Is the time right to add lightning-NO to operational air quality forecast models?

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Motivation for Including Lightning NO_x in CMAQ

- In the summer over the US, production of NO by lightning (LNO_x) is responsible for 60-80% of upper tropospheric (UT) NO_x and 20-30% of UT ozone (Zhang et al., 2003; Allen et al., 2010).
- Mid- and upper-tropospheric ozone production rates are highly sensitive to NO_x mixing ratios.
- Inversion-based estimates of NO emissions from CMAQ simulations w/o LNO_x have large errors at rural locations (Napelenok et al., 2008).
- CMAQ-calculated N deposition is much too low without LNO_x (e.g., Low-bias in CMAQ nitric acid wet deposition at NADP sites cut in half when LNO_x was added).
- LNO_x can add several ppbv to summertime surface O_3 concentrations

CMAQ Lightning-NO emission Parameterization

$LNO_x = k^* PROD^* LF$, where

k: Conversion factor (Molecular weight of N / Avogadros #)

PROD: Moles of NO produced per flash (defaults to 500 moles)

LF: Total flash rate (IC + CG), where

$LF = G * \alpha_{i,j} * (precon_{i,j} - threshold)$, where

Precon: Convective precipitation rate from WRF

***threshold*:** Value of *precon* below which the flash rate is set to zero.

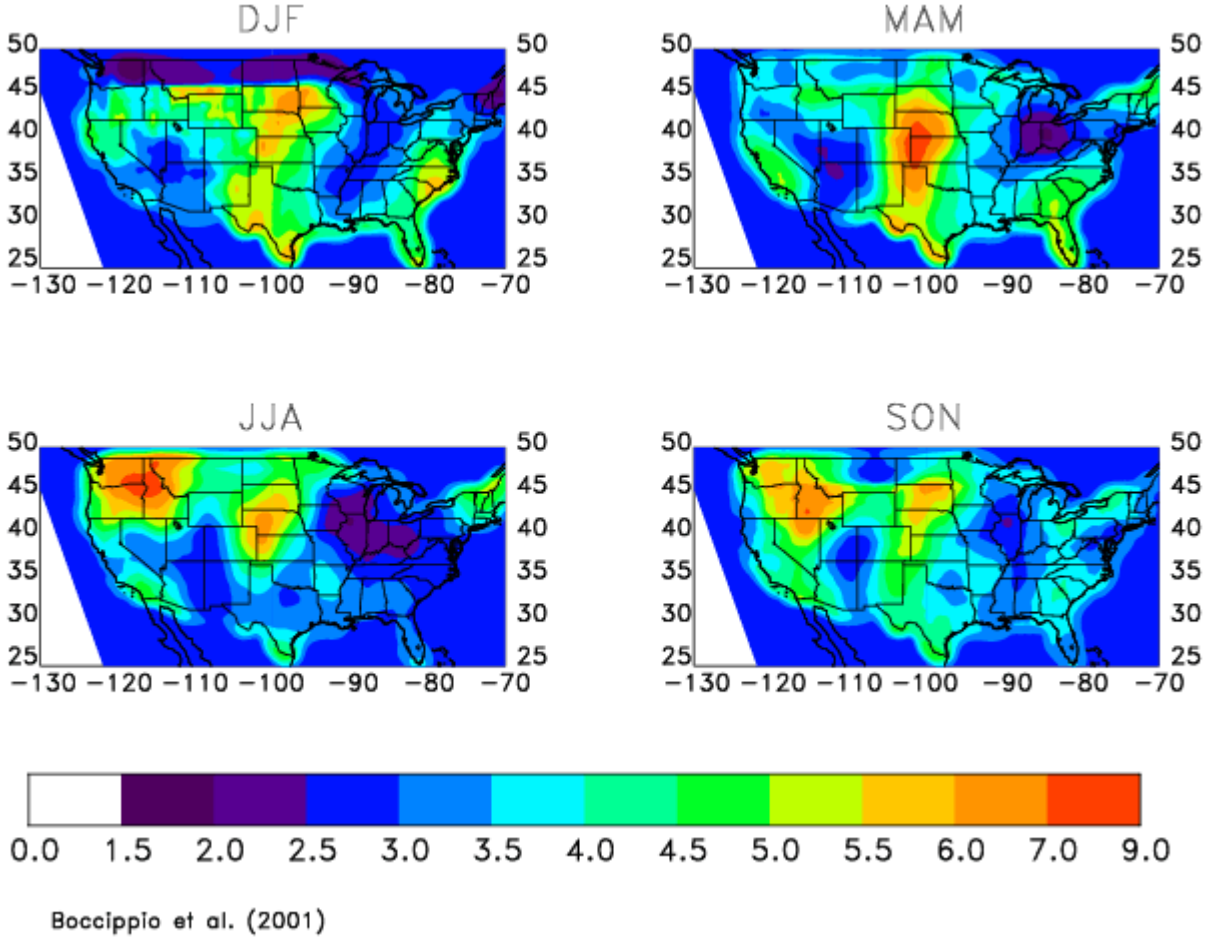
G: Scaling factor chosen so that domain-avg WRF flash rate matches domain averaged *observed* flash rate.

$\alpha_{i,j}$**:** Local or continental/marine scaling factor chosen so that monthly avg model flash rate for each grid box or region equals *observed* flash rate

For retrospective simulations, *observed* flash rate can be the United States National Lightning Detection Network (NLDN)-based monthly (or seasonal) average total flash rate for the month of interest

Operational forecasts could use satellite-retrieved or NLDN-based climatological flash rates for a season as *observations*.

NLDN records a high % of cloud-to-ground (CG) flashes and a low % of intracloud (IC) flashes. After extracting CG flashes, total flash rate is est by multiplying CG flash rate by Z+1, where Z (shown below) is the IC/CG ratio



Boccippio et al. (2001)

Note: The use of a climatological Z when estimating the total flash rate is the main source of uncertainty in the total flash rate.

Implementation of lightning-NO parameterization in v5.0 of CMAQ:

LNO_x = k* PROD*LF, where LF = G * $\alpha_{i,j}$ * ($precon_{i,j}$ – threshold),

There are four run-time options:

1. No lightning-NO

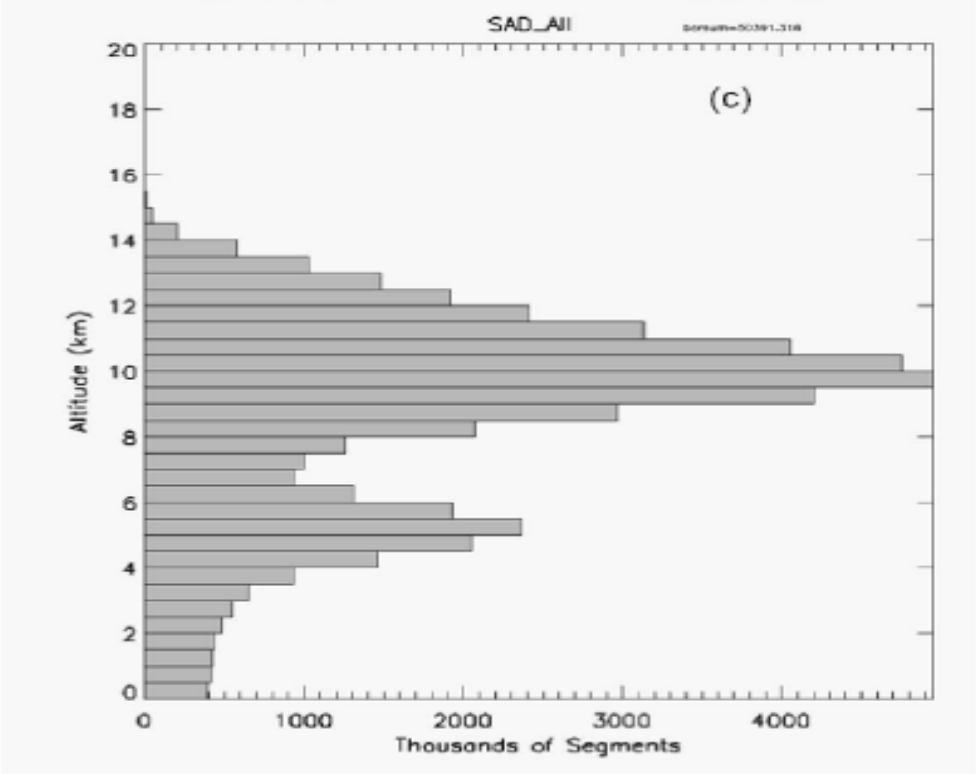
2. LNO_x read in from a 4-D input file

3. LNO_x calc online using climatological marine & continental relationships between NLDN-based total flash rate & convective precipitation rate.

4. LNO_x calc online using year and month-specific relationships between NLDN-based total flash rate & convective precipitation rate at each grid box. Note: detection-efficiency adjusted ests of monthly avg flash rates will be made available to tropospheric chemistry and AQ communities.

NO emissions per flash will default to 500 moles for both IC & CG flashes; however, user will have option of choosing separate values for IC&CG flashes.

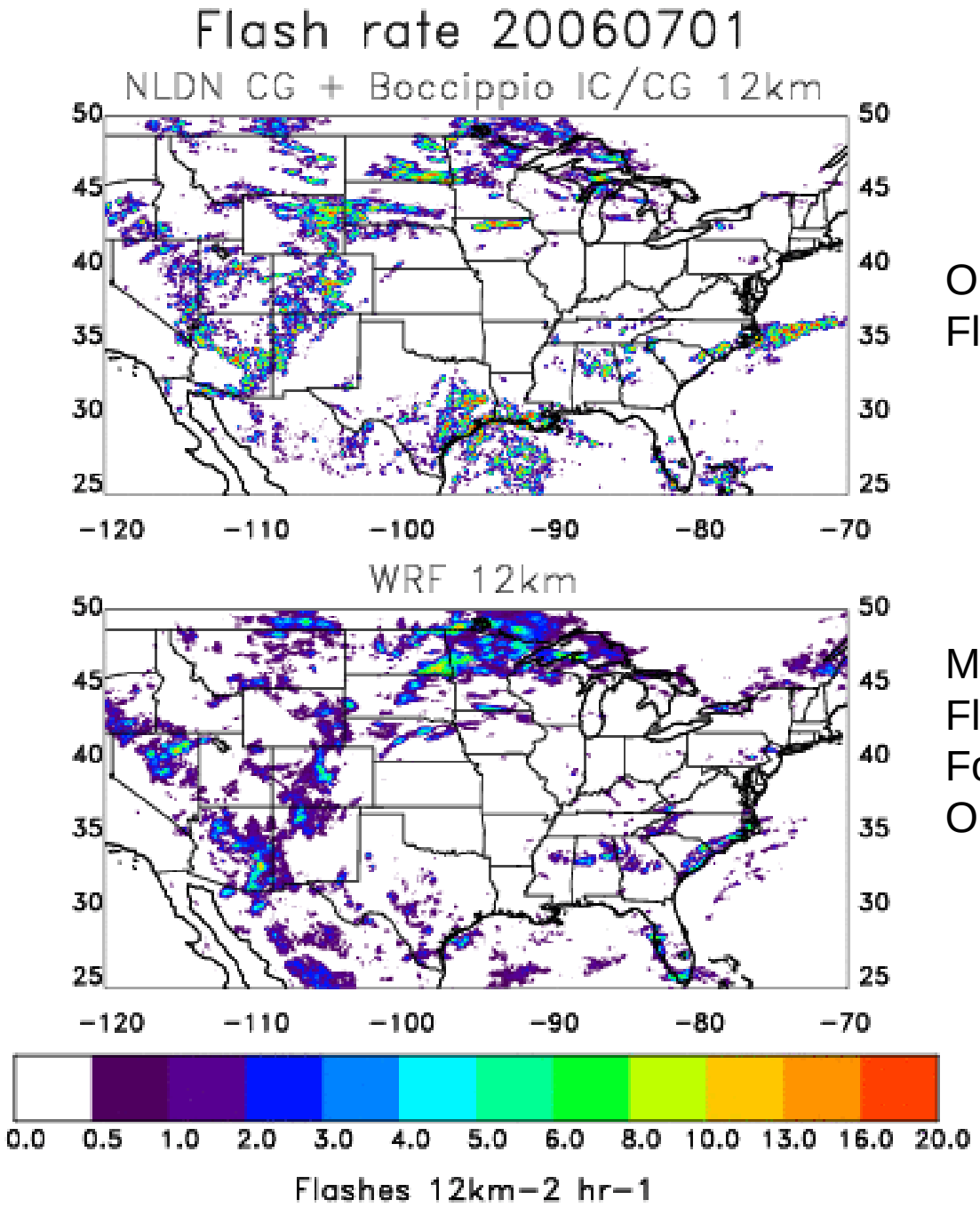
Vertical partitioning of lightning-NO emissions



