C-062 Predicting the impacts of increasing surface ozone concentration in East Asia: Risks to vegetation and losses of agricultural crops （Abstract of the Final Report）

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[Abstract] We aim to improve our capability to predict the uptake of ozone by vegetation and the loss of crop productivity by ozone in East Asia. To this end, we have improved our understandings in various key aspects of the ozone impact prediction: ozone deposition and uptake model is verified against field observations, models of air chemistry and transport are improved by using the field observations, and agronomic as well as physiological-biochemical measurements of the ozone impacts on crops were done in the field rather than in chambers. We have developed a model of ozone uptake by plant leaves on the basis of measurements of gas exchange in wheat and rice leaves subjected to the free-air concentration enrichment of ozone (FACE-Ozone) in Jiangdu, Jiangsu, China. We have also set up a model system to simulate ozone concentration across East Asia at a much finer scale than before, and predicted ozone concentration at the crop canopy height in the years of 2000 and 2020. According to the policy-failure scenario for the ozone-precursor emissions in China, the simulation showed that formation of ozone will be intensified in 2020 as compared with 2000, and hence the daytime ozone concentration will rise drastically, e.g. by 20 ppb or higher, across southern coastal China during the summer months. The world's first FACE-Ozone with rice and wheat revealed that the yield losses in the field were larger than those in chambers in the past studies. By scaling up the responses of crop yield to the enhanced stomatal ozone uptake dose (wheat) or daytime ozone concentration (rice) in the FACE-Ozone experiment, the loss of wheat production across China was projected to reach 17 % in 2020 as compared with 2000. For rice, the projected yield loss differed greatly between the varieties assumed. Assuming hybrid rice varieties all across China, we projected the loss of rice production to be greater than 40 % in 2020 relative to the year 2000, whereas an assumption of planting conventional Japonica or Indica varieties across China projected the rice production loss to be less than 18 %. There are large uncertainties in these projections, however, and the uncertainties must be reduced by expanding the FACE-Ozone experiment across years and locations.

1. Introduction

Surface ozone concentration is rising rapidly in East Asia due to increasing emissions of nitrogen oxides and other precursors of ozone. This raises serious concerns about the risks in vegetation and losses of crop production in this region, particularly in eastern China, which constitutes the world's largest crop production area. Despite the huge implications of the ozone impact on vegetation in East Asia, there are only a very limited number of studies conducted in this region on the crop losses by ozone. Therefore, previous studies had to adopt the relationships between ozone doses and crop yield losses from experiments done in Europe and USA when predicting the crop losses in East Asia. Whereas such studies have indeed demonstrated large crop losses, e.g. 40 – 60 % loss in Chinese winter wheat in 2020 [1)], the extent of the yield losses is questionable because of the use of the equations derived from chamber experiments in the other parts of the world, where climate, soil and the crop varieties differ greatly from those in East Asia.

The relationships based on ozone concentration are subjected to the perturbations by climate and soil moisture via the changes in stomatal conductance, which regulates the relationship between ozone concentration and ozone uptake with the latter being the determinant of the ozone impacts on plants. Even within Europe, the areas of high ozone concentration are not those with high ozone uptake rate in vegetation [2)]. Applying the relationships developed in northern Europe to Asia would be even more problematic.

The use of chambers could also introduce errors in predicting the crop losses based on the ozone dose – yield loss relationships. The chamber enclosure greatly alters the ozone deposition to the vegetation, and, hence, the ozone uptake rate by the plants. In addition, it is suspected that the alteration of microclimate around the plant canopy by the chamber walls would also change the plant sensitivity to elevated ozone concentration.

In order to avoid the above-mentioned problems and better predict the crop losses by ozone in East Asia, we need:

to quantify the ozone deposition to vegetation in East Asia, and

to conduct ozone exposure experiment without chambers in the field in East Asia.

