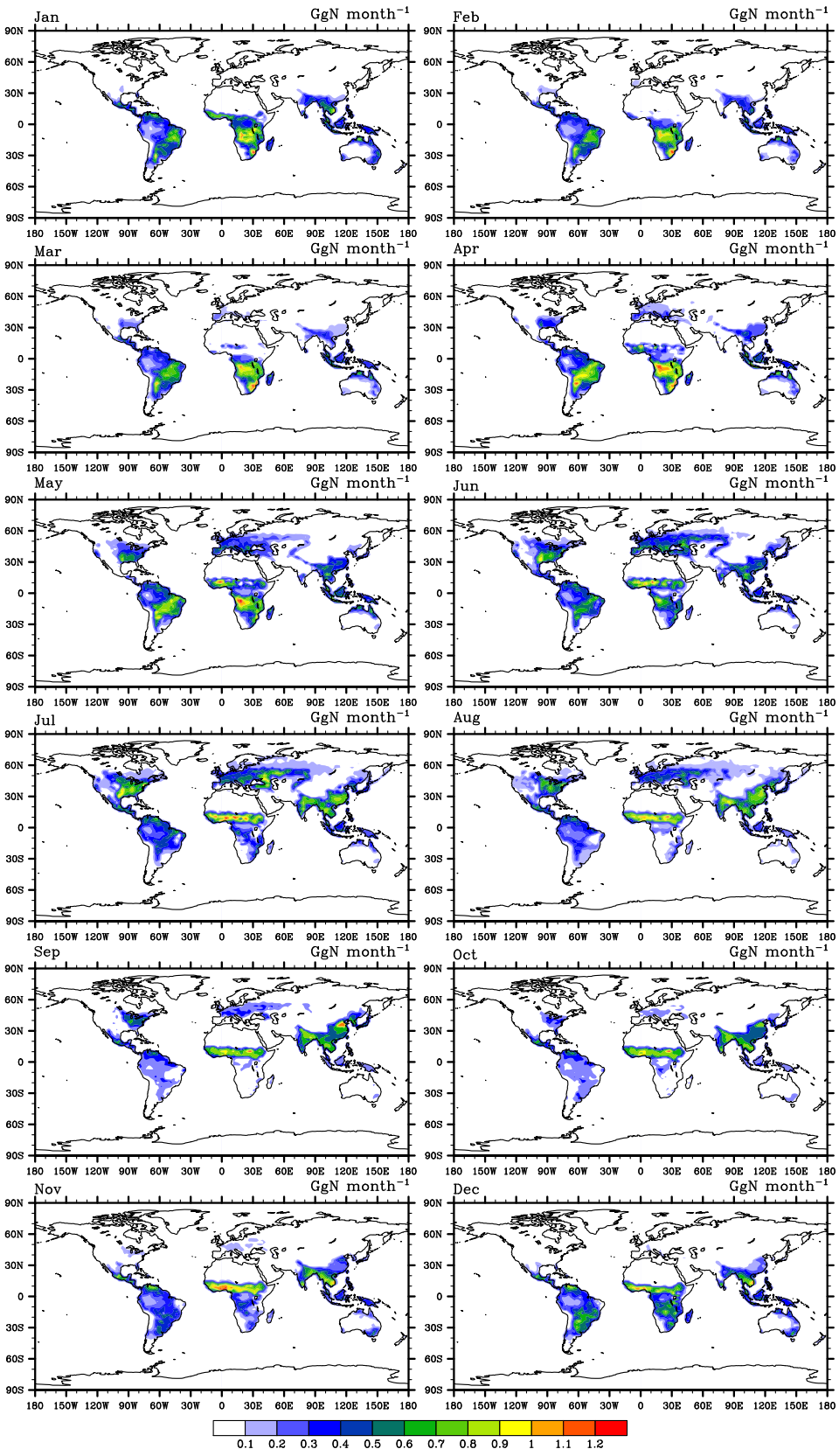

Figure 7. Global soil N_2O emissions flux estimated by the CLMCN-N_2O model using NCC forcing dataset in GgN month^{-1}.

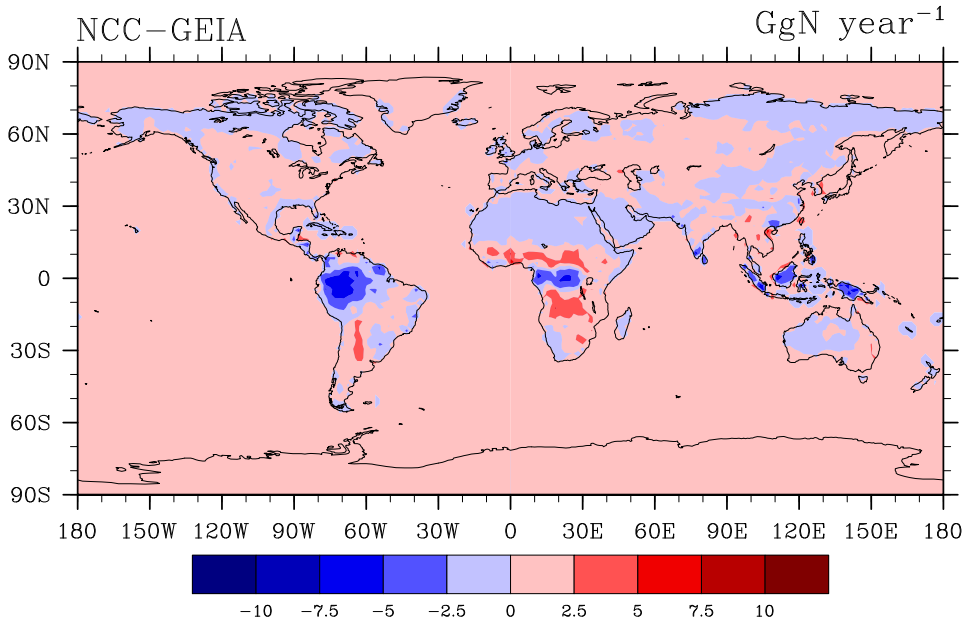

Figure 8. Difference between global soil N_2O emissions derived from CLMCN-N_2O compared to GEIA v1 in GgN month^{-1}.

