An Overview of Lightning Chemistry

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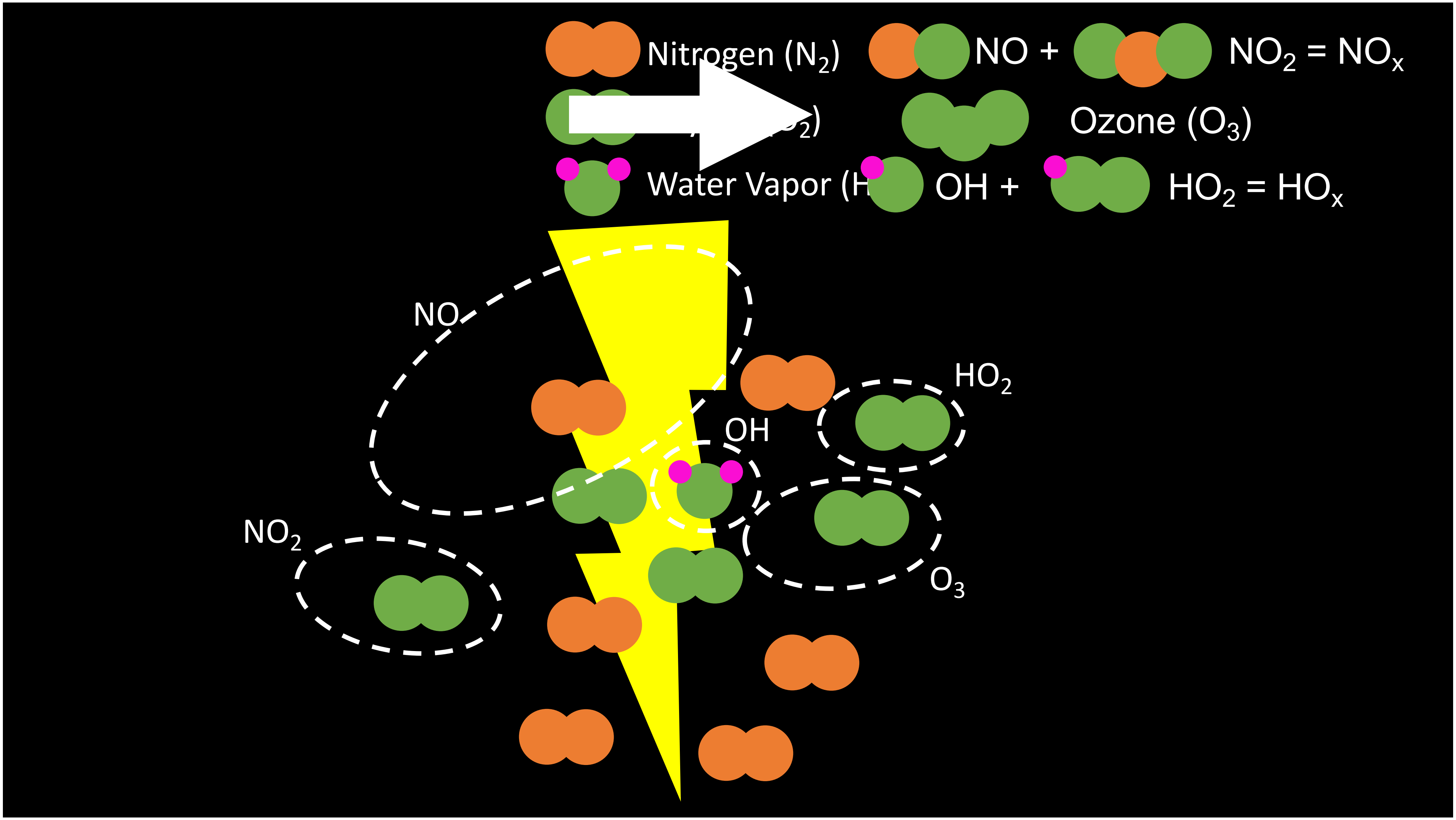
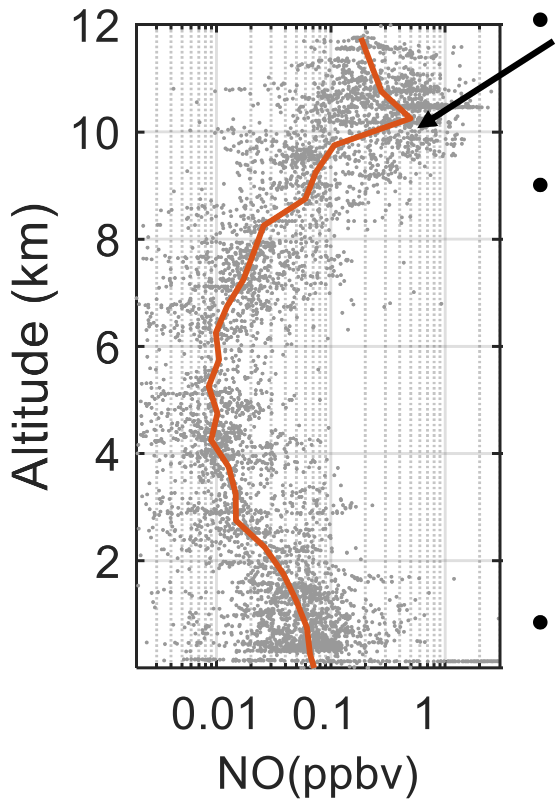
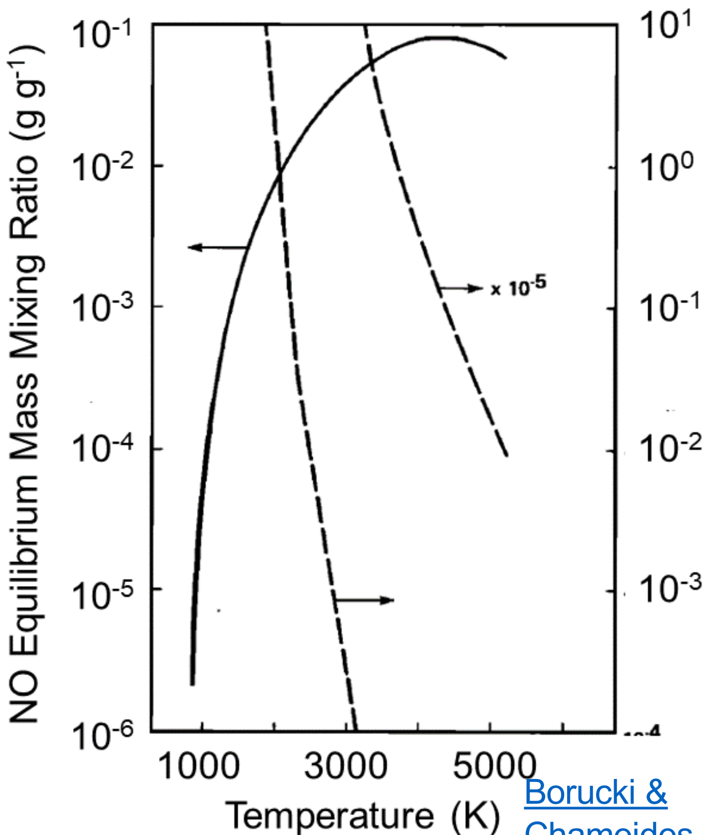

