Nitrous Acid, Nitrogen Dioxide, and Ozone Concentrations in Residential Environments

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Nitrous acid (HONO) may be generated by heterogeneous reactions of nitrogen dioxide and direct emissions from combustion sources. Interactions among nitrogen oxides and ozone are important for outdoor photochemical reactions. However, little is known of indoor HONO levels or the relationship between residential HONO, NO2, and O3 concentrations in occupied houses.

Six-day integrated indoor and outdoor concentrations of the three pollutants were simultaneously measured in two communities in Southern California using passive samplers. The average indoor HONO concentration was 4.6 ppb, compared to 0.9 ppb for outdoor HONO. Average indoor and outdoor NO2 concentrations were 28 and 20.1 ppb, respectively. Indoor O3 concentrations were low (average 14.9 ppb) in comparison to the outdoor levels (average 56.5 ppb). Housing characteristics, including community and presence of a gas range, were significantly associated with indoor NO2 and HONO concentrations. Indoor HONO levels were closely correlated with indoor NO2 levels and were about 17% of indoor NO2 concentrations. Indoor HONO levels were inversely correlated with indoor O3 levels. The measurements demonstrated the occurrence of substantial residential indoor HONO concentrations and associations among the three indoor air pollutants.

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Indoor fuel combustion has been identified as one of the most important factors that influences indoor air pollution. Indoor air pollutants arising from gas combustion include nitrogen dioxide and other nitrogen species. NO2 has been the focus of indoor nitrogen oxides due to its health effects (1). NO2 is produced by oxidation of atmospheric nitrogen during high-temperature fuel combustion. The oxidant properties of NO2 can cause adverse health effects, including throat irritation, cough, and dyspnea (2). Several epidemiologic investigations have found an association between NO2 exposure increased by indoor combustion sources and adverse respiratory health effects (1).

Nitrogen dioxide can react with surface materials commonly present indoors. Nitrous acid (HONO) is one of the possible gaseous products of heterogeneous NO2 reactions with water on indoor surfaces (3). Indoor HONO concentration from the heterogeneous reactions can be affected by indoor NO2 concentration, ventilation rate, surface material, available surface area, temperature, and humidity (4). In addition, HONO is formed directly by combustion processes (5). The presence of indoor HONO as a substantial portion of total oxides of nitrogen was suggested by a high removal rate of NO2 on indoor surfaces, the formation of HONO by heterogeneous NO2 reactions, and a relatively long lifetime for HONO (5).

A few studies have measured residential HONO concentrations because measurement of HONO at the relevant levels has been technically difficult. However, these limited measurement efforts have demonstrated that indoor levels are higher than outdoor levels. In Albuquerque, New Mexico, 24-hr average concentrations of HONO in 10 homes with gas ranges were between 2 and 8 ppb (6). In southwest Virginia, indoor 24-hr HONO levels were significantly higher than outdoor levels both in summer and winter (7). Winter indoor HONO levels of 5.46 ± 3.75 ppb and 2.43 ± 0.14 ppb were observed in houses with and without gas ranges, respectively. Higher indoor HONO levels were observed at night in a study conducted in Rome, Italy; indoor HONO levels peaked in the range of 10–21 ppb (8). In this study, long-term average residential indoor HONO concentrations were not reported.

Outdoor HONO concentrations are usually lower than indoor levels, reflecting the fact that HONO is photolytically unstable. Annual average ambient HONO levels ranged from 0.1 to 1.4 ppb across 24 U.S. and Canadian communities monitored between 1988 and 1991 (9). The highest annual average ambient HONO concentration recorded was 1.6 ppb in Livermore, California. In an urban area of Sweden, predawn 1-hr maximum HONO levels ranged from 1.3 to 3.9 ppb (10). The outdoor HONO levels were correlated with ambient NO2 concentrations. Low, but persistent, daytime HONO levels in Lubbock, Texas, ranged from 0.1 to 0.5 ppb, whereas night levels peaked at 1–2 ppb (11). In Rome, night peak HONO concentrations ranged from 3 to 6 ppb (8).

