Seasonal variation of bromine monoxide over the Rann of Kutch salt marsh seen from space

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Former tropospheric BrO observations

- Troposheric bromine monoxide (BrO) has been measured by ground-based DOAS measurements for several natural sources:

  polar sea ice (e.g. Hausmann and Platt (1992), Frieß et al. (2004), Saiz-Lopez et al. (2007))
  sea-salt aerosols (e.g. Leser et al. (2003), Saiz-Lopez et al. (2006), Read et al. (2008))
  volcanoes (e.g. Bobrowski et al. (2003), Galle et al. (2005), Lübcke et al. (2014))
  salt lakes (e.g. Matveev et al. (2001), Stutz et al. (2002), Hönniger et al. (2004))

- Rapid formation of BrO is associated with the „bromine explosion“ (requires e.g. solar radiation)

- By satellite instruments, so far, only BrO from:

  polar sea ice (e.g. Wagner and Platt (1998), Sihler et al. (2011), Theys et al. (2011))
  volcanoes (e.g. Theys et al. (2009), Hörmann et al. (2013))

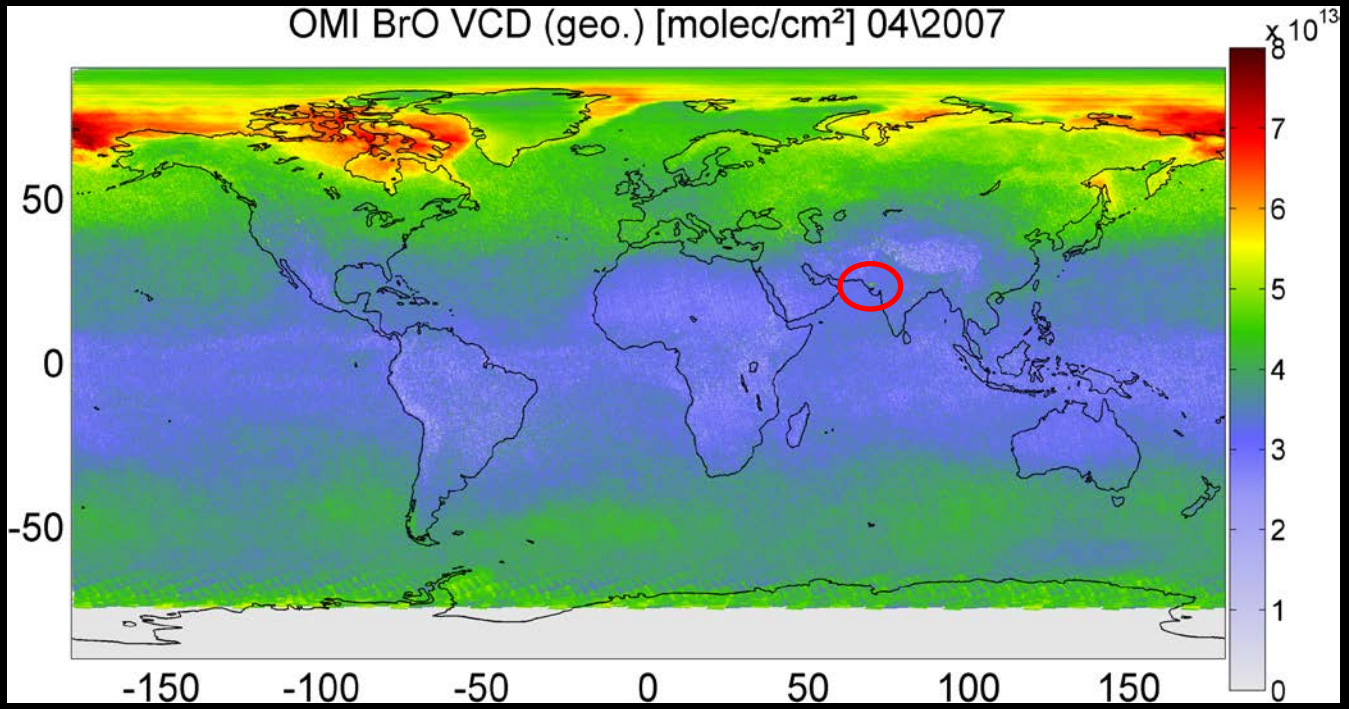
OMI BrO DOAS fit

- **O**zone **M**onitoring **I**nstrument (data available since October 2004)
  - equatorial overflight time at 13:30 LT
  - pixel size: 13x24km² (nadir), up to 28x150km² at the swath edges

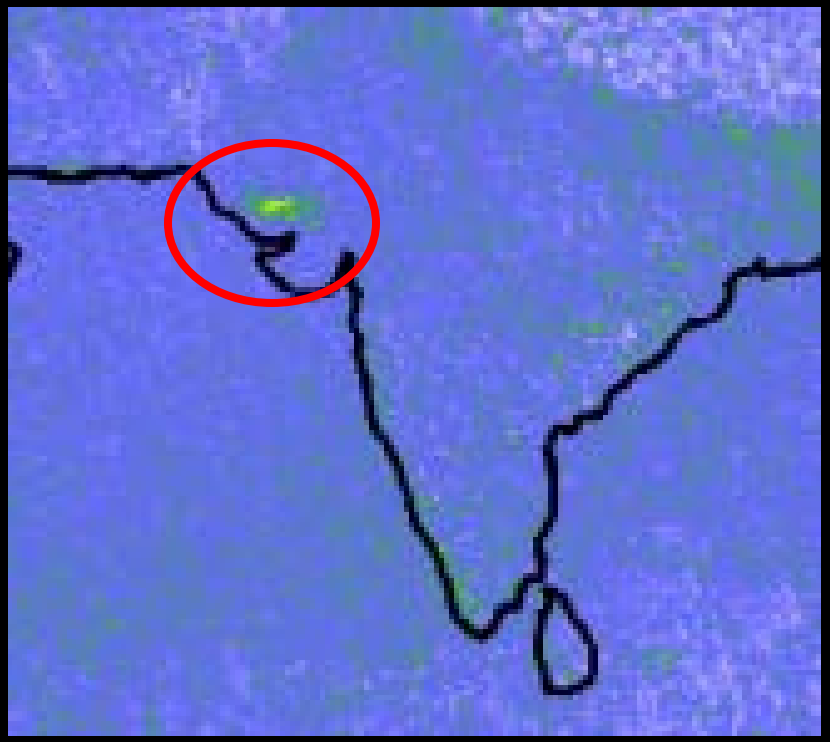
- **fit range**: 336-360 nm (based on GOME-2 retrieval by Sihler et al. (2011)

- **Cross sections**:

  BrO (228K)
  O_3 (223K/243K)
  O_4
  NO_2 (220K)
  OClO (293K)
  SO_2 (273K)
  2 x Ring
  Inverse ref



Rann of Kutch

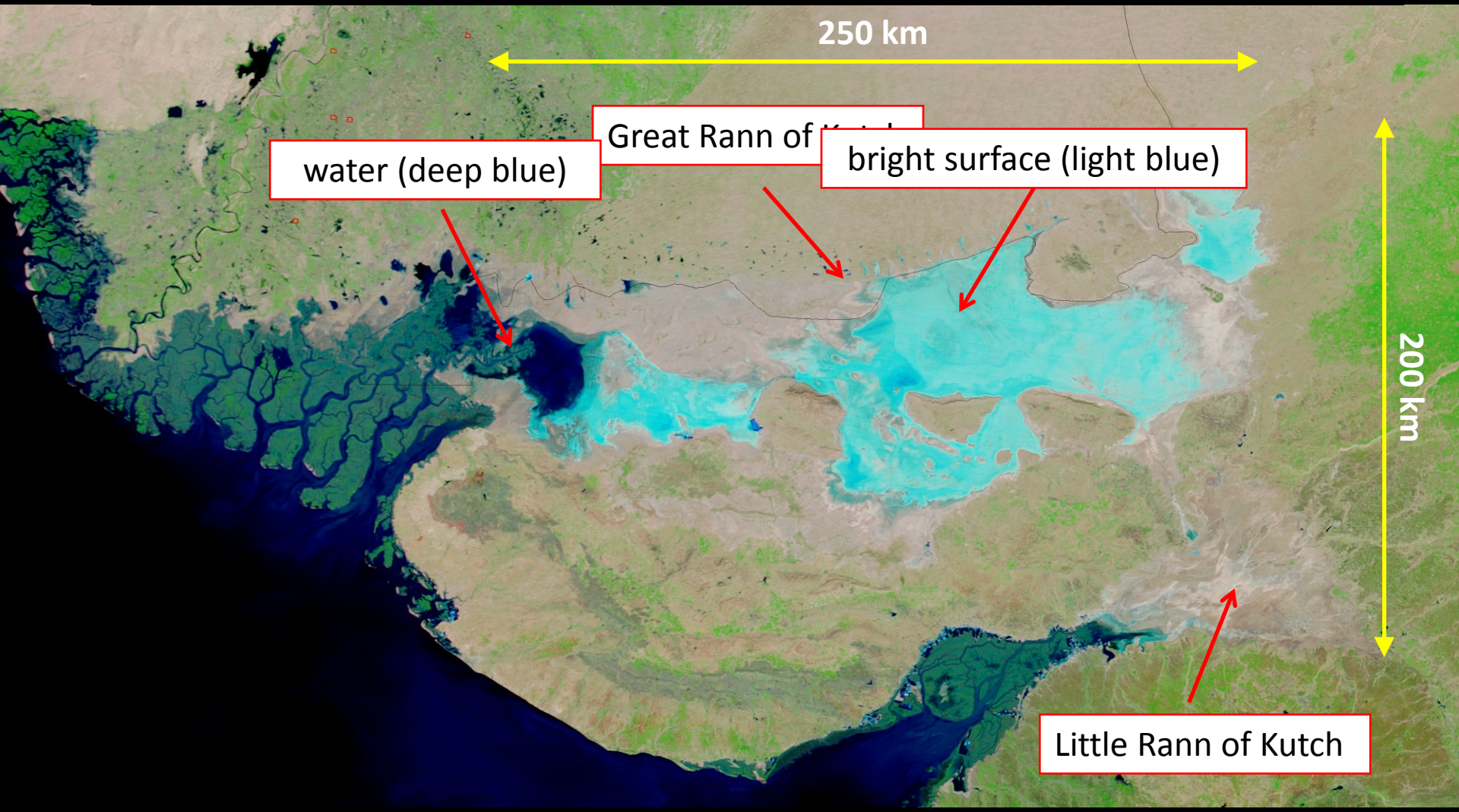


Seasonal „salt marsh“, largest salt desert in the world (>30.000 km², same size as Belgium)

1) During Indian summer monsoon, the salt marsh is filled by rain and/or tidal sea water (only 15m a.s.l.)

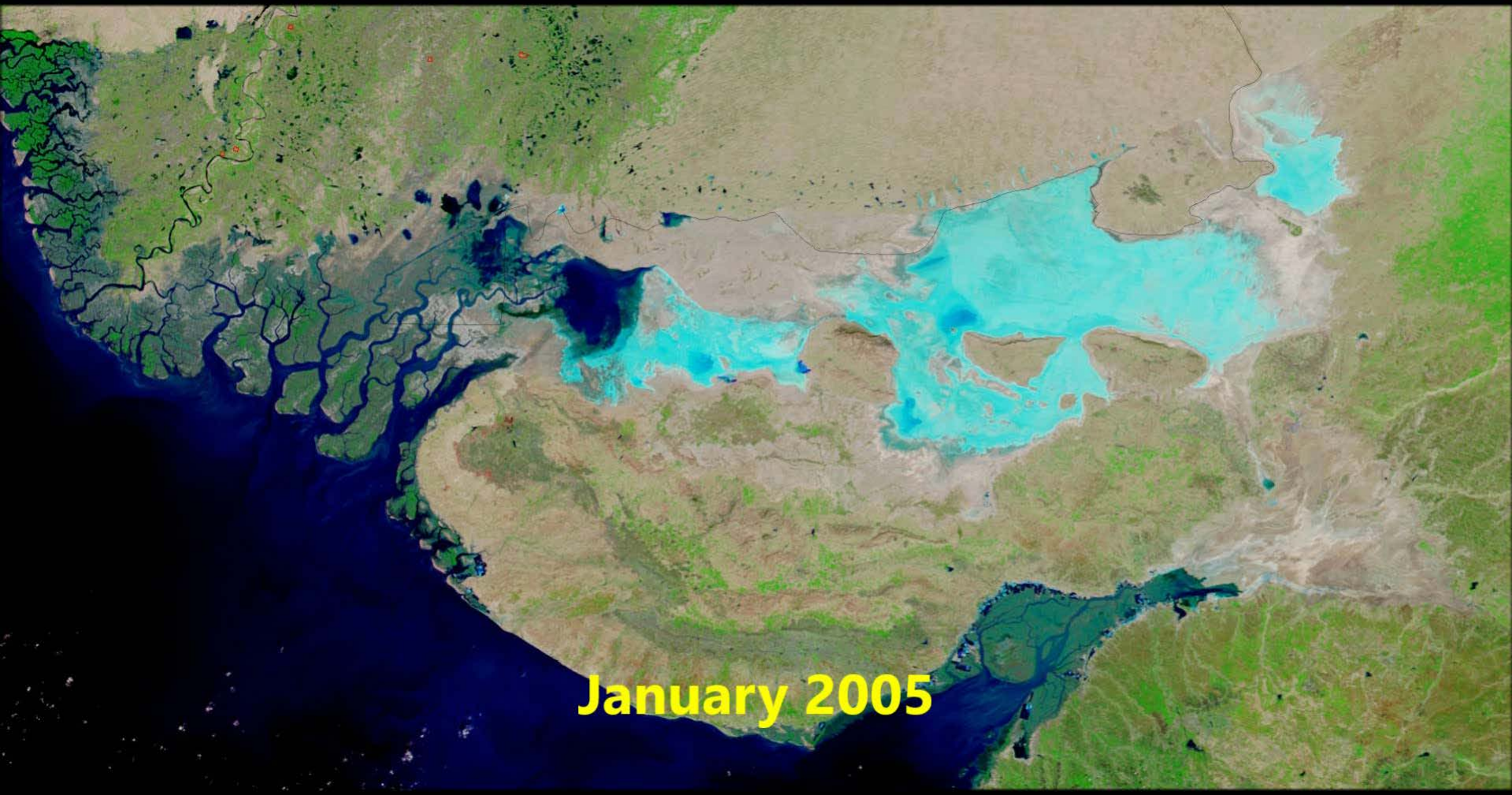
2) After the monsoon, water dries up and leaves a salt desert (→ one of the hottest areas in India, up to 50°C in summer!)