Table 1. Regional soil N_2O emissions for year 2000 (TgN year^{-1}).

Region	NCC	CAS	GOLD
AFRICA	2.07 (25.2%)	1.99 (22.5%)	1.79 (23.8%)
ASIA	1.45 (17.7%)	1.54 (17.5%)	1.27 (16.9%)
CENTRAL AMERICA	0.05 (0.60%)	0.05 (0.60%)	0.05 (0.60%)
CENTRAL ASIA	1.46 (17.8%)	1.85 (20.9%)	1.46 (19.5%)
EUROPE	0.35 (4.30%)	0.39 (4.40%)	0.35 (4.60%)
MIDDLE EAST	0.08 (1.00%)	0.10 (1.10%)	0.08 (1.10%)
NORTH AMERICA	0.76 (9.30%)	0.86 (9.70%)	0.75 (10.0%)
OCEANIA	0.30 (3.50%)	0.33 (3.70%)	0.29 (3.80%)
SOUTH AMERICA	1.69 (20.6%)	1.73 (19.6%)	1.47 (19.6%)
TOTAL	8.21	8.83	7.50

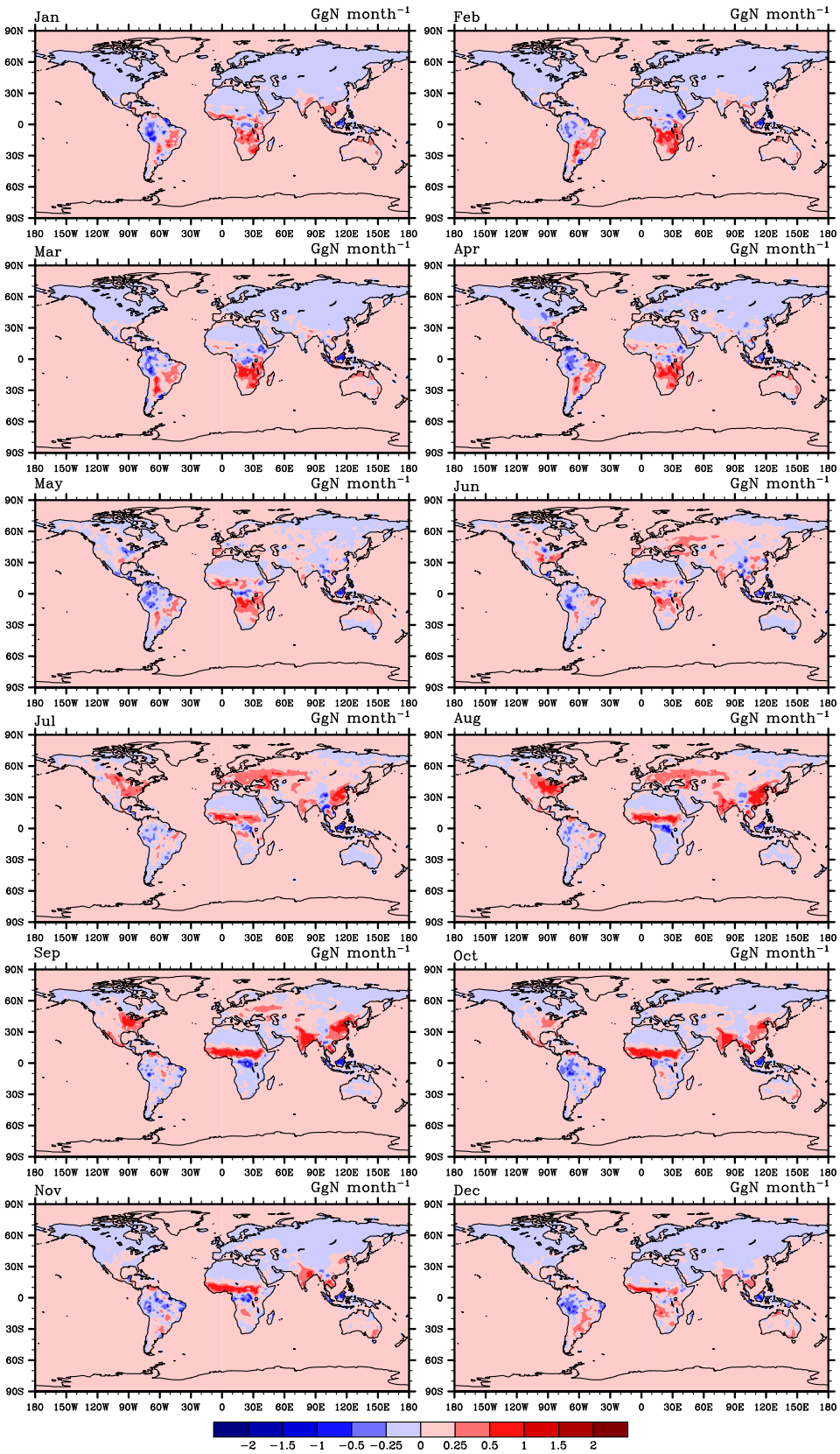

Figure 9. Difference between global soil N_2O emissions derived from CLMCN-N_2O compared to CASA in GgN month^{-1}.

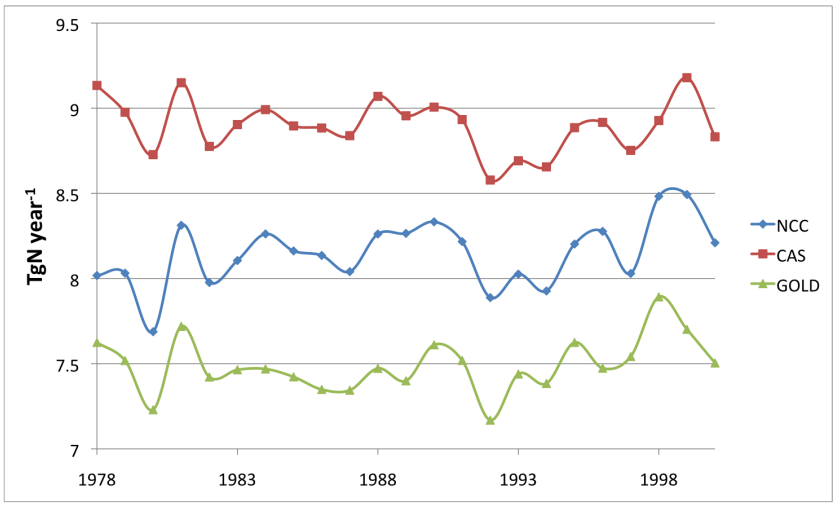

Figure 10. Inter-annual variability of global soil N_2O emissions derived from CLMCN-N_2O using 3 forcing datasets: NCEP Corrected by CRU (NCC), CAS, and Global Offline Land-Surface Dataset (GOLD).

