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Characteristics of Ethiopia Air Chemistry and Its Meteorological Context

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ABSTRACT: The concentration of trace gases and aerosols in Ethiopia is poorly characterized due to a limited history of surface measurements. Here, satellite measurements and model estimates of atmospheric composition are employed to understand space–time distributions in the period 2000–16. Methane (CH_4) and carbon monoxide (CO) display high concentrations over the highlands and provide a focus for analysis of monthly and daily data. CH_4 emissions from livestock peak at the beginning of the dry season, while CO from biomass burning rises at the end of the dry season. The seasonal cycle of dust, aerosol optical depth (AOD), and CO_2 is inversely related with CH_4 , while CO closely follows sensible heat flux, thus linking drying and rural biomass burning. Stable easterly flow in the dry season accumulates local emissions, so near-surface concentrations of CO and CH_4 are high then. The weather pattern underlying an episode of high nitrogen dioxide (NO_2) concentrations was studied. In addition to a stable lapse rate and dry anticyclonic weather, midtropospheric subsidence was related to intrusion of the northern subtropical jet stream on 24–26 December 2010. The wind shadow was cast by the Rift Escarpment limited dispersion, particularly with the dry, stable weather conditions. A key outcome of this work is that CH_4 concentrations

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over Ethiopia are high in global context and have increased >0.1 ppm from 2002 to 2016; hence, there is a need to improve livestock management and production efficiency.

KEYWORDS: Africa; Greenhouse gases; Orographic effects; Remote sensing

1. Introduction

1.1. Background

Greenhouse gas (GHG) emissions from agriculture and land-use contribute about one-quarter of global anthropogenic emissions (FAOSTAT 2016). Tropical subregions of Africa are major contributors of carbon dioxide (CO_2), carbon monoxide (CO), black carbon (BC), and nitrogen dioxide (NO_2) (Piketh et al. 1999; Jury 2000; Arino et al. 2012; Krotkov et al. 2016). Together with ozone (O_3) and methane (CH_4) emissions from biomass burning and livestock production, respectively, the GHG longwave radiation absorbers are likely to increase in the future (Dentener et al. 2005; Lamarque et al. 2010; Andreae and Ramanathan 2013). Hence, there is a need to better quantify trace gas concentrations over tropical Africa, as well as their sources and distribution in space and time. Emission estimates and inventories from rural agricultural sources have uncertainties that can be resolved via satellite observations and weather models incorporating dispersion. Unlike in situ point measurements, satellite observations provide useful information on regional-scale GHG concentrations (Bergamaschi et al. 2007; van der A et al. 2008; Marais et al. 2014a,b).

Ethiopia's ~ 100 million people subsist on a gross domestic product of $\sim \$54$ billion (in 2015) and have low energy consumption (4290 MW) and small urban industrial emissions (World Bank 2016). Electricity does not reach 73% of the population, so rural households depend on gas and fuelwood for cooking and heating. Additionally, 88% of the population live in highlands above 1500 m, which covers 44% of the country (Desalegn et al. 2014; World Bank 2016), with mean minimum temperature $<15^\circ\text{C}$ (cf. Figure 1a). The United Nations Development Program (UNDP 2011) and the Food and Agriculture Organization Statistical Database (FAOSTAT 2016) GHG emission estimates are 50%–60% from agriculture, 19%–37% land-use, 3%–7% urban, 3%–6% waste, 3% transport, 2%–3% energy, and 2%–3% industry. Agricultural burning of ~ 30 billion kg covers ~ 4.6 Mha of Ethiopia (Giglio et al. 2003; cf. Figure 3a below). Ethiopia's ~ 132 million livestock (in 2015) account for 20% of agriculture value and release significant quantities of GHG and aerosols (Teferi et al. 2013). Cattle comprise $>50\%$ of livestock (USAID 2013) and emit >30 kg of CH_4 per annum per head (Broucek 2014). Forests cover $<12\%$ of the country, savannah $>65\%$, and croplands $>16\%$ (FAS 2016). Soil bacteria and seasonal lightning release nitrates (Yienger and Levy 1995; Christian et al. 2003), but there are few volcanic or industrial sulfate sources. The dense vegetation, biomass burning, and livestock emit volatile organic compounds and CH_4 that react to form fine aerosols, ozone, and formaldehyde (Marais et al. 2014a).

