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Year 2020: Consequences of Population Growth and Development on Deposition of Oxidized Nitrogen

With a current world population of 5.3 billion, fossil fuel and biomass burning have already greatly increased the emission of fixed nitrogen to the global atmosphere. In 2020, with a projected population of 8.5 billion and an assumed 100% increase in per capita energy consumption relative to 1980 by the lesser developed countries, we predict an approximate 25% increase in total nitrogen deposition in the more-developed-country source regions such as North America. In addition, reactive nitrogen deposition will at least double in less-developed regions, such as SE Asia and Latin America, and will increase by more than 50% over the oceans of the Northern Hemisphere. Although we also predict significant increases in the deposition of nitrogen from fossil-fuel sources over most of the Southern Hemisphere, particularly Africa, the tropical eastern Pacific, and the southern Atlantic and Indian Oceans, biomass burning and the natural sources of nitrogen oxides (lightning and biogenic soil emissions) are also important in these regions. This increased deposition has the potential to fertilize both terrestrial and marine ecosystems, resulting in the sequestering of carbon. Increases in nitrogen deposition have also been shown not only to acidify ecosystems but also to increase emissions of nitric oxide (NO), nitrous oxide (N_2O), carbonyl sulfide (COS), and carbon + sulfur (CS_2) to the atmosphere and decrease methane (CH_4) consumption in forest soils. We also find that the atmospheric levels of nitrogen oxides increase significantly throughout much of the Northern Hemisphere and populated regions of the Southern Hemisphere. This increase may lead to larger ozone concentrations with resulting increases in the oxidative capacity of the remote atmosphere and in its ability to absorb IR radiation.

INTRODUCTION

The productivity of ecosystems is often limited by nitrogen hence the conversion of N_2 to reactive nitrogen by microbial nitrogen fixation is one of the underpinnings of ecosystem dynamics. The supply of reactive nitrogen to the environment has increased substantially because of the increase in human populations and their reliance on fossil fuel as an energy source. It is likely that future increases in population and per capita energy consumption, especially in less-developed regions, will result in even greater contributions from anthropogenic nitrogen fixation to nitrogen emissions on global and regional bases. Galloway (1) has estimated future increases in NO emissions; this paper uses similar estimates of current and future (year 2020) emissions of NO from fossil-fuel combustion as inputs to a global chemical transport model. This model then calculates the total deposition of reactive nitrogen to marine and terrestrial ecosystems. This paper concludes by examining environmental impacts of predicted increases in reactive nitrogen emissions and deposition. This analysis is similar to that of Rodhe et al. (2), who consider future patterns of sulfur deposition in SE Asia.

MODEL DESCRIPTION

The deposition of fossil-fuel nitrogen to the world's ecosystems is calculated from the emissions discussed above using the Global Chemical Transport Model (GCTM) of the Geophysical Fluid Dynamics Laboratory/National Oceanic and Atmospheric Administration (GFDL/NOAA) (3, 4, 5). This model, with a horizontal resolution of ~265 km and 11 vertical levels at standard pressures of 990 mb, 940 mb, 835 mb, 685 mb, 500 mb, 315 mb, 190 mb, 110 mb, 65 mb, 38 mb, and 10 mb, is driven by 6-hour time-averaged wind and total precipitation fields derived from a parent general circulation model (GCM) (6, 7) and run to annual steady state. The GCTM incorporates parameterized horizontal subgrid-scale transport, vertical mixing by dry and moist convection, vertical turbulent mixing in the boundary layer under conditions of large-scale stability, dry deposition based on measured deposition velocities of individual reactive nitrogen species, and a wet-removal scheme that distinguishes between stable or shallow-convective or deep-convective precipitation (3, 7).

The chemical partitioning of NO_y into NO_x, HNO_3, and PAN includes the nighttime conversion of NO_x ($NO + NO_2$) to HNO_3 in the bottom two model levels (5, 8). The specified fields of O_3, CH_4, CO, H_2O, NMHC, and NO_x used to calculate the OH and peroxyacetyl concentrations needed for the chemical partitioning of NO_y (8) are not changed from 1980 to 2020. Although we expect the specified precursor and NO_x concentrations to increase with increased fossil-fuel combustion, we believe that the impacts of changes in OH (see a discussion of recent model studies by Thompson (9) and the reply by Law and Pyle) (10) on the reactive nitrogen chemistry are second-order effects in this study and have been neglected.