Segment altitude distribution for
all flashes from Koshak et al. [2010]

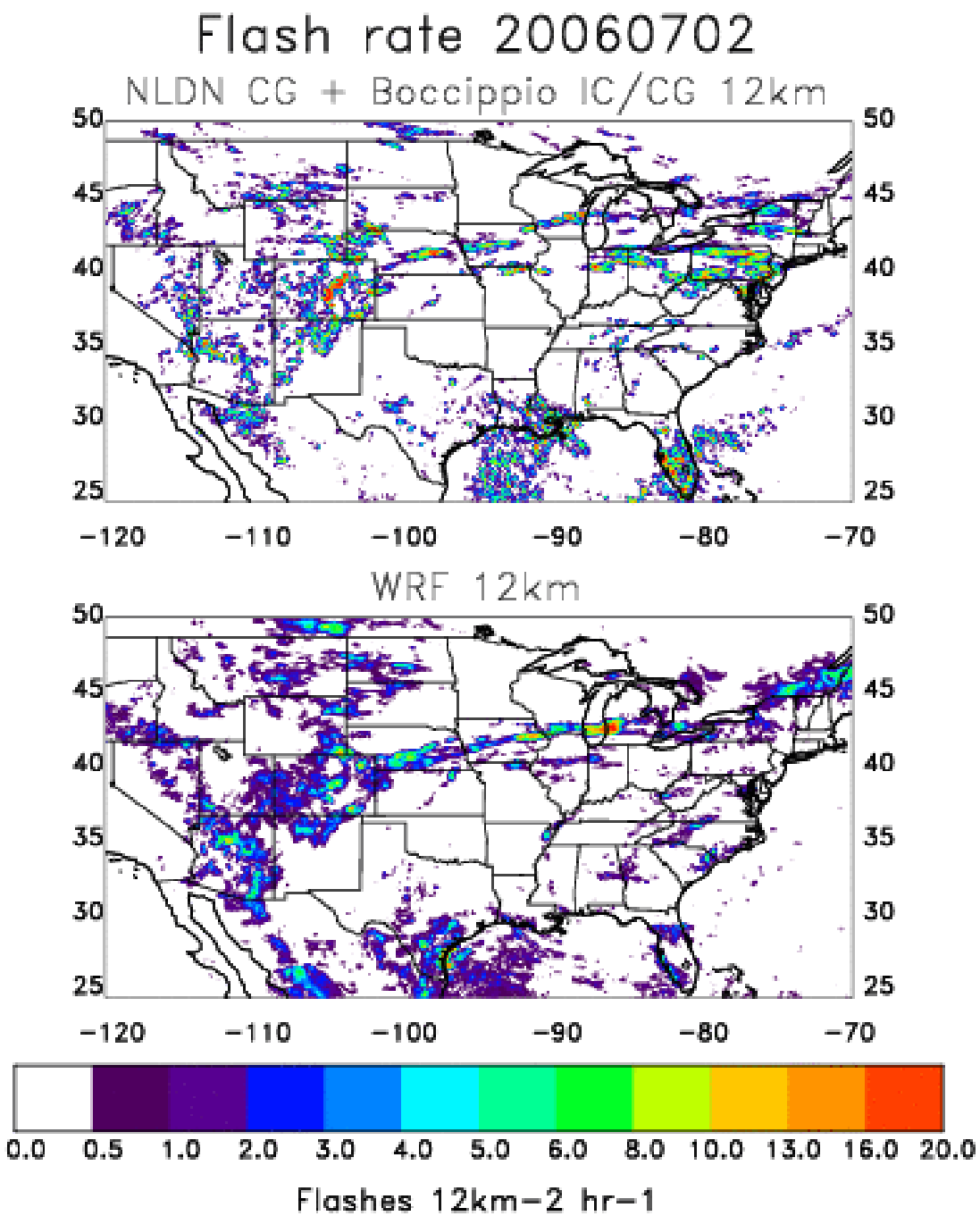
Vertical distribution of LNOx is assumed to be α To pressure X the vertical distribution of Flash channel lengths From the North Alabama Lightning Mapping Array

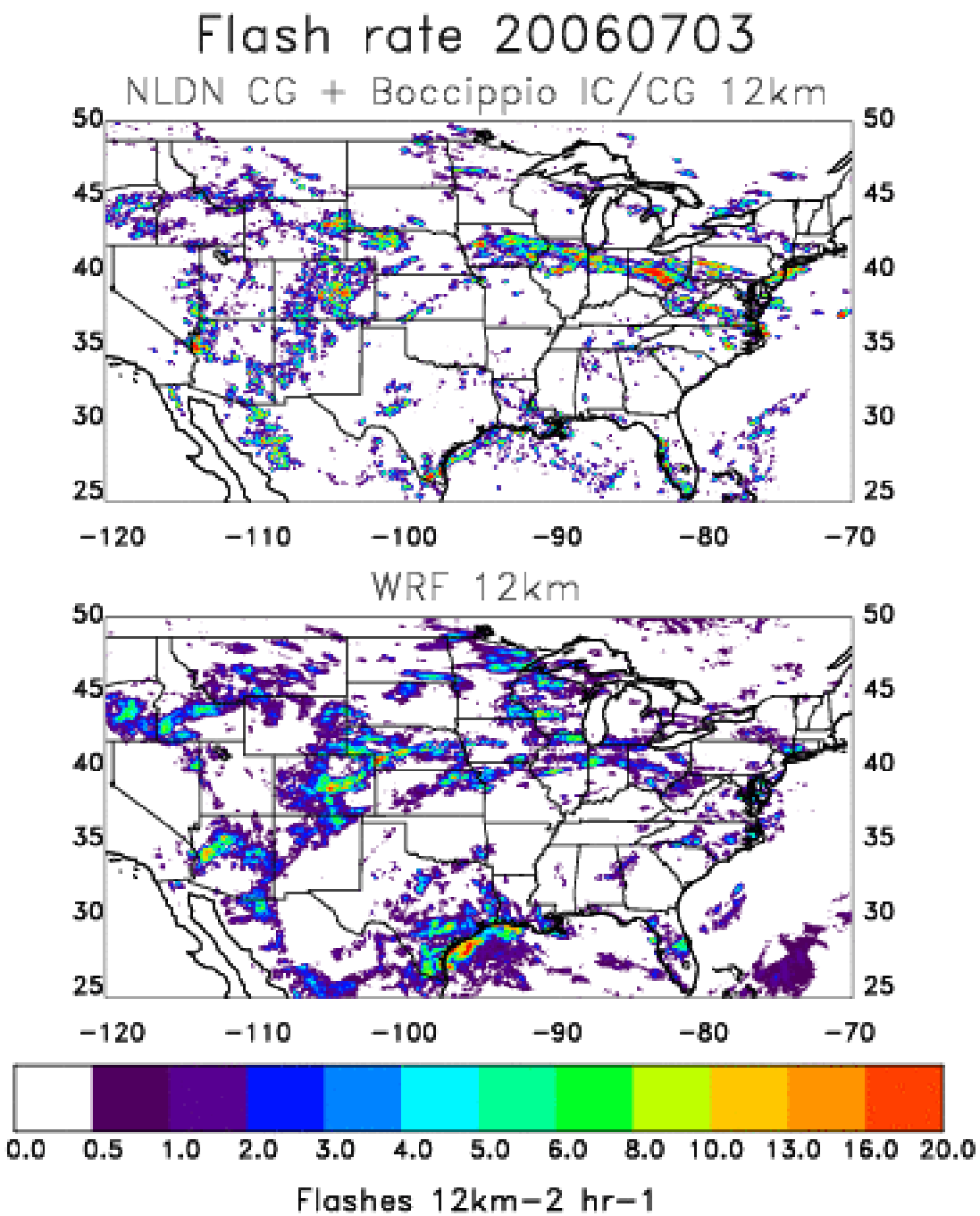
Emissions distributed Between surface and Cloud top.
T profile used to determine location of lower peak