Rann of Kutch



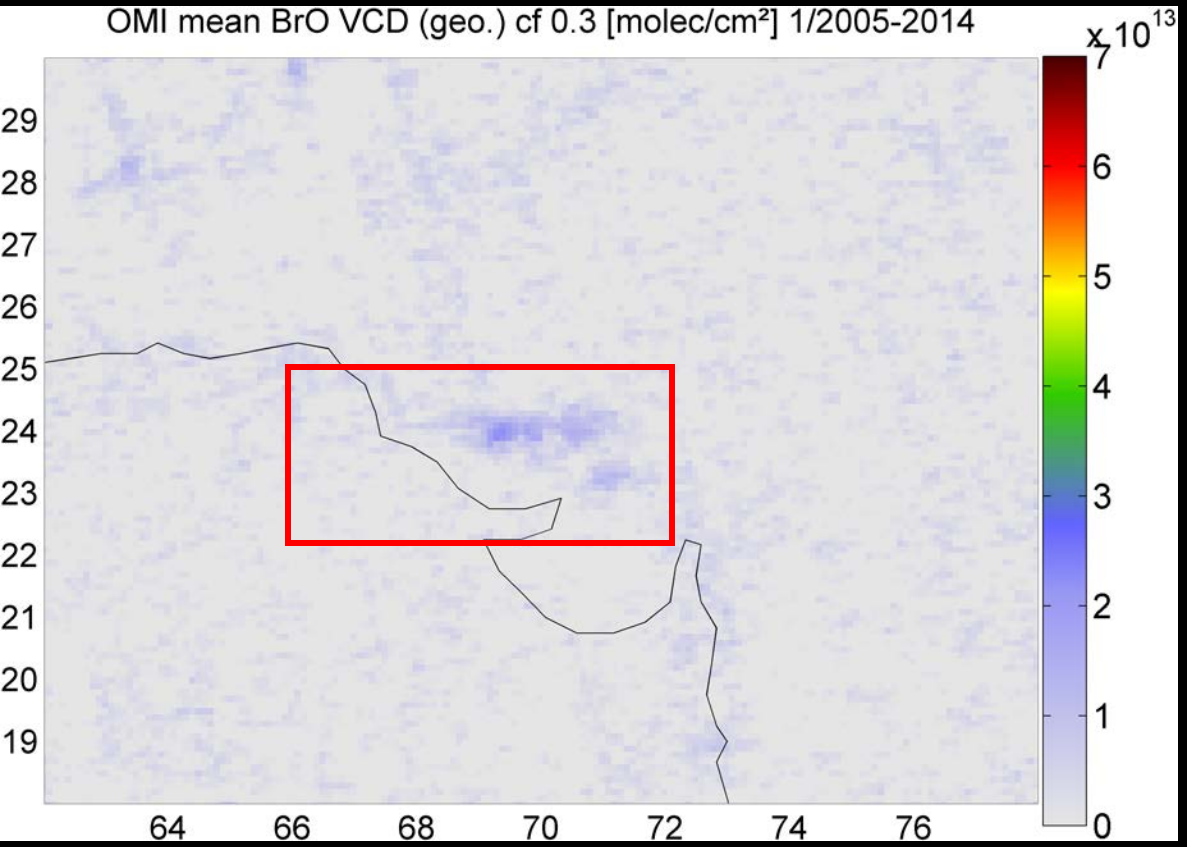
MODIS 7-2-1 January, 12 2005

Seasonal flood



Daily MODIS pictures provided by NASA EOSDIS Rapid Response

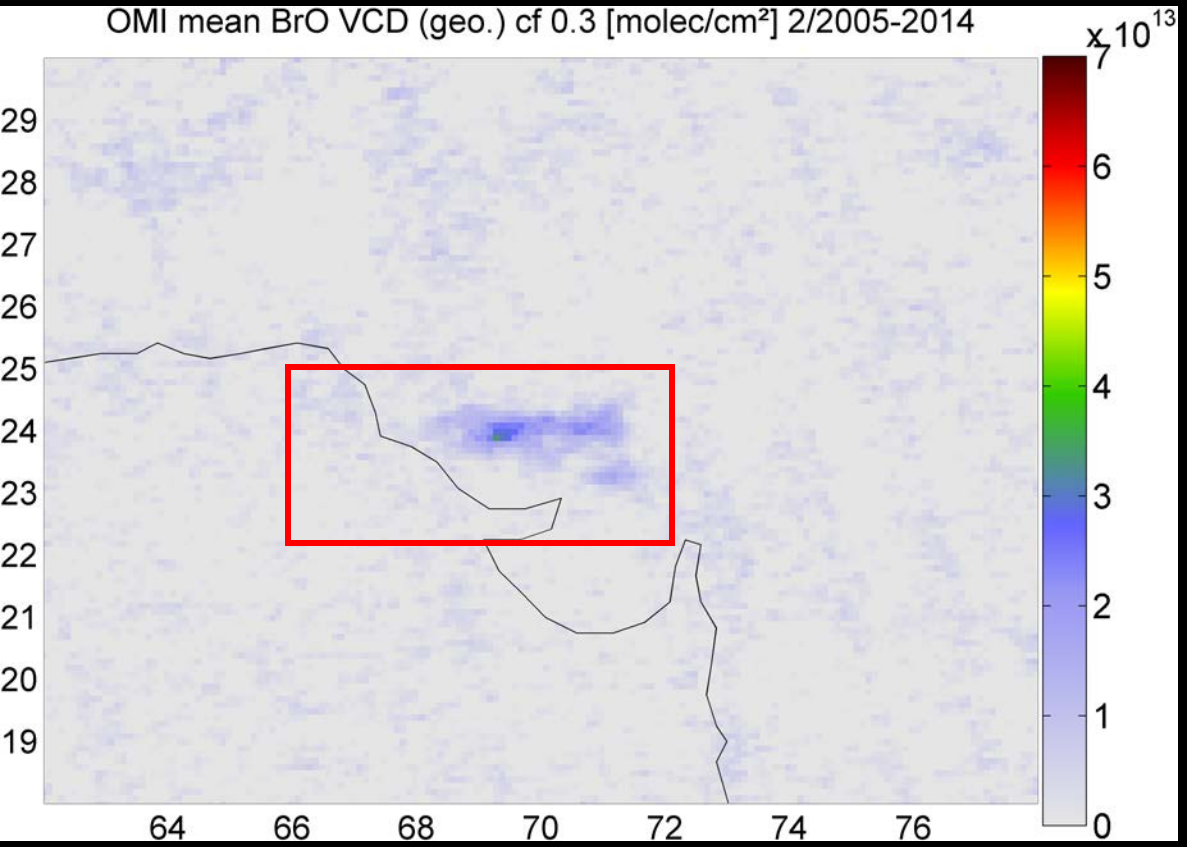
Monthly BrO VCDs

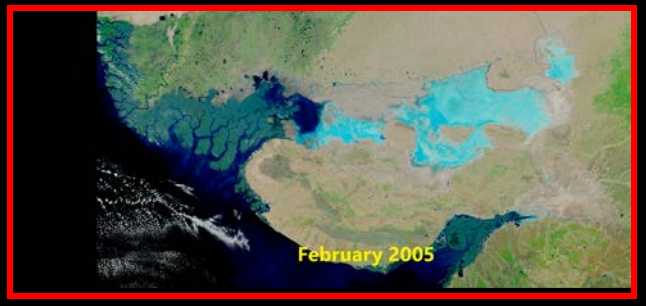


BrO VCD [molec/cm²]

January 2005-2014

Monthly BrO VCDs

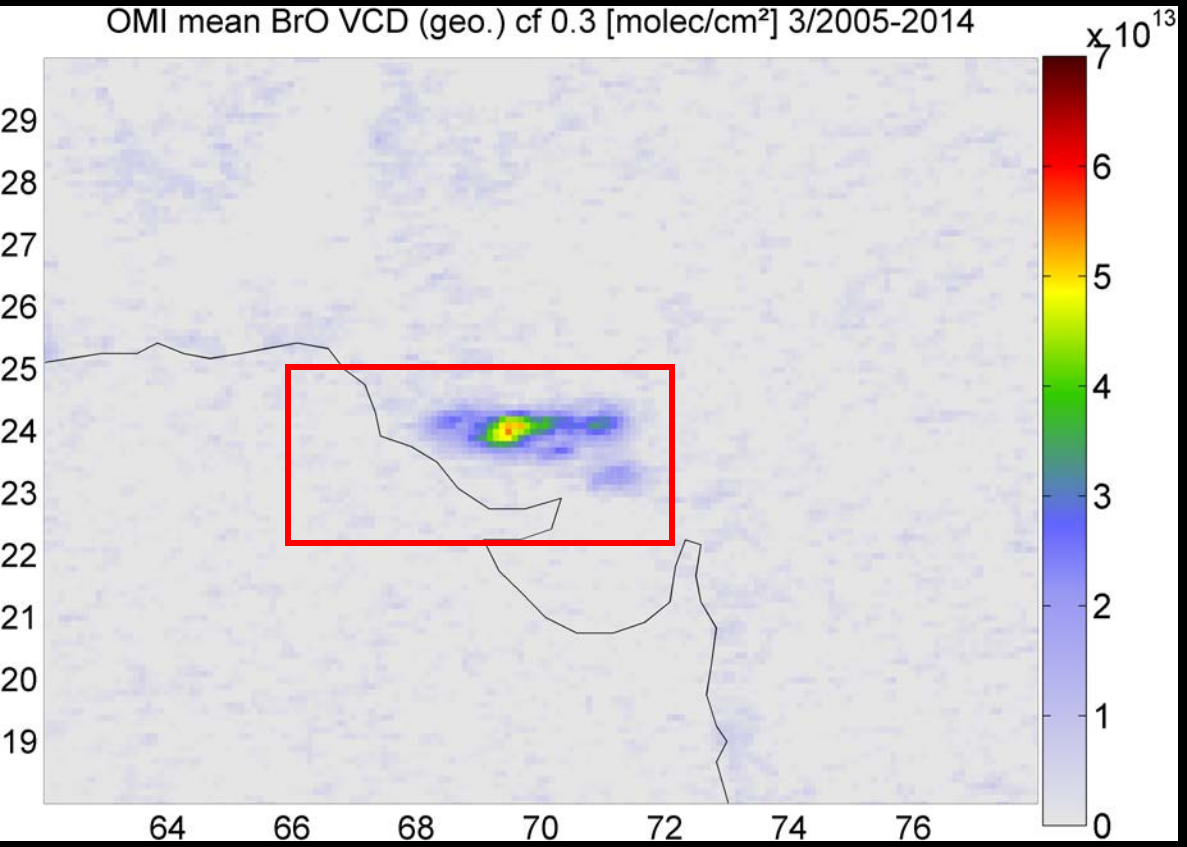


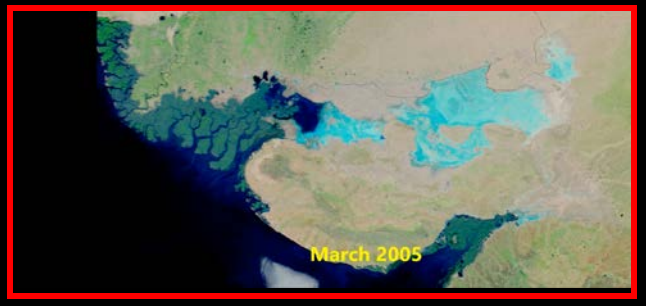


BrO VCD [molec/cm²]

February 2005-2014

Monthly BrO VCDs

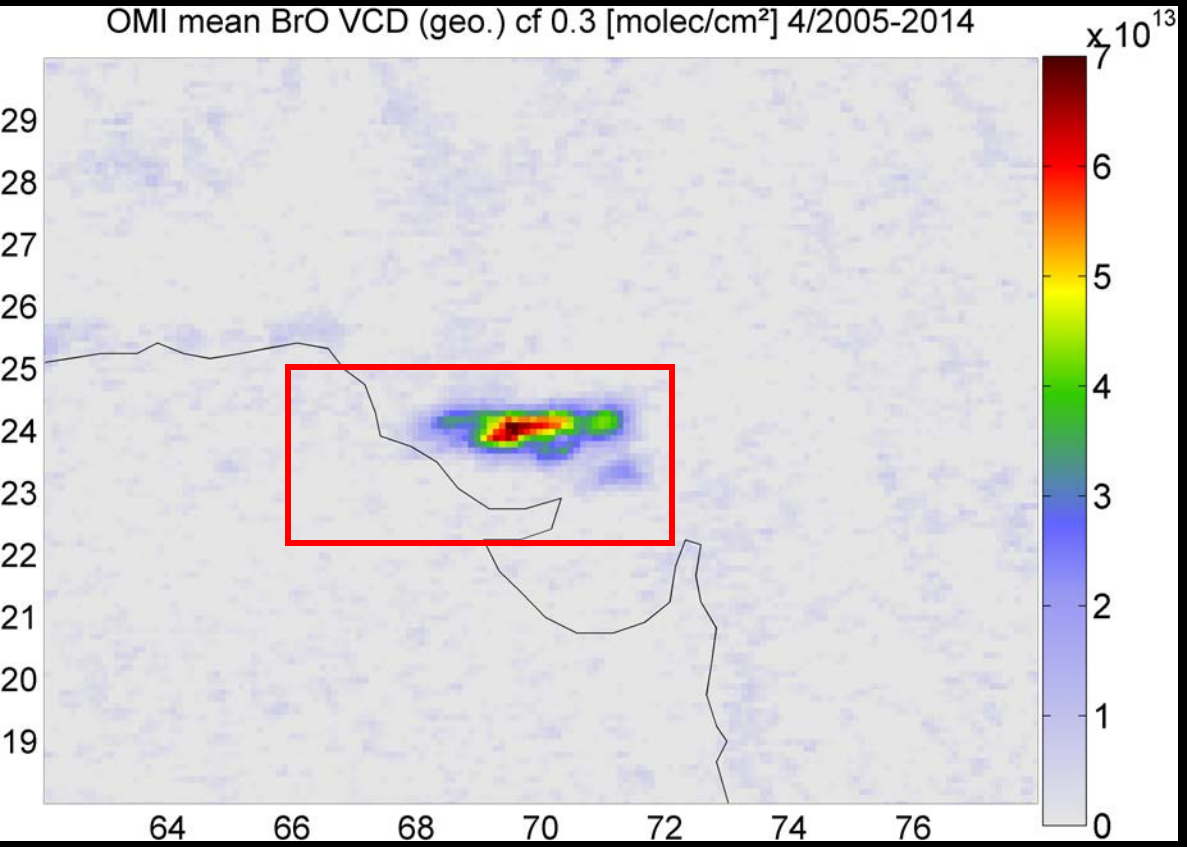


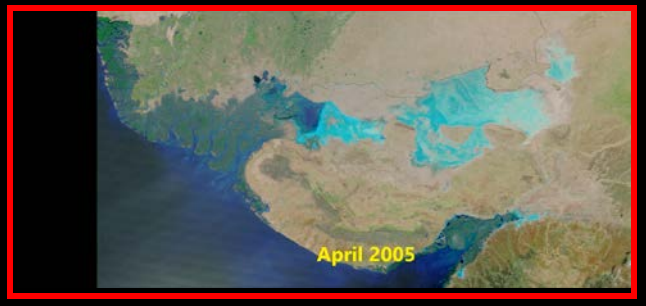


BrO VCD [molec/cm²]

March 2005-2014

Monthly BrO VCDs

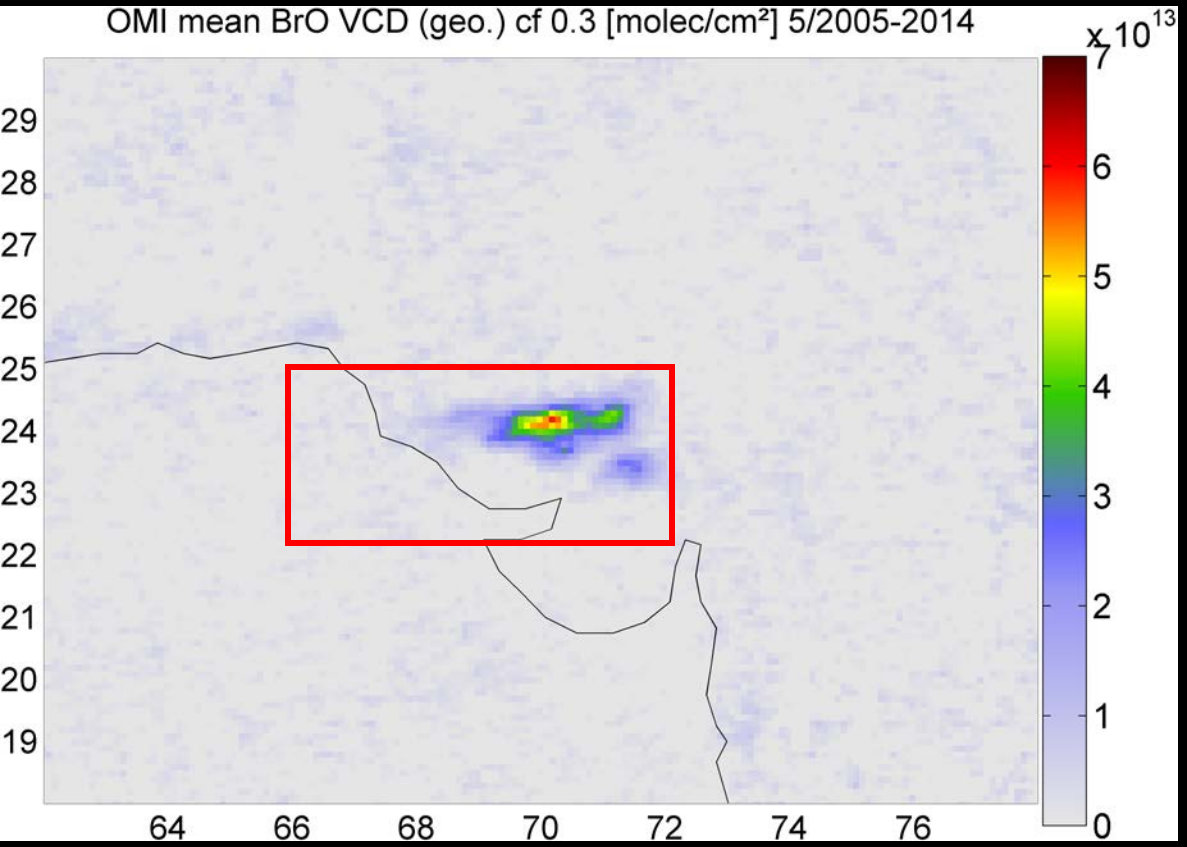




BrO VCD [molec/cm²]

April 2005-2014

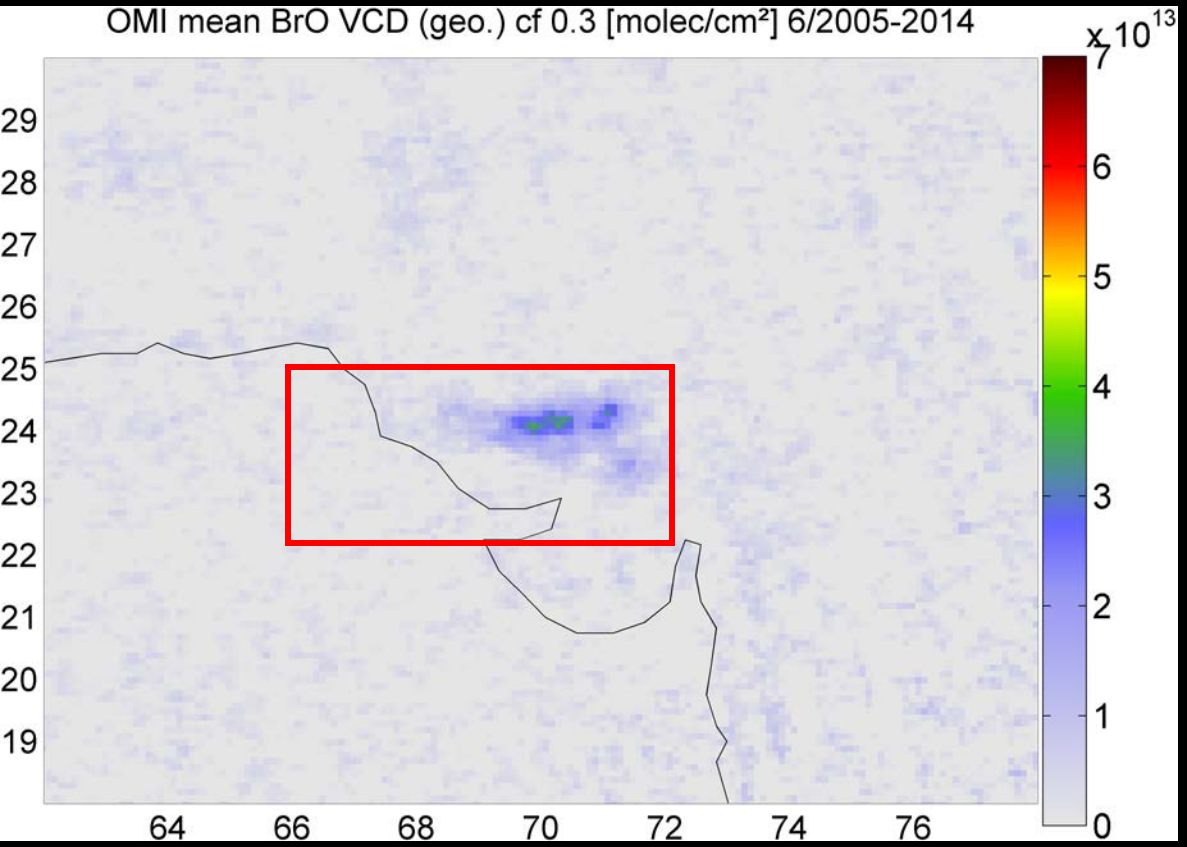
Monthly BrO VCDs



BrO VCD [molec/cm²]