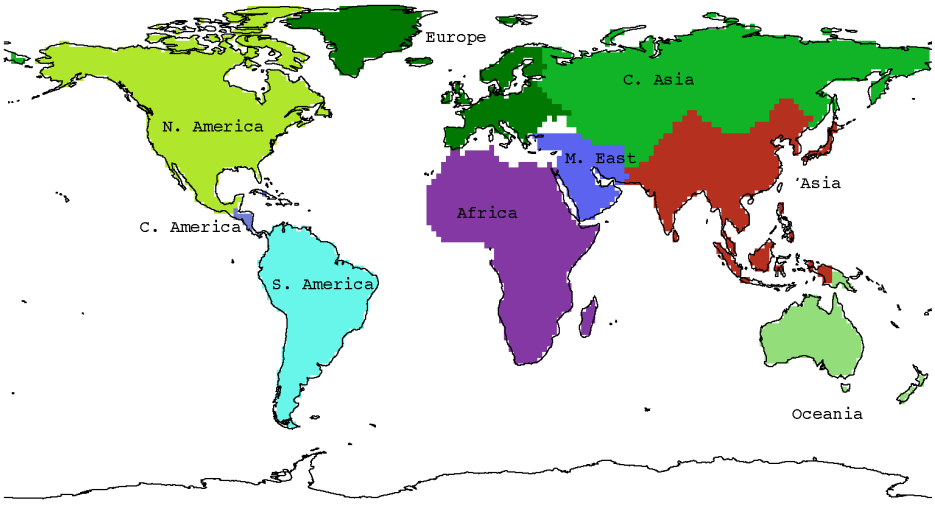

Figure 11. Regions for which CLMCN-N_2O emissions were analyzed.

existing bottom-up model estimates. Bouwman (1990) cites Seiler and Conrad (1987) that the estimated natural soil global budget of N_2O is 6 ± 3 Tg N_2O-N year^{-1}. Bouwman *et al.* (1995) estimates global natural soil N_2O emissions flux in 1990 to be 6.6-7.0 Tg N_2O-N year^{-1}, and Potter *et al.* (1996) estimates it to be 6.1 Tg N_2O-N year^{-1}. There are other estimates made in 1980s and 1990s including 7-16 Tg (Bowden, 1986), 3-25 Tg (Banin, 1986), and 6.7 Tg (Kreileman and Bouwman, 1994). Schlosser *et al.* (2007) estimates natural soil emissions from the Global Land System (GLS) to be 6.1 Tg N_2O-N year^{-1}. Conducting a top-down inversion study and assuming that oceanic flux has not changed, Hirsch *et al.* (2006) estimates the preindustrial terrestrial source to be 3.9-6.5 TgN year^{-1}. While our estimates lie within the range of the earlier studies' estimates, they are slightly higher than what the recent studies found.

Between 1978 and 2000, the lowest global soil N_2O emissions flux was in 1980 with 7.17-8.58 Tg N_2O-N year^{-1}, whereas the largest emissions was observed in 1999 with 7.89-9.18 Tg N_2O-N year^{-1}. Our model results show a large negative anomaly in soil N_2O emissions in 1980. **Figure 12** illustrates that regions such as North America, Oceania, and Africa have statistically significantly lower emissions than their 23-year mean values. We find that a heat wave and natural drought in 1980 led to high temperature and low VWC, which resulted in large N_2O emissions reduction in these regions in our model.

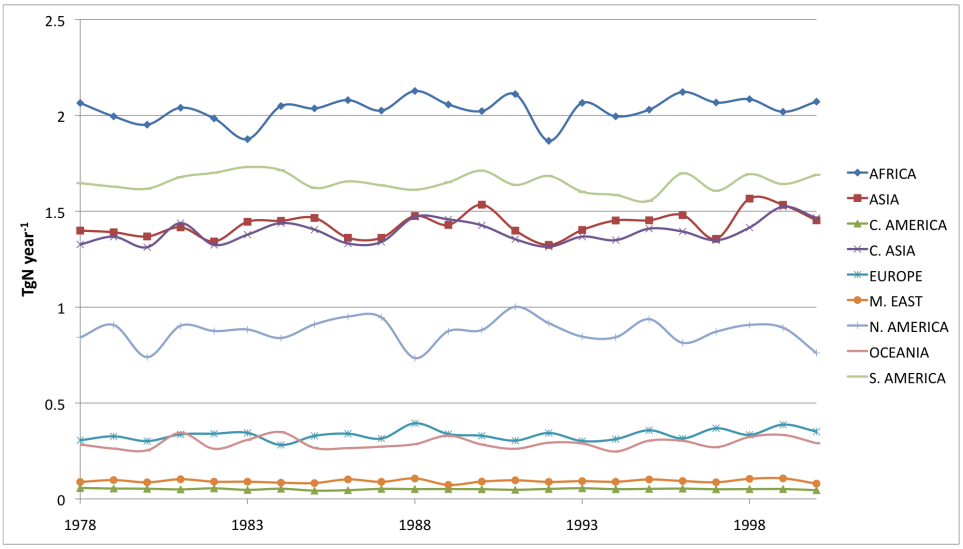

Figure 12. Regional total soil N_2O emissions between 1978 and 2000.