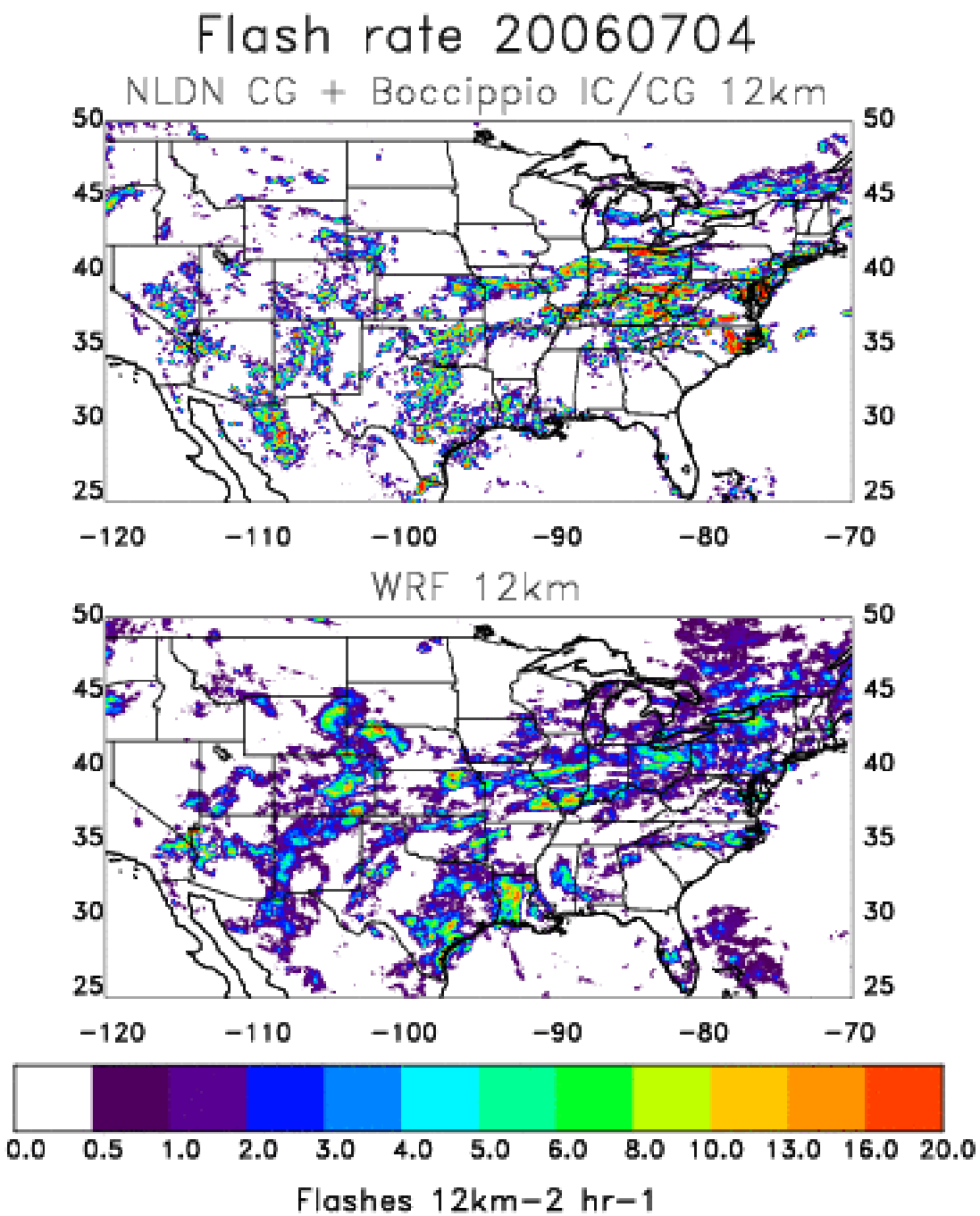


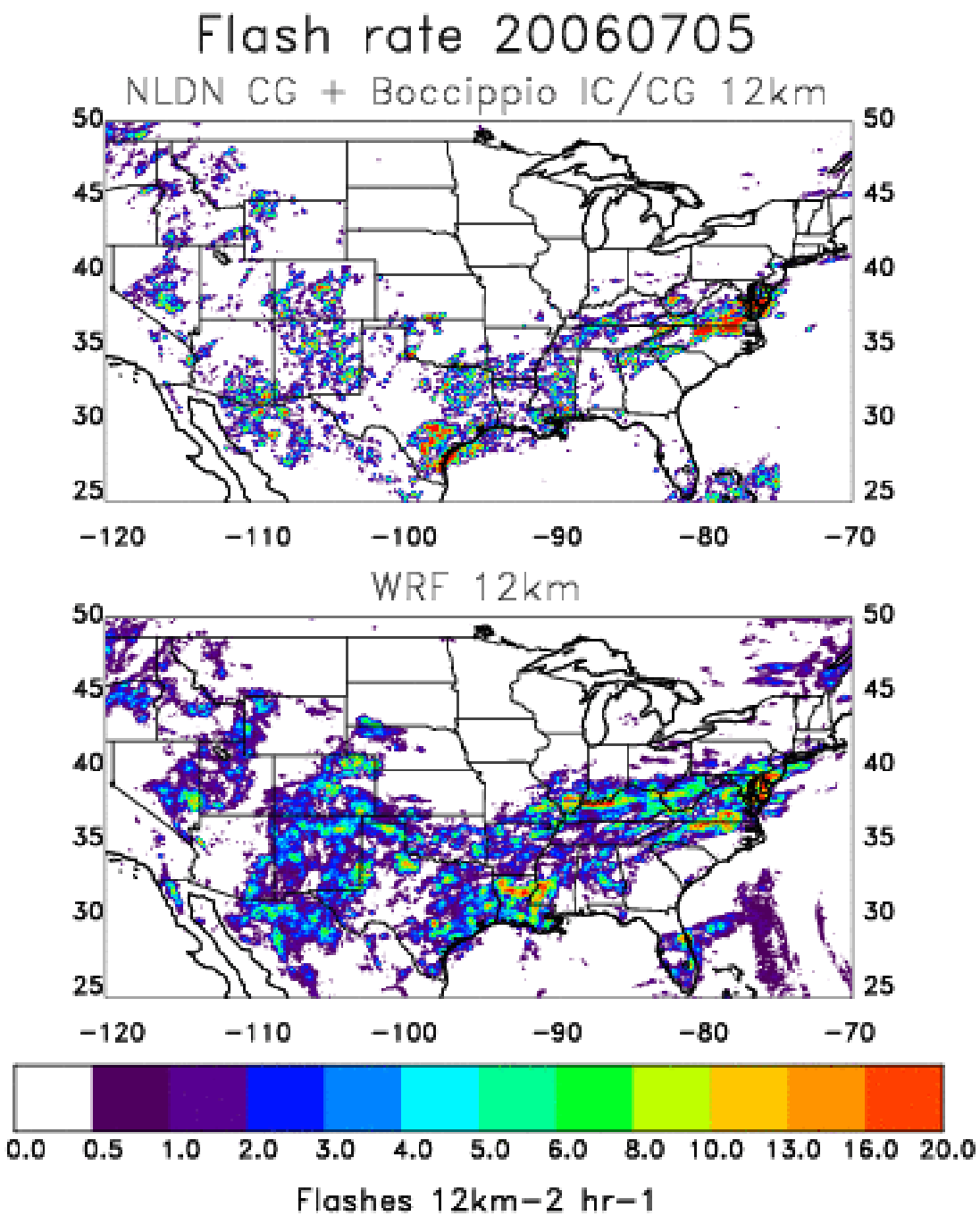
Observed
Flash rate

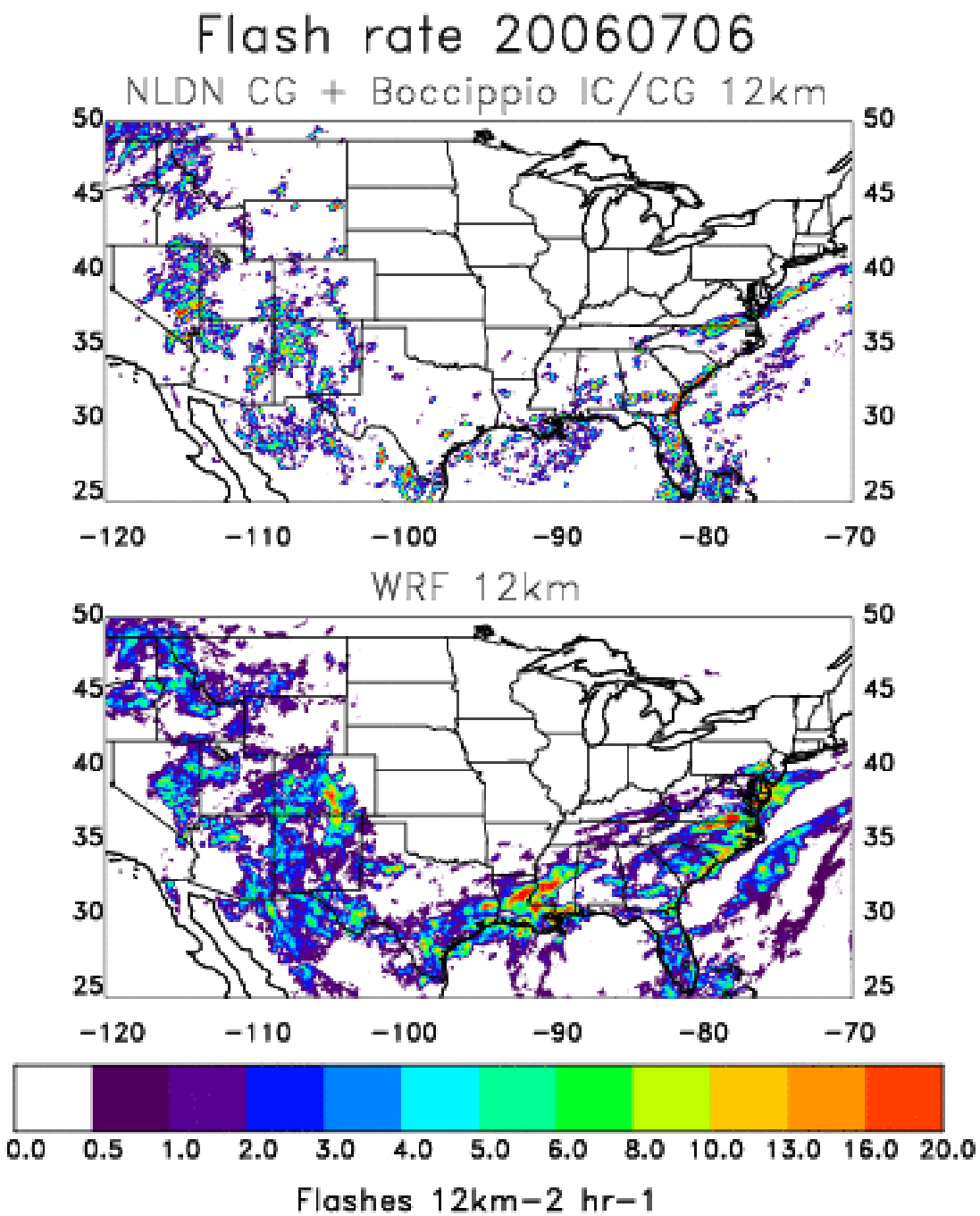
Modeled
Flash rate
For run-time
Option 4

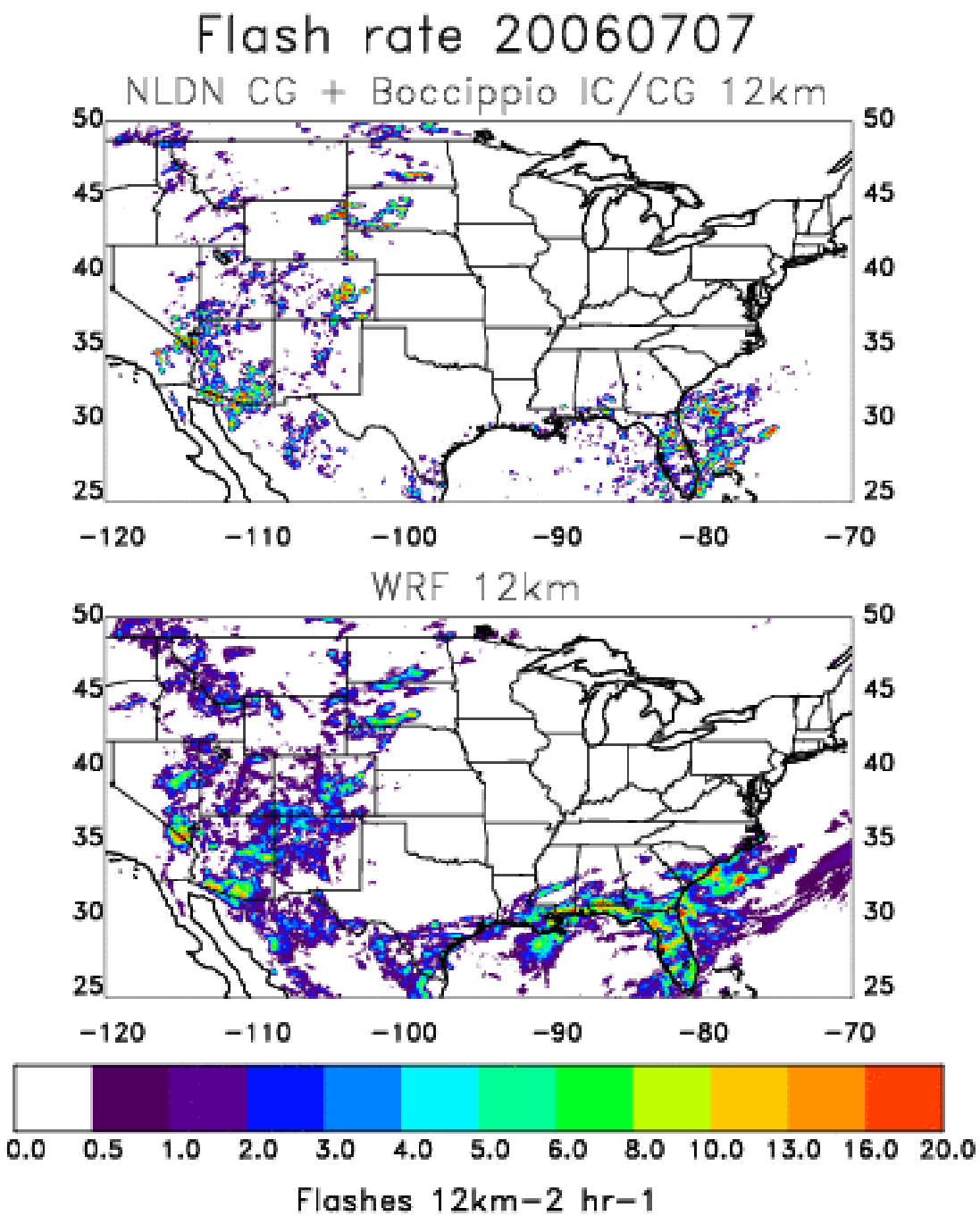

Flash rate 20060702
NLDN CG + Boccippio IC/CG 12km
WRF 12km
50
45
40
35
30
25
−120
−110
−100
−90
−80
−70
0.0
0.5
1.0
2.0
3.0
4.0
5.0
6.0
8.0
10.0
13.0
16.0
20.0
Flashes 12km−2 hr−1

