Stratospheric Ozone at South Pole Begins to Show Signs of Improvement in the Yearly Ozone Hole

Bryan Johnson, Patrick Cullis, Chance Sterling, Glen McConville, Johan Booth, Irina Petropavlovskikh

NOAA ESRL Global Monitoring Division & CIRES, Univ. of Colorado

Ozonesondes: 31 consecutive years.
1986-2017 (1,650 ozonesonde launches)

Dobson Spectrophotometer: 53 years
1964-2017 (7,300 days of measurements)

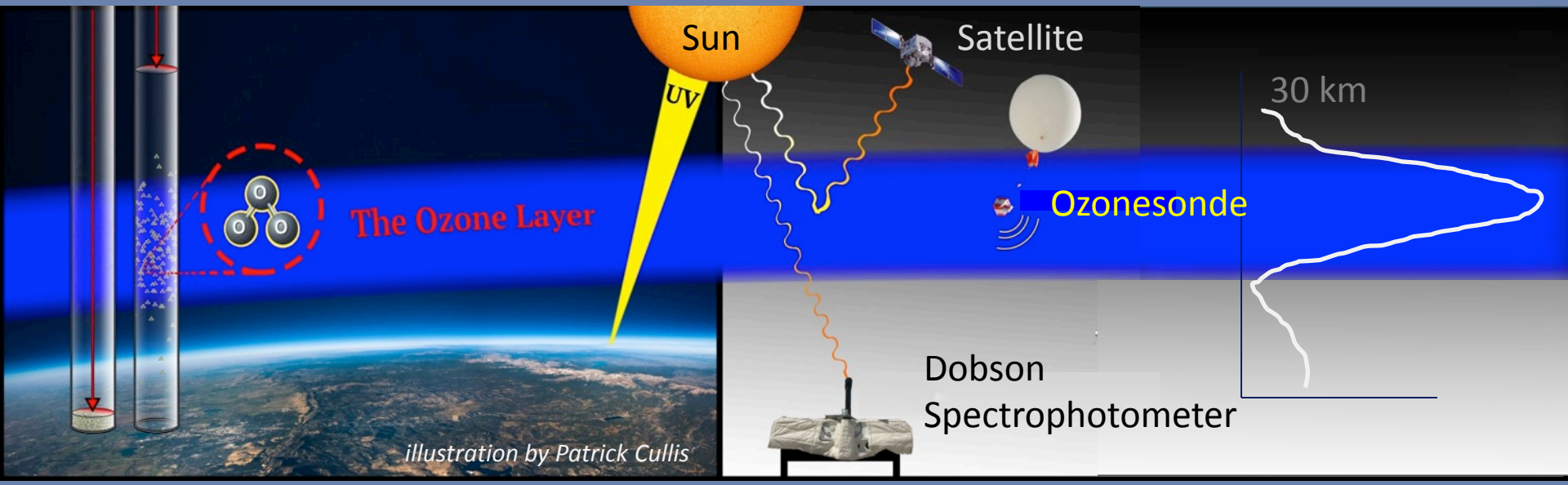
Outline

Stratospheric Ozone Measurements, Trends, Recovery.

1. Ozonesondes:
   - Total Column Ozone
   - 14-21 km Layer Column Ozone
   - September Ozone Loss Rate
2. Dobson Spectrophotometer:
   - Total Column Ozone
3. Satellites:
   - Total Column Ozone
   - Area of Ozone Hole

Photo by Christian Krueger, IceCube

Stratospheric Ozone Measurements
Total Column Ozone (Dobson Units)



Antarctica Typical Range = 260-360 DU
Ozone Hole Defined Threshold = 220 DU
Ozone Hole Minimum = 85-90 DU

Stratospheric Ozone Measurements
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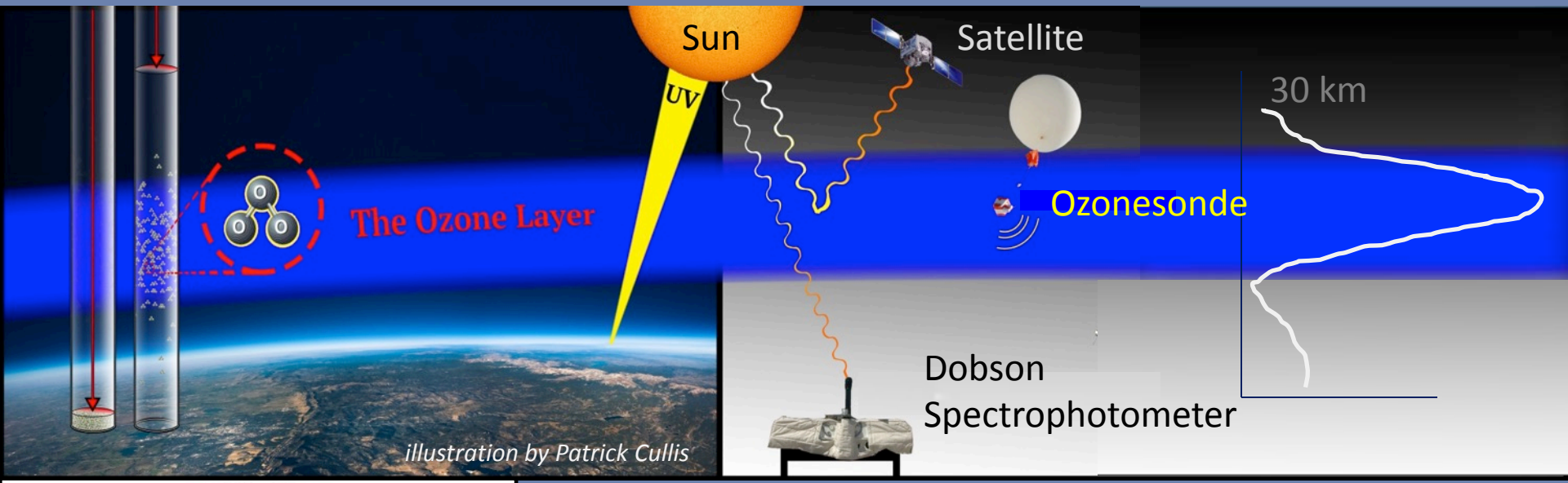

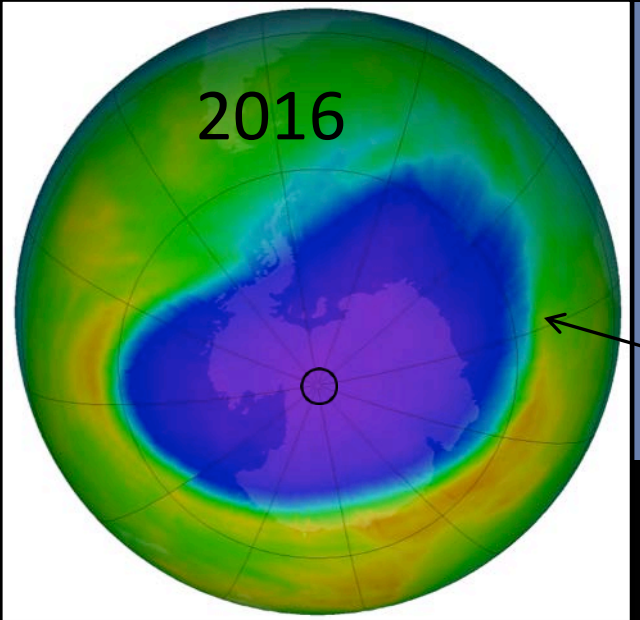

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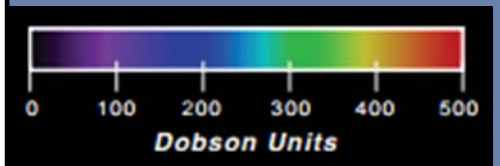
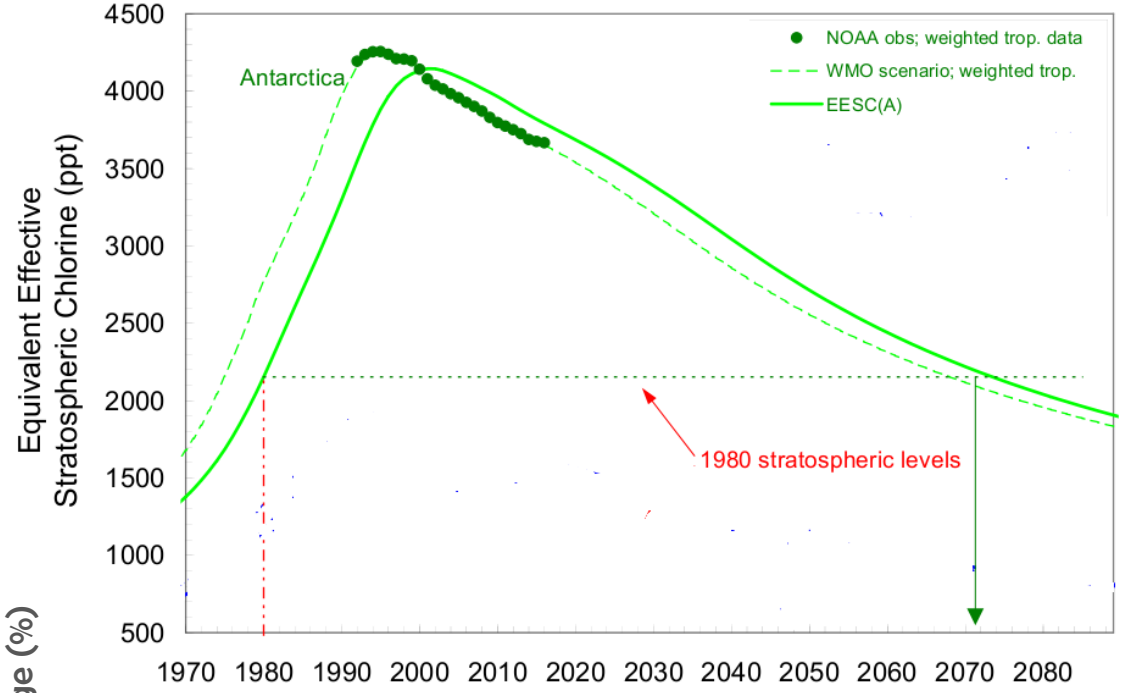
NASA Goddard Image: October 1, 2016
114 Dobson Units

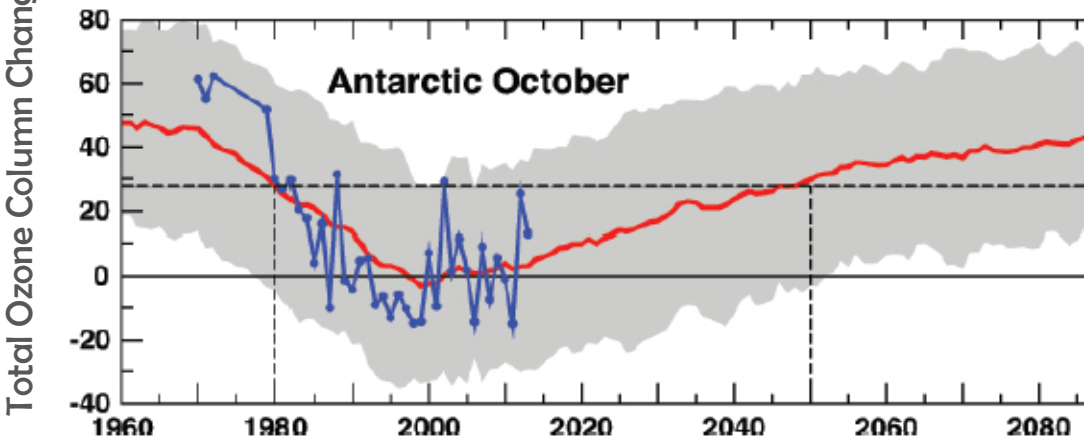


Stratospheric ozone severity & recovery depends on:

- chlorine (chemistry)
- temperature & meteorological conditions.



The NOAA Ozone Depleting Gas Index: Guiding Recovery of the Ozone Layer. Montzka, et al.



WMO Scientific Assessment of Ozone Depletion:2014

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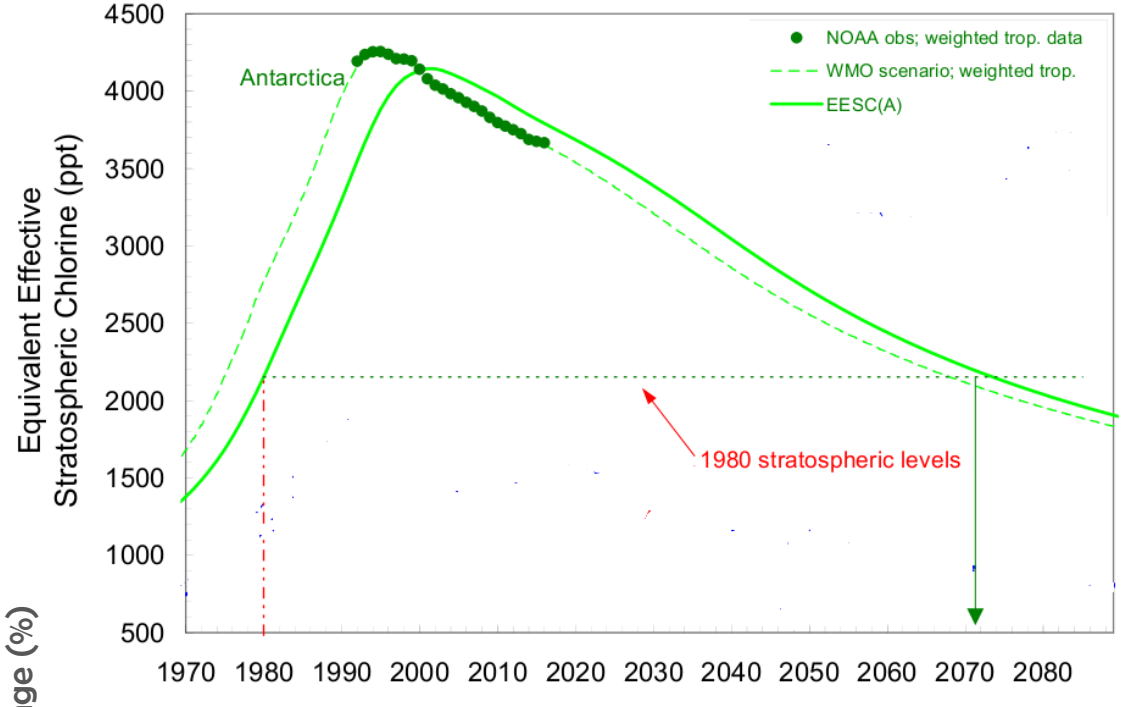
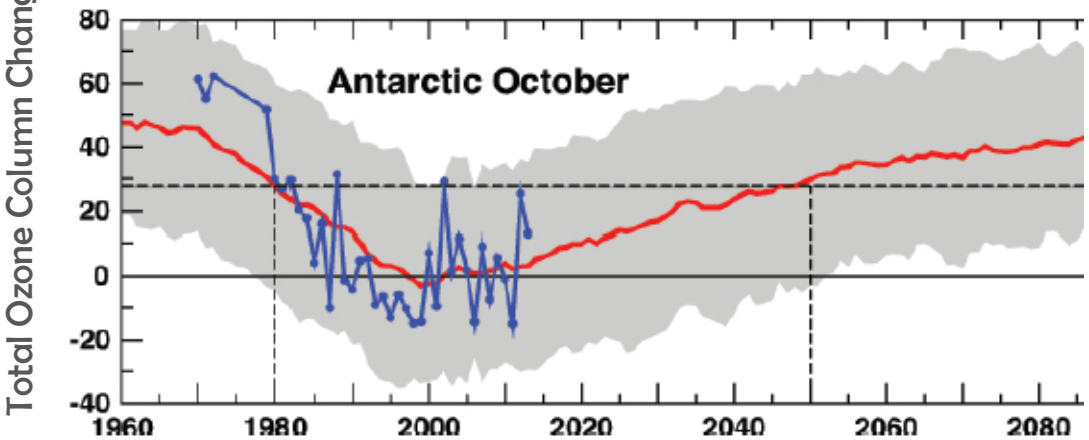




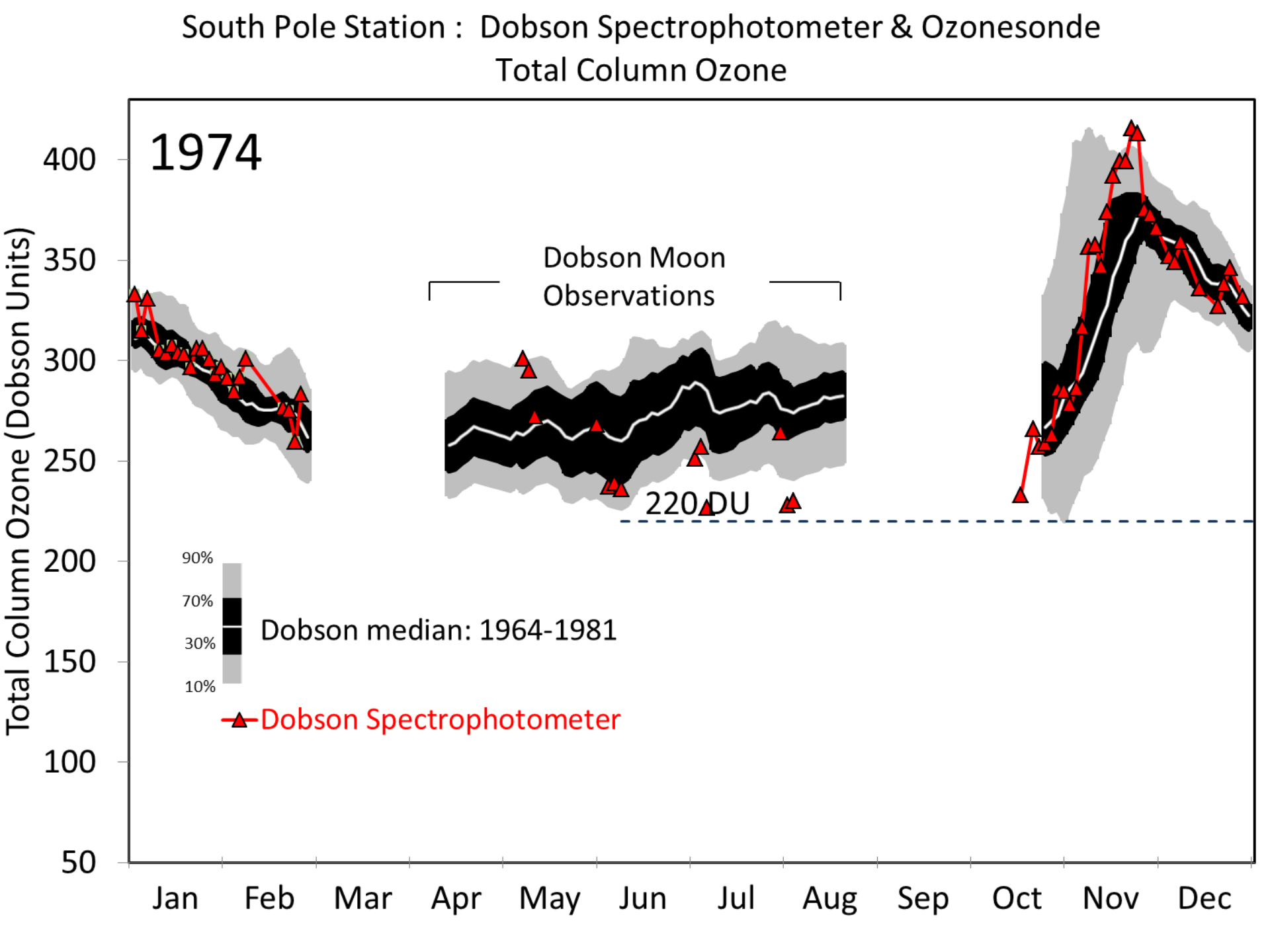
The NOAA Ozone Depleting Gas Index: Guiding Recovery of the Ozone Layer. Montzka, et al.

Antarctica ozone layer recovery publications:

2011: *Hassler, et al. An assessment of changing ozone loss rates at South Pole: 25 years of ozonesonde measurements (JGR).*

2016: *Solomon, et al. Emergence of healing in the Antarctic ozone layer (Nature).*

WMO Scientific Assessment of Ozone Depletion:2014


South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
1974
Total Column Ozone (Dobson Units)
400
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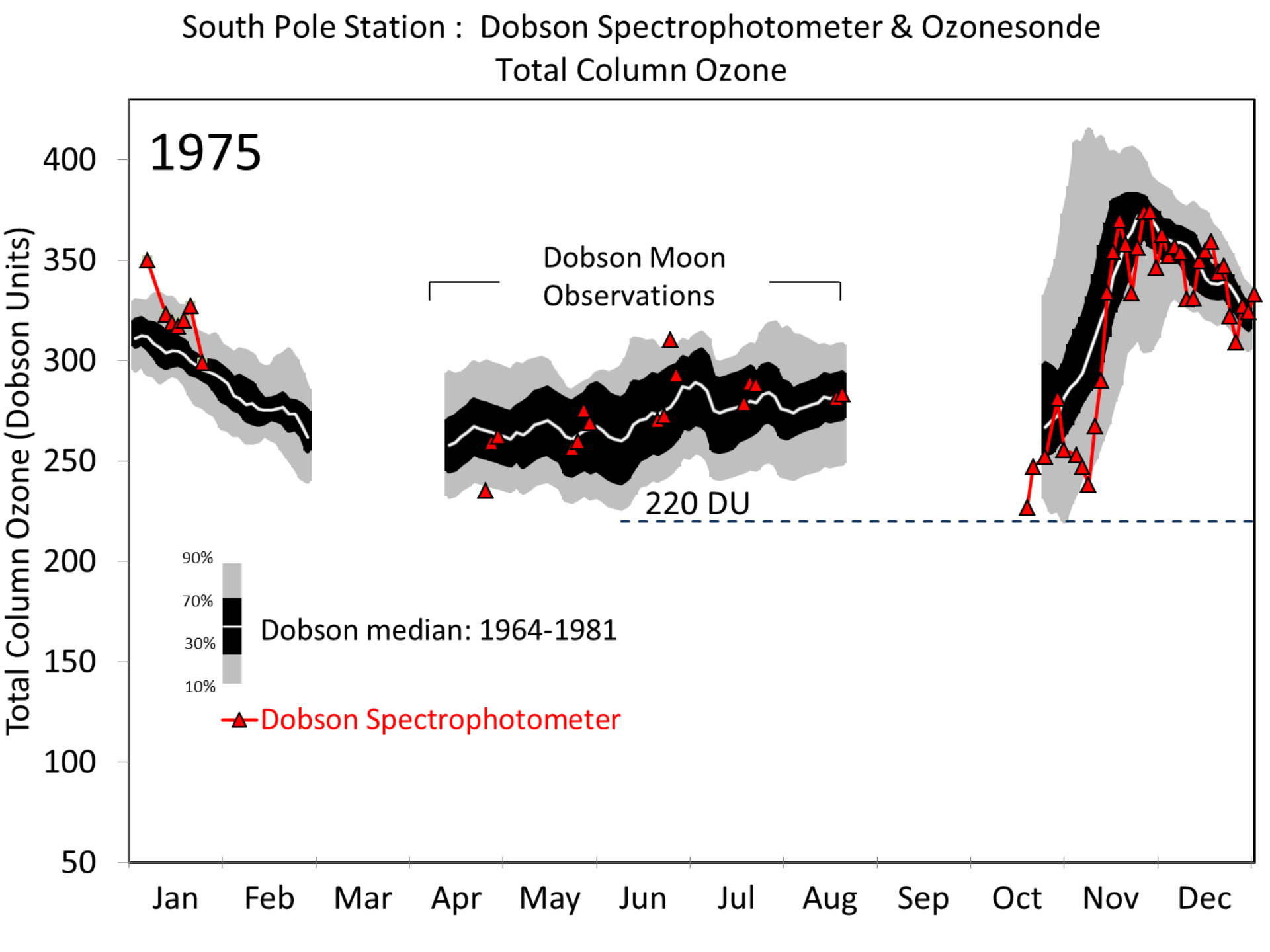
Dobson Moon
Observations
220 DU
90%
70%
30%
10%
Dobson median: 1964-1981
Dobson Spectrophotometer