HONO is one of the generators of hydroxyl radical in photochemical smog formation. The acidity, reactivity, and aqueous solubility of HONO suggest its potential respiratory toxicity. When asthmatics were exposed to 650 ppb of HONO for 3 hr, they demonstrated mild alterations in lung function and reported mild symptoms of lung irritation (12). In other controlled human exposure studies of healthy individuals, irritation to the mucous membrane was determined at concentrations of 77 and 395 ppb of HONO for 3.5 hr (13). However, the effect on human health of long-term exposure to low concentrations of HONO is unknown.

The potential toxicity of HONO and the presence of indoor HONO sources support the need for residential HONO measurements. In addition, many earlier analyses of NO2 actually measured several oxides of nitrogen, including HONO (14). It is possible that results of previous epidemiologic studies were confounded by the presence of other nitrogen oxides species, including HONO. Indoor HONO can be generated from heterogeneous NO2 reactions and indoor combustion. In this study we measured residential HONO and NO2 levels in homes participating in a chronic ozone exposure study conducted in Southern California.

Heterogeneous reactions of nitrogen oxides have been shown to vary with sources, meteorology, and ambient O3. There are limited data on residential indoor HONO levels in California and elsewhere. Indoor reactions may also vary among indoor locations as well.
O3 concentrations were measured in 119 residences. We performed the integrated indoor residential concentrations of HONO, NO2, and O3. We investigated the inverse association between indoor O3 and nitrogen oxides. These measurements were performed in a sparsely occupied, air-conditioned telephone switching building. In our study we substantially expand the information available on indoor residential concentrations of HONO, NO2, and O3. We performed the integrated 6-day measurements in 119 residences in two communities in Southern California. The objectives of this study were to measure residential indoor and outdoor HONO levels along with NO2 and O3 concentrations and to examine the relationships among housing factors and pollutants.

Materials and Methods

In April and May 1996, HONO, NO2, and O3 concentrations were measured in 119 homes. The homes were recruited from an ongoing 12-month study measuring indoor and outdoor concentrations and personal exposure to ozone of elementary school-age children in two communities in Southern California. Details of this “Harvard Southern Chronic Ozone Exposure Study” are described elsewhere (16). Among the 119 houses, 57 were located in Upland (valley site) and the remaining 62 were in towns located in the mountains at the eastern end of San Bernardino County (mountain site). Measurements occurred in the last four sampling cycles of the study, with approximately 25% of the homes sampled each cycle. Complete housing characteristic information was available for 111 houses. Informed consent was obtained.

HONO concentrations were measured using a passive sampler constructed from a 37-mm diameter polystyrene air sampling cassette containing a glass fiber filter coated with a 2% sodium carbonate solution (17). The exposed filter was analysed by ion chromatography after treatment with hydrogen peroxide. The sampling rate was 100.4 mL/min and the lower detection limit was 0.2 ppb over the 6-day sampling period. Measurements below the detection limit were assigned to 50% of the detection limit, or 0.1 ppb, for the following analyses.

NO2 concentrations were measured with a filter badge that absorbed NO2 on a cellulose fiber filter coated with a triethanolamine solution (18). Samples were analyzed spectrophotometrically. The overall mass transfer coefficient of the sampler was 0.1 cm/sec (19). The lower detection limit of the sampler was 0.5 ppb over the 6-day sampling period.

O3 concentrations were measured using the Harvard passive O3 sampler (20). The filter of the passive sampler was coated with a nitrite-containing solution. The nitrite ion on the filter of the passive sampler is oxidized to nitrate ion in the presence of O3. The exposed sampler was analyzed for nitrate ion by ion chromatography. Given sufficient face velocity, sampling rates of the passive sampler were 21.6 cm3/min and 21.3 cm3/min for outdoor and indoor sampling, respectively. The lower detection limit of the sampler was 1.2 ppb over the 6-day sampling period. Measurements below the detection limit were assigned to 50% of the detection limit, or 0.6 ppb, for the following analyses.