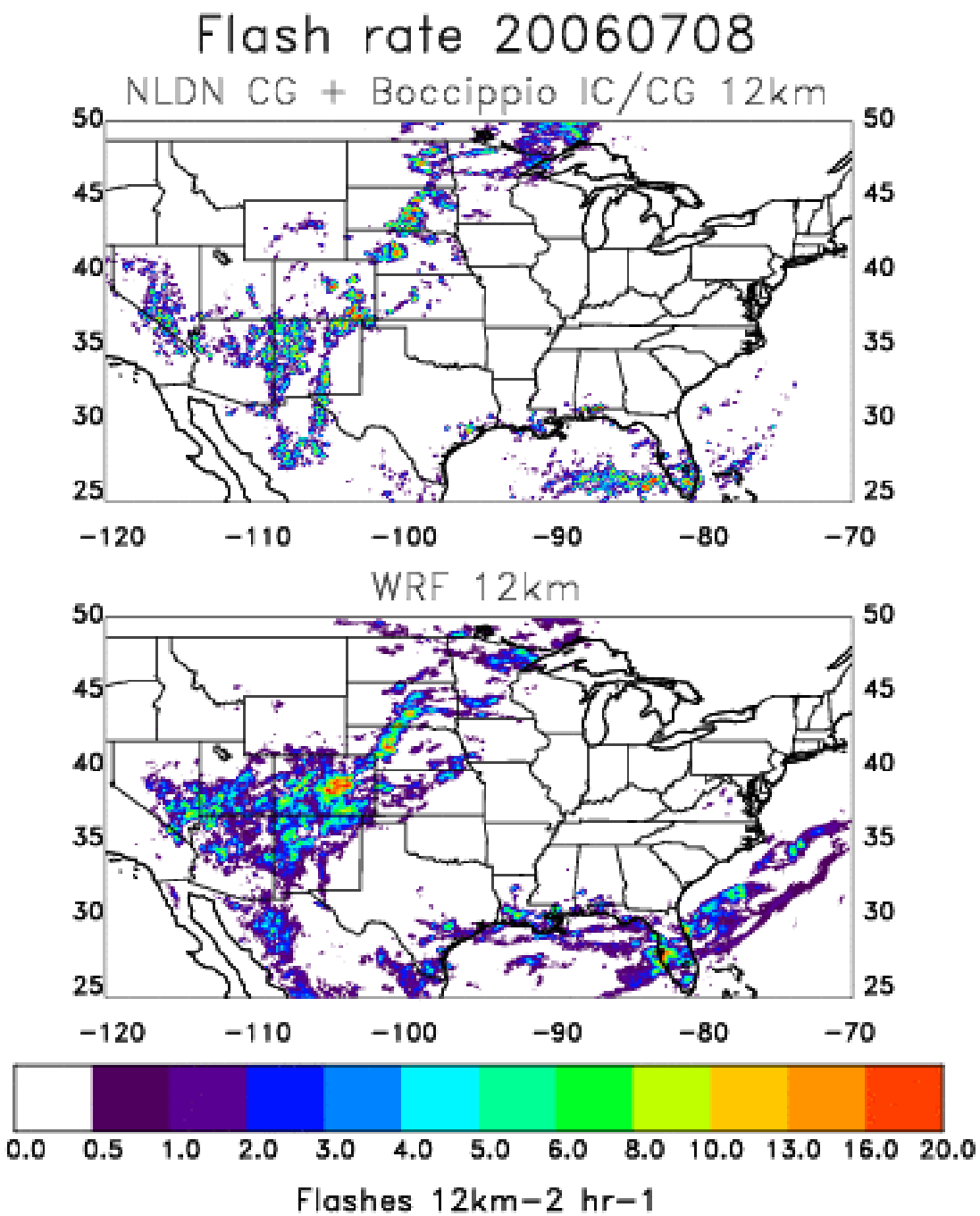

Flash rate 20060703
NLDN CG + Boccippio IC/CG 12km
WRF 12km
50
45
40
35
30
25
−120
−110
−100
−90
−80
−70
0.0
0.5
1.0
2.0
3.0
4.0
5.0
6.0
8.0
10.0
13.0
16.0
20.0
Flashes 12km−2 hr−1

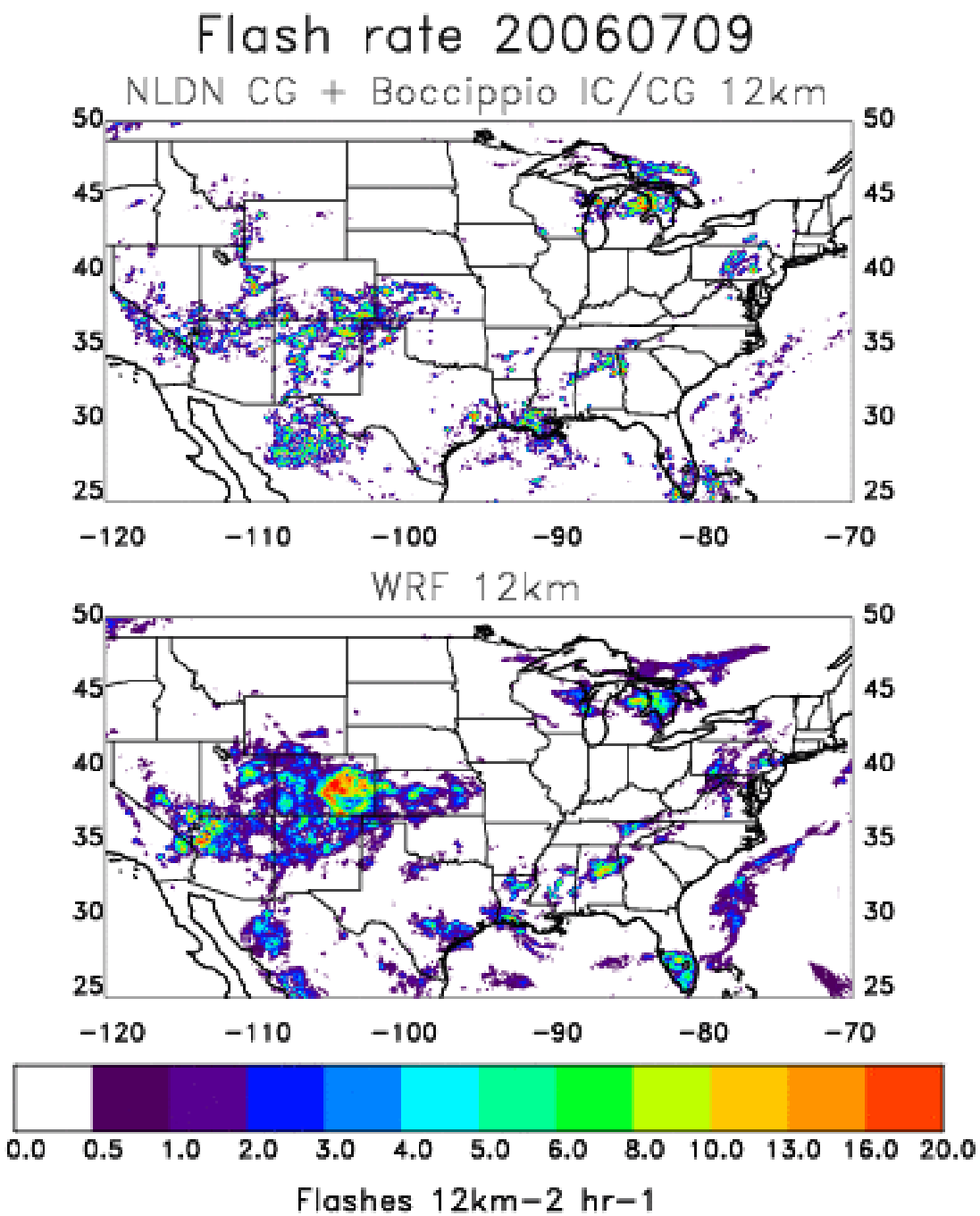

Flash rate 20060704
NLDN CG + Boccippio IC/CG 12km
WRF 12km
50
45
40
35
30
25
−120
−110
−100
−90
−80
−70
0.0
0.5
1.0
2.0
3.0
4.0
5.0
6.0
8.0
10.0
13.0
16.0
20.0
Flashes 12km−2 hr−1

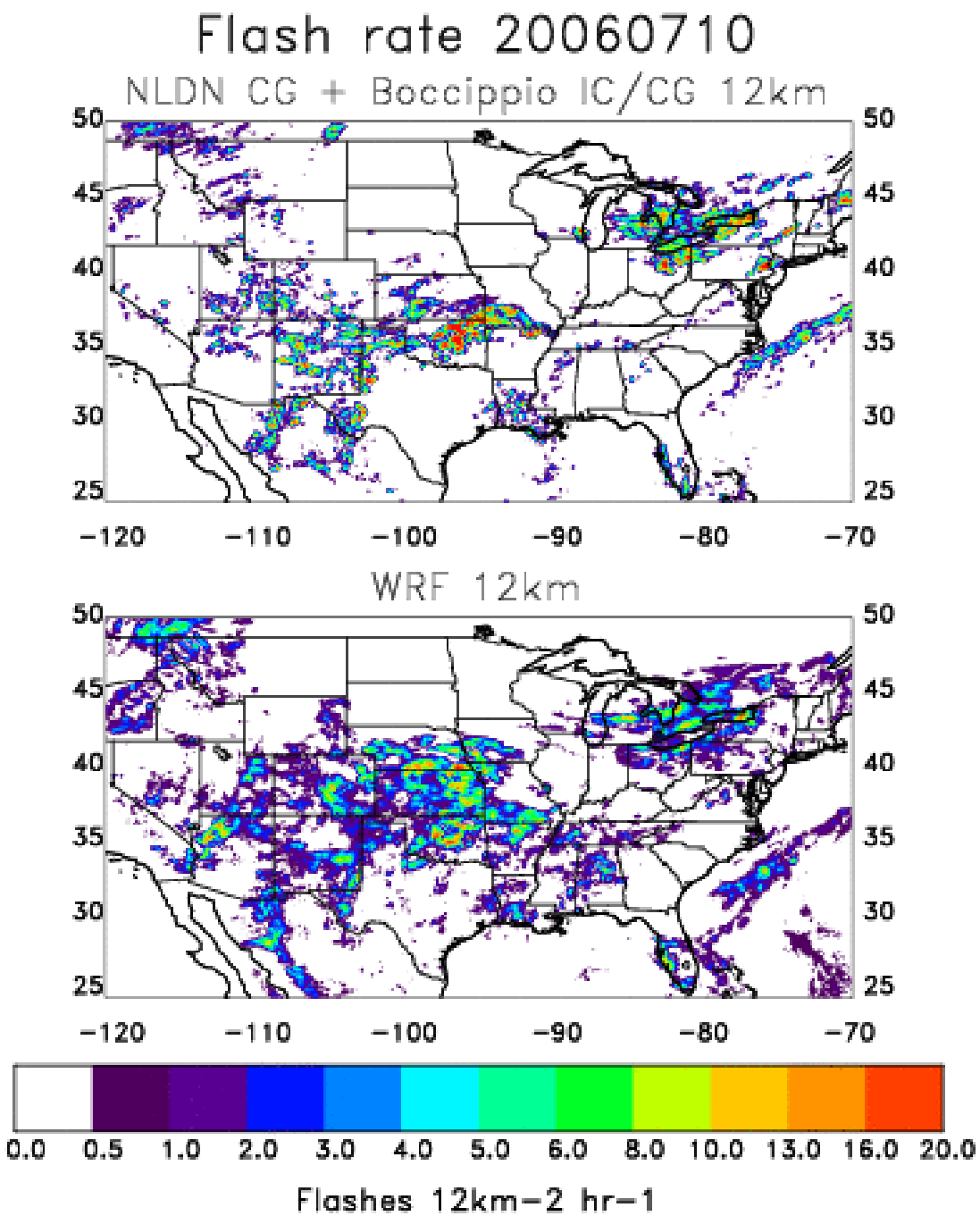

Flash rate 20060705
NLDN CG + Boccippio IC/CG 12km
WRF 12km
50
45
40
35
30
25
−120
−110
−100
−90
−80
−70
0.0
0.5
1.0
2.0
3.0
4.0
5.0
6.0
8.0
10.0
13.0
16.0
20.0
Flashes 12km−2 hr−1