Figures 13 - 16 show the soil temperature, precipitation, VWC and soil N_2O emissions anomalies between 1980 and the climatological mean (1978-2000). The results indicate a strong linkage between VWC and the soil N_2O emissions in the model. We are able to find high correlations between these meteorological variables within the U.S., Australia and Southern Africa where there were large anomalies due to drought and a heat wave in 1980.

What is interesting is that our model results for 1992 are the second lowest of all the estimated emissions over the 28 years. This result matches well with the study that finds the growth rate of N_2O in 1992 to be half that in the previous decade (Smith, 1997), despite the continued growth

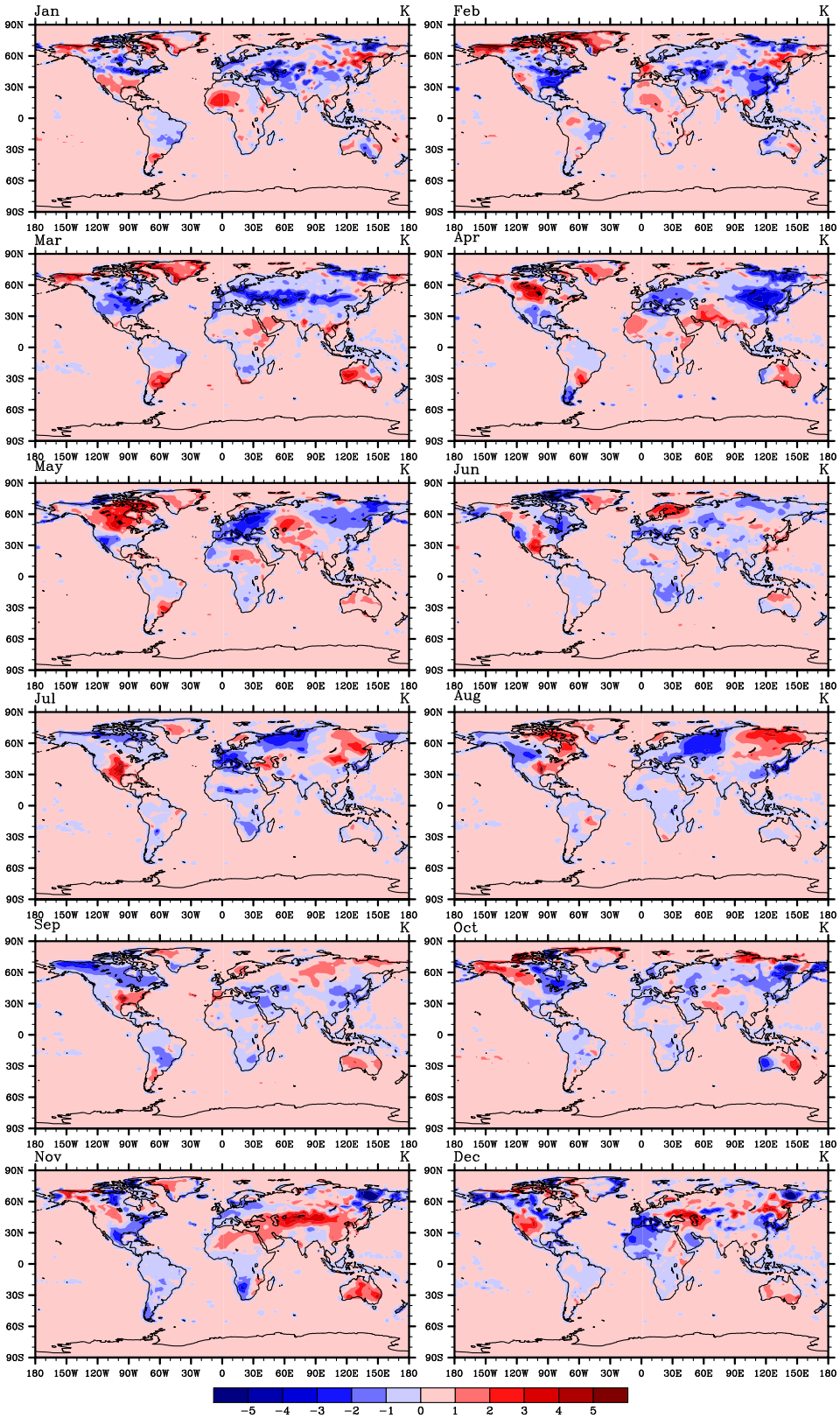

Figure 13. Soil temperature anomalies between 1980 and climatological mean over 1978-2000 in K.