Satellites have provided estimates of atmospheric particulates since 1980 (Burrows et al. 2011). Recent advances in passive remote sensing, such as NASA's Atmospheric Infrared Sounder (AIRS) and Ozone Monitoring Instrument (OMI),

Figure 1. Mean maps averaged 2003–15 of (a) MODIS daytime land-surface temperature and index area (dashed), (b) MODIS color vegetation index, and (c) MERRA zonal circulation ($W \times 70$) in vertical cross section averaged 6°–13°N with topography and calm zone U contoured. (d) Index area mean diurnal cycle of (left to right) MERRA hourly PBL height and surface wind speed and 3-hourly CMORPH rainfall. Local time is UTC + 3.

enable the mapping of near-surface GHG distributions (2003+). Trace gas estimation depends on ultraviolet absorption (λ : 0.31–0.46 μm) (Krotkov et al. 2006), while aerosols $>0.1\text{-}\mu\text{m}$ diameter and carbon gases induce near-infrared absorption (λ : 0.5–7.6 μm). Satellite retrievals for Ethiopia must contend with seasonal obscuration by Saharan dust and thick clouds. Rural and biogenic emissions are

diffused and may be insensitive to wind trajectory and planetary boundary layer (PBL) height, compared with their urban industrial counterparts. In addition to satellite retrievals, the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), reanalysis model (Molod et al. 2015) with air chemistry assimilation (Rienecker et al. 2016) helps quantify dispersion conditions over Ethiopia. Although little in situ data on urban industrial and agricultural emissions are available, source inventories provide adequate information (CAIT 2016).

1.2. Motivation and objectives

Harmful air constituents can limit productivity through human respiratory complications and reduced resource yields (van Wesenbeeck et al. 2009; Fantaye 2016). Ethiopia experiences a mortality rate of 57/100 000 from air pollution exposure (WHO 2016), with total pollution-related deaths of 129 000 in 2015 (Landrigan et al. 2018). The country is a major source of CH₄ emissions (FAOSTAT 2016).

The central objective of this work is to characterize the near-surface air chemistry at daily to seasonal time scales by analysis of satellite- and model-estimated trace gases, particulates, and meteorological conditions over the Ethiopian highlands. Scientific questions include the following:

- (i) What are the characteristic patterns and seasonality of near-surface air constituents?
- (ii) Which are regionally imported versus locally generated?
- (iii) How are local emissions transported and dispersed?
- (iv) Which meteorological factors affect Ethiopia's air chemistry at annual and daily time scales?

2. Data and methods

Anticipating rural agricultural emissions from the Ethiopian highlands, our study of air chemistry covers 3°–17°N, 31.5°–48°E, and the subset “index” area for the time series is 5°–14°N, 35°–41.5°E (Figure 1a). The geographic focus excludes the lowlands surrounding Ethiopia, where vegetation fraction and agricultural emissions are half the highlands. Maps of MODIS fire counts (Justice et al. 2002), livestock density (Robinson et al. 2014), and lightning strikes (Cecil et al. 2015) yield insights on emission sources. Short-lived trace gas estimates from the OMI satellite include cloud-screened tropospheric NO₂ (Bucsela et al. 2013; Lamsal et al. 2014) and (low level) PBL sulfur dioxide (SO₂; Krotkov et al. 2006) interpolated to 25-km resolution from October 2004 to December 2015. Multilevel trace gas estimates of CH₄, CO, CO₂, and O₃ derive from the AIRS satellite (Maddy et al. 2008; Xiong et al. 2008; Yurganov et al. 2008; Warner et al. 2010; Thonat et al. 2012; Levy et al. 2013) at 100-km resolution from September 2002 to December 2015, as daytime retrievals averaged in the 850–700-hPa layer. MISR satellite 0.55 μm aerosol optical depth (AOD) at 50-km resolution describes mineral dust intrusions from adjacent deserts. MERRA-2 air chemistry data (Molod et al. 2015) include monthly near-surface SO₂, BC, dust particulates (<10 μm) and O₃ concentration at ~50-km resolution from January 2000 to December 2015. The GEOS-5 system assimilates in situ and satellite observations,

Table 1. Datasets used in the analysis. All data are sourced from NASA Giovanni website, except as footnoted.