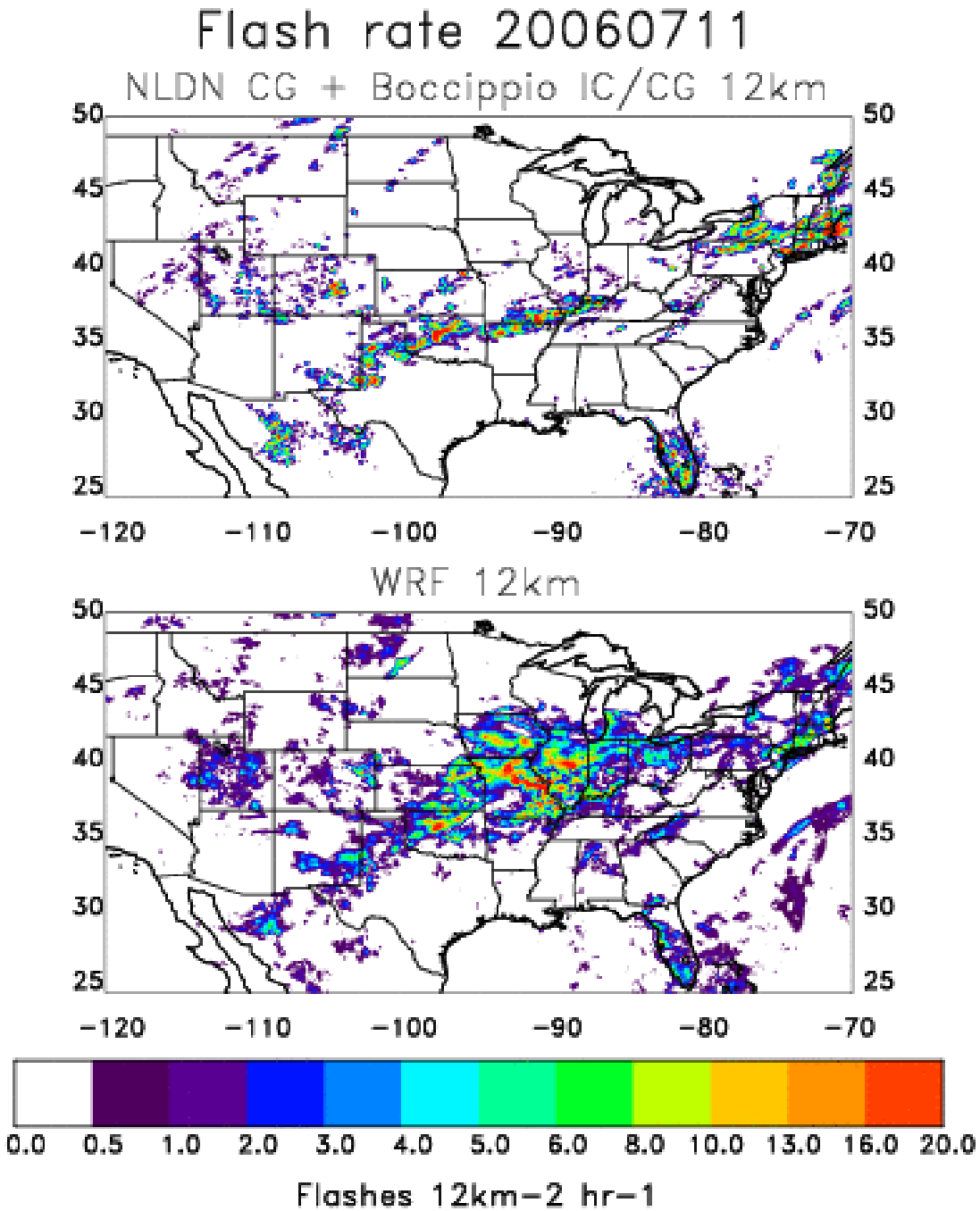

Flash rate 20060706
NLDN CG + Boccippio IC/CG 12km
WRF 12km
50
45
40
35
30
25
−120
−110
−100
−90
−80
−70
0.0
0.5
1.0
2.0
3.0
4.0
5.0
6.0
8.0
10.0
13.0
16.0
20.0
Flashes 12km−2 hr−1

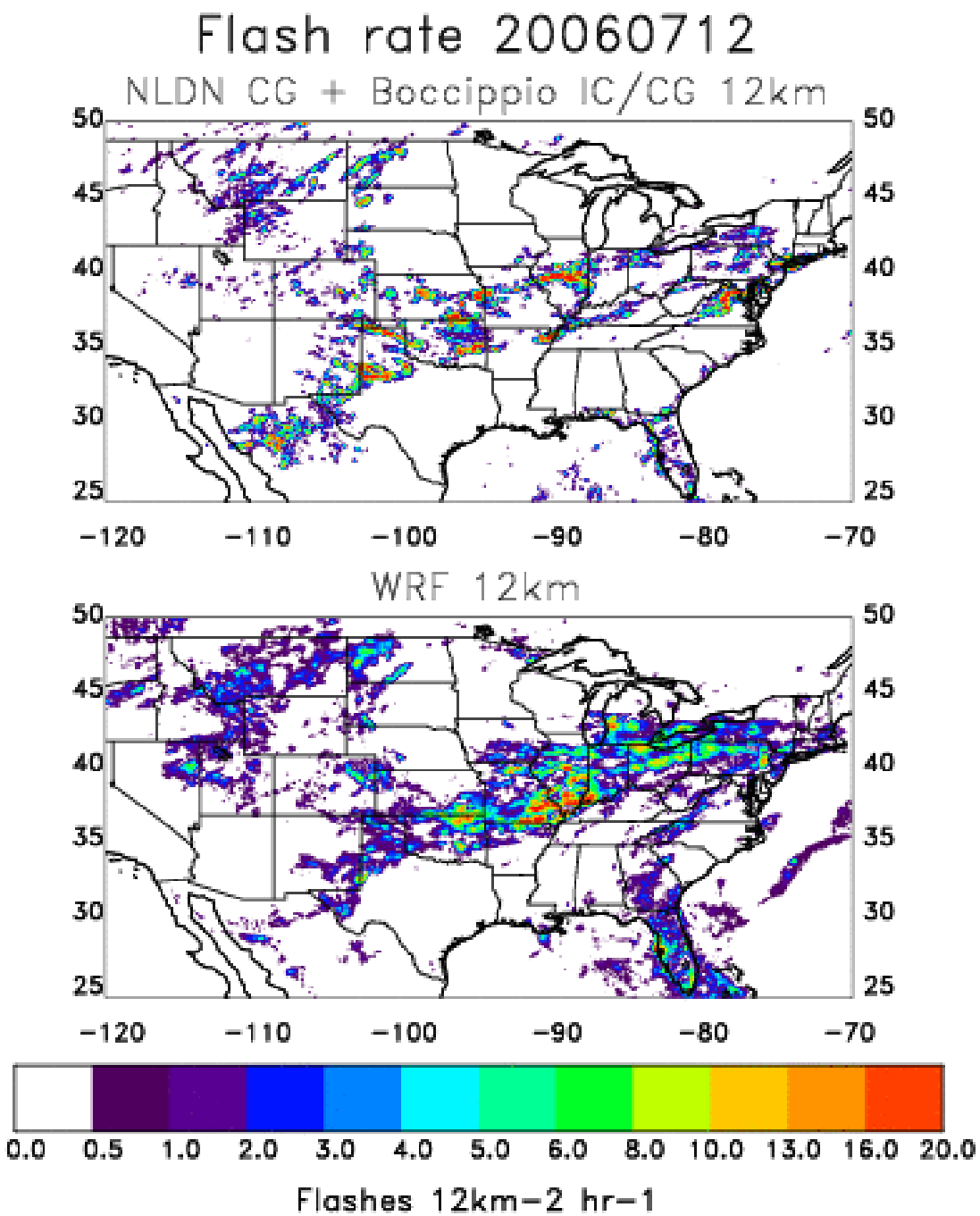

Flash rate 20060707
NLDN CG + Boccippio IC/CG 12km
WRF 12km
50
45
40
35
30
25
−120
−110
−100
−90
−80
−70
0.0
0.5
1.0
2.0
3.0
4.0
5.0
6.0
8.0
10.0
13.0
16.0
20.0
Flashes 12km−2 hr−1

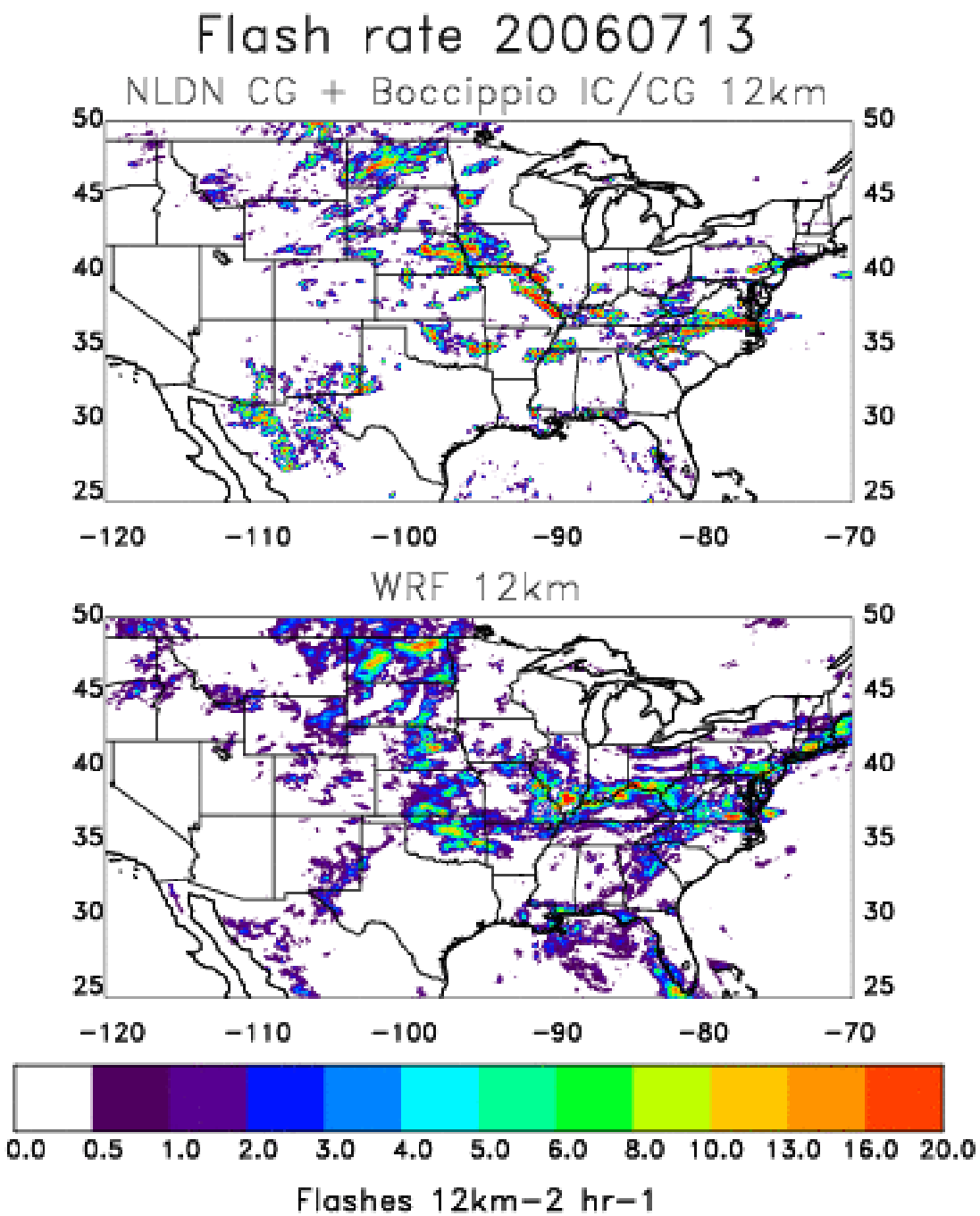

Flash rate 20060708
NLDN CG + Boccippio IC/CG 12km
WRF 12km
50
45
40
35
30
25
−120
−110
−100
−90
−80
−70
0.0
0.5
1.0
2.0
3.0
4.0
5.0
6.0
8.0
10.0
13.0
16.0
20.0
Flashes 12km−2 hr−1