Trained field technicians deployed and collected the samplers. Indoor samplers were placed in living rooms, and outdoor samplers were placed near the houses and protected from rain. Residents completed a questionnaire describing housing factors.

Results

Average indoor HONO and NO2 concentrations were significantly higher than outdoor concentrations, whereas indoor O3 concentrations were significantly lower than outdoor concentrations, as shown in Table 1. The average indoor HONO concentration was 4.6 ppb, and the average outdoor HONO concentration was 0.9 ppb. Average indoor and outdoor NO2 concentrations were 28 and 20.1 ppb, respectively. The mean (± SD) of the ratio of indoor to outdoor NO2 was 2.08 ± 1.69. Average indoor and outdoor O3 concentrations were 14.9 and 56.5 ppb, respectively. The mean (± SD) ratio of indoor to outdoor O3 was 0.24 ± 0.18.

Twenty-two pairs of the HONO passive samplers were collocated. Precision (i.e., the SD of the absolute difference between each pair) of the HONO passive sampler was 0.98 ppb. Relative precision was 23.5%. Twenty-one pairs of the NO2 passive samplers were collocated. Precision of the NO2 measurements was 2.5 ppb and relative precision was 12.6%. Results of the duplicate passive samplers are shown in Figure 1.

Housing characteristics of the two communities are shown in Table 2. Housing characteristics were significantly associated with indoor HONO and NO2 concentrations, including the community (valley vs. mountain), presence of an air conditioner, and presence of a gas range, as shown in Table 3. No single housing characteristic was associated with indoor O3 concentration, but outdoor O3 concentrations were significantly higher in the mountain site than in the valley site. Indoor HONO and NO2 concentrations were significantly higher in the valley site than in the mountain site. When the houses had an air conditioner or gas range, both indoor HONO and NO2 concentrations were significantly higher. The presence of an air conditioner was significantly associated with the

Table 1. HONO, NO2, and O3 concentrations (ppb).

| Pollutant, location | No. | Mean ± SD | Med | Min | 90th percentile | 95th percentile | Max | No. < LOD | t-Test | p-Value |
|---------------------|-----|-----------|-----|-----|----------------|----------------|-----|-----------|---------|---------|
| HONO                |     |           |     |     |                |                |     |           |         |         |
| Indoor              | 99  | 4.6 ± 4.3 | 3.3 | 0.1 | 9.7            | 12.3           | 21.1| 40        | 7.62    | < 0.001 |
| Outdoor             | 102 | 0.9 ± 2.3 | 0.1 | 0.1 | 1.7            | 7.1            | 12.2| 82        |         |         |
| Indoor/outdoor      |     |           |     |     |                |                |     |           |         |         |
| NO2                 |     |           |     |     |                |                |     |           |         |         |
| Indoor              | 92  | 28.0 ± 12.6| 28.9| 4.3 | 43.1           | 49.3           | 52.0| 0         | 3.99    | < 0.001 |
| Outdoor             | 88  | 20.1 ± 14.0| 17.6| 3.7 | 39.3           | 42.1           | 47.8| 0         |         |         |
| Indoor/outdoor      | 87  | 2.08 ± 1.69| 1.33| 0.22| 4.51           | 5.41           | 10.62|          |         |         |
| O3                  |     |           |     |     |                |                |     |           |         |         |
| Indoor              | 106 | 14.9 ± 13.3| 11.1| 0.6 | 34.2           | 41.0           | 67.8| 9         | −16.38  | < 0.001 |
| Outdoor             | 100 | 56.5 ± 22.3| 49.8| 18.4| 89.6           | 96.7           | 160.1| 0         |         |         |
| Indoor/outdoor      | 96  | 0.24 ± 0.18| 0.19| 0.01| 0.53           | 0.85           | 0.75|           |         |         |

Abbreviations: LOD, limit of detection; Max, maximum; Med, median; Min, minimum.