Nitrogen (N_2)
NO +
NO_2 = NO_x
Ozone (O_3)
Water Vapor (H
OH +
HO_2 = HO_x
NO
OH
HO_2
NO_2
O_3

Lightning impacts of atmospheric chemistry



- Lightning is the primary natural source of upper tropospheric NO_x
  - Precursor to OH, O_3 formation
- OH is the atmosphere's primary oxidant
  - Initiates processes to add oxygen to molecules
  - Example: converts CO to CO_2
  - Drives daytime atmospheric chemistry
  - Lightning directly produces OH and H by splitting H_2O
  - H immediately reacts with O_2 to form HO_2
  - HO_2 is a secondary oxidant that cycles with OH
  - $OH + HO_2 = HO_x$
- O_3 important greenhouse gas in the upper troposphere
  - Lightning directly produces O_3 by splitting O_2 to make O
  - O rapidly reacts with O_2 to form O_3

Lightning NO_x (LNO_x)

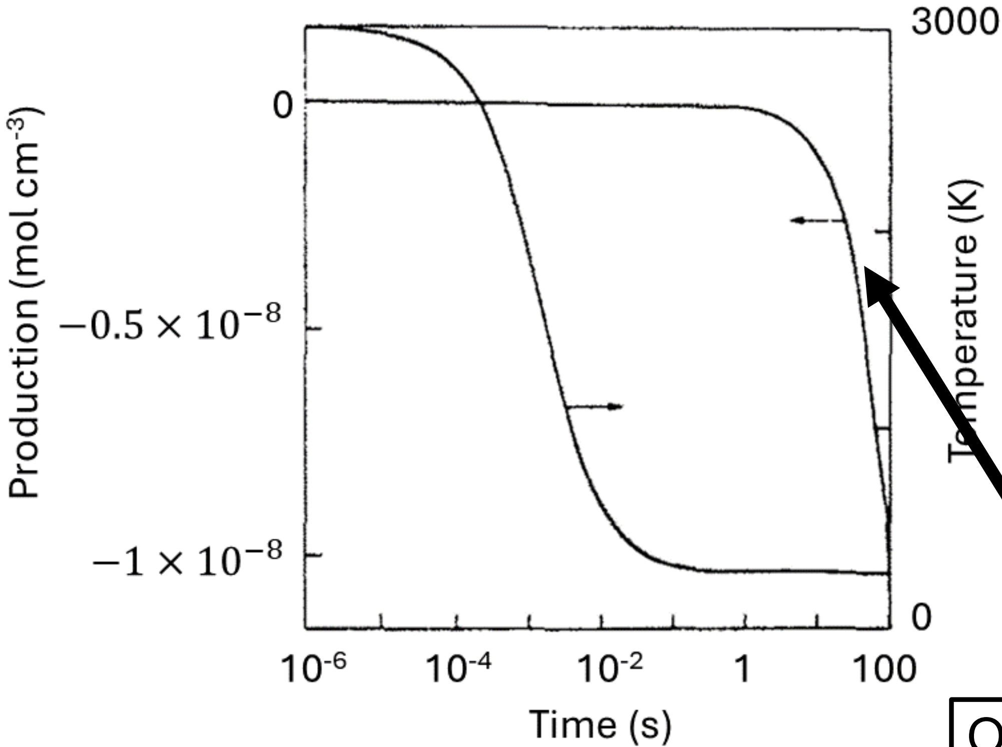


[Borucki & Chameides, 1984]

- LNO_x is produced by the Zel'Dovich Mechanism ([Zel'dovich & Raizer, 1966])
  - Dissociation of N_2, O_2 into N, O
  - Rapidly reacts to form NO
- NO equilibrium concentration, adjustment time are strong functions of temperature
  - Hot-channel core produces lots of NO_x
  - Hot-channel core rapidly cools, "freezing in" LNO_x
- Total LNO_x produced remains uncertain
  - 2-9 Tg N year^{-1} (Schumann & Huntrieser, 2007; Nault et al., 2017)
  - NO_x produced per flash depends on flash size/rate (Buscela et al., 2019; Allen et al., 2019)

