Hydrological controls on the tropospheric ozone greenhouse gas effect

Le (Elva) Kuai¹, Kevin W. Bowman², Helen Worden³, Robert L. Herman², Susan S. Kulawik⁴

1. JIFRESSE/UCLA;
2. JPL/Caltech;
3. NCAR;
4. BAER Institute/NASA Ames;
The estimated radiative forcing (RF) of tropospheric O₃ range widely from +0.2 to +0.6 Wm⁻².
This range is computed using varieties of chemical-climate models.
97% of the O₃ long wave RF is due to the ozone absorption in the 9.6 μm band [Rothman et al., 1987].
Objectives and Motivations

**AURA TES**
*(Tropospheric Emission Spectrometer)*

- Attribute the TOA band flux change/bias due to dominant physical quantities.

\[
\Delta F_{TOA} = \frac{\partial F_{TOA}}{\partial O_3} \Delta O_3 + \frac{\partial F_{TOA}}{\partial T_{sur}} \Delta T_{sur} + \frac{\partial F_{TOA}}{\partial T_{atm}} \Delta T_{atm} + \frac{\partial F_{TOA}}{\partial H_2O} \Delta H_2O + \frac{\partial F_{TOA}}{\partial \tau_{cloud}} \Delta \tau_{cloud} + r_s
\]

- 9.6 μm band flux change
- O₃
- Surface temperature
- Atmos. temperature
- Water vapor
- Cloud
- residual

**Instantaneous Radiative Kernels (IRK):**

\[
IRK_{O_3}(z) = \frac{\partial F_{TOA}(q)}{\partial O_3(z)}
\]
Objectives and Motivations

- Attribute the TOA flux change due to dominant physical quantities.
- Understand the dependence of $O_3$ IRK variation on $H_2O$, temperature, and clouds.

**Instantaneous Radiative Kernels (IRK):**

\[
\text{IRK}_{O_3}(z) = \frac{\partial F_{TOA}(q)}{\partial O_3(z)}
\]
Objectives and Motivations

- Attribute the TOA flux change due to dominant physical quantities.
- Understand the dependence of O$_3$ IRK variation on H$_2$O, temperature, and clouds.

Instantaneous Radiative Kernels (IRK): \[ \text{IRK}_{O_3}(z) = \frac{\partial F_{\text{TOA}}(q)}{\partial O_3(z)} \]
5-angle Gaussian Quadrature integration method

Top of atmospheric flux (9.6μm ozone band):

\[ F_{TOA} = \int \int \int L(\theta) \cos \theta \sin \theta d\theta d\phi d\nu \]

Instantaneous Radiative Kernel (mW/m²/ppb):

\[ \text{IRK}(z_i) = \frac{\partial F_{TOA}}{\partial q_i(z_i)} \]

Logarithm IRK (mW/m²):

\[ \text{LIRK}(z_i) = \frac{\partial F_{TOA}}{\partial \ln q_i(z_i)} \]

Long Wave Radiative Effect (Tropospheric column) (W/m²):

\[ \text{LWRE} = \Delta F_{TOA} = \sum_{l=\text{surface}} \left( \frac{\partial F_{TOA}}{\partial q_i(z_i)} q_i(z_i) \right) \]

\[ K(\theta_{Nadir}^i) = \sum \left[ \frac{\partial L(\nu, \theta_{Nadir}^i)}{\partial q(z_i)} \right] \Delta \nu \]

\( q(z_i) \) could be any atmospheric state, such as profiles of \( O_3, T_{atm}, H_2O, \) or \( T_{sur}, \) cloud OD, emissivity, etc.

\[
\begin{array}{|c|c|}
\hline
w_i & \theta_{Nadir}^i (°) \\
\hline
0.015748 & 63.6765 \\
0.073909 & 59.0983 \\
0.146387 & 48.1689 \\
0.167175 & 32.5555 \\
0.096782 & 14.5752 \\
\hline
\end{array}
\]

[Worden et al., 2011] [Doniki et al., 2015]
Tropospheric ozone GHG effect

• Two secondary strong flux sensitivity in LIRK is near subtropical mid and upper troposphere in both hemispheres.

• Highest LWRE over Middle East during boreal summer (> 1 Wm$^{-2}$).

• Subtropical maximum and tropical low in LWRE.
Similar spatial pattern in LWRE and RH
Spatiotemporal change oppositely

Mediterranean Basin and Middle East: Mild rainy winters Hot, dry summers
Less saturate in summer


<table>
<thead>
<tr>
<th>LWRE (Wm²)</th>
<th>RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>&gt;0.6</td>
</tr>
<tr>
<td></td>
<td>&gt;80</td>
</tr>
<tr>
<td>Low</td>
<td>&lt;0.4</td>
</tr>
<tr>
<td></td>
<td>&lt;30</td>
</tr>
</tbody>
</table>

Low LWRE within ITCZ deep convection zones.
High LWRE over subtropical low RH regions.
O$_3$ LWRE and RH