Acronym	Name	Space, time resolution	Quantity
AIRS	Atmospheric Infrared Sounder v6	100 km, twice daily with gaps	CH ₄ , CO, O ₃ 925–500-hPa layers
CALIPSO	Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations L3	~10 km at zenith, weekly pass	Fine aerosol density
GFS ^a	Global Forecast System, operational weather data	50 km, 3-hourly	Meteorology for HYSPLIT model
HYSPLIT1 ^a	Hybrid Single Particle Lagrangian Integrated Trajectory Model	~10 km, within plume	Forward dispersion simulation
LIS	Lightning Imaging Sensor (TRMM satellite)	50 km	Flash density climatology
MERRA-2	Modern-Era Retrospective Analysis for Research and Applications, v2, with GEOS-5 air chemistry v5	~50 km, daily, monthly	SO ₂ , O ₃ , BC, fine dust, meteorology
MISR	Multangle Imaging Spectroradiometer v4	50 km, daily with gaps	Aerosol index of fine dust
MODIS ^b	Moderate Resolution Imaging Spectroradiometer (<i>Terra</i>)	~8 km, multiday composite	Land-surface temperature, vegetation
OMI	Ozone Monitoring Instrument (<i>AURA</i>) v3	25 km, twice daily with gaps	Near-surface NO ₂ and SO ₂

^a Sourced from NOAA ARL Ready website.^b Sourced from IRI Climate Library website.

combined with emission inventories (Buchard et al. 2015; da Silva et al. 2015). The satellite inputs are incremental and start with tropospheric O₃ and AOD in 1980 (Torres et al. 2002), CO in the 1990s, and tropospheric trace gases in the 2000s. The above references provide information on how the individual satellites retrieve air chemistry measurements. Algorithms that convert radiometer responses to measurements depend on in situ validations in a variety of environments. Similar work in the more industrialized South Africa (Jury 2017) has determined that satellite SO₂ estimates are ambiguous, whereas other variables show agreement with in situ measurements and inventory-based model simulations.

The MERRA-2 meteorological data employed here include 850- and 775-hPa air temperature and lapse rate (dT/dz), 850–700-hPa wind components, 850–775-hPa relative divergence, 700-hPa specific humidity, 500-hPa geopotential height and vertical motion, and PBL height, calculated as the depth of surface-induced turbulence. “Near surface” averages in the 850–700-hPa layer represent transport and dispersion over the Ethiopian highlands. Additional data include satellite color vegetation fraction at 8-km resolution (NDVI; Tucker et al. 2005) and multisatellite estimated rainfall at 25-km resolution (CMORPH; Joyce et al. 2004). Table 1 summarizes the datasets, acronyms, and characteristics.

Time series of index area-averaged monthly and daily AIRS, MISR, and OMI satellite data and MERRA-2 model data were formulated. Gaps in daily satellite retrievals 2003–15 (from passive polar-orbiting radiometers) were in-filled by calculation of a 3-day running maximum. Statistical analyses utilized Pearson product–moment cross-correlation of air constituents and meteorology for the mean seasonal cycle and continuous daily fluctuations. Given the temporal filtering and serial autocorrelation, 192 months reduced to 4 degrees of freedom, and 4748

days reduced to ~ 30 degrees of freedom, yielding statistical thresholds for 90% confidence of $|0.7|$ monthly and $|0.3|$ daily. Comparisons of global and local averages were made for seasonal cycles of CO_2 and CH_4 .