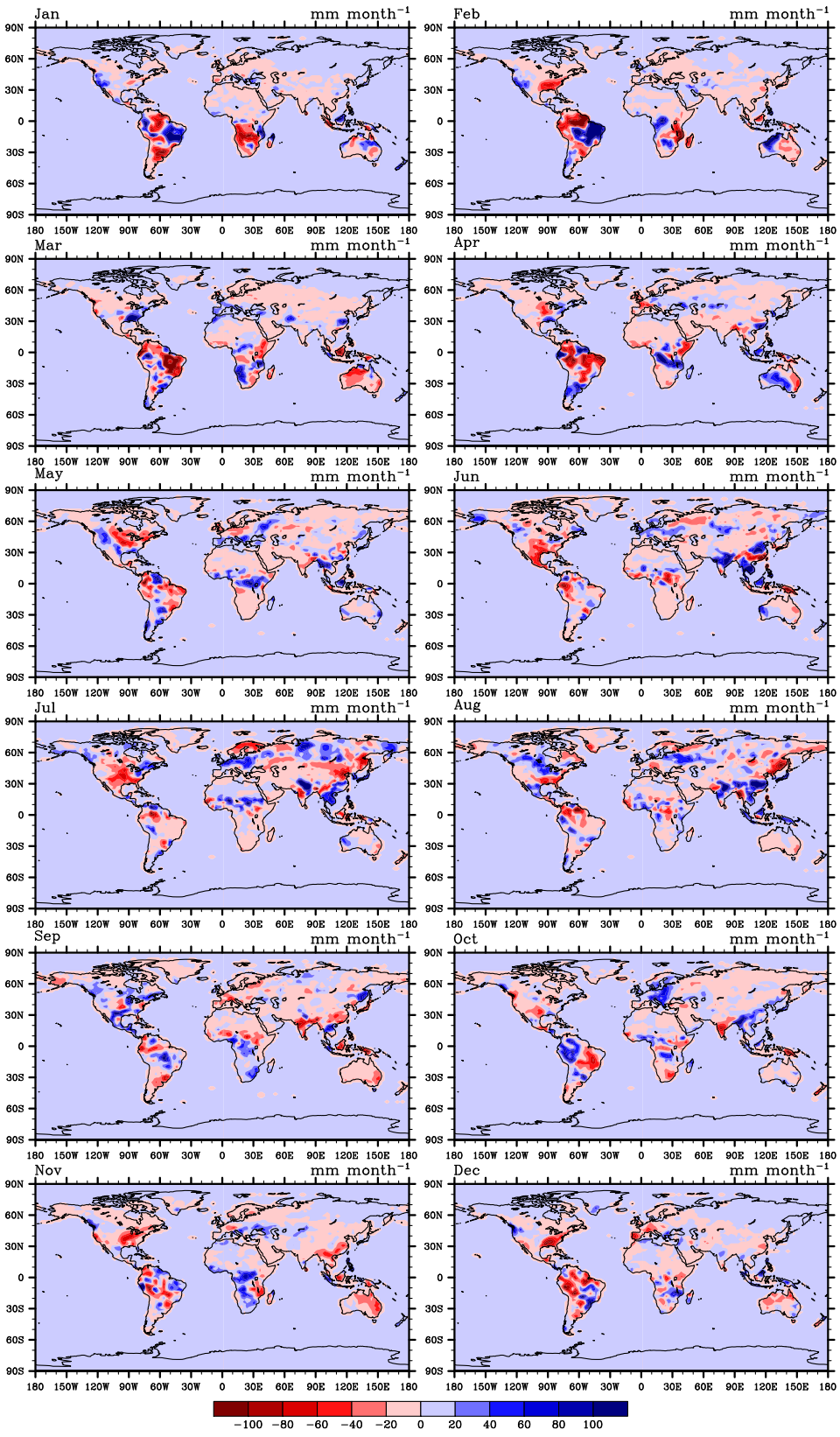

Figure 14. Precipitation anomalies between 1980 and climatological mean over 1978-2000 in mm month^{-1}.

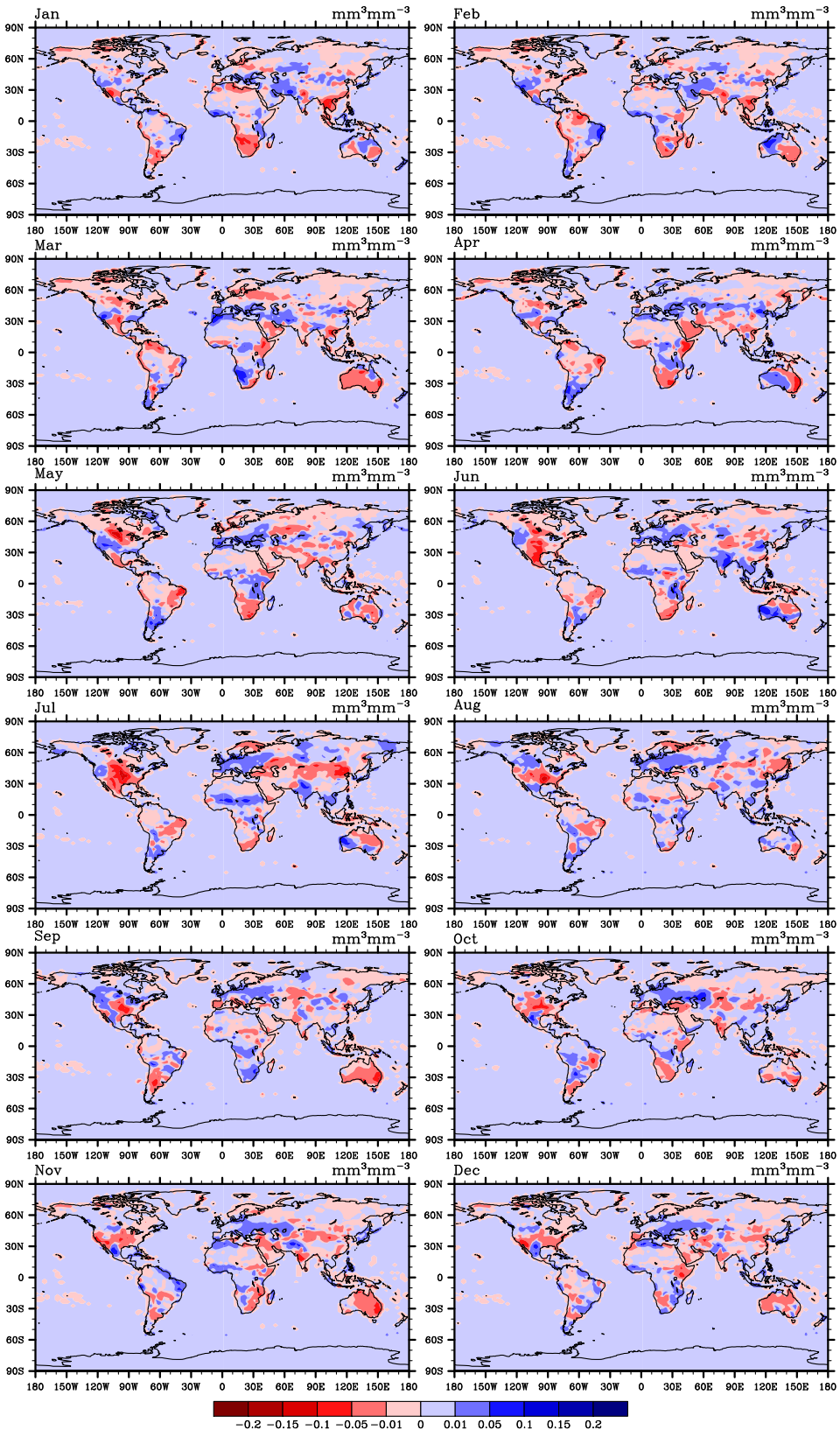

Figure 15. Volumetric Water Content anomalies between 1980 and climatological mean over 1978-2000 in $mm^3\ mm^{-3}$.