May 2005-2014

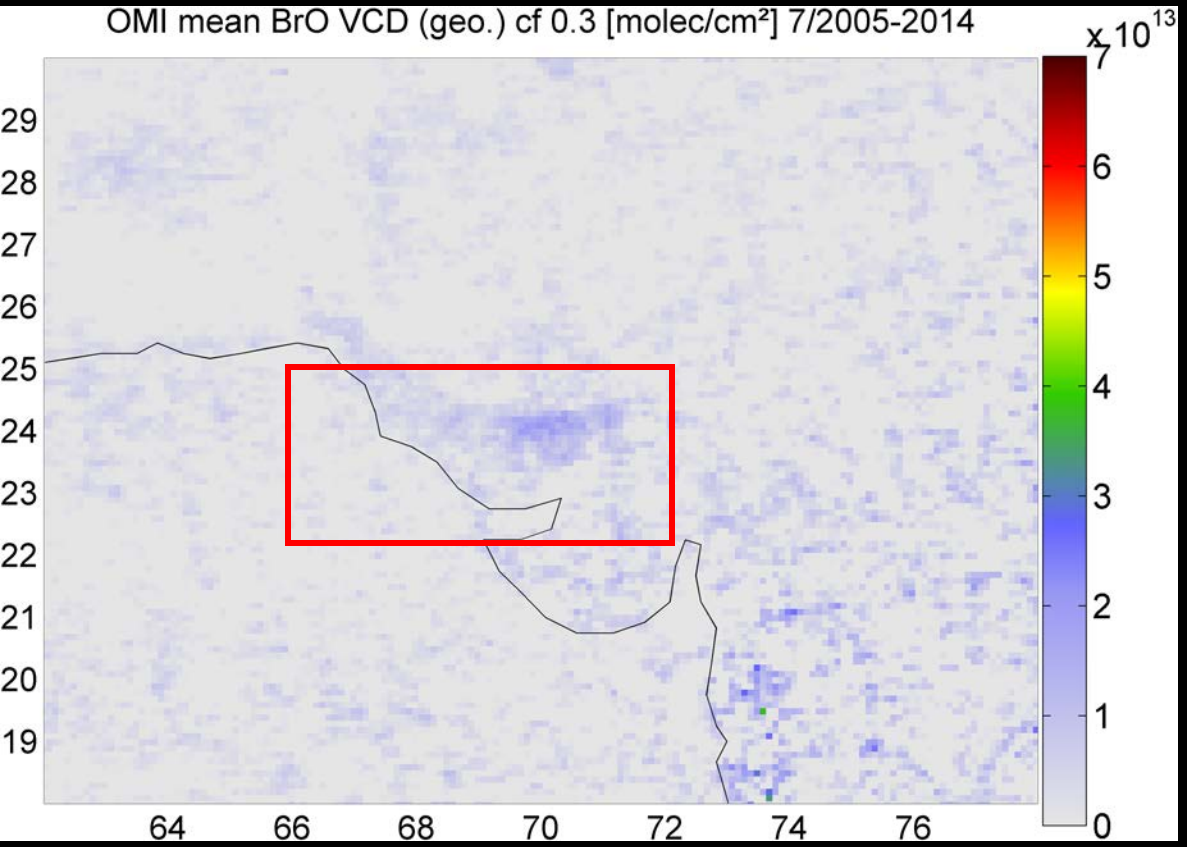
Monthly BrO VCDs

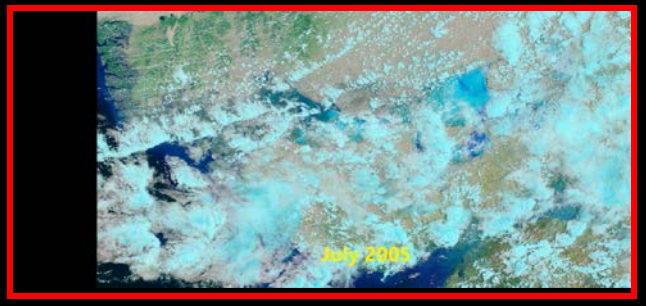


BrO VCD [molec/cm²]

June 2005-2014

Monthly BrO VCDs

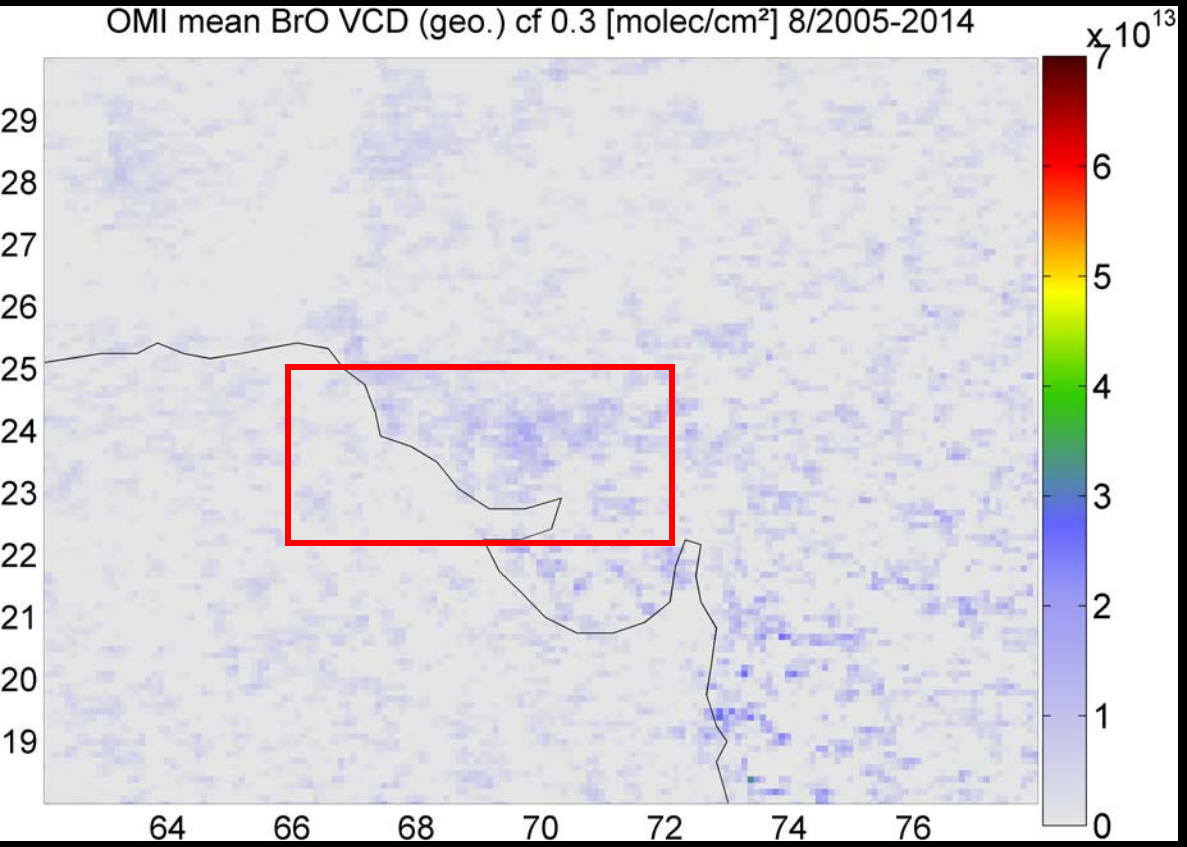


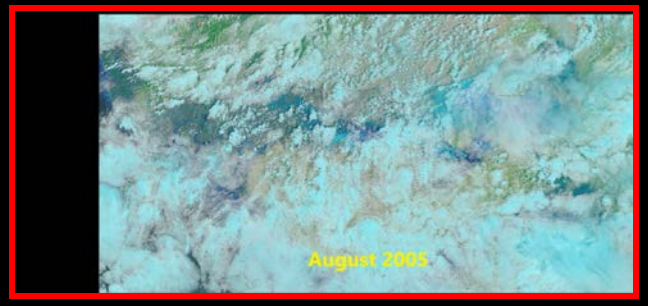


BrO VCD [molec/cm²]

July 2005-2014

Monthly BrO VCDs

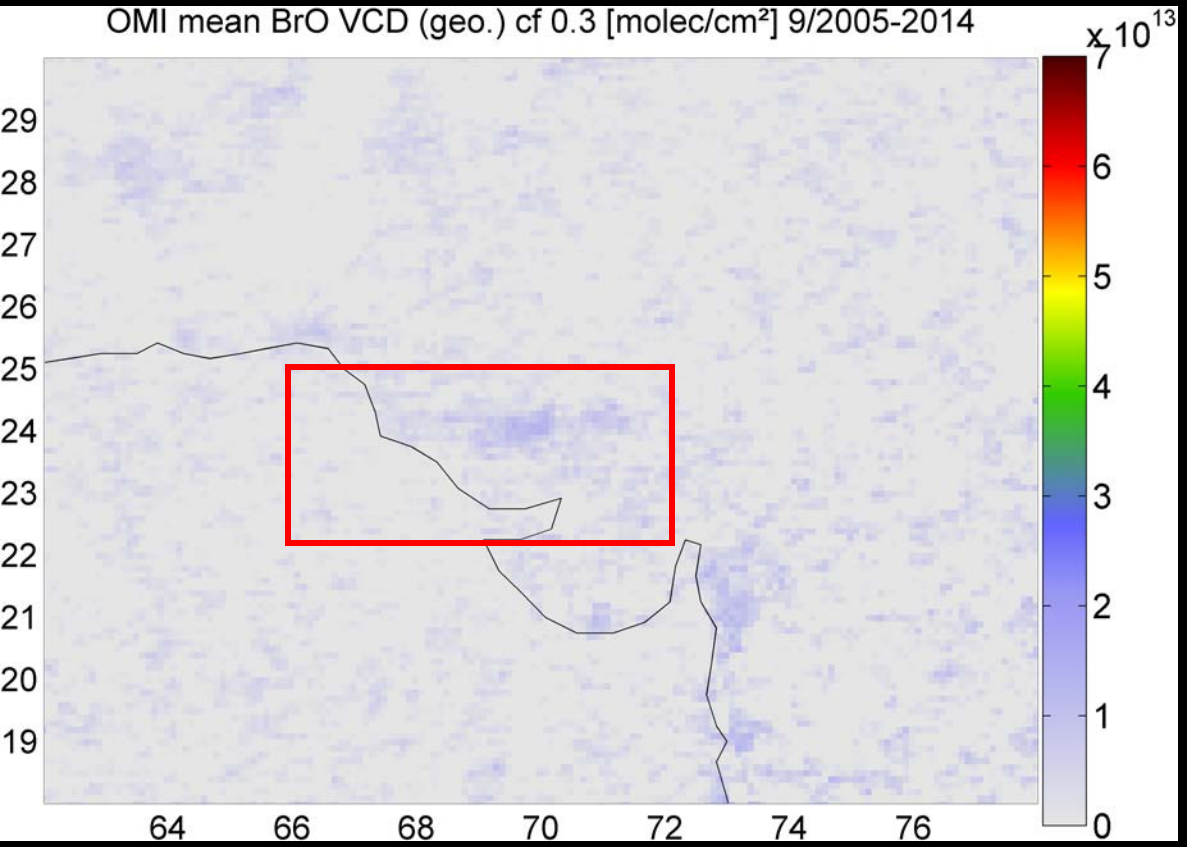


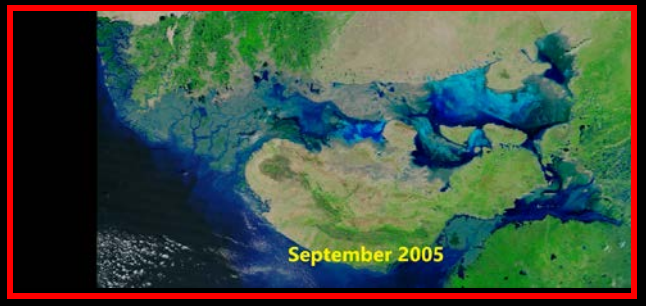


BrO VCD [molec/cm²]

August 2005-2014

Monthly BrO VCDs

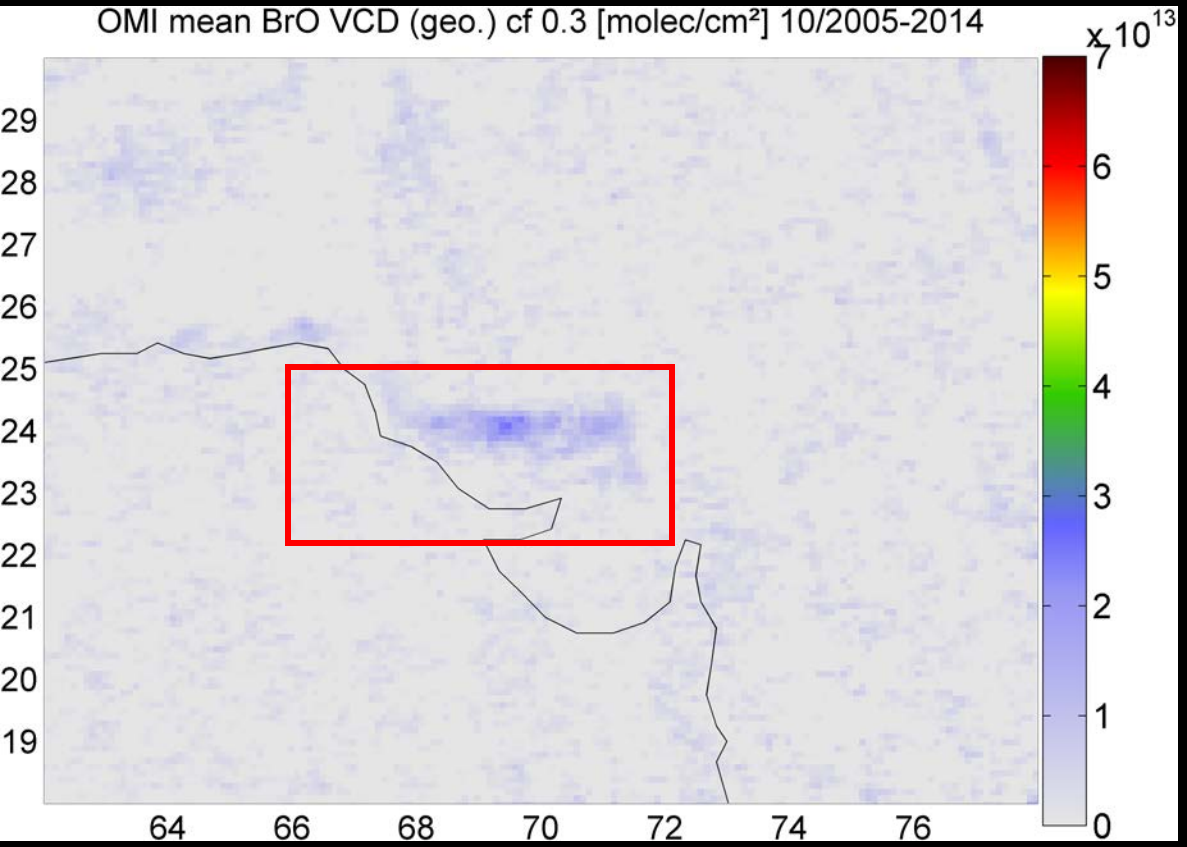


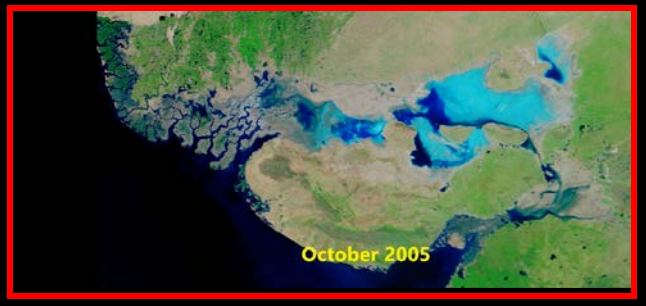


BrO VCD [molec/cm²]

September 2005-2014

Monthly BrO VCDs

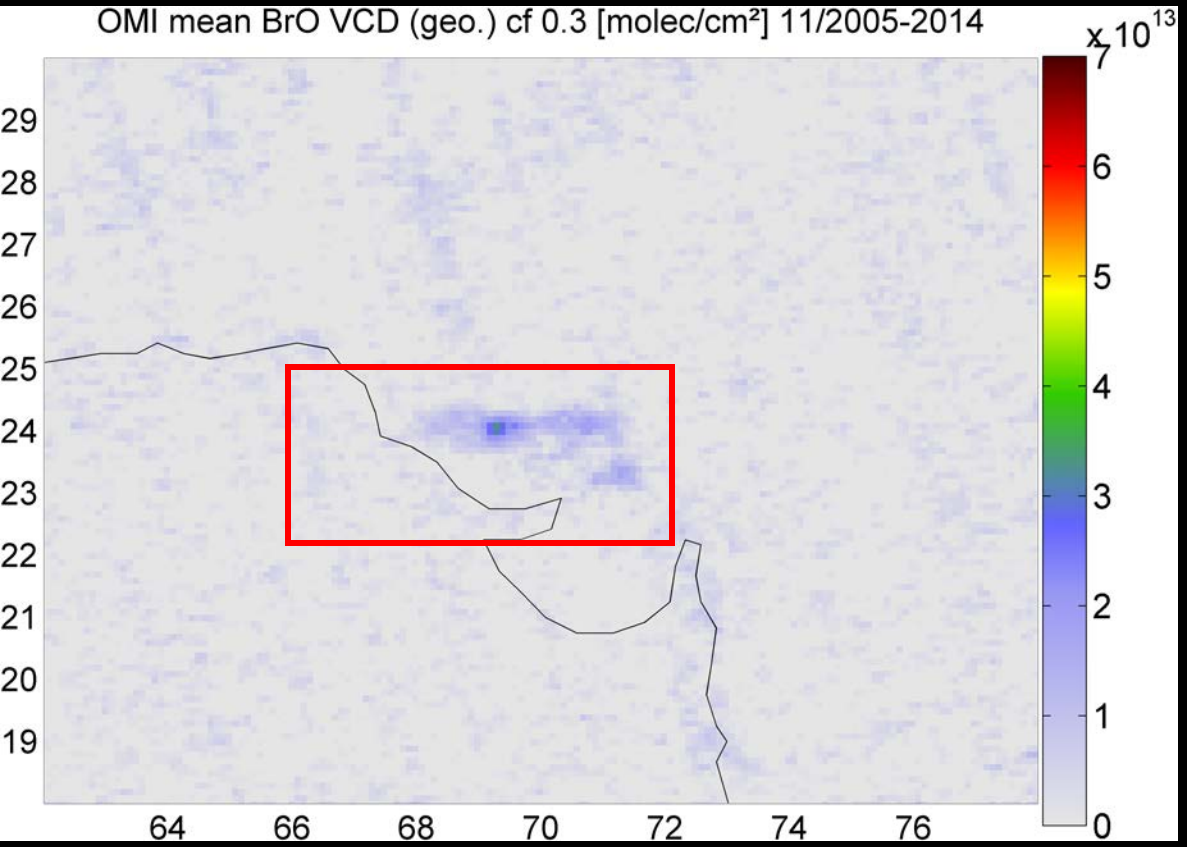




BrO VCD [molec/cm²]