*Indoor/outdoor of HONO was excluded due to a large number of measurements < LOD.
community (chi-square test, \( p < 0.01 \)). Ninety-three percent of the valley homes had an air conditioner in contrast to only one mountain home.

Associations between house characteristics and indoor/outdoor ratios for NO\(_2\) and O\(_3\) are shown in Table 4. The indoor/outdoor ratios for HONO were not evaluated because only 14 houses had both indoor and outdoor HONO levels above the detection limit. The indoor/outdoor NO\(_2\) ratio was significantly associated with community, presence of an air conditioner, presence of a gas range, and number of bedrooms. The ratio of indoor to outdoor NO\(_2\) levels was significantly higher in the mountain site, although indoor NO\(_2\) concentrations were significantly higher in the valley site. The indoor/outdoor NO\(_2\) ratio was higher in the houses with a gas range and more than 3 bedrooms. The ratio of indoor to outdoor O\(_3\) was significantly associated with community (\( p < 0.05 \)), the presence of an air conditioner, and the number of bedrooms (\( p < 0.1 \)). The relationships between indoor and outdoor concentrations of the three air pollutants were determined by Pearson correlation coefficients, as shown in Table 5. The analysis was confined to houses for which all three pollutants were measured simultaneously. Indoor HONO concentrations were significantly correlated with indoor NO\(_2\), indoor O\(_3\), and outdoor NO\(_2\) concentrations. Indoor NO\(_2\) concentrations were significantly correlated with outdoor NO\(_2\) concentrations. Indoor O\(_3\) concentrations were significantly correlated with outdoor O\(_3\) concentrations.

Associations between indoor HONO, O\(_3\), and NO\(_2\) and outdoor NO\(_2\) levels were determined by a stepwise multiple regression analysis. Outdoor NO\(_2\) level was excluded from the analysis at a significance level of 0.05. Indoor HONO was correlated negatively with indoor O\(_3\) and positively with indoor NO\(_2\).

\[
\text{Indoor HONO} = 2.65 - 0.13 \times \text{Indoor O}_3 + 0.15 \times \text{Indoor NO}_2, \quad [1]
\]

where \( n = 74 \) and \( r = 0.65 \).

Indoor HONO concentrations were inversely correlated with indoor O\(_3\) concentrations, as shown in Figure 2. Indoor HONO and O\(_3\) concentrations were simultaneously measured in 89 houses. We performed a linear regression analysis for indoor HONO as a function of indoor NO\(_2\) for the 76 houses where both were measured simultaneously (Figure 3). Indoor HONO levels were about 17% of indoor NO\(_2\) levels. The 95% confidence interval for the ratio of indoor HONO to indoor NO\(_2\) was 0.14–0.21. No single housing characteristic was significantly associated with the ratio of indoor HONO to indoor NO\(_2\) concentrations. However, the ratio of indoor HONO to indoor NO\(_2\) was slightly higher in homes with electric ranges.

### Table 2. Housing characteristics of the two communities.

| Variables                  | Valley | Mountain |
|----------------------------|--------|----------|
| No. of houses              | 56     | 55       |
| No. of bedrooms (mean ± SD)| 3.6 ± 0.9 | 3.7 ± 1.0 |
| Presence of gas range      | Yes    | 43       |
|                           | No     | 12       |
| Presence of air conditioning| Yes   | 51       |
|                           | No     | 4        |
| Presence of humidifier     | Yes    | 15       |
|                           | No     | 41       |
| Window open                | Sometimes | 12 |
|                           | Often  | 44       |