South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
1975
Total Column Ozone (Dobson Units)
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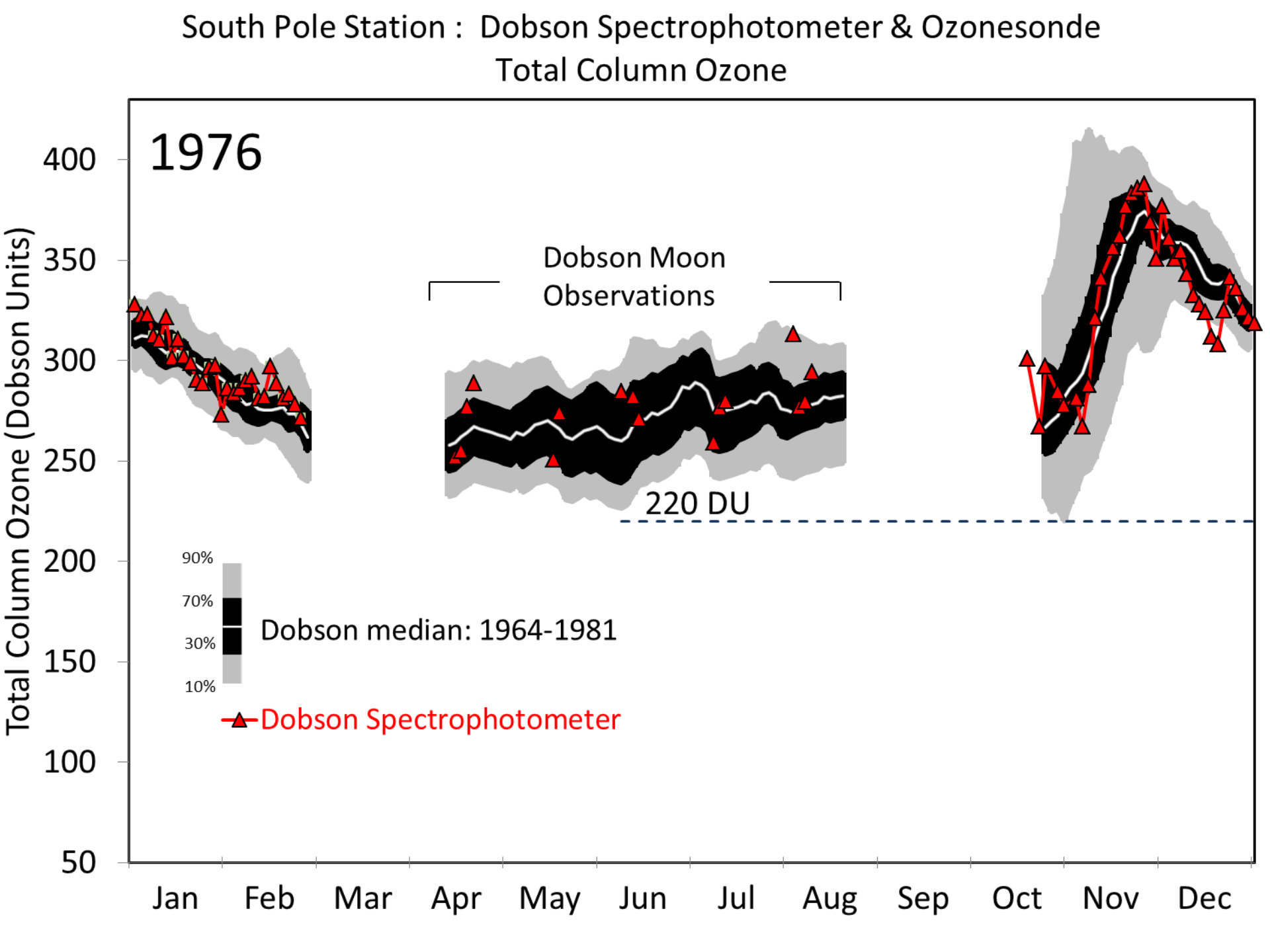
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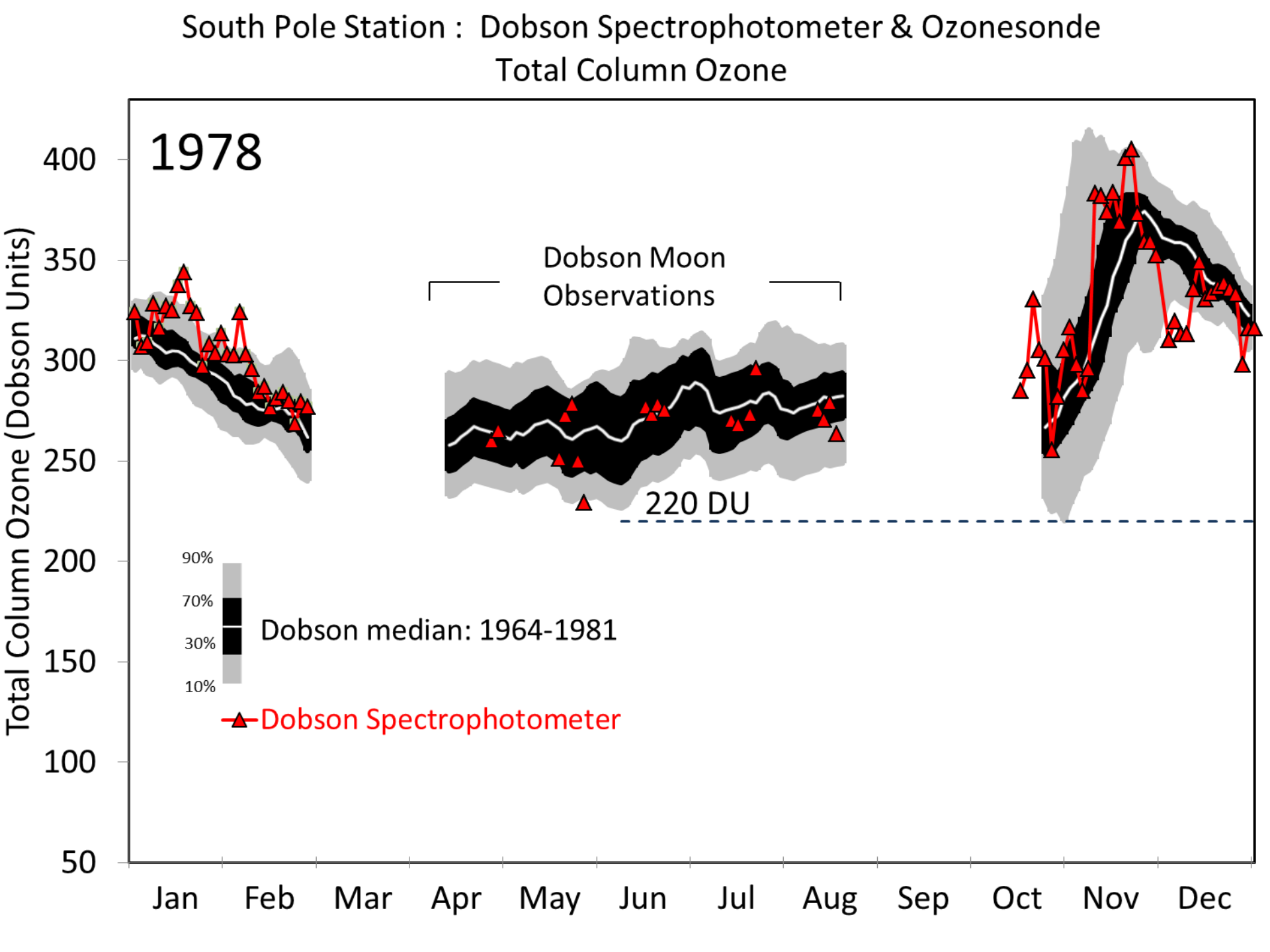
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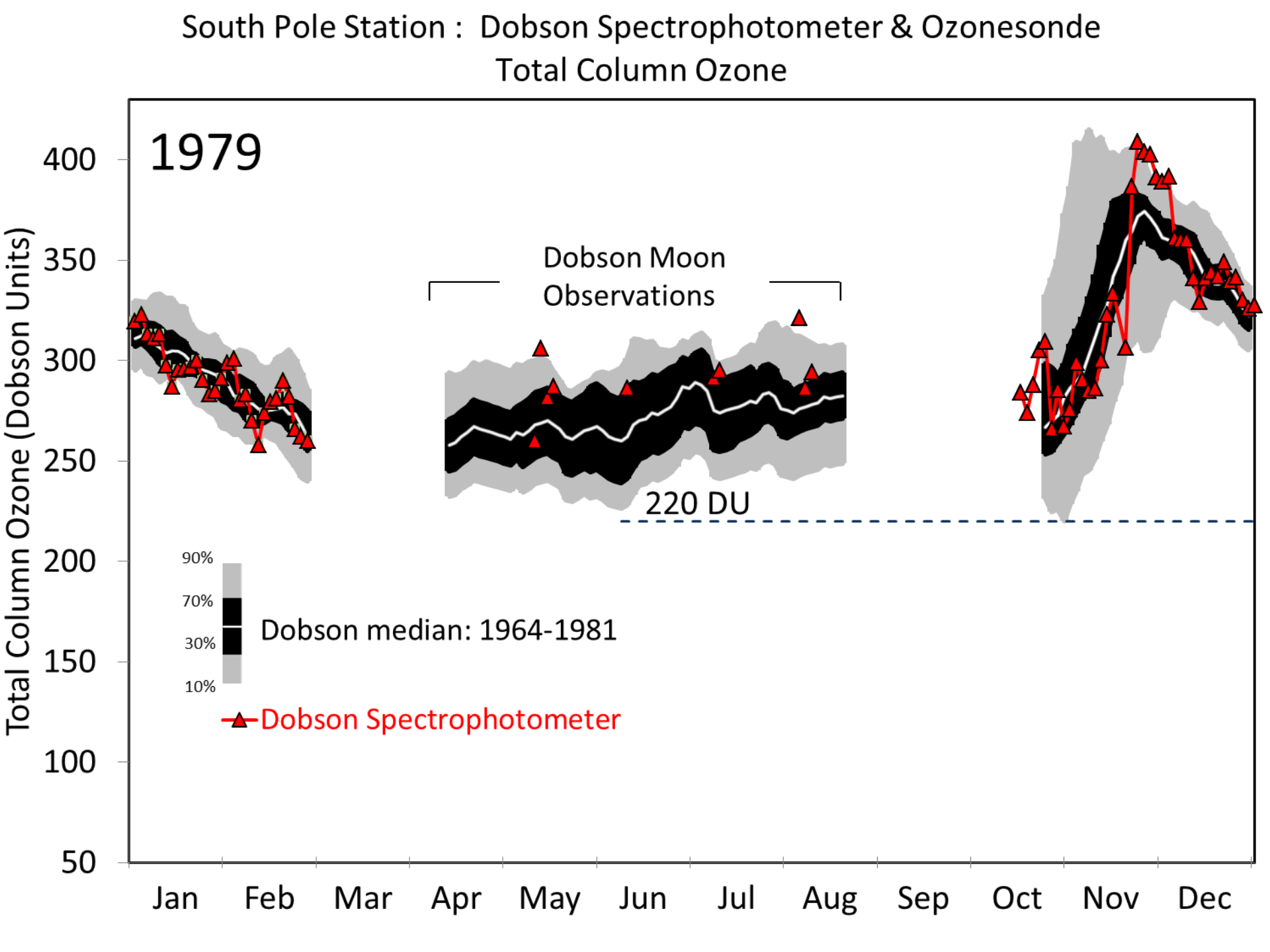
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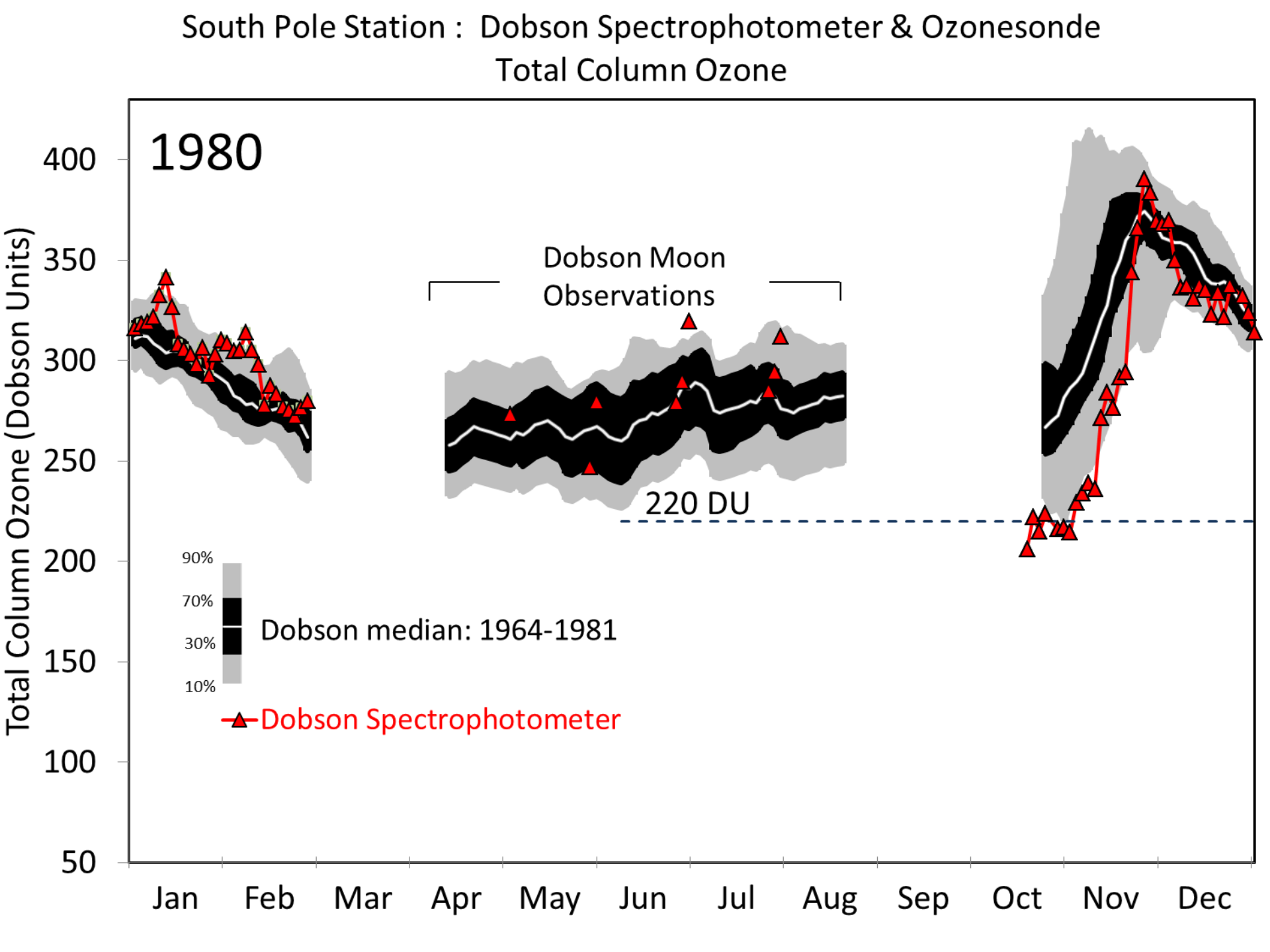
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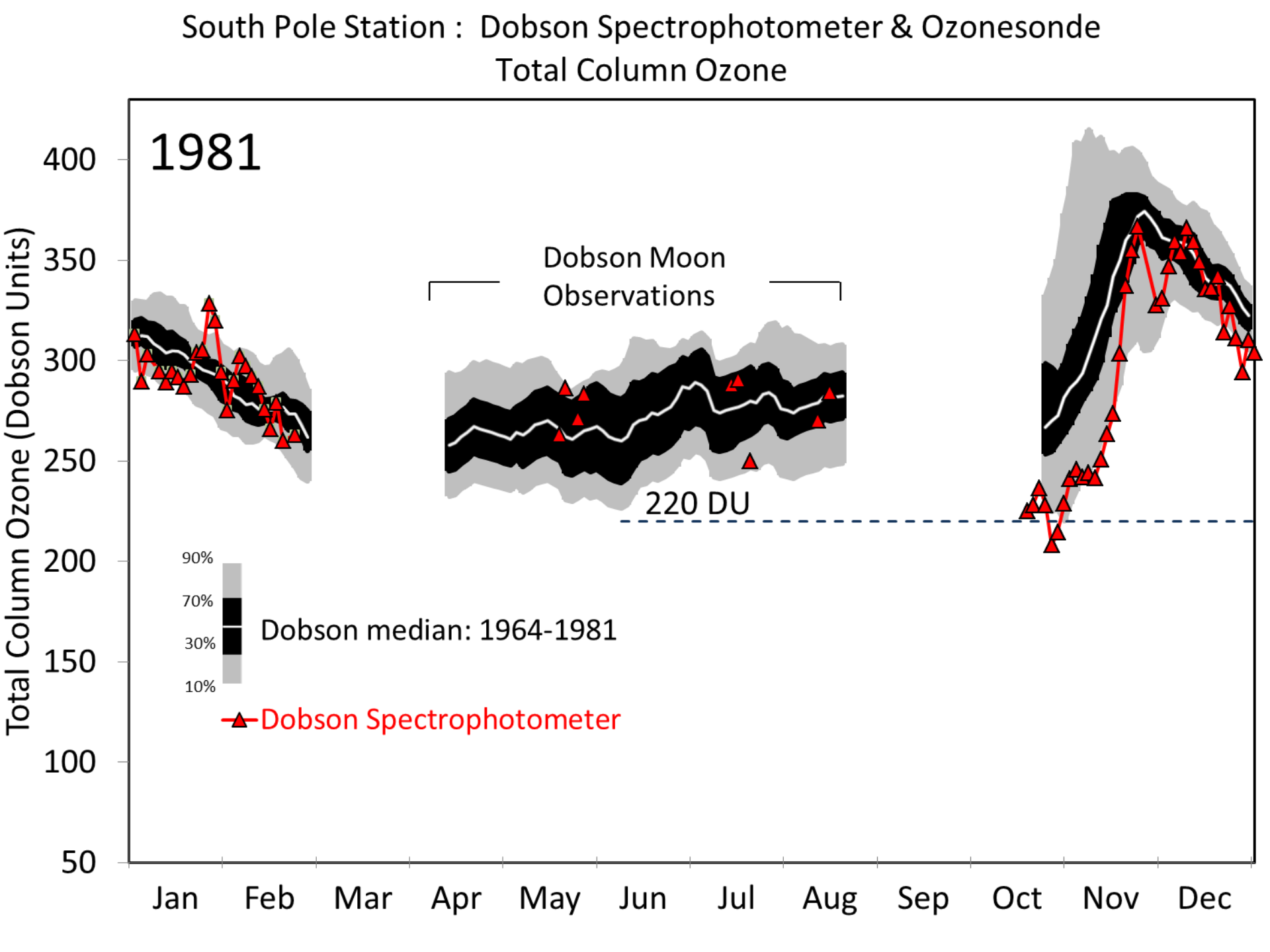
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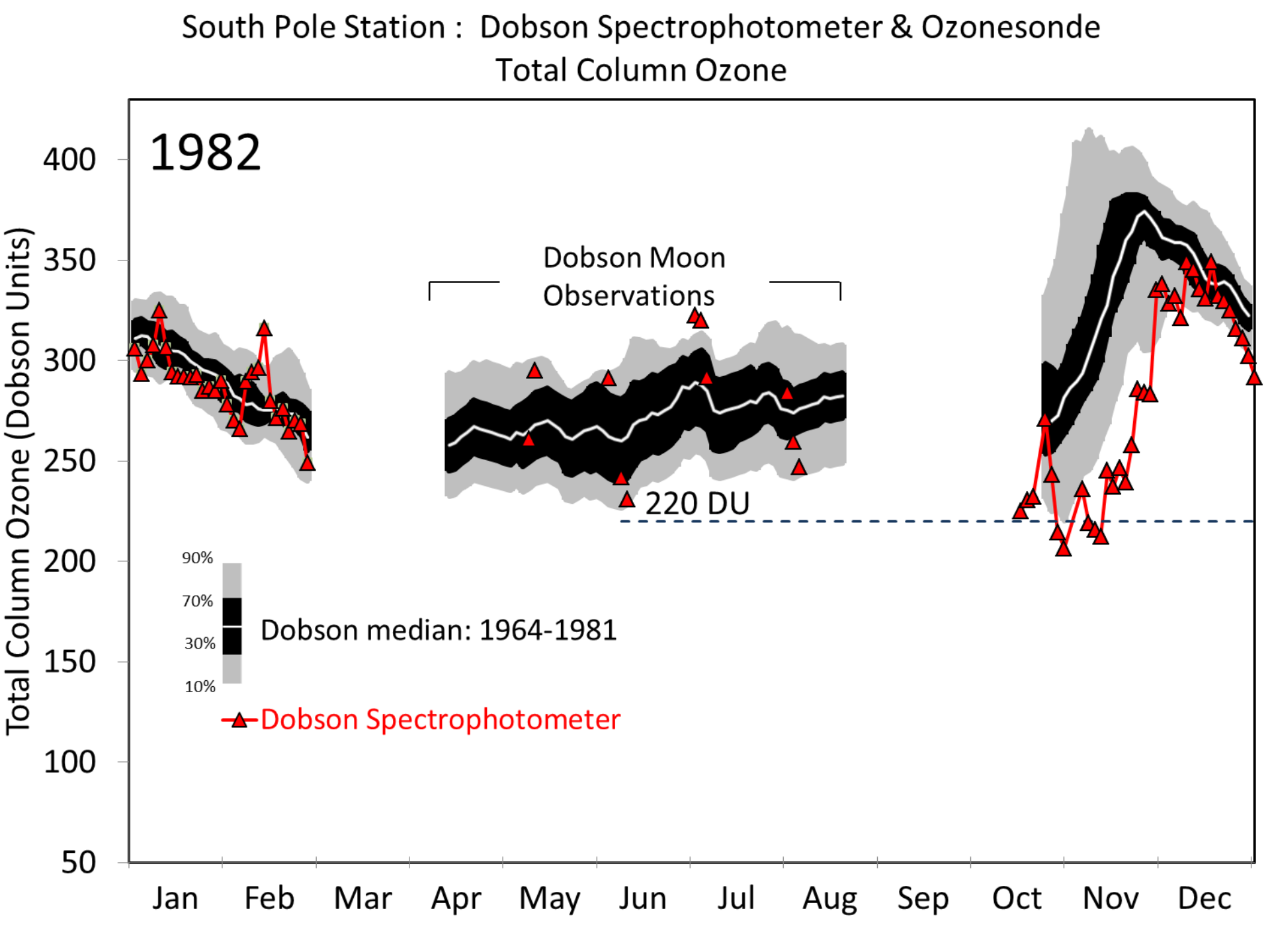
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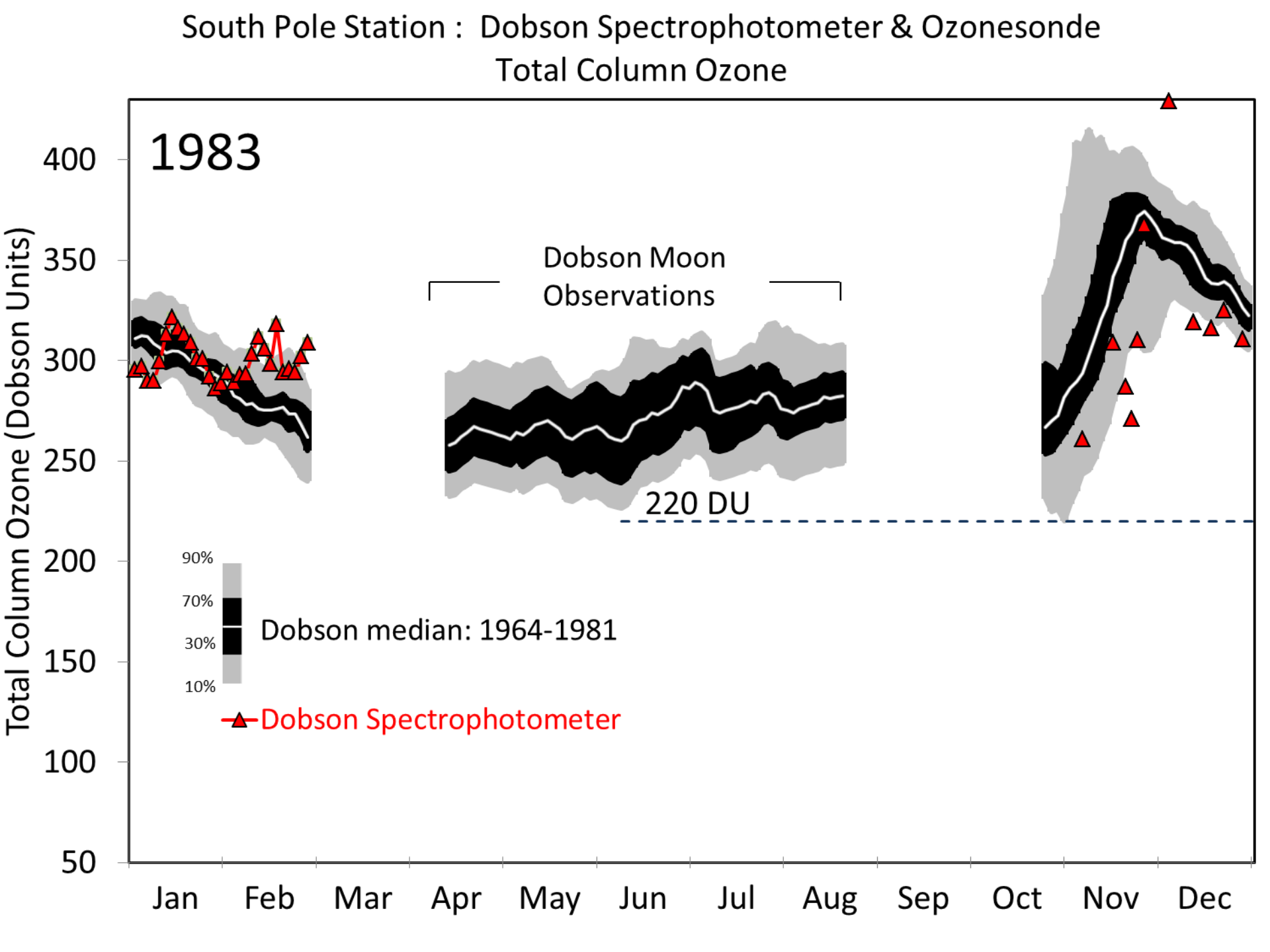
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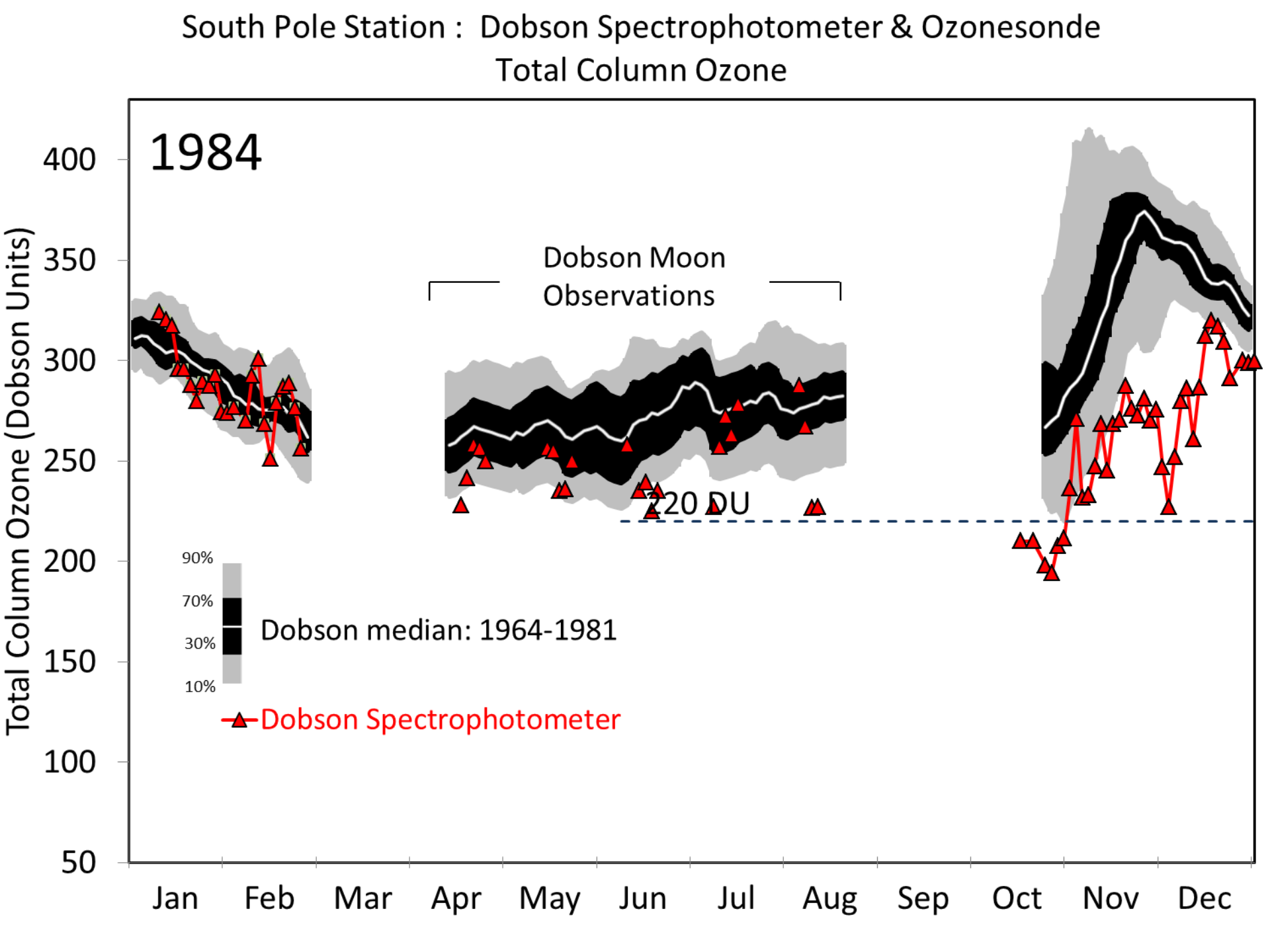
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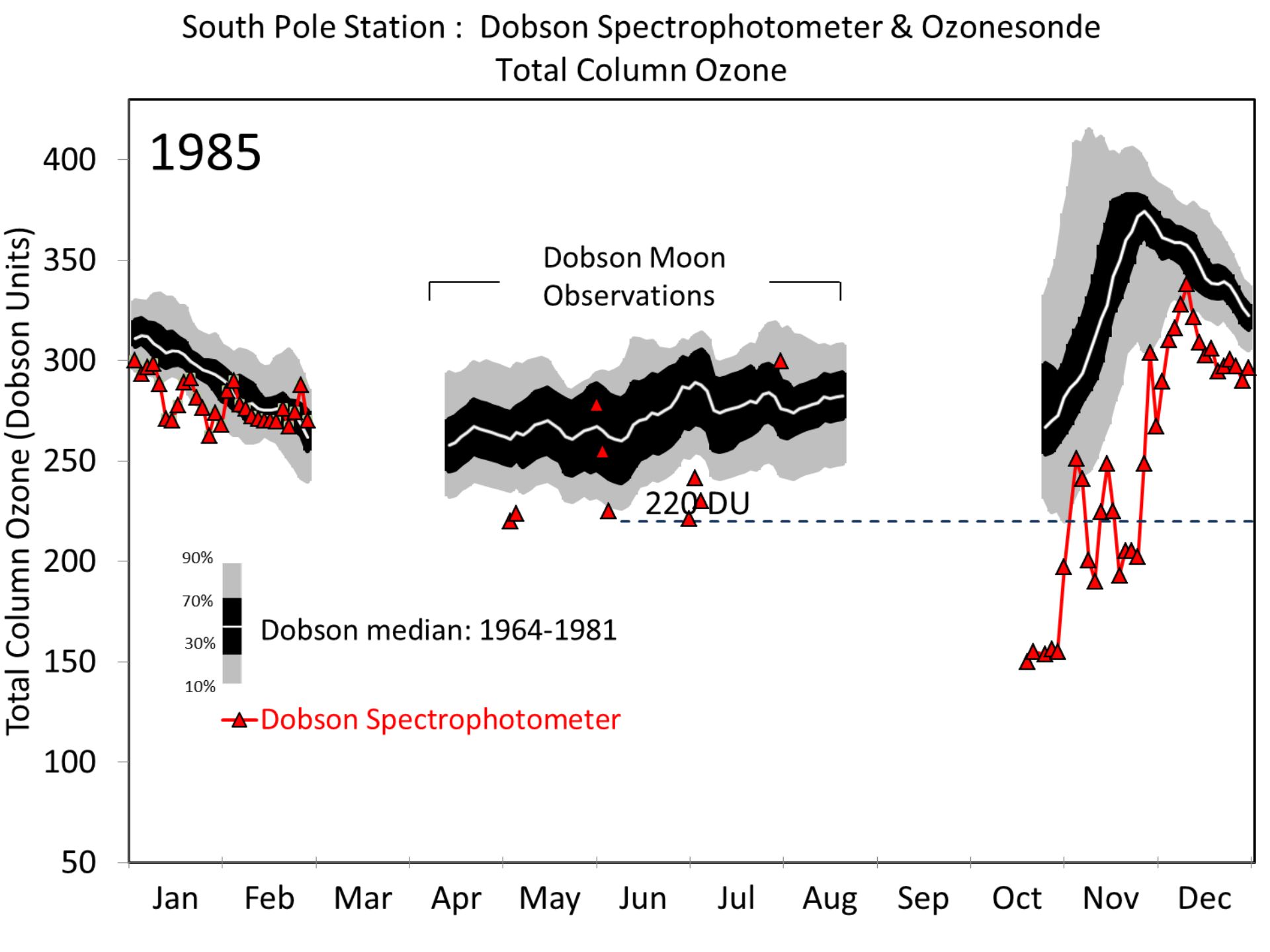
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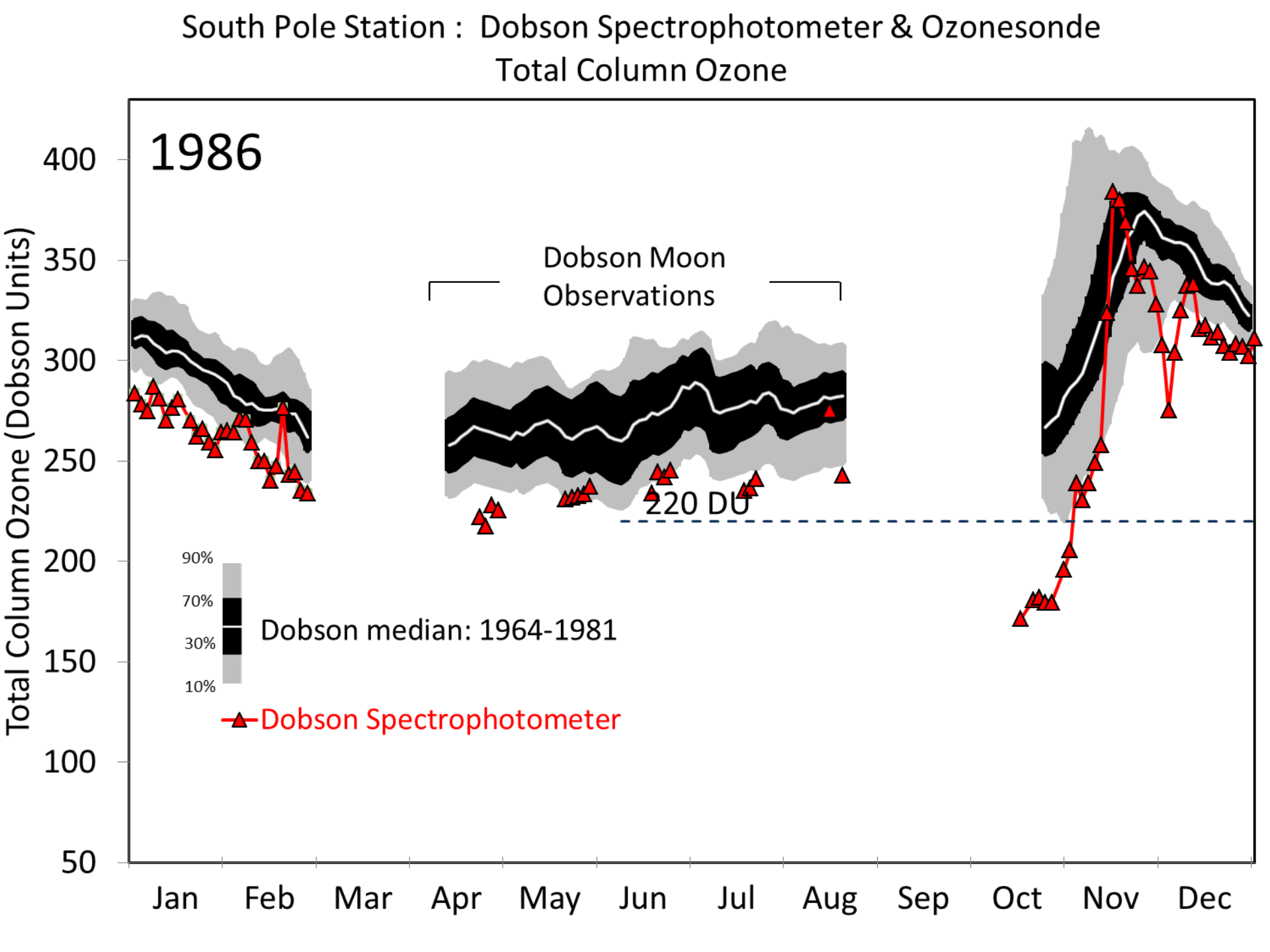
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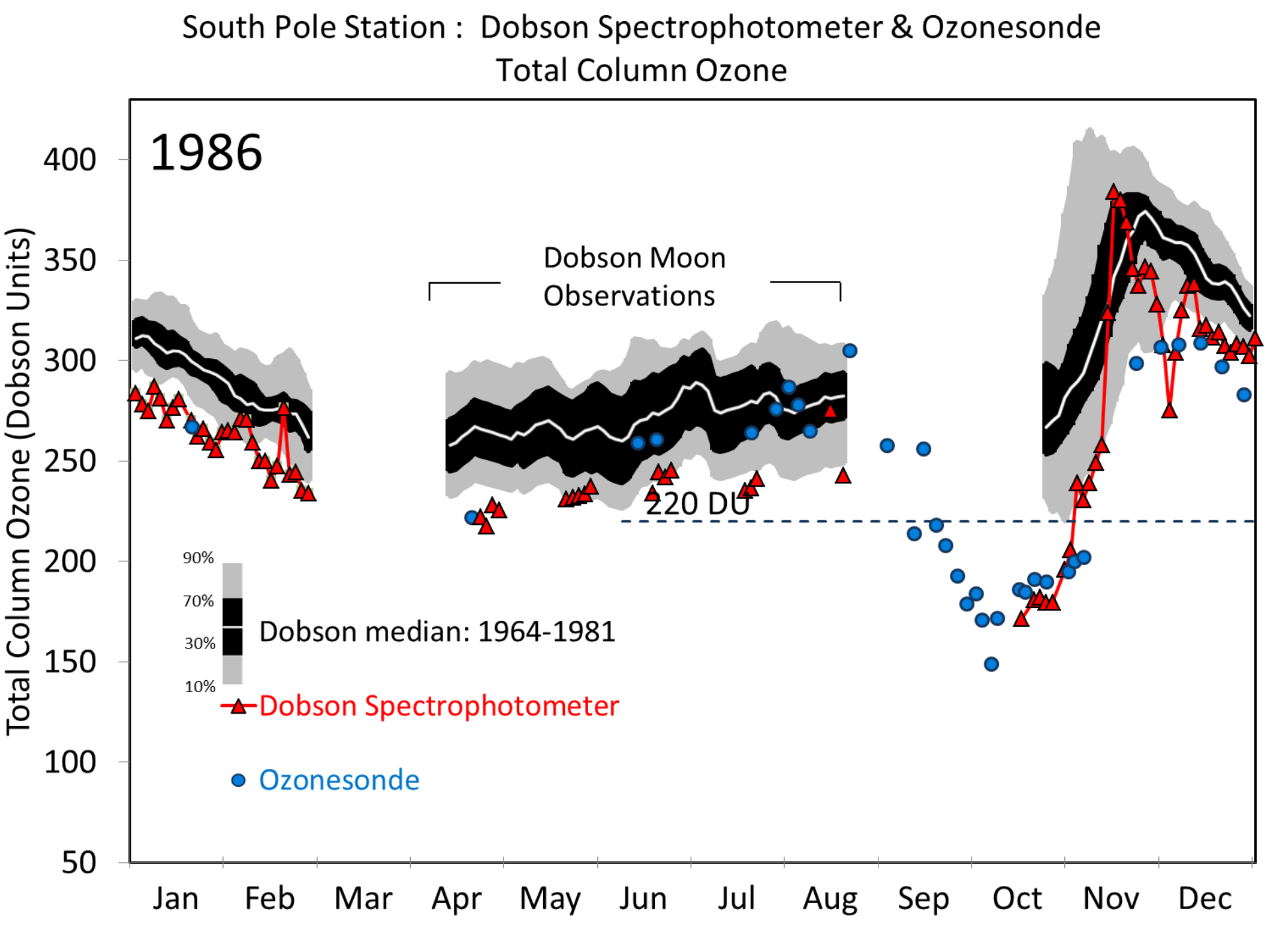
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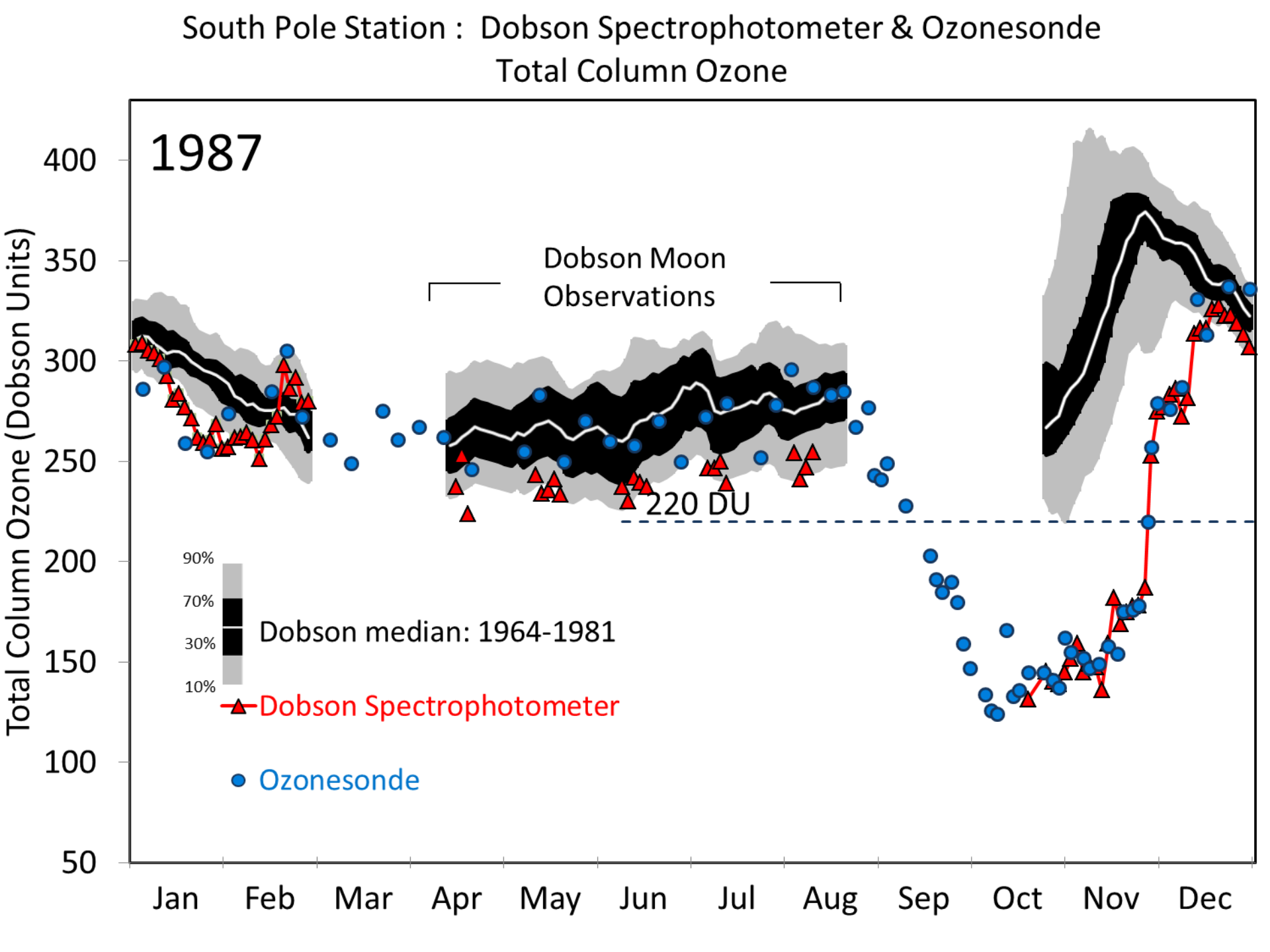