NITROGEN EMISSIONS

Our study requires estimates of the natural rate of N emissions and of fossil-fuel nitrogen emissions in 1980 and 2020. Our estimates for natural N emissions are biogenic soil emissions, 5.6 Tg N yr^{-1} (Levy, Kasibhatla and Moxim. 1994. Global distribution of tropospheric NO_x, past, present and future; manuscript in preparation.); biomass burning, 8.5 Tg N yr^{-1} (11); lightning, 3.0 Tg N yr^{-1} (Levy, Kasibhatla and Moxim 1994. Global distribution of tropospheric NO_x, past, present and future; manuscript in preparation); and injection from the stratosphere, 0.6 Tg N yr^{-1} (5). These natural rates are applied to both 1980 and 2020. The 1980 global fossil-fuel emission source of 21 Tg N (Fig. 1) (3, 12) is concentrated in the mid- and high latitudes of the Northern Hemisphere. Emission estimates for fossil-fuel combustion in 2020 are based on UN population projections (13) and the assumption of a factor-of-two increase in the per capita NO_x

emission rate for less-developed regions (LDR) with no change in the per capita rate for the more-developed regions (MDR). The resulting increase in the total global emission of fossil-fuel NO_x between 1980 and 2020 is 24.4 Tg N yr^{-1}, an approximate doubling relative to 1980 (Table 1). This estimate is conservative. From 1950 to 1987, the increases in per capita energy consumption for Asia, South America, and Africa were factors of 7, 3, and 1.7, respectively (14). Another indication that this is a conservative estimate is that the per capita CO_2 emissions increased by about a factor of four over the past forty years for many MDRs (15).

Emissions of fossil-fuel NO_x to the global atmosphere in 1980 were concentrated in the MDRs of the Northern Hemisphere and in the relatively less-developed Asian region (Table 1). In 2020, because of population increases only, there will be about a 20% increase in emissions in the MDRs, relative to 1980. However, the LDR fossil-fuel emissions in 2020 will jump from 7.8 Tg N yr^{-1} in 1980 to about 29.1 Tg N yr^{-1} (Table 1). Of this 21.3 Tg N yr^{-1} increase, population factors account for 6.7 Tg N yr^{-1} and increases in per capita NO emission account for the remaining 14.6 Tg N yr^{-1}.

NITROGEN DEPOSITION

For 1980 the deposition of nitrogen to the world's ecosystems (Fig. 1) is strongly controlled by patterns of population, fossil-fuel combustion, biomass burning and biogenic soil emissions. This control is mostly evident in the mid-latitudes of the Northern Hemisphere and areas downwind of continents with significant NO_X emissions (e.g., even though eastern Asia is not considered to be a MDR, there is large deposition due to the large population). For 2020, we forecast a large increase in nitrogen deposition from fossil-fuel combustion for regions of South