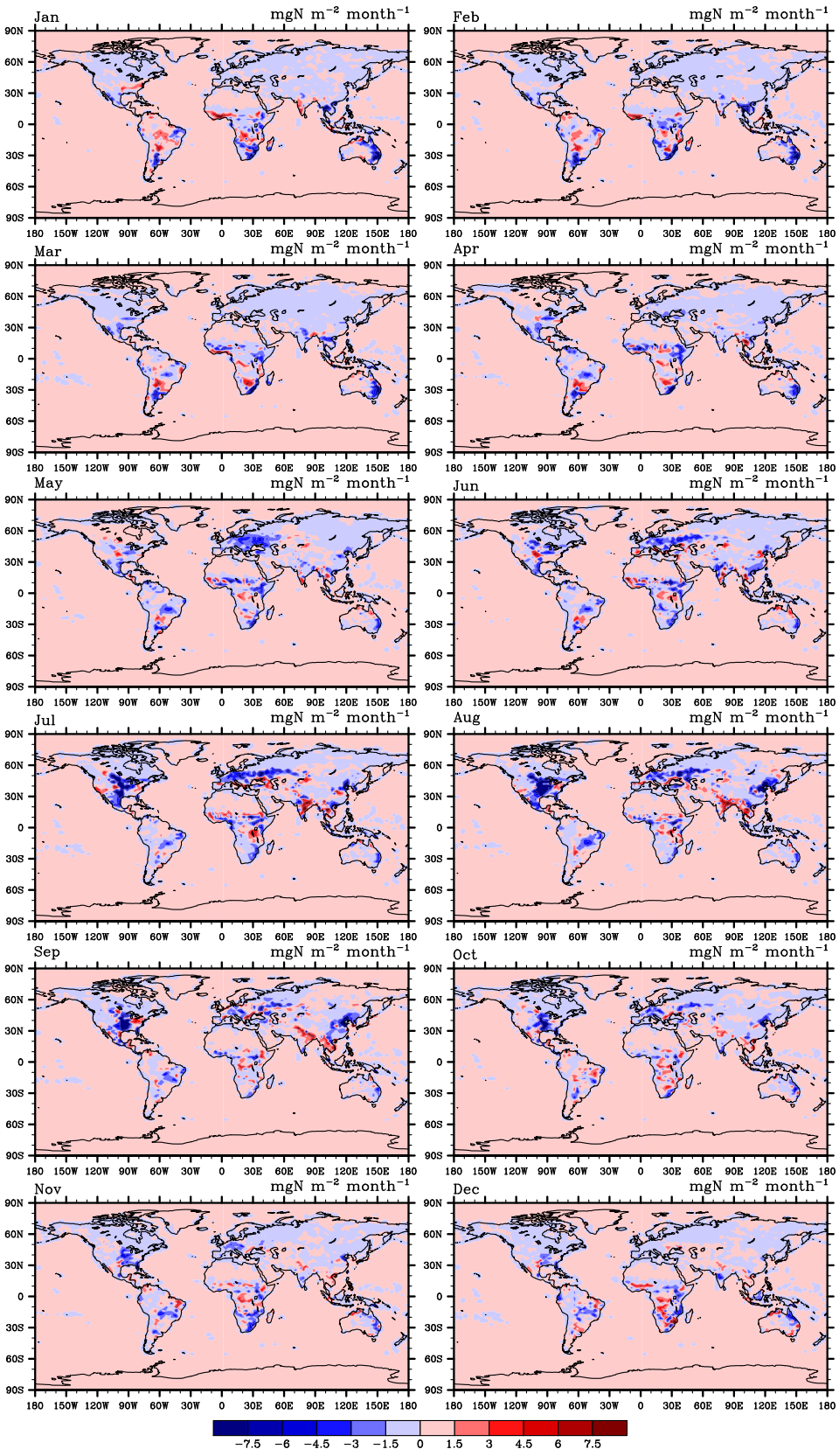

Figure 16. Soil emissions flux anomalies between 1980 and climatological mean over 1978-2000 in mgN m^{-2} month^{-1}.

before and after 1992. Bouwman *et al.* (1995) suggested that this was possibly due to the observed global cooling associated with the eruption of Mount Pinatubo in 1991, which caused lower N_2O emissions in soils.

Figure 12 illustrates that low emissions were estimated in 1992 within Asia, Central Asia and Africa, close to the source of aerosol emissions in Mount Pinatubo (located in the Philippines, 15°N and 121°E). However, we find that lower emissions may be more likely due to the El Niño event that took place in 1992. For example, the response of lower emissions close to the volcano eruption is not visible in 1983 after the El Chichón eruption in Mexico in 1982. Emissions from Central America in 1982 and 1983 are, on the contrary, estimated to have increased. Furthermore, our model results illustrate a significant impact of other El Niño years on soil emissions as well, and the impact differs by regions, as shown in Figure 12. Compared to 1981, we find lower emissions in Africa in 1982, 1987, and 1992; and Oceania, Middle East, Asia, and Central Asia in all El Niño years. To quantify the impact of El Niño on soil N_2O emissions, we use 1981 as the ENSO neutral year based on the ENSO index that is closest to zero among the years we analyze.

Figure 17 illustrates that during these El Niño years, there are large negative emissions anomalies around 30°S in a part of Australia, Southern Africa and Southern America. There are negative emissions anomalies in these regions throughout the year, but the largest negative anomaly of more than -20 mgN m^{-2} $month^{-1}$ is evident between February and April. Soil temperature, precipitation and VWC are important parameters for determining soil N_2O emissions in the CLMCN-N_2O model. However, when we analyze the anomaly of these variables between strong El Niño years and a neutral year, we do not see corresponding negative anomalies in any of the meteorological variables within these regions in March or April (**Figure 18**). We therefore focus our analysis on these two months to better understand what is driving this negative anomaly in our model.