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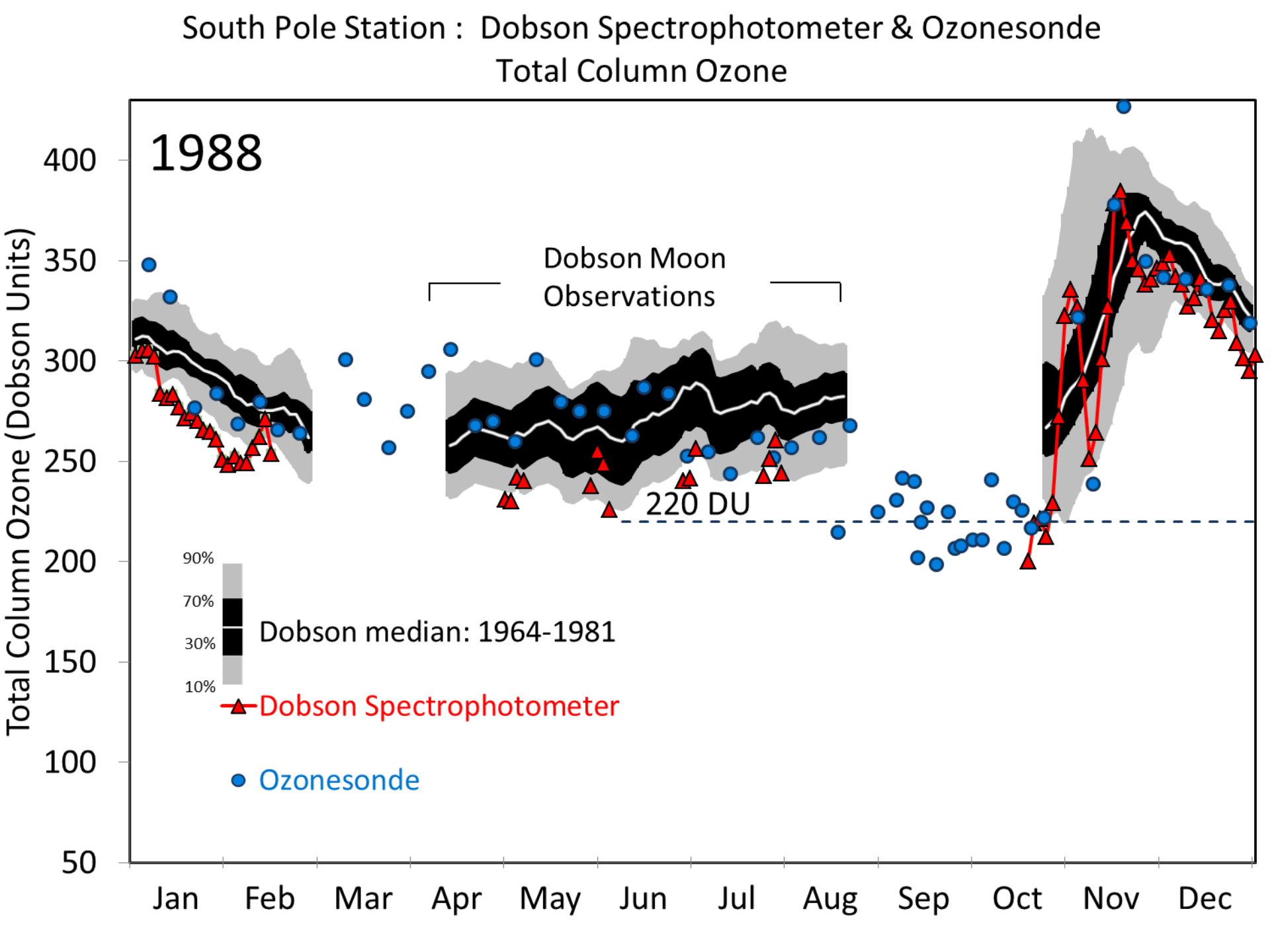
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Total Column Ozone
1988
Dobson Moon
Observations
220 DU
90%
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Dobson median: 1964-1981
Dobson Spectrophotometer
Ozonesonde
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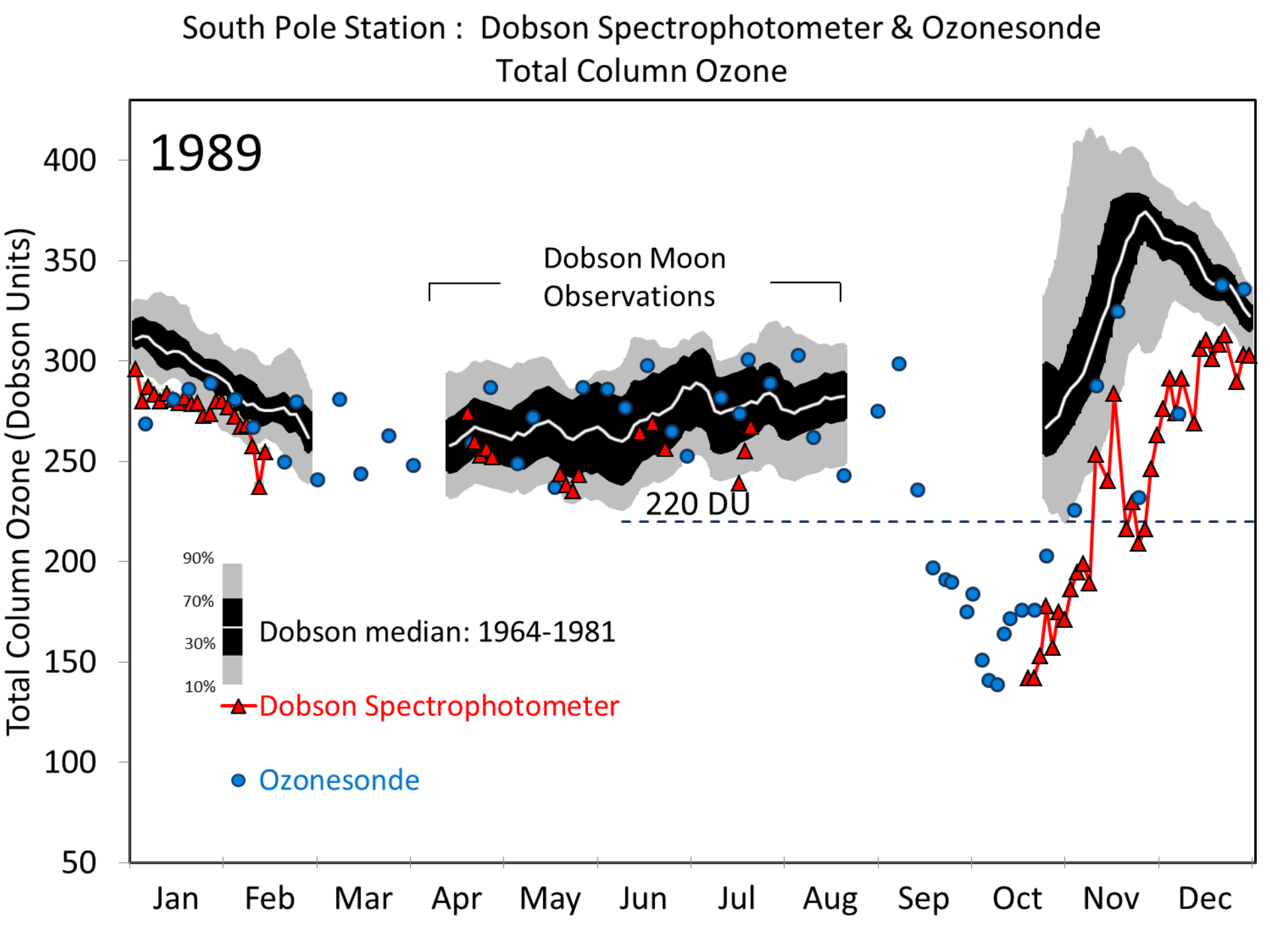
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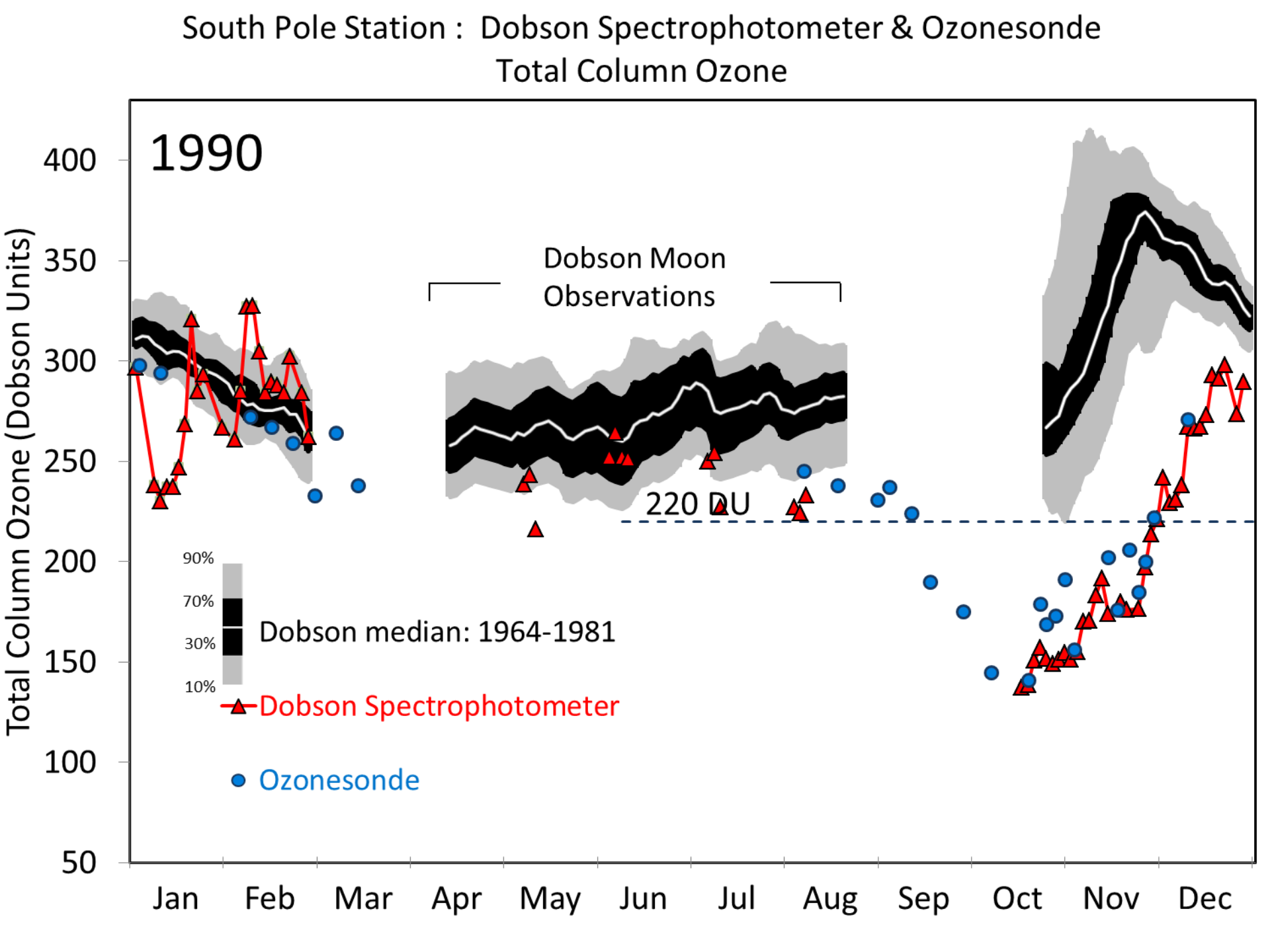
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1990
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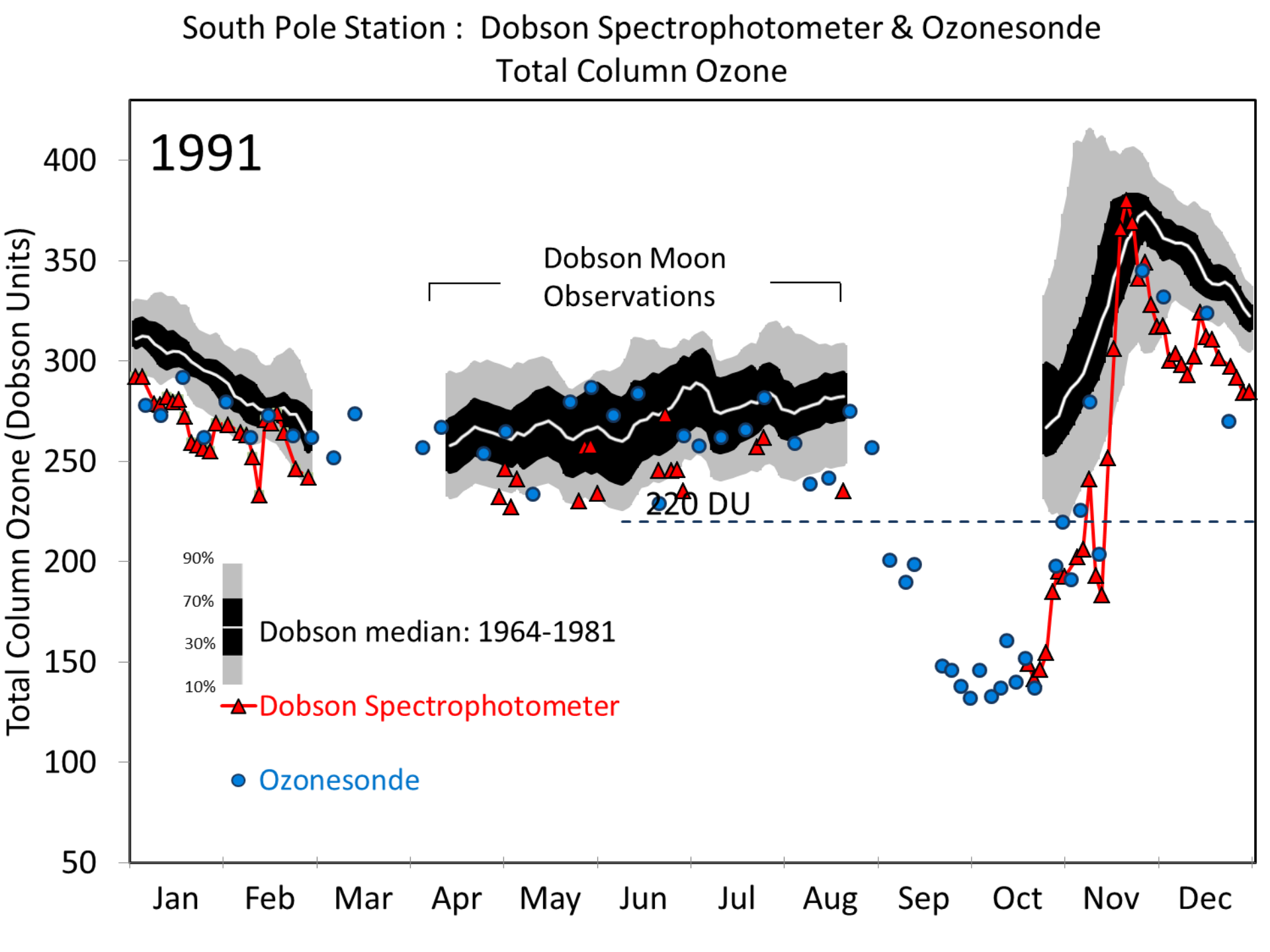
South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
1991
Total Column Ozone (Dobson Units)
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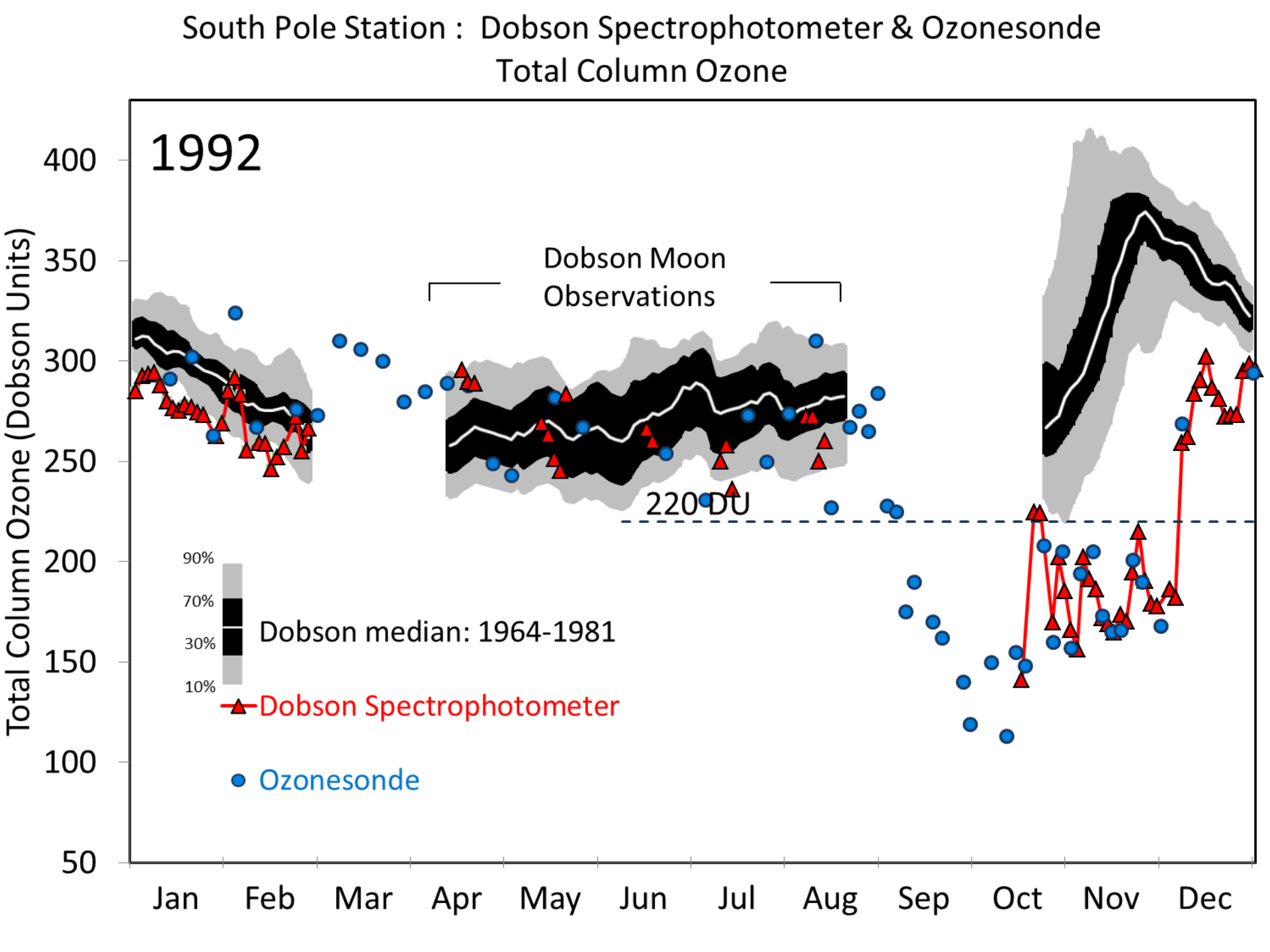
South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
1992
Total Column Ozone (Dobson Units)
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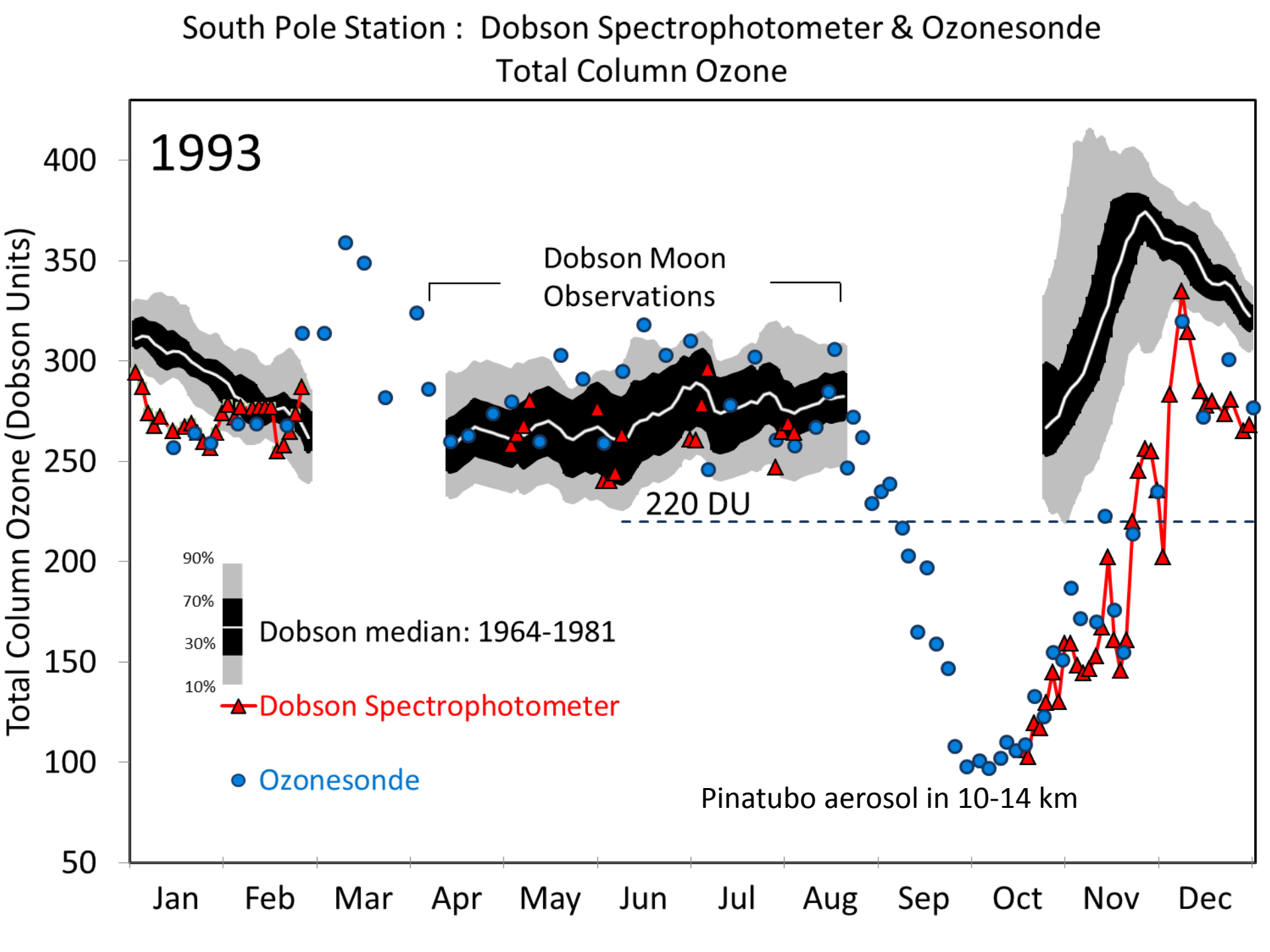
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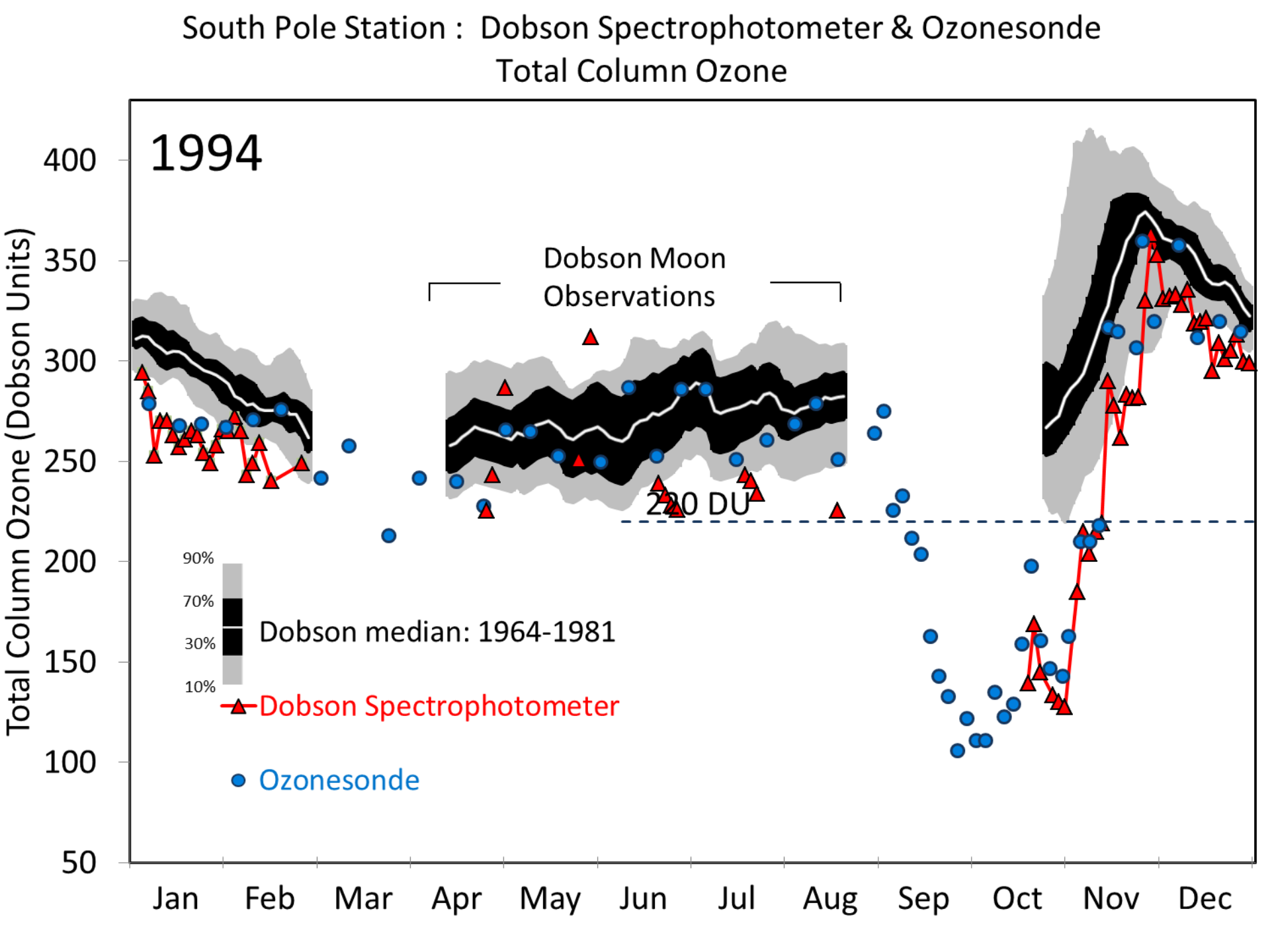
Pinatubo aerosol in 10-14 km