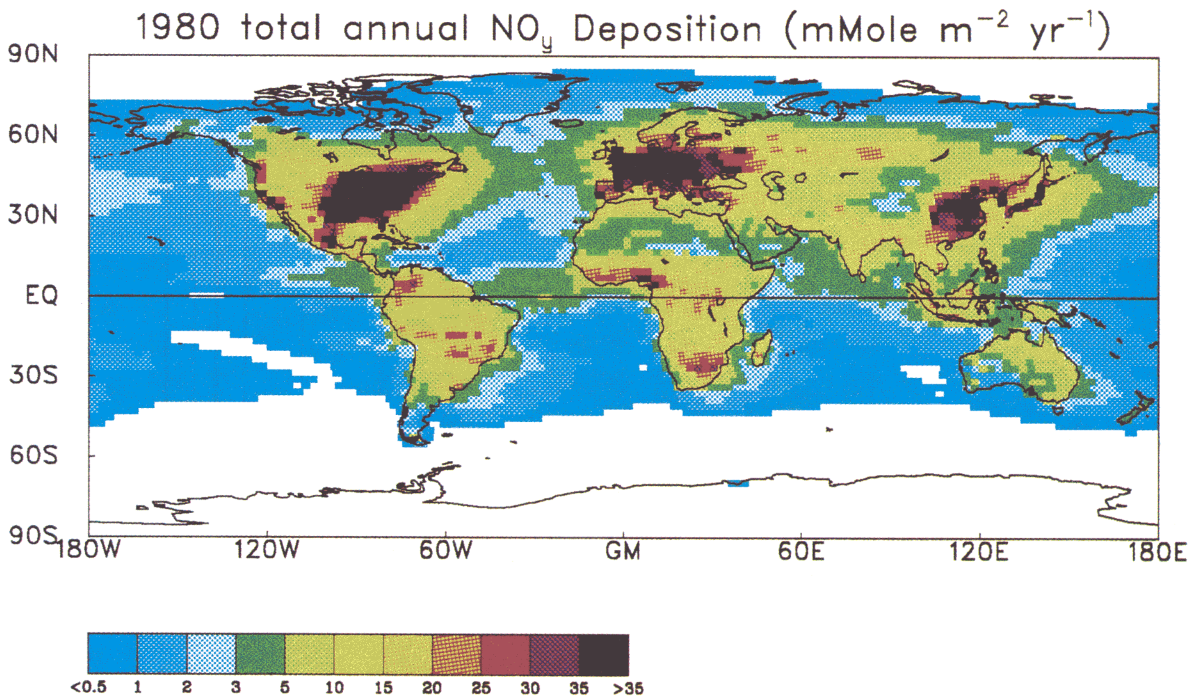


Figure 1. The 1980 deposition of oxidized nitrogen to the earth's surface (mmol m^{-2} yr^{-1}).

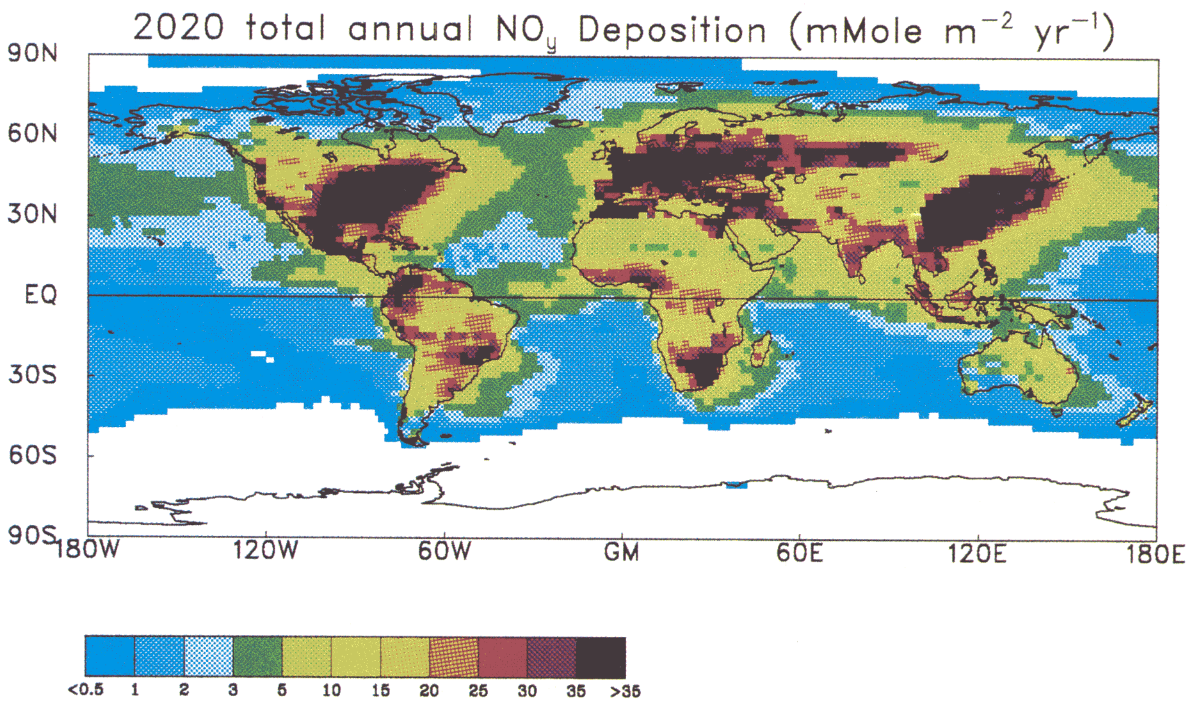
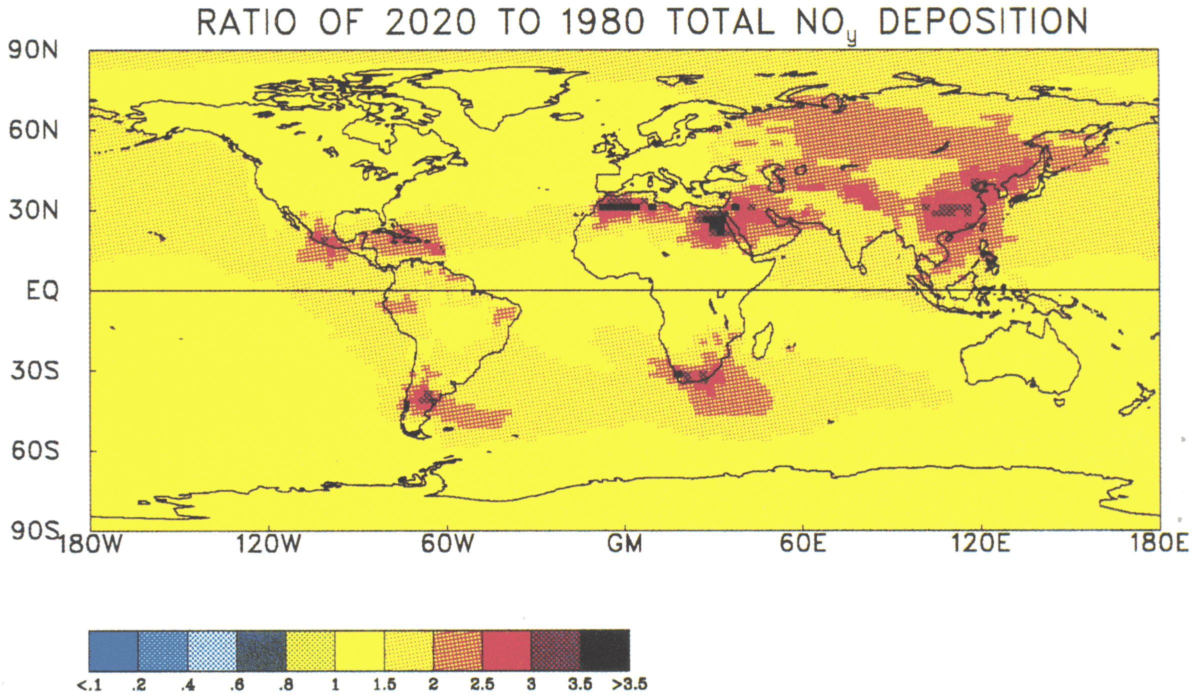