We find that the negative anomalies in soil N_2O emissions around 30°S in March and April during El Niño years are not due to anomalies in soil temperature, precipitation, or VWC. Rather, it is due to negative anomalies in the net N mineralization rate and consequently the soil NH_4^+ concentrations (Figure 18). These negative anomalies are the result of the reduction in gross primary product (GPP), which creates a decrease in available C. The negative anomaly in available C leads to reduced plant N demand, which then creates the reduction in plant C and N allocation. The cascade of these events produce a decrease in total soil organic C. Within CLM-CN, the net N mineralization rate is calculated based on the movement between a more active soil layer to the other, as well as that between litter C (inorganic) to soil C (organic). By reducing the former and increasing the latter, the net N mineralization rate is reduced. The reduced net N mineralization rate leads to a decrease in soil NH_4^+ concentrations and thus as a result, we find a strong negative anomaly in soil N_2O emissions. We indeed find negative anomalies in all the variables where we see large reduction in soil N_2O emissions around 30°S, as illustrated in Figure 18.

Ciais *et al.* (2005) finds that European heatwave and drought in 2003 caused a reduction in GPP, due to stomatal closure. This supports our aforementioned analyses that we find a reduction

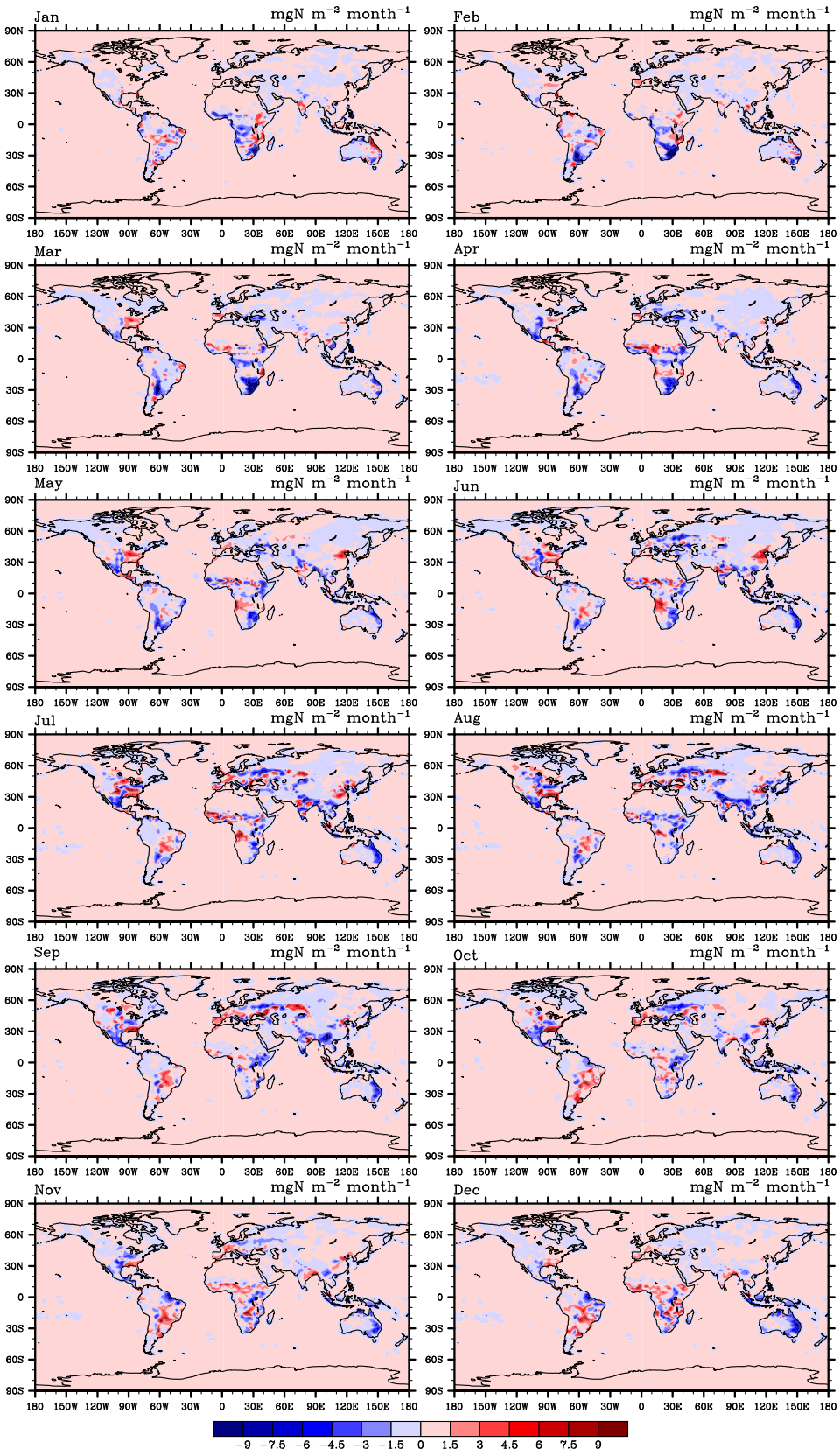

Figure 17. Average of the soil emissions flux anomalies between the strong El Niño years (1982, 1987, 1992 and 1997) and the El Niño neutral year in mgN m^{-2} month^{-1}.