South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
1994
Total Column Ozone (Dobson Units)
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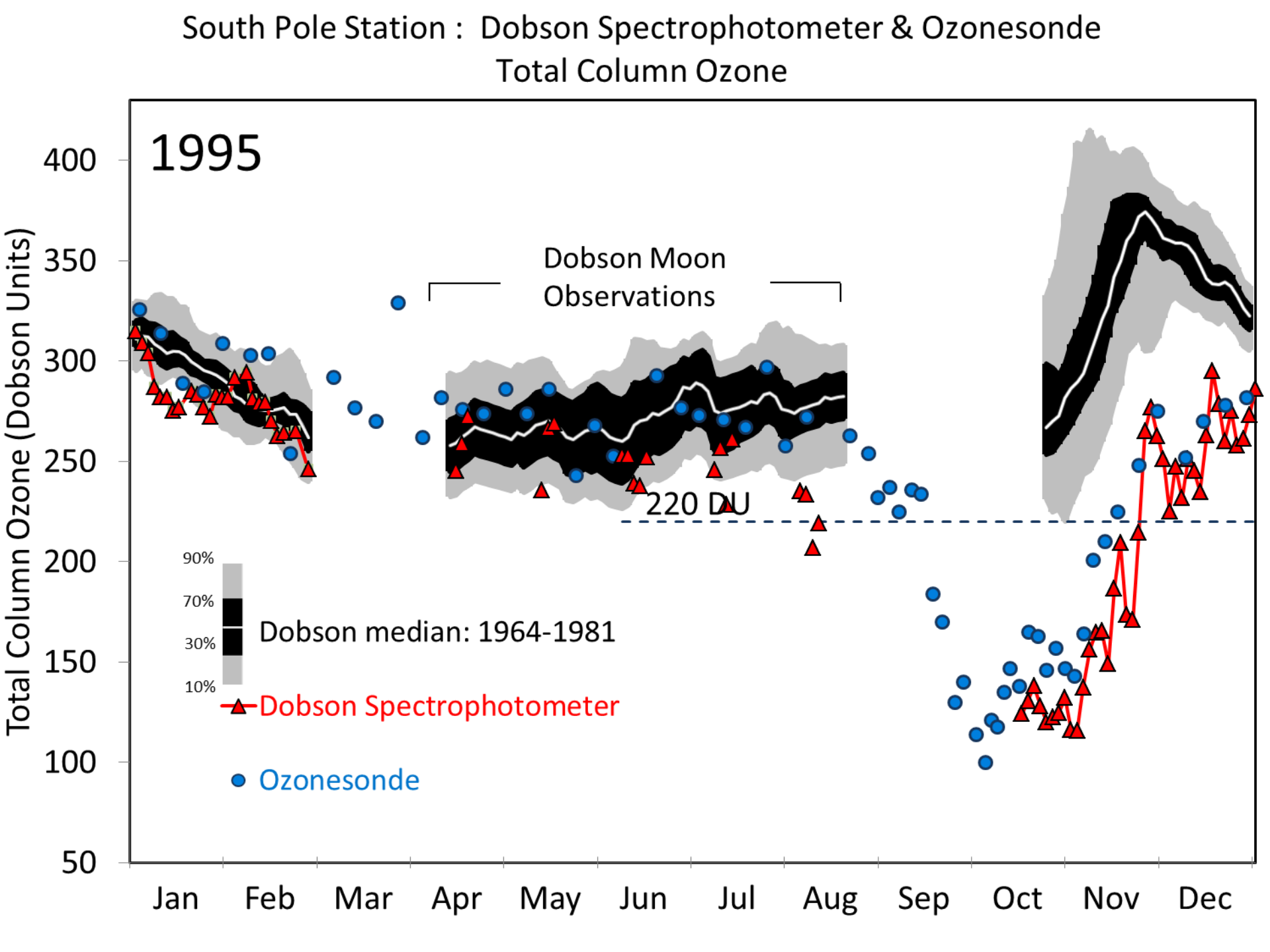
South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
1995
Total Column Ozone (Dobson Units)
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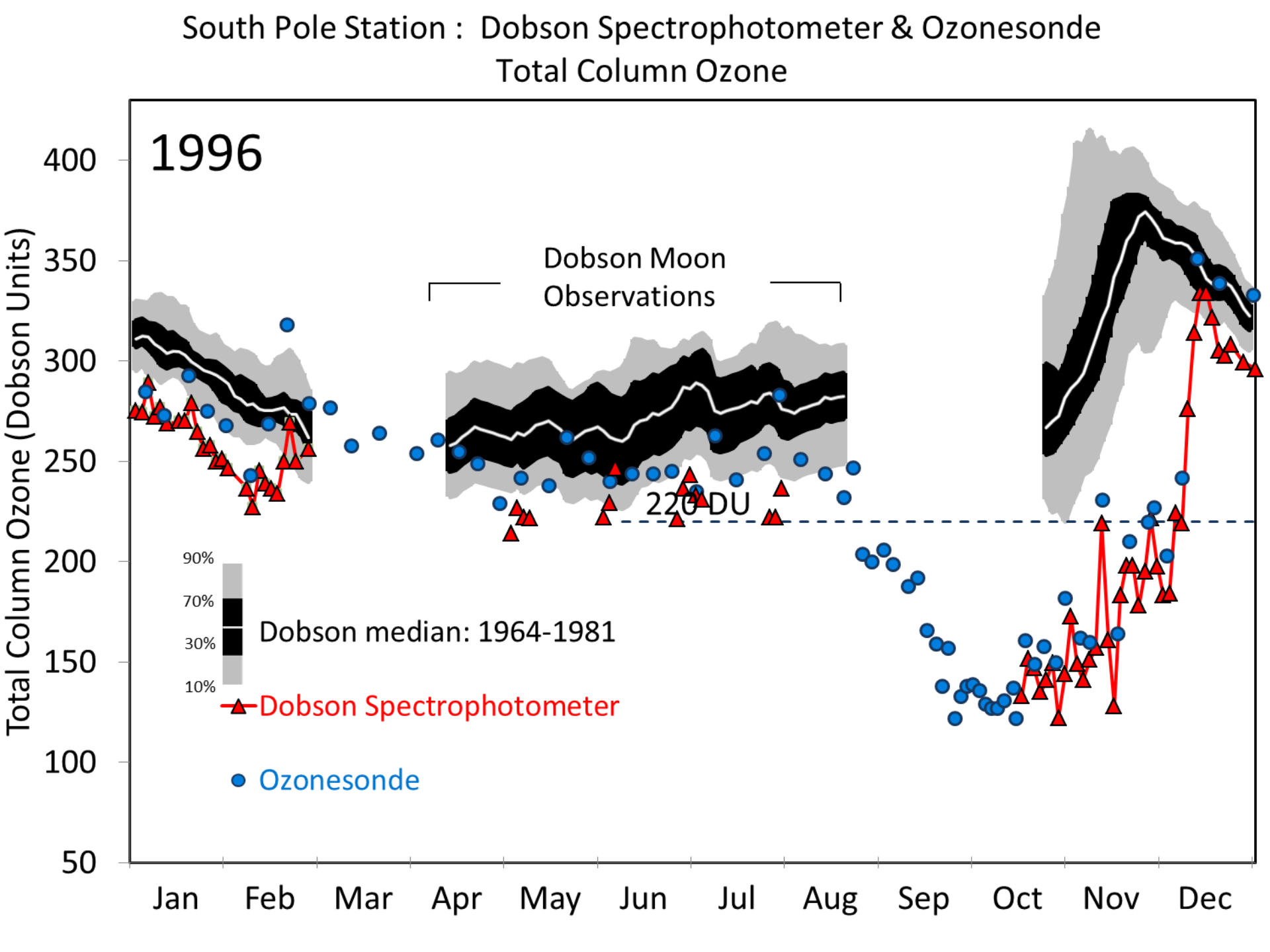
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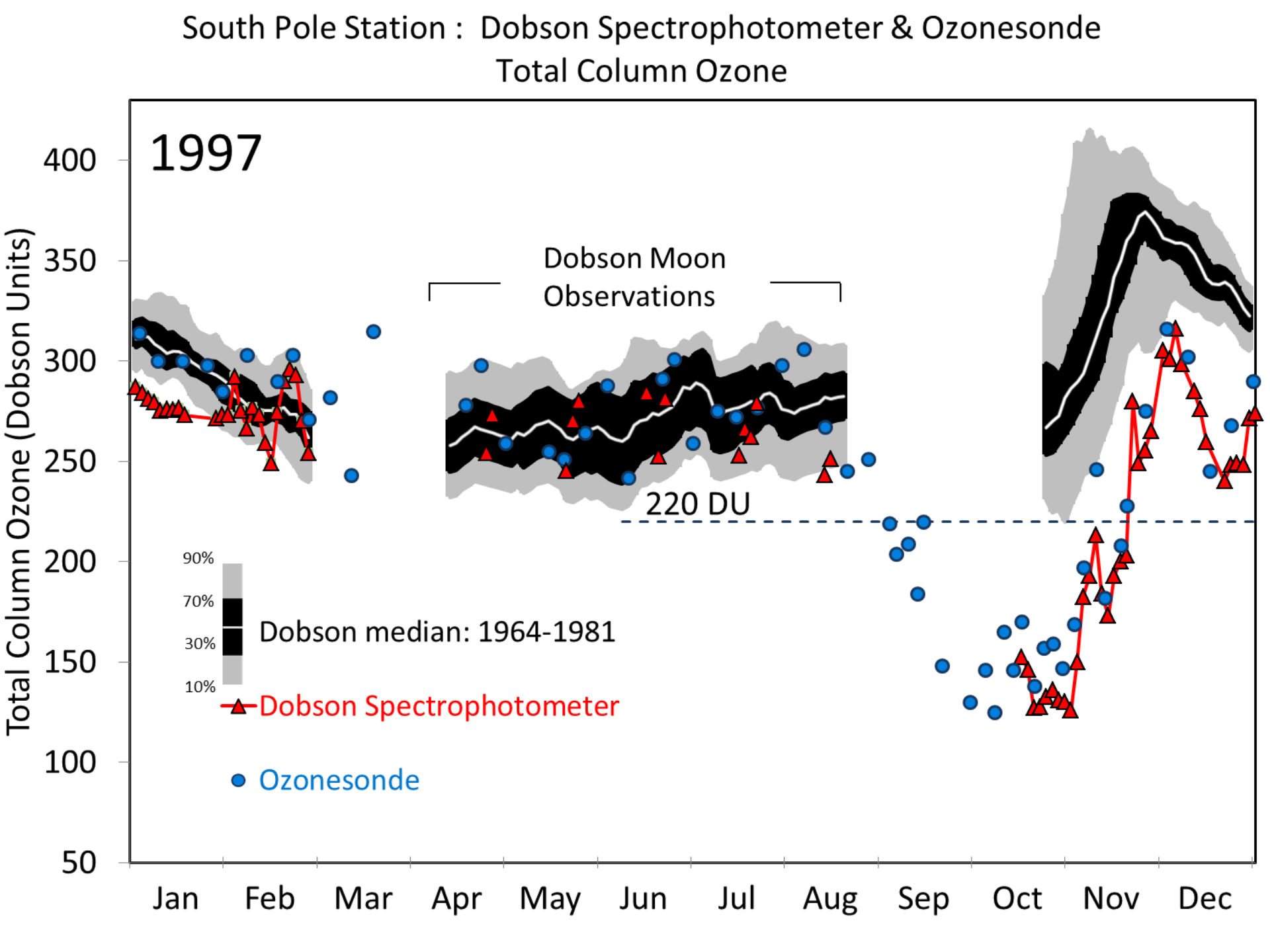
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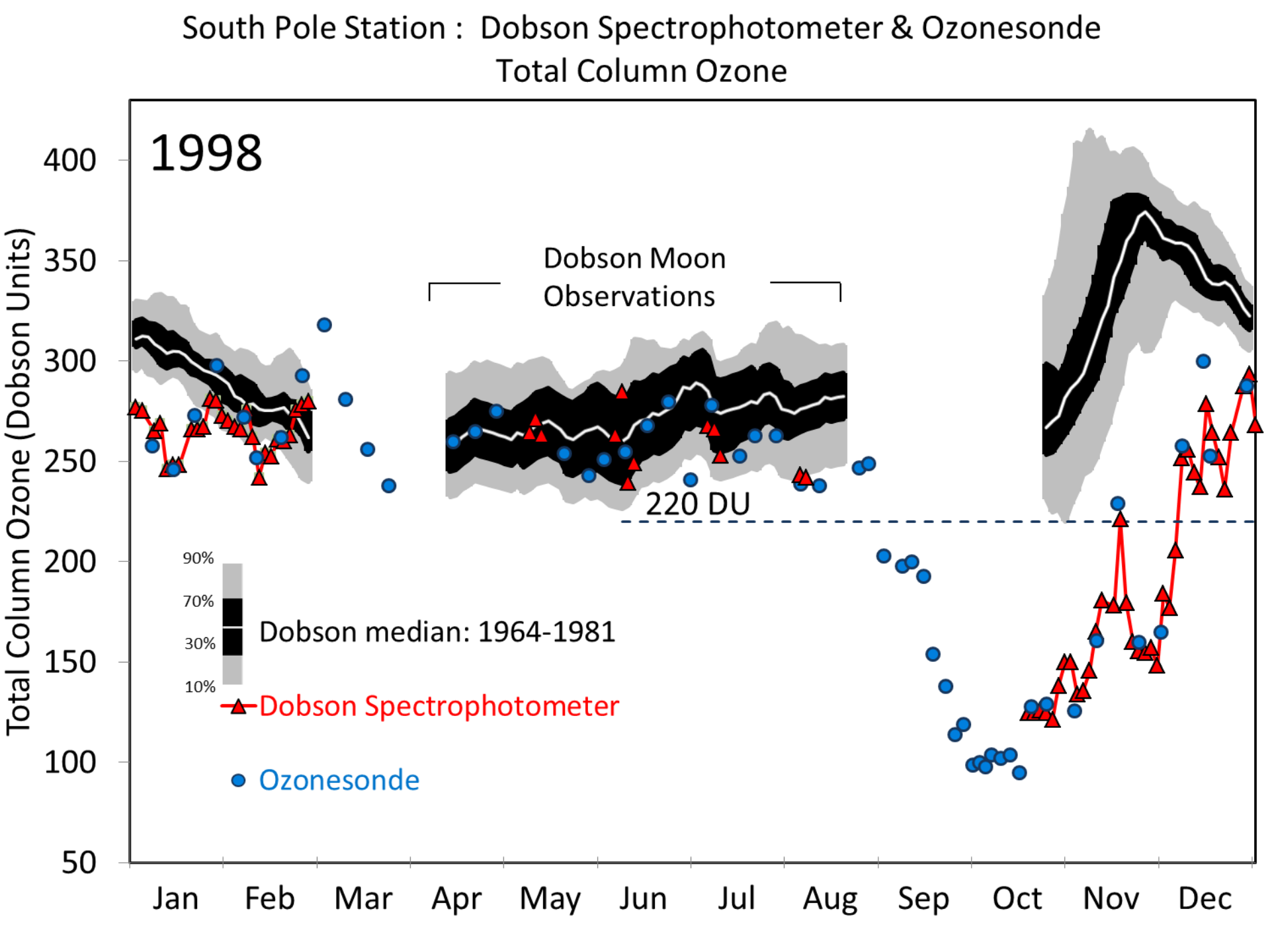
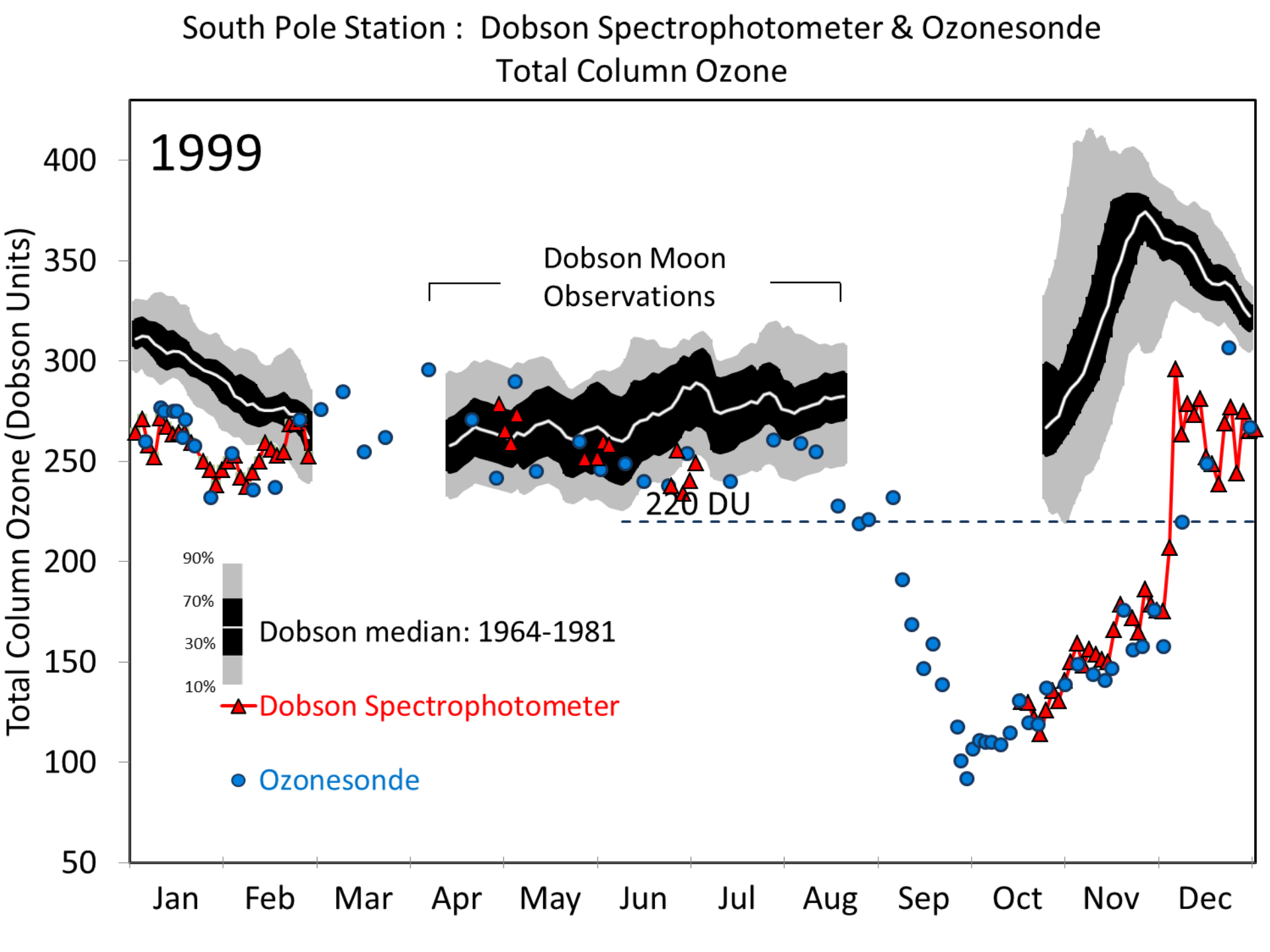
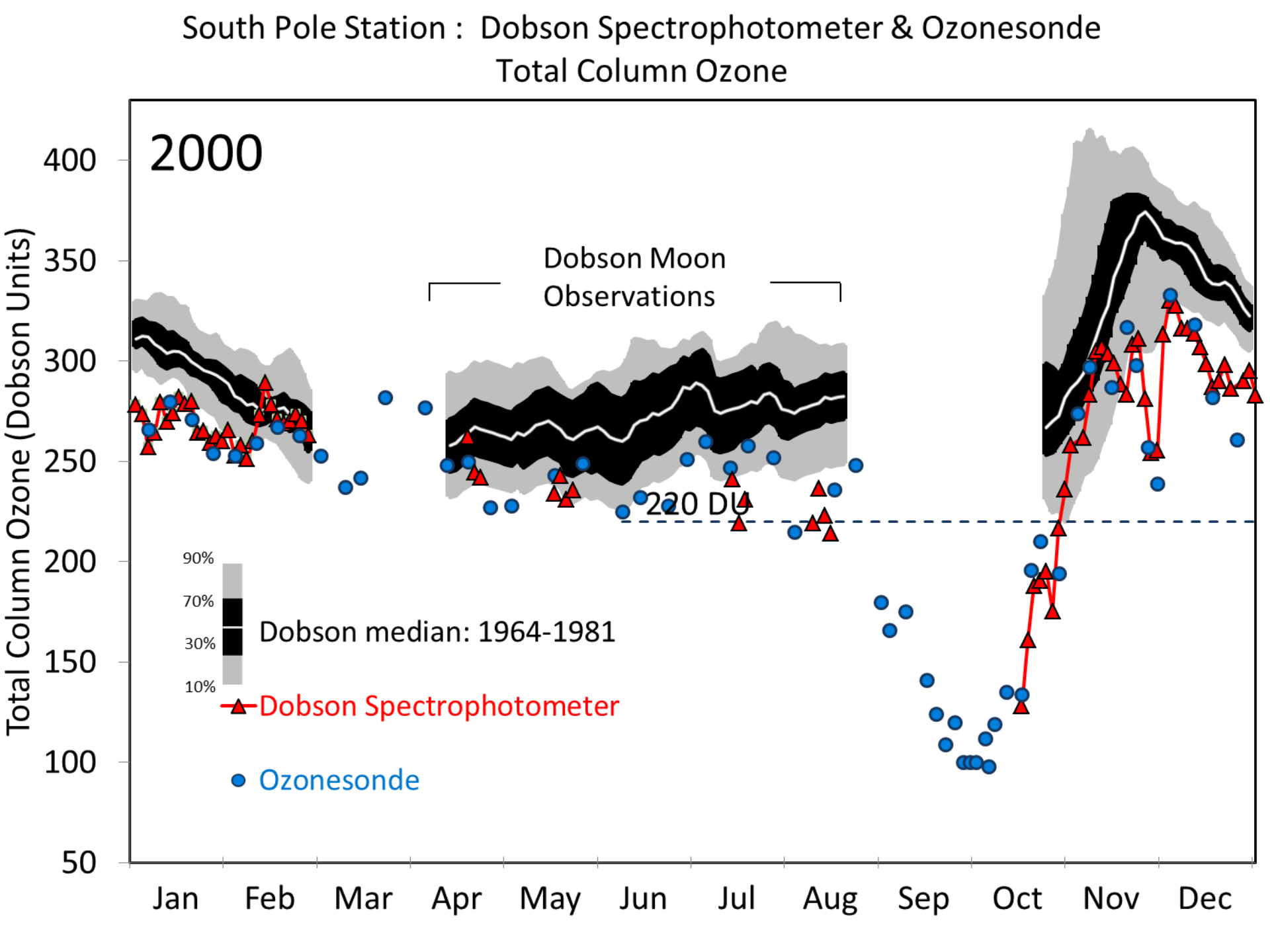
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
1998
Total Column Ozone (Dobson Units)
400
350
300
250
200
150
100
50
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Dobson Moon
Observations
220 DU
90%
70%
30%
10%
Dobson median: 1964-1981
Dobson Spectrophotometer
Ozonesonde


