Transport of halogenated VSLS from the Indian Ocean to the stratosphere through the Asian monsoon circulation

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The tropical Indian Ocean is projected to be a strong source region for stratospheric bromine based on climatological emission estimates.
Bromoform emission climatologies

Top-down climatology

Bottom-up climatology

No measurements exist in the Indian Ocean except for the Bay of Bengal (Ziska et al., 2013; Yamamoto et al., 2001).

Liang et al., 2010, ACP

(Liang et al., 2010, ACP)

(global: 5.32 Gmol Br yr\(^{-1}\))

(global: 2.5 Gmol Br yr\(^{-1}\))

(after Ziska et al., 2013, ACP)

Bromoform water concentrations

(Ziska et al., 2013, ACP)
OASIS-SONNE cruise

- July and August 2014
- West Indian Ocean
- VSLS concentrations measured in air and water every 3 h
- Emissions calculated after Nightingale et al. (2000):

\[ F = k \cdot \Delta C \]

The Indian Ocean is a strong source region for VSLS.
Monsoon circulation during NH summer

Surface winds, July 2014 - ERA-Interim

Strong surface wind above IO during monsoon; flow towards India/ Bay of Bengal.

HCN VMR (ppbv) - ACE satellite

Polluted air in the stratosphere through Asian monsoon circulation (Randel et al. 2010).

How much does the Indian Ocean contribute to stratospheric bromine?
FLEXPART model

• Lagrangian transport model with convection scheme (Stohl et al., 2005) using 6-hourly ERA-Interim fields
• Forward and backward trajectories, run for 3 month
• Output: 6 hourly

Simulations for 2014:

1. Bromoform emissions from OASIS-SONNE cruise
   10,000 forward trajectories from measurement sites
   Atmospheric lifetime profile for emitted VSLS

2. General transport from Indian Ocean
   Forward trajectories from 1°x1° grid over West Indian Ocean surface
   961 trajectories released every day during July

3. Source regions of Asian monsoon anticyclone
   Backward trajectories from 1°x1° grid at 17 km
   27,000 trajectories released on July 31st
1. OASIS-SONNE simulations

OASIS-SONNE transport regimes

Subtropical westerlies

Monsoon circulation

Tropical convection

10 day forward trajectories
More entrainment from the Indian Ocean than from the equatorial Atlantic (1 %) but less than from the tropical West Pacific (3-10 %; Tegtmeier et al. 2012, ACP).
2. Indian-Ocean simulations

Entrainment of air from the Indian Ocean

Trajectories after 10 days:
Release from the sea surface

July 2014

Trajectories (fwd) after 30 days -
Entrainment @17 km

Convective outflow

8.2 %

Density of trajectories @17 km

Main entrance region to the stratosphere is above India, Bangladesh, and Myanmar.

Median age: 35 days
3. Anticyclone simulations

Asian monsoon anticyclone

Geopotential height anomaly and horizontal winds at 100 hPa

ERA-I July 2014

Vertical velocity and geopotential height anomaly at 100 hPa

ERA-I July 2014

Strong anticyclone in July at 100 hPa.

Upward movement above Bay of Bengal, Tibetan Plateau, Southeast Asia, and China.
3. Anticyclone simulations

Anticyclone - air masses

Release at 17 km
10 day backward trajectories

Median age: 25 days

Transit time: BL to 17 km

Boundary layer (BL) source regions

70% of the air masses at 17 km origin from the boundary layer. From this, 48% origin from the oceanic boundary layer and 52% from land.
3. Anticyclone simulations

Anticyclone - oceanic source regions

Oceanic boundary layer source region, July 2014

Anticyclonic entrainment from Bay of Bengal and tropical West Pacific is even larger than from tropical West Indian Ocean.
Anticyclonic bromoform source regions

Strong bromoform emissions from Bay of Bengal, Arabian Sea and equatorial Indian Ocean combined with effective transport are projected to lead to intense stratospheric entrainment of bromoform above Asian monsoon circulation.
Conclusions

• The subtropical and tropical Indian Ocean is a strong source region for VSLS (bromoform, dibromomethane, and methyl iodide).

• The Asian monsoon circulation provides an effective pathway for oceanic VSLS to the stratosphere.

• High modeled stratospheric bromine mixing ratios result from high bromoform emissions from the Bay of Bengal, Arabian Sea and tropical Indian Ocean.