To understand the air chemistry concentration, transport, and dispersion, seasonal mean maps were calculated for BC, CH_4 , CO, 700-hPa winds, sinking motion, surface temperature, and rainfall. Vertical cross-sections of mean AIRS satellite CO, CH_4 , and O_3 were analyzed up to 500 hPa, and the diurnal cycle of MERRA-2 hourly PBL height, near-surface wind speed, and 3-hourly CMORPH rainfall was calculated. Vertical cross-sections of the MERRA-2 meridional circulation and wind vorticity were analyzed for key features, such as the equatorial trough and subtropical jet.

The daily time series were ranked, and MERRA-2 near-surface winds were analyzed for the peak episode of 24–26 December 2010, when NO_2 and other trace gas concentrations were high. The atmospheric dispersion of a continuous virtual source at 9°N , 37°E , 100 m in the period 24–26 December 2010 was simulated by the HYSPLIT model underpinned with GFS weather data and by radiosonde profiles from southwestern Arabia. Aerosol density cross sections were obtained on 24 December 2010 from the *Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations* (CALIPSO; Winker et al. 2007). Each air constituent has certain units: MERRA-2 variables are kg m^{-3} (typically $\times 10^{-9}$); AIRS O_3 , CH_4 , and CO is ppm or $\mu\text{g m}^{-3}$ (typically $\times 10^{-8}$); and OMI NO_2 is cm^{-2} ($\times 10^{16}$).

The research outcomes subdivide into (i) climatology and seasonal cycle, (ii) temporal statistics and relative influence, and (iii) daily air chemistry fluctuations and scenario of maxima. The scope of work excludes validations due to unavailability of local in situ measurements. Work elsewhere has sought to minimize uncertainties in satellite trace gas retrievals through algorithm refinement (Maddy et al. 2008; Xiong et al. 2008; Yurganov et al. 2008; Jury 2017). With regard to CH_4 , Bergamaschi et al. (2007) note $\pm 1.5\%$ uncertainty in satellite retrievals and ± 3 -ppb uncertainty in surface measurements. Frankenberg et al. (2006) found that “cloud screening” reduces systematic errors below 3% for satellite retrievals of constituents such as CH_4 , CO_2 , and NO_2 .

3. Results

3.1. Climatology and seasonal cycle

MODIS satellite data averaged 2003–15 (Figures 1a,b) characterize the highland climate: cool land temperatures ($\sim 25^\circ\text{C}$) and moderate vegetation fraction (~ 0.4). The mean zonal circulation (Figure 1c) reveals winds from the east with a rising component in the low levels and a sinking component in the upper levels. There is a wind shadow just west of the Rift Escarpment, where trace gases tend to accumulate. The mean diurnal cycle averaged over the highlands area (Figure 1d) displays large-amplitude changes in PBL height (120–1800 m) and rainfall (0.8 – 3.6 mm h^{-1}) and modest changes of wind speed (4 – 5 m s^{-1}). The daytime satellite overpass corresponds with a deep boundary layer prior to moist convection. Daytime near-surface winds tend to converge onto the highlands (cf. Figure 6c; also Jury 2016) and tend to limit (enhance) horizontal (vertical) dispersion.

Figure 2. Mean 2003–15 vertical cross-sections (left: S–N avg 35°–41.5°E; right: W–E avg 6°–13°N) of AIRS daytime (a) CO, (b) CH₄, and (c) O₃, all in ppm with topography. The index area is dashed.

The 2003–15 mean north–south and east–west cross-sections (Figures 2a–c) of AIRS CO, CH₄, and O₃ characterize the vertical structure of trace gases over Ethiopia, while emission sources (Figures 3a–c) provide context. CO (Figure 2a) displays a low-level maximum over the western highlands (~10°N, 36°E, 850 hPa) consistent with biomass burning (cf. Figure 3a) and westward transport, forming the African smoke plume (Giglio et al. 2003). CH₄ (Figure 2b) also displays a low-level maximum over the highlands (~9°N, 39°E, 700 hPa) where the livestock are located (cf. Figure 3b). In contrast, O₃ (Figure 2c) increases aloft and to the north, indicating photochemical production from more distant sources in the subtropics (Cooper et al. 2014). The mean climatology map for NO₂ (Figure 3c) illustrates plumes extending westward from the highlands, attributable to biomass burning, lightning, and minor urban industrial sources (van der A et al. 2008). The NO₂ plume emanating from the city of Addis Ababa (population 4.6 million in 2016) corresponds with in situ particulate concentrations up to 1 mg m⁻³ (Abate 2015; Tefera et al. 2016).