South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
1999
Total Column Ozone (Dobson Units)
400
350
300
250
200
150
100
50
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Dobson Moon
Observations
220 DU
90%
70%
30%
10%
Dobson median: 1964-1981
Dobson Spectrophotometer
Ozonesonde


South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
2000
Dobson Moon
Observations
220 DU
90%
70%
30%
10%
Dobson median: 1964-1981
Dobson Spectrophotometer
Ozonesonde
Total Column Ozone (Dobson Units)
400
350
300
250
200
150
100
50
Jan
Feb
Mar
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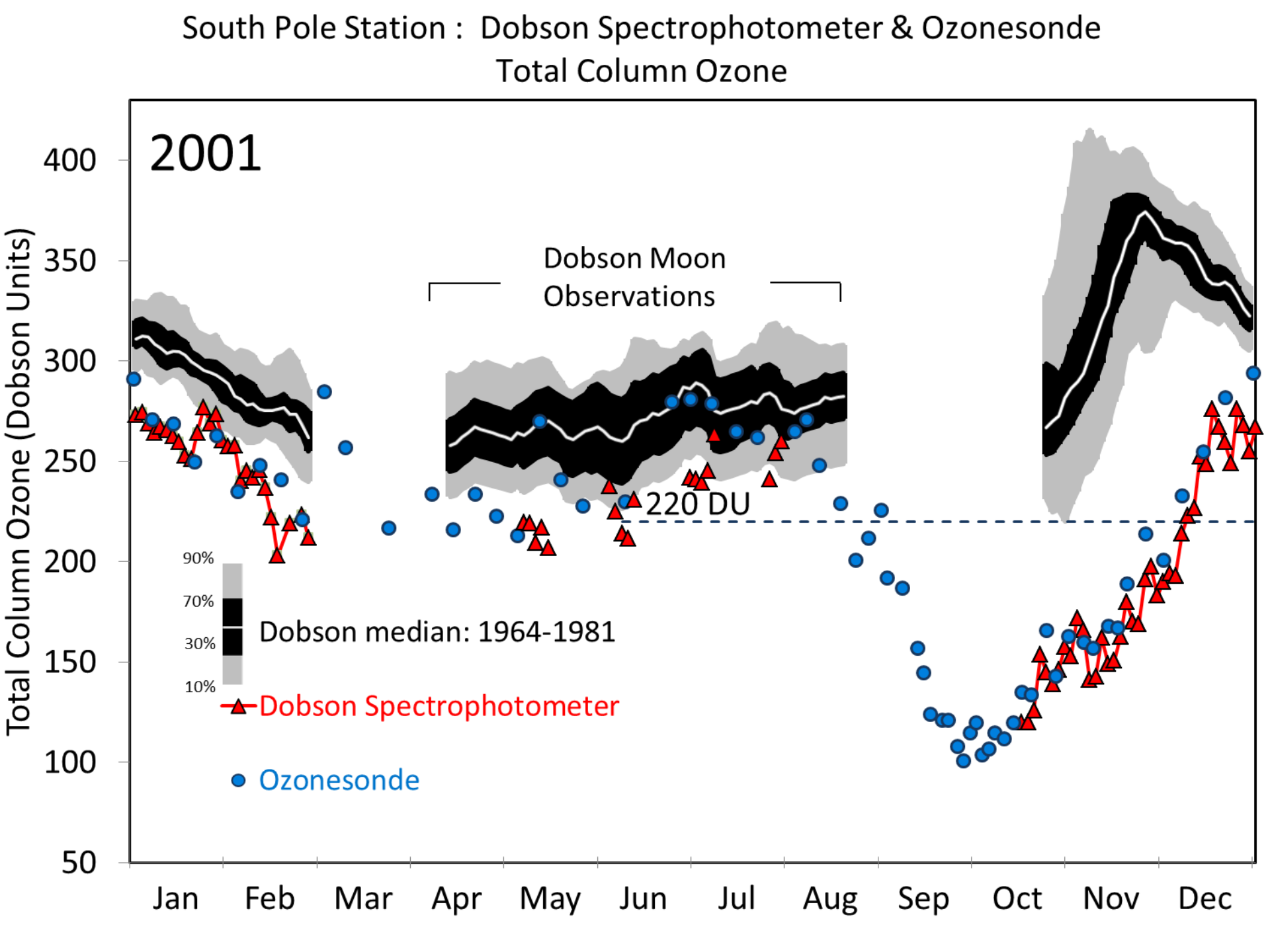
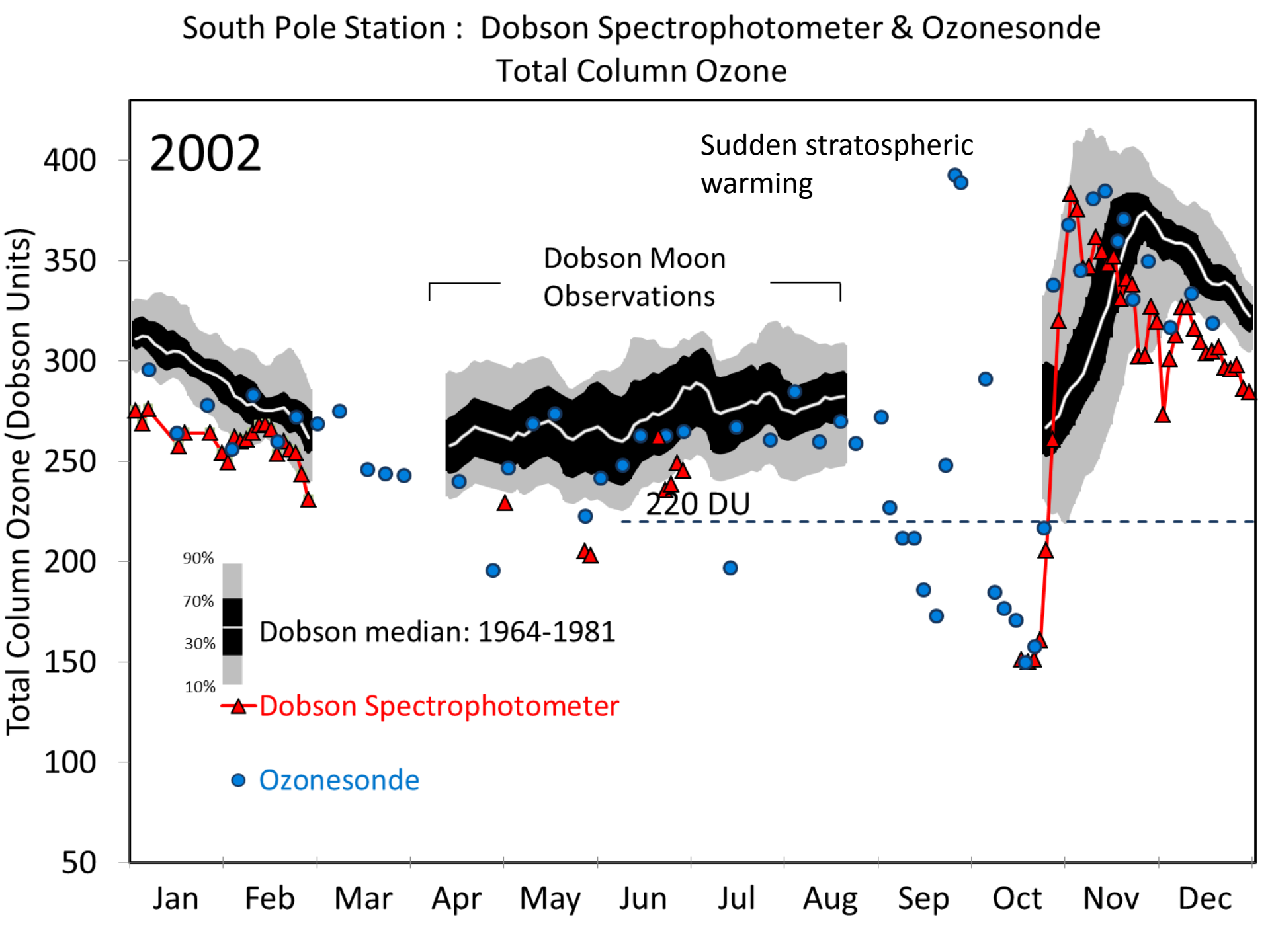
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
2001
Total Column Ozone (Dobson Units)
400
350
300
250
200
150
100
50
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Dobson Moon
Observations
220 DU
90%
70%
30%
10%
Dobson median: 1964-1981
Dobson Spectrophotometer
Ozonesonde


South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
2002
Sudden stratospheric warming
Dobson Moon Observations
220 DU
90%
70%
30%
10%
Dobson median: 1964-1981
Dobson Spectrophotometer
Ozonesonde
Total Column Ozone (Dobson Units)
400
350
300
250
200
150
100
50
Jan
Feb
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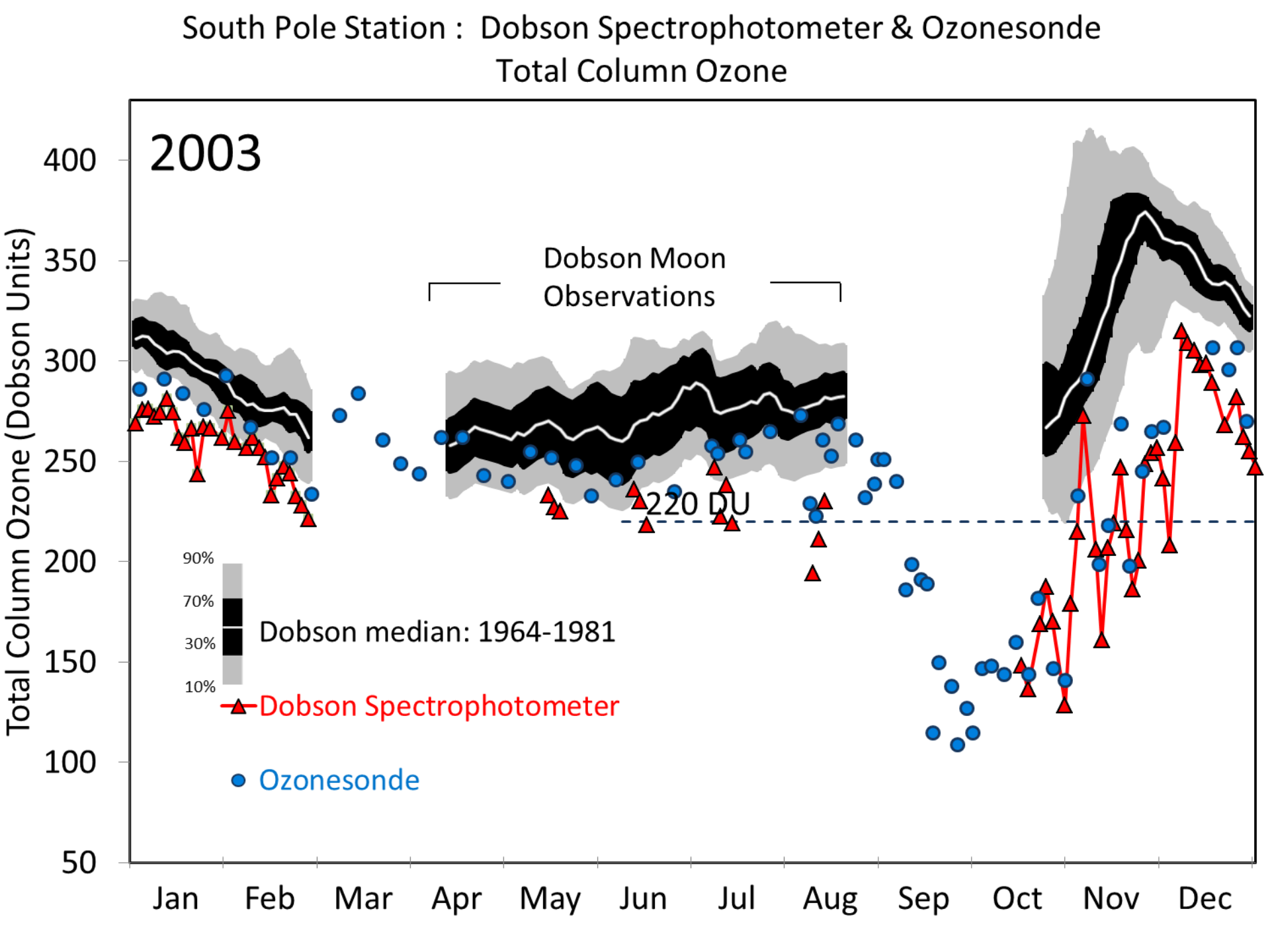
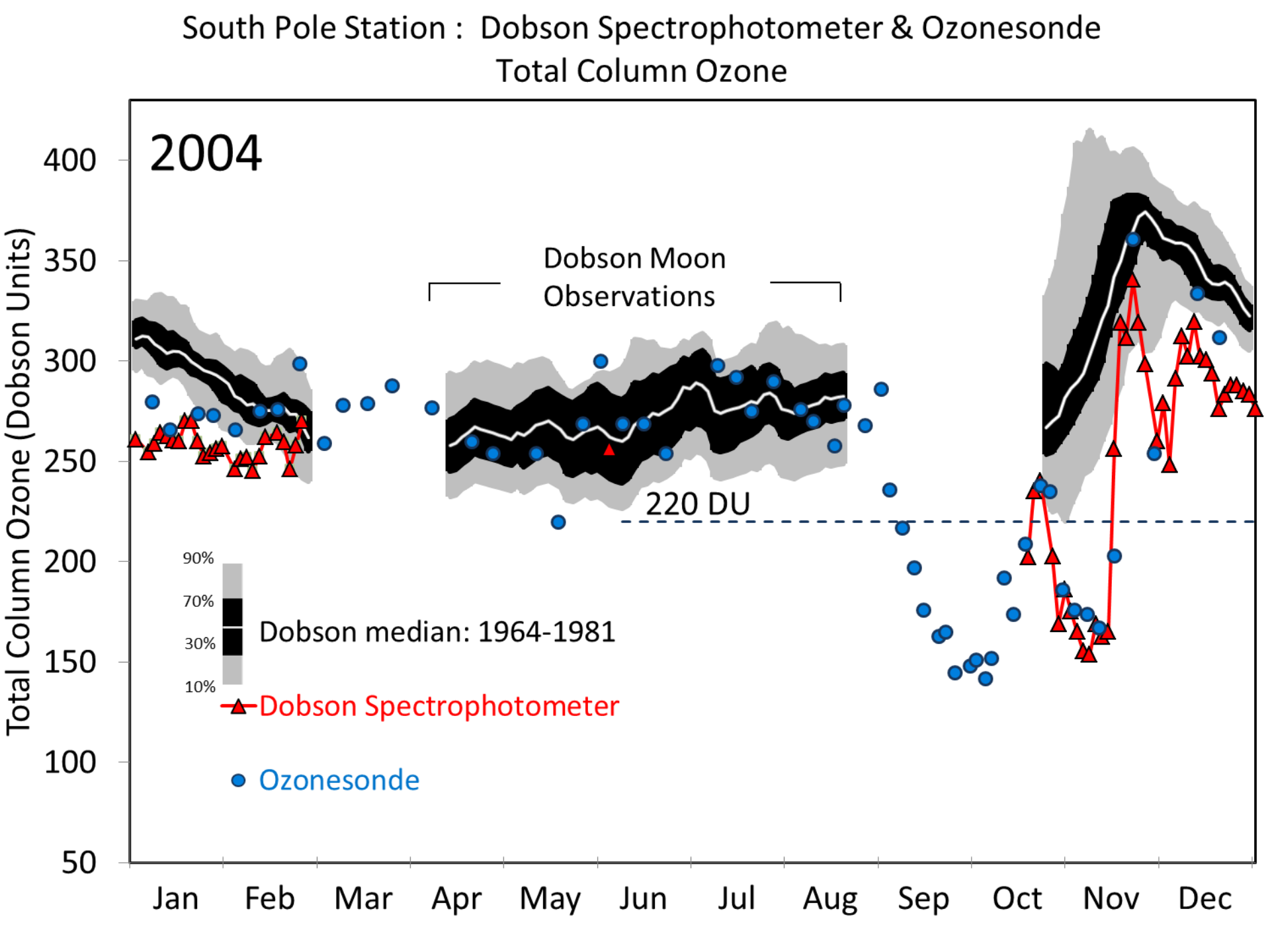
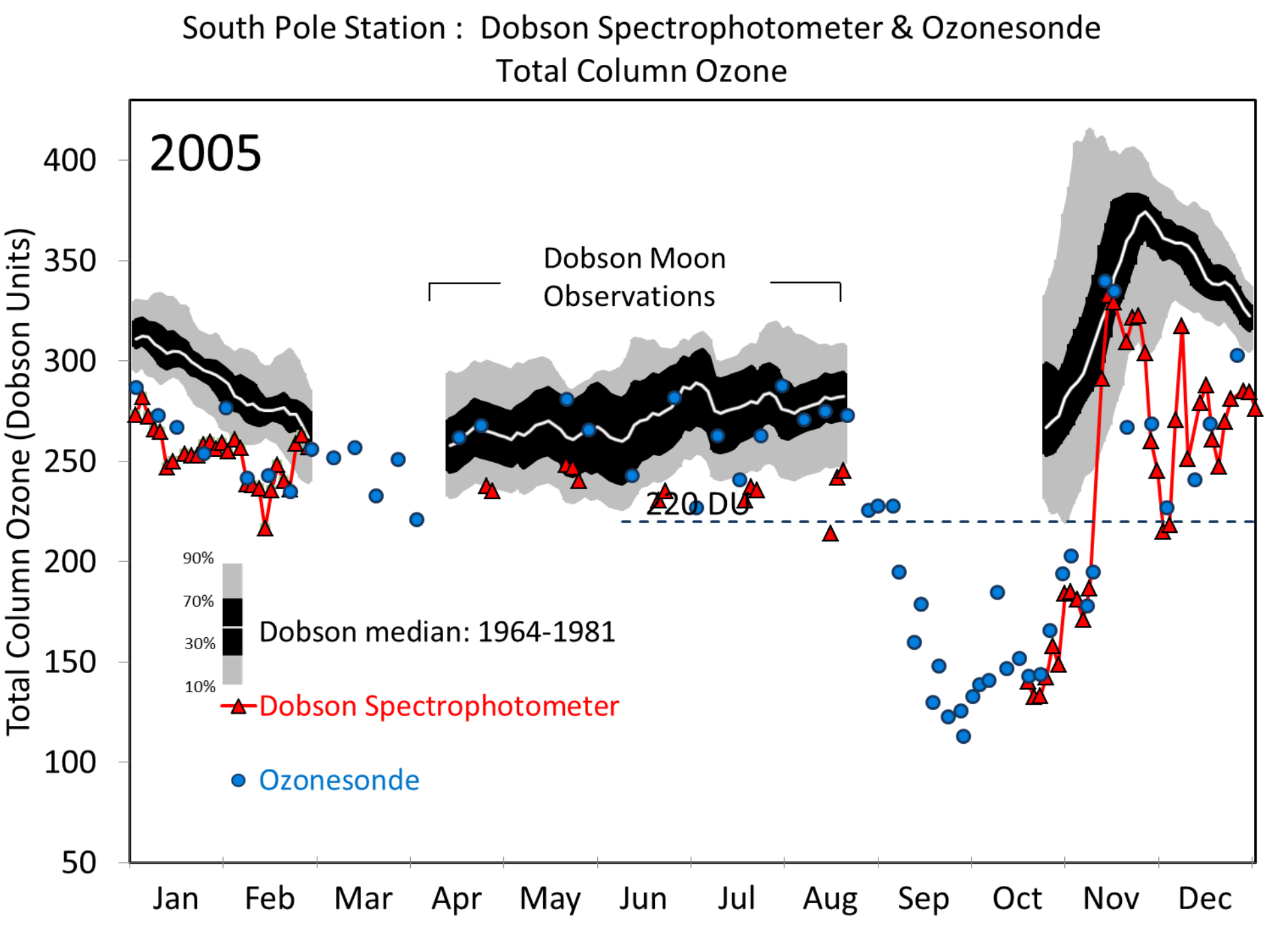
Sep
Oct
Nov
Dec


South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
2003
Total Column Ozone (Dobson Units)
400
350
300
250
200
150
100
50
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Dobson Moon
Observations
220 DU
90%
70%
30%
10%
Dobson median: 1964-1981
Dobson Spectrophotometer
Ozonesonde


South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
2004
Total Column Ozone (Dobson Units)
400
350
300
250
200
150
100
50
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Dobson Moon
Observations
220 DU
90%
70%
30%
10%
Dobson median: 1964-1981
Dobson Spectrophotometer
Ozonesonde


South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
2005
Total Column Ozone (Dobson Units)
400
350
300
250
200
150
100
50
Jan
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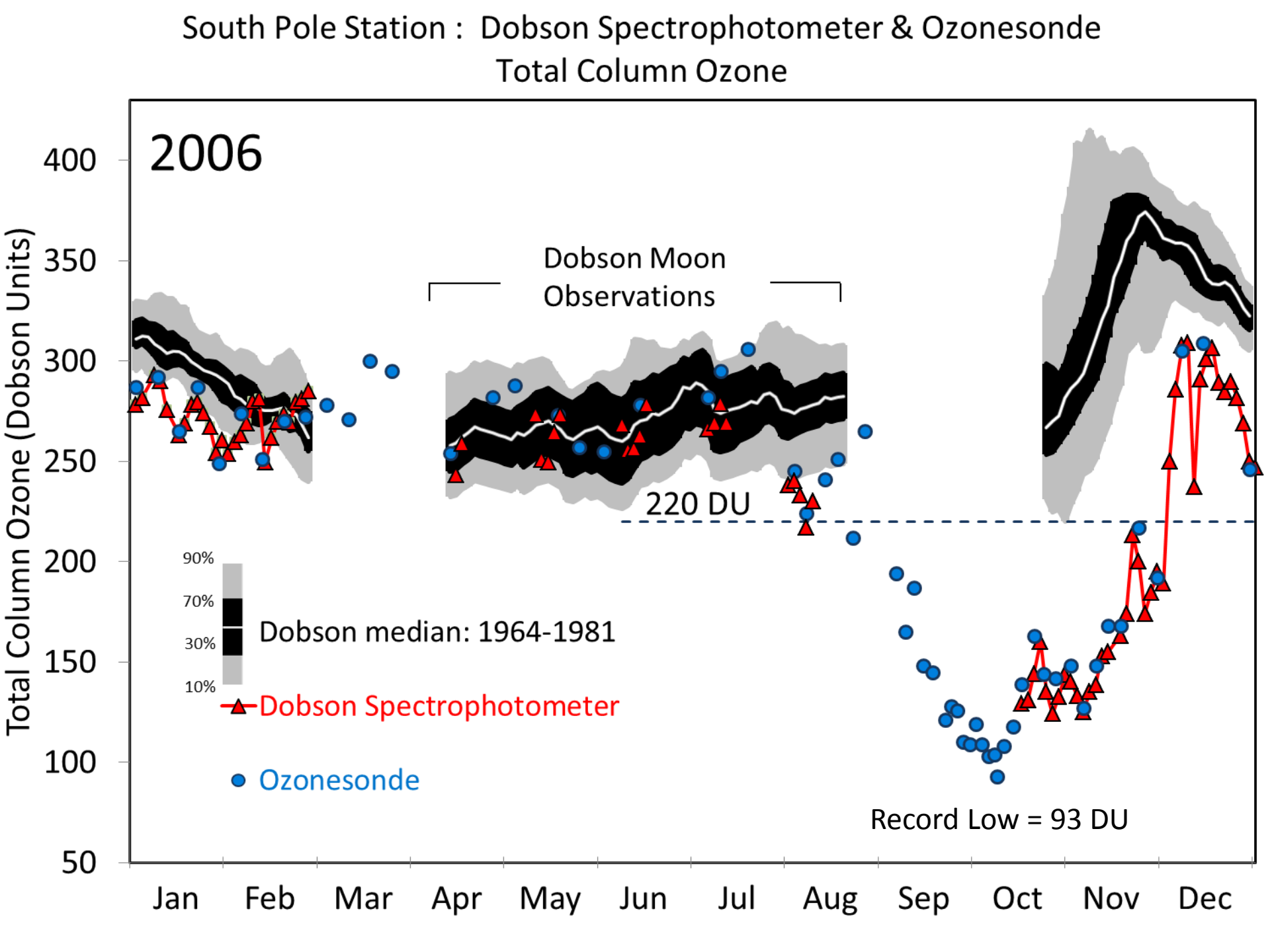
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Dobson Moon
Observations
220 DU
90%
70%
30%
10%
Dobson median: 1964-1981
Dobson Spectrophotometer
Ozonesonde


South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
2006
Total Column Ozone (Dobson Units)
400
350
300
250
200
150
100
50
Jan
Feb
Mar
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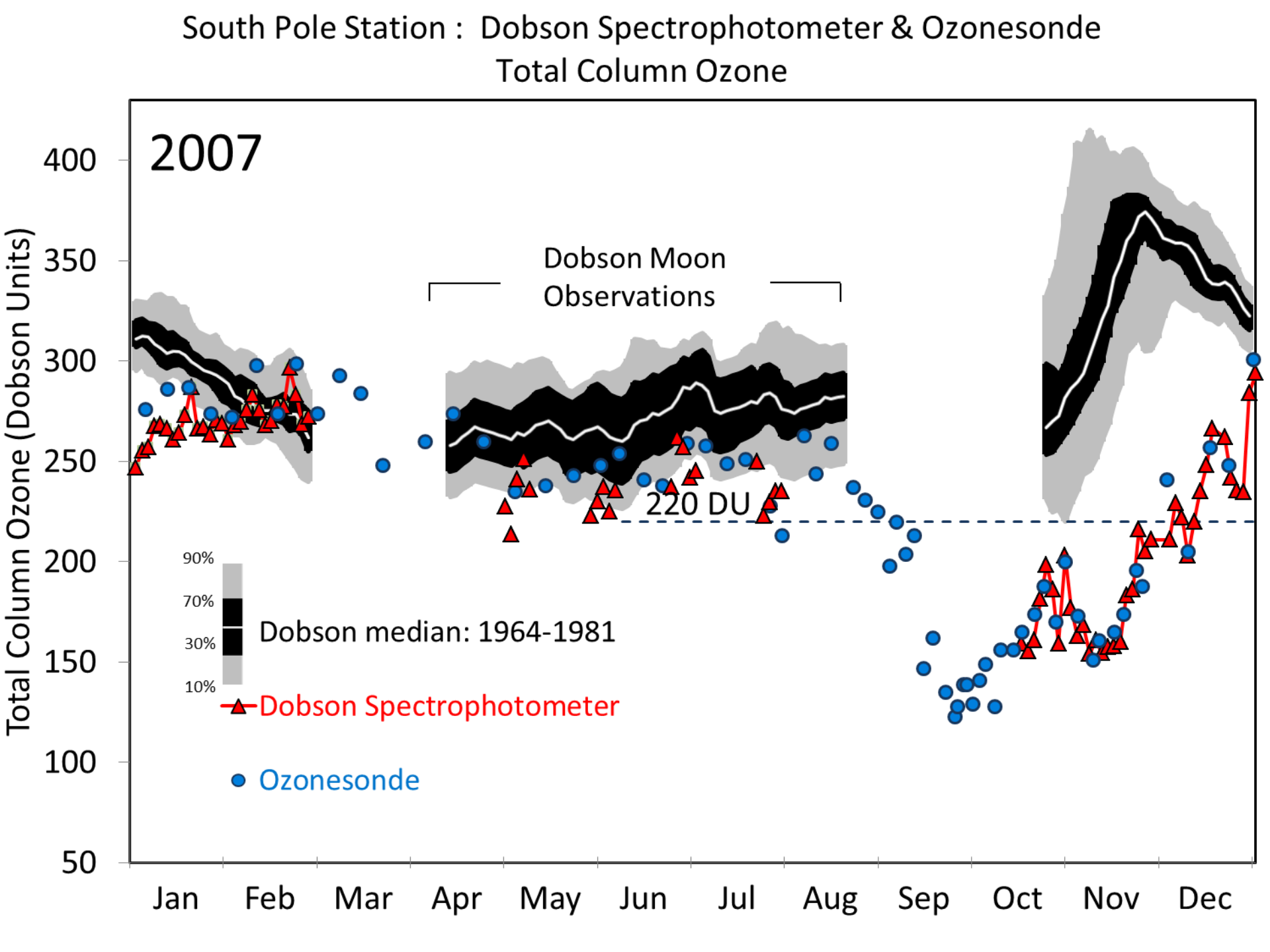
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Dobson Moon
Observations
220 DU
90%
70%
30%
10%
Dobson median: 1964-1981
Dobson Spectrophotometer
Ozonesonde
Record Low = 93 DU


South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
2007
Dobson Moon
Observations
220 DU
90%
70%
30%
10%
Dobson median: 1964-1981
Dobson Spectrophotometer
Ozonesonde
Total Column Ozone (Dobson Units)
400
350
300
250
200
150
100
50
Jan
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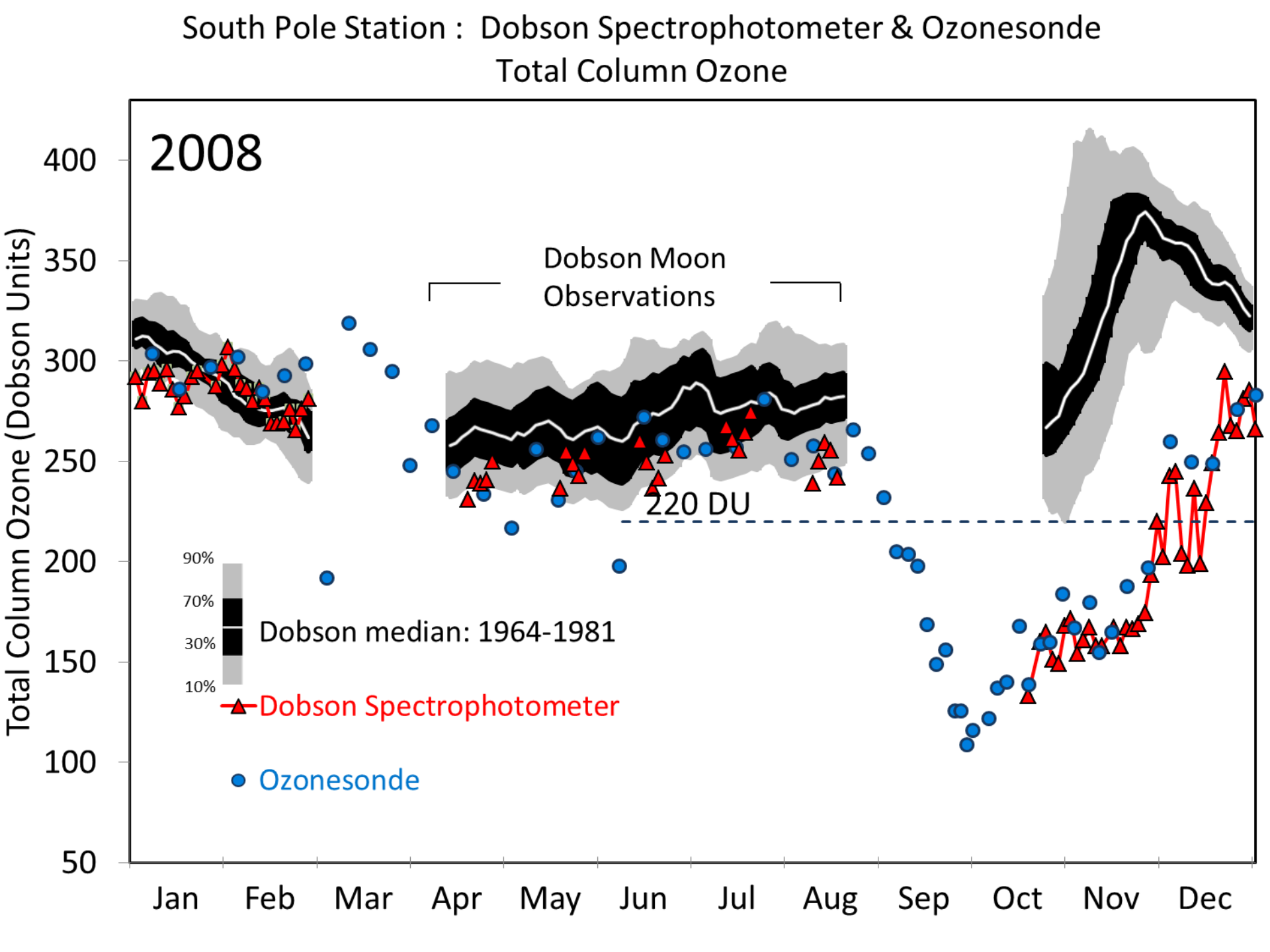
Sep
Oct
Nov
Dec