A hot channel lightning core is necessary to generate appreciable NO_x

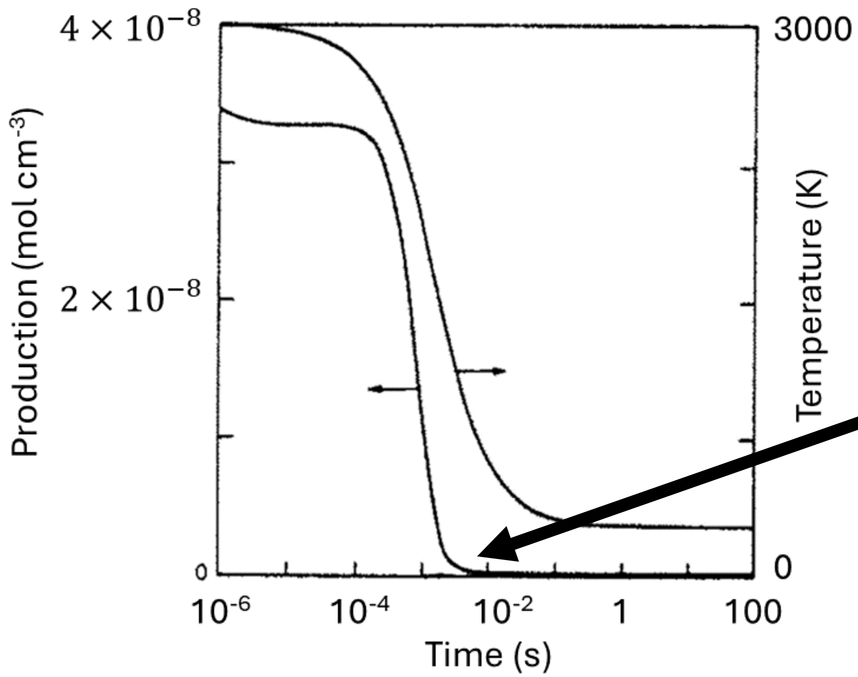
Lightning O_3 (LO_3)



- O_3 produced by dissociation of O_2
  - O reacts with O_2 to form O_3
  - Dissociation of O_2 requires ultraviolet (UV) radiation with E ≥ ~6 eV (λ<~200 nm)
- O_3 is not produced in the hot-channel core (Bhetanabhotla et al., 1985 ; Levine et al., 1981)
  - Too reactive at high temperatures
- As hot-channel cools, O_3 production turns negative
  - O_3 quickly consumed by NO_x
  - Converts NO to NO_2

O_3 made in hot-channel lightning core is unimportant

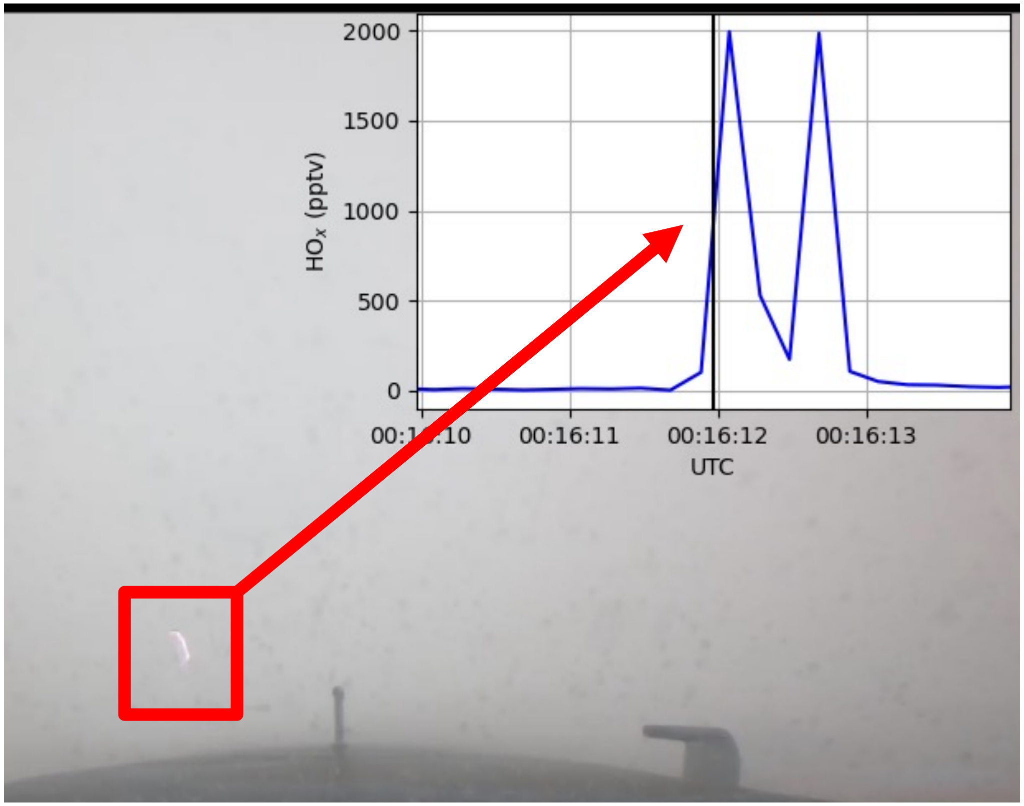
Lightning HO_x (LHO_x)



