**We thank both reviewers for their constructive and thoughtful comments.**

**Response to common elements of the reviewer's comments:** Both reviewers comment on our report of a factor of 3 difference between estimated $NO_x$ emissions based on the correlation between OMI observations and MODIS FRP and previous emission estimates. Reviewer #1 suggests that MODIS FRP may be underestimated by a factor of 3 based on data from other studies, and is concerned that accounting for this underestimation in our analysis would lead to an unreasonably large discrepancy of a factor of 9. Reviewer #2 questions the usefulness of the numbers presented in our work if this discrepancy is primarily due to a bias in the instruments or methodology. These comments inspired us to take a deeper look at our analysis and the prior literature.

MODIS might underestimate FRP due to undetected fire pixels which may be obscured by clouds, smoke or canopy cover, as has been acknowledged in our paper (Table 2) and by several prior studies (e.g. Ichoku and Kaufman, 2005; Vermote et al., 2009; Wooster et al., 2003). For example, Wooster et al. (2003) indicate that MODIS-derived FRE differs by ~15-45% from BIRD-derived FRE for several fires detected by both instruments, and that total MODIS FRP is ~60% of total BIRD FRP over the full region of study. We note that this result suggests a more modest underestimation of FRP by MODIS than the factor of 3 suggested by Reviewer #1. The reviewer's concerns about underestimation of MODIS FRP by as much as a factor of 3 stem from an integrated assessment of the results from several studies. First, the reviewer notes that Vermote et al. (2009) find aerosol EFs from fires as measured via MODIS are higher than currently accepted values, and the authors mention underestimation of FRP by MODIS as a potential source for this discrepancy. The reviewer also highlights the results of Ellicott et al. (2009), who report that their FRP-derived biomass burned estimates are lower than those in GFEDv2 by a factor of 3, and the results of Kopacz et al. (2010) who find that GFEDv2 underestimates total CO observed via several satellite platforms. Kopacz et al. (2010) interpret this result to mean that GFED biomass burned is an underestimate, suggesting to the reviewer that the discrepancy between GFEDv2 and the estimates presented by Ellicott et al. (2009) is likely due to a low bias in MODIS FRP of a factor of 3.

However, an analysis of these studies in the context of our results yields an interesting alternative proposal. First, Ellicott et al. (2009) conclude that GFEDv2 may overestimate biomass burned; they derive fuel loading from their biomass burned estimate in Africa that is more consistent with several estimates of savannah fuel loading in the literature than the savannah fuel loading used in GFEDv2. Given this result, we note that the result in Kopacz et al. (2010) may instead be explained if the CO and hydrocarbon EFs used in GFEDv2 are too low, rather than that GFEDv2 biomass burned is underestimated. This idea is entirely consistent with the proposal described in our paper that currently accepted EFs underestimate smoldering contributions to wildfire emissions; this underestimation would mean currently used EFs are too low for smoldering-phase compounds, e.g. CO, hydrocarbons, and aerosol, while flaming-phase compounds e.g. $NO_x$ are overestimated. The discrepancy between aerosol EFs measured via MODIS by Vermote et al. (2009) and previously measured EFs can also be explained by this hypothesis, as opposed to the underestimation of FRP by MODIS. The consistency across multiple species and platforms strongly supports this hypothesis and suggests that the factor-of-3 difference presented in Ellicott et al. (2009) is not primarily due to underestimation of FRP by MODIS, and the bias already proposed in this work for this underestimation is appropriate. Since this proposal also indicates that discrepancies between our reported $NO_x$ EFs and those currently accepted may be due to inadequacies of previous measurements instead of bias in our own work, it is possible that they are in fact more accurate than EFs currently used in modeling and thus are a useful addition to the literature.

In our manuscript we will add text to expand on and clarify the argument that all of these prior results are consistent with an increase in estimates of the smoldering component of fires. The new text is as follows:

**Changes to paper:**

P 5352 L 8

Changed: "However, the magnitude of these coefficients is lower than prior estimates, which suggests either a negative bias in the OMI $NO_2$ retrieval over regions of active emissions, or that the average fire observed in our study has a smaller ratio of flaming to smoldering combustion than measurements used in prior estimates of emissions."

To: "However, the magnitude of these coefficients is lower than prior estimates, suggesting a possible negative bias in the OMI $NO_2$ retrieval over regions of active emissions. Comparison with several other studies of fire emissions using satellite platforms also indicates that prior emission factors may overestimate the contributions of flaming combustion to total fire emissions."