South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
2008
Dobson Moon Observations
220 DU
90%
70%
30%
10%
Dobson median: 1964-1981
Dobson Spectrophotometer
Ozonesonde
Total Column Ozone (Dobson Units)
400
350
300
250
200
150
100
50
Jan
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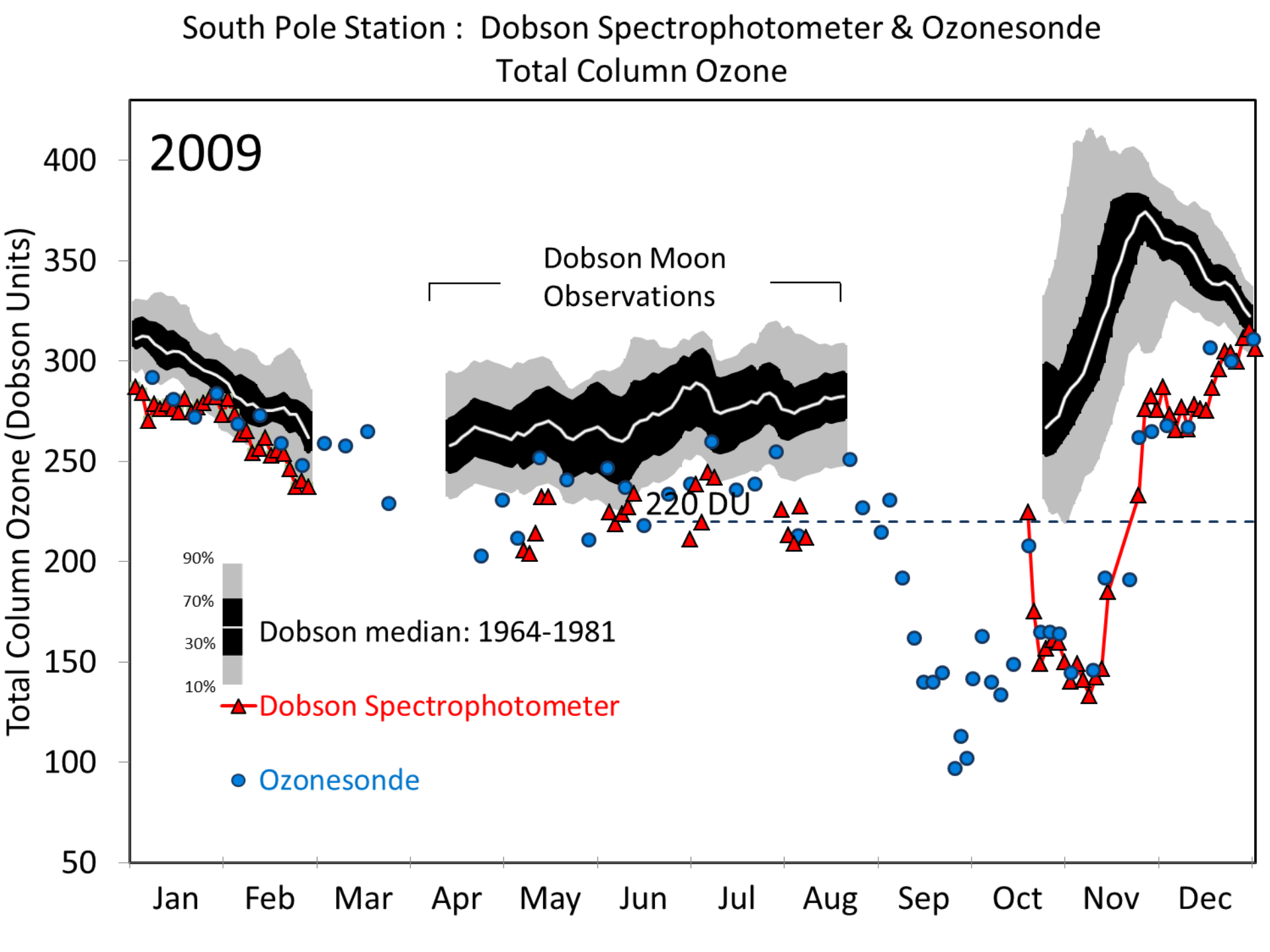
Nov
Dec


South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
2009
Dobson Moon Observations
220 DU
90%
70%
30%
10%
Dobson median: 1964-1981
Dobson Spectrophotometer
Ozonesonde
Total Column Ozone (Dobson Units)
400
350
300
250
200
150
100
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Jan
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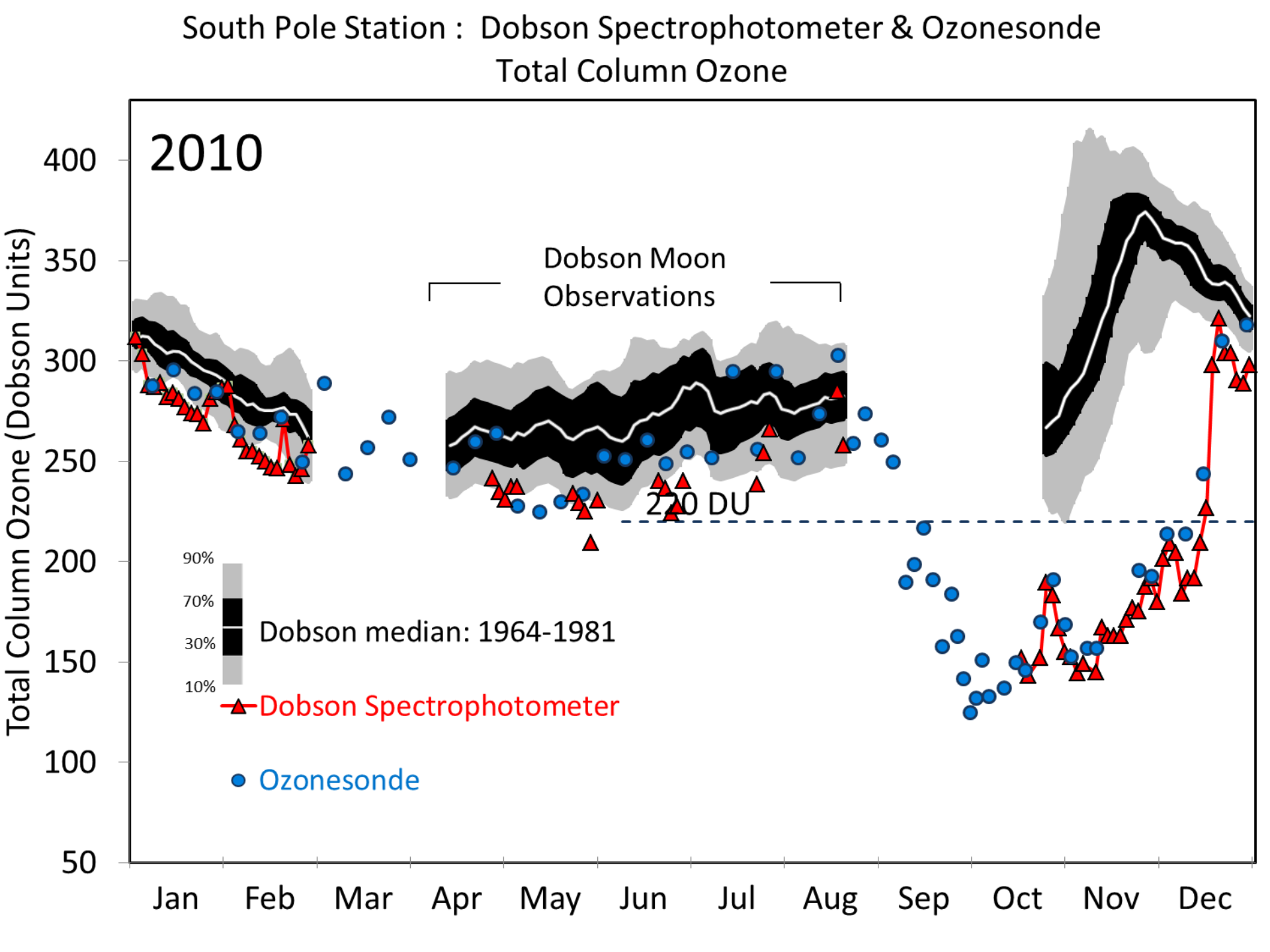
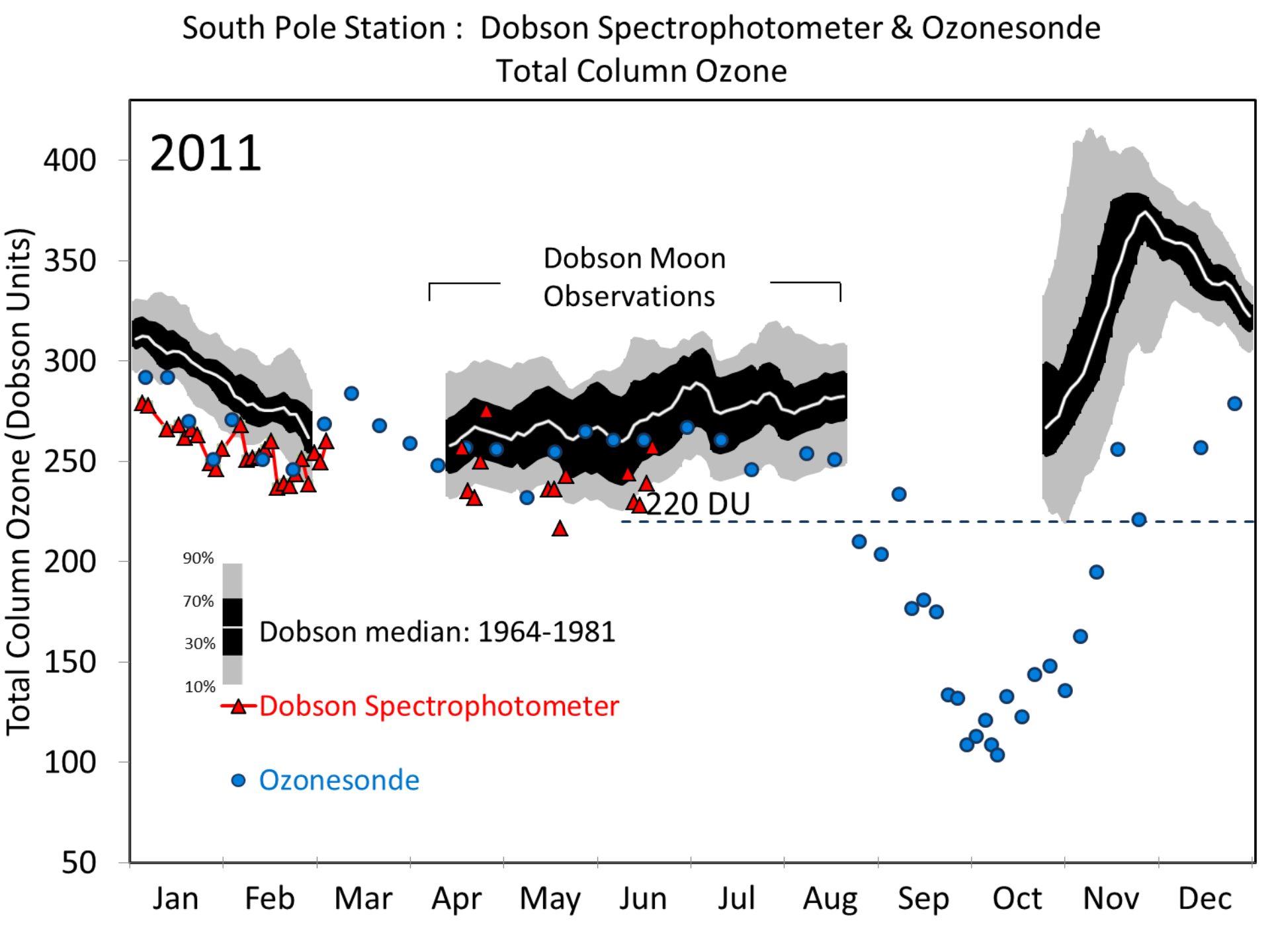

South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
2010
Total Column Ozone (Dobson Units)
400
350
300
250
200
150
100
50
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Dobson Moon
Observations
220 DU
90%
70%
30%
10%
Dobson median: 1964-1981
Dobson Spectrophotometer
Ozonesonde


South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
2011
Total Column Ozone (Dobson Units)
400
350
300
250
200
150
100
50
Jan
Feb
Mar
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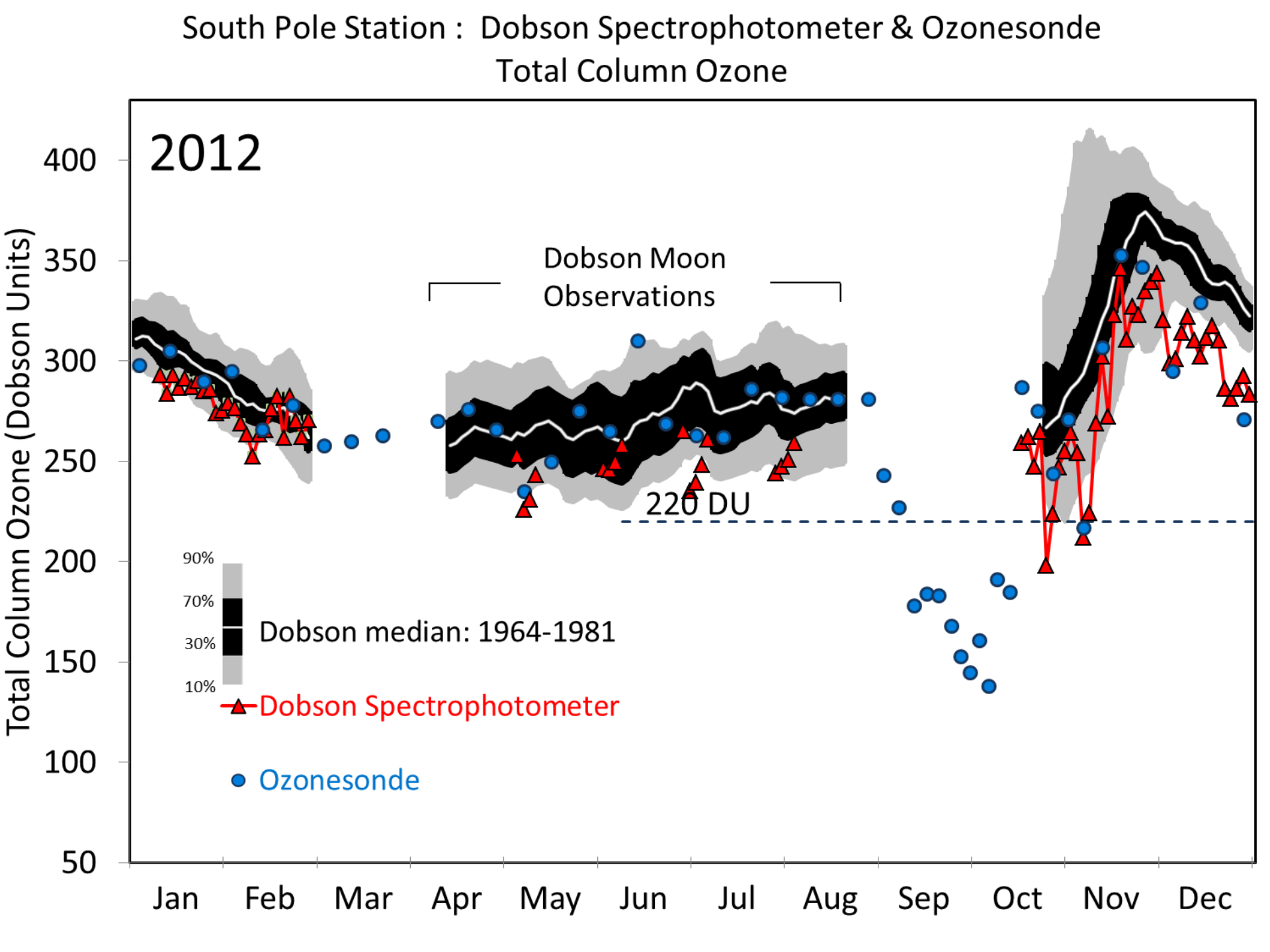
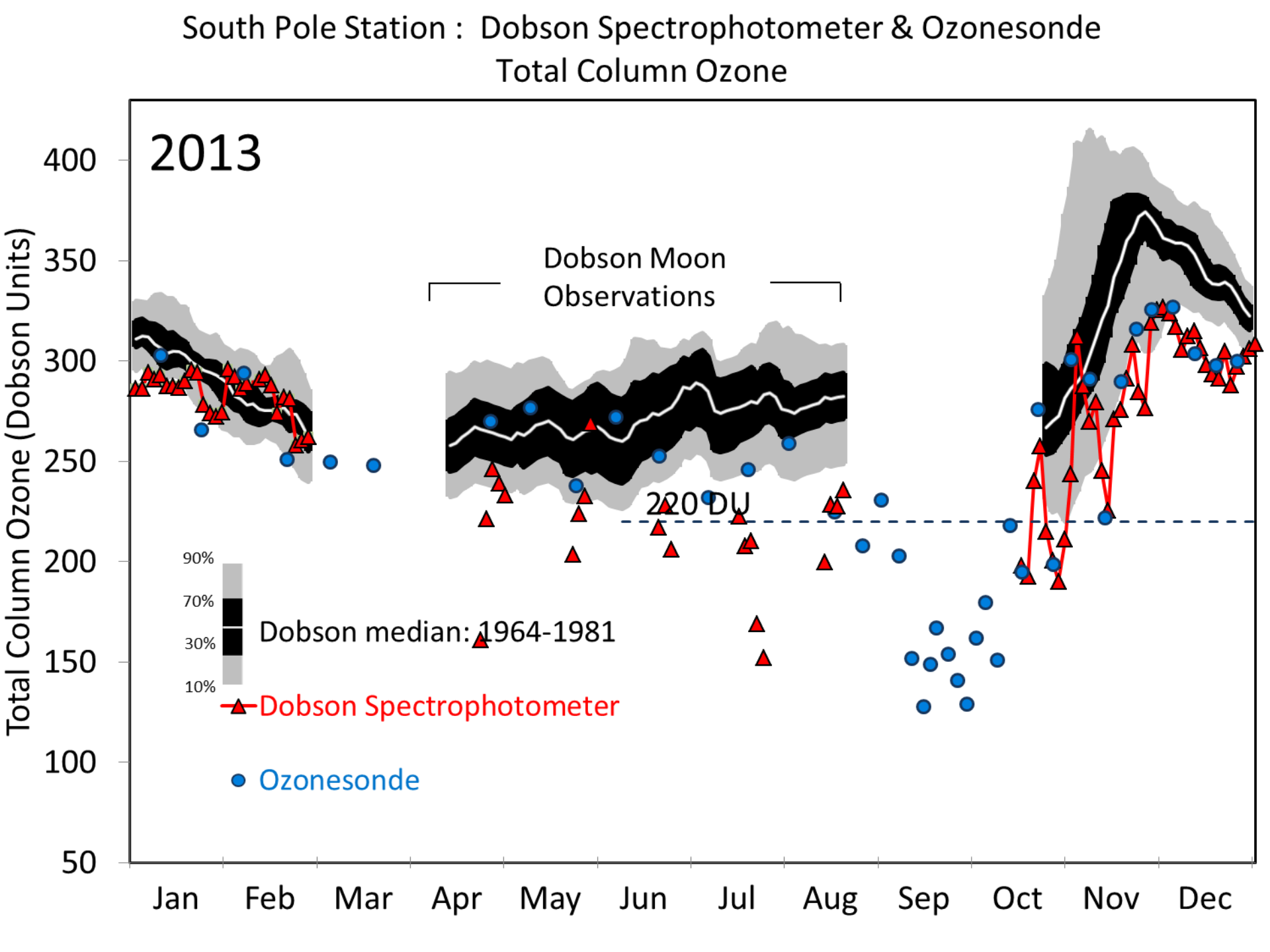
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Dobson Moon
Observations
220 DU
90%
70%
30%
10%
Dobson median: 1964-1981
Dobson Spectrophotometer
Ozonesonde


South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
2012
Total Column Ozone (Dobson Units)
400
350
300
250
200
150
100
50
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Dobson Moon
Observations
220 DU
90%
70%
30%
10%
Dobson median: 1964-1981
Dobson Spectrophotometer
Ozonesonde


South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
2013
Dobson Moon
Observations
220 DU
90%
70%
30%
10%
Dobson median: 1964-1981
Dobson Spectrophotometer
Ozonesonde
Total Column Ozone (Dobson Units)
400
350
300
250
200
150
100
50
Jan
Feb
Mar
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May
Jun
Jul
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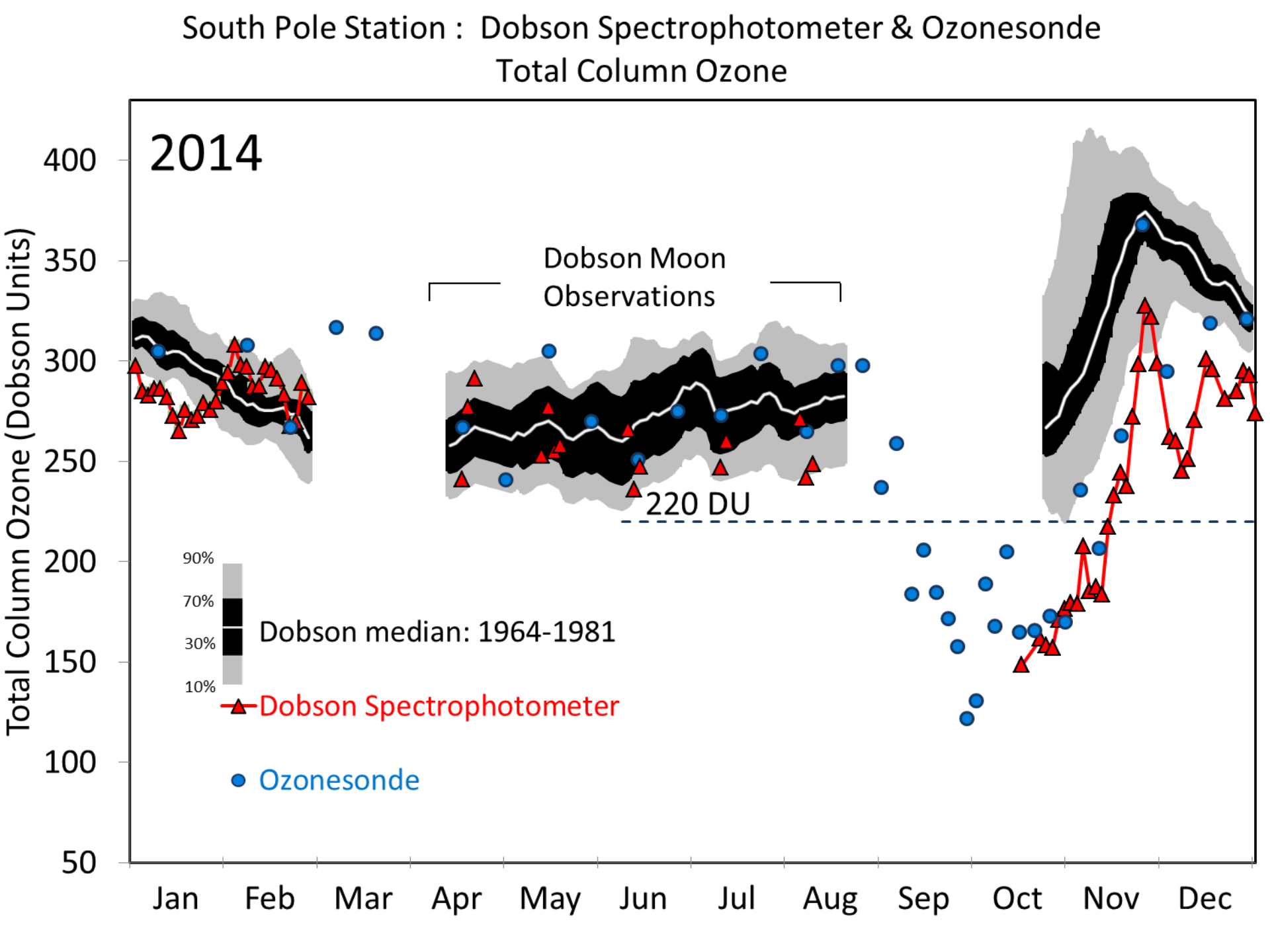
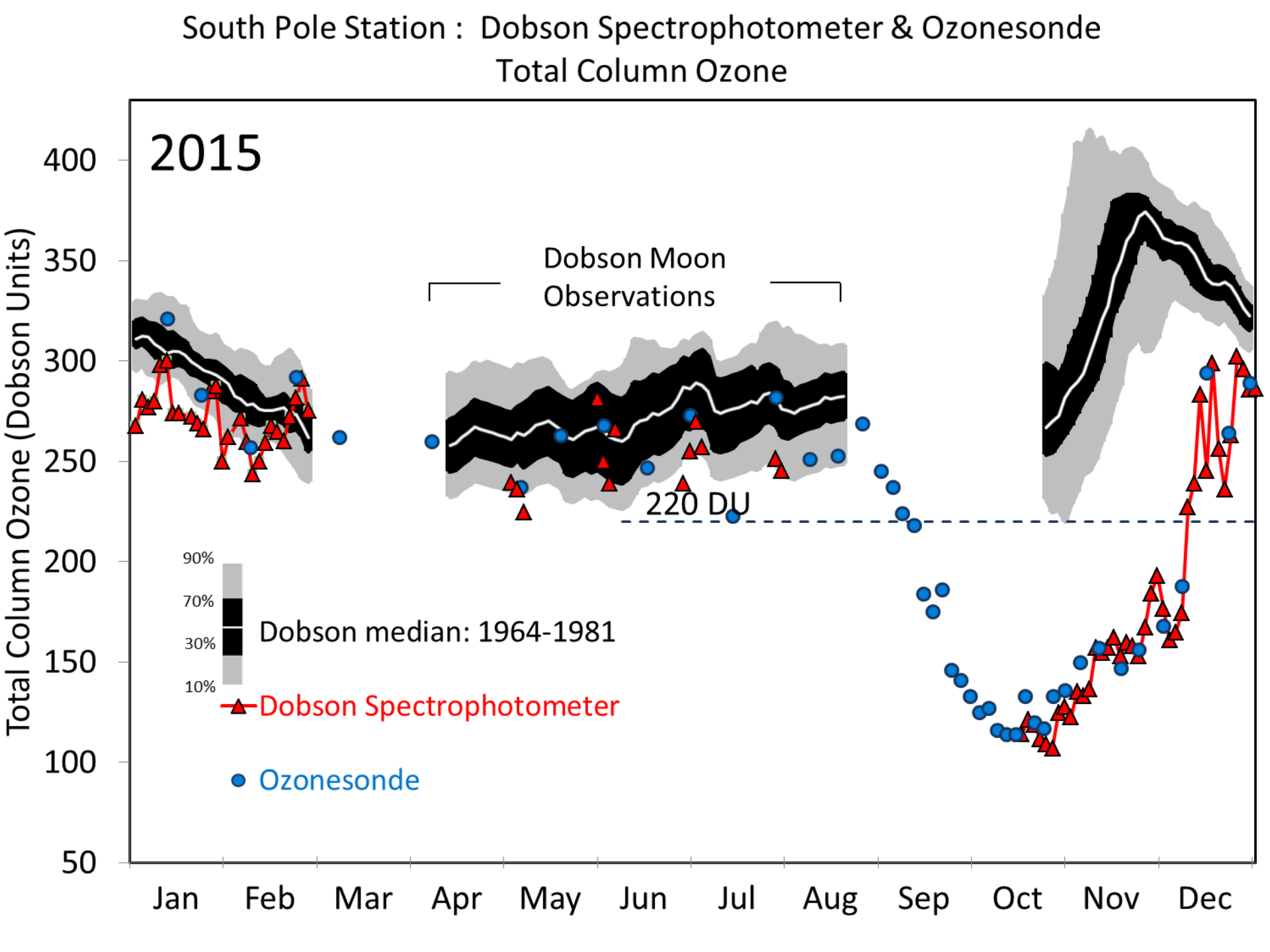
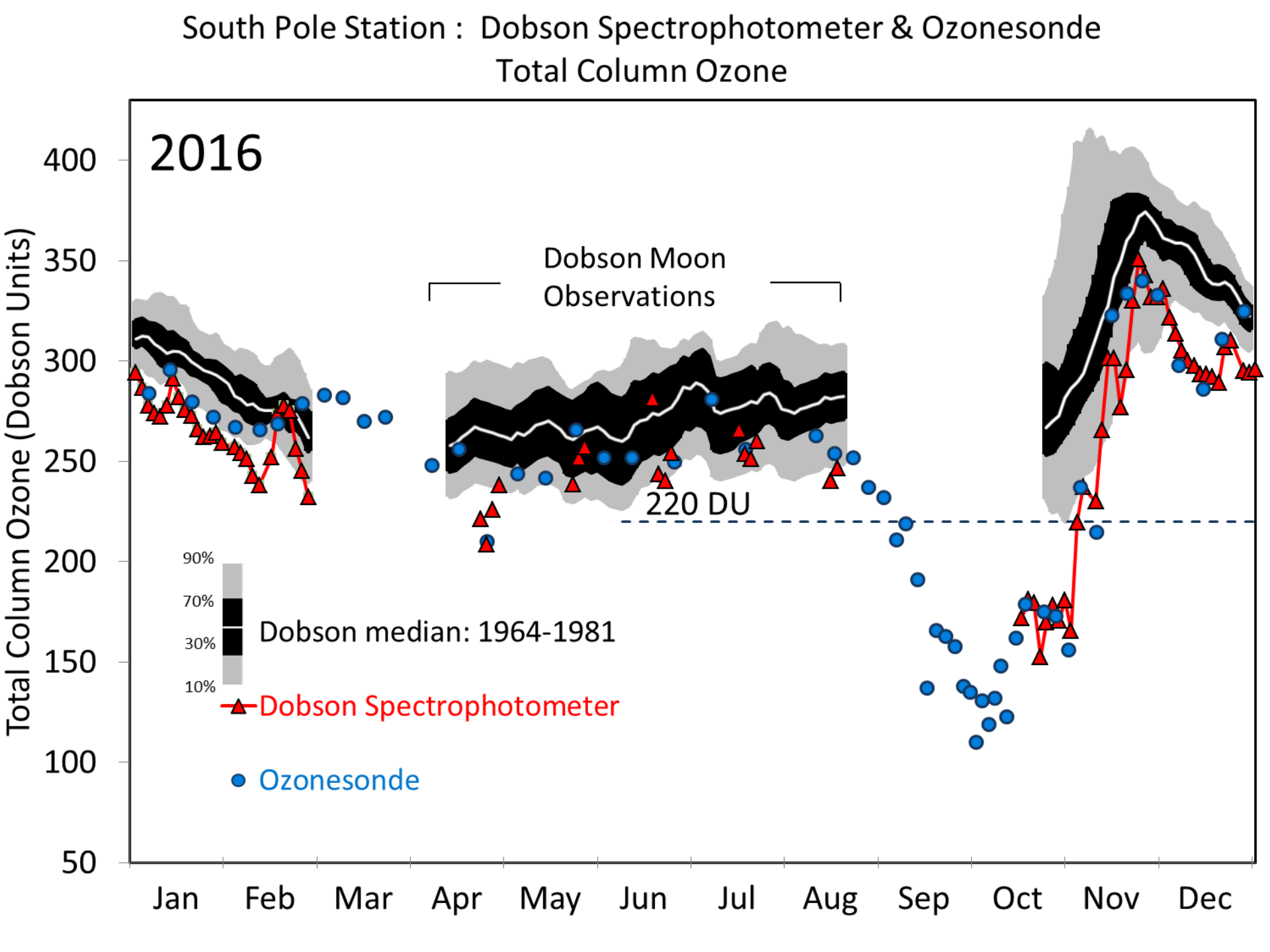
Sep
Oct
Nov
Dec