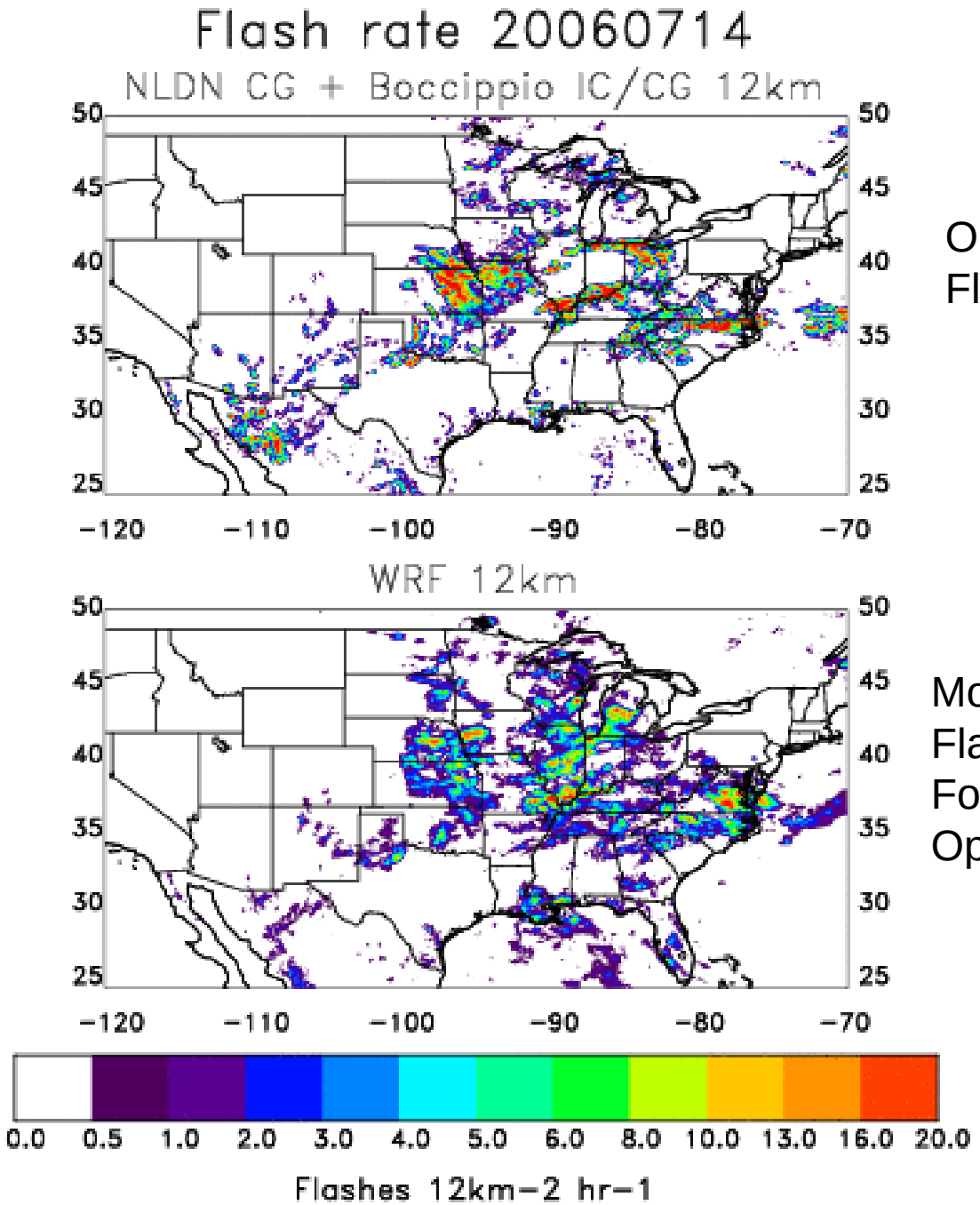

Flash rate 20060709
NLDN CG + Boccippio IC/CG 12km
WRF 12km
50
45
40
35
30
25
−120
−110
−100
−90
−80
−70
0.0
0.5
1.0
2.0
3.0
4.0
5.0
6.0
8.0
10.0
13.0
16.0
20.0
Flashes 12km−2 hr−1


Flash rate 20060710
NLDN CG + Boccippio IC/CG 12km
WRF 12km
50
45
40
35
30
25
−120
−110
−100
−90
−80
−70
0.0
0.5
1.0
2.0
3.0
4.0
5.0
6.0
8.0
10.0
13.0
16.0
20.0
Flashes 12km−2 hr−1


Flash rate 20060711
NLDN CG + Boccippio IC/CG 12km
WRF 12km
50
45
40
35
30
25
−120
−110
−100
−90
−80
−70
0.0
0.5
1.0
2.0
3.0
4.0
5.0
6.0
8.0
10.0
13.0
16.0
20.0
Flashes 12km−2 hr−1

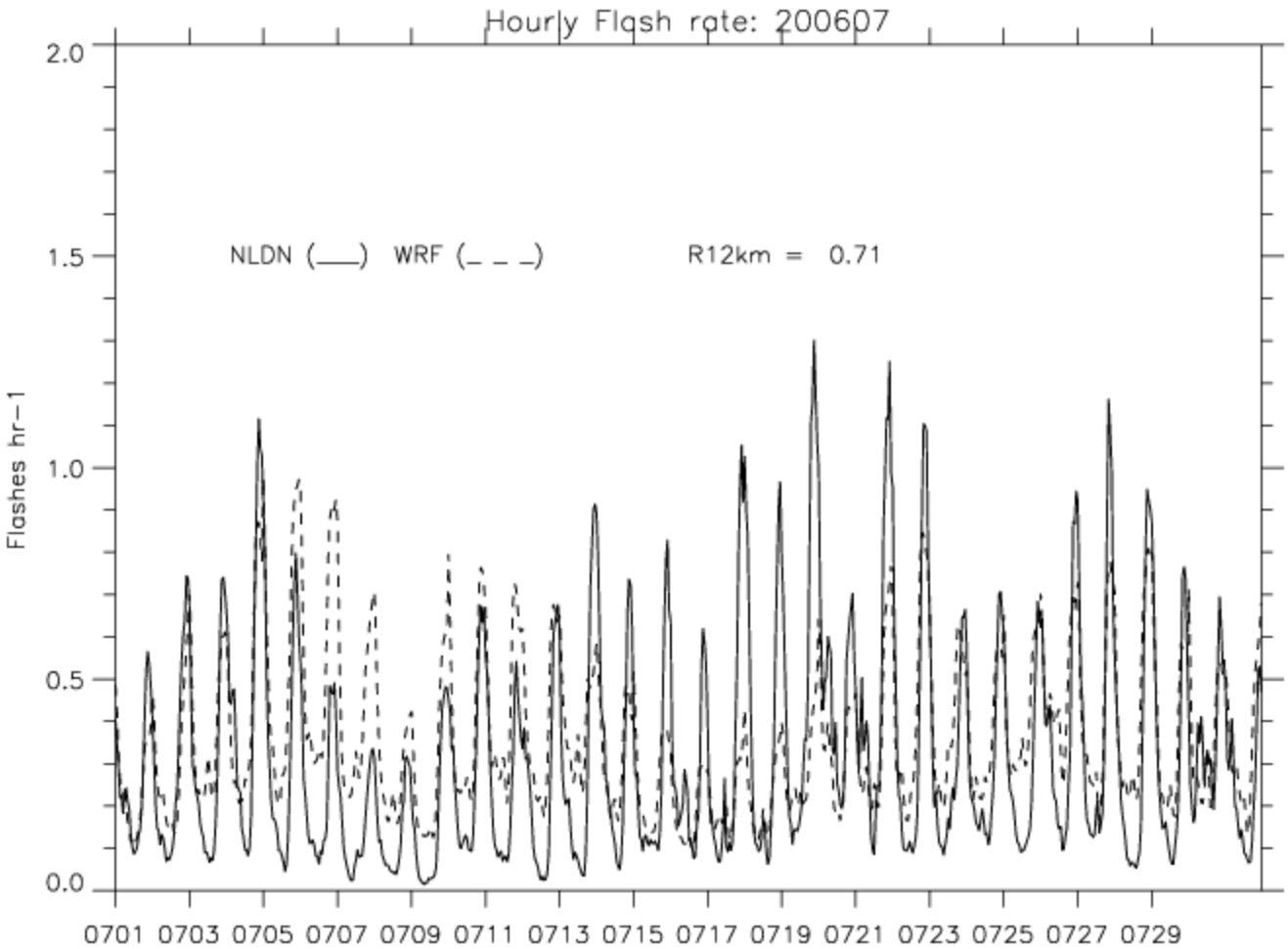

Flash rate 20060712
NLDN CG + Boccippio IC/CG 12km
WRF 12km
50
45
40
35
30
25
−120
−110
−100
−90
−80
−70
0.0
0.5
1.0
2.0
3.0
4.0
5.0
6.0
8.0
10.0
13.0
16.0
20.0
Flashes 12km−2 hr−1


Flash rate 20060713
NLDN CG + Boccippio IC/CG 12km
WRF 12km
50
45
40
35
30
25
−120
−110
−100
−90
−80
−70
0.0
0.5
1.0
2.0
3.0
4.0
5.0
6.0
8.0
10.0
13.0
16.0
20.0
Flashes 12km−2 hr−1