- HO_x produced by dissociation of H_2O into OH and H
  - H immediately reacts with O_2 to form HO_2
  - Dissociation of H_2O requires UV with E ≥ ~6 eV (λ<~200 nm)
- HO_x directly produced in the hot-channel core (Bhetanabhotla et al., 1985)
  - HO_x decays to background levels within milliseconds
  - Quickly consumed by LNO_x in/around hot-channel core

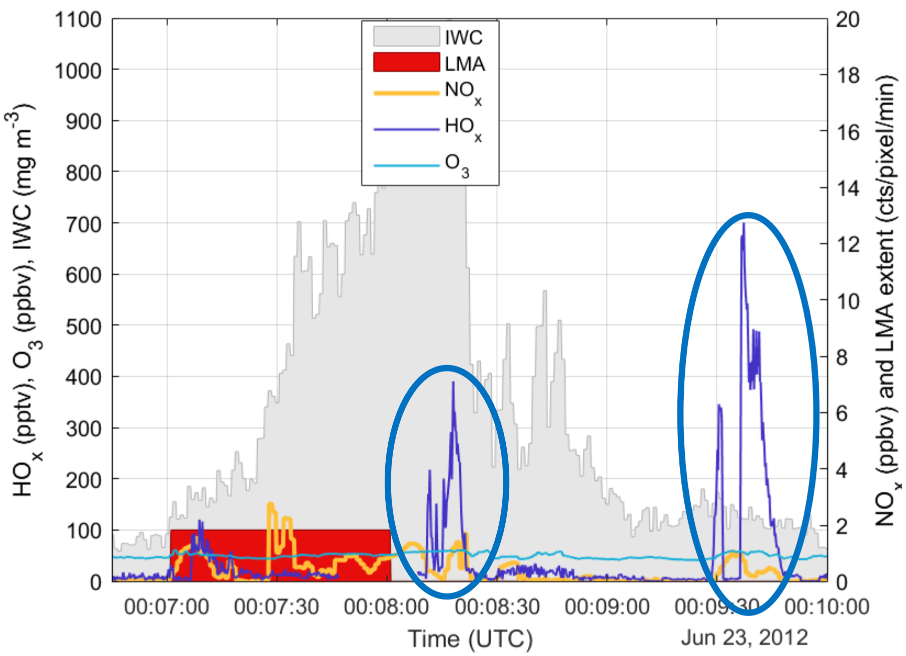
HO_x made in hot-channel lightning core is unimportant

LHO_x & LO_3 can be made outside hot-channel



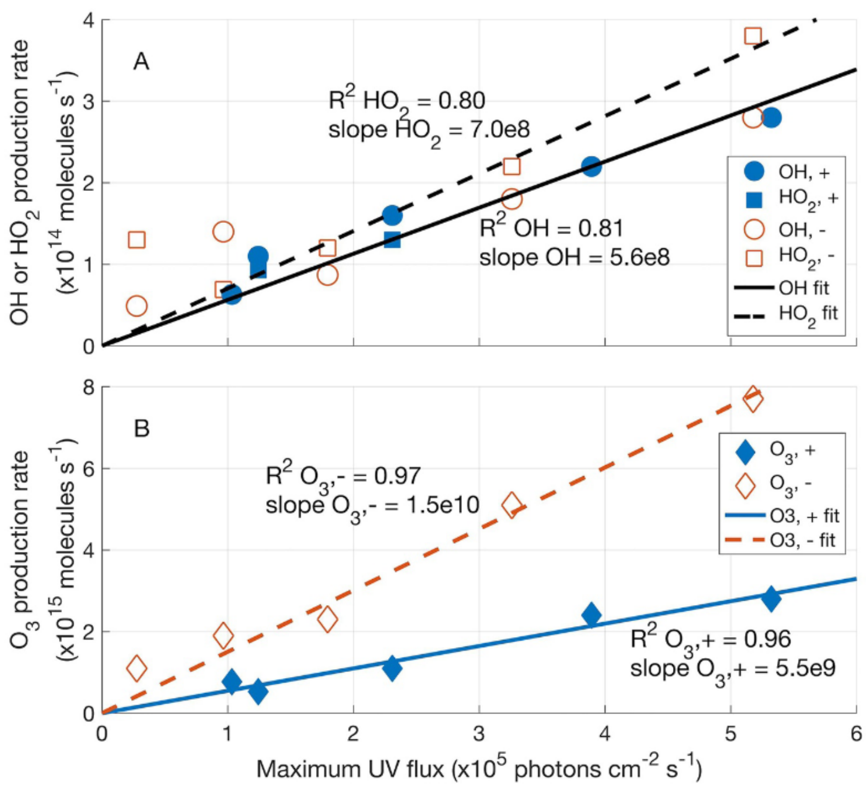
- UV radiation with E > 6 eV extends a few meters outside hot-channel core
  - UV dissociates H_2O, O_2 to make OH + HO_2 (=HO_x), O_3
  - No LNO_x made outside hot-channel core
  - With no LNO_x, LHO_x and LO_3 exist long enough to affect atmospheric chemistry
- LHO_x increases atmosphere's oxidative capacity
- LO_3 alters radiative balance
  - 15 O_3 molecules made for every 1 HO_x molecule (Mao et al., 2021)

