Comparison of interannual flash rate variability from

aura4light2

aura4synoz

g5_aura

Merra

OTD/LIS

How were flash rates (F) determined?

- **Assume $F = G * \alpha_{i,j} * (zmmu_{i,j} - threshold)^{\gamma}$, where**

zmmu: Updraft convective mass flux in upper troposphere

g4dasold:	GEOS-4 model layer 9
g4das:	GEOS-4 model layer 10
g5das:	GEOS-5 model layer 26
merra:	GEOS-5 model layer 26

threshold and γ: Flash rate set to zero for 0 < zmmu < threshold)

g4dasold:	threshold = 0.57 kg $m^{-2}min^{-1}$	$\gamma = 2$
g4das:	threshold = 0.57 kg $m^{-2}min^{-1}$	$\gamma = 1$
g5das:	threshold = 0.35 kg $m^{-2}min^{-1}$	$\gamma = 1$
merra:	threshold = 0.35 kg $m^{-2}min^{-1}$	$\gamma = 1$

How were flash rates (F) determined?

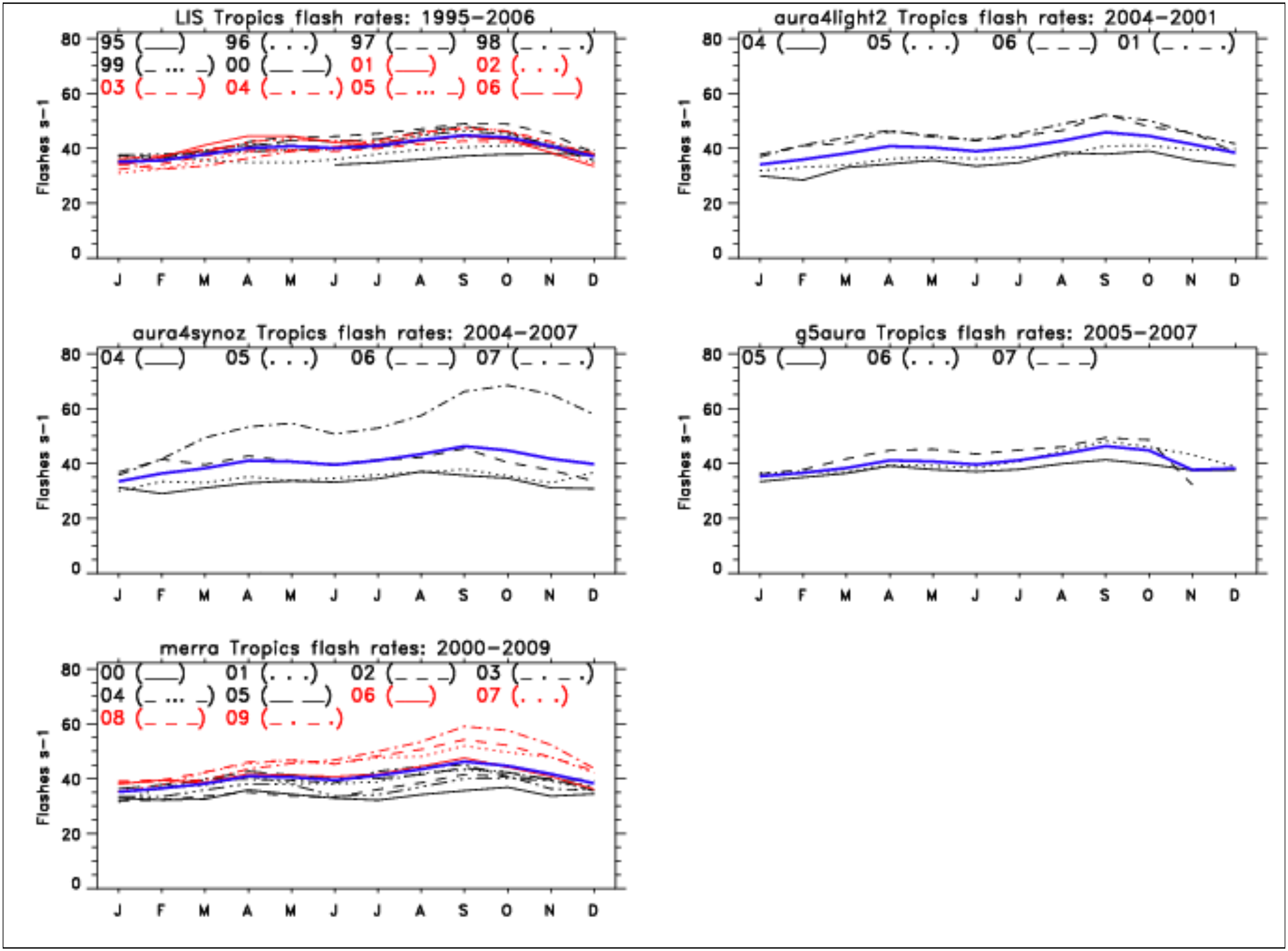
- **Assume $F = G * \alpha_{i,j} * (zmmu_{i,j} - threshold)^{\gamma}$, where**

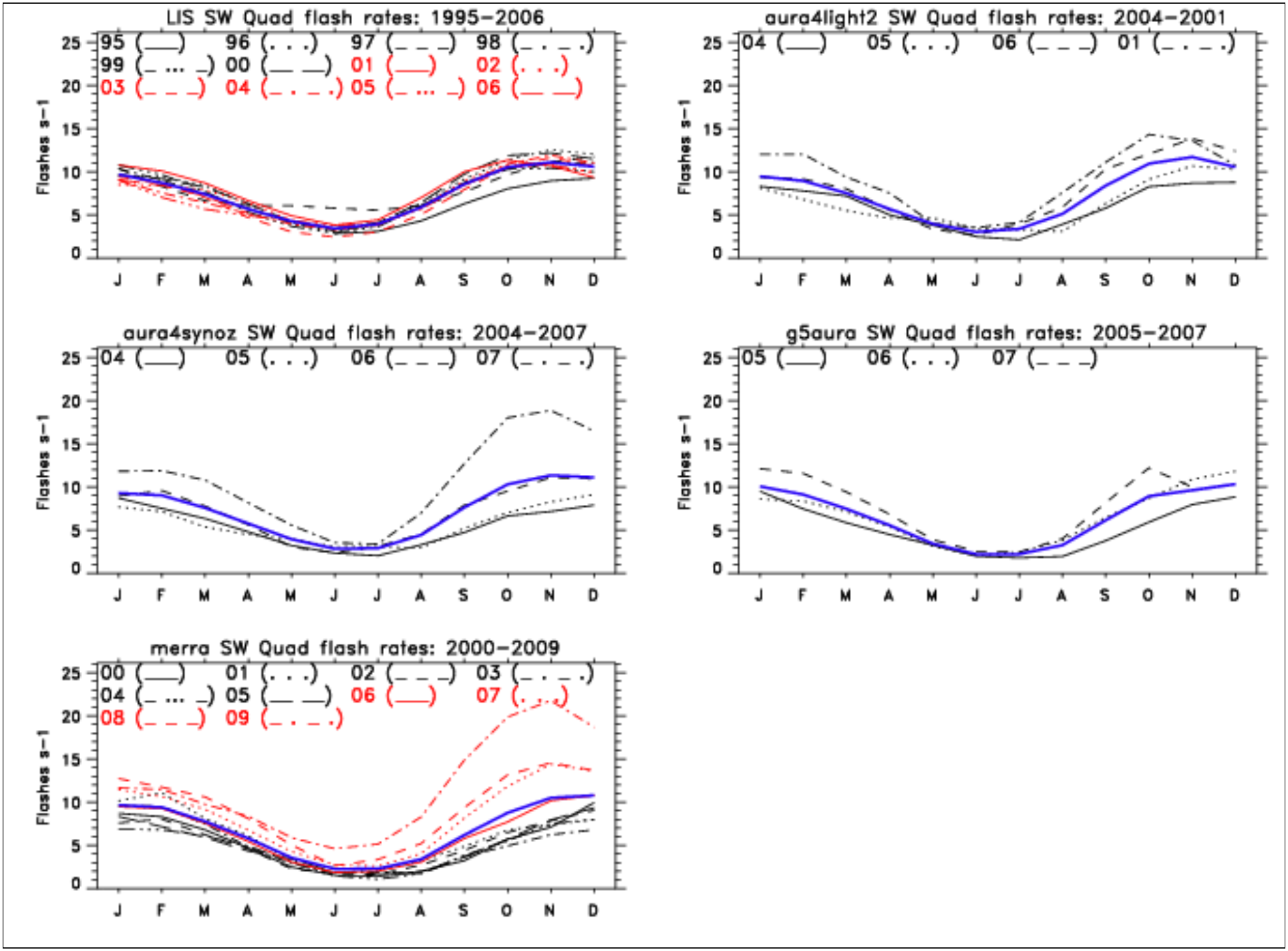
G: Global scaling factor chosen so that the *mean* model-calculated flash rate for each month matches v2.2 OTD/LIS climatology.

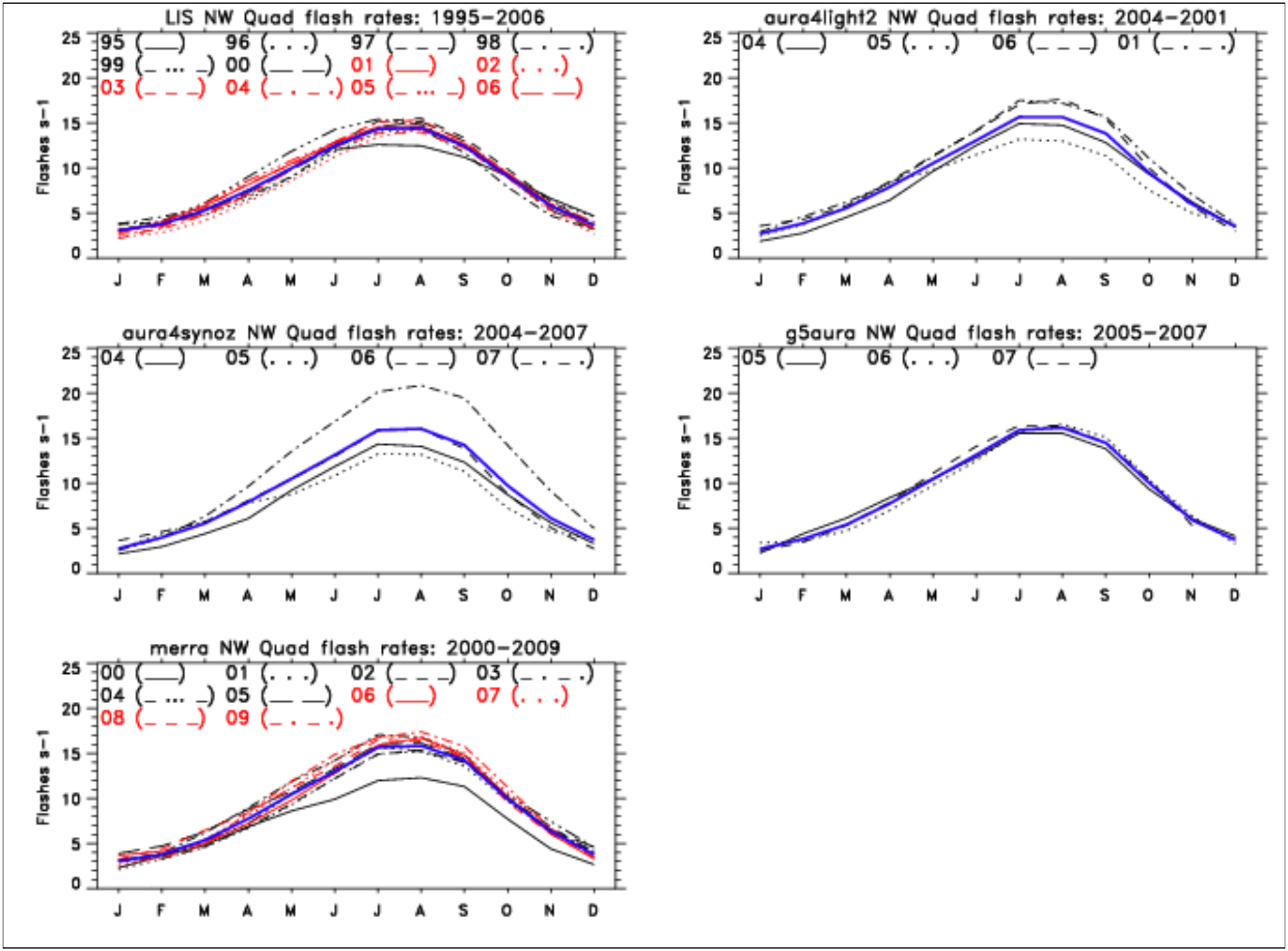
g4dasold:	*mean* equals avg of 2004, 2005, 2006, & 2001
g4das:	*mean* equals avg of 2004, 2005, 2006, & 2007
g5das:	*mean* equals avg of 2005, 2006, & 2007 (2007 unavailable)
merra:	*mean* equals avg of 2000-2009

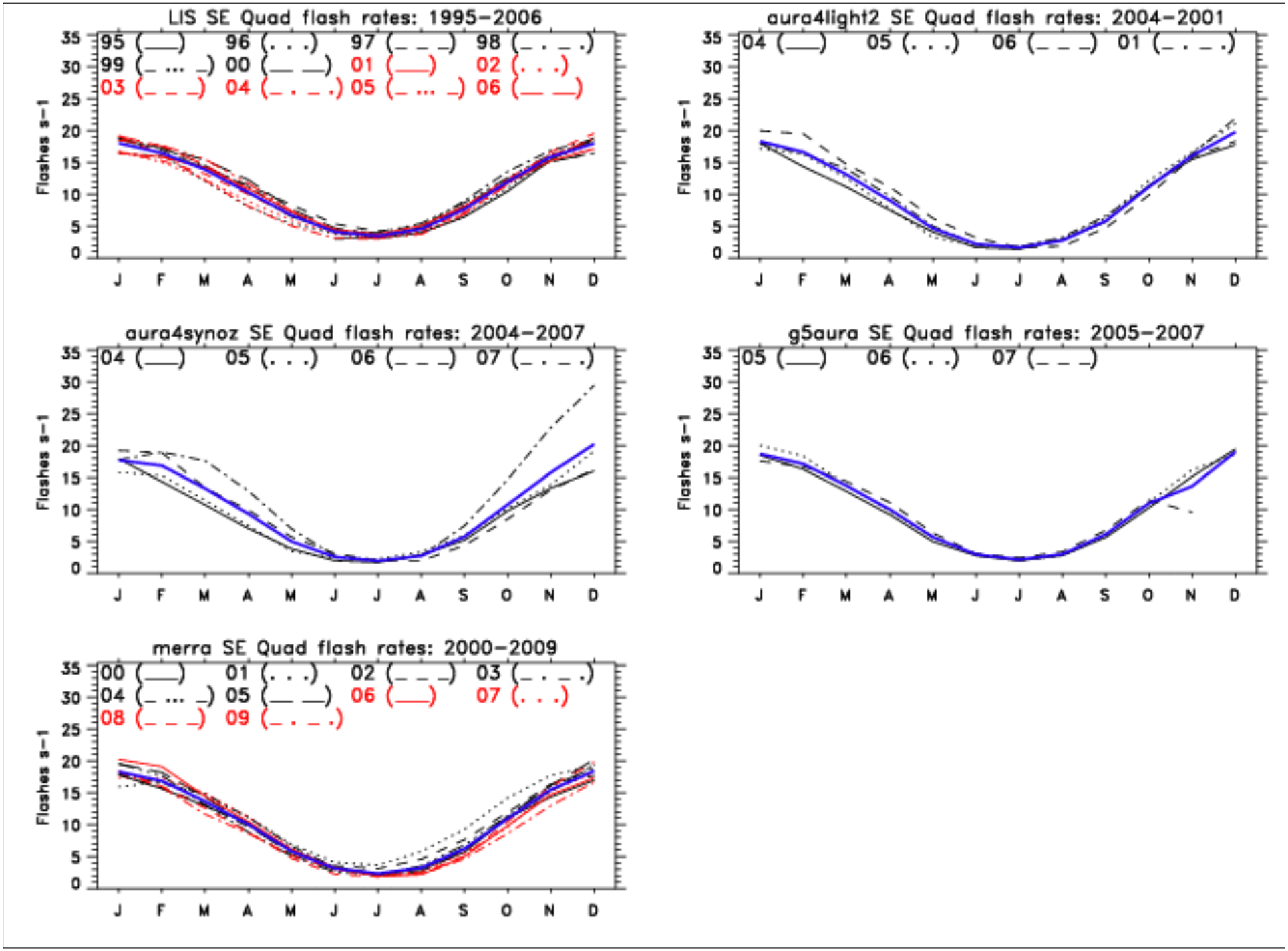
$\alpha_{i,j}$: Local adjustment factor chosen so that mean model-calculated flash rate for each grid box matches v2.2 OTD/LIS climatology.

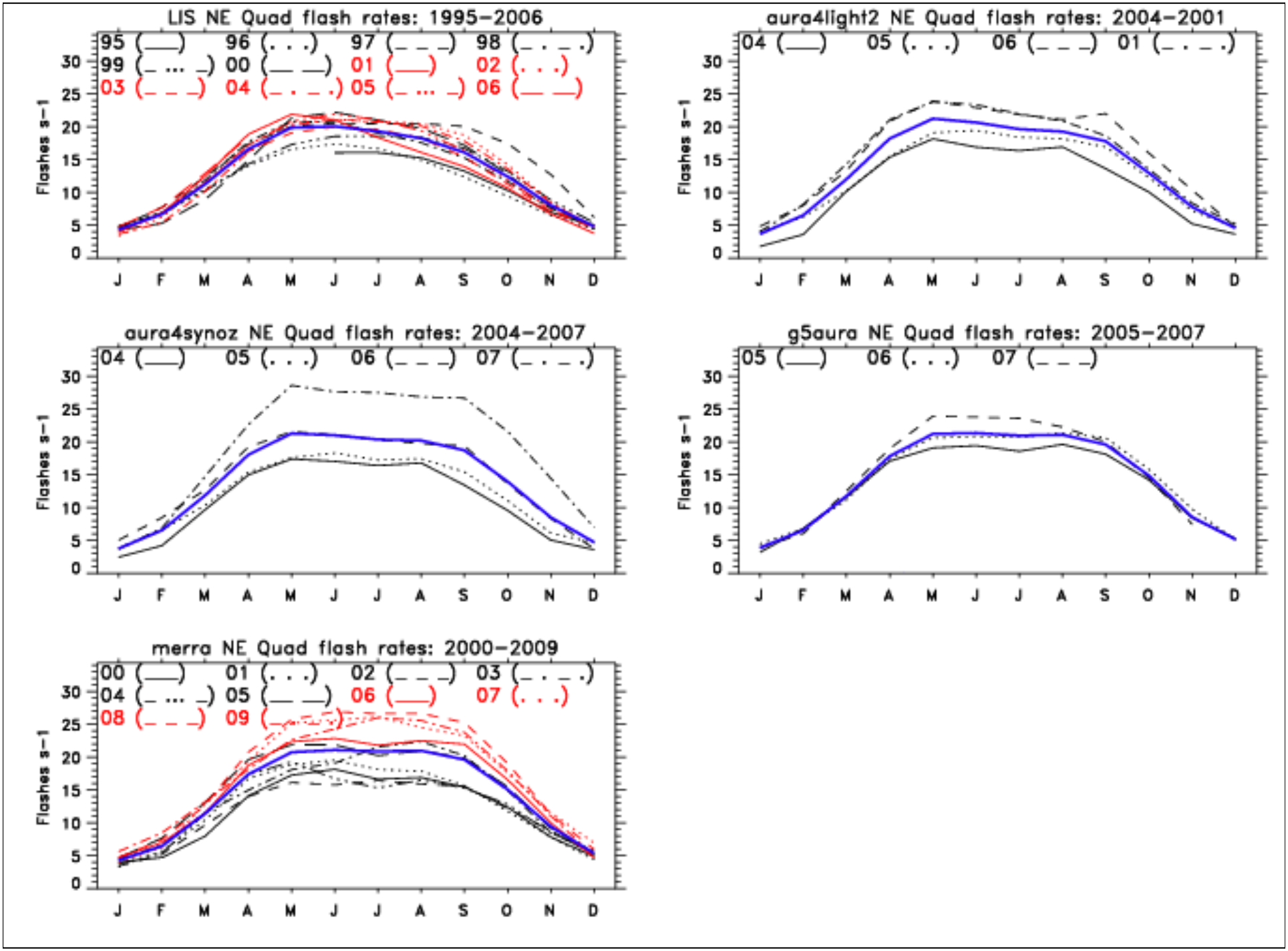
g4dasold:	[0.021,22.3]
g4das:	[0.103,11.1]
g5das:	[0.106,11.6]
merra:	[0.203,5.52]