Figure 3. (a) Map of MODIS fire counts summed over 2003–15 with 1500-m elevation contour. (b) Livestock density (number per square kilometer; adapted from Wint and Robinson 2007) with index area (dashed). (c) OMI satellite tropospheric NO_2 climatology 2005–16 number per square centimeter) with LIS satellite lightning flash density $>300 \text{ km}^{-2}$ raster gray shaded. Largest city is shown as a circle.

Figure 4. Mean seasonal cycle ($\times 2$) within the index area of (a) MERRA air constituents, (b) AIRS methane and vegetation, (c) MERRA BC, AIRS CO, and SHF, (d) AIRS global and local CO₂, (e) MERRA meteorological variables, and (f) CMORPH rainfall and near-surface wind divergence. Seasonal cycle correlations are listed in Table 2.

The Ethiopian highland mean seasonal cycle (Figures 4a–f) displays low amplitude for SO₂, O₃, PBL height, and V wind and high amplitude for other variables. The climatic insensitivity of SO₂, O₃, and dust (AOD) suggests inward transport from distant sources (Knippertz and Todd 2012). PBL height is flat because of the offsetting effect of moist convection during summer, while the north–south shift of the equatorial trough exerts minimal influence on V winds due to orography. Among those variables with large seasonal cycle, CH₄ lags vegetation and maximizes in October–December, while the BC and CO peak in January–February with biomass burning. The Ethiopian area-averaged CH₄ is above the global average CH₄ from November to March (cf. Figure 4b). Meteorological variables with large but narrow seasonal range include rainfall and humidity (July–August peak). Wind convergence rises to a maximum in June, whereas westward transport ($-U$ wind) displays a broad peak in the October–May dry season.

Ethiopia CO₂ values are 1–2 ppm below global due to small industrial emissions, whereas CH₄ values are 2–3 ppm above global due to agricultural emissions.

Among the seasonal cycle correlations in Table 2, AOD, dust, and CO₂ are inversely related with CH₄. The BC increases in dry weather, and CO follows sensible heat flux (SHF), indicating that drying is linked with biomass burning. The wind variables reveal transport and mixing influences: northerly winds ($-V$) increase CO₂, southerlies increase BC concentrations, westerly winds bring dust (AOD), and easterlies ($-U$) raise CO, CH₄, and O₃ concentrations. These links suggest horizontal advection as the main driver. NDVI is negative correlated with SHF, CO, and PBL height, which rise in the dry season.

3.2. Seasonal features

The seasonal distribution of near-surface trace gases is illustrated in Figures 5a–c. Having outlined the mean seasonal cycle, both CO and BC show high concentration over the southwest highlands in the December–February season and low concentration during the wet season. The CH₄ shows a persistent livestock “footprint” at higher elevations with a maximum at the end of the growing season (September–November) over the north-central highlands.

The seasonal atmospheric circulation (Figures 6a–d) is dominated by upper-level anticyclonic vorticity (and subsidence) imparted by the subtropical jet stream, especially in the December–February season. By March–May, a shallow overturning circulation develops in the south as the subtropical jet weakens. North-easterly flow shifts to easterly and surface air temperatures rise in March–May before the wet season. The equatorial trough and its cyclonic vorticity push northward to the highlands in the June–August season. Increasing rainfall and wet deposition reduces trace gas and aerosol concentrations, except for CH₄. The meridional overturning circulation weakens in the September–November season, and near-surface easterly flow is reestablished.