Weaker Discharges also produce HO_x & O_3



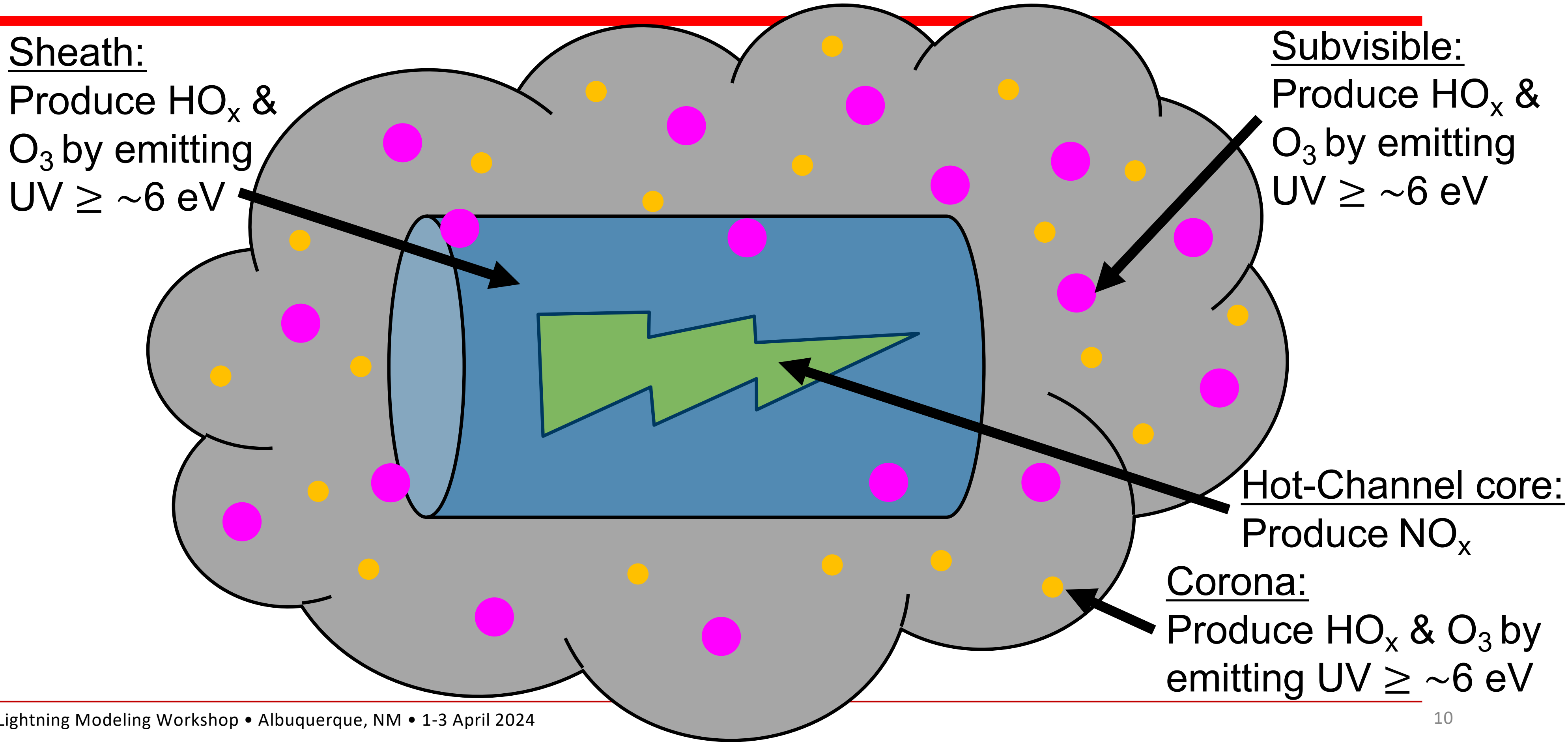
- Subvisible discharges are weak, short pulse discharges that cannot be seen or heard
  - Too weak to be detected by Lightning Mapping Array (LMA)
  - Emit UV ≥ ~6 eV to produce HO_x & O_3 100-1000 times above background levels (Jenkins et al., 2021)
  - Produce no NO_x
  - Contribute additional 2-16% to global OH (Brune et al., 2021)
- HO_x may be more sensitive indicator of discharge activity
  - HO_x spikes unmatched to LMA lightning
  - How prevalent are these subvisible discharges?