2.Research Objective

In this program, we plan to improve our understandings in various key aspects of the ozone impact prediction:

a. Air chemistry and transport shall be modeled at much finer spatial and temporal scales than the previous studies and with a better representation of the land surface.

b. Ozone deposition will be modeled on the basis of observations at typical agricultural fields in East Asia, and will be incorporated into the air chemistry-transport model (a).

c. Open-air ozone exposure will be conducted to study the ozone impacts on major crops in the field without any enclosures which could alter the crop yield responses to ozone.

d. Crop growth processes shall be considered as the determinants of the ozone impacts: from ozone uptake and detoxification to the reduction in crop yield. The crop process responses shall be used in interpreting the observed yield losses in the open-air ozone exposure (c).

e. The crop loss will be predicted on the basis of the open-air ozone exposure (c) in combination with the improved air chemistry-transport model (b).

Our findings will scientifically underpin the policy-making efforts toward the management of air quality across East Asia.

3. Methods and results of the sub-projects

The project consists of six subprojects, of which the first one (C062-1) addresses the ozone deposition monitoring, the second one (C062-2) develops models of the ozone deposition processes, and the third one (C062-3) develops air chemistry and transport model. The fourth subproject (C062-4) addresses biochemical and physiological responses of plants to elevated ozone concentration, and the fifth one (C062-5) develops the crop growth models and test them against the observations in the open-air ozone exposure experiment. The last subproject (C062-6) focuses on the ozone impacts on photosynthetic processes in wheat varieties in China.

C062-1. Observations of ozone deposition to vegetation.

We have been monitoring ozone deposition onto vegetation in a rice-wheat field near the city of Jiangdu, Jiangsu Province, China since December 2006. The daytime ozone concentration ($[O_3]$) rose gradually since March and reached maxima in late May and in July. The first seasonal peak in $[O_3]$ corresponds to grain-filling to maturity stages in wheat, and the second one corresponds to vegetative to early reproductive stages in rice. Diurnally, [O3] reached the peak at around 2 to 4 pm, and the minimum at 6 am. Ozone uptake to the plant canopy also showed a diurnal pattern with the peak around noon. The ozone flux to the rice canopy exhibited a seasonal change along the plant development: the daily mean deposition velocity showed a minimum of 0.05 cm s^{-1} just after flooding of the paddy fields, and increased gradually toward the maximum of 0.8 cm s^{-1} in grain-filling phase. In wheat, by comparison, the maximum daily mean deposition velocity was 0.5 during the flowering to maturity stages, whereas it stayed at a comparable level after the harvest of the wheat plants. Stomatal uptake of ozone in plants contributed to about 66 % of total ozone flux during the flowering to maturity period in wheat, and 59 % in rice on average across the entire growth duration. The estimated amount of stomatal uptake of ozone was 19 m mol m^{-2}, of which 55 % was absorbed through the period from transplanting to flowering. These measurements of $[O_3]$ and ozone uptake were used for the sub-project #2.

C062-2. Modeling the ozone deposition processes.

We have developed models of ozone deposition to and uptake processes by rice and wheat canopies in cooperation with the sub-project #1 at the Chinese fields. The model of stomatal uptake of ozone was developed for wheat (1 variety) and rice (4 varieties) on the basis of the field measurements, and is parameterized as a collection of functions of weather variables, leaf phenology, accumulative ozone dose, and the time of day. The model exhibited the decline in stomatal ozone uptake as the leaf experiences accumulative ozone exposures. The leaf ozone uptake model was developed for the flag leaves of wheat, but was also applicable to the lower leaves in wheat also. We found that the model of stomatal uptake required different sets of parameters across the inter- and intra-specific contrasts in the crops studied.

We also developed a model to estimate [O_3] at the canopy height from [O_3] at a height above the canopy, which is noticeably higher than that at the canopy height. This model was incorporated into the air chemistry-transport model in the sub-project #3.

The modeled ozone uptake was related with the changes in photosynthetic rate observed in the field under the open-air ozone release experiment (see sub-project #5 for details). Stomatal closure caused by the increase in [O_3] was closely linked with the reduction in leaf photosynthetic rate (P), which is characterized by a function of AOT40 (accumulated hourly mean [O_3] over 40 ppb during the daytime) with the sensitivity parameter differing among the rice varieties.