*Note: Significance values are not provided in the table.*

### Table 3. Housing characteristics significantly associated with indoor HONO, NO\(_2\), and O\(_3\) concentrations.

| Variable                  | HONO | NO\(_2\) | O\(_3\) |
|---------------------------|------|----------|---------|
| Community                 |      |          |         |
| Valley                    |      |          |         |
| Mountain                  |      |          |         |
| Presence of air conditioner|      |          |         |
| Yes                       | 39   | 5.4 ± 4.6| −1.69   |
|                           |      | −0.094   | −3.26   |
| No                        | 50   | 3.9 ± 4.0| 42      |
|                           |      | 23.8 ± 13.9| 2.19   |
| Presence of humidifier    |      |          |         |
| Yes                       | 32   | 2.6 ± 2.6| 3.34    |
|                           |      | 0.010    | 2.19    |
| No                        | 58   | 5.6 ± 4.7| 56      |
|                           |      | 30.5 ± 11.6| 0.32   |
| Presence of gas range     | Yes  | 72       | 4.8 ± 4.6|
|                           |      | −1.48    | 68      |
|                           |      | 0.142    | 60      |
| No                        | 17   | 3.1 ± 2.5| 19      |
|                           |      | 19.7 ± 10.4| 0.011  |

*Note: t-Test values and p-values are not provided in the table.*

### Table 4. Housing characteristics significantly associated with indoor/outdoor NO\(_2\) and O\(_3\) concentrations.

| Variable                  | Indoor/outdoor NO\(_2\) | Indoor/outdoor O\(_3\) |
|---------------------------|------------------------|-----------------------|
| Community                 |                        |                       |
| Valley                    |                        |                       |
| Mountain                  |                        |                       |
| Presence of air conditioner|                      |                       |
| Yes                       | 45                     | 0.28 ± 0.19           |
|                           | 37                     | 0.19 ± 0.16           |
| No                        | 40                     | 0.26 ± 0.18           |
|                           | 41                     | 0.20 ± 0.17           |
| Presence of humidifier    |                        |                       |
| Yes                       | 29                     | 0.28 ± 0.23           |
|                           | 53                     | 0.22 ± 0.15           |
| No                        | 64                     | 0.24 ± 0.18           |
|                           | 17                     | 0.22 ± 0.19           |
| Presence of gas range     |                        |                       |
| Yes                       |                        |                       |
|                           |                        |                       |
| No                        |                        |                       |
| ≤ 3                       | 39                     | 0.27 ± 0.21           |
|                           | 42                     | 0.21 ± 0.15           |
| > 3                       |                        |                       |
than in those with gas ranges (0.22 ± 0.21 vs. 0.16 ± 0.14).

**Discussion**

Indoor and outdoor NO₂ levels were similar to those reported in other studies conducted in Southern California (22). Lower ambient outdoor HONO levels are expected because HONO photolyses fairly quickly outdoors. However, HONO formed indoors is less susceptible to photolysis. Spicer et al. (5) have shown that HONO has a low surface removal rate, only 0.02–0.05/hr greater than the removal of nonreactive tracer gas due to the air exchange rate. This is significantly lower than the surface removal rate of NO₂ (5). The HONO measurements reported in the present study clearly establish that HONO levels tend to be higher in homes than outdoors.

The precisions of the HONO and NO₂ passive samplers were comparable to previously reported values (17,18). During the entire 12-month sampling period, the relative precision of the passive O₃ sampler was 12% for indoor and 4% for outdoor samplers (16). Forty percent of the indoor HONO measurements were below the 0.2 ppb detection limit for the 6-day monitoring period, and 80% of the outdoor HONO measurements were below the detection limit. The number of HONO samplers that recorded values below the detection limit was significantly higher than expected. Longer sampling times for outdoor HONO samplers may be necessary in future studies.

HONO is a weak acid (pKa = 3.35), but at the pH of the body fluids that it is likely to come in contact with during respiration, it should be almost completely ionized. The delivered dose is approximately 1.278 µg (= 760 µg/m³ HONO × 8 × 10⁻³ m²/min breathing rate × 210 min). At indoor levels of 10 ppb (90th percentile in this study), an adult (15 m³/day breathing rate) and a child (10 m³/day breathing rate) would have the equivalent delivered dose of hydrogen ion from HONO in about 4.5 days and 6.6 days, respectively. This simple estimate assumes constant exposure and does not include activities and concentrations that vary across time. Calculation of the biologically relevant acid dose to children and adults is obviously more complicated than this simple estimation. Nonetheless, the above example demonstrates that indoor exposures to even a weak acid may be relevant. Given the prevalence in the Southern California residences, it is reasonable to consider indoor HONO as an important contributor to hydrogen ion exposures.