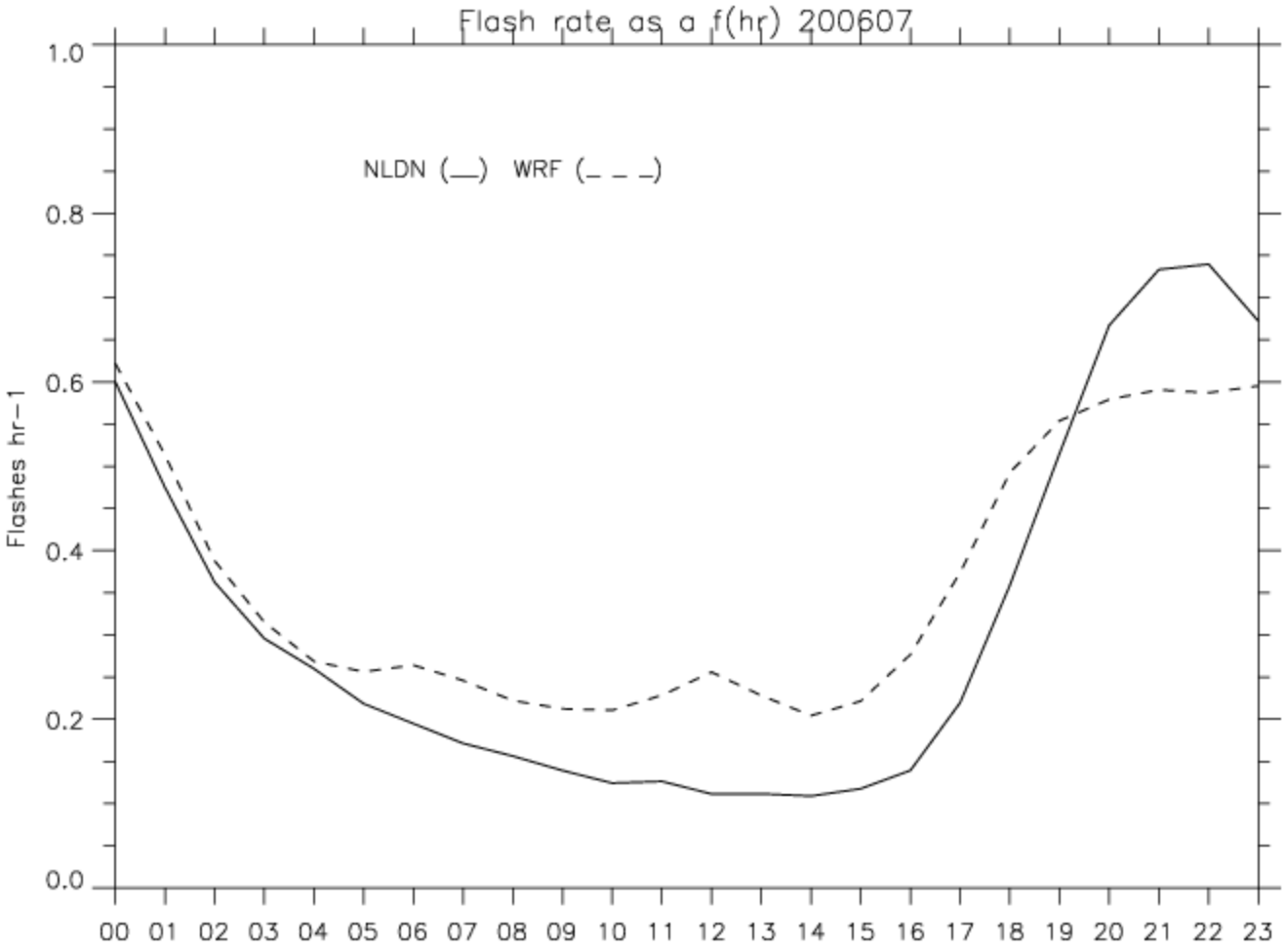


Observed
Flash rate

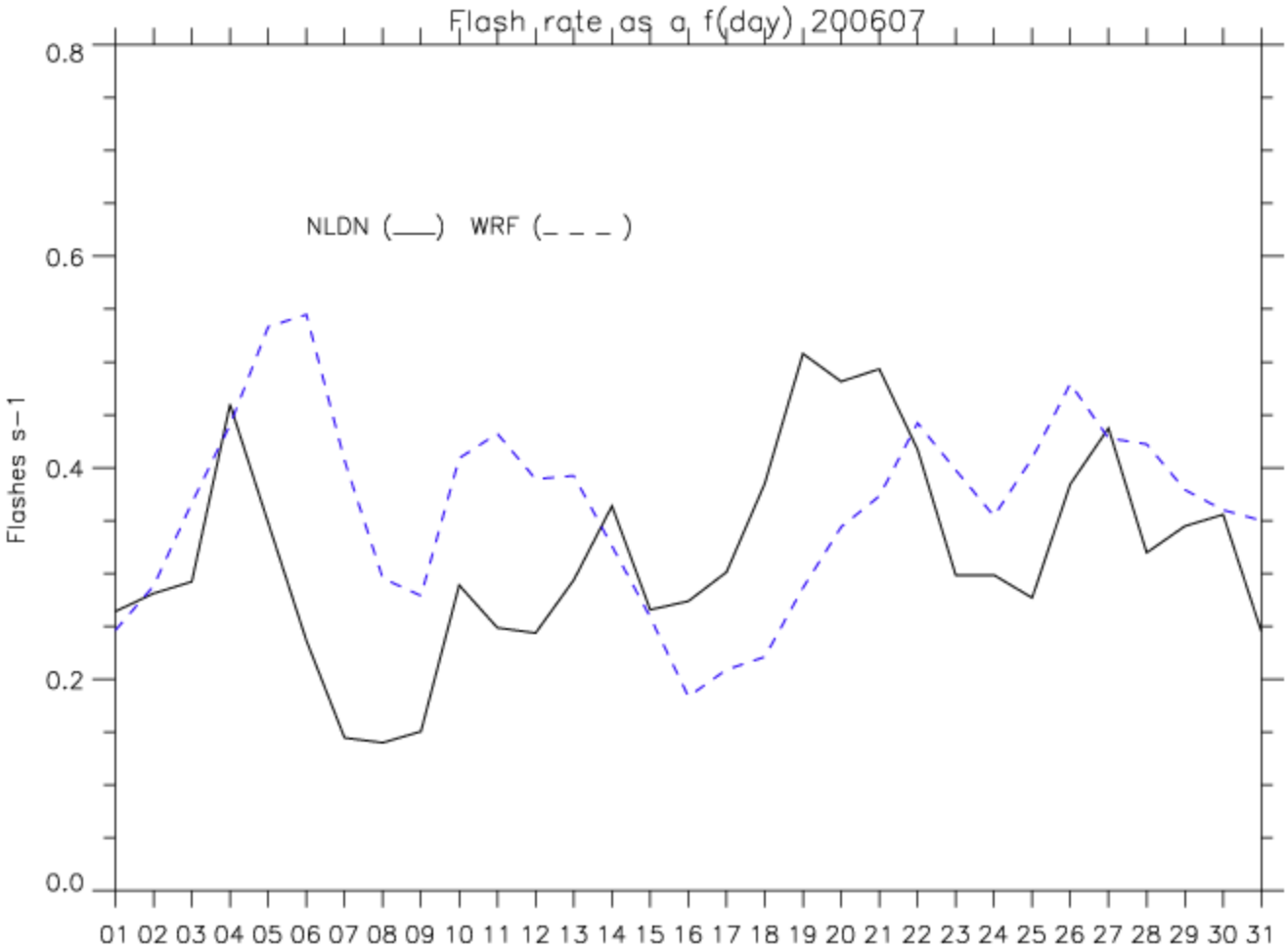
Modeled
Flash rate
For run-time
Option 4


Hourly Flash rate: 200607
NLDN (___) WRF (_ _ _)
R12km = 0.71
Flashes hr−1
2.0
1.5
1.0
0.5
0.0
0701 0703 0705 0707 0709 0711 0713 0715 0717 0719 0721 0723 0725 0727 0729

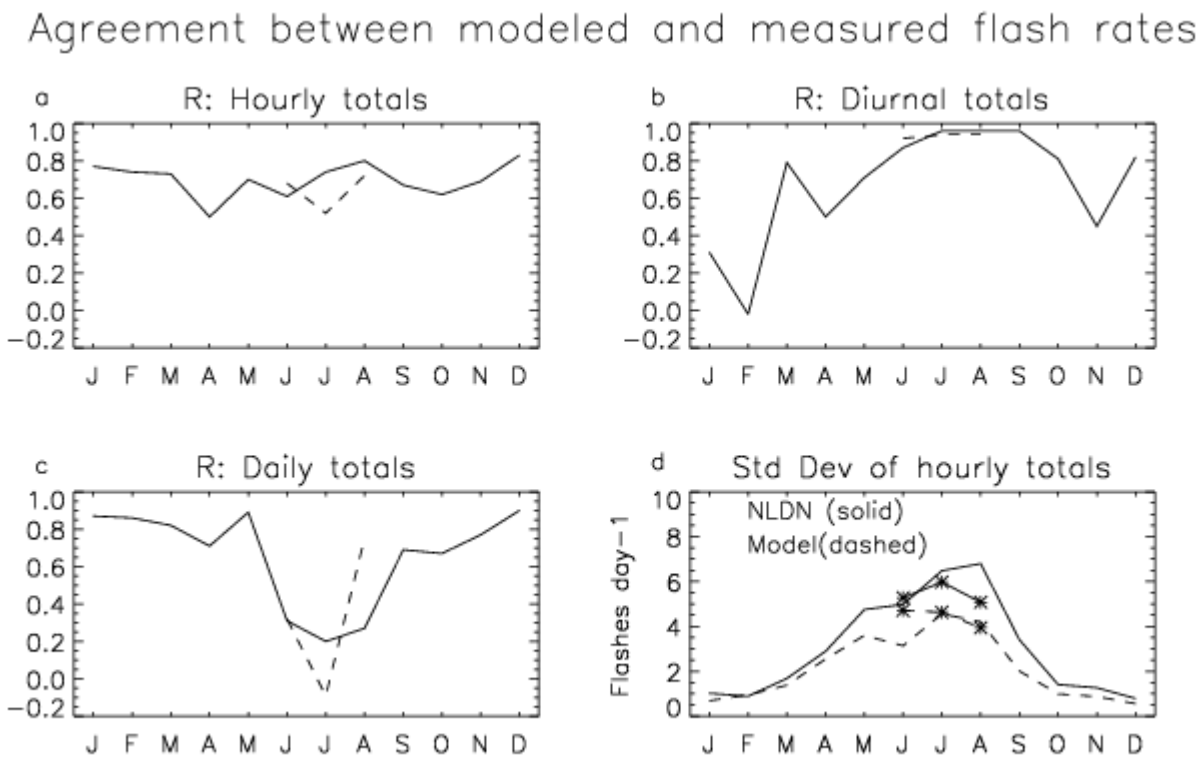
Diel variations in flash rate well captured during the summer



Temporal variations in daily-average flash rate poorly Captured during the summer



Summary of hourly, diurnal, and daily correlations for 2006 (solid) And 2004 (dashed)



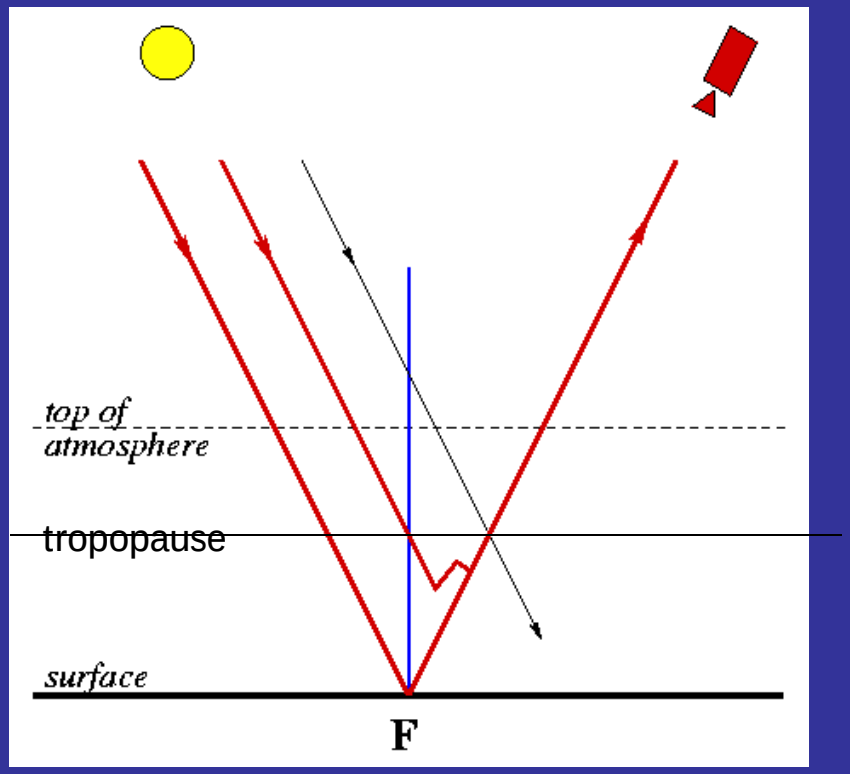
CMAQ simulation of summer 2006

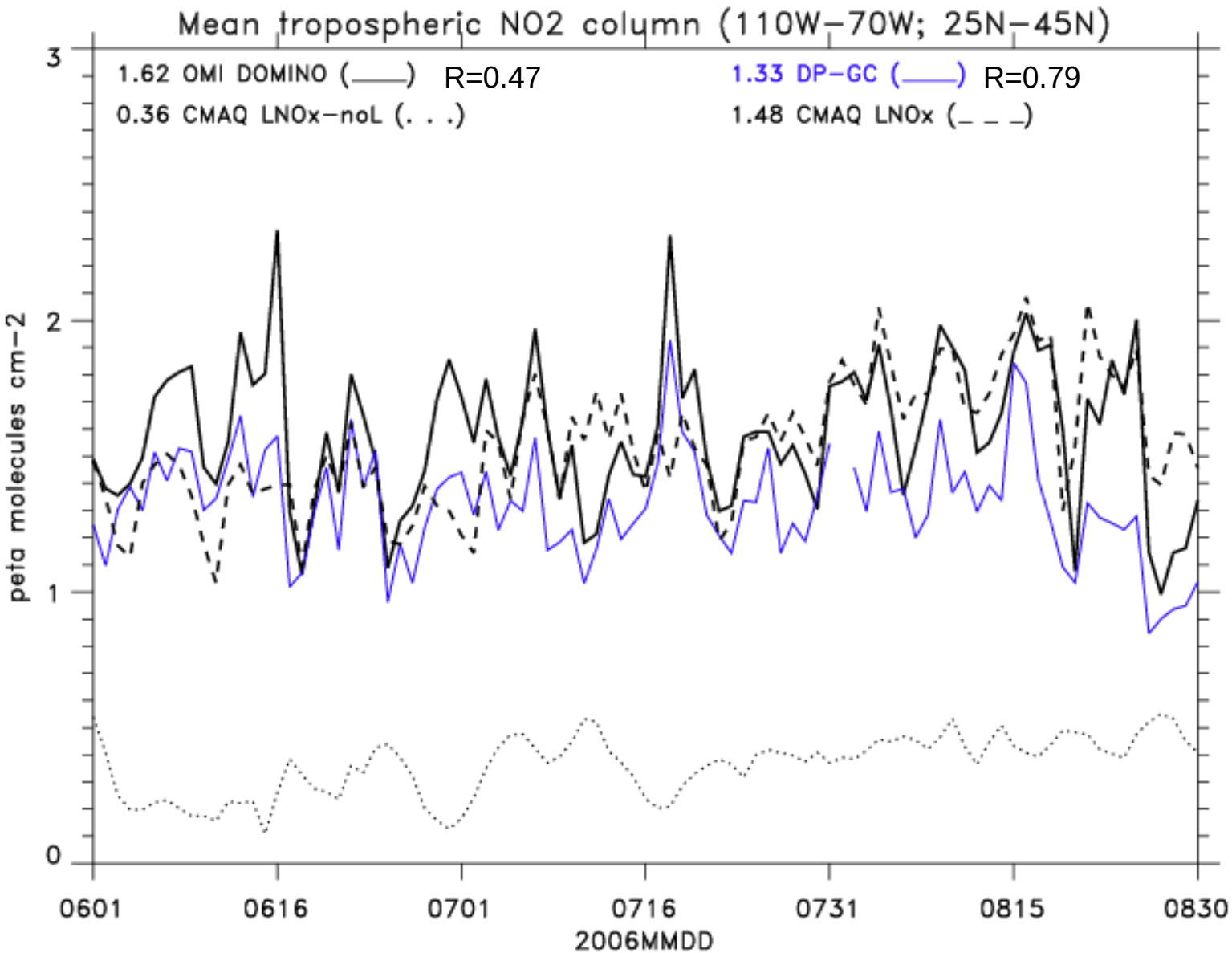
- Simulations of 2006 air quality performed at EPA under the management of Wyat Appel and Shawn Roselle as part of the Air Quality Model Evaluation International Initiative (AQMEII) http://aqmeii.jrc.ec.europa.eu/doc/AQMEII_activity_description.pdf
- Version 4.7.1 of CMAQ used with CB-05 chemical mechanism
- NEI-based emissions with year specific power plant emissions from CEMS and satellite-derived wildfire emissions
- Chemical boundary conditions from GEMS (European-led assimilation effort)
- http://ozone.meteo.be/meteo/view/en/1550484-GEMS.html