South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
2014
Total Column Ozone (Dobson Units)
400
350
300
250
200
150
100
50
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Dobson Moon
Observations
220 DU
90%
70%
30%
10%
Dobson median: 1964-1981
Dobson Spectrophotometer
Ozonesonde


South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
2015
Total Column Ozone (Dobson Units)
400
350
300
250
200
150
100
50
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Dobson Moon
Observations
220 DU
90%
70%
30%
10%
Dobson median: 1964-1981
Dobson Spectrophotometer
Ozonesonde


South Pole Station : Dobson Spectrophotometer & Ozonesonde
Total Column Ozone
2016
Total Column Ozone (Dobson Units)
400
350
300
250
200
150
100
50
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Dobson Moon
Observations
220 DU
90%
70%
30%
10%
Dobson median: 1964-1981
Dobson Spectrophotometer
Ozonesonde

Ozonesonde Profiles from selected years:

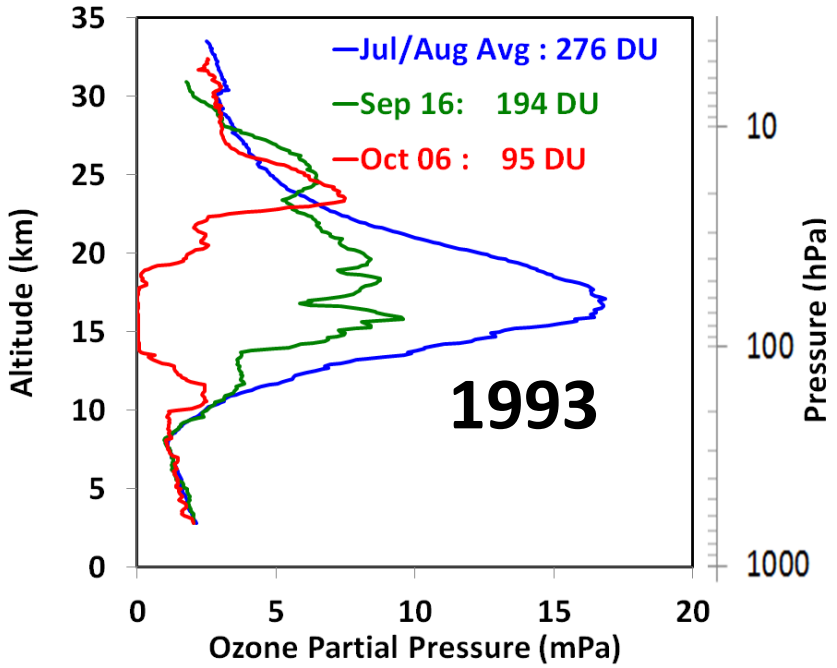
1993 – Pinatubo aerosol

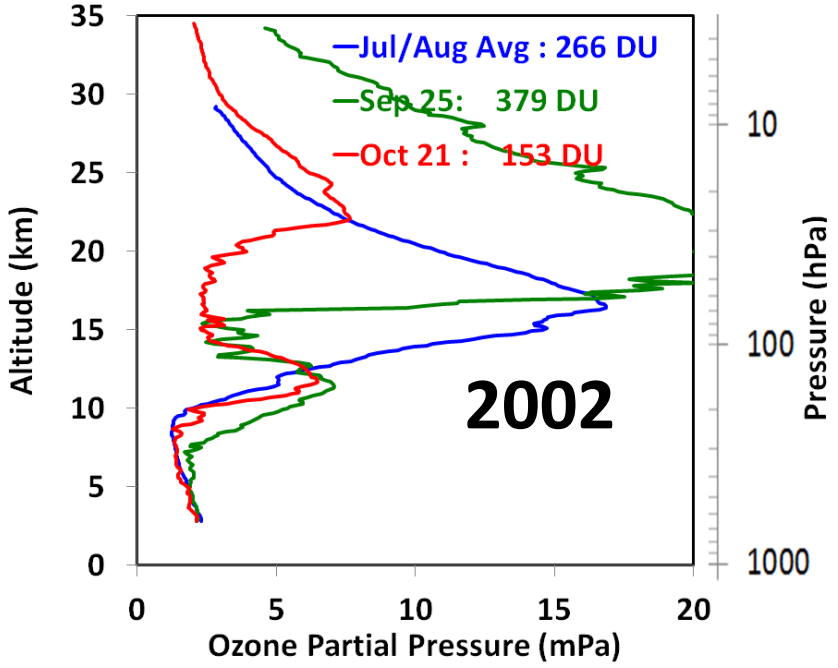
2002 – Sudden stratospheric warming

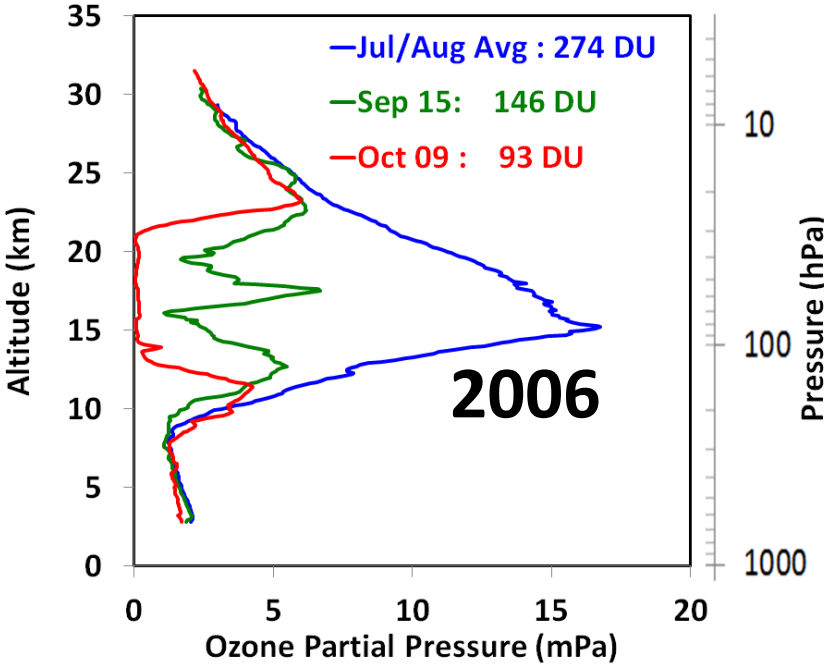
2006 – Record low ozone hole

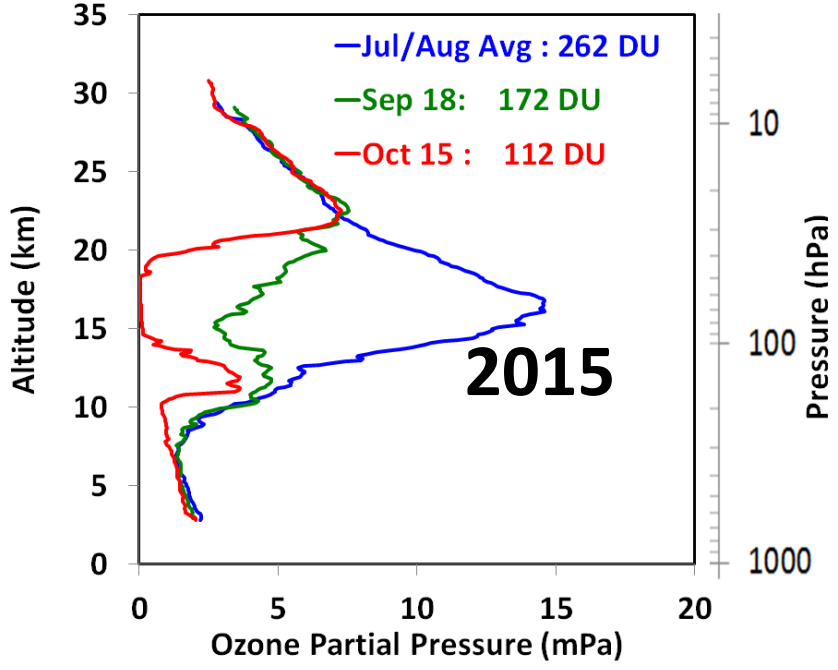
2015 – longest stable vortex

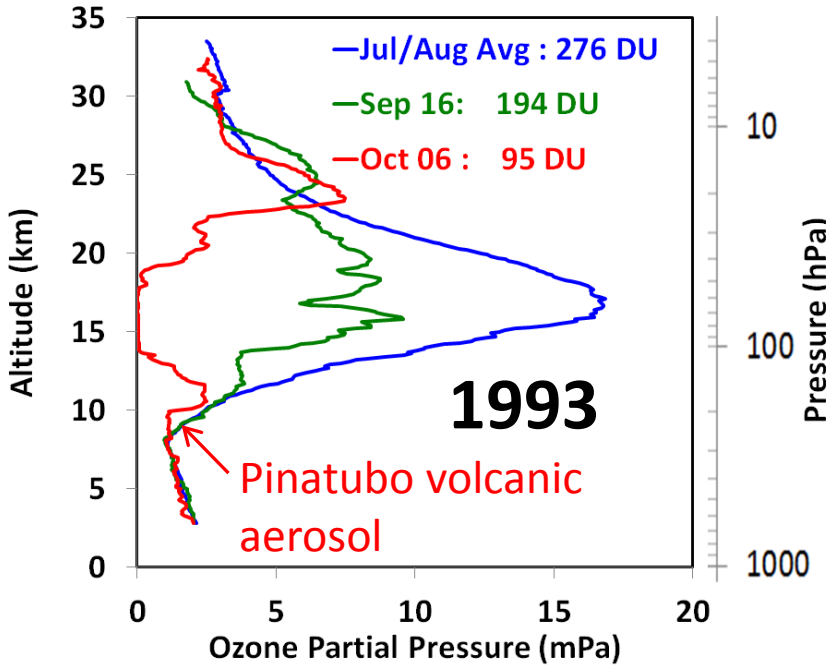
2016 – most recent

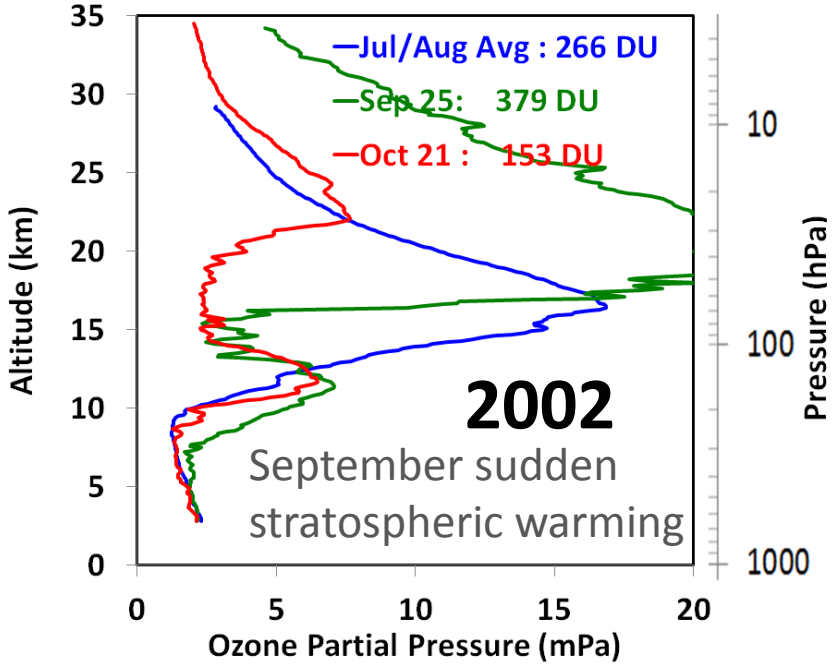

—Jul/Aug Avg : 276 DU
—Sep 16: 194 DU
—Oct 06 : 95 DU
1993
Altitude (km)
Pressure (hPa)
Ozone Partial Pressure (mPa)

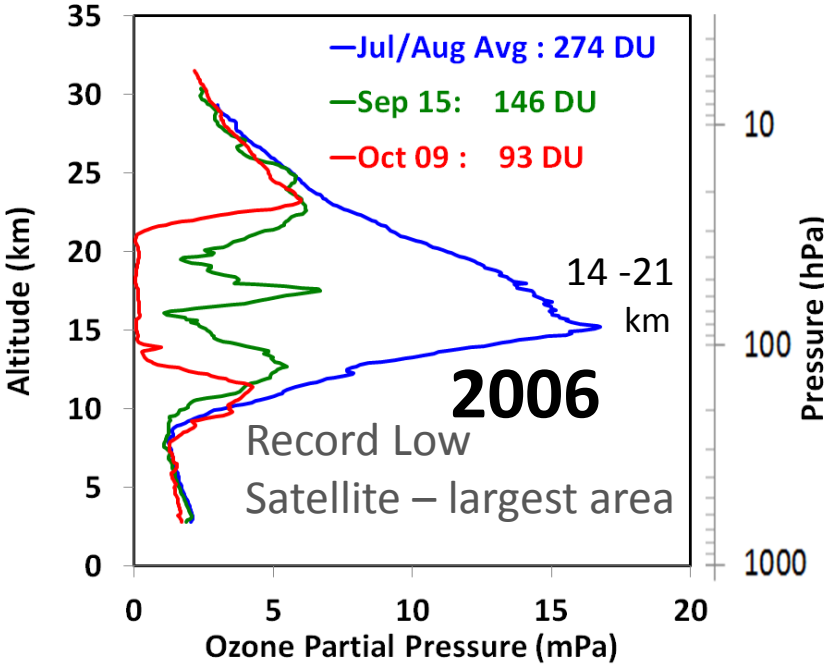

—Jul/Aug Avg : 266 DU
—Sep 25: 379 DU
—Oct 21 : 153 DU
2002
Altitude (km)
Pressure (hPa)
Ozone Partial Pressure (mPa)

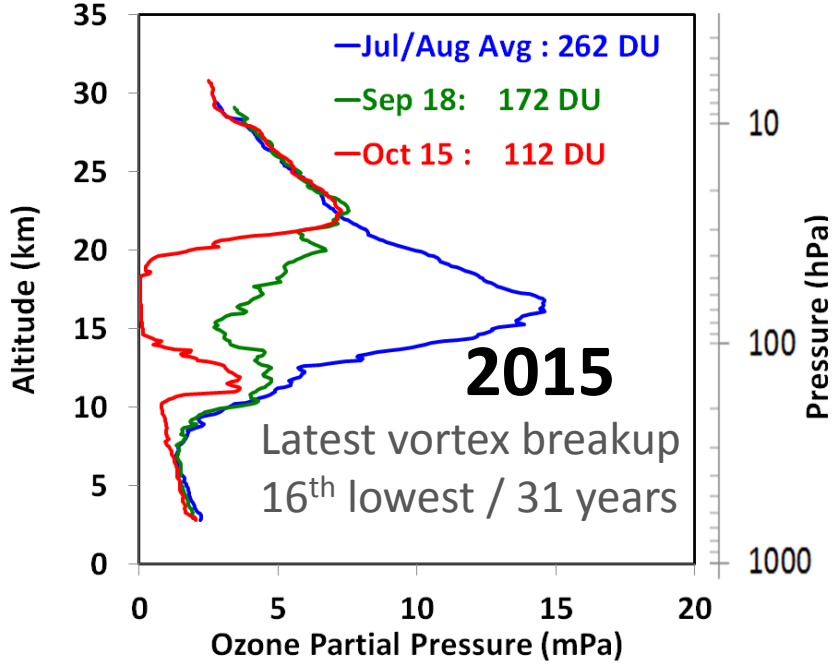

—Jul/Aug Avg : 274 DU
—Sep 15: 146 DU
—Oct 09 : 93 DU
2006
Altitude (km)
Pressure (hPa)
Ozone Partial Pressure (mPa)

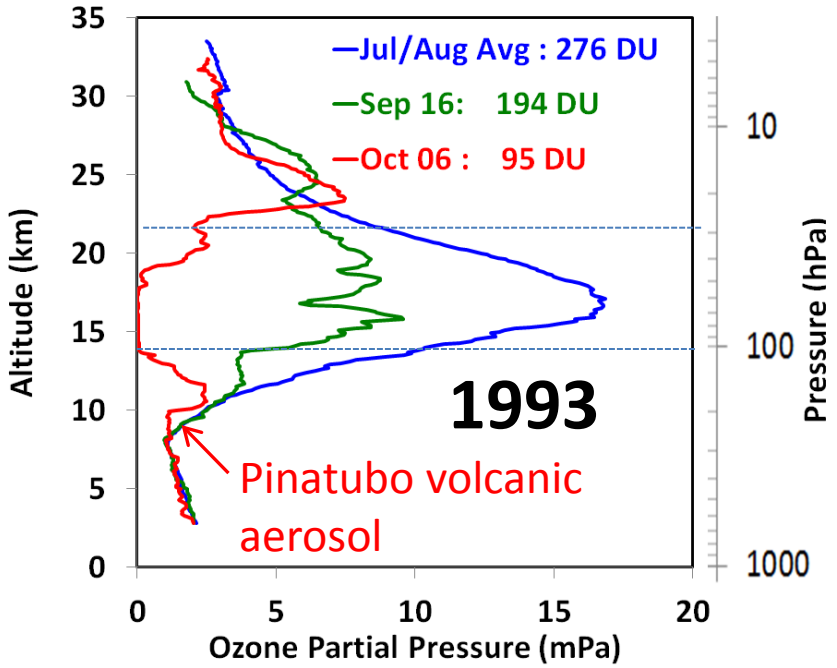

—Jul/Aug Avg : 262 DU
—Sep 18: 172 DU
—Oct 15 : 112 DU
2015
Altitude (km)
Pressure (hPa)
Ozone Partial Pressure (mPa)

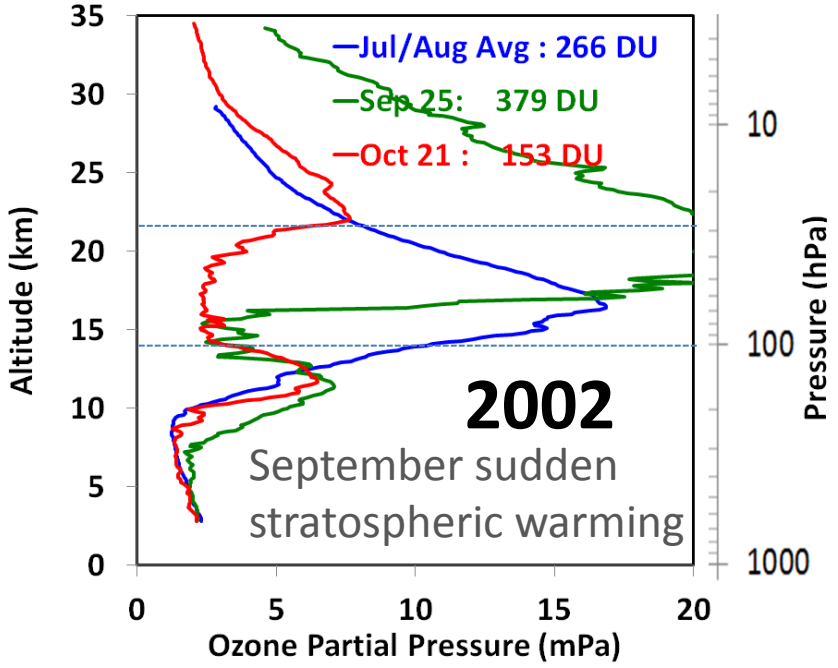

—Jul/Aug Avg : 276 DU
—Sep 16: 194 DU
—Oct 06 : 95 DU
1993
Pinatubo volcanic aerosol
Altitude (km)
Pressure (hPa)
Ozone Partial Pressure (mPa)

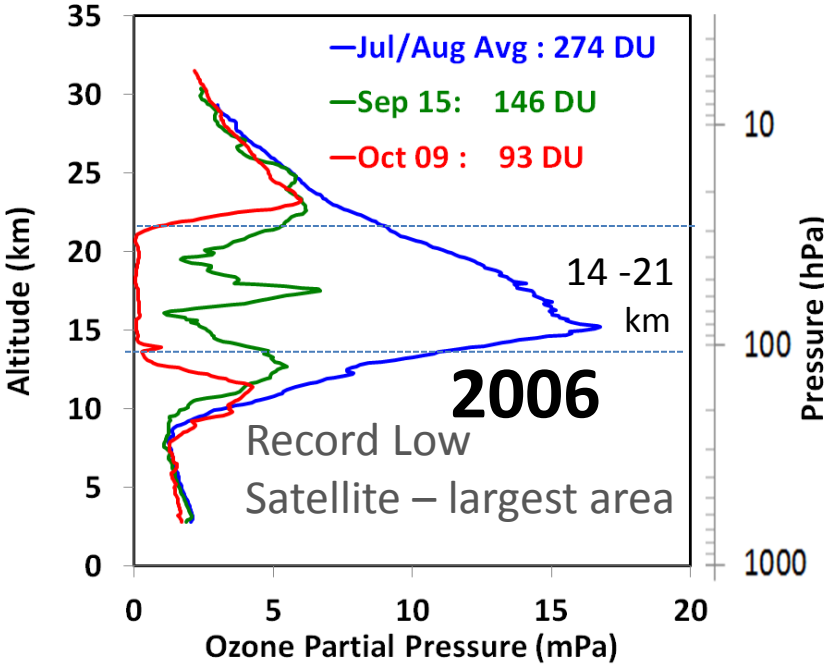

—Jul/Aug Avg : 266 DU
—Sep 25: 379 DU
—Oct 21 : 153 DU
2002
September sudden stratospheric warming
Altitude (km)
Pressure (hPa)
Ozone Partial Pressure (mPa)

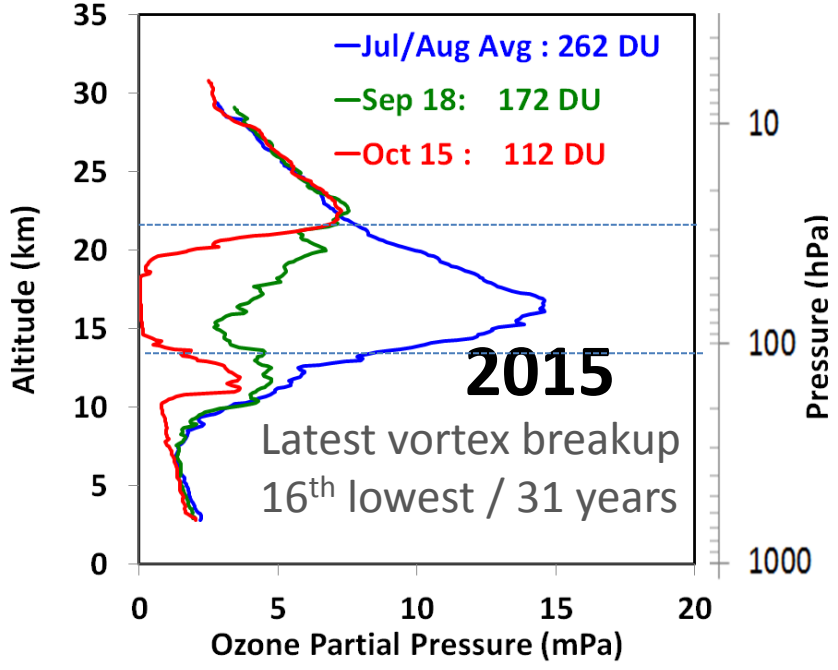

—Jul/Aug Avg : 274 DU
—Sep 15: 146 DU
—Oct 09 : 93 DU
14 -21 km
2006
Record Low
Satellite – largest area
Altitude (km)
Pressure (hPa)
Ozone Partial Pressure (mPa)

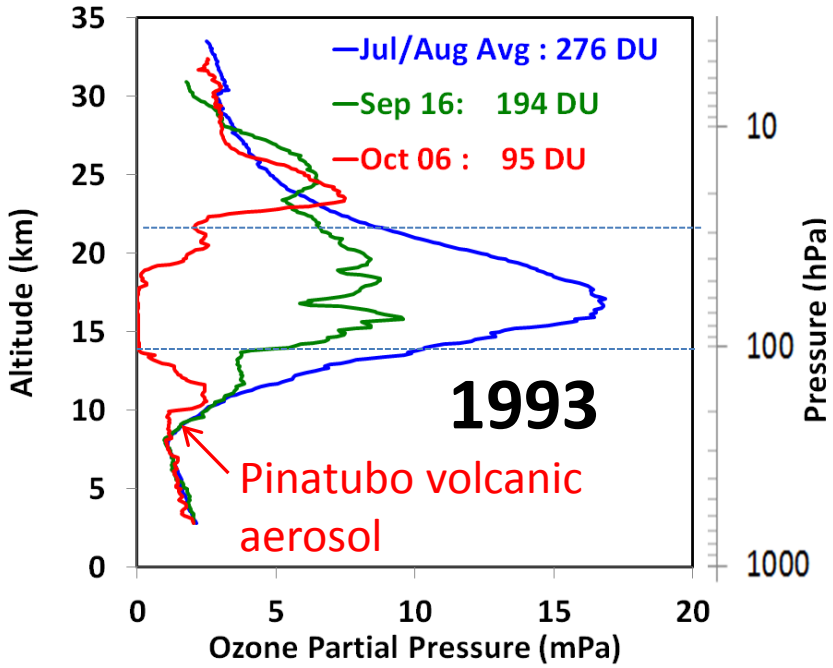

—Jul/Aug Avg : 262 DU
—Sep 18: 172 DU
—Oct 15 : 112 DU
2015
Latest vortex breakup
16th lowest / 31 years
Altitude (km)
Pressure (hPa)
Ozone Partial Pressure (mPa)

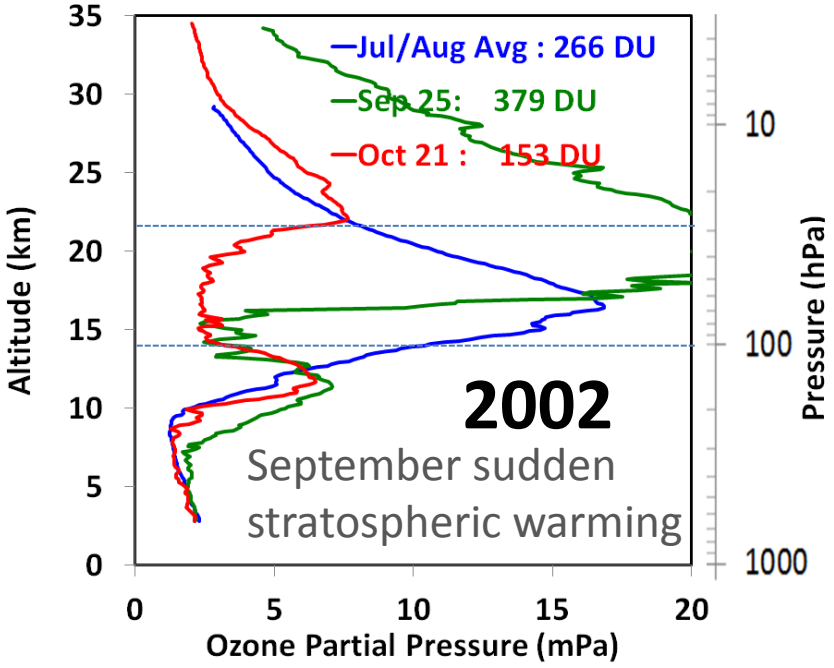

—Jul/Aug Avg : 276 DU
—Sep 16: 194 DU
—Oct 06 : 95 DU
1993
Pinatubo volcanic aerosol
Altitude (km)
Pressure (hPa)
Ozone Partial Pressure (mPa)

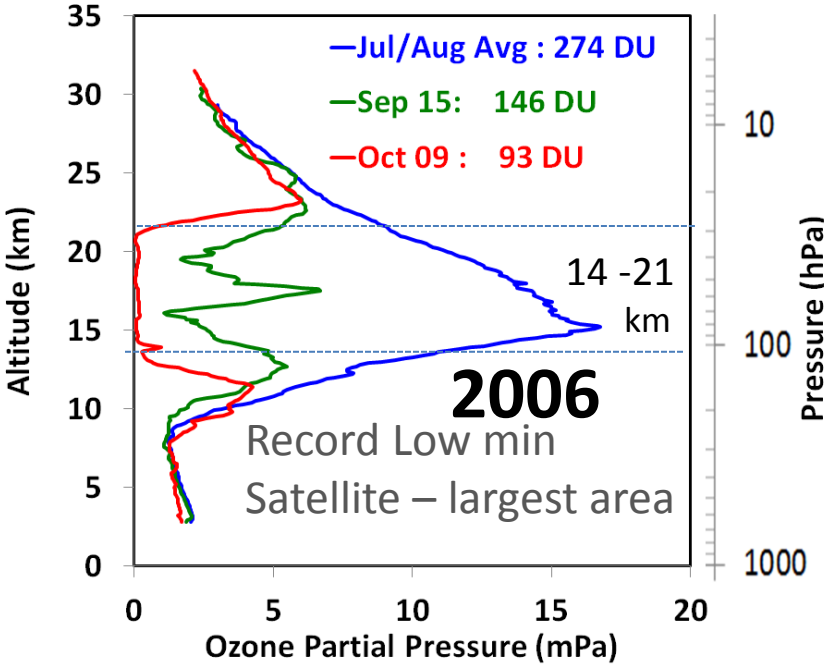

—Jul/Aug Avg : 266 DU
—Sep 25: 379 DU
—Oct 21 : 153 DU
2002
September sudden stratospheric warming
Altitude (km)
Pressure (hPa)
Ozone Partial Pressure (mPa)