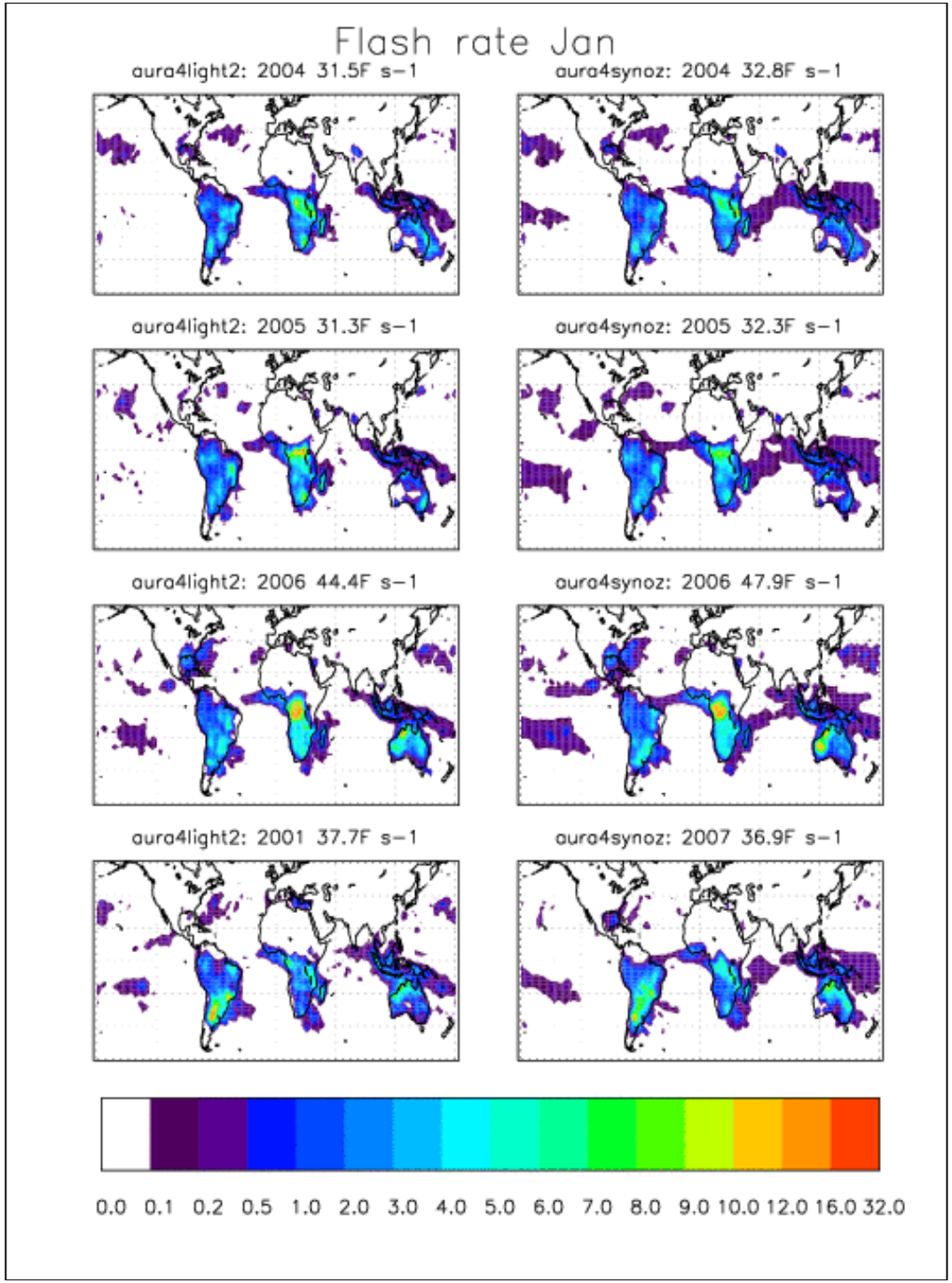

LIS Tropics flash rates: 1995–2006
95 (___) 96 (. . .) 97 (_ _ _) 98 (_ . _ .)
99 (_ ... _) 00 (__ __) 01 (___) 02 (. . .)
03 (_ _ _) 04 (_ . _ .) 05 (_ ... _) 06 (__ __)
aura4light2 Tropics flash rates: 2004–2001
04 (___) 05 (. . .) 06 (_ _ _) 01 (_ . _ .)
aura4synoz Tropics flash rates: 2004–2007
04 (___) 05 (. . .) 06 (_ _ _) 07 (_ . _ .)
g5aura Tropics flash rates: 2005–2007
05 (___) 06 (. . .) 07 (_ _ _)
merra Tropics flash rates: 2000–2009
00 (___) 01 (. . .) 02 (_ _ _) 03 (_ . _ .)
04 (_ ... _) 05 (__ __) 06 (___) 07 (. . .)
08 (_ _ _) 09 (_ . _ .)
Flashes s−1
0
20
40
60
80
J F M A M J J A S O N D

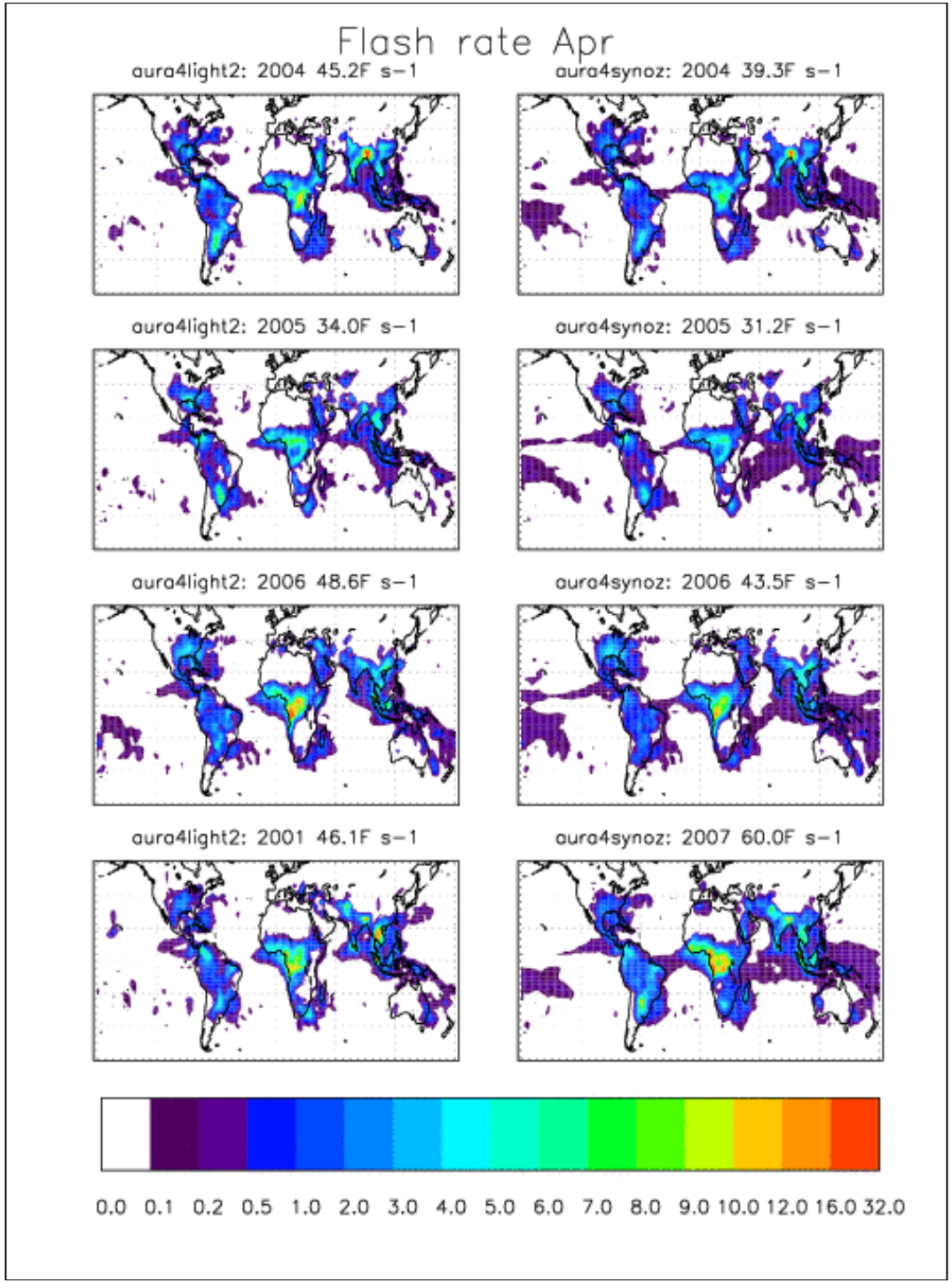

LIS SW Quad flash rates: 1995–2006
95 (___) 96 (. . .) 97 (_ _ _) 98 (_ . _ .)
99 (_ ... _) 00 (__ __) 01 (___) 02 (. . .)
03 (_ _ _) 04 (_ . _ .) 05 (_ ... _) 06 (__ __)
aura4light2 SW Quad flash rates: 2004–2001
04 (___) 05 (. . .) 06 (_ _ _) 01 (_ . _ .)
aura4synoz SW Quad flash rates: 2004–2007
04 (___) 05 (. . .) 06 (_ _ _) 07 (_ . _ .)
g5aura SW Quad flash rates: 2005–2007
05 (___) 06 (. . .) 07 (_ _ _)
merra SW Quad flash rates: 2000–2009
00 (___) 01 (. . .) 02 (_ _ _) 03 (_ . _ .)
04 (_ ... _) 05 (__ __) 06 (___) 07 (. . .)
08 (_ _ _) 09 (_ . _ .)
Flashes s−1
0 5 10 15 20 25
J F M A M J J A S O N D

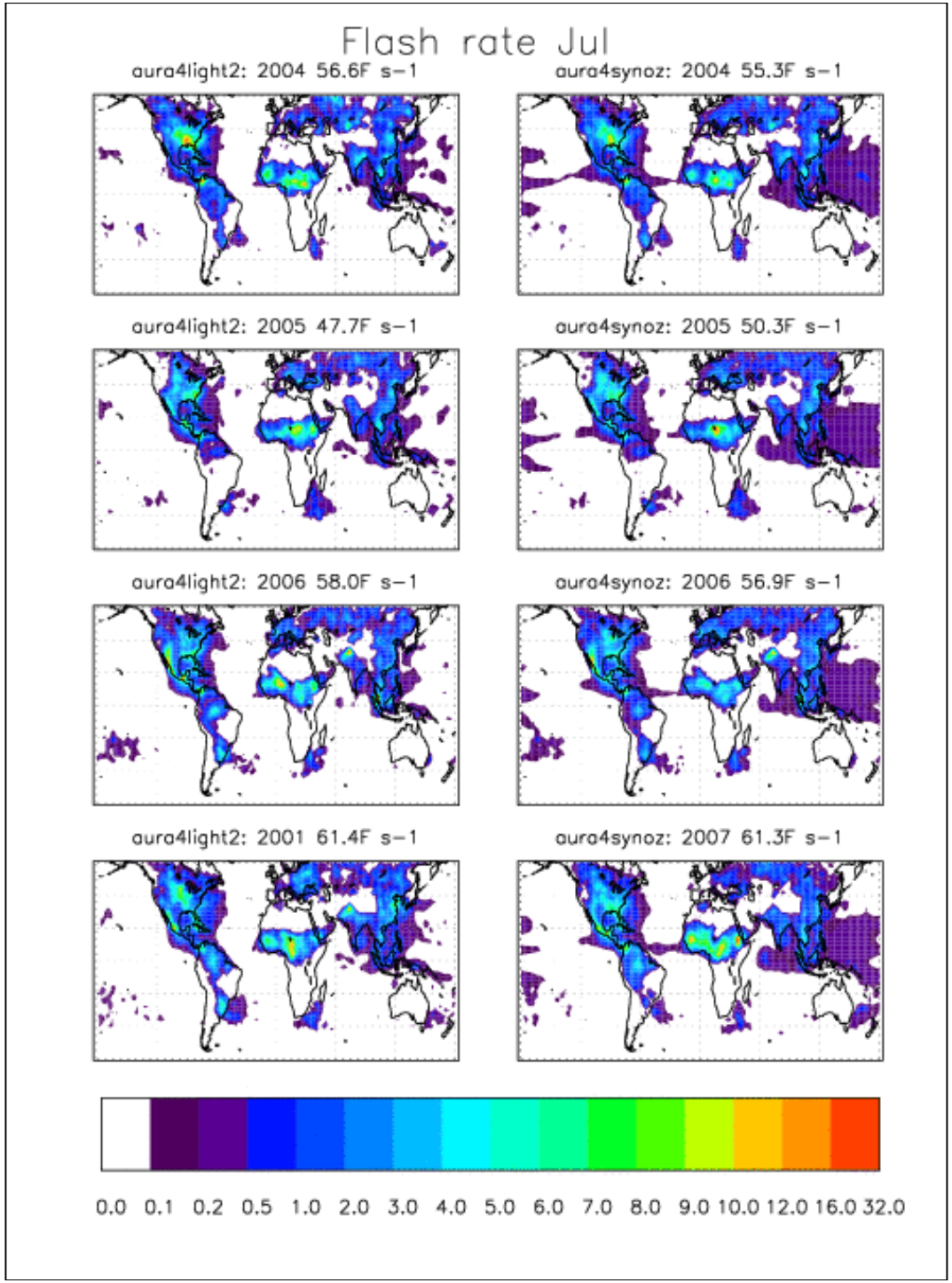

LIS NW Quad flash rates: 1995–2006
95 (___) 96 (. . .) 97 (_ _ _) 98 (_ . _ .)
99 (_ ... _) 00 (__ __) 01 (___) 02 (. . .)
03 (_ _ _) 04 (_ . _ .) 05 (_ ... _) 06 (__ __)
aura4light2 NW Quad flash rates: 2004–2001
04 (___) 05 (. . .) 06 (_ _ _) 01 (_ . _ .)
aura4synoz NW Quad flash rates: 2004–2007
04 (___) 05 (. . .) 06 (_ _ _) 07 (_ . _ .)
g5aura NW Quad flash rates: 2005–2007
05 (___) 06 (. . .) 07 (_ _ _)
merra NW Quad flash rates: 2000–2009
00 (___) 01 (. . .) 02 (_ _ _) 03 (_ . _ .)
04 (_ ... _) 05 (__ __) 06 (___) 07 (. . .)
08 (_ _ _) 09 (_ . _ .)
Flashes s−1
0 5 10 15 20 25
J F M A M J J A S O N D

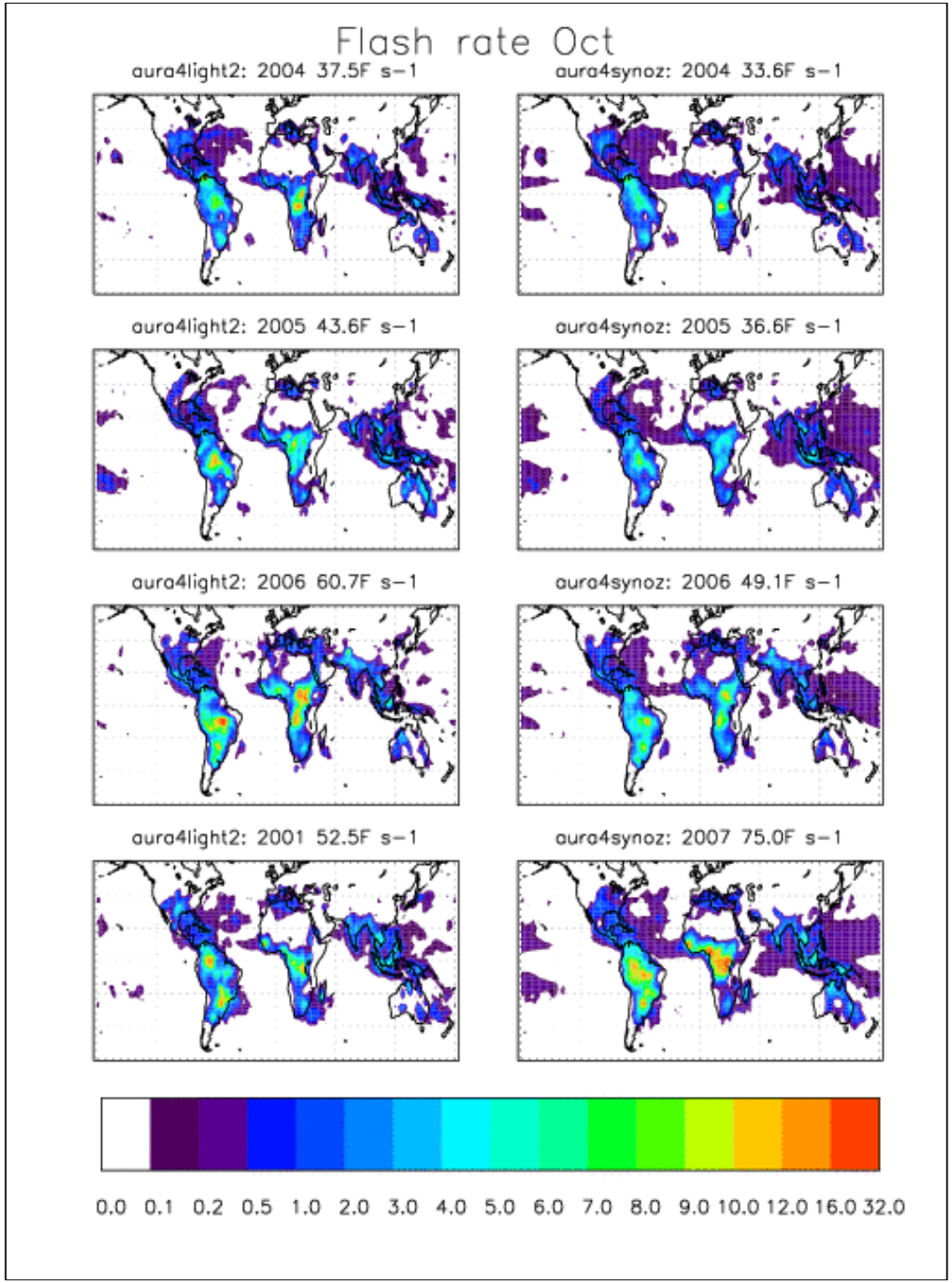

LIS SE Quad flash rates: 1995–2006
95 (___) 96 (. . .) 97 (_ _ _) 98 (_ . _ .)
99 (_ ... _) 00 (__ __) 01 (___) 02 (. . .)
03 (_ _ _) 04 (_ . _ .) 05 (_ ... _) 06 (__ __)
aura4light2 SE Quad flash rates: 2004–2001
04 (___) 05 (. . .) 06 (_ _ _) 01 (_ . _ .)
aura4synoz SE Quad flash rates: 2004–2007
04 (___) 05 (. . .) 06 (_ _ _) 07 (_ . _ .)
g5aura SE Quad flash rates: 2005–2007
05 (___) 06 (. . .) 07 (_ _ _)
merra SE Quad flash rates: 2000–2009
00 (___) 01 (. . .) 02 (_ _ _) 03 (_ . _ .)
04 (_ ... _) 05 (__ __) 06 (___) 07 (. . .)
08 (_ _ _) 09 (_ . _ .)
Flashes s−1
0 5 10 15 20 25 30 35
J F M A M J J A S O N D