Figure 2. The 2020 deposition of oxidized nitrogen to the earth's surface. Deposition is larger because of increases in population and per capita energy consumption (mmol m^{-2} yr^{-1})

Figure 3. The increase in deposition of oxidized nitrogen to the earth's surface in 2020 relative to 1980. The values are calculated by dividing the data in Figure 2 by those in Figure 1.



America, Africa, and Asia from growing populations and increased per capita fuel use (Fig. 2). The largest relative increases of nitrogen deposition from fossil-fuel combustion are in South America, southern and northern Africa, Central America, and Asia, which receive up to three times increased nitrogen deposition. Deposition increases by up to a factor of two in the southwest USA, primarily because of increases in fossil-fuel combustion in Mexico. Marine regions downwind of these areas also receive increased nitrogen deposition. Since we assume that 50% of the savannas are already being burned each year, we chose to hold emissions from biomass burning constant.

Thus, we conclude that the expected increase in fossil-fuel emission by 2020 will result in large increases in reactive nitrogen deposition in the Northern Hemisphere, in South America, and in Africa. These estimates for 2020 may be lower limits because they are only based on increases in fossil-fuel combustion and do not address possible increases in emissions of NO from biomass burning and NO emissions from increased agricultural activity. In addition, no consideration has been made for the human impact on reduced nitrogen emissions (e.g., NH_3).

Table 1. Emissions of NO_x to the atmosphere of global regions* (Tg N yr^{-1}).

Region	Fossil Fuel: Present	Fossil Fuel: 2020
More-Developed Regions		
United States and Canada	7.6	10.1
Europe	4.8	5.2
Australia	0.3	0.4
Japan	0.7	0.8
Subtotals	13.4	16.5
*Less-Developed Regions***		
Asia	3.5	13.2
Mexico, Latin/South America	1.5	5.9
Africa	0.7	4.2
Russia	2.1	5.7
Subtotals	7.8	29.1
Totals	21.2	45.6

* Europe and Asia are defined as the portion of the Eurasian continent to the east and west of the Ural Mts., respectively.
** The estimate for 2020 allows for an increase in population and a 100% per-capita increase in NO emission.