October 2005-2014

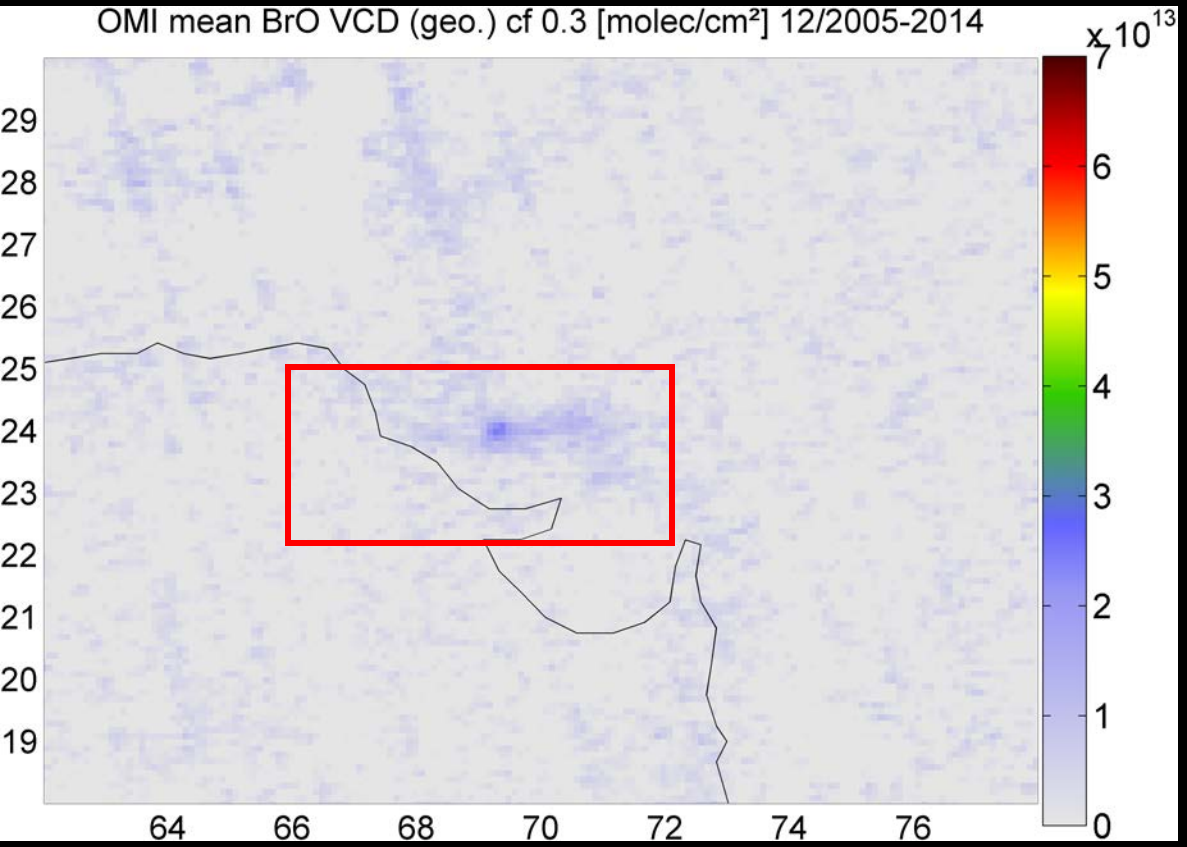
Monthly BrO VCDs

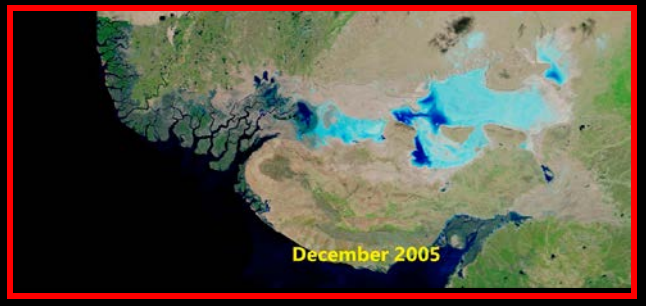


BrO VCD [molec/cm²]

November 2005-2014

Monthly BrO VCDs





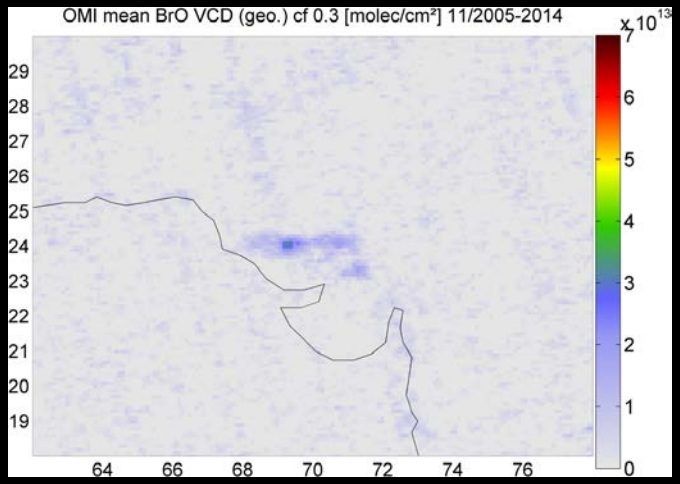
BrO VCD [molec/cm²]

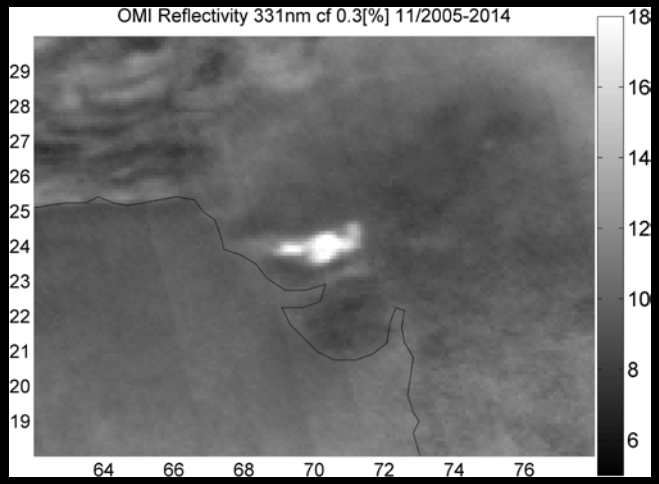
December 2005-2014

BrO VCDs vs. Reflectivity

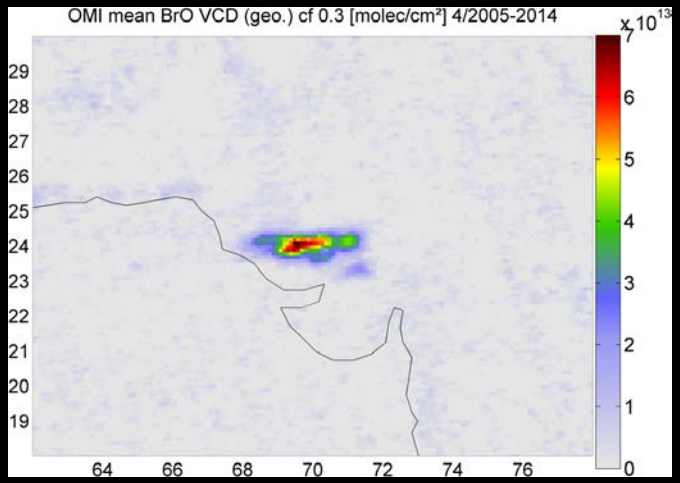
BrO VCD [molec/cm²] **Reflectivity@331nm [%]**

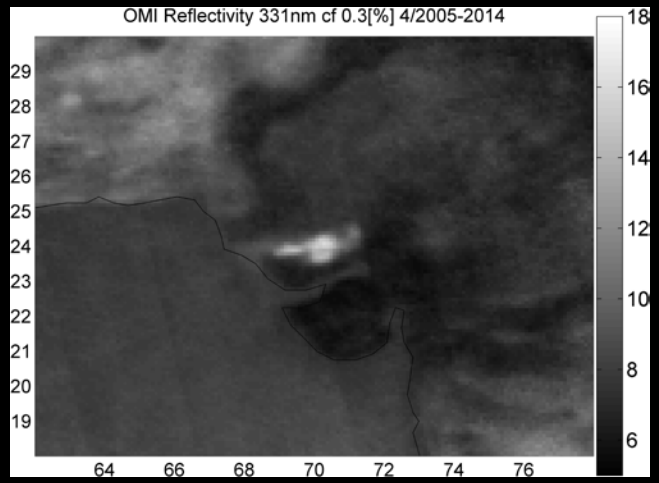
November 2005-2014





April 2005-2014





After monsoon season, the Rann shows maximum reflectivity

→ But only slightly enhanced BrO VCDs

Monthly mean BrO

- Daily measurements are corrected for stratospheric background (2D poly.) and averaged on a 0.1 x 0.1° regular grid

- Cloud filter (NASA OMCLDRR L2 product)
  → all measurements with an effective cloud fraction > 30% are skipped

- AMF calculation at 338.5nm using McArtim (Deutschmann et al. ,2011)

  → Model runs for homogeneous BrO layer (0-400m, **0-1km**, 0-2km):

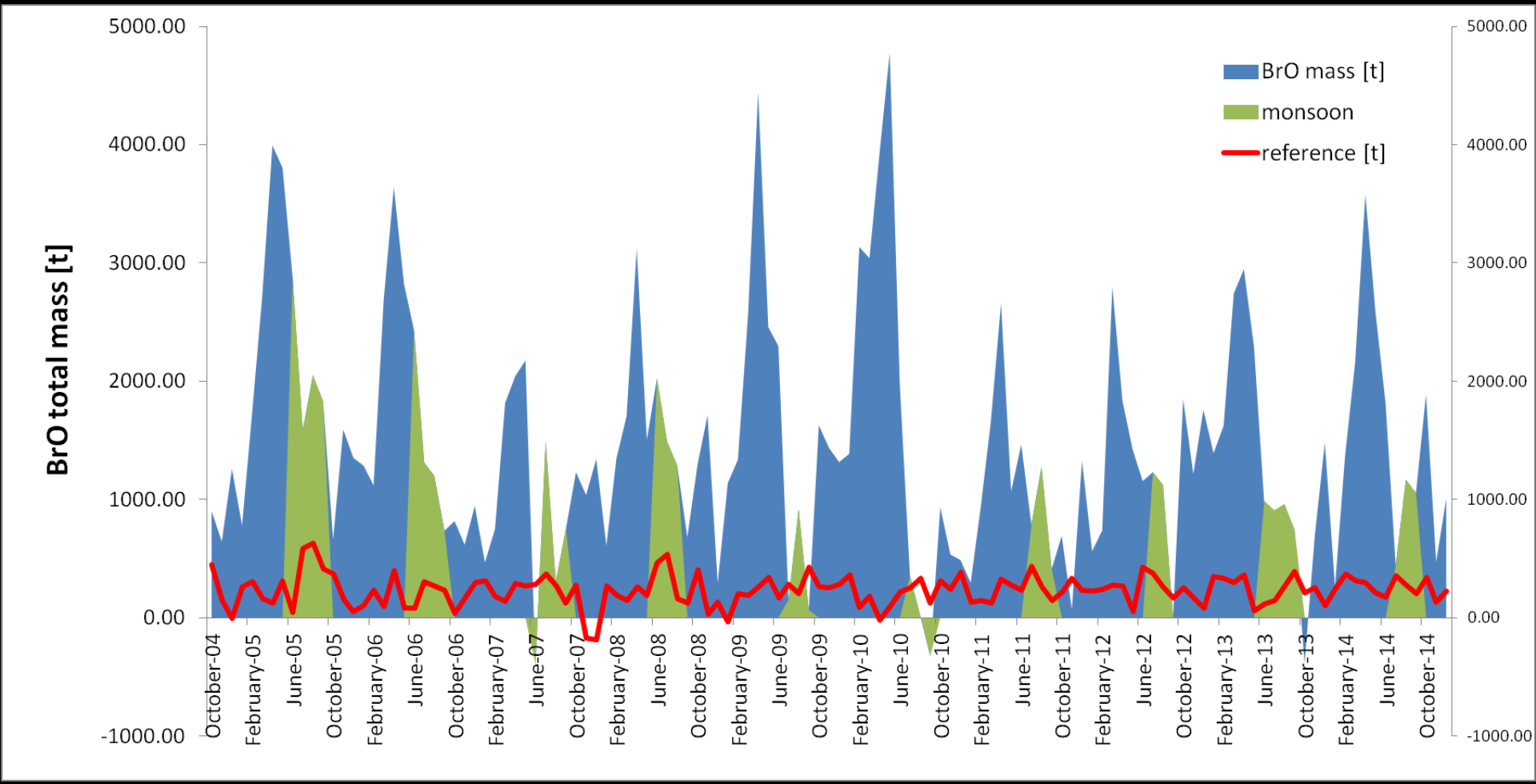
  1) No additional aerosols
     - surface albedo 10, **15**, 20 %

  2) Additional aerosol layer:
     - homogeneous (0-1km)
     - single scattering albedo: 0.9
     - asymmetry parameter: 0.72
     - varying AOD (0.4, **0.7**, 1)
     - surface albedo 10, 15, 20 %

  baseline values based on monthly averaged NASA OMAEROG aerosol product and reflectivity @331nm (OMSO2)

  → Large uncertainty due to unknown profile/albedo (about factor of 2)

Timeseries total BrO mass



1) Maximum BrO masses in April/May → minimum during monsoon season/shield effect ?
2) After monsoon: slightly enhanced BrO VCDs, local minimum in winter

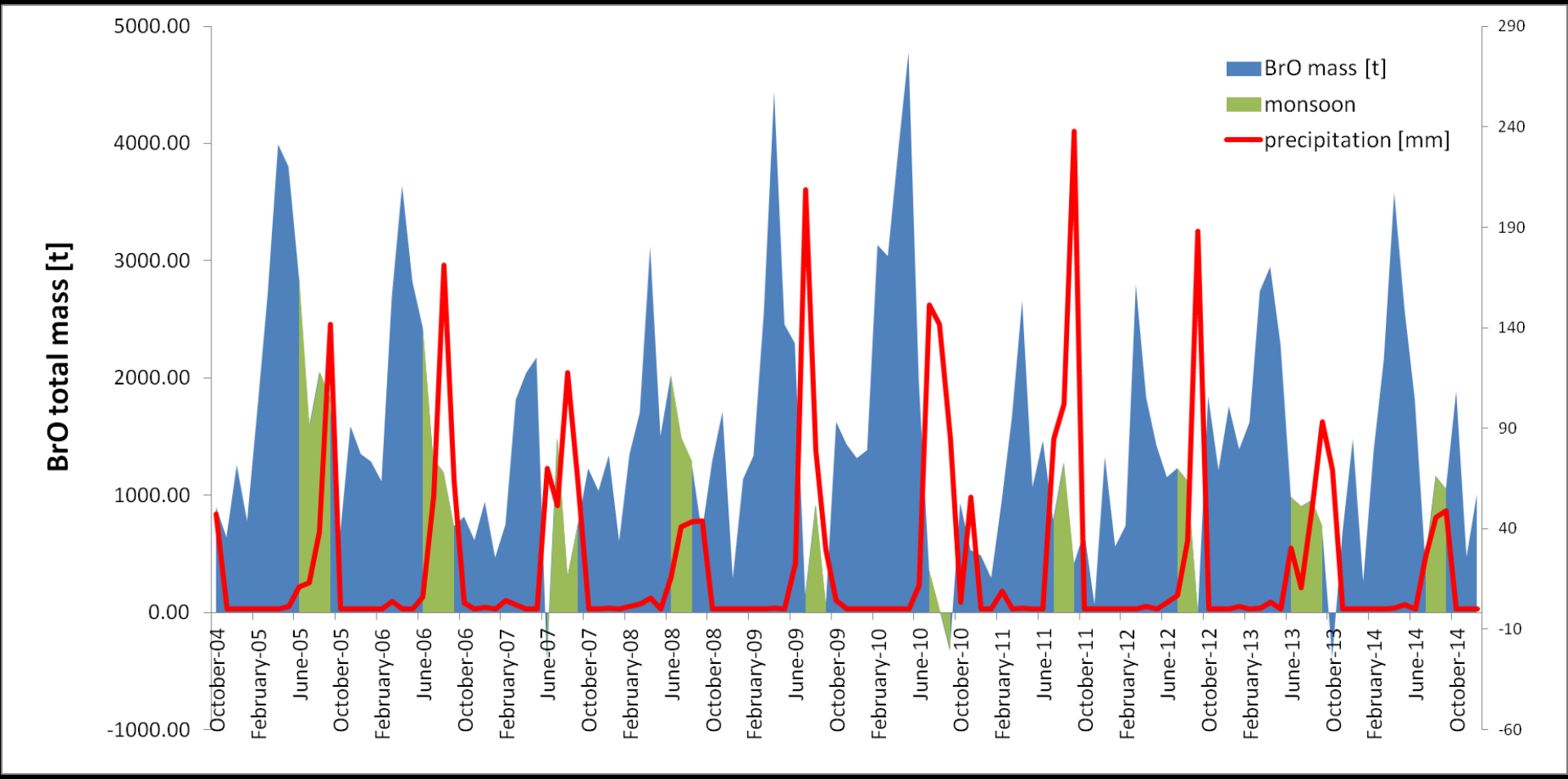
Correlation to meteorological data

Use ECMWF model data (incl. measurements)

Monthly mean values for central region over Great Rann of Kutch (1x1°, 9UTC) of:

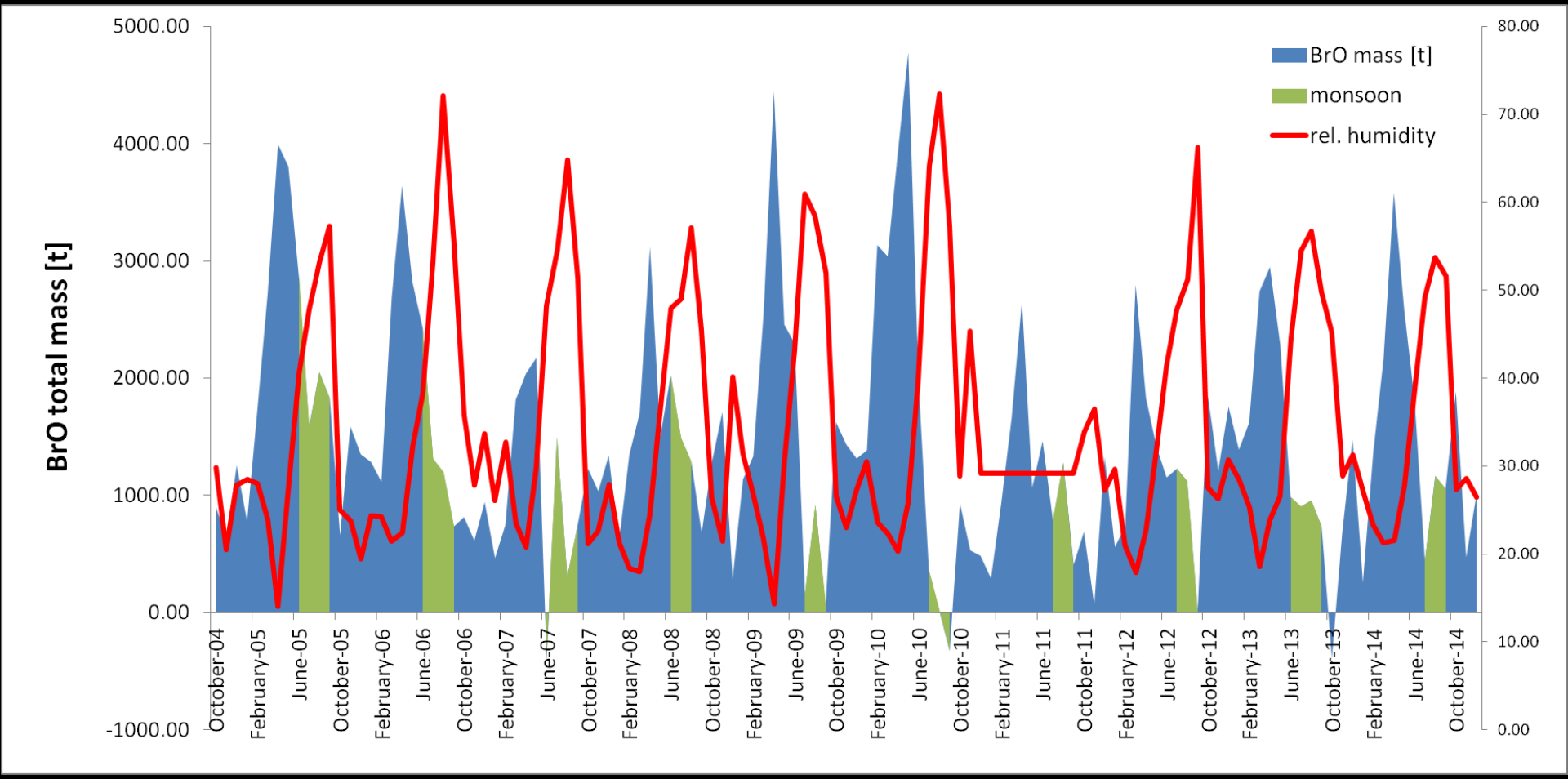
- precipitation
- relative humidity
- UV radiation
- temperature
- boundary layer height

BrO mass vs. precipitation



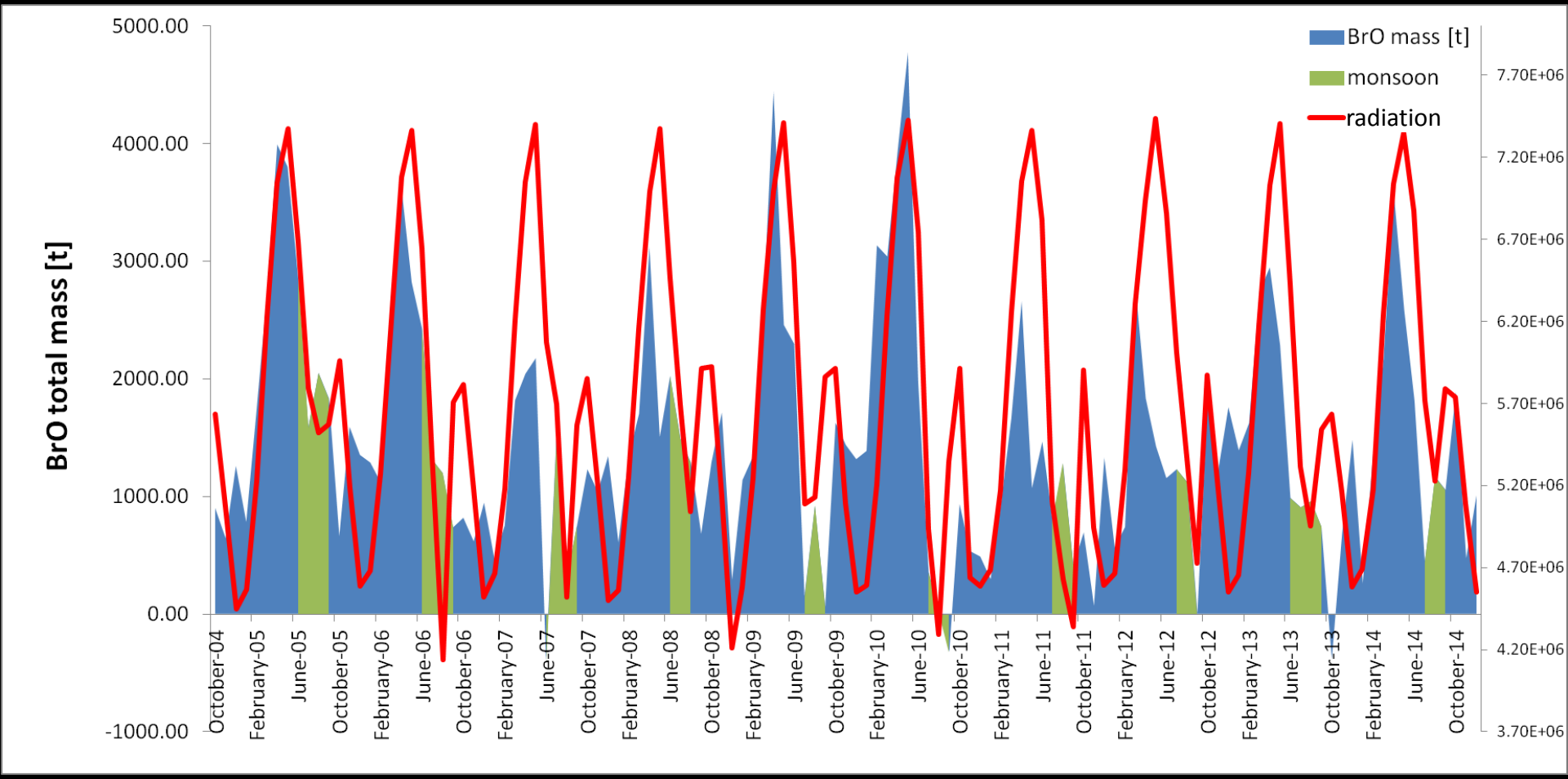
1) Heavy rain during monsoon season (July – September)
2) During BrO maximum in April/May only light rain (< 10mm)

BrO mass vs. rel humidity



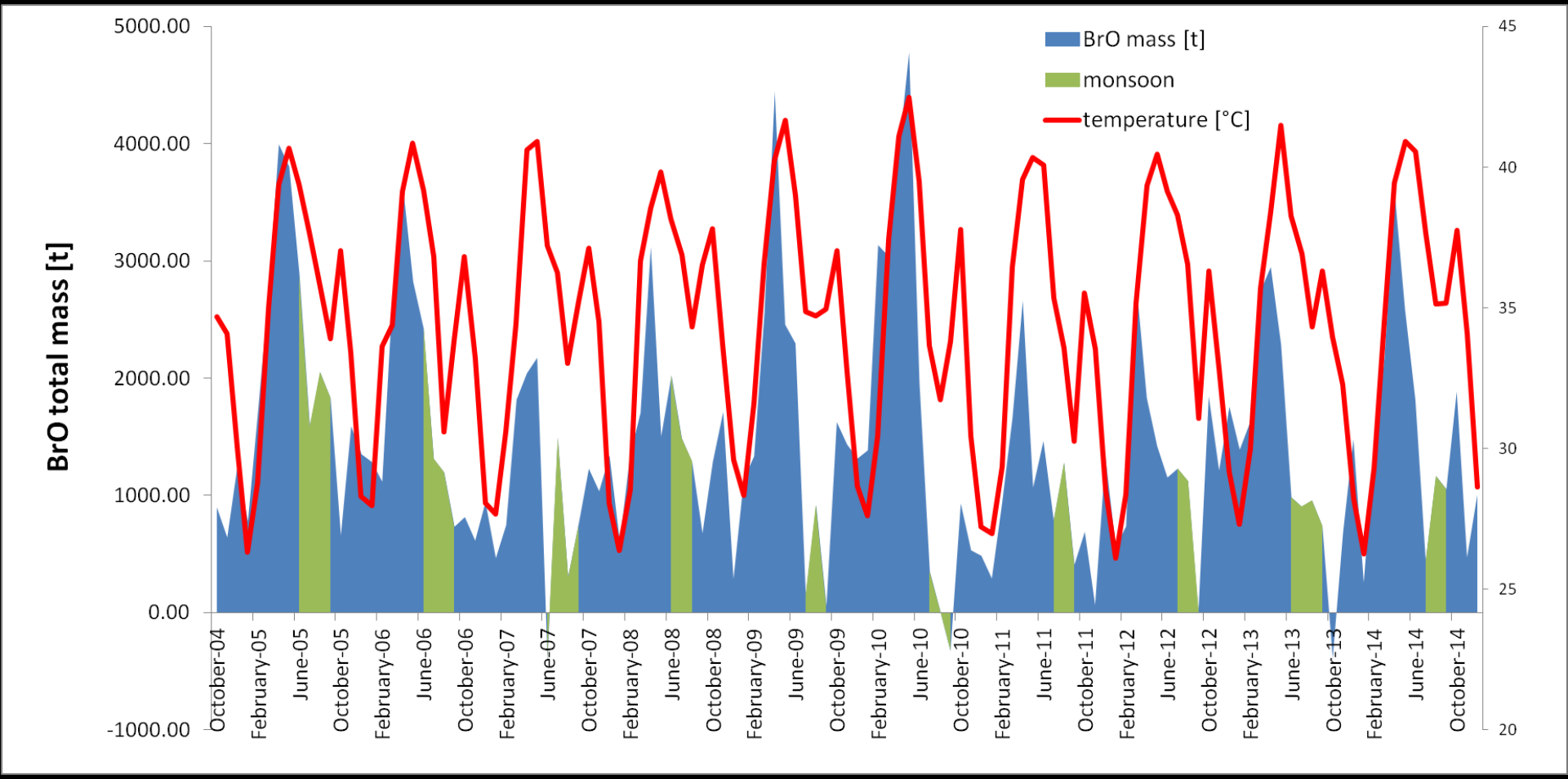
1) Minimum RH corresponds to BrO maximum (< 25%)
2) Maximum RH during monsoon

BrO mass vs. UV radiation



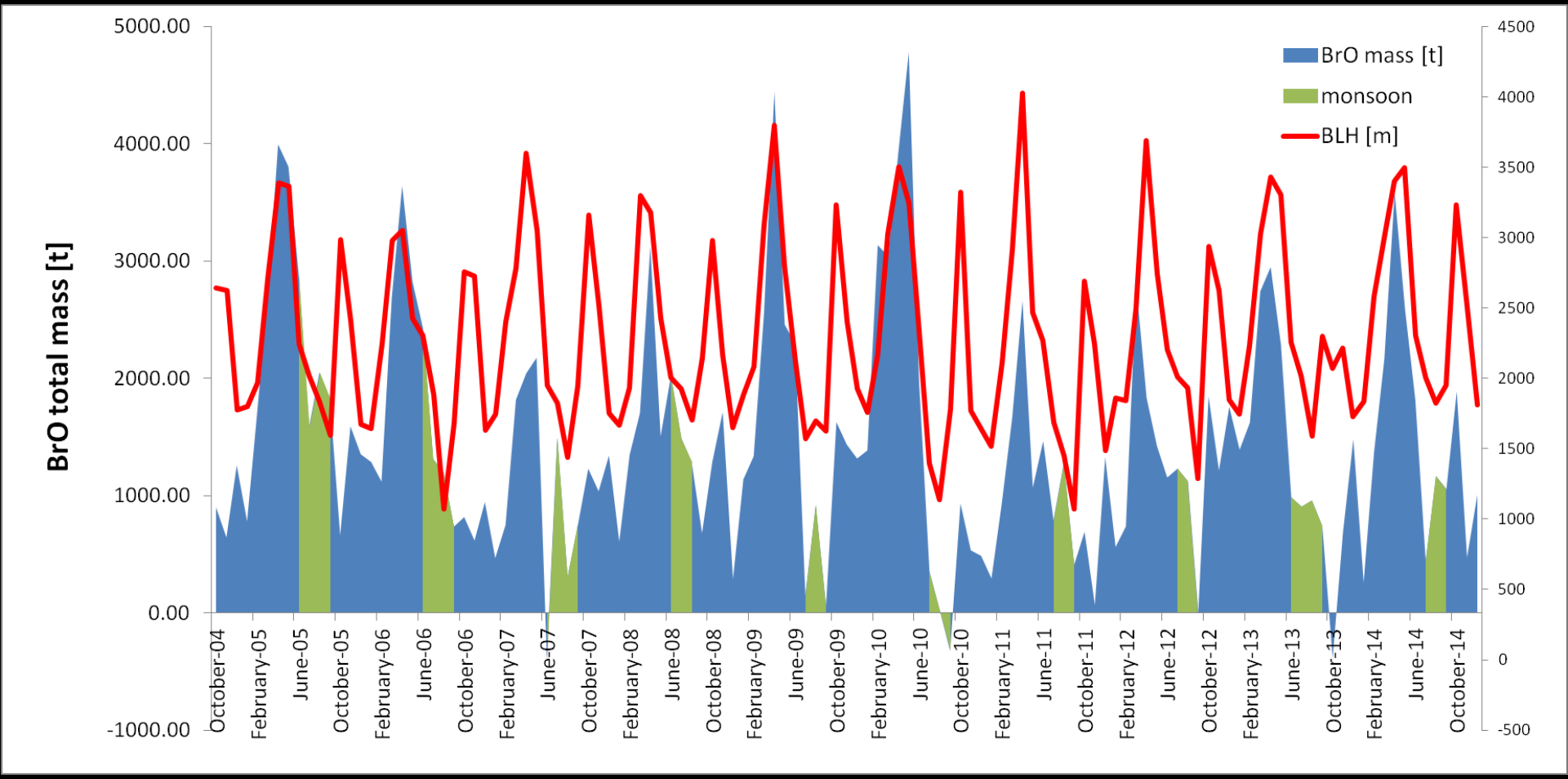
1) Maximal UV radiation corresponds to BrO maximum (April/May)
2) Minimal UV radiation corresponds to local BrO minimum (December/January)
→ similar for temperature (40°C during April/25°C during winter)

BrO mass vs. temperature



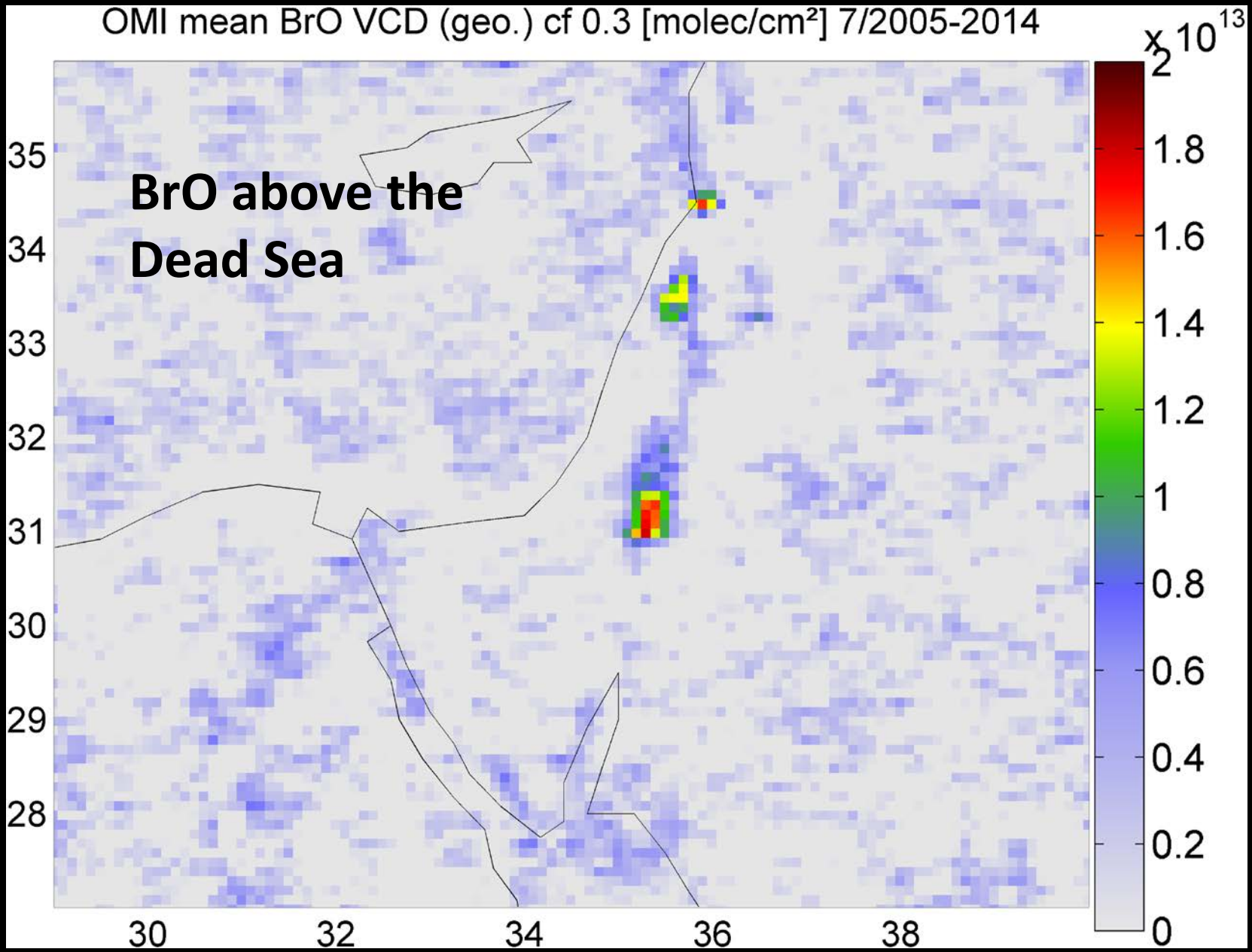
1) Maximum temperature during maximum BrO VCDs (April/May)
2) Minimum temperature during winter (still > 25°C)