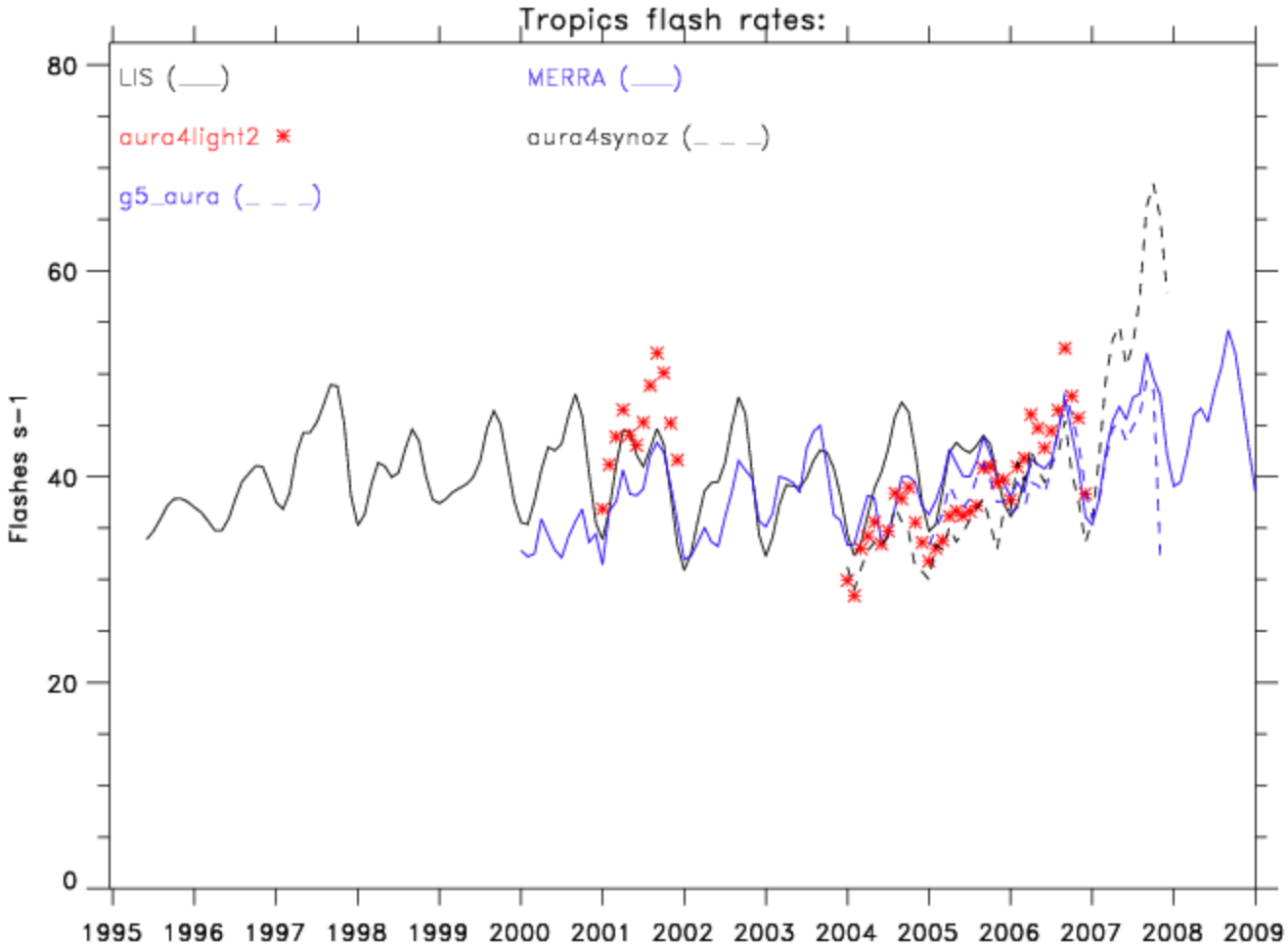

LIS NE Quad flash rates: 1995–2006
95 (___) 96 (. . .) 97 (_ _ _) 98 (_ . _ .)
99 (_ ... _) 00 (__ __) 01 (___) 02 (. . .)
03 (_ _ _) 04 (_ . _ .) 05 (_ ... _) 06 (__ __)
aura4light2 NE Quad flash rates: 2004–2001
04 (___) 05 (. . .) 06 (_ _ _) 01 (_ . _ .)
aura4synoz NE Quad flash rates: 2004–2007
04 (___) 05 (. . .) 06 (_ _ _) 07 (_ . _ .)
g5aura NE Quad flash rates: 2005–2007
05 (___) 06 (. . .) 07 (_ _ _)
merra NE Quad flash rates: 2000–2009
00 (___) 01 (. . .) 02 (_ _ _) 03 (_ . _ .)
04 (_ ... _) 05 (__ __) 06 (___) 07 (. . .)
08 (_ _ _) 09 (_ . _ .)
Flashes s−1
0 5 10 15 20 25 30
J F M A M J J A S O N D

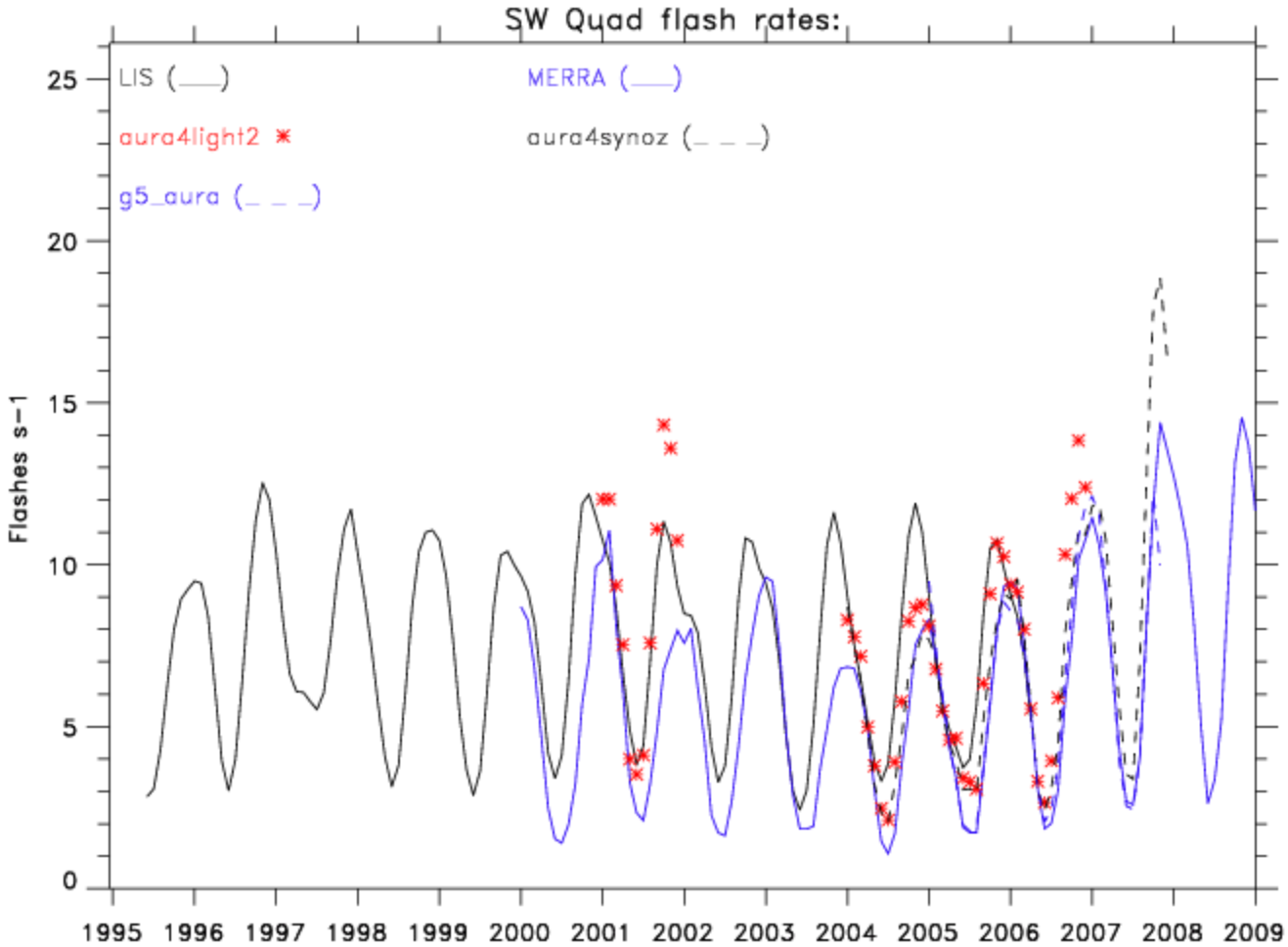

Flash rate Jan
aura4light2: 2004 31.5F s−1
aura4synoz: 2004 32.8F s−1
aura4light2: 2005 31.3F s−1
aura4synoz: 2005 32.3F s−1
aura4light2: 2006 44.4F s−1
aura4synoz: 2006 47.9F s−1
aura4light2: 2001 37.7F s−1
aura4synoz: 2007 36.9F s−1
0.0 0.1 0.2 0.5 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 16.0 32.0

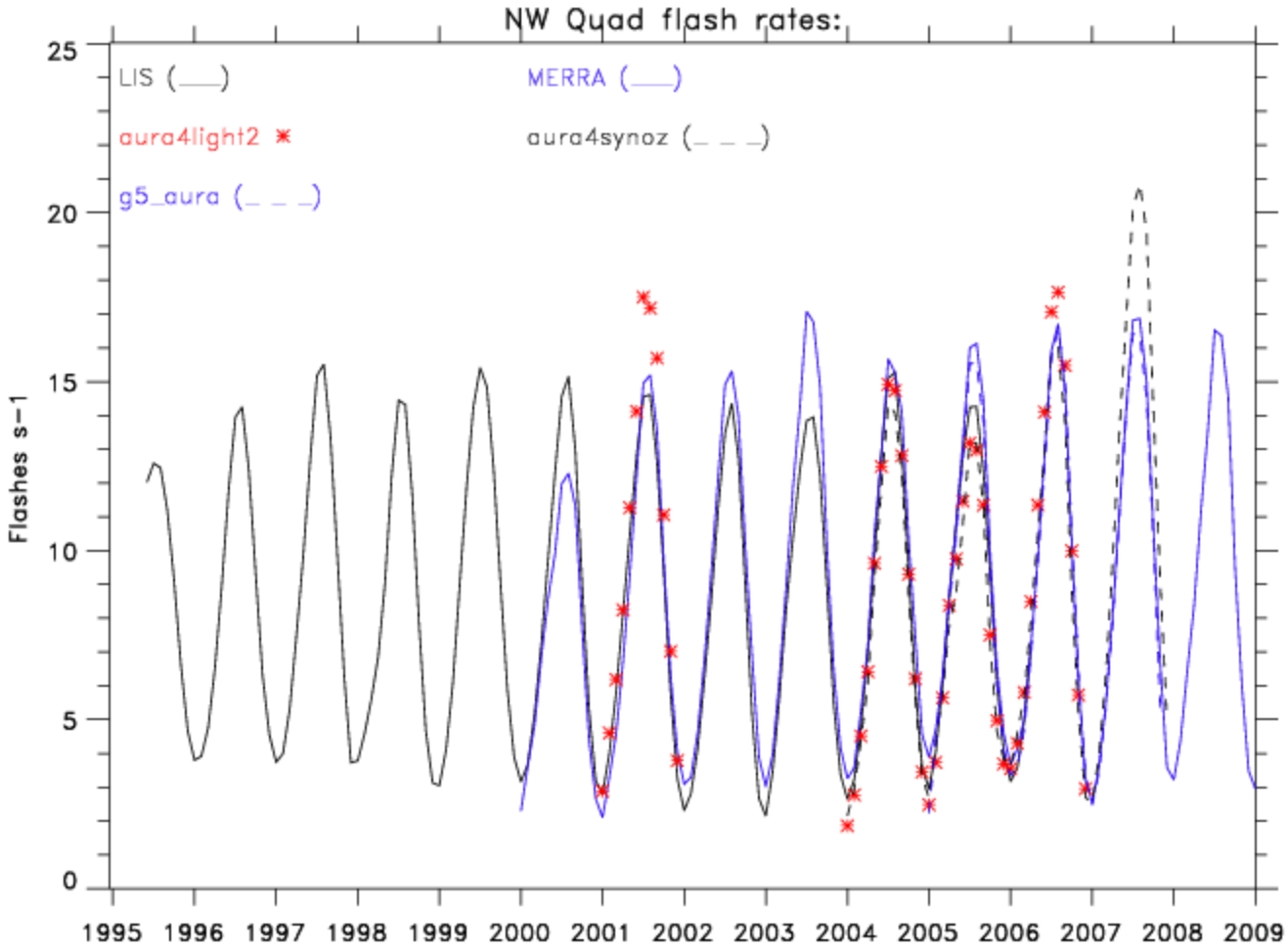

Flash rate Apr
aura4light2: 2004 45.2F s−1
aura4synoz: 2004 39.3F s−1
aura4light2: 2005 34.0F s−1
aura4synoz: 2005 31.2F s−1
aura4light2: 2006 48.6F s−1
aura4synoz: 2006 43.5F s−1
aura4light2: 2001 46.1F s−1
aura4synoz: 2007 60.0F s−1
0.0 0.1 0.2 0.5 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 16.0 32.0

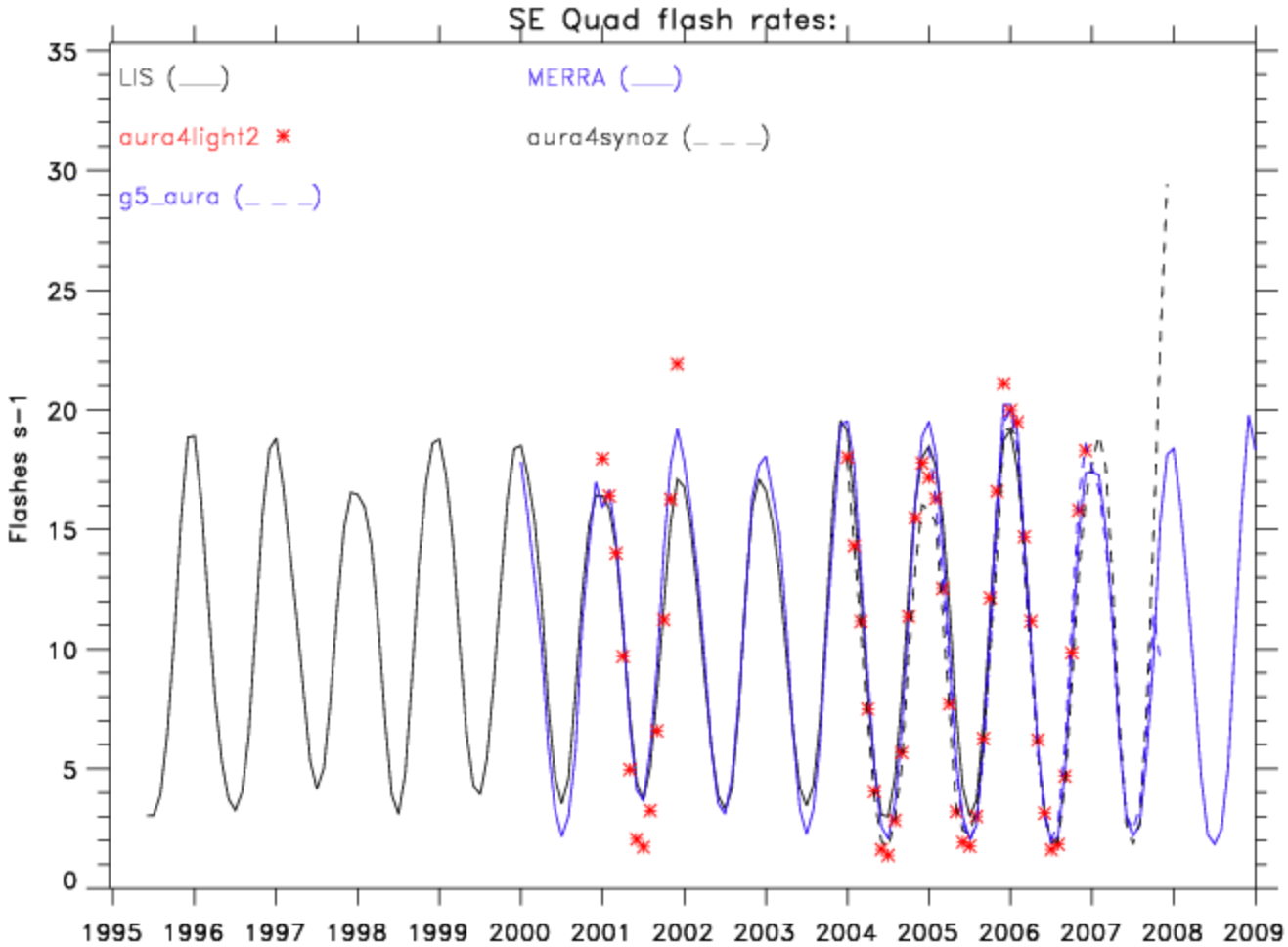

Flash rate Jul
aura4light2: 2004 56.6F s−1
aura4synoz: 2004 55.3F s−1
aura4light2: 2005 47.7F s−1
aura4synoz: 2005 50.3F s−1
aura4light2: 2006 58.0F s−1
aura4synoz: 2006 56.9F s−1
aura4light2: 2001 61.4F s−1
aura4synoz: 2007 61.3F s−1
0.0 0.1 0.2 0.5 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 16.0 32.0

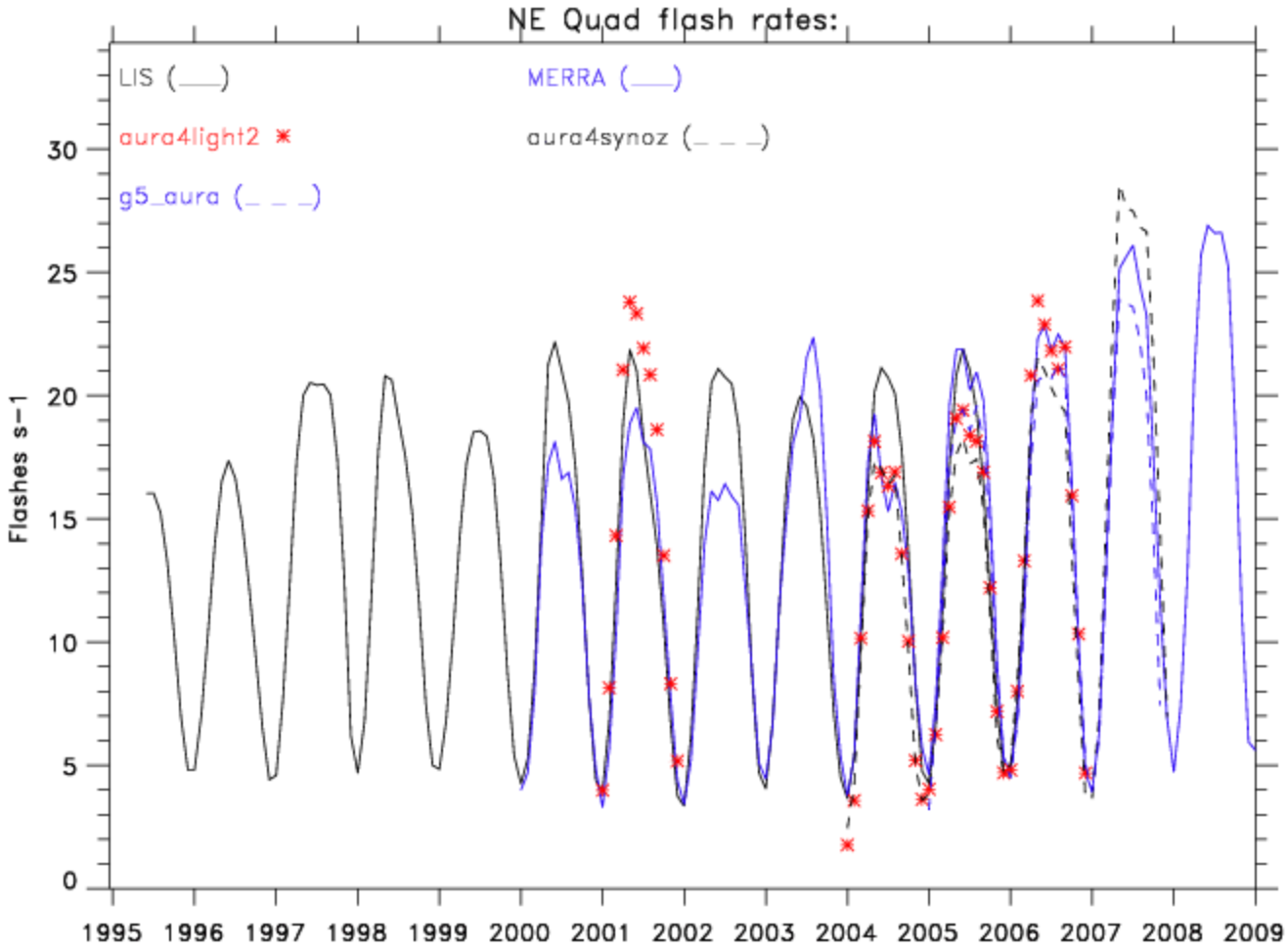

Flash rate Oct
aura4light2: 2004 37.5F s−1
aura4synoz: 2004 33.6F s−1
aura4light2: 2005 43.6F s−1
aura4synoz: 2005 36.6F s−1
aura4light2: 2006 60.7F s−1
aura4synoz: 2006 49.1F s−1
aura4light2: 2001 52.5F s−1
aura4synoz: 2007 75.0F s−1
0.0 0.1 0.2 0.5 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 16.0 32.0