IMPACTS OF INCREASED NITROGEN DEPOSITION

There are several known impacts of increased levels of oxidized nitrogen in the atmosphere. NO_x levels are believed to control the balance between the chemical production and destruction of O_3 (16) in the troposphere, and fossil-fuel emissions are already thought to have shifted this balance in favor of photochemical production over the MDRs (17). Tropospheric O_3 is estimated to increase over the continental midlatitudes of the Northern Hemisphere at a rate of approximately 1% per year (18). Most increases in O_3 concentrations have occurred since 1950, which coincides with known trends in the atmospheric abundance of O_3 precursors, particularly NO_x (19). The impact of increased fossil-fuel combustion on NO_x levels in the troposphere is similar to that predicted for total nitrogen deposition. O_3 levels will continue to be strongly influenced by increasing NO_x over the MDRs. Over the middle of the North Atlantic Ocean, we predict that tropospheric NO_x levels, which currently are at a level between O_3 production and destruction, will increase 20–40%, enough to support significant O_3 production (15, 17). Similarly, the current levels over the North Pacific Ocean, which may also support both production and destruction (20), are predicted to increase by at least 50% because of the greatly increased emissions from China and the rest of Southeast Asia. This increase may also lead to significant O_3 production over the North Pacific Ocean and will enhance the ability of the troposphere to adsorb infrared radiation. In 2020, over most of the remote tropics and southern oceans, although the predicted NO_x contribution from fossil-fuel combustion will increase by as much as a factor of three, the total NO_x levels will remain very low and O_3 chemistry will continue to be dominated by destruction.

Increased mobilization of nitrogen will also impact ecosystems. The direct effects, fertilization and acidification, are well known. In terrestrial and freshwater ecosystems, increased deposition of nitrate can either fertilize or acidify or both, depending on the nutrient status and acid-neutralizing capacity of the ecosystem. Large areas of tropical ecosystems are nitrogen limited (21) or have low acid-neutralizing capacity (22). There are also indirect effects. Terrestrial ecosystems release NO and

N_2O to the atmosphere by the processes of nitrification and denitrification (23). Their emission rates to the atmosphere have been shown to increase as the amount of nitrate in the soil increases or as the rate of nitrate deposition increases (24–26). In addition, the increased deposition of nitrate can result in increased emissions of COS and CS_2 and decrease the rate of CH_4 consumption in forest soils (27), perhaps leading to increased emissions. Any changes in the emissions of NO, N_2O, COS, CS_2, and CH_4 are critically important because they all have significant roles in many atmospheric processes such as the radiative and chemical balance of the troposphere and stratosphere.

Increased nitrogen deposition will also fertilize marine ecosystems. Coastal systems in North America have been shown to respond to increases in both episodic and long-term nitrogen deposition (28). We expect similar effects in regions adjacent to continents that experience increases in nitrogen deposition. Impacts are not limited to coastal marine ecosystems. Since mid-oceanic regions are removed from riverine nitrogen sources, atmospheric deposition can provide nitrogen required for phytoplankton productivity. A recent analysis shows that, in the western North Atlantic Ocean, the episodic nitrogen supply from the atmosphere can exceed the minimum amount of nitrogen supplied by upwelling sources required for new production especially under stratified conditions (29, 30). Therefore, as nitrogen deposition increases to the world's oligotrophic oceans, we project impacts on new production.

In summary, we predict that increases in the population and level of industrial activity, especially in less-developed regions of the world, will result in significant increases in nitrogen deposition over large regions. Our projections for the NO_x emissions and reactive nitrogen deposition in 2020 are necessarily based upon several assumptions. The assumptions concerning the rate of increase in per capita NO_x emission, although conservative, are the most tenuous. LDRs may not develop as quickly or, if they do, they (or MDRs) may institute NO emission-reduction programs that will counterbalance the increases. However, even if the 2020 estimates are too high, it is probable that they will eventually occur unless there is some global catastrophe. In reality, the estimates reflected in Figure 2 may be underestimates since they do not include the impact of population growth on the emission of NH_3 to the atmosphere or an increase in biogenic soil emissions from population-driven increases in fertilizer use.

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