A few housing factors were associated with indoor HONO and other pollutants. The community (mountain vs. valley) was significantly associated with both indoor HONO and NO₂ levels. Homes with an air conditioner and a gas range had higher indoor NO₂ concentrations. Homes with an air conditioner had lower O₃ concentrations, indicating either greater removal or lower air exchange rates. Pandian et al. (23) and Suh et al. (24) both have shown that homes with air conditioners have lower air exchange rates. Earlier, Dockery and Spengler (25) reported that the impact of environmental tobacco smoke concentrations was twice as large for air-conditioned homes than for non–air-conditioned homes, suggesting lower ventilation rates. Because both HONO and NO₂ have indoor sources, it is reasonable to expect high concentrations in the homes that have lower air exchange. However, the lack of a significant association for HONO with the housing factors studied may indicate that there may be other factors that influence indoor HONO concentrations.

Houses with humidifiers had lower HONO levels. Increased humidity from humidifier should have increased moisture on surfaces thus increasing aqueous phase heterogeneous formation of HONO in the presence of NO₂ (15). In addition to a larger formation rate, more moisture on surfaces would also mean a larger reservoir for HONO (5,26). However, our measurements do not support this hypothesis. Unfortunately, we do not have information regarding the use of humidifiers or indoor relative humidity during this study, which limits our ability to interpret the association. The influence of indoor moisture and humidification on HONO production rate needs to be investigated further in more detailed field and chamber studies.

Although HONO was higher in homes with higher NO₂, the relationship between indoor HONO and cooking on a gas range was not obvious. Because housing characteristics and ambient concentrations of all pollutants were different between the valley and mountain sites, it was difficult to see a clear relationship between indoor HONO and cooking on a gas range. Under controlled conditions, Traynor et al. (27) showed that gas ranges emit HONO at about 11% the rate of NO₂ emissions. Variations in other variables across the homes studied here and the fact that cooking times were not recorded prevented us from examining the direct impacts from cooking on a gas range.

Community was associated with all three contaminants. Indoor and outdoor O₃ levels were higher in the mountain sites than in the valley sites. The difference between communities for indoor O₃ was not statistically significant. However, indoor and outdoor NO₂ levels and indoor HONO levels were significantly lower in mountain sites. In this study, the community was significantly associated with ambient levels and housing characteristics influencing residential ventilation rates. It is possible that the association between community and the three air pollutants may be different when ambient ozone levels are different. Indoor measurements of NO₂ and HONO were made in Albuquerque, New Mexico, during a period when ambient O₃ was low (6). Indoor HONO levels ranged

**Table 5. Pearson correlation coefficient between air pollutants.**

|                | Indoor HONO | Indoor NO₂ | Indoor O₃ | Outdoor HONO | Outdoor NO₂ |
|----------------|-------------|------------|-----------|--------------|-------------|
| Indoor NO₂     | 0.511**     | —          | —         | —            | —           |
| Indoor O₃      | -0.514**    | -0.136     | —         | —            | —           |
| Outdoor HONO   | -0.021      | -0.186     | -0.223*   | —            | —           |
| Outdoor NO₂    | 0.352**     | 0.602**    | -0.052    | -0.083       | —           |
| Outdoor O₃     | -0.180      | -0.220*    | 0.556**   | -0.092       | -0.341**    |

* p < 0.05; ** p < 0.01.

**Figure 2.** Association between indoor HONO and indoor O₃ concentrations.

**Figure 3.** Association between indoor NO₂ and HONO concentrations. Y = 0.03 + 0.17X; r = 0.51; n = 76.
from 5 to 15% of indoor NO$_2$ concentrations. The relationship between indoor NO$_2$ and HONO (6) was less than that found here, suggesting a possible role of O$_3$ and indoor moisture in the relationship.