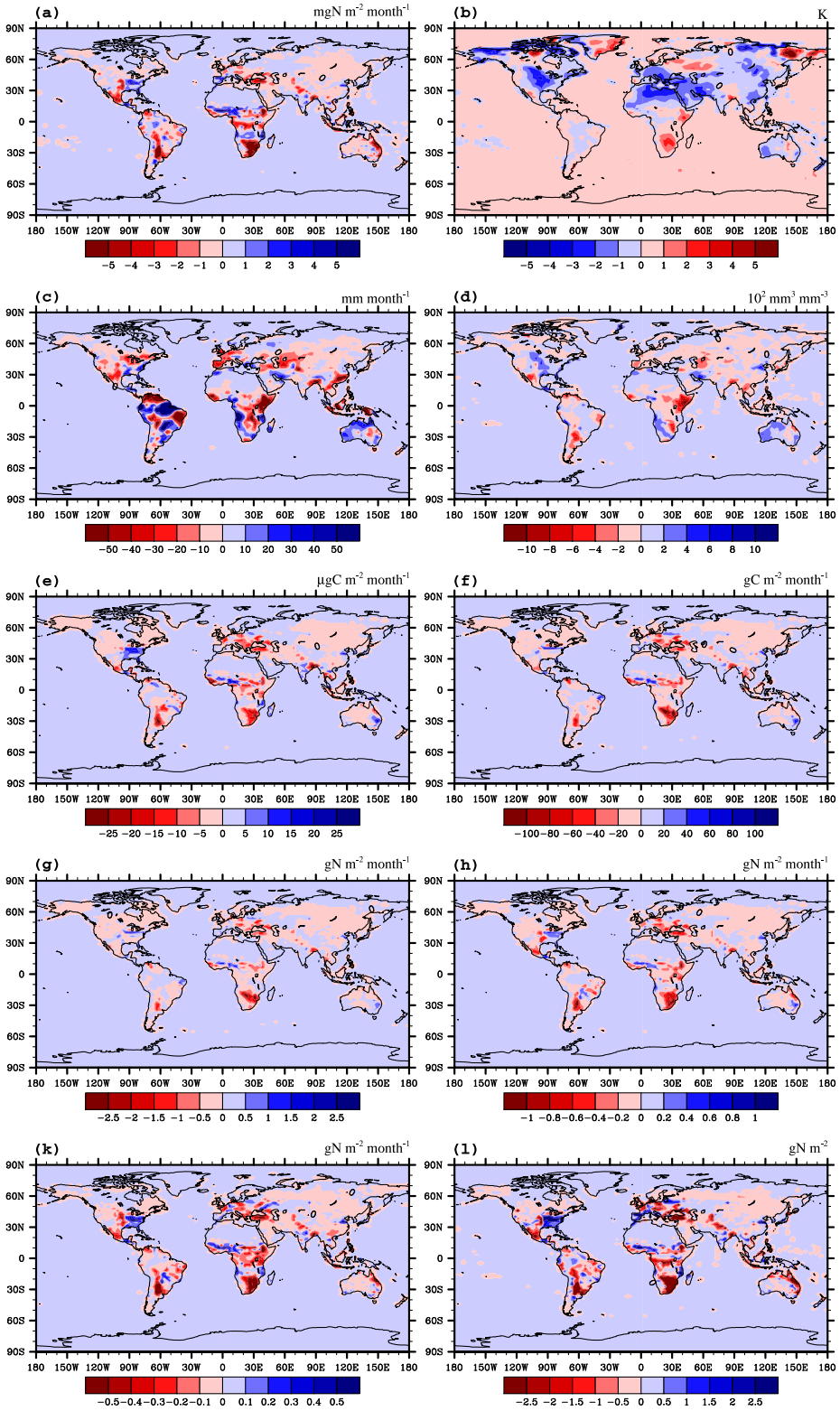

Figure 18. Anomalies of different variables between the average of March and April of El Niño years (1982, 1987, 1992 and 1997) and the El Niño neutral year. (a) Soil N_2O emissions (mgN m^{-2} $month^{-1}$), (b) Soil temperature (K), (c) precipitation (mm $month^{-1}$), (d) VWC (10^2 mm^3 mm^{-3}), (e) gross primary production (μgC m^{-2} $month^{-1}$), (f) available C (gC m^{-2} $month^{-1}$), (g) plant N demand (gN m^{-2} $month^{-1}$), (h) plant N allocation (gN m^{-2} $month^{-1}$), (k) net N mineralization rate (gN m^{-2} $month^{-1}$), and (l) soil NH_4^+ (gN m^{-2}).

in soil N_2O emissions in 1980 due to heatwave and drought. We furthermore find large negative GPP and net N mineralization rate anomalies in 1980 when compared to the climatological mean, as we did for El Niño years. Our model thus reconfirms that direct climate impact from drought and heat waves as well as the non-local influence due to El Niño may have more impacts on soil N_2O emissions than any response associated with a climate-altering volcanic event.

5. CONCLUDING REMARKS

In this study, we have linked the Community Land Model (CLM) with a process-based model of N_2O soil emissions. When comparing with available measurements, we find that the model reproduces the observations quite well at the two Amazon sites: the Tapajós National Forest and Fazenda Vitoriá, but not so well at the White Mountain National Forest in the U.S., probably due to the lack of winter activity in the upper latitudinal regions in the model. Our model results thus reconfirm that we need to understand the winter dynamics in the upper northern hemisphere regions in order to better model soil N_2O exchange. Further research needs to explore the possibility of including the winter soil biological processes to capture the increased soil N_2O emissions from soil freezing and thawing as well as the ability to capture N_2O uptake events that are observed.

An analysis of annual and seasonal variation of global soil N_2O emissions reveals some interesting insights. We find significant inter-annual variations in global natural soil N_2O emissions in our model simulation. There is known inter-annual variability in atmospheric mole fractions of N_2O (Nevison *et al.*, 2007), and our results suggest that natural soil emissions could play an important role. For example, the past measurements find that the growth rate of atmospheric N_2O in 1992 was half the amount of the previous decade (Smith, 1997). In our model results, we find reduced global emissions in 1992 regardless of the forcing datasets we use to run the model. The main reductions of soil N_2O emissions take place in Asia, Central Asia, and Africa, as shown in Figure 12. We find strong evidence that this is due to the El Niño Southern Oscillation. We also observe the impact of other El Niño years on soil emissions, and we find a large reduction in GPP around 30°S, leading to a negative anomaly in soil N_2O emissions in the region during February through April. Similarly, heat waves and droughts caused by high temperature and less precipitation have a similar effect on natural soil N_2O emissions.

We find a clear relationship between the climate and soil N_2O emissions in our model. It is thus possible that climate change will have a large impact on global soil N_2O emissions and vice versa. More study is necessary to understand this feedback mechanism as well as to improve the model to predict the soil N_2O emissions better in a different environment.

Acknowledgements

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