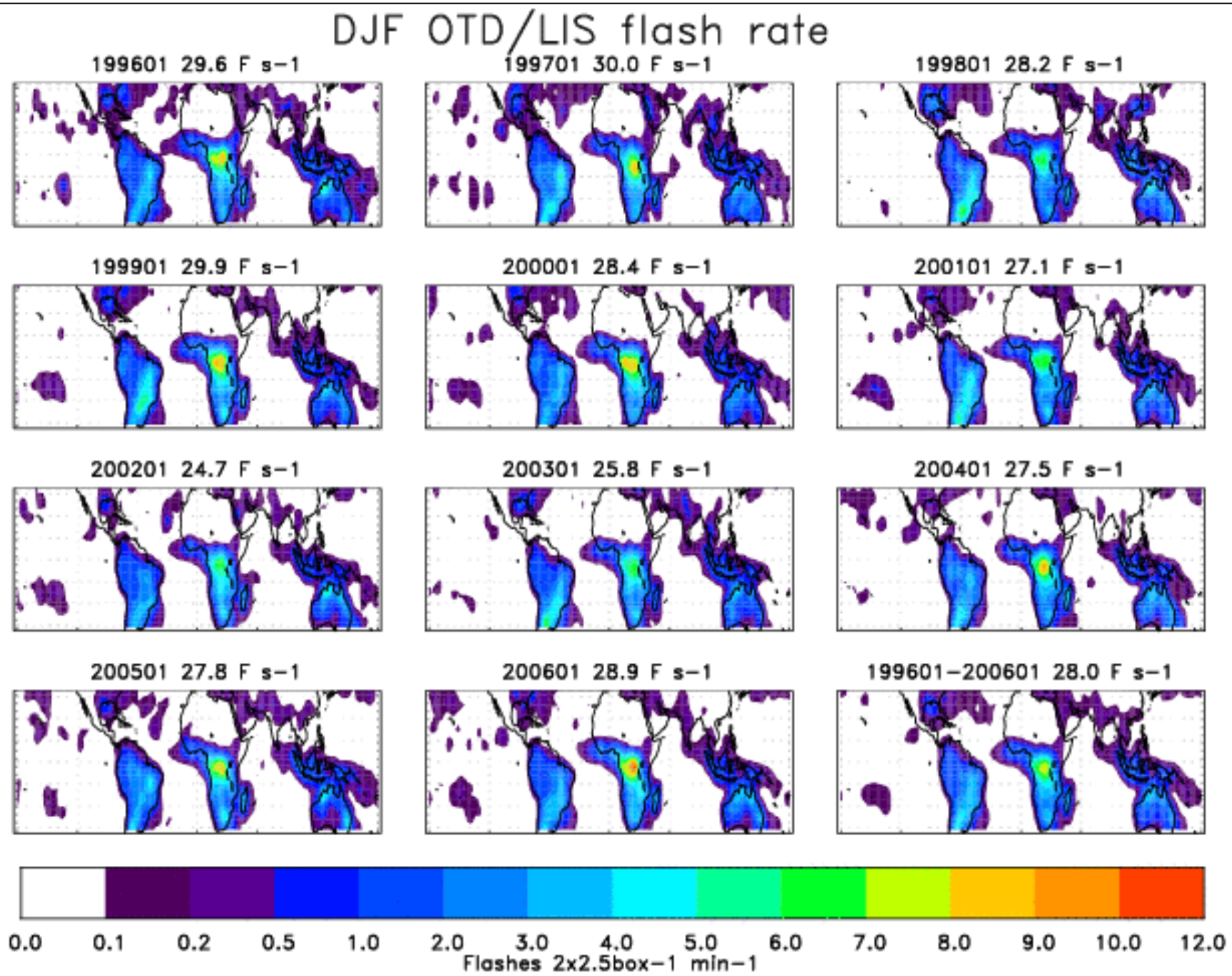

Tropics flash rates:
LIS (___)
MERRA (___)
aura4light2
aura4synoz (_ _ _)
g5_aura (_ _ _)
Flashes s−1
0
20
40
60
80
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009

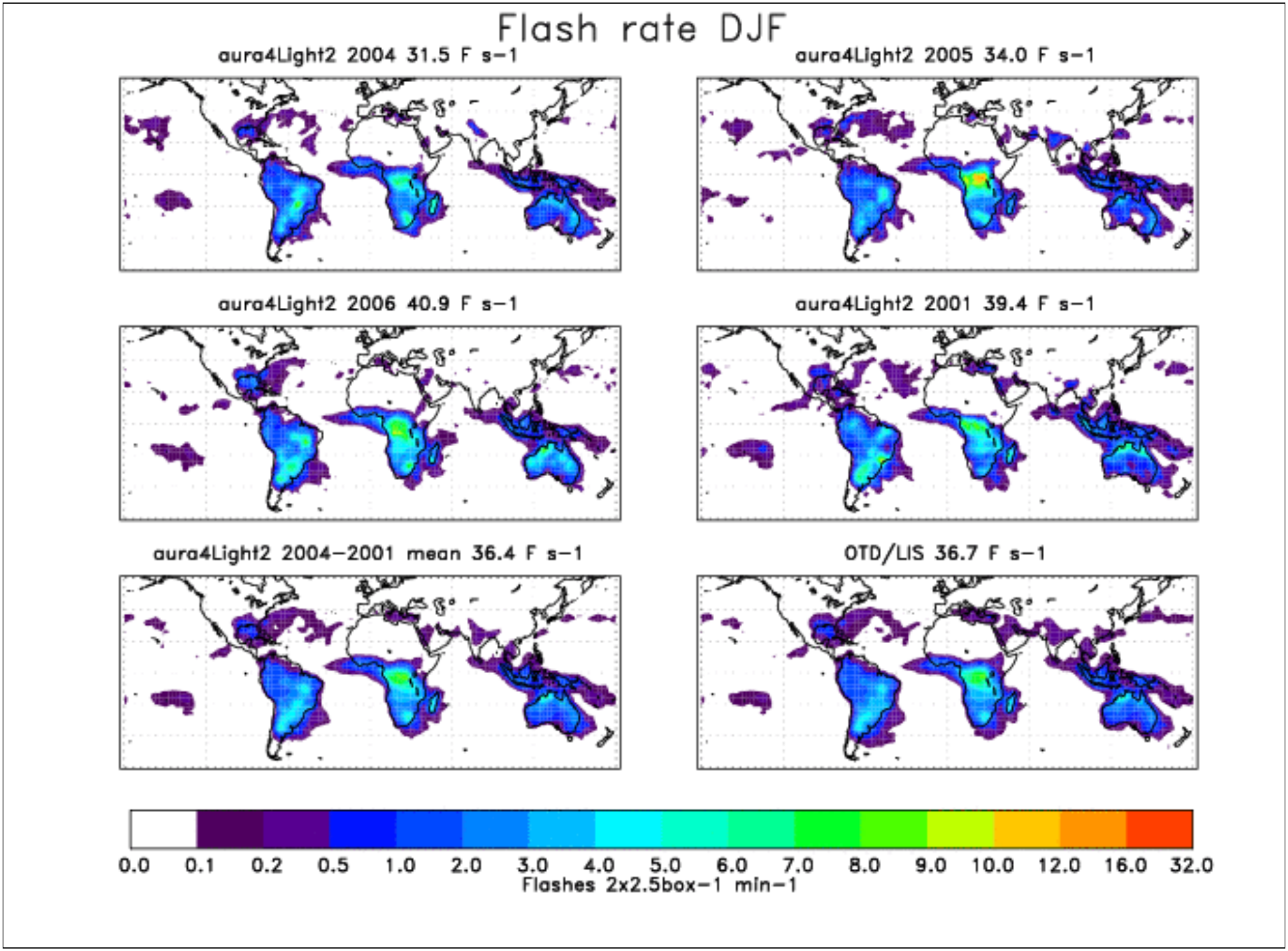

SW Quad flash rates:
LIS (___)
MERRA (___)
aura4light2
aura4synoz (_ _ _)
g5_aura (_ _ _)
Flashes s−1
0
5
10
15
20
25
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009

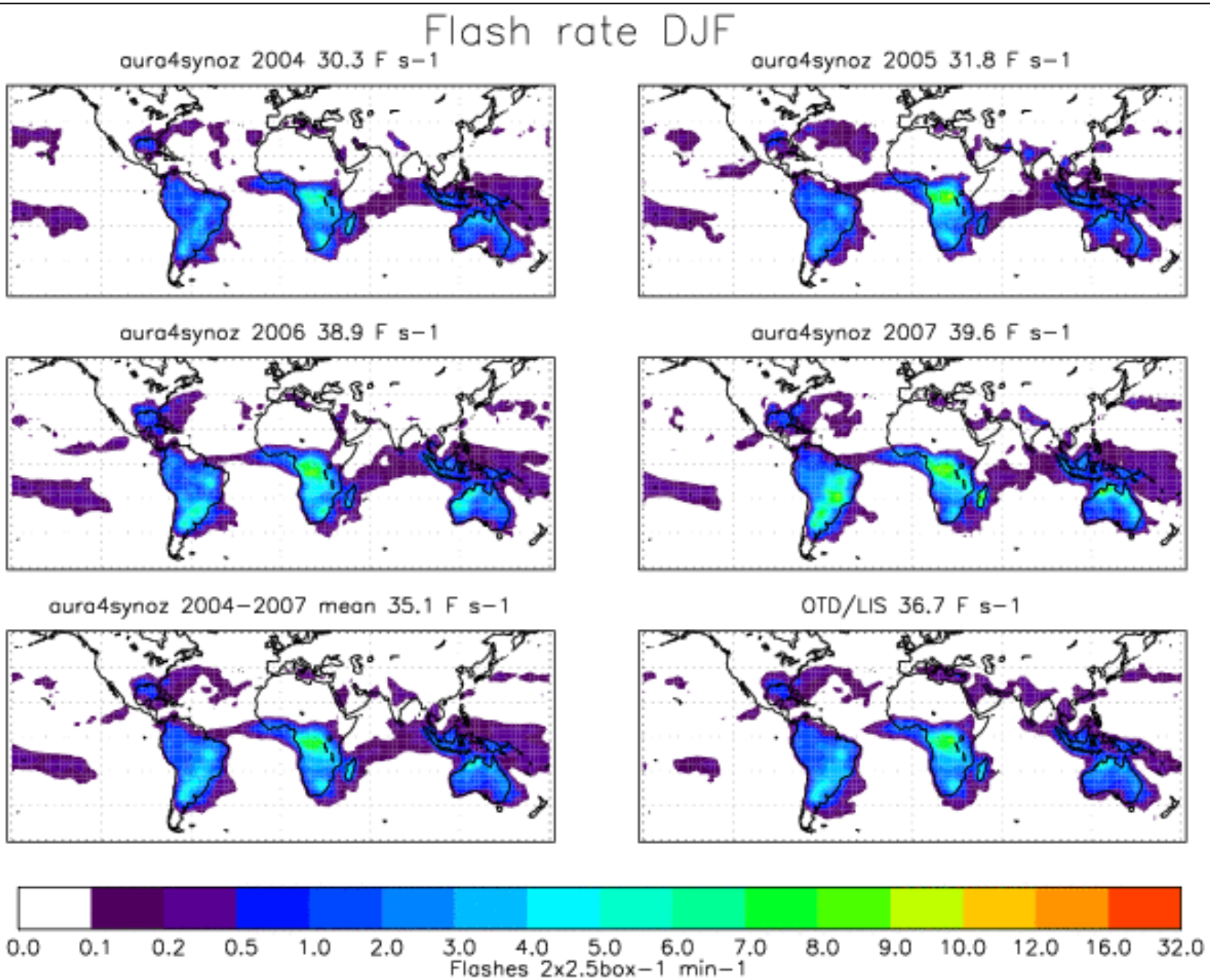

NW Quad flash rates:
LIS (___)
MERRA (___)
aura4light2
aura4synoz (_ _ _)
g5_aura (_ _ _)
Flashes s−1
0
5
10
15
20
25
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009

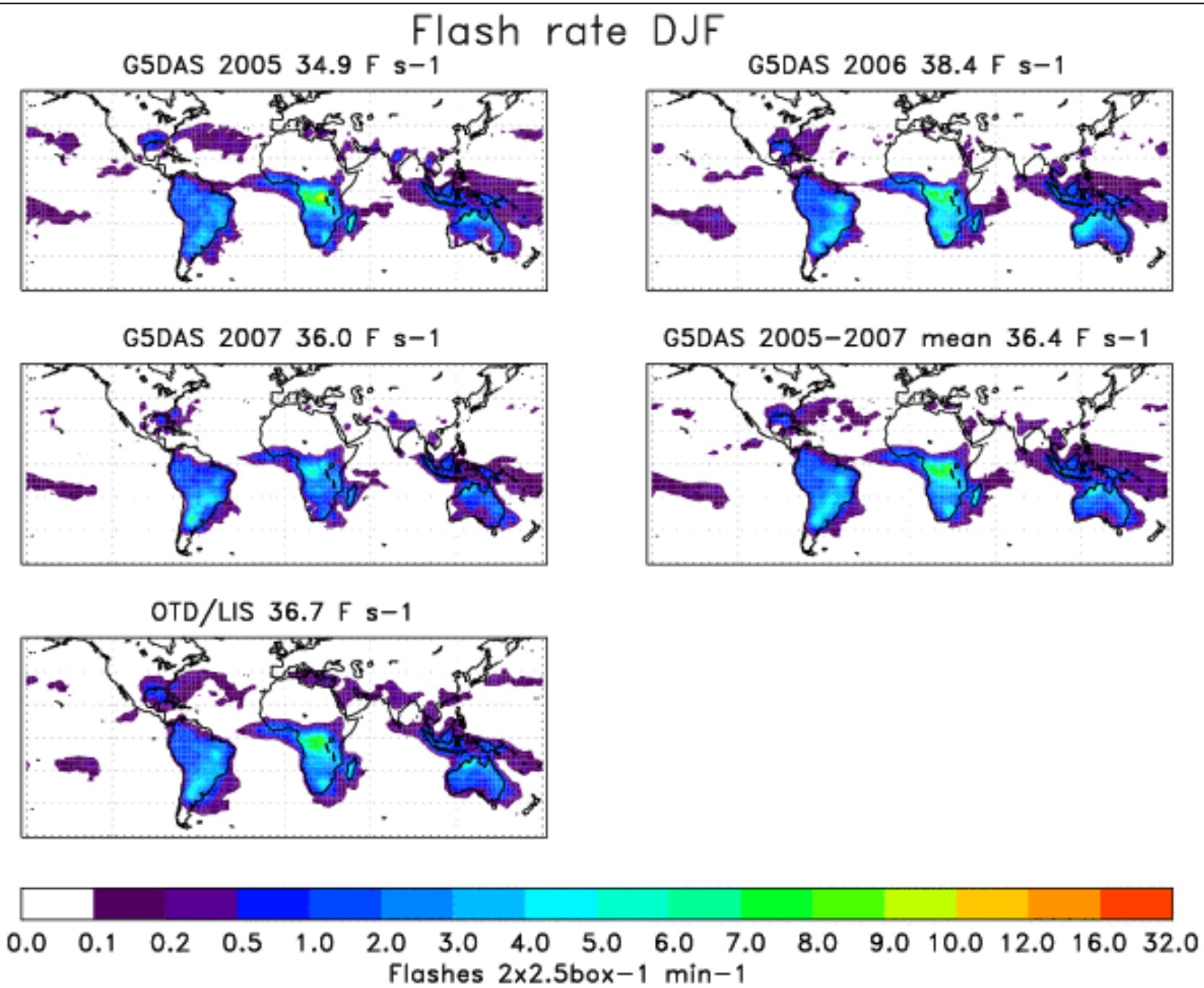

SE Quad flash rates:
LIS (___)
MERRA (___)
aura4light2
aura4synoz (_ _ _)
g5_aura (_ _ _)
Flashes s−1
35
30
25
20
15
10
5
0
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009

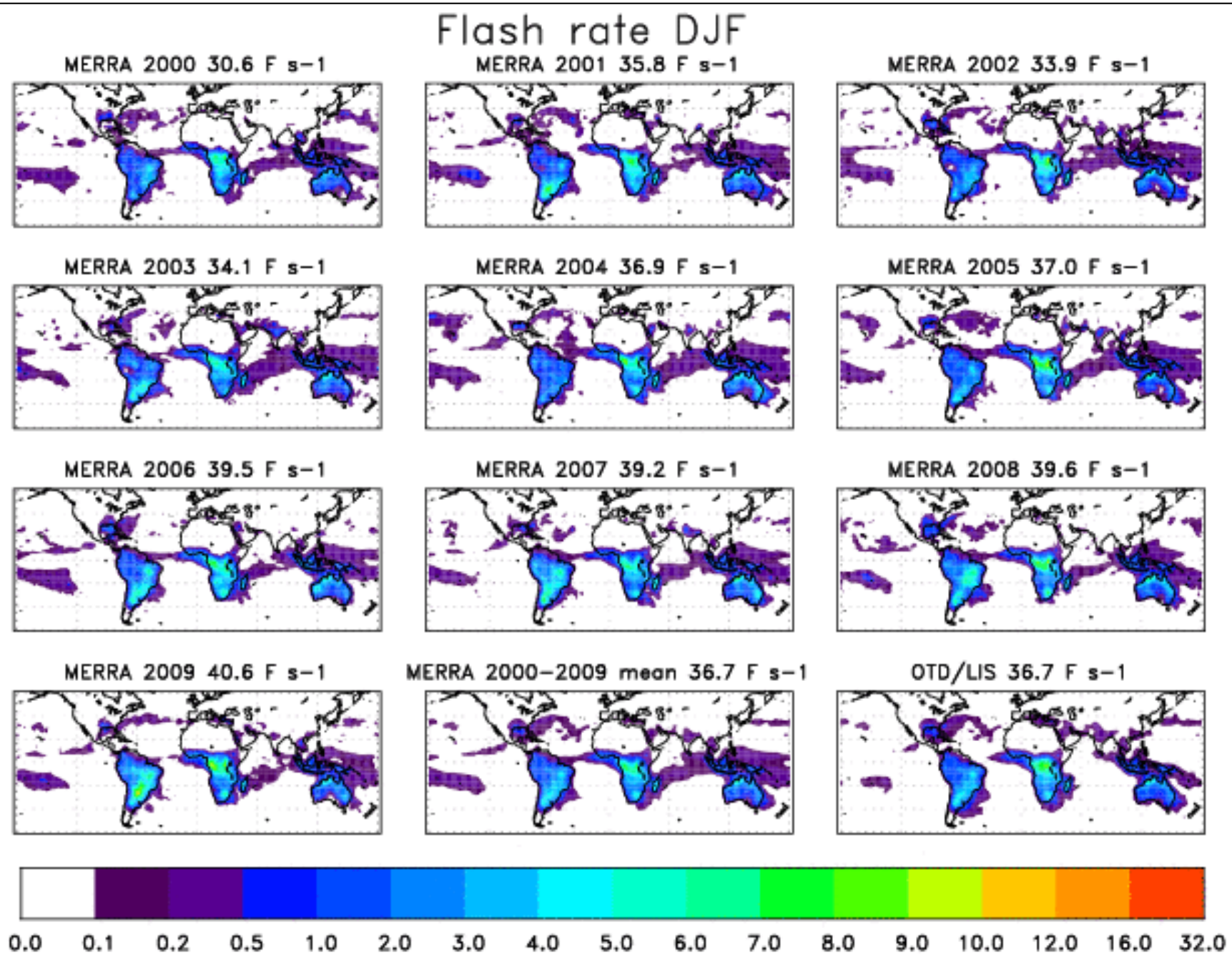

NE Quad flash rates:
LIS (___)
MERRA (___)
aura4light2
aura4synoz (_ _ _)
g5_aura (_ _ _)
Flashes s−1
0
5
10
15
20
25
30
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009

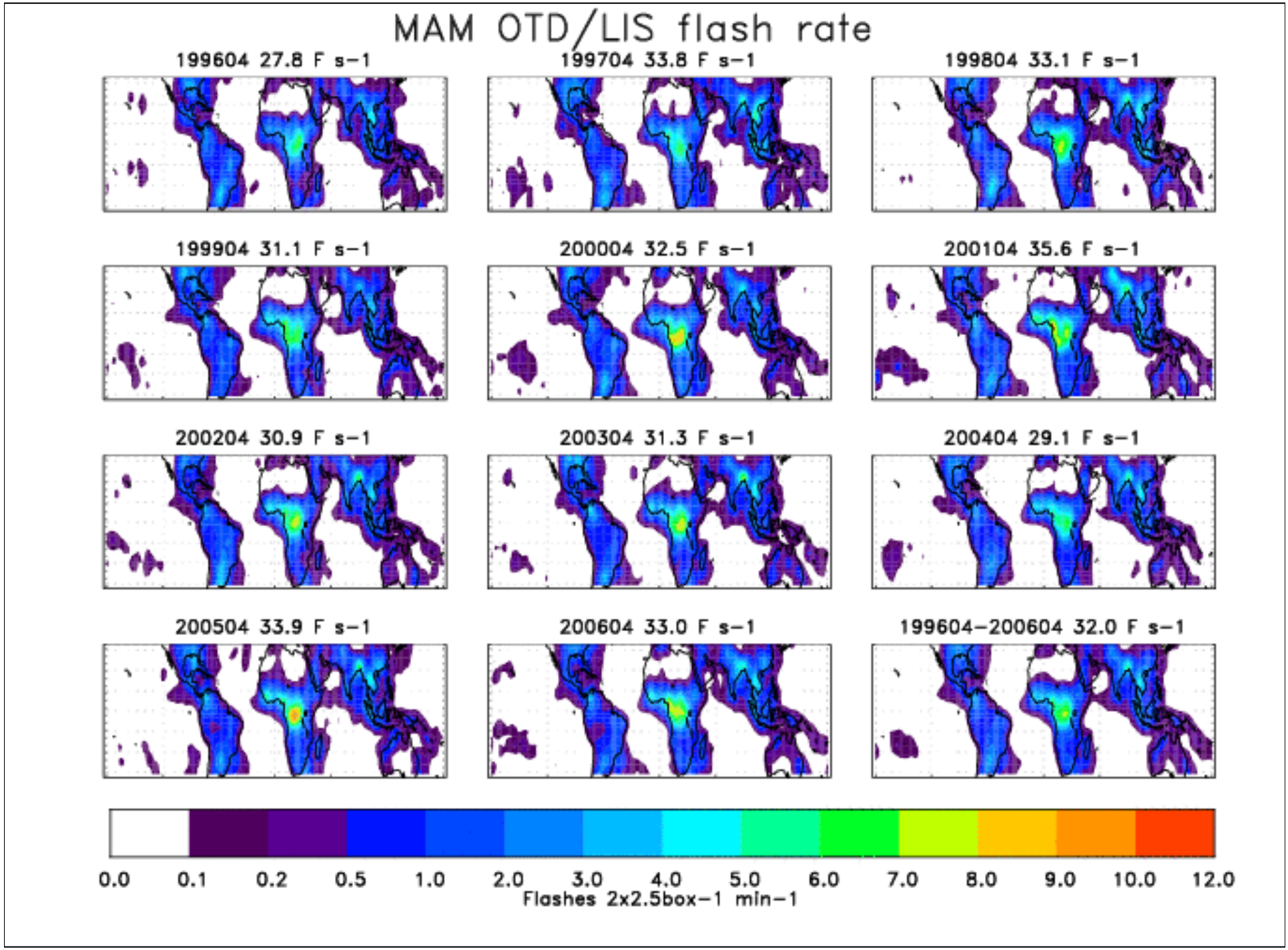

DJF OTD/LIS flash rate
199601 29.6 F s−1
199701 30.0 F s−1
199801 28.2 F s−1
199901 29.9 F s−1
200001 28.4 F s−1
200101 27.1 F s−1
200201 24.7 F s−1
200301 25.8 F s−1
200401 27.5 F s−1
200501 27.8 F s−1
200601 28.9 F s−1
199601−200601 28.0 F s−1
0.0
0.1
0.2
0.5
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
12.0
Flashes 2x2.5box−1 min−1