Although indoor HONO is partially generated from heterogeneous NO$_2$ reactions, previously reported associations between HONO and NO$_2$ levels in residences are available only from a few homes. None of the previous measurements included O$_3$ concentrations (6,20). In the current study, the average ratio of indoor HONO to indoor NO$_2$ was 0.17 (95% confidence interval, 0.14–0.21), slightly higher than those recorded in previous studies. Brauer et al. (28) found ratios in two research homes at peak NO$_2$ concentrations to be on the order of 0.1–0.12. In the Albuquerque study, in which indoor NO$_2$ concentrations were reported as averages of bedroom, living room, and kitchen NO$_2$ concentrations, the average ratio of HONO to NO$_2$ was 0.08 (6). The ratio of HONO to NO$_2$ levels ranged from 0.03 to 0.15. Indoor HONO is generated by indoor sources and heterogeneous NO$_2$ reactions; the heterogeneous NO$_2$ reactions are affected by various environmental conditions. The different ratios may be due to differences of NO$_2$ concentration, ventilation rate, surface material, available surface area, temperature, and humidity.

Comparisons of indoor HONO and O$_3$ levels indicate that indoor NO$_2$ levels are high only when indoor O$_3$ concentrations are low. Weschler et al. (15) reported a similar inverse correlation in a telephone switching office. The authors suggested that this reflected the rapid reaction of ozone with nitrous acid in aqueous films. HONO in the gas phase is in equilibrium with HONO in sorbed moisture films on surfaces (5,26). HONO in the aqueous surface films, in turn, is in equilibrium with its conjugate base, the nitrite ion. Ozone rapidly oxidizes the nitrite ion to nitrate. When indoor ozone concentrations are elevated, nitrite ions in aqueous surface films are rapidly oxidized to nitrate ions. This process depletes the surface reservoir of HONO, which ultimately reduces the gas phase concentration of HONO.

Hence, an inverse correlation between indoor O$_3$ and indoor HONO is anticipated.

The indoor O$_3$ and HONO concentrations reported in this study are average concentrations over a 6-day period. However, it is well established that O$_3$ concentrations vary in a diurnal fashion. If indoor O$_3$ and HONO concentrations had been measured with sufficient time resolution to fully capture their daily concentration changes, the inverse correlation between these two pollutants would be expected to be even stronger than that observed in the current study.

Differential assessment of health effects associated with NO$_2$ and HONO may be difficult in community studies because of potential confounding factors. Indoor HONO is correlated with indoor NO$_2$; however, substantial home variation of HONO is not explained by indoor NO$_2$ measurements. Potential health effects of HONO would not be completely determined by measuring NO$_2$ only. Characterization of outdoor NO$_2$, HONO, and O$_3$ in the Southern California communities alone did not predict indoor HONO concentrations. Including indoor O$_3$ improves the correlation between indoor HONO and indoor NO$_2$, with an increase in the coefficient of correlation from 0.51 to 0.65. However, housing characteristics that could be considered proxies for surface area, surface wetness, and air exchange rates did not lead to any substantial improvement of HONO prediction.

**Conclusion**

Six-day residential HONO, NO$_2$, and O$_3$ concentrations were simultaneously measured using passive samplers. Indoor HONO levels were higher than outdoor HONO levels. Several housing characteristics, including community and the presence of a humidifier, were significantly associated with both indoor NO$_2$ and HONO concentrations. Additional housing factors, primarily presence of a gas range or air conditioner, were associated with indoor NO$_2$. No housing characteristic was significantly associated with indoor O$_3$ concentrations, but factors associated with higher air exchange rates were associated with higher indoor/outdoor ratios for O$_3$. Indoor HONO levels were correlated with indoor NO$_2$ levels and inversely correlated with indoor O$_3$ levels. Indoor HONO levels were about 17% of indoor NO$_2$ levels. No significant amounts of HONO were measured when indoor O$_3$ levels were high. The measurements demonstrated the occurrence of substantial residential indoor HONO concentrations and showed association between indoor HONO, NO$_2$, and O$_3$ concentrations.

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