We then investigated the relationship between the accumulative ozone uptake dose: AFst6 (integral ozone uptake over 6 nmol m^{-2} s^{-1}) and the accumulated net photosynthetic carbon fixation (NPP) in the wheat variety and the rice varieties. In wheat, the relationship between AFst6 and the relative yield has been used to estimate crop yield reduction[3)], but, for rice, we found that the ozone dose may not be applicable because of the very high sensitivity in the hybrid rice varieties to AOT40. The enhancement in AFst6 was smallest in the rice variety with largest decline in NPP, because of the stomatal closure due to the decline in NPP under elevated [O_3]. We may suggest the model of NPP in response to [O_3] as a more direct estimator of crop losses due to elevated [O_3].

C062-3. Prediction of ozone uptake by vegetation in East Asia.

The goal of this sub-project was to predict the impact of increased surface ozone concentration ([O_3]) as caused by the increased emission of ozone precursors on plant ozone uptake in East Asia in the near future. We adopted a model system consisting of a global photochemistry and transport model: CHASER and a regional air chemistry-transport model WRF/Chem v. 2.1.2 to estimate surface [O_3] at much finer spatial and temporal scales over East Asia than ever been done before. The model system incorporated the scheme for estimating [O_3] at canopy height as developed in the sub-project #2. We first compared the model estimated canopy-height [O_3] with our own observation at the experimental site in China, and found a good agreement between the model estimates and observations for daytime [O_3]. The model tends to overestimate night-time [O_3], but this would have only a very small effect on our estimation of ozone uptake and impacts on crop production since the plants close stomata at night and, hence, night-time [O_3] can have little effects on plant processes.

We then predicted the impacts of increased ozone precursors on surface [O_3], resultant increase in ozone uptake by plants, and eventually the increase in crop losses due to ozone over East Asia. We assumed the 'Policy-failure' scenario of the REAS emission inventory for China in the year 2020 with the year 2000 being the reference. The predicted impacts are as follows:

Surface [O_3] in May will rise by more than 20 ppbV (monthly mean daytime [O_3]) over the large area of coastal China from Shanghai to Gouangdong between 2000 and 2020. The corresponding increase in surface [O_3] in May will be around 5 ppbV in the down-stream regions including Japan. May corresponds to flowering stage of wheat in the provinces of Henan, Hebei, Jiangsu, Shangdong, and Anhui: the major wheat producers, the increase in surface [O_3] will drastically change the ozone uptake dose AFst6 with the wheat plants. In the year 2000, only 0.2 % of the entire wheat production areas in East Asia experiences AFst6 greater than 4 mmol m^{-2}, whereas, in the year 2020, the corresponding figure jumps up to 17 %. The maximum increase in AFst6 is about 2 mmol m^{-2} which takes place in Anhui Province. Such a large increase in the ozone uptake dose will cause a large decline in the crop production. In the year 2000, the crop yield loss ranges from 8 to 14% in the major wheat production provinces, but the yield loss rises to the range from 15 to 20 % in 2020. Total wheat production loss in the entire China will double to 16% in 2020 from 8% in 2000.

The ozone uptake dose was calculated for rice also, and in most areas of East Asia, a substantial increase is predicted for the duration from the years 2000 to 2020. Nevertheless, in some areas, a small decrease in the ozone uptake dose was predicted not because of a decline in [O_3] but of *increase* in [O_3]. This can be explained by the high sensitivity in rice stomatal conductance to the ozone impacts, and indicated the problem of the accumulated stomatal uptake dose to be used for crop losses estimation as found in our sub-project #2. We therefore decided to estimate the ozone impacts with concentration rather than stomatal uptake of ozone in this sub-project. Using an ozone dose-rice yield loss relationship, we predicted that the increase of over 20 ppb in daytime surface [O_3] across the large areas of southern China will increase the loss of Chinese rice production due to ozone from 4 % in 2000 to 7 % in 2020. The rice production loss in Japan will increase from 3.1 % to 3.7 %, and that in Korean Republic will increase from 3.6 % to 4.4 % between 2000 and 2020. Thus the increased rice production loss is quite modest even in China, and is negligible in other countries of East Asia. It must be noted, however, that the ozone dose-rice yield loss relationship used in this prediction is based on a chamber experiment with Japanese varieties, and, therefore, that we are significantly underestimating the ozone impacts on Chinese varieties. The Chinese rice varieties, especially the hybrid varieties were found to be much more sensitive to ozone than the conventional varieties in the open-air ozone exposure experiment (sub-project #5).