Considering the dry-season map (Figure 6a), a key feature is the horizontal diffluence of easterly flow reaching the Rift Escarpment. Subtropical troughs channel flow into the Red Sea and draw air from the northern highlands, while easterlies pass across the southern highlands and Turkana Valley. North–south bands of subsiding air create standing waves and a dry stable layer ($dT/dz - 5^{\circ}\text{C km}^{-1}$). The Froude number $Fr = U/Nh$ (wind speed divided by buoyancy index and mountain height; Reisner and Smolarkiewicz 1994) falls below 0.3, so a wind shadow forms west of the Rift Escarpment and accumulates trace gases.

3.3. Intraseasonal variability

Daily time series of near-surface satellite trace gases are given in Figures 7a–c. Of concern is the rising trend of daily CH₄ that accounts for a remarkable 43% of total variance related to the concomitant growth of human and livestock populations. The seasonal cycle is of similar amplitude to episodic fluctuations, suggesting steady emissions influenced more by slowly varying vegetation cover than dispersion conditions. In contrast, CO exhibits a weak decline and large episodic fluctuations (from biomass burning). NO₂ episodes far exceed the seasonal cycle,

Table 2. Correlation of the seasonal cycle of near-surface air constituents and meteorology averaged over the Ethiopia index area; values above 90% confidence with $N = 12$ are in bold font. Data identifications are as follows. r: MISR, m: MERRA-2, Dust: particulate matter <10 μm , a: AIRS, PBL: planetary boundary layer height, U and V : wind components, Humid: specific humidity, NDVI: vegetation, DIV: wind divergence, s: satellite, and SHF: sensible heat flux. Graphs are shown in Figure 4.

Annual	r	AOD	m dust	a CO ₂	a CO	a CH ₄	m SO ₂	m BC	m O ₃	m PBL	m U	m V	Humid	NDVI	DIV	s.rain
m Dust		0.66														
a CO ₂	0.72		0.67													
a CO	-0.59	0.01		-0.38												
a CH ₄	-0.87	-0.79	-0.68	-0.92	0.44											
m SO ₂	-0.74	-0.68	-0.66	-0.66	0.10	0.73										
m BC	-0.57	-0.25	-0.25	-0.79	0.71	0.66	0.31									
m O ₃	-0.25	0.33	0.33	0.33	0.63	-0.14	-0.15	-0.05								
m PBL	-0.41	0.33	0.33	-0.07	0.81	0.13	0.12	0.35	0.79							
m U	0.80	0.47	0.38	0.38	-0.40	-0.62	-0.66	-0.10	-0.45	-0.51						
m V	-0.37	-0.40	-0.40	-0.71	0.55	0.65	0.26	0.72	-0.15	0.17	-0.10					
Humid	0.79	0.21	0.21	0.67	-0.86	-0.68	-0.44	-0.87	-0.33	-0.66	0.47	-0.52				
NDVI	0.13	-0.52	-0.52	-0.06	-0.82	0.10	0.34	-0.49	-0.68	-0.77	-0.03	-0.20	0.61			
DIV	-0.51	-0.89	-0.89	-0.75	-0.08	0.74	0.55	0.37	-0.56	-0.45	-0.23	0.49	-0.21	0.50		
s Rain	0.86	0.23	0.23	0.65	-0.78	-0.69	-0.57	-0.72	-0.40	-0.71	0.66	-0.38	0.95	0.50	-0.18	
m SHF	-0.41	0.29	0.29	-0.19	0.94	0.21	0.00	0.59	0.70	0.93	-0.32	0.38	-0.78	-0.90	-0.35	-0.72

Figure 5. Seasonal mean maps of daytime near-surface (a) CO, (b) CH₄, (c) O₃, and (d) BC. Each column has the same scale, and maximum values are labeled; 1500-m elevation is contoured.

particularly in the dry seasons of 2010–11 and 2014–15. Spikes in the NO₂ record tend to grow with time and relate to weather conditions (cf. [section 3.4.](#)), yet the overall trend is minimal.