P 5366 L 22

Added:

A third possible explanation for the difference is that previous in situ and laboratory studies overestimate $NO_x$ emissions from wildfires, due to oversampling of flaming emissions in the laboratory or from airborne platforms. There is evidence that laboratory and airborne emission measurements sample plumes with higher MCE and greater $NO_x$ emissions than ground stations (e.g. Yokelson et al. 2008). These low-level smoldering emissions have been suggested to contribute only very minimally to total fire emissions (Andreae and Merlet, 2001); however, if smoldering combustion contributes more significantly to overall emissions than previously suggested, that would result in an overestimation of EFs of species associated with flaming combustion (e.g. $NO_x$) when these EFs are measured in the laboratory or via airborne platforms and then applied to large-scale fires. We note that results from other studies producing ECs for aerosol (Ichoku and Kaufman 2005, Vermote et al. 2009) are consistent with this hypothesis; aerosol is more strongly emitted during smoldering combustion, and both of the aforementioned studies measure higher aerosol ECs than would agree with currently accepted aerosol EFs. Kopacz et al. (2010) also constrain CO emission sources using data from several satellite platforms, and find that wildfire emissions as a source of CO are underestimated using GFEDv2 emissions. While Kopacz et al. (2010) conclude that GFEDv2 biomass burned is underestimated, other studies suggest that GFEDv2 biomass burned is overestimated (e.g. Ellicott et al., 2009), and the result in Kopacz et al. (2010) would also be consistent with the hypothesis that current EFs underestimate contributions of smoldering combustion, as emissions of both CO and hydrocarbons ultimately producing CO are associated with smoldering combustion. The support of this hypothesis across studies that measure different species emitted during different stages of combustion across different satellite platforms is remarkably consistent. As such, the authors recommend future study of the possibly underestimated contribution of smoldering combustion to wildfire emissions; the $NO_x$ ECs and EFs presented here are a useful lower bound on $NO_x$ emissions and, if the contribution of smoldering combustion to total wildfire emissions is indeed underestimated, may provide a more accurate characterization of fire emissions than currently used values.

P 5367 L 4

Changed: "Systematic biases in assumptions within the analysis and in FRP measurement may bias these values low by up to 33%, an amount too small to explain these differences. We conclude either: (a) there exists a large (50–100%) negative bias in the OMI retrieval of $NO_2$ columns over wildfire plumes, presumably due to errors in assumed profile shape; (b) $NO_x$ emissions from fires in California are lower on average than those represented by previously reported EFs; or (c) these previously reported EFs are overestimated, due to oversampling of flaming combustion by in situ measurements. Whatever the source of these differences, the parameters derived here are unambiguously a lower bound on fire $NO_x$ emissions."

To: "Systematic biases in assumptions within the analysis and in FRP measurement cannot fully account for these differences. We conclude that there may be a large (50–100%) negative bias in the OMI retrieval of $NO_2$ columns over wildfire plumes, presumably due to errors in assumed profile shape. However, comparison of our results with those of Ichoku and Kaufman (2005), Vermote et al. (2009), and Kopacz et al. (2010) also indicates that previously reported $NO_x$ EFs are likely overestimated, due to oversampling of flaming combustion by laboratory and airborne measurements. Regardless of the contributions of these factors, the parameters derived here are unambiguously a lower bound on fire $NO_x$ emissions."

**The reviewers also suggested** that we test the item in our conclusions regarding the possibility that low emissions from CA/NV fires are partly responsible for the large discrepancy between these and previously reported values of $NO_x$ from fires. We do not believe that this is a likely source of the discrepancy and only included it for completeness. We will clarify that point in the paper and add a comment about our ongoing work to develop a more comprehensive analysis of fires across the globe. In that work we find that fires across the globe are similar. In the revised paper we will refer to those preliminary results as evidence that CA/NV fires are not unusual.

**Changes to paper:**

P 5366 L 4

Removed this paragraph and the word "Alternatively" from the beginning of the next paragraph.

P 5366 L 20

Changed: "Despite our inability to quantify these biases, we include uncharacteristically low CA emissions and a bias in the OMI retrieval in Table 2."

To: "Despite our inability to quantify the contributions to the values presented in this work, we include a bias in the OMI retrieval in Table 2."