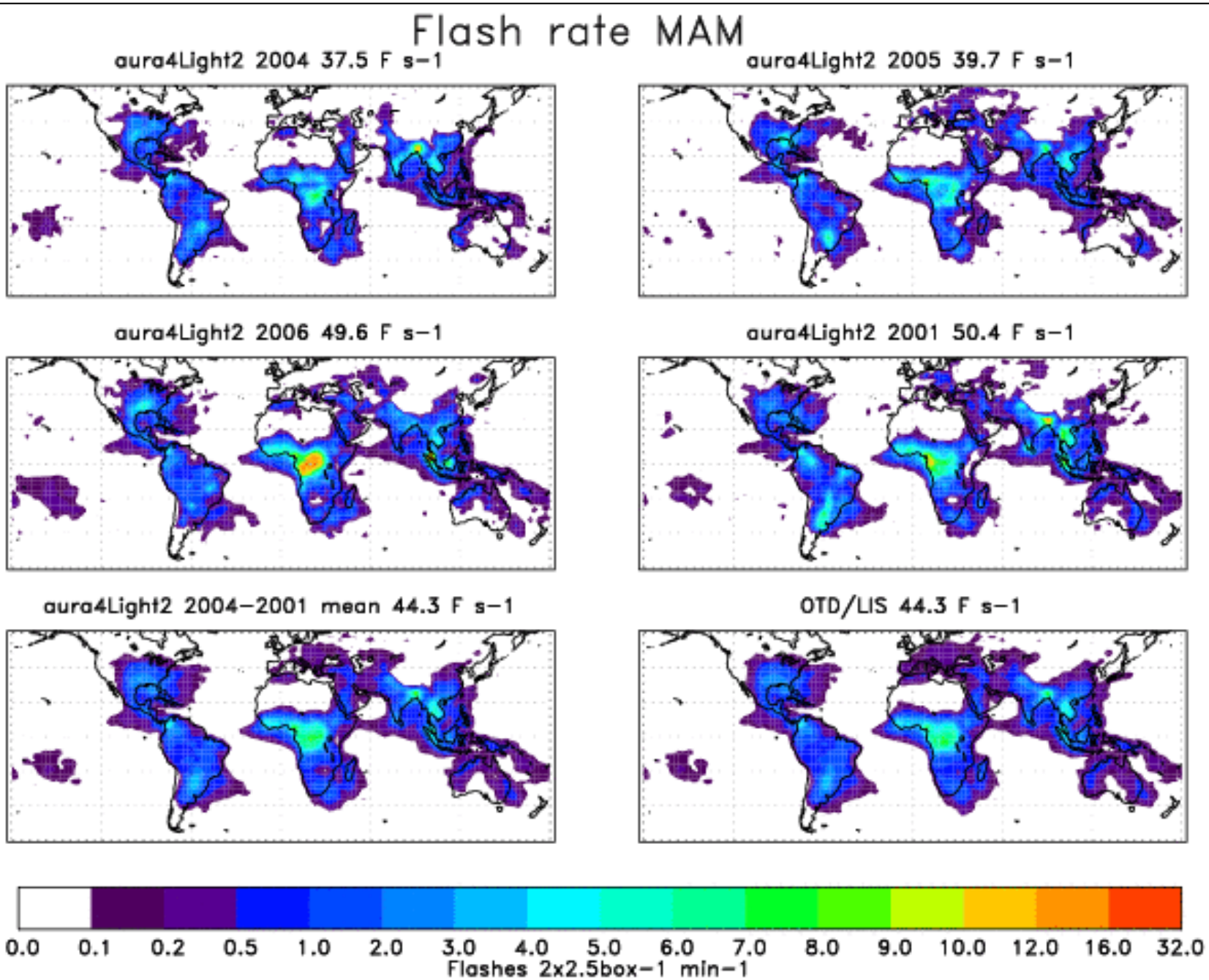

Flash rate DJF
aura4Light2 2004 31.5 F s−1
aura4Light2 2005 34.0 F s−1
aura4Light2 2006 40.9 F s−1
aura4Light2 2001 39.4 F s−1
aura4Light2 2004−2001 mean 36.4 F s−1
OTD/LIS 36.7 F s−1
0.0 0.1 0.2 0.5 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 16.0 32.0
Flashes 2x2.5box−1 min−1

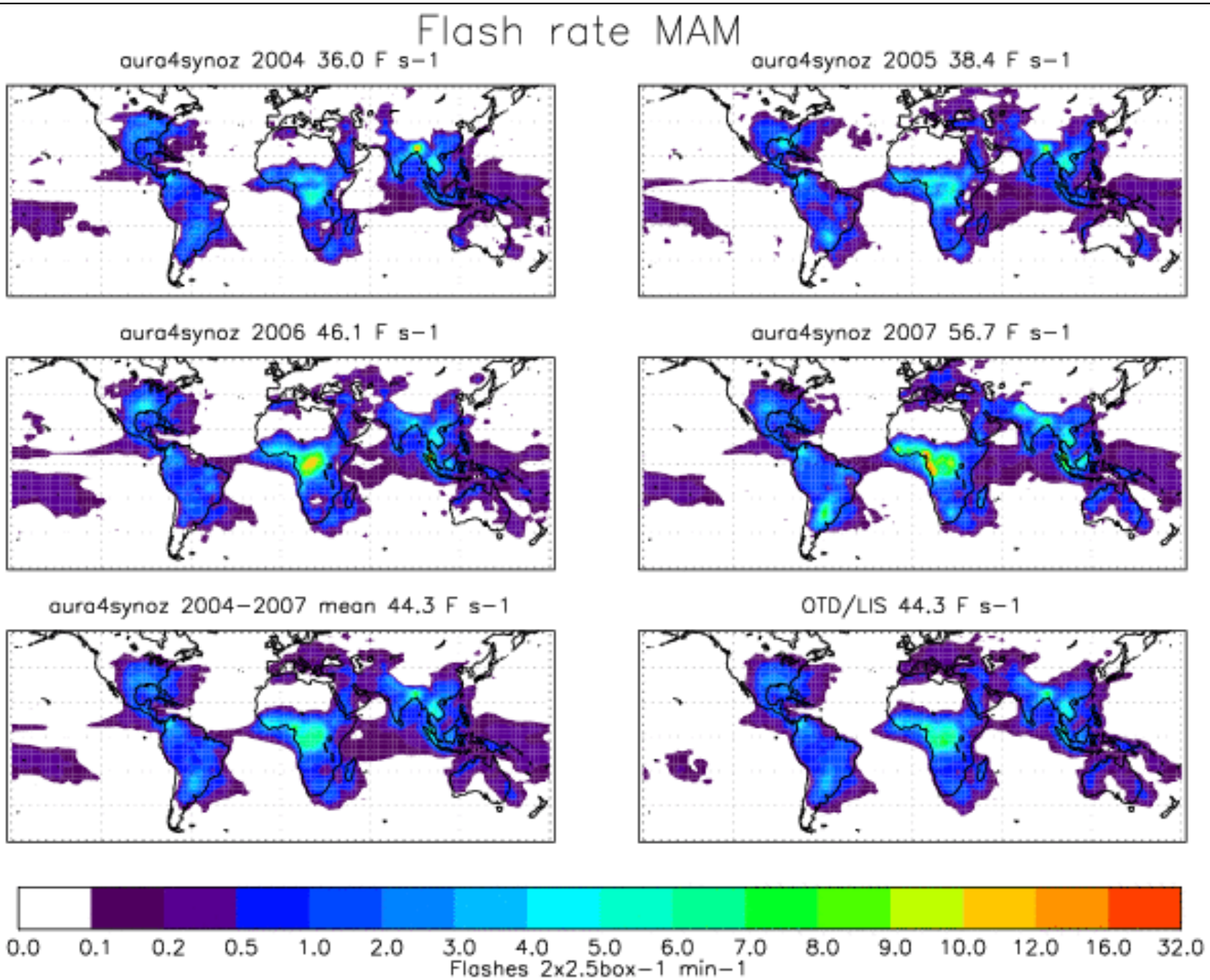

Flash rate DJF
aura4synoz 2004 30.3 F s−1
aura4synoz 2005 31.8 F s−1
aura4synoz 2006 38.9 F s−1
aura4synoz 2007 39.6 F s−1
aura4synoz 2004−2007 mean 35.1 F s−1
OTD/LIS 36.7 F s−1
0.0 0.1 0.2 0.5 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 16.0 32.0
Flashes 2x2.5box−1 min−1

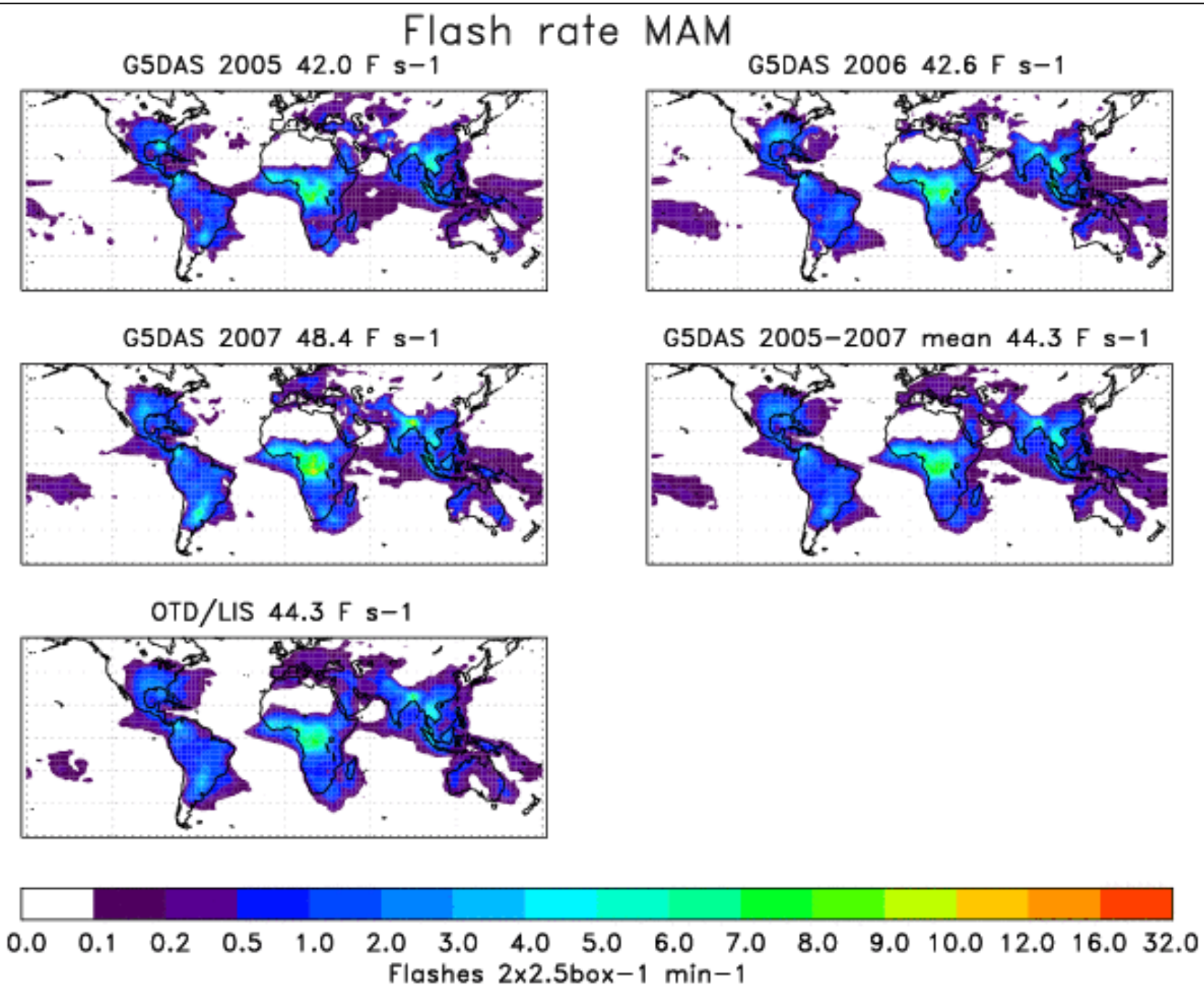

Flash rate DJF
G5DAS 2005 34.9 F s−1
G5DAS 2006 38.4 F s−1
G5DAS 2007 36.0 F s−1
G5DAS 2005−2007 mean 36.4 F s−1
OTD/LIS 36.7 F s−1
0.0 0.1 0.2 0.5 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 16.0 32.0
Flashes 2x2.5box−1 min−1

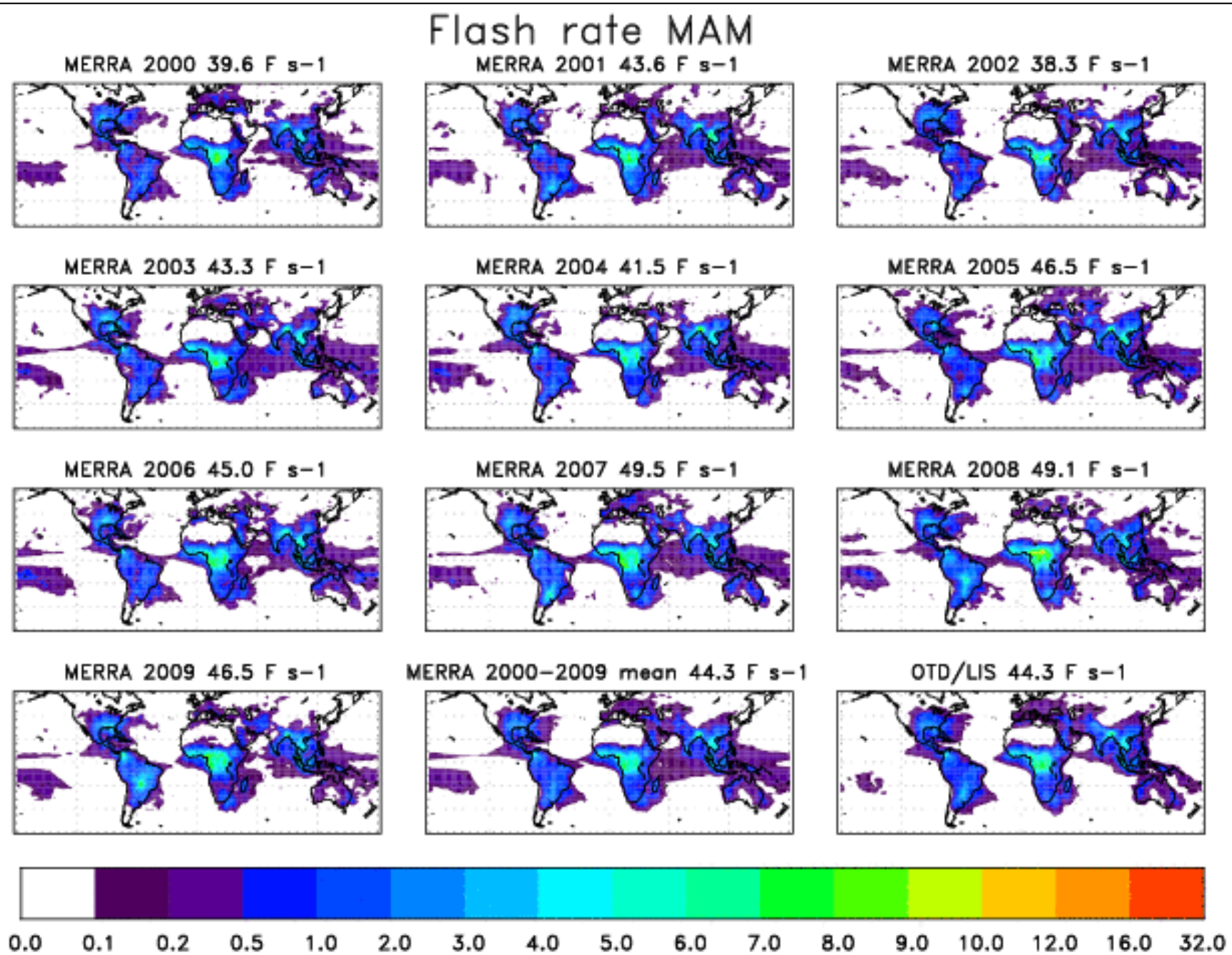

Flash rate DJF
MERRA 2000 30.6 F s−1
MERRA 2001 35.8 F s−1
MERRA 2002 33.9 F s−1
MERRA 2003 34.1 F s−1
MERRA 2004 36.9 F s−1
MERRA 2005 37.0 F s−1
MERRA 2006 39.5 F s−1
MERRA 2007 39.2 F s−1
MERRA 2008 39.6 F s−1
MERRA 2009 40.6 F s−1
MERRA 2000−2009 mean 36.7 F s−1
OTD/LIS 36.7 F s−1
0.0
0.1
0.2
0.5
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
12.0
16.0
32.0

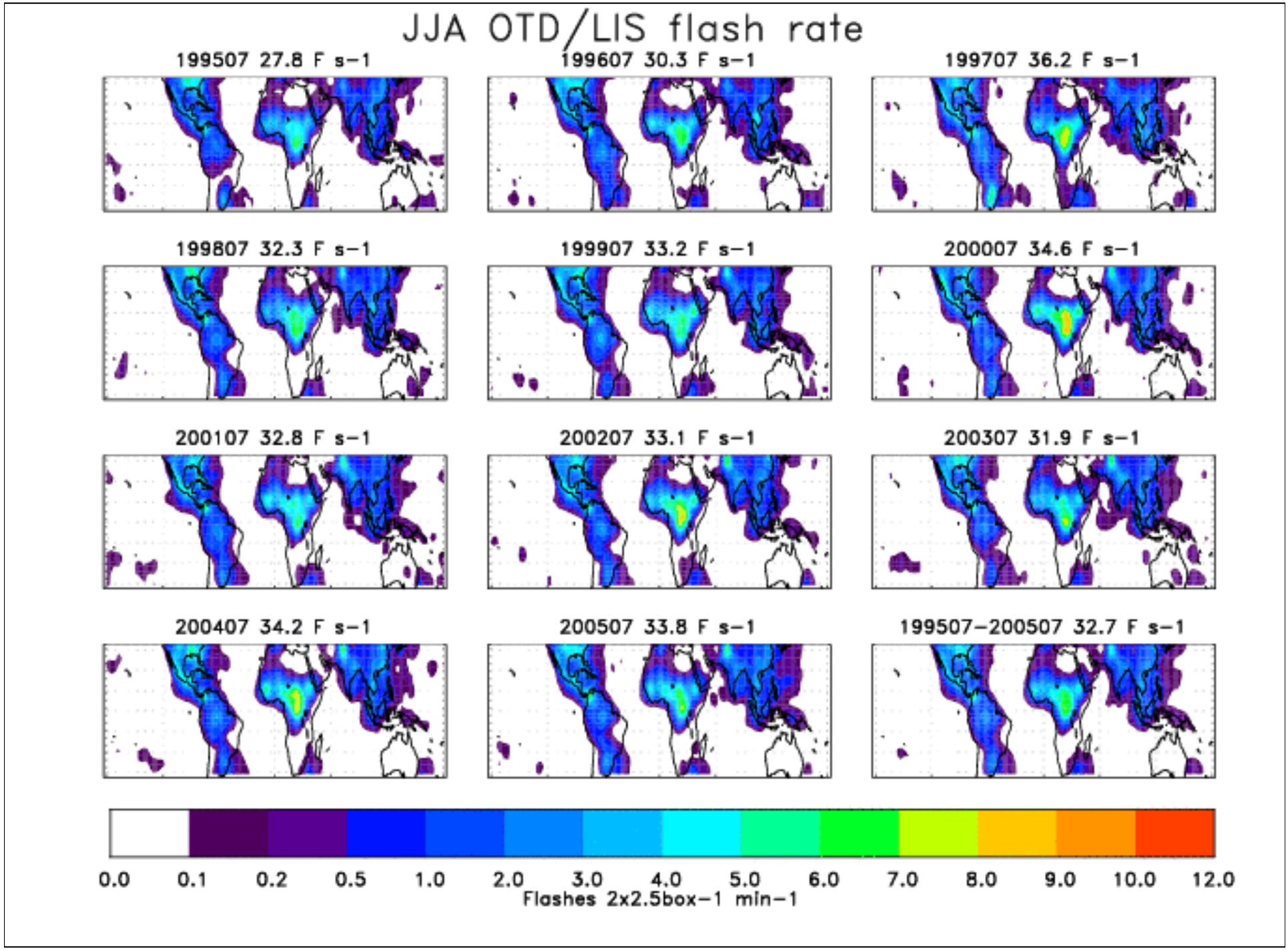

MAM OTD/LIS flash rate
199604 27.8 F s−1
199704 33.8 F s−1
199804 33.1 F s−1
199904 31.1 F s−1
200004 32.5 F s−1
200104 35.6 F s−1
200204 30.9 F s−1
200304 31.3 F s−1
200404 29.1 F s−1
200504 33.9 F s−1
200604 33.0 F s−1
199604−200604 32.0 F s−1
0.0 0.1 0.2 0.5 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0
Flashes 2x2.5box−1 min−1