Weaker Discharges also produce HO_x & O_3



- Corona discharges are weak, more continuous discharges
  - Emit UV ≥ ~6 eV to produce HO_x, O_3 100-1000 times above background
  - Produce no NO_x
  - Increase oxidative capacity of atmosphere
- HO_x, O_3 production scales with UV flux, electric field strength (Jenkins et al., 2022)
  - O_3 production also depends on polarity
- Corona form beneath the thunderstorm on trees, lightning rods (Brune et al., 2022)
  - Form within thunderstorm clouds (Bozem et al., 2014)
  - How widespread are corona within thunderstorms?

Modeling Approach



Uncertainties

- LHO_x potentially more important than LNO_x, LO_3 for impacting tropospheric oxidation chemistry and ozone radiative balance
- 2-16% of global OH may be due to lightning
  - How many lightning flashes occur across the globe annually?
    - Satellite-derived lightning climatologies undercount lightning by a factor of 2+ (McFarland & Brune, 2023)
  - What volume of air has LNO_x frozen in?
  - What volume surrounding lightning are HO_x & O_3 made?
  - How prevalent are weaker subvisible and corona discharges?
- Future Targets
  - Better global estimate of lightning facilitated by expansion of LMAs
  - Characterize electrical discharge environment across different thunderstorm environments
    - Including prevalence of weaker subvisible and corona discharges
  - More measurements LNO_x, LHO_x, LO_3, especially with instruments unaffected by electrified environments

Funding Sources

Sponsoring organization	Funding program	Funding program element	Funding cadence (R = regular interval; I = irregular intervals; L = time-limited opportunity)	Comments
NSF	Atmospheric & Geospatial Science	Atmospheric Chemistry	R	Support for our research on LHO_x
NASA	Atmospheric Composition Focus Area	Tropospheric Composition Program	R/L	L = Field campaign to measure HO_x, NO_x, O_3
NSF	Atmospheric & Geospatial Science	Physical & Dynamic Meteorology	R	Atmospheric Electricity

Avenues for Collaborations

- Interagency collaborations
  - NSF & NASA
  - Future field campaigns like Deep Convective Clouds & Chemistry (DC3; Barth et al., 2015)
- Across universities, government, research labs
  - Critical need to understand the prevalence of weaker electrical discharges, associated HO_x production
  - Develop new aircraft-compatible HO_x detection instruments
- International collaborations
  - Institute of Atmospheric Physics, German Aerospace Center (DLR)
  - Institute of Astrophysics of Andalusia (Spain)
- Mix of students, post-docs, and career-experts