Variability of Reactive Nitrogen Species linked to the stratospheric QBO

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Key Questions

1. What is observed **interannual variability** in NO$_y$ and O$_3$ in the stratosphere?

2. How does satellite (**OSIRIS & MLS**) data compare to global climate-chemistry model (**WACCM4**)?
Odin OSIRIS

- The **Odin** spacecraft was launched in Feb. 2001, into a 600-km, sun-synchronous orbit.
- The Optical Spectrograph and Infra-Red Imaging System (**OSIRIS**) measures limb scattered-sunlight.
- **OSIRIS** is limited to measurements in sunlit hemisphere.
- 14-15 orbits per day (82°S-82°N).
- Aerosols, O$_3$, NO$_2$ and BrO.

Admas *et al.* (2014)
Aura MLS

• The **EOS** Microwave Limb Sounder (MLS) is onboard on **Aura** satellite, launched on July 15, 2004.
• **MLS** makes measurements of atmospheric composition, T, RHI and IWC.
• **Limb-viewing**, measures thermal emission (up to ~ 90 km).
• A near-polar 705 km orbit; daily global coverage (~13 orbits per day).
• **HNO₃**, **N₂O**, and **O₃**

**MLS O₃ (20150915)**  68 hPa

MLS provides daily global coverage.
• Whole Atmosphere Community Climate Model, version 4 (WACCM4)

• Specified Dynamics fields  [Lamarque et al., 2012]

• NASA Global Modeling and Assimilation Office (GMAO) Modern-Era Retrospective Analysis for Research and Applications (MERRA) [Reinecker et al., 2011]

• Period: Jan 2003 to Nov 2014

• QBO (internal to MERRA)

• 1.9° × 2.5° (lat x lon), 88 vertical levels (surface - 150 km)
Reactive Nitrogen (NOy)

\[ \text{NOy} = N + \text{NO} + \text{NO}_2 + \text{NO}_3 + \text{N}_2\text{O}_5 + \text{HNO}_3 + \text{NO}_2\text{NO}_2 + \text{ClONO}_2 + \text{BrONO}_2 \]

Big five --> \(\text{NOy} = \text{NO} + \text{NO}_2 + 2\times\text{N}_2\text{O}_5 + \text{HNO}_3 + \text{ClONO}_2\)

**NOx proxy from OSIRIS [Brohede et al., 2008]**

- OSIRIS measures \(\text{NO}_2\)
- \(\text{NOx} = \text{NO}_2 \times (1 + \text{NO}/\text{NO}_2)\)
- \(\text{NO}/\text{NO}_2 \) (ratio) photochemical box model [Prather et al., 1992]
- \(\text{NO} = \text{NOx} - \text{NO}_2\)
- \(\text{NOx} = \text{NO} + \text{NO}_2\)

Primary source of stratospheric NOy is the oxidation of \(\text{N}_2\text{O}\)

\(\text{N}_2\text{O} \) (natural + anthro.) --> +2.6%/year [Forster et al., 2007]

[NCAR]
Largest contributors to $O_3$ destruction in the middle atmosphere ($NO$ and $NO_2$)

- **N$_2$O**
  - Source
  - Increase with altitude

- **NOy**
  - Max

- **O$_3$**
  - Max

**Sources in the troposphere**
- Decrease with altitude

**Increase with altitude**

- NO + $O_3$ → $NO_2$ + $O_2$
- $NO_2$ + $O$ → $NO$ + $O_2$
- Net: $O_3$ + $O$ → 2$O_2$

**NOx catalytic cycle**
$O_3$-$HNO_3$-$N_2O$ (time series, tropics, 10 hPa)

QBO is the dominant variability in the tropical stratosphere

Strong correlation between MLS $O_3$-$HNO_3$-$N_2O$ (& OSIRIS $O_3$-NOx)
Tracer-tracer correlations (10 hPa)

Strong correlation $\text{N}_2\text{O}-\text{O}_3$ (MLS & WACCM4)

OSIRIS $\text{O}_3$ & NOx – MLS $\text{N}_2\text{O}$ more scatter than WACCM4 NOx-$\text{N}_2\text{O}$
QBO in Ozone