BrO mass vs. Boundary layer height

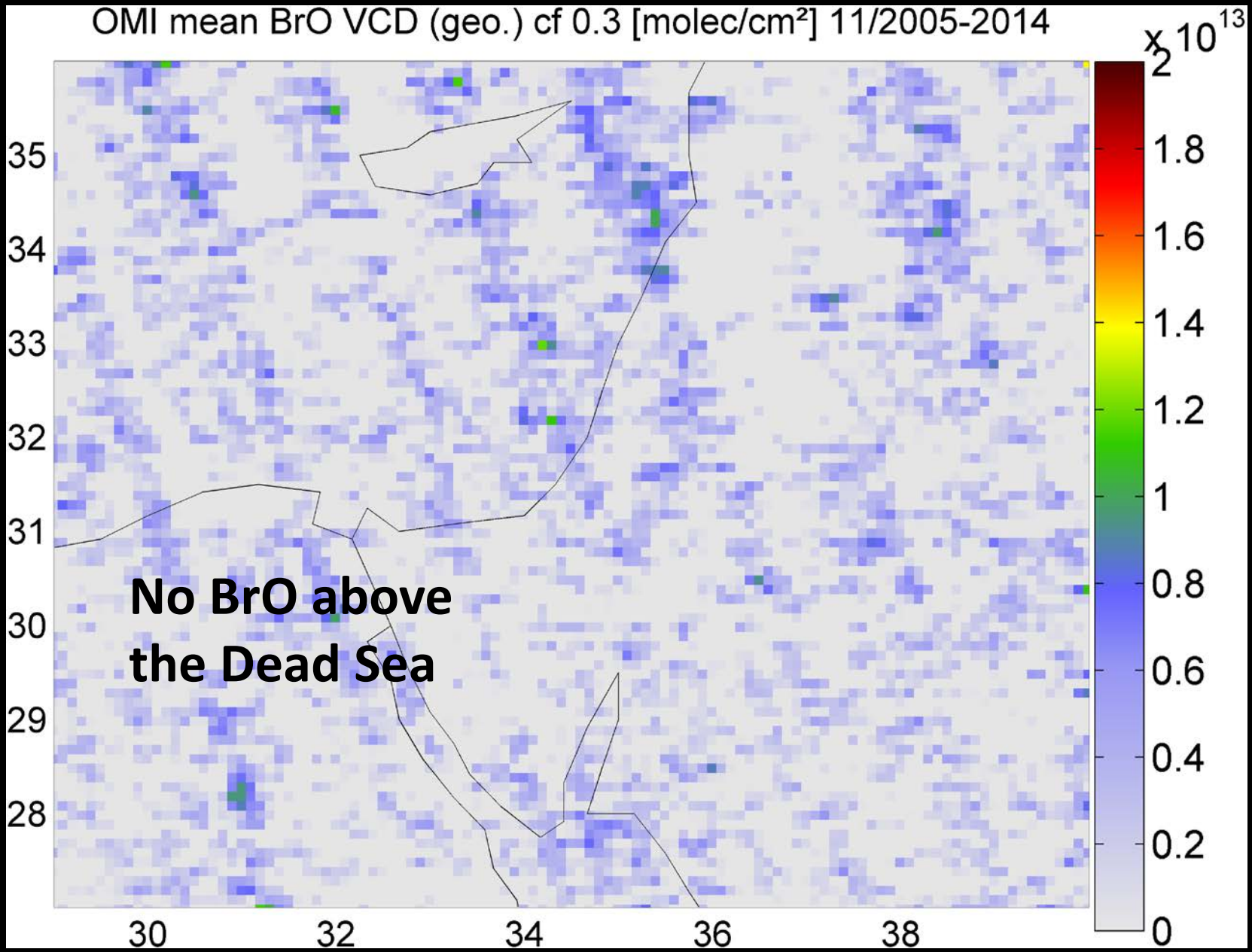


1) Maximal BLH corresponds to BrO maximum (3-3.5km), 2nd maximum after monsoon
2) Minimal BLH during monsoon and winter (December/January)

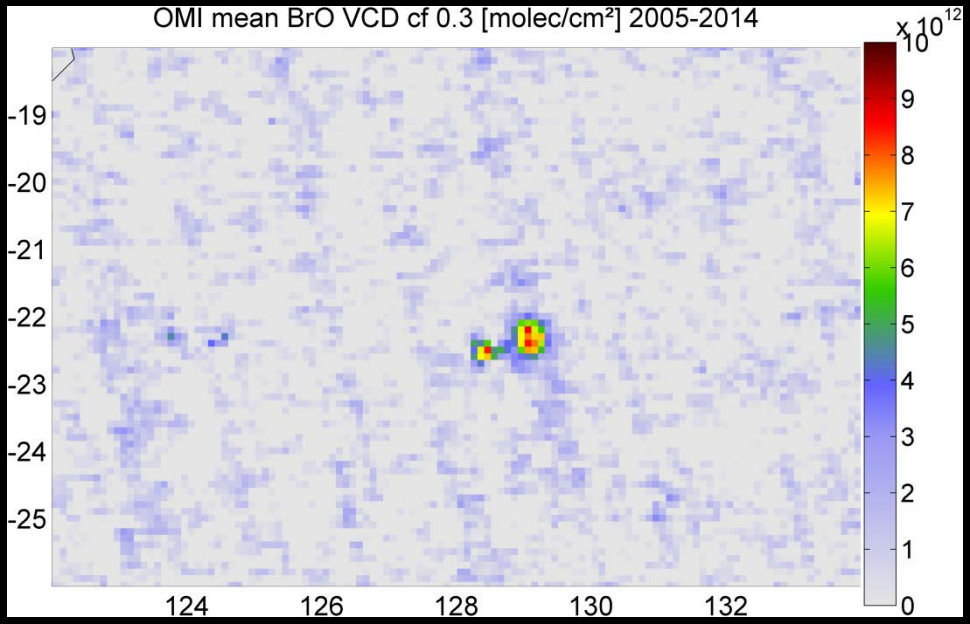
July 2005 - 2014



November 2005 - 2014



BrO over Lake MacKay (Australia)



BrO VCD [molec/cm²]

2005-2014

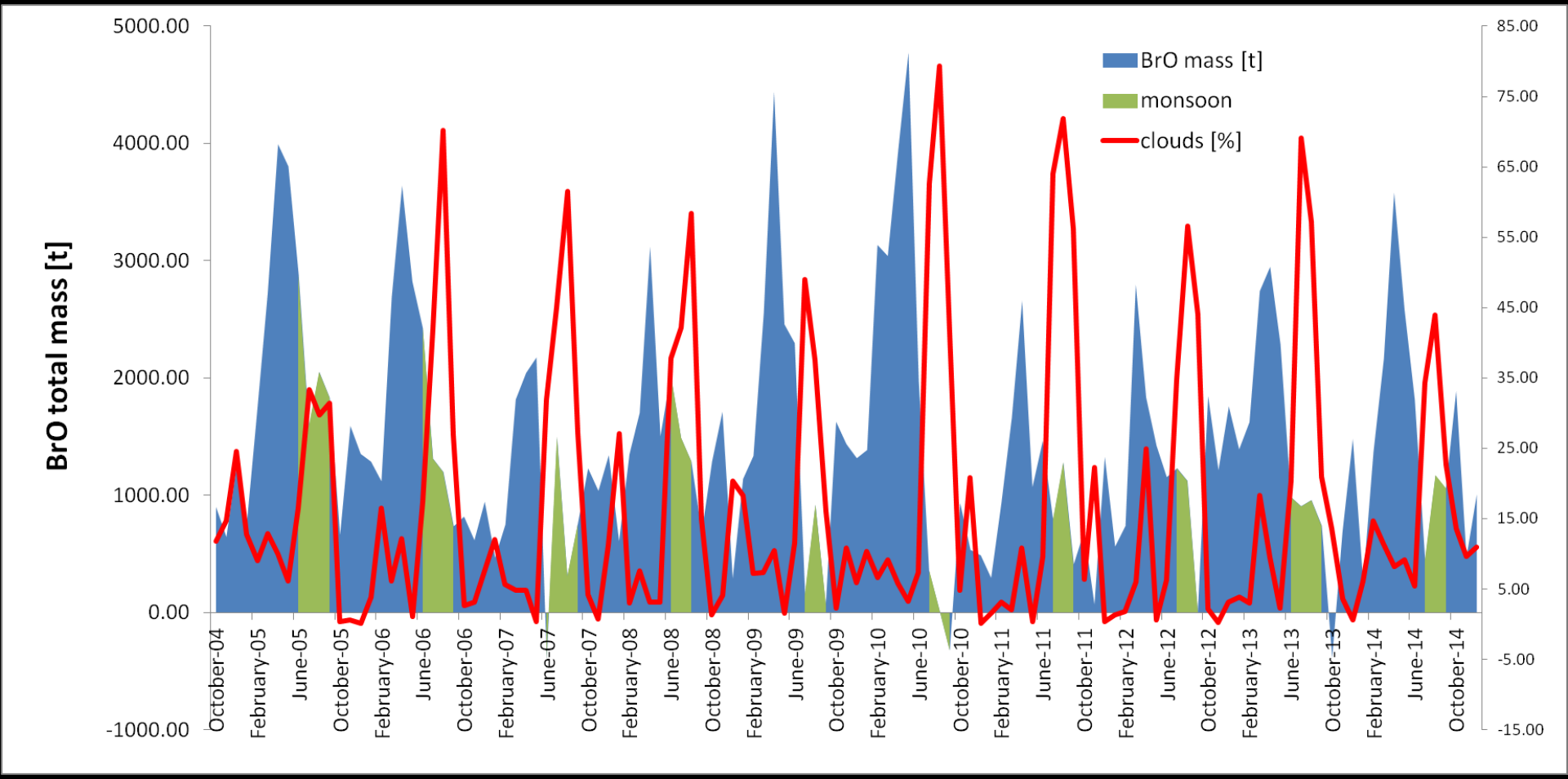
→ Clear BrO VCD enhancement over some parts, but 9x lower than over Rann of Kutch
→ Comparably high reflectivity / possibly only caused by high surface albedo
→ Usually dry, only sporadic rain fall (→standing water)

Conclusions:

- ✓ First satellite detection of BrO over a salt marsh
  (no ground-based measurements yet conducted at Rann of Kutch)
- ✓ Clear seasonal BrO variation (up to 10-40ppt)
  (maximum VCDs during April/May, minimum during monsoon season and winter)
- ✓ Total BrO mass (anti-) correlates to meteorological parameters
  (correlated especially to temperature, BLH and UV radiation)
- ✓ Enhanced BrO also over dead sea and Lake MacKay
  (but factor of 5 to 10 smaller)

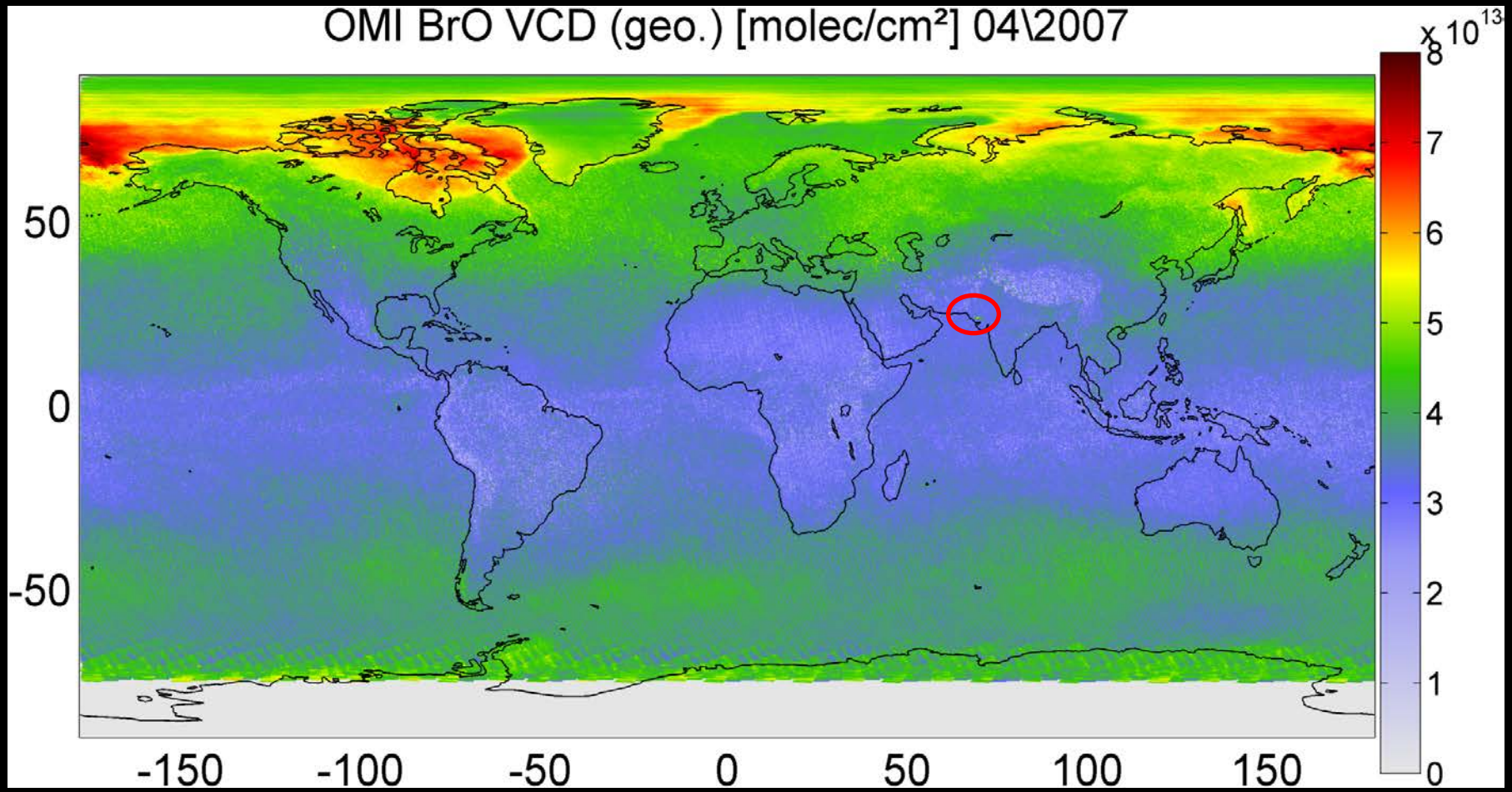
Thanks for your attention!

BrO mass vs. cloud cover

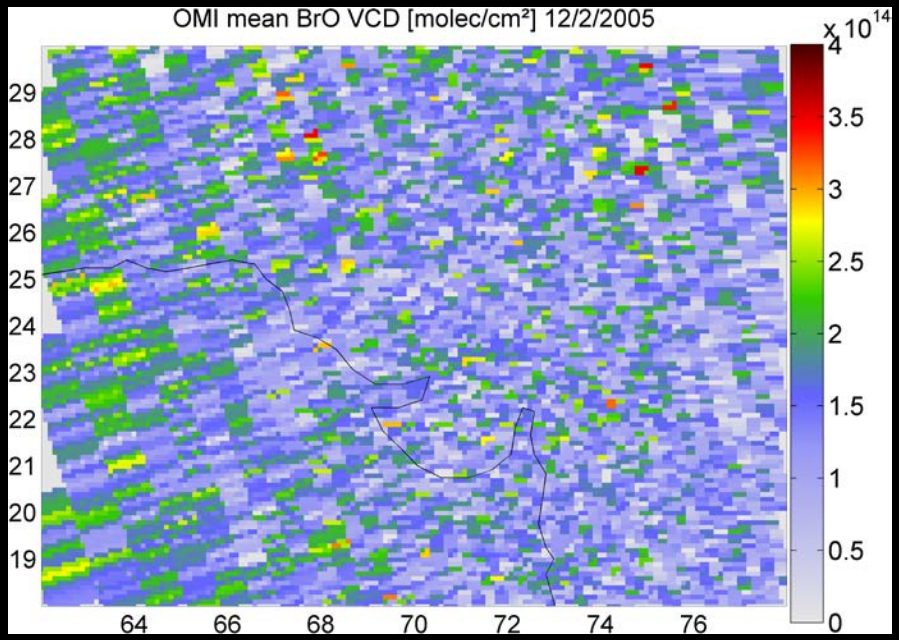


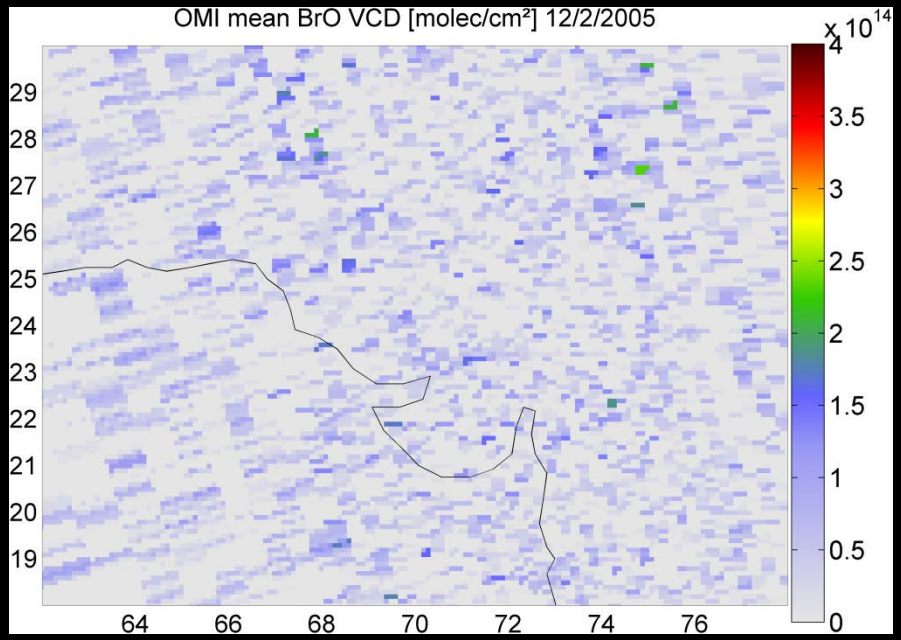
1) Increased cloud cover corresponds to monsoon season (June/July – September/October)
2) During BrO maximum, cloud cover is typically very low (<10%)