[Table 3](#) lists the daily correlations and shows interdependence of near-surface CO and NO₂ ($r = +0.50$) and CO and satellite O₃ ($+0.70$). The correlation of model versus satellite O₃ is disappointing ($+0.23$), likely because retrievals are tuned for the upper troposphere. CO relates to humidity and dewpoint temperature (-0.52 , -0.55 drier), lapse rate ($+0.45$ stable), and OLR ($+0.44$ warmer). NO₂ mirrors the CO meteorology correlations; both show negative association with vorticity and U wind. Although anticyclonic easterly winds could draw air pollution from the Arabian Peninsula ([Farahat 2016](#)), most distribution maps (cf. [Figures 2, 5](#)) show low concentrations over the Red Sea and Gulf of Aden. Thus, we infer an accumulation of local emissions within the highlands wind shadow. CH₄ shows relatively weaker meteorological influence, except for OLR ($+0.37$ warmer). Daily near-surface O₃ from the model correlates with air temperature

Figure 6. (left) Seasonal mean vertical cross sections averaged $35^\circ\text{--}41.5^\circ\text{E}$ of wind vorticity (shaded $\times 10^{-5}$, anticyclonic negative orange), zonal wind (contours $> 10 \text{ m s}^{-1}$), and meridional circulation (vectors, $W \times 60$) with topography; (lower left) index area bracket. (right) Seasonal mean maps of (850–700 hPa) near-surface winds, with same scale. Map overlays (a) DJF: 700-hPa sinking motion $> 0.045 \text{ Pa s}^{-1}$ and flow channeling; (b) MAM: air temp $> 30^\circ\text{C}$; (c) JJA: CMORPH rainfall $> 5 \text{ mm day}^{-1}$; and (d) SON: 1500-m elevation contour.

Figure 7. Daily time series of Ethiopia index area near-surface (a) AIRS CH₄, (b) AIRS CO, and (c) OMI NO₂, incorporating a 3-day running maximum. Linear trends are given in (a),(b); arrow points to case study in (c).

Table 3. Correlation of daily time series of near-surface air constituents and meteorology averaged over the Ethiopia index area; values above 90% confidence with $N = 4748$ are in bold font. Data identification areas follows. o: OMI, T : 775-hPa air temperature, dT/dz : lapse rate, OLR: satellite outgoing longwave radiation, Vort: wind vorticity (anticyclonic negative), and T dew: surface dewpoint temperature. Duplicate items are consistent with Table 2. Scatterplots are shown in Figure 8.

Daily	a CH ₄	a CO	o NO ₂	m O ₃	a O ₃	Humid	m U	m T	dT/dz	OLR	Vort	DIV
a CO	-0.03											
o NO ₂	0.23	0.50										
m O ₃	-0.22	0.31	0.11									
a O ₃	0.36	0.70	0.28	0.23								
Humid	-0.19	-0.52	-0.38	-0.13	-0.55							
m U	-0.28	-0.36	-0.26	-0.26	-0.55	0.46						
m T	-0.12	0.24	0.05	0.64	0.33	-0.29	-0.19					
dT/dz	0.11	0.45	0.32	0.13	0.28	-0.32	-0.44	-0.08				
OLR	0.36	0.44	0.35	0.07	0.48	-0.75	-0.61	0.24	0.45			
Vort	-0.26	-0.35	-0.30	0.10	-0.45	0.28	0.34	0.17	-0.31	-0.36		
DIV	0.33	0.22	0.28	-0.11	0.18	-0.37	-0.54	-0.17	0.37	0.55	-0.44	
T dew	-0.23	-0.55	-0.42	-0.03	-0.56	0.90	0.43	-0.19	-0.38	-0.79	0.35	-0.42

(+0.64 warmer), while O₃ from the satellite relates to dry conditions. Figures 8a–f illustrate scatterplots of the leading air constituent–meteorology interrelationships are listed in Table 3. The CO scatterplot (cf. Figure 8b) is more coherent at low concentrations, corresponding with high humidity and wet deposition. A key feature is the insensitivity of methane concentrations to meteorological forcing.