C062-4. Physiology and biochemistry of crop responses to elevated ozone concentration.

It is necessary to understand the processes that occur in plant leaves after the ozone uptake via stomata to estimate the crop yield loss, which is a result of the combined changes in physiological-biochemical processes in response to the increased uptake of ozone into plant interior. We installed sun-lit chambers in Japan, and conducted ozone exposure experiments in 2007 and 2008.

In 2007, we found that the two varieties: Koshihikari and Kinuhikari, are comparable in terms of growth and yield responses to ozone exposure in contrary to a previous study which found a clear difference between the two varieties[4)]. In 2008, we used the rice variety Koshihikari for the detailed studies on the responses of photosynthetic and biochemical responses to elevated [O_3]. We found a close relationship between the photosynthetic reduction and the increased accumulative ozone uptake with zero threshold value. We also found that the plants respond to the increased [O_3] by elevating anti-oxidant activities in the leaf apoplast as well as symplast. Despite such protective responses, however, the plant tissues exhibited accumulated damages as they are exposed to elevated [O_3] for extended period, and, thus the protection mechanisms are not effective enough to eliminate the oxidative damages to cell membranes.

We also compared two wheat varieties with respect to photosynthetic and antioxidative responses to elevated [O_3]. The variety 'Shirogane-Komugi' exhibited a larger responses to ozone than the variety 'Norin 61', and the varietal difference can be explained by the varietal difference in anti-oxidative scavenging capacity in the leaves. Catalase and mono-dehydroascorbate reductase were the most critical enzymes that play major roles in the varietal difference in the ozone sensitivity.

C062-5. Prediction of the impacts of increasing ozone concentration on crops in East Asia.

We conducted the world's first open-air ozone exposure for rice and wheat in farmers fields in Jiangdu, Jiangsu, China in 2007 and 2008. In the wheat experiment, daytime 7-h mean ozone concentration was increased by 18 ppb (2007) and 12 ppb (2008), and the yield loss ranged from 17 to 27 % on average across the four varieties and two years. No varietal difference was detected in the yield loss, but a significant varietal difference was found in the reduction of individual grain weight, which is the dominant cause of the yield loss.

In the rice experiment, we used one Japonica and one Indica varieties of both conventional type, and two hybrid varieties. The seasonal mean daily [O_3] was increase by 10 ppb in both 2007 and 2008, and the resultant yield loss ranged from 5 to 24 % with a weakly significant variety x ozone interaction. Testing the yield losses for individual variety, we found that the hybrid varieties showed a significant yield loss, but that the yield losses in the conventional varieties were not significant. The varietal difference was clearer in the reduction of the number of spikelet per panicle, which is the largest contributor to the yield losses.

The results of the open-air ozone exposure were compared with the existing dose-response relationships, and, in wheat and rice crops, our results showed larger losses than the dose-response functions based on chamber experiments. We further tried to scale-up our experimental results to estimate the increased ozone impacts in entire East Asia between the years 2000 and 2020. In wheat, the estimated yield loss amounted to 17 % for the entire China, whereas that for Japan was only 2 % when comparing the yield in 2020 with that in 2000. In rice, the increase in [O_3] from 2000 to 2020 is estimated to cause only 3 % increase of the yield loss when using the dose-response relationship for the Japanese varieties (sub-project 3), but it was estimated to be over 40 % with the hybrid varieties and 15 % with the conventional varieties when we scaled-up the results of the open-air ozone exposure. There are large uncertainties in these estimates, however, as discussed later.