OMI BrO DOAS fit



Daily stratospheric background correction

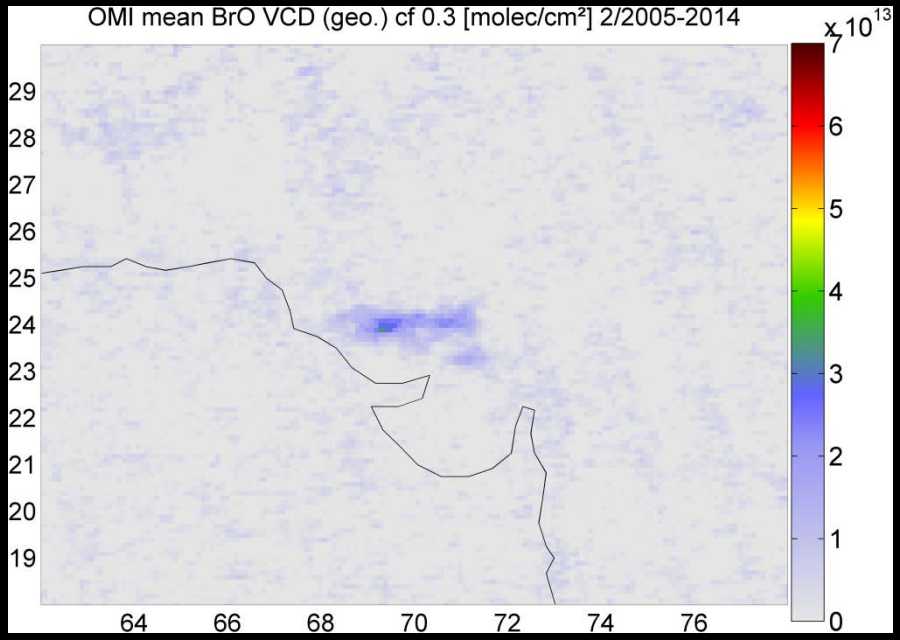




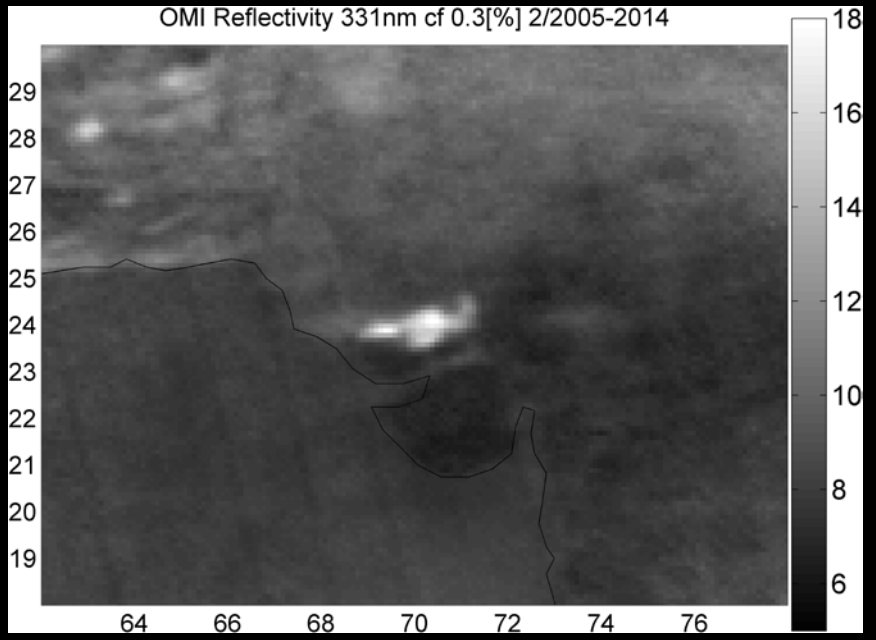
Tropospheric BrO signal is superimposed by lat-/longitudinal dependent stratospheric BrO

Daily background correction by 2D-polynomial (4th degree)

BrO VCDs vs. Reflectivity



BrO VCD [molec/cm²]



Reflectivity@331nm [%]

February 2005-2014

Increased reflectivity indicates bright surface of the Rann
→ no clear correlation visible

Error estimation

- Total BrO masses are strongly dependent on a priori assumptions (layer profile, aerosol properties, surface albedo)

a priori	baseline	alternatives	ΔBrO_{tm} [%]
layer profile	0-1km	0-400m 0-2km	+ 40% - 25%
AOD	0.7	0.4 1.0	- 5% + 5%
Surface albedo	15%	10% 20%	+ 20% - 15%

- Largest uncertainties due to unknown BrO profile, large influence of surface albedo, but too weak for false BrO signal

- Total error estimated to range from -35 to +100 % (based on baseline)

ECMWF 6UTC vs. 9UTC:

Temperature:	3-5°C less for 6UTC (2-3%)
Cloud cover:	similar
Precipitation:	lower in the morning
BLH:	much lower in the morning (1.5km vs. 3km)
UV radiation:	about 50% in the morning
Rel. Humidity:	RH by 20-30% higher in the morning (<35% RH)

Correlation to meteorological data

- Closest automatic weather stations are about 100km away (2x Pakistan, 2x India)

- At the moment only Pakistani data for 2013/2014 available:

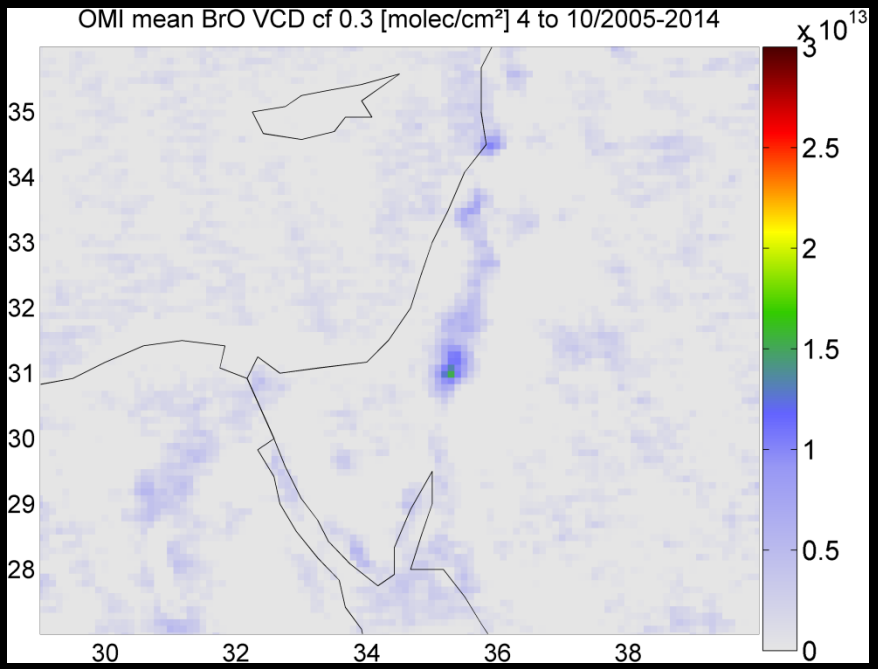
  - min/max temperature
  - total precipitation

  → comparison to measured data has to be postponed

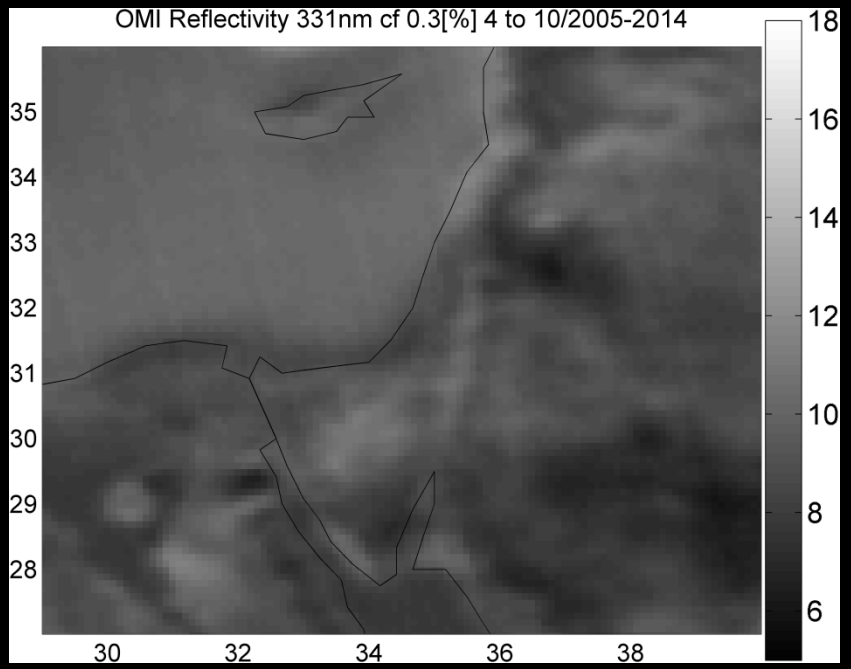
Use ECMWF model data instead (incl. measurements)

Monthly mean values for central region over Great Rann of Kutch (1x1°, 9UTC)

BrO vs. Reflectivity (Dead Sea)



BrO VCD [molec/cm²]

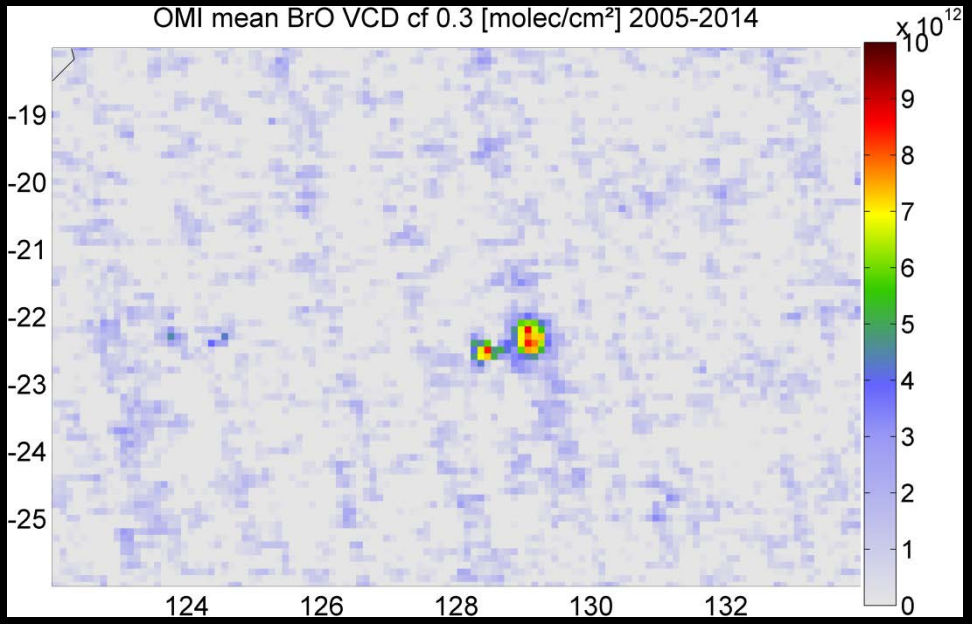


Reflectivity@331nm [%]

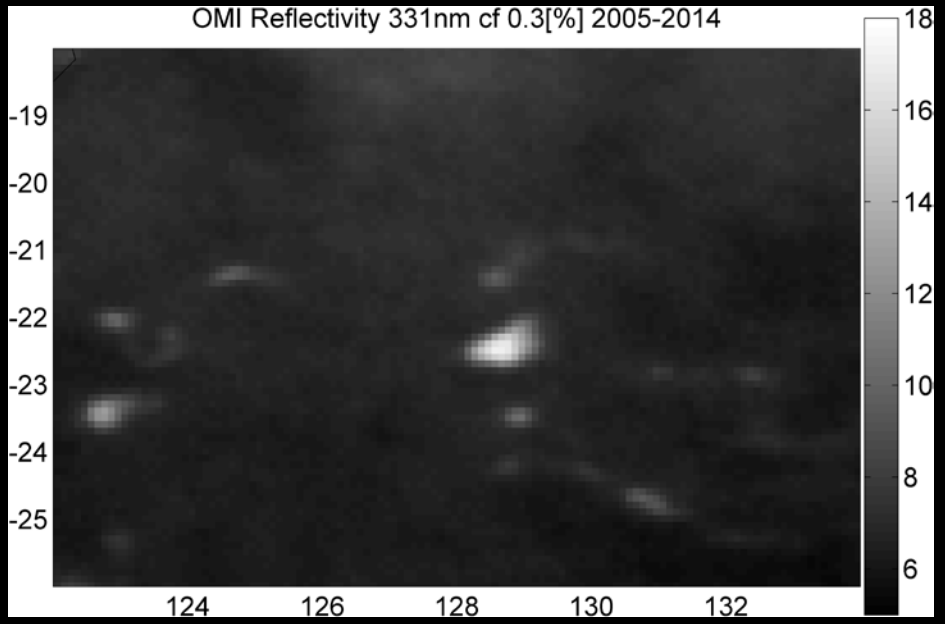
April-October 2005-2014

→ Clear BrO VCD enhancement over Southern Basin, but 5x lower than over Rann of Kutch
→ Much lower reflectivity/surface albedo
→ General problems: 1) Influence of topography (Ring effect)
2) Increased cloud cover

BrO vs. Reflectivity (Lake MacKay)



BrO VCD [molec/cm²]

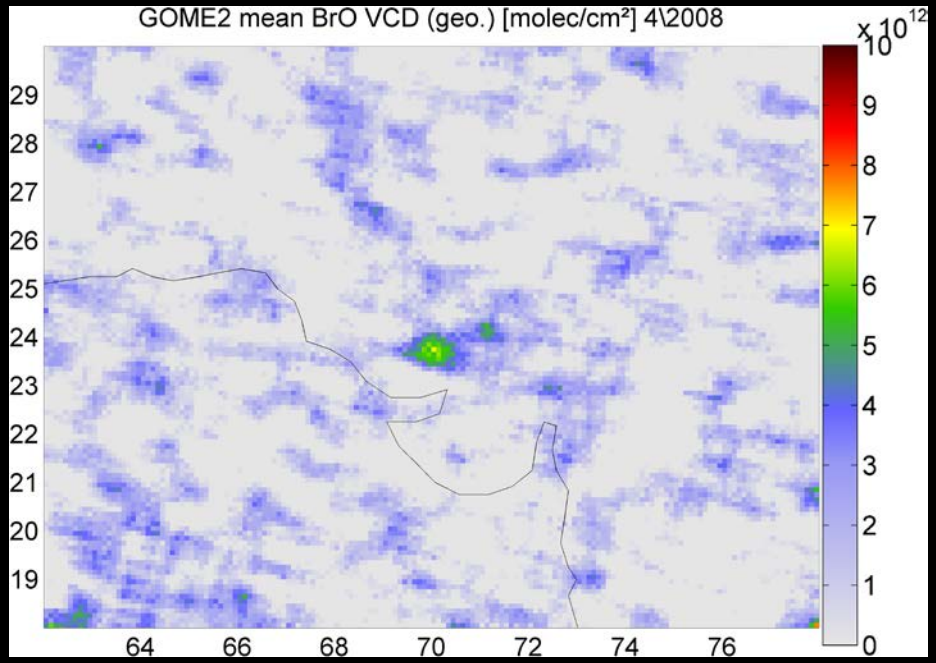


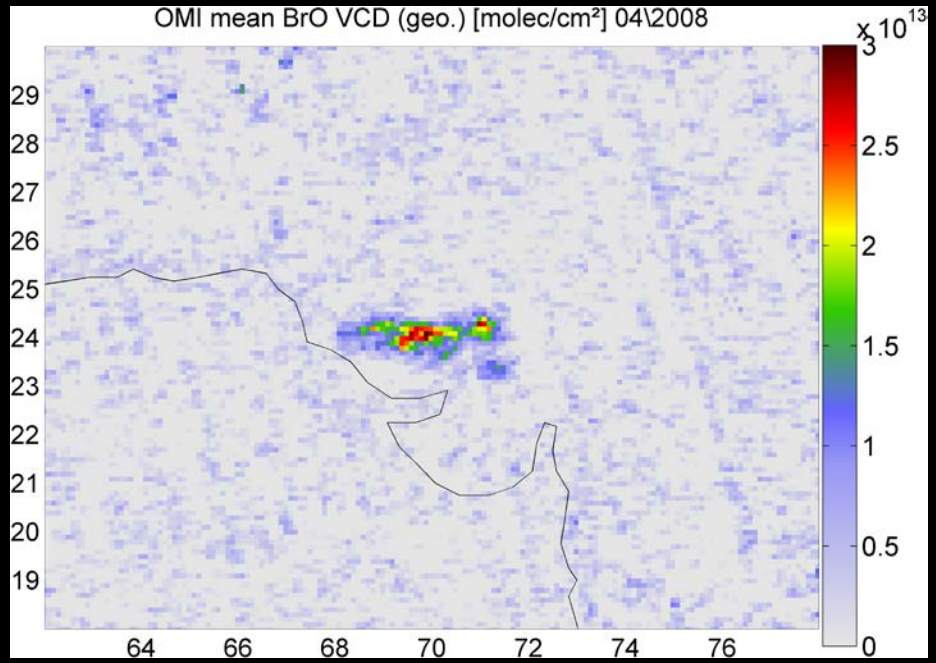
Reflectivity@331nm [%]

2005-2014

→ Clear BrO VCD enhancement over some parts, but 9x lower than over Rann of Kutch
→ Comparably high reflectivity / possibly only caused by high surface albedo
→ Usually try, only sporadic rain fall (→standing water)