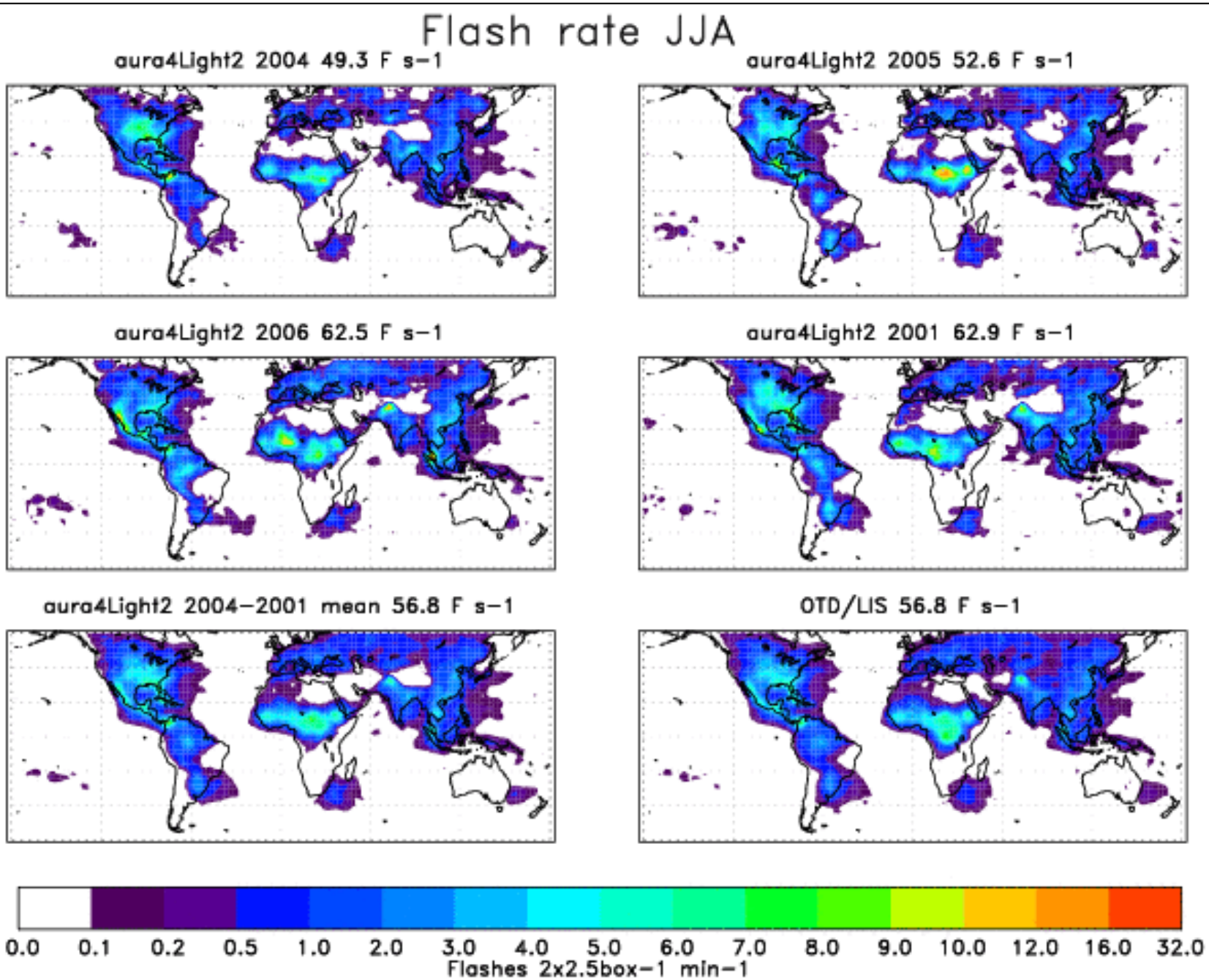

Flash rate MAM
aura4Light2 2004 37.5 F s−1
aura4Light2 2005 39.7 F s−1
aura4Light2 2006 49.6 F s−1
aura4Light2 2001 50.4 F s−1
aura4Light2 2004−2001 mean 44.3 F s−1
OTD/LIS 44.3 F s−1
0.0 0.1 0.2 0.5 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 16.0 32.0
Flashes 2x2.5box−1 min−1

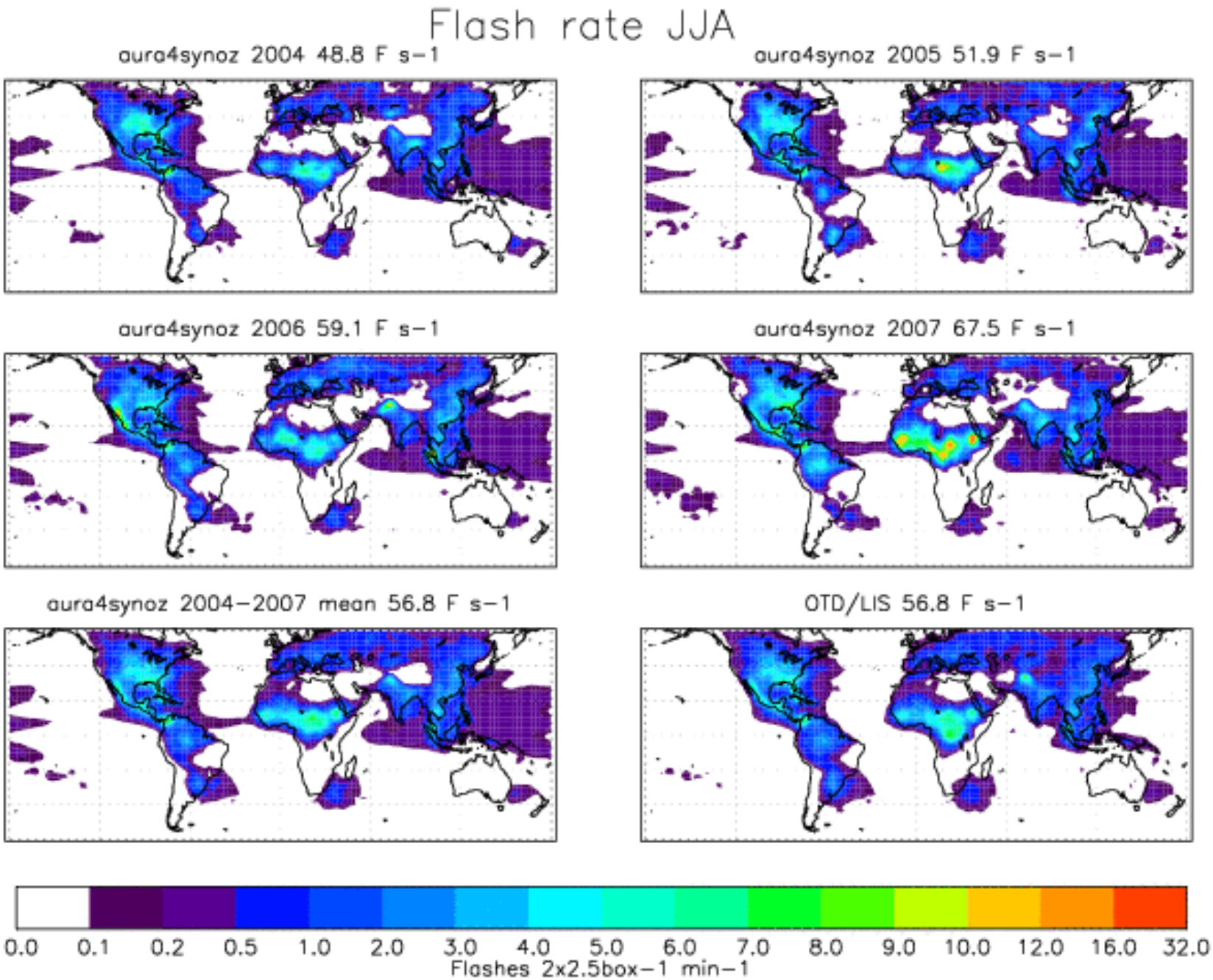

Flash rate MAM
aura4synoz 2004 36.0 F s−1
aura4synoz 2005 38.4 F s−1
aura4synoz 2006 46.1 F s−1
aura4synoz 2007 56.7 F s−1
aura4synoz 2004−2007 mean 44.3 F s−1
OTD/LIS 44.3 F s−1
0.0 0.1 0.2 0.5 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 16.0 32.0
Flashes 2x2.5box−1 min−1

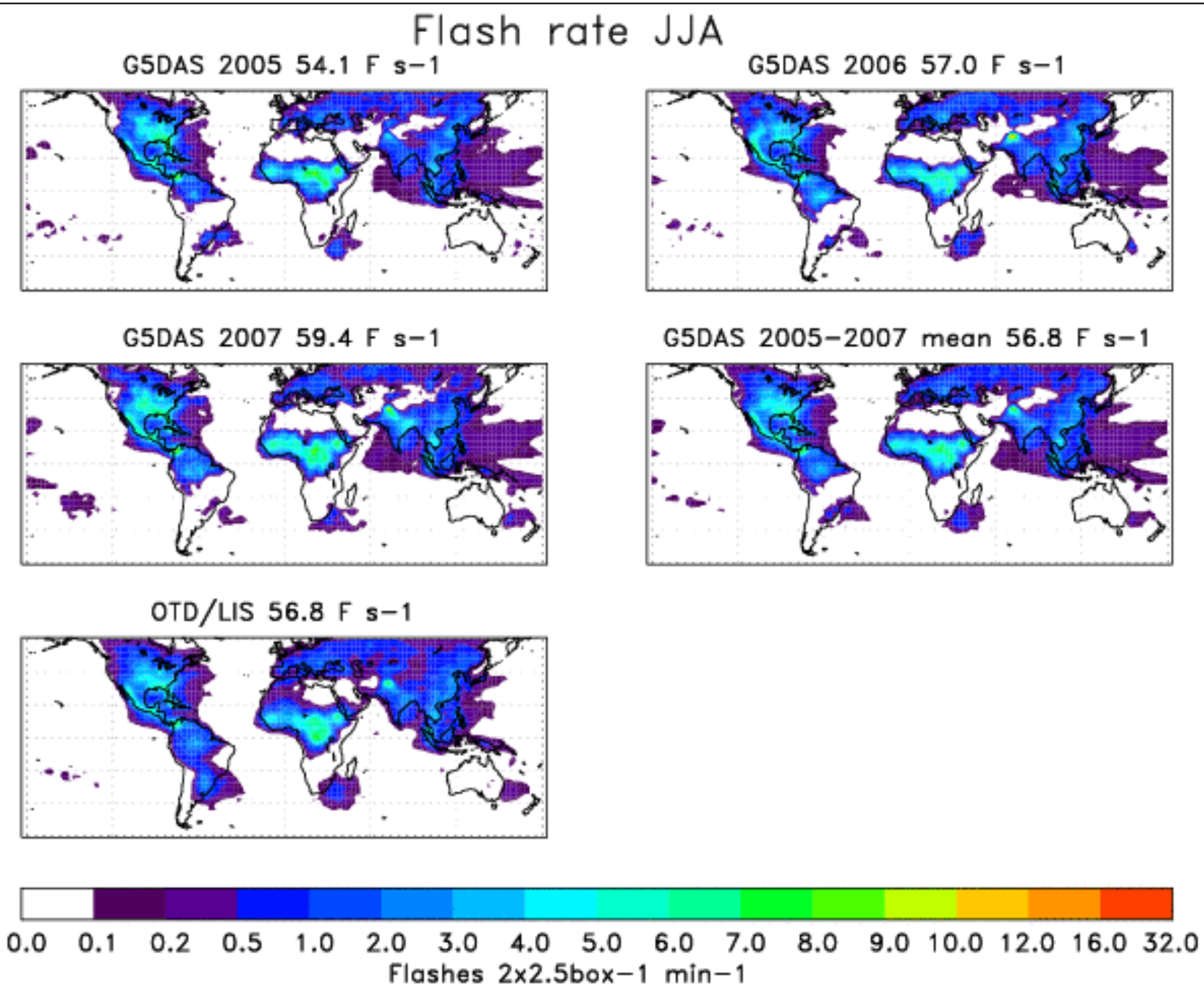

Flash rate MAM
G5DAS 2005 42.0 F s−1
G5DAS 2006 42.6 F s−1
G5DAS 2007 48.4 F s−1
G5DAS 2005−2007 mean 44.3 F s−1
OTD/LIS 44.3 F s−1
0.0 0.1 0.2 0.5 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 16.0 32.0
Flashes 2x2.5box−1 min−1

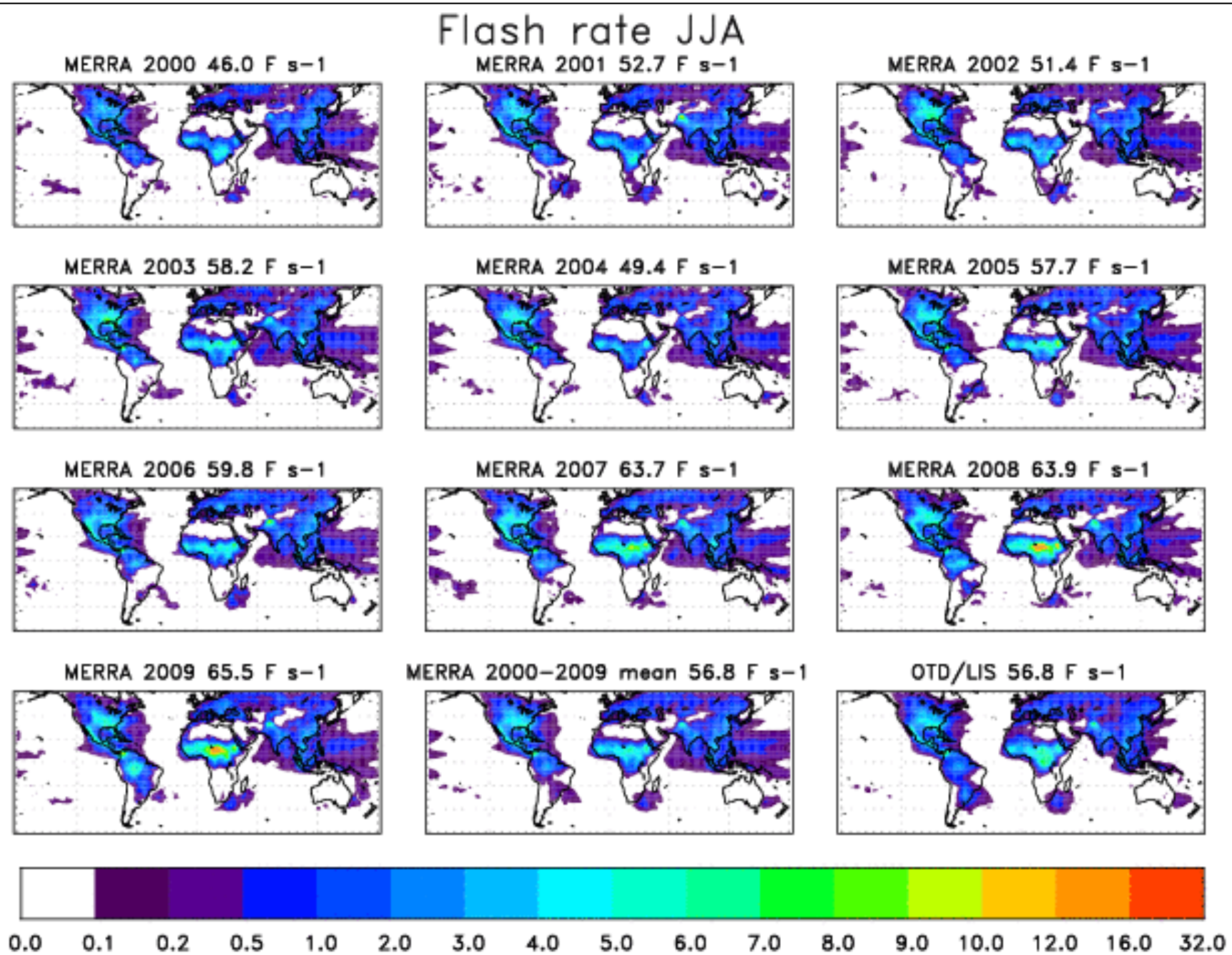

Flash rate MAM
MERRA 2000 39.6 F s−1
MERRA 2001 43.6 F s−1
MERRA 2002 38.3 F s−1
MERRA 2003 43.3 F s−1
MERRA 2004 41.5 F s−1
MERRA 2005 46.5 F s−1
MERRA 2006 45.0 F s−1
MERRA 2007 49.5 F s−1
MERRA 2008 49.1 F s−1
MERRA 2009 46.5 F s−1
MERRA 2000−2009 mean 44.3 F s−1
OTD/LIS 44.3 F s−1
0.0
0.1
0.2
0.5
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
12.0
16.0
32.0

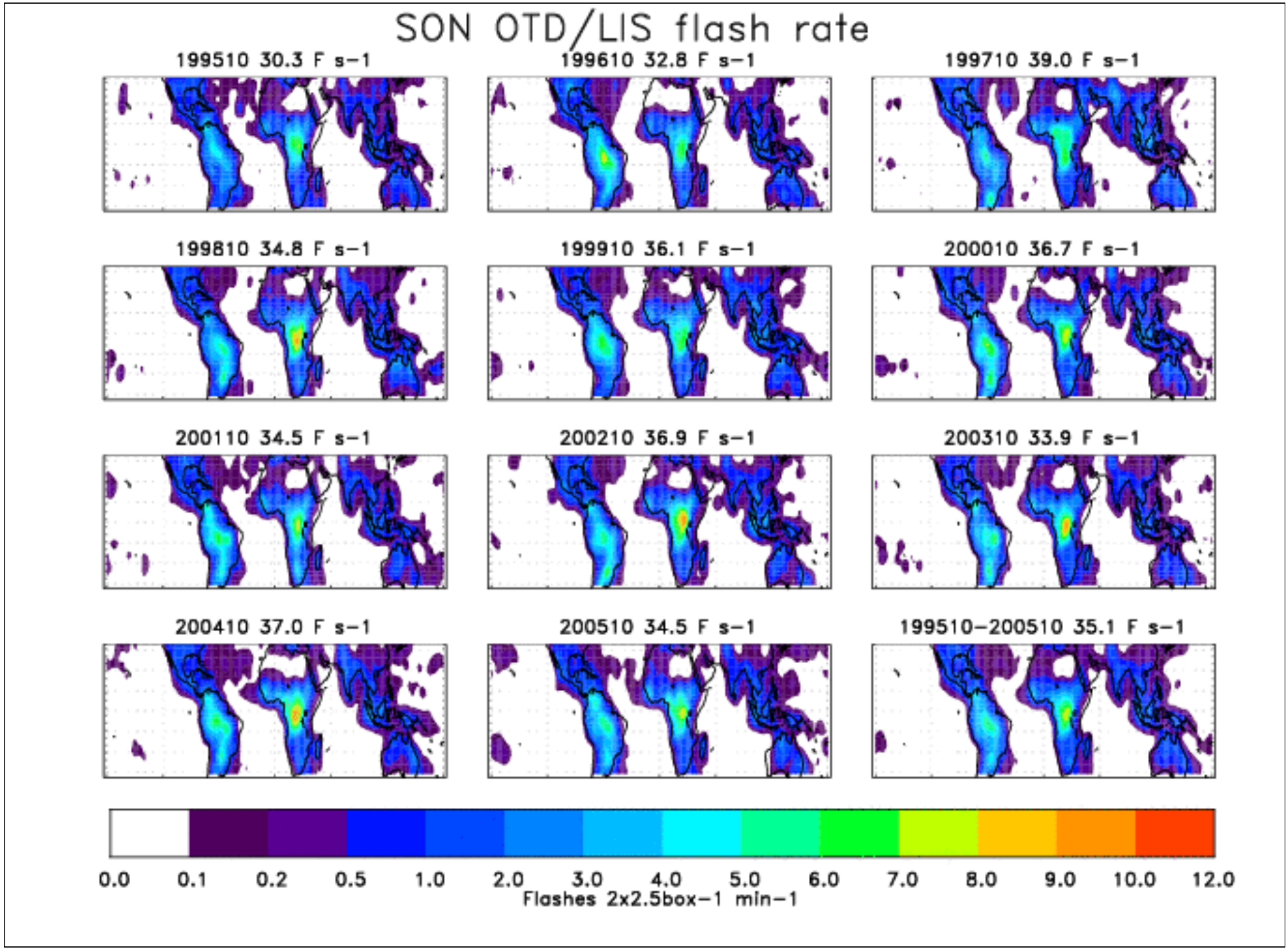

JJA OTD/LIS flash rate
199507 27.8 F s−1
199607 30.3 F s−1
199707 36.2 F s−1
199807 32.3 F s−1
199907 33.2 F s−1
200007 34.6 F s−1
200107 32.8 F s−1
200207 33.1 F s−1
200307 31.9 F s−1
200407 34.2 F s−1
200507 33.8 F s−1
199507−200507 32.7 F s−1
0.0 0.1 0.2 0.5 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0
Flashes 2x2.5box−1 min−1