Added:

Another possibility is that emissions from wildfires in California are lower than emissions used to derive prior estimates. However, this is not observed in previous measurements of emissions (e.g. Battye and Battye, 2002). Our preliminary analysis of global measurements using the methods outlined in this paper also provides no evidence that CA/NV fires are uniquely different from fires in other geographic locations. Nonetheless, we include this in Table 2 as a potential source of bias for the sake of completeness.

**Response to other comments by Reviewer #1**

The reviewer suggests that we assess the potential bias in FRP-based estimates of emissions using burned area and fuel consumption. While such an assessment may be a useful contribution to the literature, we believe it is beyond the scope of this paper. The relationship established by Wooster et al. (2005) between these quantities indicates that biomass burned is proportional to total FRE, or time-integrated FRP. Thus any comparison between FRP-based and traditional biomass burned estimates requires a method to integrate FRP measurements over time. Development of such a method is rather involved and has been approached by several other authors (e.g. Wooster et al., 2003; Ellicott et al., 2009; Vermote et al., 2008), and the results in some cases already address the uncertainty in MODIS FRP. Our assessment of these issues is that incorporating the reviewer's suggestion will not reduce uncertainty in our result.

**Response to other comments by Reviewer #2**

**# 1:** In line 220 the authors state that errors in wind speed and direction are difficult to address and hence were neglected. Have they explored how the results change when using different data sets (e.g. NCEP Eta North American Analysis) or a different vertical level? What impacts would they expect when emissions are injected at higher altitudes such as could be the case for especially forest fires?

**Response:** We have investigated the effects of changing wind level or wind data set on the results; a summary of this investigation is added to the paper.

**Changes to paper:**

P 5365 L 17

Added:

Another potential source of bias is from the use of NARR data at the selected wind level (900 hPa). Plume height varies significantly between individual fires; 900 hPa, which corresponds to approximately 1 km altitude, was selected as a result of data presented by val Martin et al. (2010) indicating that average fire plume heights in North America are less than 1 km, and that the majority of fire plumes remain within the boundary layer. As a result, we expect wind level selection to induce some random error for individual fires, but the choice should be appropriate for an average fire. However, any bias in NARR wind speed at this level would result in a bias in this work. Additionally, val Martin et al. (2010) note a correlation with plume height and measured FRP, although the correlation is weak and the relationship may not be applicable to our analysis since the data presented in the study was obtained in the morning as opposed to the early afternoon, when meteorology governing plume injection height is very different. Still, increases in injection height with FRP could induce a bias in our results due to differences in wind speeds through the troposphere. However, even when fire plumes inject emissions to heights of a few kilometers, the vertical distribution of emissions is not well known (val Martin et al., 2010); the majority of emissions may remain in the boundary layer, and thus the selection of a lower level wind value may not be inappropriate.

We performed three separate tests to determine the magnitude of any possible bias due to wind selection. First, we repeated the analysis using 850 hPa wind (~1.5 km altitude) from NARR. Obtained $NO_2$ EC values were within 0.020 g $MJ^{-1}$ of the values obtained using 900 hPa wind, less than a 10% change and well within our reported uncertainties. We concluded that small changes in wind level do not significantly bias the results. In the second test, we repeated the analysis using wind at 850 hPa from the NCEP Climate Forecast System Reanalysis, a global reanalysis and forecast produced at 0.5° x 0.5° resolution (Saha et al., 2010). Differences in $NO_2$ EC values calculated via the two data sets were all less than 0.070 g $MJ^{-1}$ and again were within the reported uncertainties for all three land types. This test ensured that there is no obvious large bias as a result of using NARR values instead of an alternative reanalysis. Finally, we performed the analysis again using NARR wind at 700 hPa (~3 km) for fires with FRP greater than 5000 MJ $s^{-1}$ and NARR wind at 900 hPa for smaller fires. Due to increased wind speeds with increasing altitude in the troposphere, the use of this higher wind resulted in an increase in $NO_2$ ECs for all three land types, ranging from 20% to 50%. Thus we consider our assumption of plume injection height a possible source of negative bias.

P 5365 L 24

Removed:

Winds also represent a possible source of error due to variations in plume height and accuracy and spatiotemporal resolution of the reanalysis; however, these errors are expected to be random and small relative to other errors and thus should not contribute a bias.