GOME-2 vs. OMI





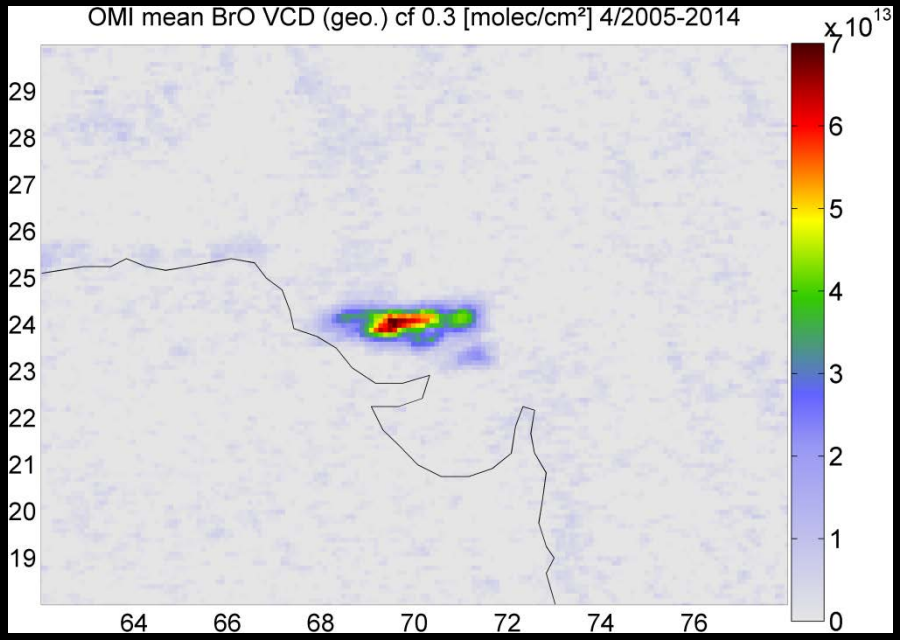
GOME-2 (9 LT) **OMI (13 LT)**

April 2008

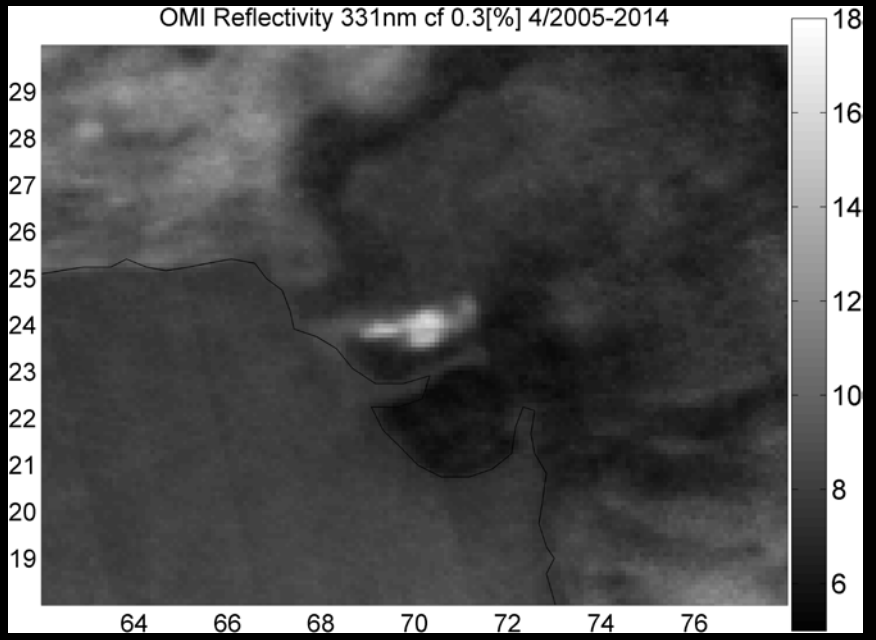
→ GOME-2 shows 5x lower BrO VCDs (geo.) over Rann of Kutch (even in April)
→ Signal is close to noise background signal (GOME-2 degradation)

Possible reasons: 1) Instrumental: GOME-2 pixel size is much larger (40x80km²)/degradation
2) Chemical: Measurements take place 4h earlier
→ UV radiation and BLH 50% lower, RH 30% higher (< 35%)

BrO VCDs vs. Reflectivity



BrO VCD [molec/cm²]

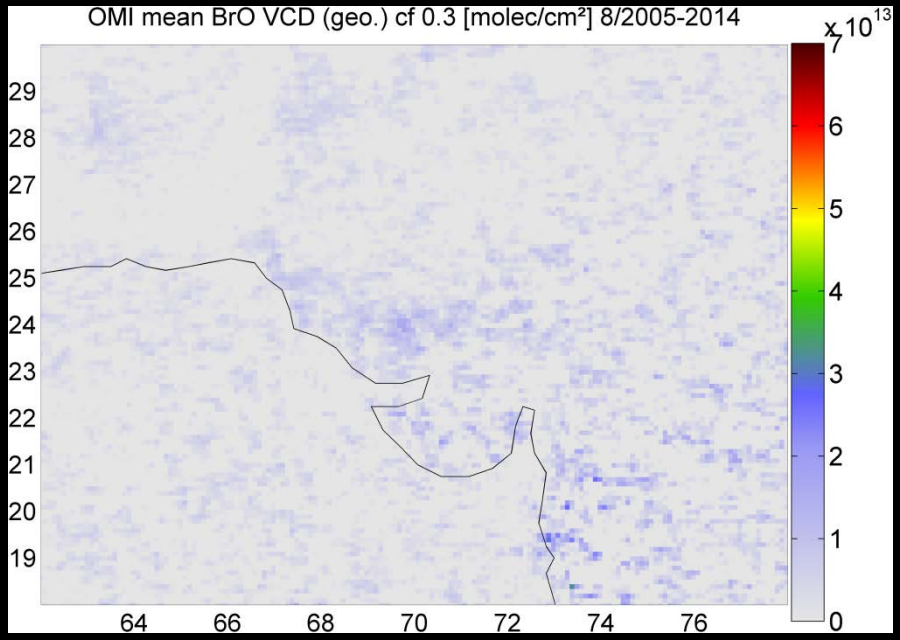


Reflectivity@331nm [%]

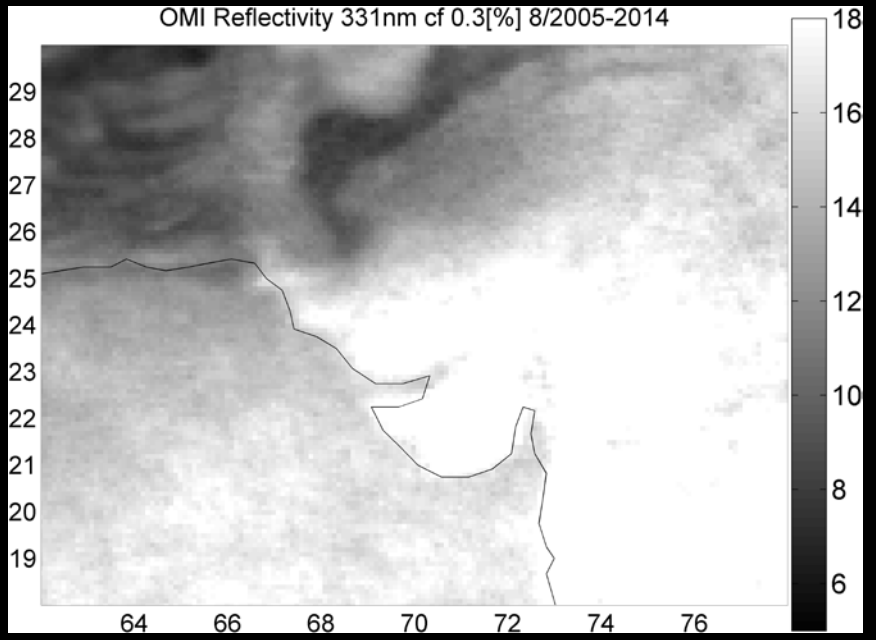
April 2005-2014

Towards month of maximum BrO VCDs, reflectivity generally decreases due to lower cloud influence (+ first rain events?)

BrO VCDs vs. Reflectivity



BrO VCD [molec/cm²]

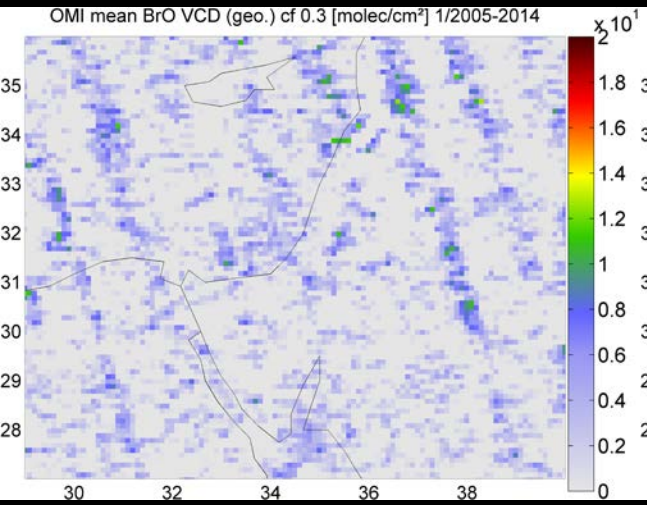


Reflectivity@331nm [%]

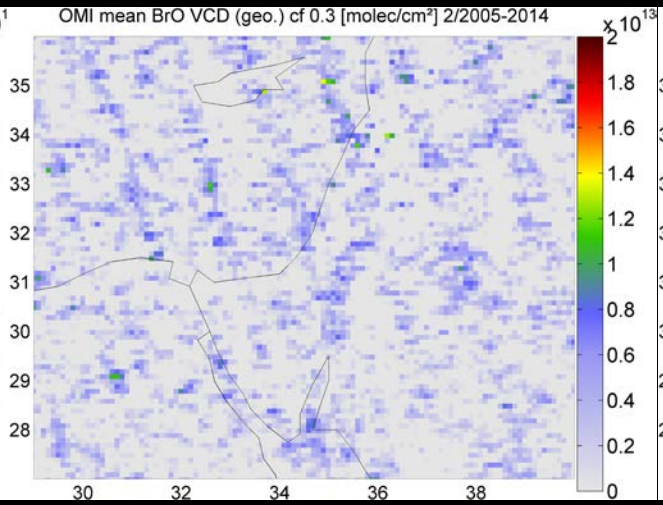
September 2005-2014

During the monsoon season, clouds shield the Rann from OMI
→ almost all measurements affected by clouds (despite CF < 30%)

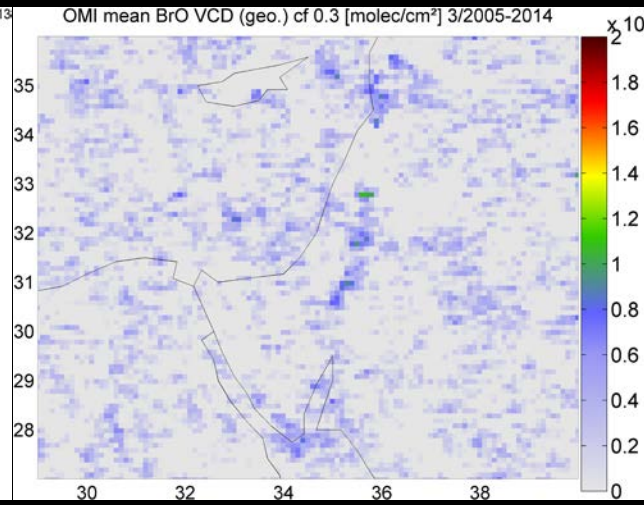
January



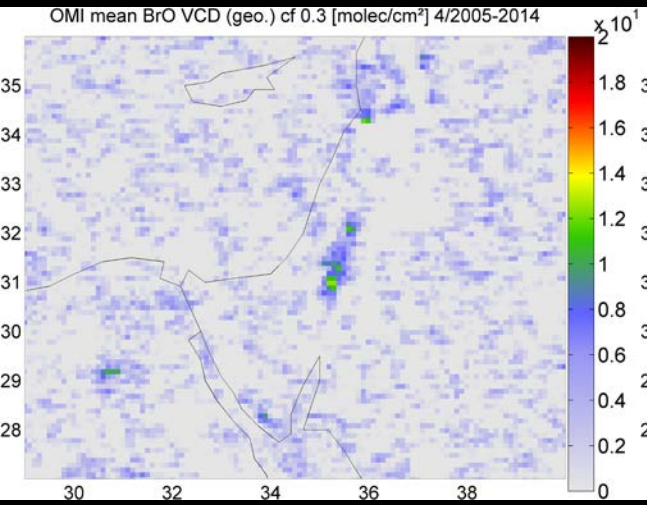
February



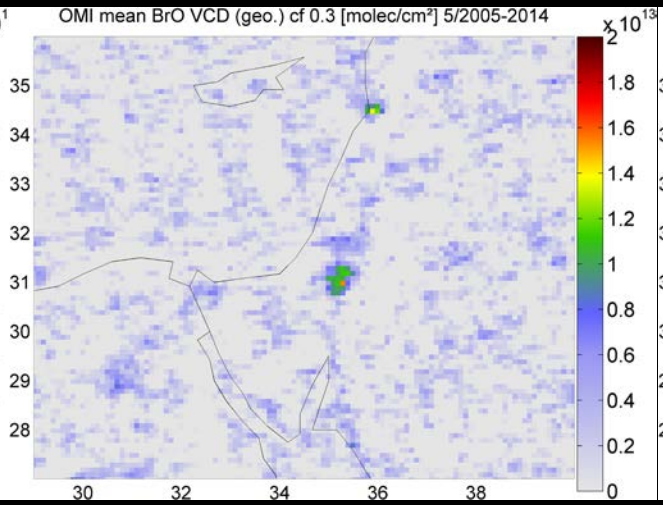
March



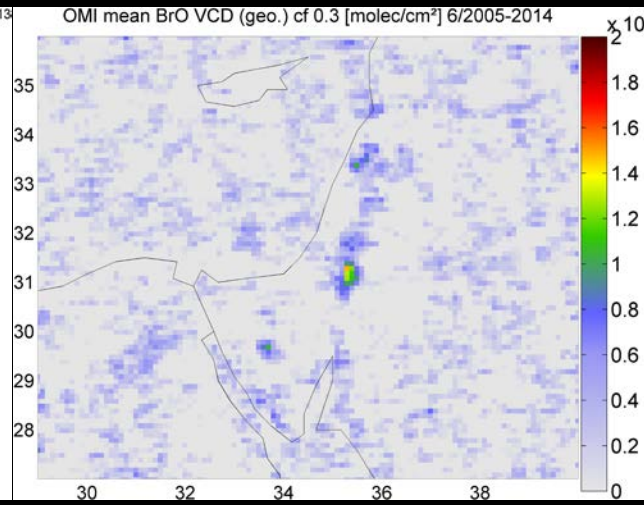
April



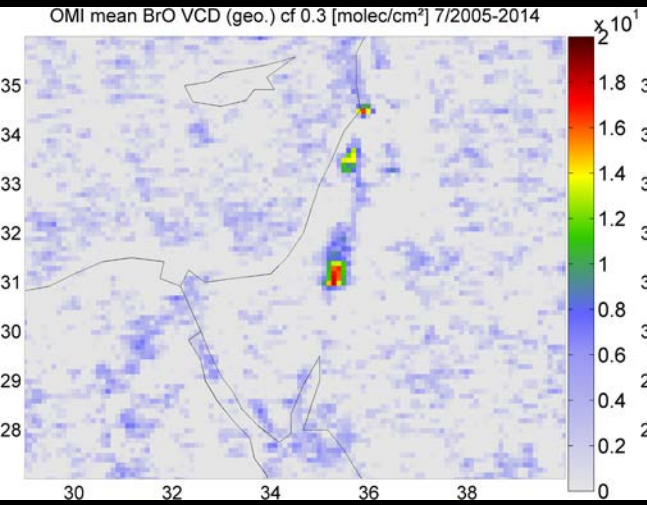
May



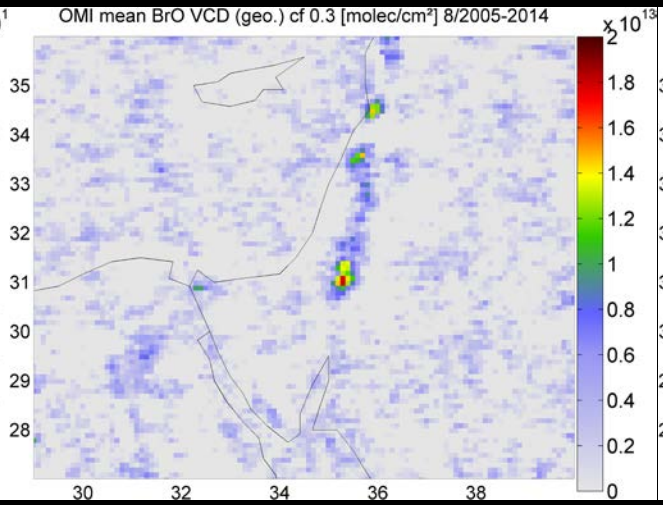
June



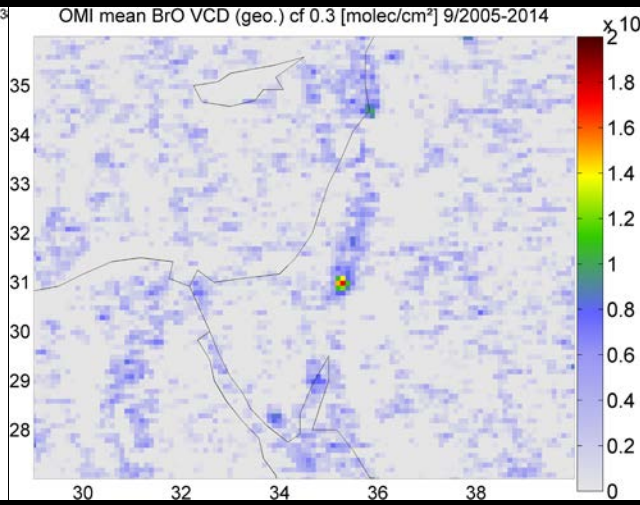
July



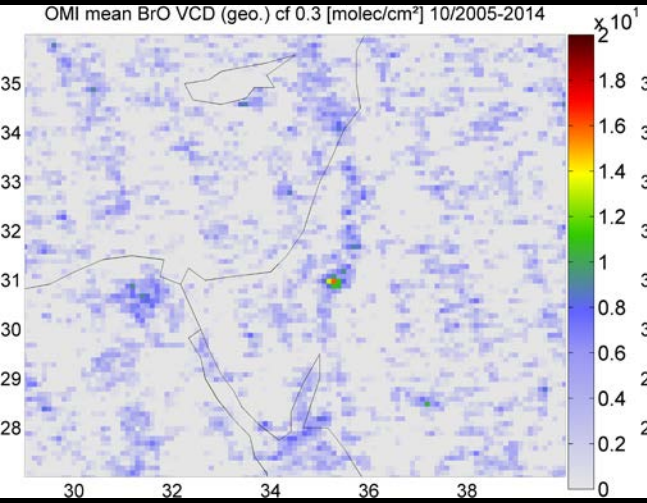
August



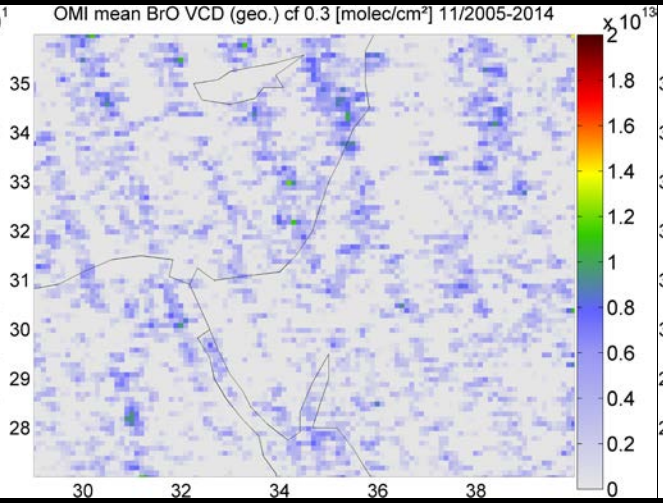
September



October



November



December