3.4. Meteorology of trace gas episode

The NO₂ episode of 24–26 December 2010 (Figures 9a–c) features dry anticyclonic easterly flow that slows abruptly on reaching the Rift Escarpment, creating a calm area over the central highlands of Ethiopia. The HYSPLIT simulation shows trace gas accumulation in the wind shadow to the west of the mountains. Radiosonde profiles over Arabia measured low dewpoint temperature (-30°C at 800 hPa) under westerly flow. CALIPSO aerosol sections and corresponding atmospheric circulation features during this event (Figure 9c) illustrate subsidence above the PBL along the edge of the subtropical jet stream. The top of the dense aerosol layer rises over the highlands but is constrained by meridional rotors on either side. The upper-level anticyclonic vorticity induces midlevel sinking motion and near-surface drying. The key feature of the episode is a deflection of stable easterly flow on reaching the Rift Escarpment. The consequent wind shadow acts like a magnet for trace gases from diverse sources.

4. Concluding discussion

This study advances our understanding of agricultural emissions that contribute to greenhouse warming using satellite estimates of key air constituents and, thus, has broad relevance to the wider scientific community.

The air chemistry of Ethiopia has been studied using seasonal and daily satellite estimates and inventory-based model products in the period 2000–16. CH₄ reaches

Figure 8. Scatterplots of daily time series comparing meteorology and air constituents averaged over the Ethiopia index area: (a) OLR vs CO, (b) specific humidity vs CO, (c) dT/dz vs CO, (d) air temperature vs O₃, (e) OLR vs CH₄, and (f) wind divergence vs CH₄. Linear fit is given; daily correlations are listed in Table 3.

Figure 9. (a) HYSPLIT simulated dispersion (shaded 0.1 , 1 , $10 \times 10^{-6} \text{ kg m}^{-3}$) 24–26 Dec 2010 from 9°N , 37°E , near-surface wind (vectors); dashed red line highlights the wind barrier. (b) Arabian radiosonde profiles of temperature, dewpoint, and wind at 0000 UTC 25 Dec 2010. (c) CALIPSO aerosol density at 1400 UTC 24 Dec 2010, with wind circulation (meridional vectors and zonal contours $>10 \text{ m s}^{-1}$) and topography overlay.

high concentrations due to livestock emissions over the north-central highlands and is above the global average from November to March (cf. Figure 4b). In contrast, CO rises over the western highlands in the dry season. Among the seasonal cycle correlations, dust, AOD, and CO_2 are inversely related with CH_4 ; BC and CO are negatively related with humidity and rainfall; and CO closely follows SHF, indicating that drier conditions favor biomass burning. Northerly (southerly) winds enhance CO_2 (BC), and westerly winds enhance AOD, whereas easterly winds drive up CO, CH_4 , and O_3 . Hence, the slowly varying seasonal circulation and

Figure A1. Participants in the Wollo University air chemistry and meteorology data analysis workshop, 16 Dec 2016.

agricultural land-use underlie short-term weather fluctuations, which collectively determine trace gas concentrations.

Daily correlations reveal interdependence of CO and NO₂ and of meteorological sensitivity to dry, stable weather conditions and anticyclonic easterly winds that create a calm area next to the Rift Escarpment. CH₄ fluctuations are relatively insensitive to weather conditions, whereas near-surface O₃ increases with air temperature. Dispersion conditions underlying high CO, CH₄, and NO₂ episodes are characterized by stable, dry, anticyclonic weather and midtropospheric subsidence from intrusion of the northern subtropical jet stream. The circulation and trace gas patterns suggest that many GHGs are locally generated, not imported. The wind shadow cast by the Rift Escarpment accumulates emissions such as CH₄, which has increased >0.1 ppm from 2002 to 2016. Its linear upward trend accounts for 43% of variance and suggests the need to improve the efficiency of livestock production in Ethiopia. Future work will compare new in situ data with satellite retrievals.

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Appendix

[Figure A1](#) is a photo of participants in the Wollo University air chemistry and meteorology data analysis workshop on 16 December 2016.

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