- Similar spatial pattern in LWRE and RH
- Spatiotemporal change oppositely

Mediterranean Basin and Middle East: Mild rainy winters
Hot, dry summers


Less saturate in summer
Higher water amount in summer
**O$_3$ LWRE, Tropospheric O$_3$ column, & T$_{sur}$**

- **Australia** high LWRE in Jan. is due to higher T$_{sur}$ because large thermal contrast amplify the sensitivity.
- **Middle East** LWRE maximum also relevant to summer O$_3$ enhancement (Li et al., 2001; Liu et al., 2009) and high T$_{sur}$.
- **Africa savanna** high LWRE in Jan. is related to biomass burning and O$_3$ enhancement.
- **Congo basin** high LWRE in Jul. is due to O$_3$ enhancement.
In January, at central Pacific, Amazon, Congo basin, and Indonesia, deep convection zones correspond to low ozone flux sensitivity.

The Walker circulation is the primary driver for the deep convection zones at tropical central Pacific.
N. Tropics belt (0°~5°N) (July)

High RH at E. Tropical Pacific and moderate high RH at Africa savanna are another two places corresponding to low LIRK.

In July, Asian monsoon is the primary driver to bring deep convection and heavy precipitation to India and southeast Asia, where LIRK are found low.
• Similar anti-correlation between RH and Ozone LIRK.

• Two mid tropospheric maximum in Ozone LIRK correspond to the subtropical arid regions where the tropopause tends to sink and the downwelling of Hadley cell dominants.
H₂O, cloud, T, O₃ signatures on O₃ GHG effect

- C. Tropical Pacific, Amazon basin, Congo basin, Indonesia (Jan.)
- E. Tropical Pacific, Savanna, Southeast Asia (Jul.)

**H₂O & Cloud** → Atmospheric opacity

**Relative Humidity (RH)**

**Tₘ and Tₐ** → **Thermal contrast**

**Tropospheric O₃**

**Middle East (Jul.)**

**Australia (Jan.)**

**Savanna (Jan.)**

Congo basin (Jul.)

- **Attenuate**
- **Strengthen**

Weak GHG effect RH high

Strong GHG effect RH low
Conclusions

• The tropospheric O$_3$ GHG effect is low in tropics but maximized in subtropics in both hemisphere.
• RH is a useful quantity to help identify the primary driver, the large-scale circulation, that determine H$_2$O, temperature and cloud distribution. It also helps to understand the hydrological control on the tropospheric O$_3$ GHG effect.
• Tropics:
  – H$_2$O and clouds cause the low O$_3$ GHG effect.
  – The primary drivers are walker circulation and Asia summer monsoon for the deep convection.
• Subtropics:
  – Surface temperature and O$_3$ enhancement contribute to high O$_3$ GHG effect.
  – The primary drivers are the descent of tropopause height and downwelling of Hadley cell.
  – The maximum O$_3$ GHG effect are found at Middle East during its hot dry summer (>1 W/m$^2$). Ozone enhancement and high Tsur over dry desert with clear sky.
• **Hadley cell expansion (Seidel and Randel, 2007)**
  – The width expanding; poleward shift of the downward branch
  – A shift in the ITCZ farther away from the equator due to the response to CO$_2$ forcing (Held, 2000; Kang and Lu, 2012; Lu et al., 2007)
  – Increase of global T and pole-to-equator T gradient (Frierson et al., 2007)

• **Inhabitability of Middle East due to global warming (Pal et al., 2016)**
  – Additional O$_3$ radiative forcing to this region

• **The Asia monsoon strengthen (Li et al., 2010; Singh et al., 2014)**
  – Another positive feedback to the Middle East O$_3$ GHG effect

*Kuai et al. 2016 submitted to ELEMENTA*
Thank you!
IASI-TES LWRE comparisons

- IASI = TES ± 0.5 ° lat/lon
- <6 hour time difference, 2011.07.15
Clouds significantly reduce the TOA flux sensitivity to O$_3$ in the lower troposphere compared to the clear sky kernels (Soden et al., 2008).

Tropical clouds also greatly reduce the mid tropospheric maximum in O$_3$ IRK and contribute to tropical low LWRE.
ITCZ shift from south of equator to north of equator from January to July.

- Inside ITCZ belt:
  - Deep convection
  - Wet, rainy season, and cloudy sky

- Outside ITCZ belt:
  - Subsidence region
  - Arid and clear sky

- January: deep convection zone at central Pacific, Amazon, S. Africa (Congo basin), and Indonesia.

- July: deep convection zone occur north of equator at E. Tropical Pacific, Africa Savanna, southeast Asia.
Relative Humidity (RH)

The amount of water vapor present in air expressed as a percentage of the amount needed for saturation at the same temperature.

The ratio of the partial pressure of water vapor in the mixture to the equilibrium vapor pressure of water at a given temperature.

\[
RH = \frac{e_w(H_2O,P)}{e^*_w(T,P)}
\]

\[
e^*_w(T,P) = (1.0007 + 3.46 \times 10^{-6} P) \times (6.1121)e^{\left(\frac{17.502T}{240.97+T}\right)}
\]

RH describes the state of atmospheric saturation and suggests the cloud distribution based on the combination of water vapor and temperature.