P 5374 Table 2

Included 20-50% negative bias for plume injection height assumption after diurnal FRP cycle

**#2:** Line 416: what is this error estimate of 10-20% based on?

**Response:** The estimate of 10-20% has been replaced by an estimate of 0-40%, obtained via calculations using results from other work on changes in emissions with MCE, as well as work looking at seasonal variations in $NO_x$ emissions from fires.

**Changes to paper:**

P 5365 L 23

Removed:

Since most wildfires are a mix of flaming and smoldering components, we estimate that bias from this source is 10–20%.

Added:

This uncertainty is difficult to quantify, since precise measurements of diurnal patterns in $NO_x$ emission factors have not yet been performed. In addition, the diurnal pattern in wildfire flaming to smoldering fraction is not established, and while $NO_x$ emissions are correlated with flaming combustion and higher modified combustion efficiency (MCE), this correlation is small—$R^2$ = 0.11 in Battye and Battye (2002)—and the slope of the line very uncertain. However, MCE for most fires ranges between 0.80 and 1.0 (McMeeking et al., 2009; Yokelson et al., 2008; Battye and Battye, 2002) and thus any diurnal change in average MCE would likely be well within this range. Using the Battye and Battye (2002) fit despite the weak correlation, we determine that for changes in average MCE from 0.95 to 0.90, there is a 30% decrease in $NO_x$ EF; for changes in average MCE from 0.90 to 0.85, there is a 40% decrease in $NO_x$ EF. This is consistent when compared to seasonal variations in $NO_x$ emission ratios presented by Lapina et al. (2008), who attribute the observed seasonal change in emission ratio of $NO_y$ to CO for boreal forests, from 7.3 mol $mol^{-1}$ to 2.8 mol $mol^{-1}$, to higher smoldering fraction in the late-season fires. In order to translate these values to differences in $NO_x$ EFs, the increase in CO emissions with increasing smoldering fraction must be accounted for. Unfortunately, Lapina et al. do not report MCE for the fires, but using equations presented in Battye and Battye (2002), a decrease in MCE from 0.95 to 0.90 results in a factor of ~2.3 increase in the CO emission factor (from 45.6 g $kg^{-1}$ to 103 g $kg^{-1}$); a decrease from 0.90 to 0.85 results in a factor of ~1.5 increase. If these CO emission factors are used with the $NO_y$ emission ratios from Lapina et al. to calculate $NO_x$ EFs, then the seasonal decrease in $NO_x$ EF inferred from the reported data would be 15-40%. Thus, while it is currently impossible to accurately quantify the potential bias induced by this diurnal variation in $NO_x$ EF, we suggest that the bias is at most 40%.

P 5374 Table 2

Changed diurnal variation to 0-40%.

P 5366 L 1

Changed: “A summary of all quantified potential biases is presented in Table 2, in the first six rows. Summing these biases suggests that our values are actually likely to be biased high by approximately 5–35%, with potential bias ranging from 50% underestimation to 90% overestimation. This bias is small compared to the difference between our emission coefficients and prior estimates, and probably in the opposite direction.”

To: “A summary of all quantified potential biases is presented in Table 2, in the first seven rows. Summing these biases suggests that our values are nearly equally likely to be biased high or low (likely bias ranging from approximately 55% low to 35% high). In addition, these potential biases cannot entirely account for the discrepancy between our emission coefficients and prior estimates.”

**#5:** Could SCIAMACHY NO2 data be used to test if and to what degree the discrepancy between these and previous estimates is due to a bias in the OMI NO2 retrievals?

**Response:** A comparison with SCIAMACHY $NO_2$ data would be difficult due to several factors. The data would be subject to a lower signal-to-noise ratio due to the larger pixel size; limitations in spatial and temporal coverage would significantly reduce the number of fires that could be measured, and differences in overpass times imply that any perceived bias could equally be the result of diurnal variations in fire emissions or biases in the instrument retrievals. Additionally, there is no reason to suspect that SCIAMACHY would not be subject to a similar bias, given that the retrieval process is generally similar to that of OMI.

**Changes to paper:**

P 5366 L 19

Add:

Unfortunately, any bias cannot be assessed using data from another $NO_2$ remote sensing platform e.g. SCIAMACHY, due to differences in overpass times and spatial coverage, lower spatial resolution, or the fact that these instruments generally use a similar retrieval process and so may be subject to similar biases.