ERA-Interim zonal wind  
MLS O$_3$  
2004-2014

photochemical control

~ 28 km
dynamical control

strong QBO signal

WCCM4 O$_3$  
2003-2014

Ozone anomalies are strongly tied to QBO in zonal wind
QBO – composite means

**westerly/easterly** – composited relative to the time of wind shear onset at 20 hPa [Hommel et al., 2015]

- Simple diagnostic of QBO
- Mixing Ratio Residual Anomalies
- WACCM O_3 (composites)
- time [month] relative to westerly onset at 18 hPa

Hommel et al. [2015]
stratospheric aerosols

[NSF logo]

[NCAR logo]
MLS $\text{O}_3$ (composites) 

ERA-Interim Zonal Wind
MLS $\text{O}_3$ (2005-2014)

OSIRIS $\text{O}_3$ (composites)

ERA-Interim Zonal Wind
OSIRIS $\text{O}_3$ (2005-2014)

MLS and OSIRIS $\text{O}_3$ QBO agree/ WACCM4 has larger amplitude
Consistent QBO in WACCM4 & OSIRIS NOx
Differences in amplitudes
O$_3$ QBO - out of phase (Equator vs. Subtropics)
Very good agreement between MLS & WACCM4 – robust!
NOx variability is dependent on altitude.
WACCM4 NOx at 83 hPa (2003-2014)

NOx Anomaly (deseasonalized)

Positive anomaly

Positive trend

2008-2009

2010-2011

NOx Trend

positive trend
WACCM4 NOx at 83 hPa (cont.)

QBO Westerly positive NOx

La-Nina positive NOx

QBO westerly & La-Nina -> positive NOx (2008-2009, 2010-2011)
QBO & ENSO influences on NOx

Westerly Acceleration Phase

downwelling – QBO (westerly)

weaker upwelling – La-Nina
OSIRIS NO$_2$ sampling (20111001)

OSIRIS (630am) vs. WACCM4 (DailyMean)

Q. Does this contribute to OSIRIS vs. WACCM4 differences?

OSIRIS NO$_2$ 26.5 km

WACCM4 NO$_2$ 21.5 hPa

WACCM4 NO$_2$ (daily mean) much higher than OSIRIS NO$_2$ (630am)
Diurnal cycle in NOx (22 hPa)

06:30 am LST (OSIRIS data)

WACCM4 NO\textsubscript{y} (0, 0.94)

OSIRIS NO\textsubscript{2}@0630h

NO\textsubscript{2} close to daily min. at 6:30am.

A. It can contribute to OSIRIS vs. WACCM4 NOx differences.
OSIRIS NO$_2$ sampling (20111001)

OSIRIS (630am) vs. WACCM4 (sampled like OSIRIS)

WACCM4 NO$_2$ (sampled like OSIRIS) similar to OSIRIS NO$_2$ (630am)
NO$_2$ - OSIRIS & WACCM4 (sampled like OSIRIS)

OSIRIS NO$_2$ (5S-5N) deseasonalized

WACCM4 NO$_2$ (5S-5N) deseasonalized

WACCM4 NO$_2$ agrees better with OSIRIS NO$_2$
WACCM4 NO$_2$ has positive trends (2013-2014)
Key Points

- Robust **QBO** in the tropical stratosphere (max ~ 15 hPa)
- **OSIRIS**, **MLS** and **WACCM4** show consistent interannual variability

- Positive **trend** in WACCM4 NOx, O₃, and HNO₃
- **QBO westerly** and **La-Nina** have influence on positive **NOx** anomaly in the tropical lower stratosphere

- **NOx proxy** from OSIRIS is a valuable source in analyzing NOy budget in the stratosphere
**ENSO effect**

[Calvo et al., 2010]

**ENSO (warm) -> T**

**ENSO (cold) -> T**

**ENSO (cold)**

Cooling (trop) and **warming (LS)** -> weaker tropospheric jets (subtropics) -> changes in gravity waves and wave drag -> forces weaker tropical upwelling -> **positive O₃ anomaly**

parameterized orographic gravity waves!