C062-6. Effects of ozone on photosynthetic processes in wheat varieties in East Asia.

We performed a meta-analysis with 53 peer-reviewed articles published between 1980 and 2007, and demonstrated that the wheat yield is lost by 29 % on average by elevated concentration of ozone in the range from 31 to 200 ppb.

We also conducted measurement of photosynthetic response in wheat to elevated [O3] in the open-air ozone exposure experiment in China. Two modern cultivars of winter wheat (Y16 and Y2) with the same phenology were investigated for the impacts of elevated ozone concentration ([O_3]) on physiological characters related to photosynthesis under fully open air conditions. A 50 % elevation of [O_3] above ambient [O_3] was conducted from tillering stage to final harvest, with an actual elevation being 27%. Measurements of leaf pigment contents, gas exchange and lipid oxidation were made in three replicated plots during flag leaf development. Elevated [O_3] significantly accelerated the senescence of Y2, as indicated by significant decreases in chlorophyll, carotenoid content, photosynthetic rate and an increase in lipid oxidation, whereas only pigment contents were reduced in Y16. The elevated [O_3] induced significant decrease in photosynthetic rate of Y2 through impacts on stomatal and non-stomatal factors as evidenced by significant decrease in carboxylation capacity. Such changes were not observed in Y16. The detrimental effects of O_3 on Y2 were increased with aging of the flag leaves, whereas this was the case only partially in Y16. Besides the significant interactions at late grain filling stage between O_3 and cultivars, O_3-induced negative effects were observed in Y2 about 10 days earlier than those in Y16. It was thus suggested that Y2 was more sensitive to O_3 than Y16, and that non-stomatal factors should account for the varietal difference in the responses to elevated [O_3].

4. Discussion

Our findings in this project can be summarized as follows:

A. We predicted surface ozone concentration and the ozone uptake by crop plants more accurately than before. Our results indicated a very large increase in ozone concentration, e.g. 20 ppb, in large areas in Southern China, such a large increase in ozone will cause significant yield loss in wheat at relatively large certainty, and even greater loss, e.g. 20 % or more, in rice production despite large uncertainties in the estimated yield loss.

B. We obtained better understandings of the processes in the responses of the crop plants to elevated ozone concentrations. We have located varietal difference in wheat and rice responses to ozone in the experiments in China and Japan. The varietal difference cannot be fully accounted for by the difference in the ozone uptake amount. Rather, it was suggested that the detoxification capacity in plant leaves may play the major roles in the varietal difference. In rice, we have found that the Chinese hybrid varieties are clearly more sensitive to ozone than the conventional varieties[5, 6].

We must be cautious about the estimated yield loss in rice, because the increase in the predicted surface [O_3] in China is often greater than 20 ppb, whereas, in our open-air ozone exposure, the increase in [O_3] is only 10 ppb or less. We are therefore extrapolating our experimental results, and, hence, our estimated yield loss should be largely uncertain. It is more certain, however, that there will be rice yield losses greater than what we found in the ozone FACE rings with the 10 ppb increase of [O_3]. The greater-than-20 % yield loss predicted for the hybrid varieties is large enough to have siginificant implications to the Chinese food security in the near future. The hybrid varieties have been one of the key technologies to support food security in China, and their high sensitivity to ozone makes the food security in this region quite uncertain. The increased wheat production loss to ozone will only add more certain evidences to our concerns about the impact of rapid increase in surface [O_3] on food security in East Asia.

It can be pointed out that the varietal difference in rice exposed to elevated ozone concentration may provide us with the possible countermeasures to protect the rice plants against the rising surface [O_3], although the protection may be only partial. A better understanding of the protection mechanisms will play the central role in finding out the genetic and/or biochemical measures for the protection of crop production against the increasing surface [O_3].

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