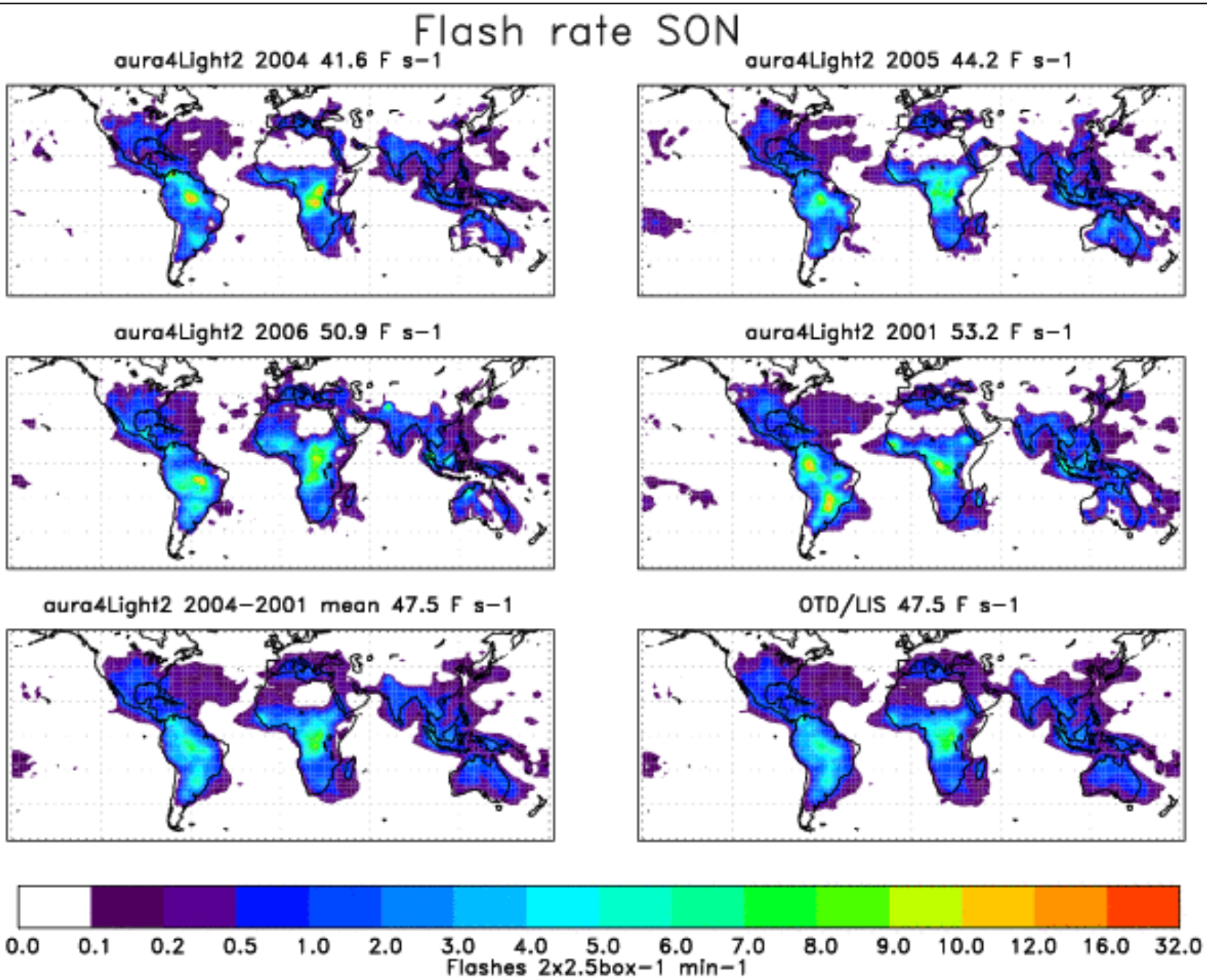

Flash rate JJA
aura4Light2 2004 49.3 F s−1
aura4Light2 2005 52.6 F s−1
aura4Light2 2006 62.5 F s−1
aura4Light2 2001 62.9 F s−1
aura4Light2 2004−2001 mean 56.8 F s−1
OTD/LIS 56.8 F s−1
0.0 0.1 0.2 0.5 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 16.0 32.0
Flashes 2x2.5box−1 min−1

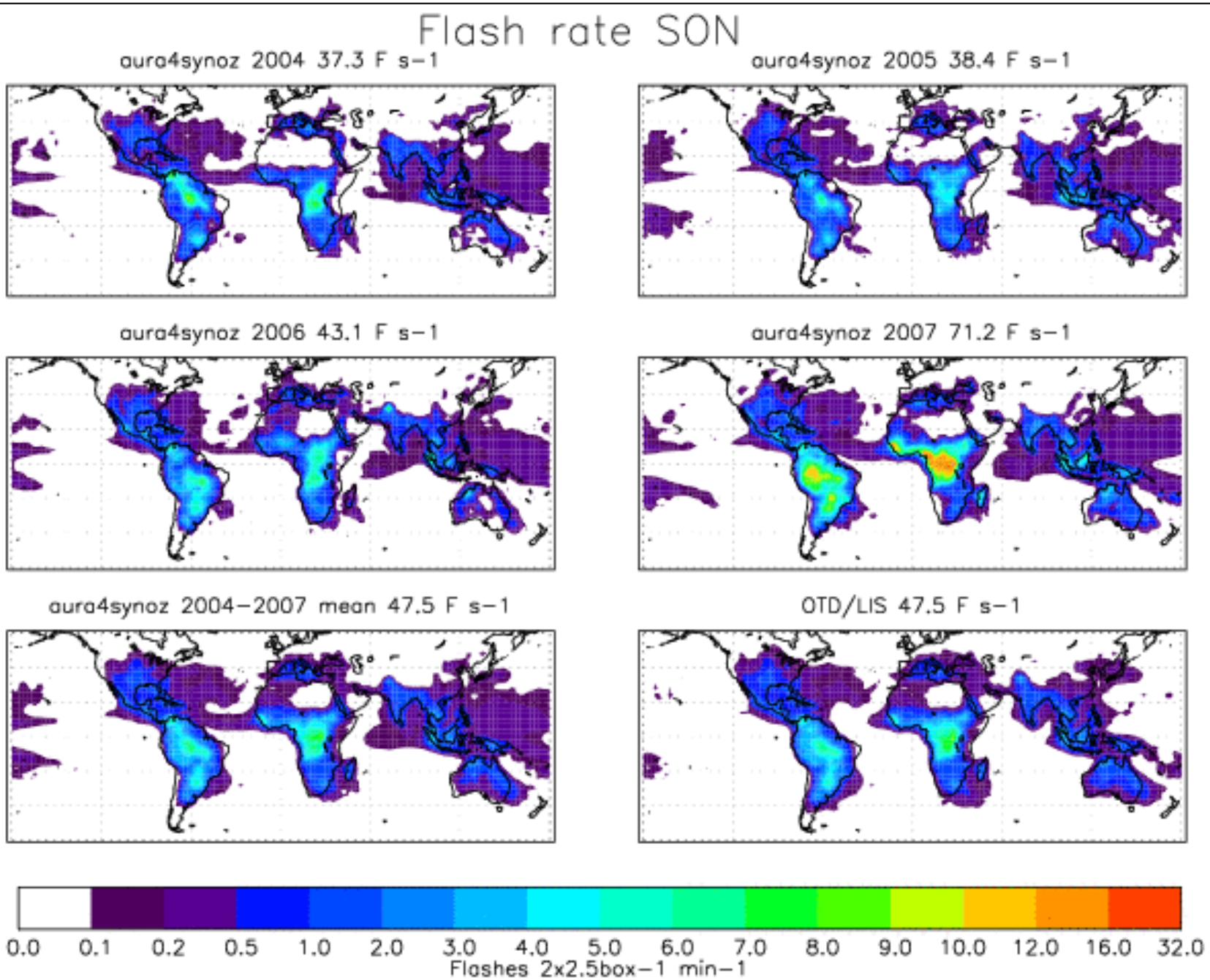

Flash rate JJA
aura4synoz 2004 48.8 F s−1
aura4synoz 2005 51.9 F s−1
aura4synoz 2006 59.1 F s−1
aura4synoz 2007 67.5 F s−1
aura4synoz 2004−2007 mean 56.8 F s−1
OTD/LIS 56.8 F s−1
0.0 0.1 0.2 0.5 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 16.0 32.0
Flashes 2x2.5box−1 min−1

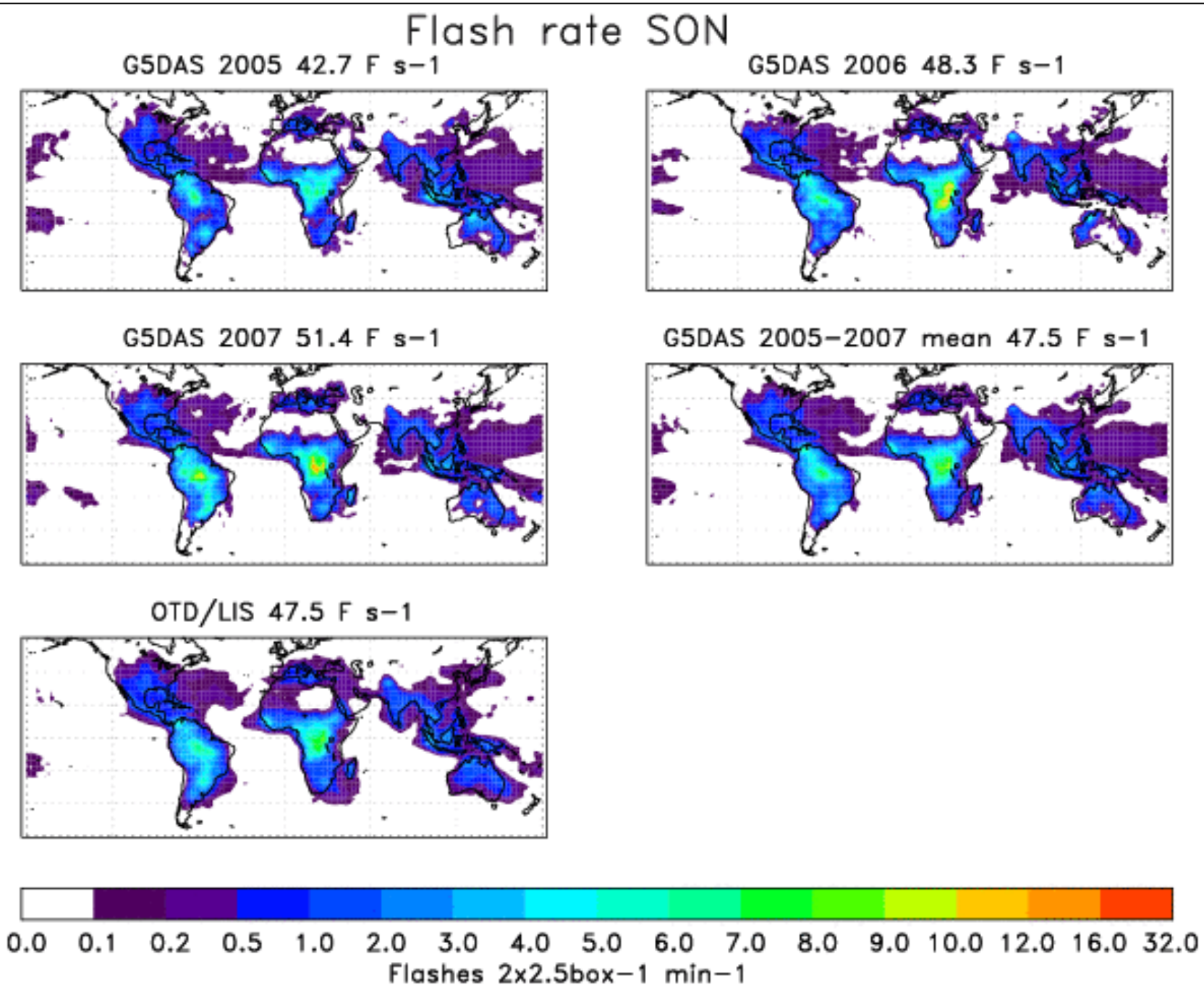

Flash rate JJA
G5DAS 2005 54.1 F s−1
G5DAS 2006 57.0 F s−1
G5DAS 2007 59.4 F s−1
G5DAS 2005−2007 mean 56.8 F s−1
OTD/LIS 56.8 F s−1
0.0 0.1 0.2 0.5 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 16.0 32.0
Flashes 2x2.5box−1 min−1

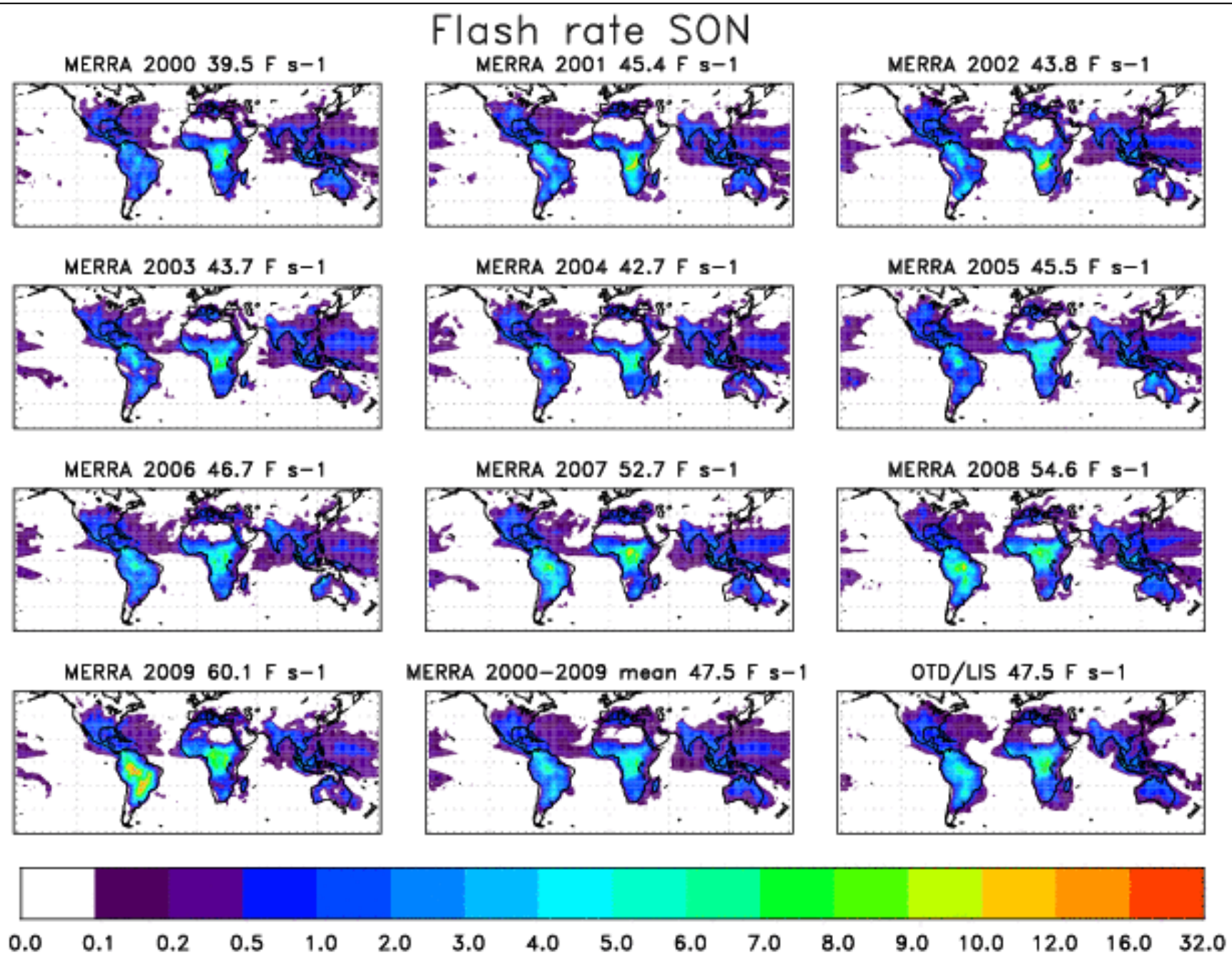

Flash rate JJA
MERRA 2000 46.0 F s−1
MERRA 2001 52.7 F s−1
MERRA 2002 51.4 F s−1
MERRA 2003 58.2 F s−1
MERRA 2004 49.4 F s−1
MERRA 2005 57.7 F s−1
MERRA 2006 59.8 F s−1
MERRA 2007 63.7 F s−1
MERRA 2008 63.9 F s−1
MERRA 2009 65.5 F s−1
MERRA 2000−2009 mean 56.8 F s−1
OTD/LIS 56.8 F s−1
0.0 0.1 0.2 0.5 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 16.0 32.0

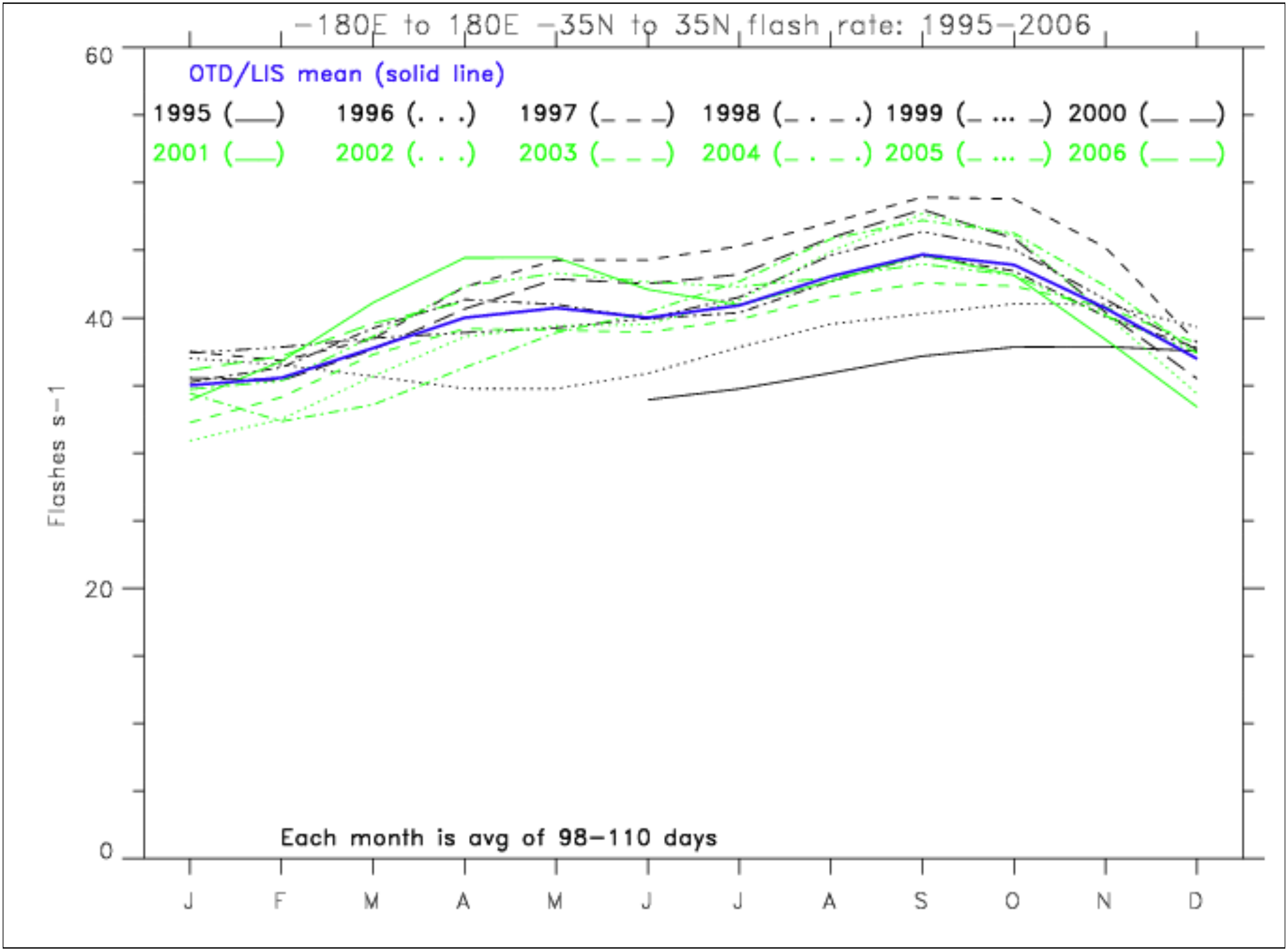

SON OTD/LIS flash rate
199510 30.3 F s−1
199610 32.8 F s−1
199710 39.0 F s−1
199810 34.8 F s−1
199910 36.1 F s−1
200010 36.7 F s−1
200110 34.5 F s−1
200210 36.9 F s−1
200310 33.9 F s−1
200410 37.0 F s−1
200510 34.5 F s−1
199510−200510 35.1 F s−1
0.0 0.1 0.2 0.5 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0
Flashes 2x2.5box−1 min−1