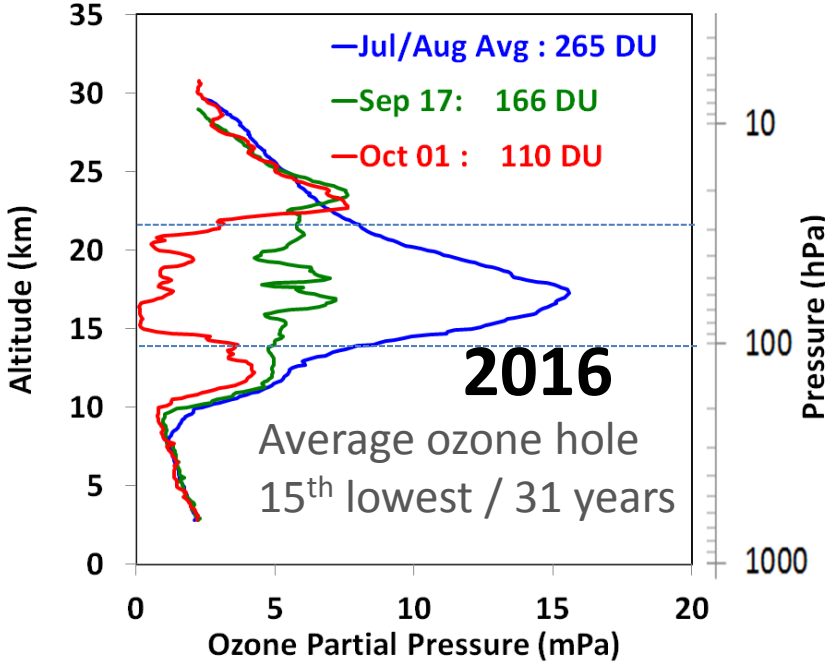

—Jul/Aug Avg : 274 DU
—Sep 15: 146 DU
—Oct 09 : 93 DU
14 -21 km
2006
Record Low
Satellite – largest area
Altitude (km)
Pressure (hPa)
Ozone Partial Pressure (mPa)

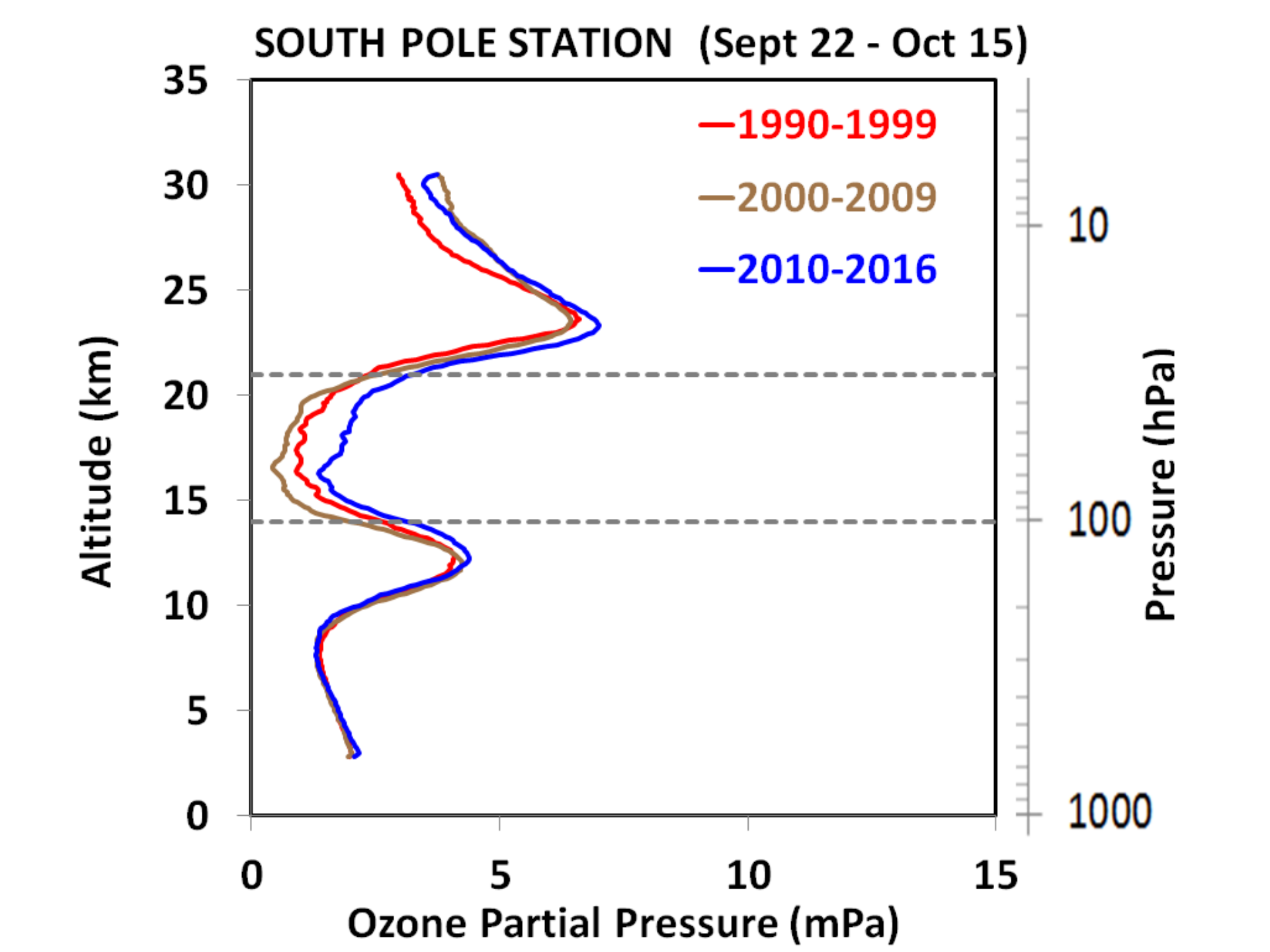

—Jul/Aug Avg : 262 DU
—Sep 18: 172 DU
—Oct 15 : 112 DU
2015
Latest vortex breakup
16th lowest / 31 years
Altitude (km)
Pressure (hPa)
Ozone Partial Pressure (mPa)

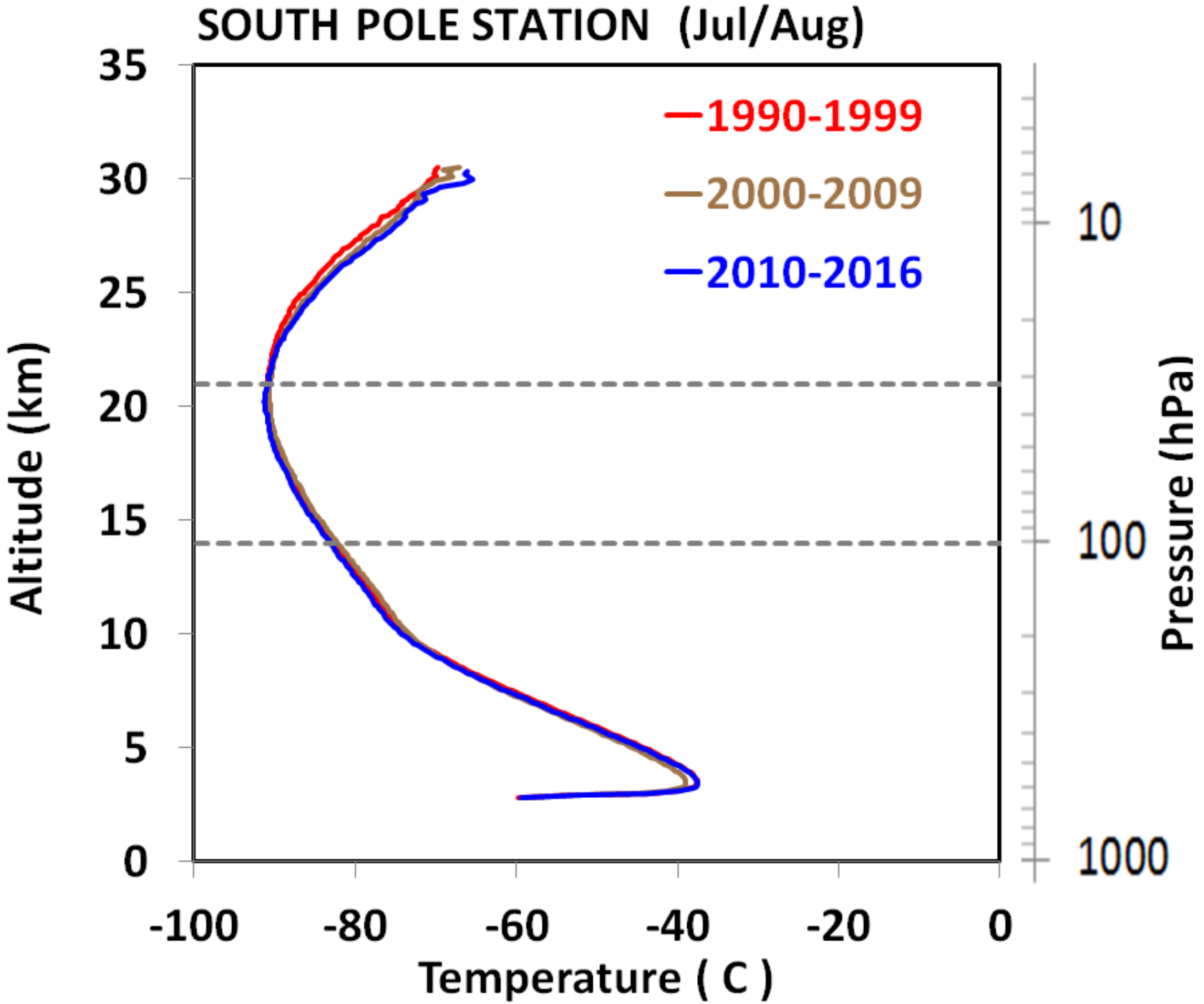

—Jul/Aug Avg : 276 DU
—Sep 16: 194 DU
—Oct 06 : 95 DU
1993
Pinatubo volcanic aerosol
Altitude (km)
Pressure (hPa)
Ozone Partial Pressure (mPa)


—Jul/Aug Avg : 266 DU
—Sep 25: 379 DU
—Oct 21 : 153 DU
2002
September sudden stratospheric warming
Altitude (km)
Pressure (hPa)
Ozone Partial Pressure (mPa)

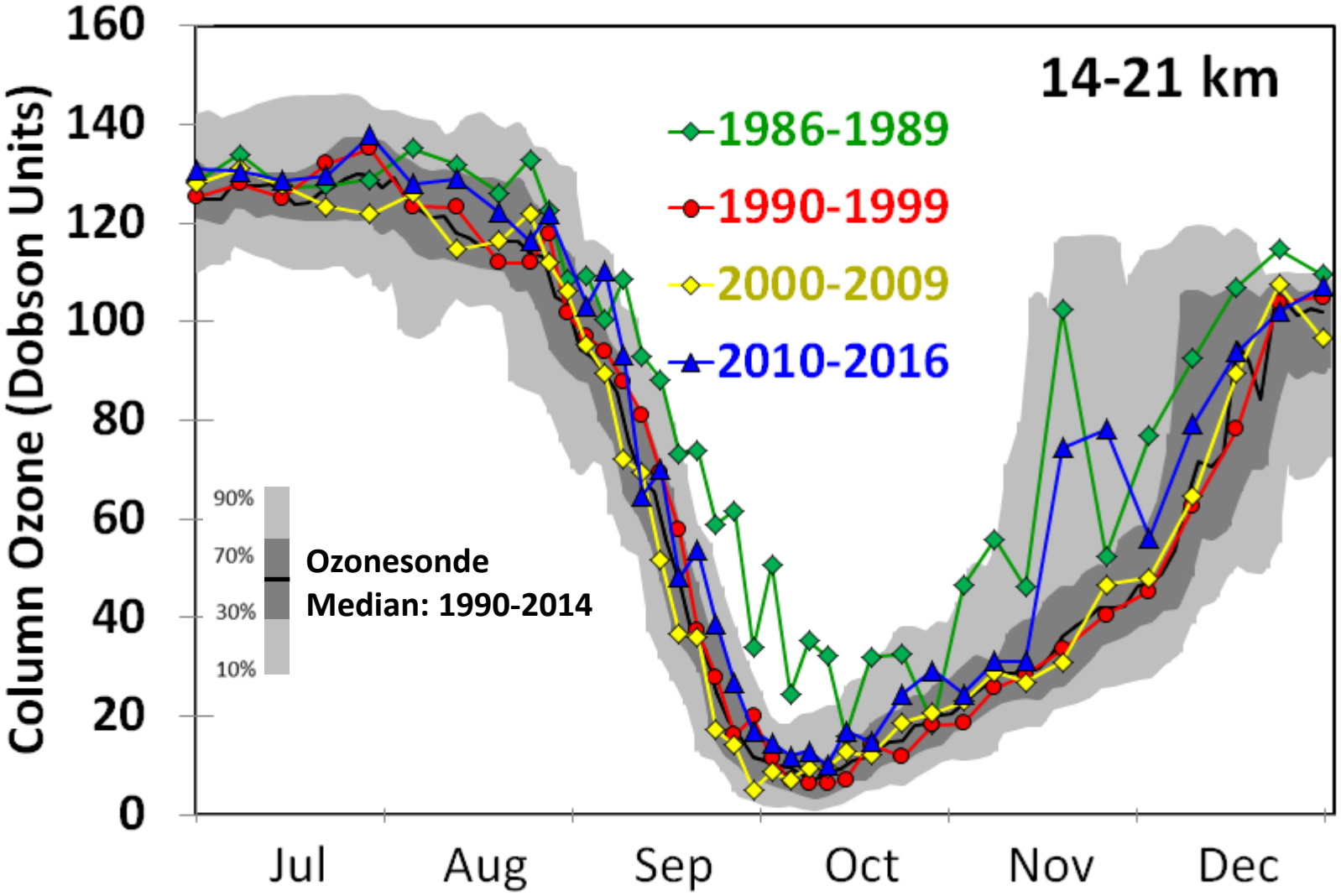

—Jul/Aug Avg : 274 DU
—Sep 15: 146 DU
—Oct 09 : 93 DU
14 -21 km
2006
Record Low min
Satellite – largest area
Altitude (km)
Pressure (hPa)
Ozone Partial Pressure (mPa)


—Jul/Aug Avg : 265 DU
—Sep 17: 166 DU
—Oct 01 : 110 DU
2016
Average ozone hole
15th lowest / 31 years
Altitude (km)
Pressure (hPa)
Ozone Partial Pressure (mPa)

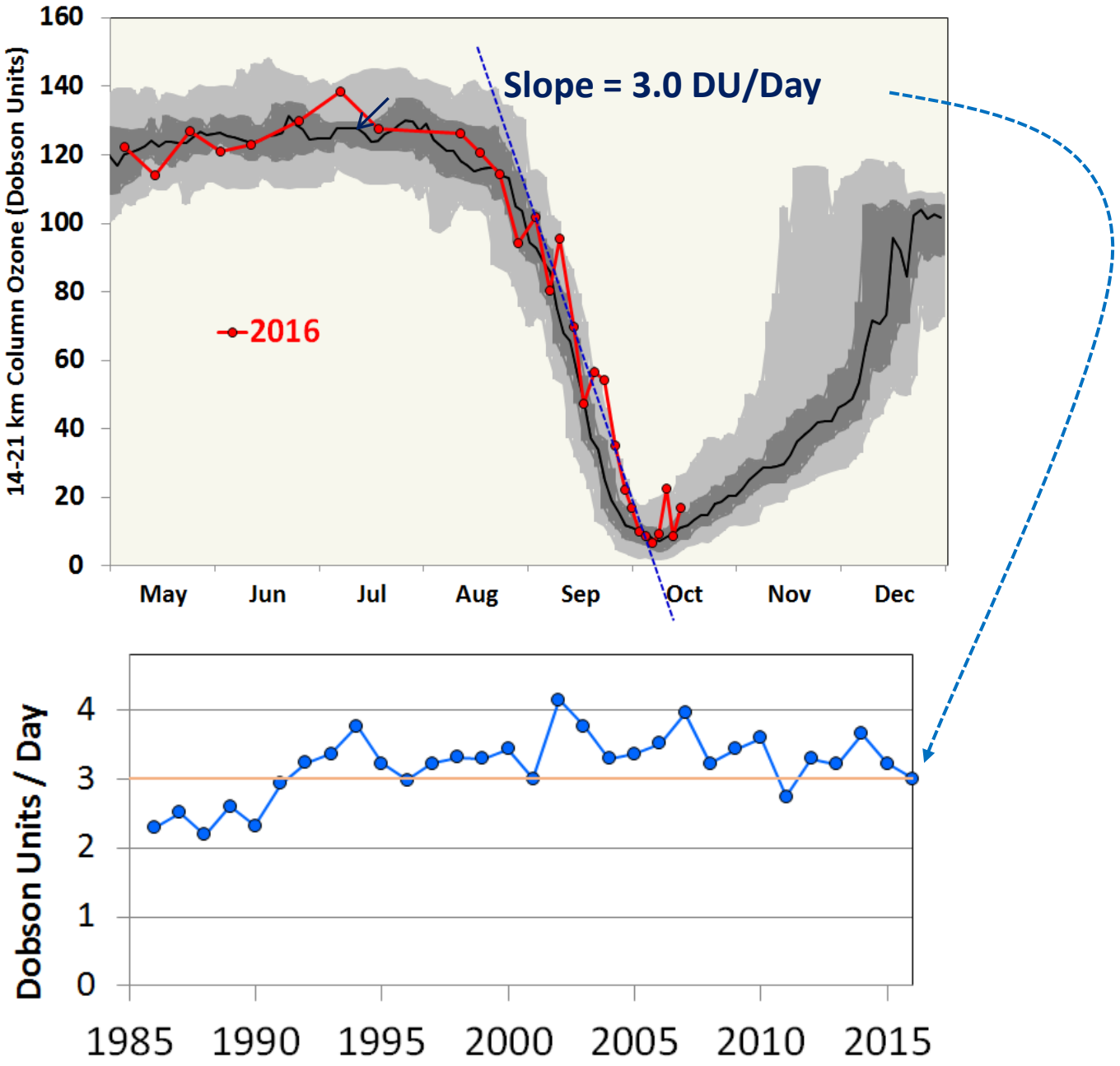

SOUTH POLE STATION (Sept 22 - Oct 15)
—1990-1999
—2000-2009
—2010-2016
Altitude (km)
35
30
25
20
15
10
5
0
0
5
10
15
Ozone Partial Pressure (mPa)
10
100
1000
Pressure (hPa)


SOUTH POLE STATION (Jul/Aug)
1990-1999
2000-2009
2010-2016
Altitude (km)
0
5
10
15
20
25
30
35
-100
-80
-60
-40
-20
0
Temperature (C)
10
100
1000
Pressure (hPa)

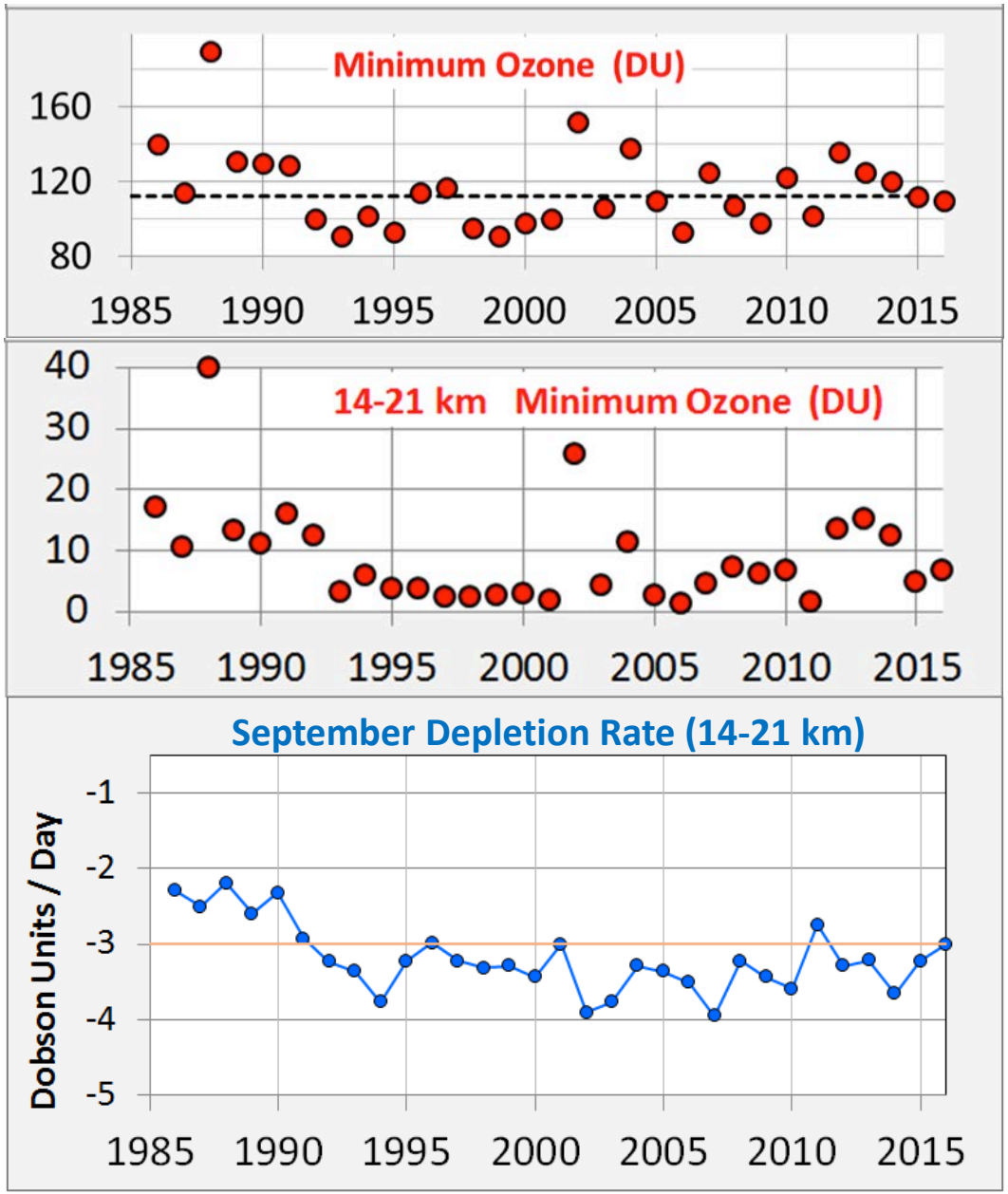
South Pole Ozonesondes



South Pole 14-21 km Layer: September Depletion Rate



Summary Charts and Table



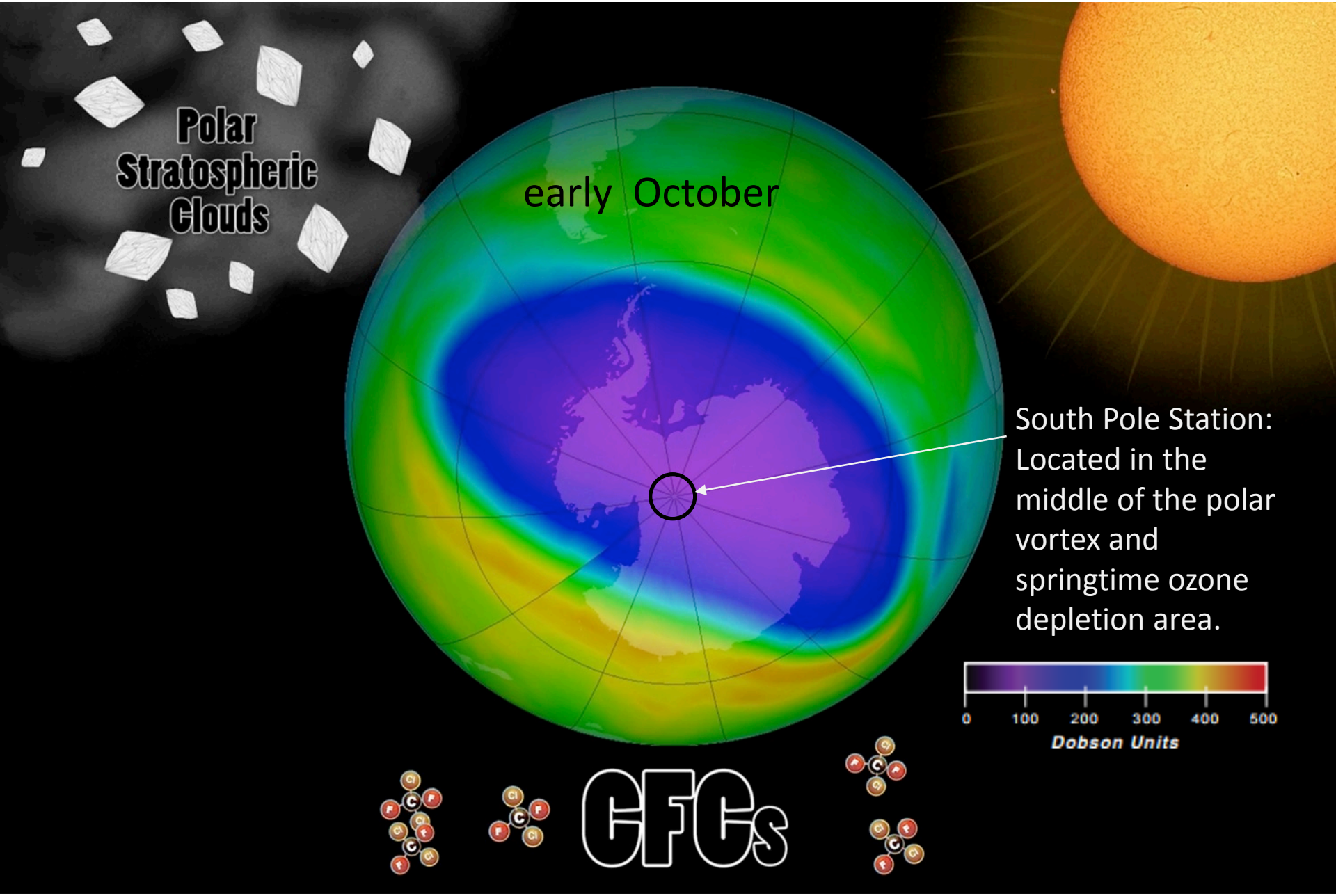
Minimum **Total** Column Lowest to Highest			
RANK	MIN (DU)	YEAR	DATE
1	91	1993	6-Oct
2	91	1999	29-Sep
3	93	1995	5-Oct
4	93	2006	9-Oct
5	95	1998	5-Oct
6	98	2000	29-Sep
7	98	2009	25-Sep
8	100	1992	11-Oct
9	100	2001	28-Sep
10	102	1994	5-Oct
11	102	2011	9-Oct
12	106	2003	26-Sep
13	107	2008	28-Sep
14	110	2005	28-Sep
15	110	2016	1-Oct
16	112	2015	15-Oct
17	114	1987	9-Oct
18	114	1996	6-Oct
19	117	1997	8-Oct
20	120	2014	29-Sep
21	122	2010	30-Sep
22	125	2007	8-Oct
23	125	2013	29-Sep
24	129	1991	7-Oct
25	130	1990	7-Oct
26	131	1989	9-Oct
27	136	2012	5-Oct
28	138	2004	4-Oct
29	140	1986	7-Oct
30	152	2002	21-Oct
31	190	1988	10-Oct

SUMMARY

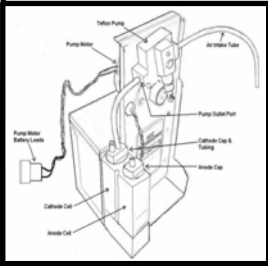
- The previous 3 summary charts indicate improvement, but next several years of ozonesonde data will help smooth out the year- to-year variability in ozone due to stratospheric temperature and meteorological conditions.

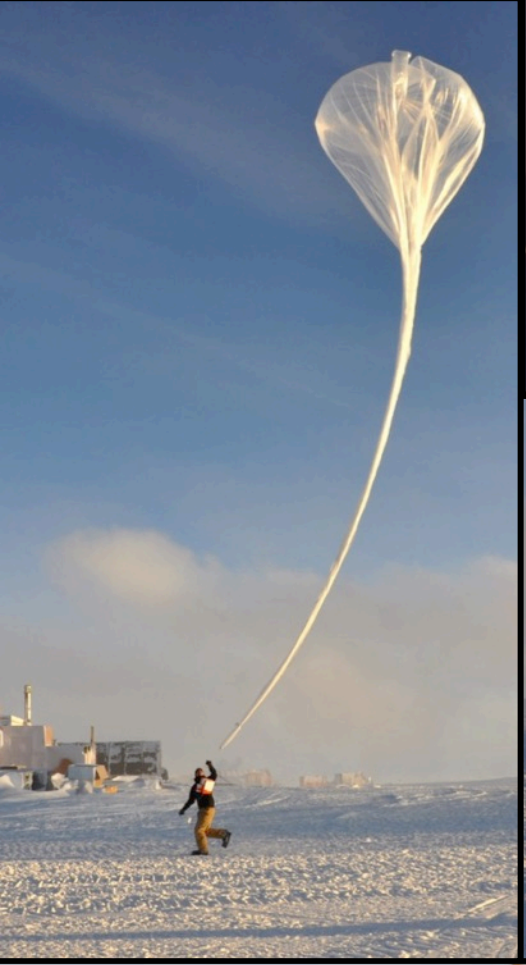
- 2010-2016 (last 7 years) shows improvement over 1990-1999 and 2000-2009 decades.

20-24 km ozone layer shows significant improvement. Indicator for recovery predicted by Hofmann (1997).


Polar Stratospheric Clouds
early October
South Pole Station: Located in the middle of the polar vortex and springtime ozone depletion area.
0
100
200
300
400
500
Dobson Units
CFCs

Electrochemical
Concentration
Cell ozonesonde





South Pole Station