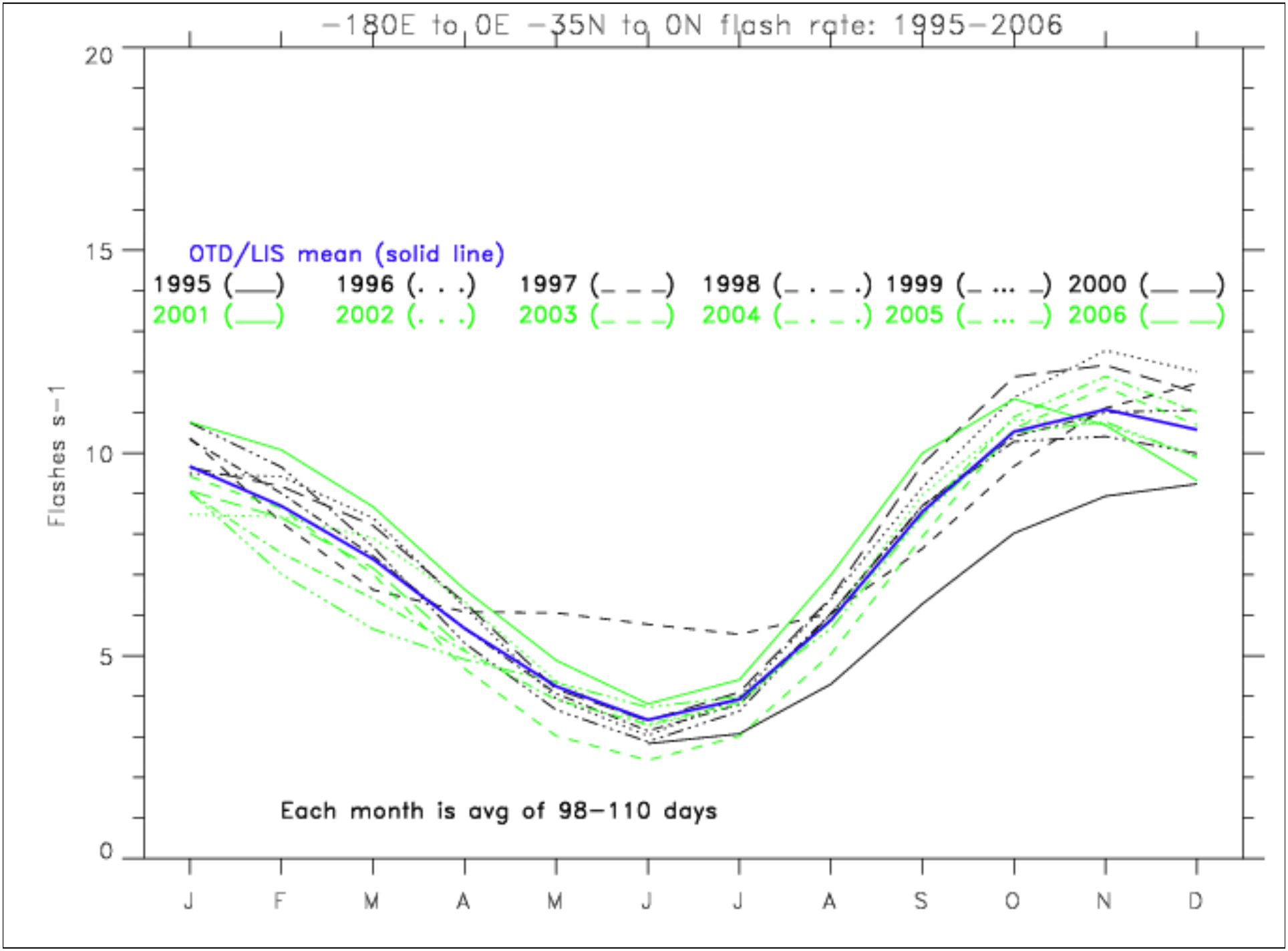

Flash rate SON
aura4Light2 2004 41.6 F s−1
aura4Light2 2005 44.2 F s−1
aura4Light2 2006 50.9 F s−1
aura4Light2 2001 53.2 F s−1
aura4Light2 2004−2001 mean 47.5 F s−1
OTD/LIS 47.5 F s−1
0.0 0.1 0.2 0.5 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 16.0 32.0
Flashes 2x2.5box−1 min−1

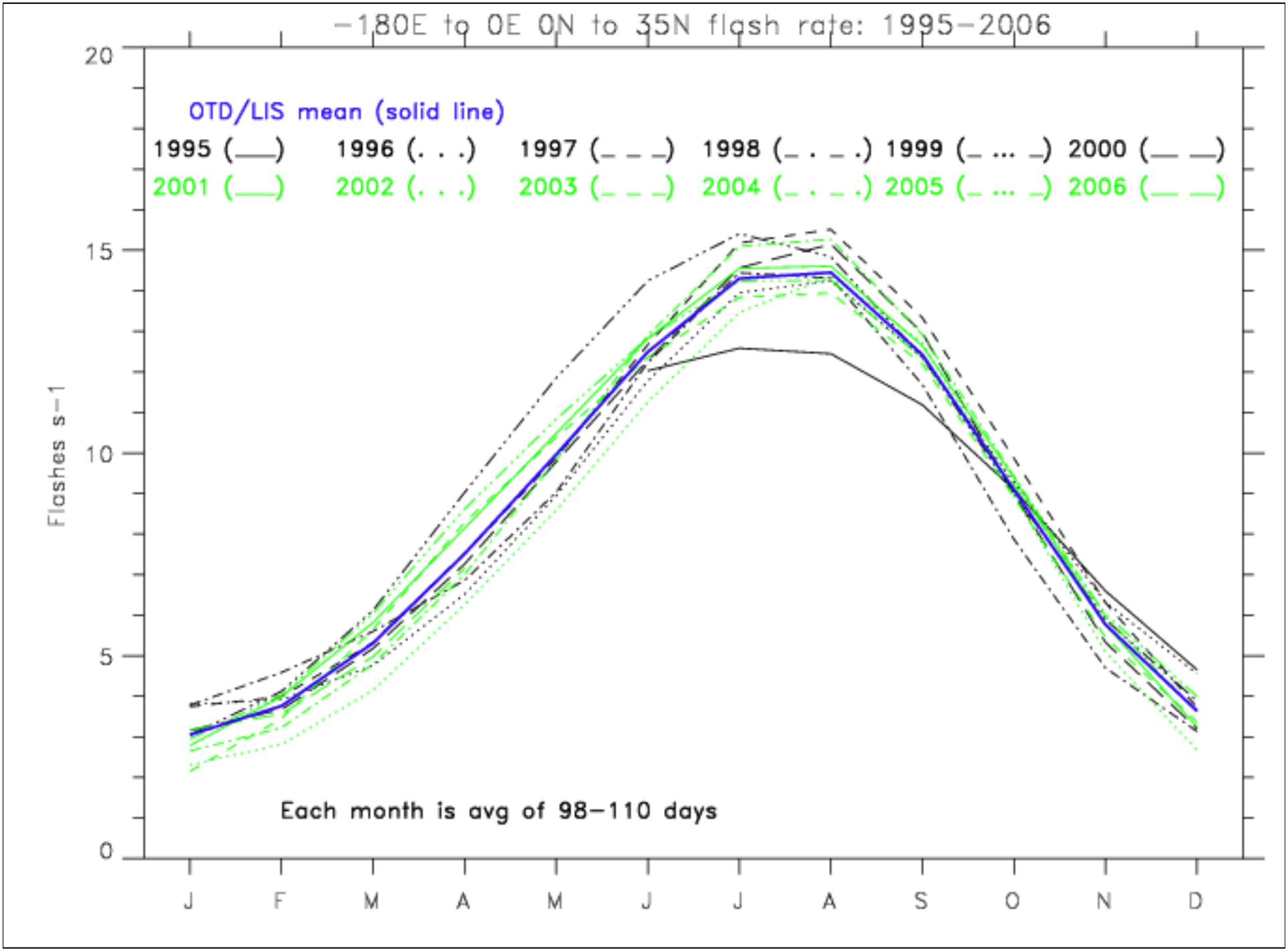

Flash rate SON
aura4synoz 2004 37.3 F s−1
aura4synoz 2005 38.4 F s−1
aura4synoz 2006 43.1 F s−1
aura4synoz 2007 71.2 F s−1
aura4synoz 2004−2007 mean 47.5 F s−1
OTD/LIS 47.5 F s−1
0.0 0.1 0.2 0.5 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 16.0 32.0
Flashes 2x2.5box−1 min−1

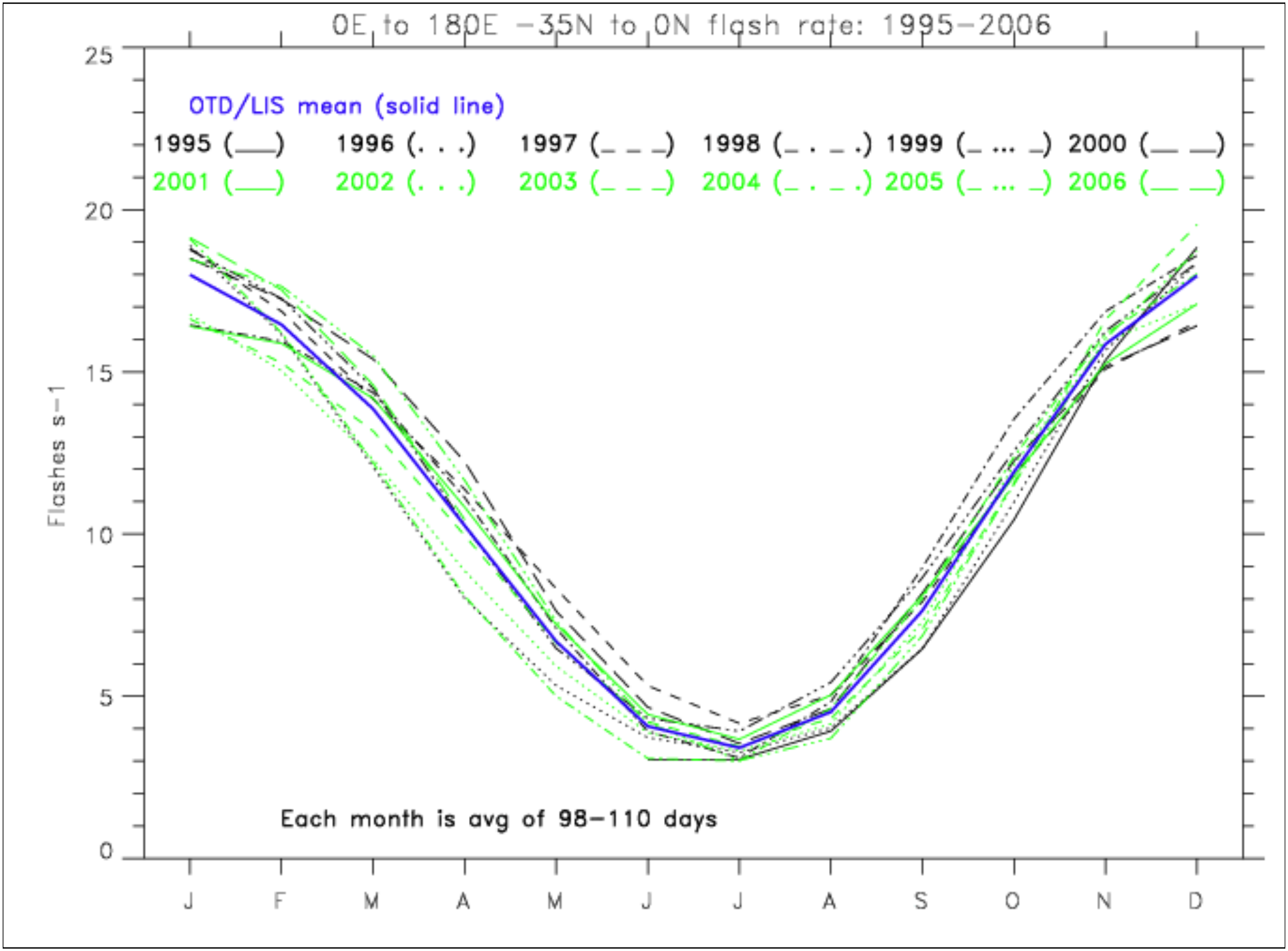

Flash rate SON
G5DAS 2005 42.7 F s−1
G5DAS 2006 48.3 F s−1
G5DAS 2007 51.4 F s−1
G5DAS 2005−2007 mean 47.5 F s−1
OTD/LIS 47.5 F s−1
0.0 0.1 0.2 0.5 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 16.0 32.0
Flashes 2x2.5box−1 min−1

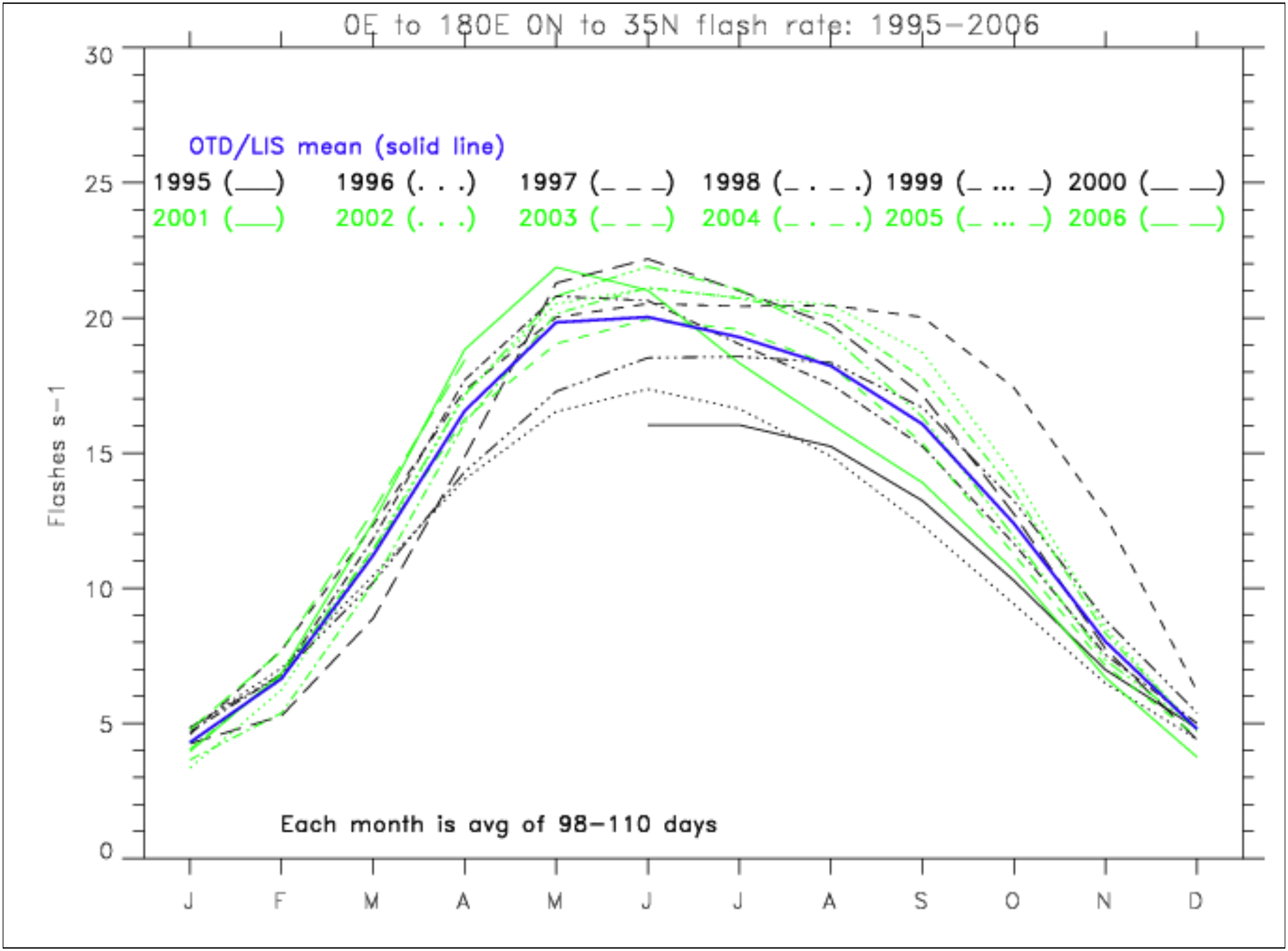

Flash rate SON
MERRA 2000 39.5 F s−1
MERRA 2001 45.4 F s−1
MERRA 2002 43.8 F s−1
MERRA 2003 43.7 F s−1
MERRA 2004 42.7 F s−1
MERRA 2005 45.5 F s−1
MERRA 2006 46.7 F s−1
MERRA 2007 52.7 F s−1
MERRA 2008 54.6 F s−1
MERRA 2009 60.1 F s−1
MERRA 2000−2009 mean 47.5 F s−1
OTD/LIS 47.5 F s−1
0.0 0.1 0.2 0.5 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 16.0 32.0


−180E to 180E −35N to 35N flash rate: 1995−2006
OTD/LIS mean (solid line)
1995 (___)
1996 (. . .)
1997 (_ _ _)
1998 (_ . _ .)
1999 (_ ... _)
2000 (__ __)
2001 (___)
2002 (. . .)
2003 (_ _ _)
2004 (_ . _ .)
2005 (_ ... _)
2006 (__ __)
Flashes s−1
60
40
20
0
Each month is avg of 98−110 days
J
F
M
A
M
J
J
A
S
O
N
D


−180E to 0E −35N to 0N flash rate: 1995−2006
OTD/LIS mean (solid line)
1995 (___)
1996 (. . .)
1997 (_ _ _)
1998 (_ . _ .)
1999 (_ ... _)
2000 (__ __)
2001 (___)
2002 (. . .)
2003 (_ _ _)
2004 (_ . _ .)
2005 (_ ... _)
2006 (__ __)
Flashes s−1
20
15
10
5
0
Each month is avg of 98−110 days
J
F
M
A
M
J
J
A
S
O
N
D


−180E to 0E 0N to 35N flash rate: 1995−2006
OTD/LIS mean (solid line)
1995 (___)
1996 (. . .)
1997 (_ _ _)
1998 (_ . _ .)
1999 (_ ... _)
2000 (__ __)
2001 (___)
2002 (. . .)
2003 (_ _ _)
2004 (_ . _ .)
2005 (_ ... _)
2006 (__ __)
Flashes s−1
20
15
10
5
0
Each month is avg of 98−110 days
J
F
M
A
M
J
J
A
S
O
N
D


0E to 180E −35N to 0N flash rate: 1995−2006
OTD/LIS mean (solid line)
1995 (___)
1996 (. . .)
1997 (_ _ _)
1998 (_ . _ .)
1999 (_ ... _)
2000 (__ __)
2001 (___)
2002 (. . .)
2003 (_ _ _)
2004 (_ . _ .)
2005 (_ ... _)
2006 (__ __)
Flashes s−1
0
5
10
15
20
25
Each month is avg of 98−110 days
J
F
M
A
M
J
J
A
S
O
N
D


0E to 180E 0N to 35N flash rate: 1995–2006
OTD/LIS mean (solid line)
1995 (___)
1996 (. . .)
1997 (_ _ _)
1998 (_ . _ .)
1999 (_ ... _)
2000 (__ __)
2001 (___)
2002 (. . .)
2003 (_ _ _)
2004 (_ . _ .)
2005 (_ ... _)
2006 (__ __)
Flashes s−1
30
25
20
15
10
5
0
Each month is avg of 98–110 days
J
F
M
A
M
J
J
A
S
O
N
D

How were lightning NO emissions determined?

- IC and CG flashes are assumed to produce the same amount of NO per flash.
- Extratropical flashes (Latitudes poleward of 26°) are assumed to produce ~500 moles per flash while tropical flashes are assumed to produce ~250 moles per flash.

- Lightning NO emissions are placed in the model according to typical vertical profiles derived from cloud-resolved modeling (Ott et al., 2011)