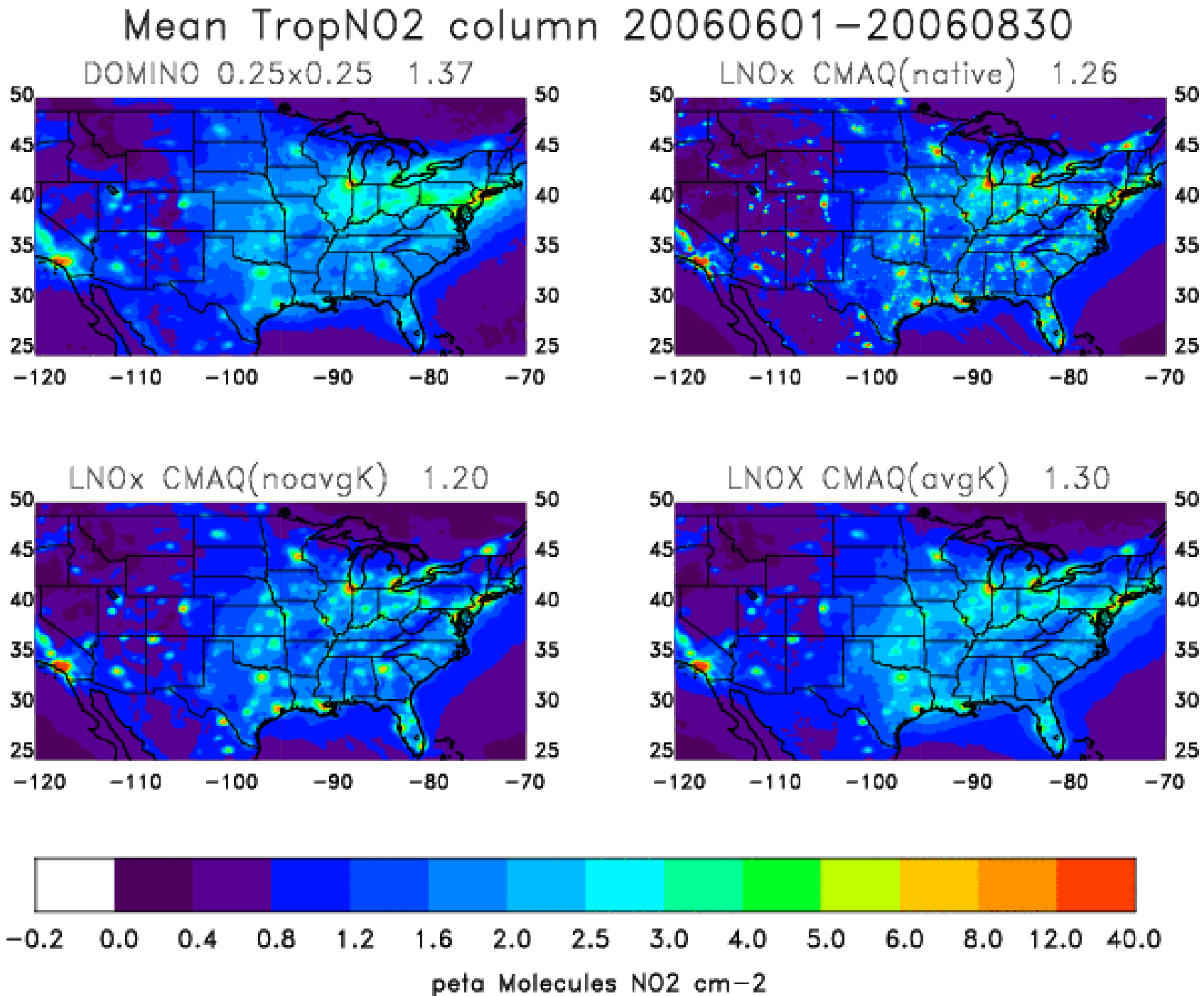
OMI tropospheric NO_2 products

1.DP-GC product [*Lamsal et al., 2010*]
2. v2.0 DOMINO product [*Boersma et al.*, 2007; Boersma et al., 2011]

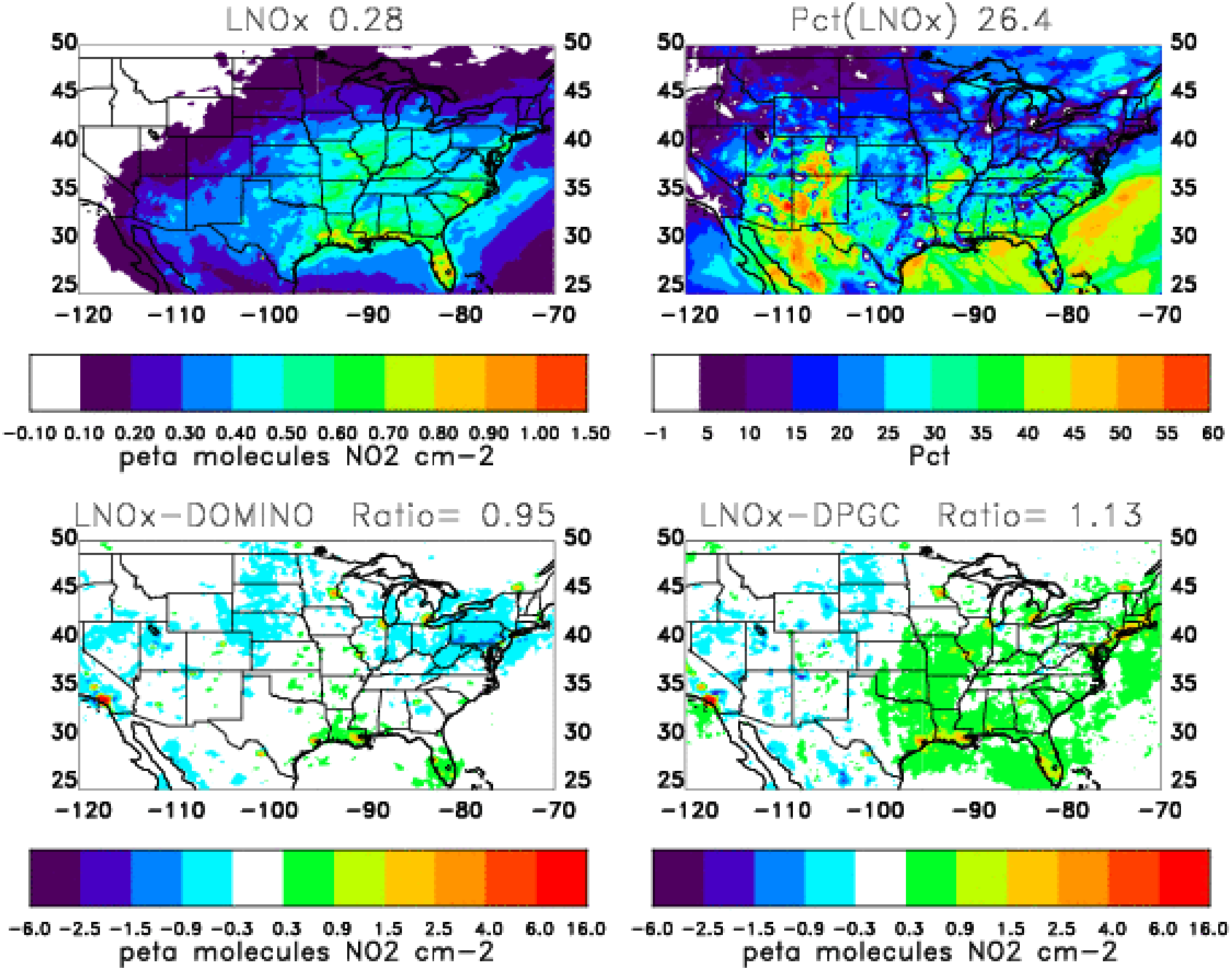
DP-GC and DOMINO products begin with same slant column & use same method to remove stratospheric column.
Different methods used to convert tropospheric slant cols to overhead cols
→ Yield different tropospheric vertical column amounts



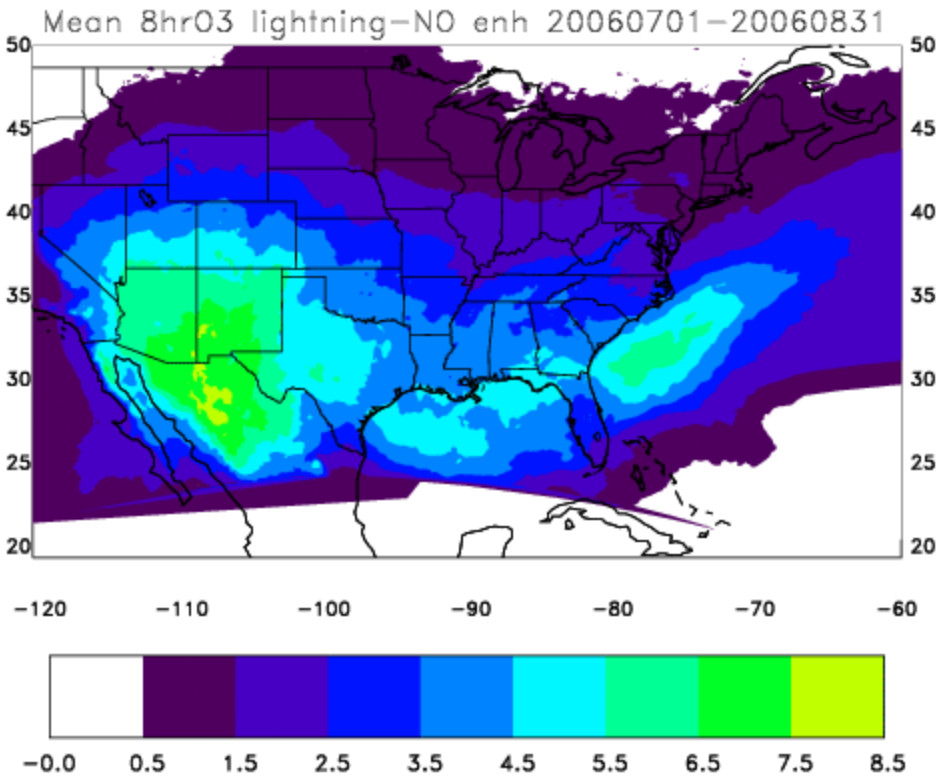

Mean tropospheric NO2 column (110W–70W; 25N–45N)
1.62 OMI DOMINO (____) R=0.47
0.36 CMAQ LNOx–noL (. . .)
1.33 DP–GC (____) R=0.79
1.48 CMAQ LNOx (_ _ _)
peta molecules cm–2
3
2
1
0
0601
0616
0701
0716
0731
0815
0830
2006MMDD


Mean TropNO2 column 20060601-20060830
DOMINO 0.25x0.25 1.37
LNOx CMAQ(native) 1.26
LNOx CMAQ(noavgK) 1.20
LNOX CMAQ(avgK) 1.30
50
45
40
35
30
25
-120
-110
-100
-90
-80
-70
-0.2
0.0
0.4
0.8
1.2
1.6
2.0
2.5
3.0
4.0
5.0
6.0
8.0
12.0
40.0
peta Molecules NO2 cm-2

TropNO2 column 20060601–20060830

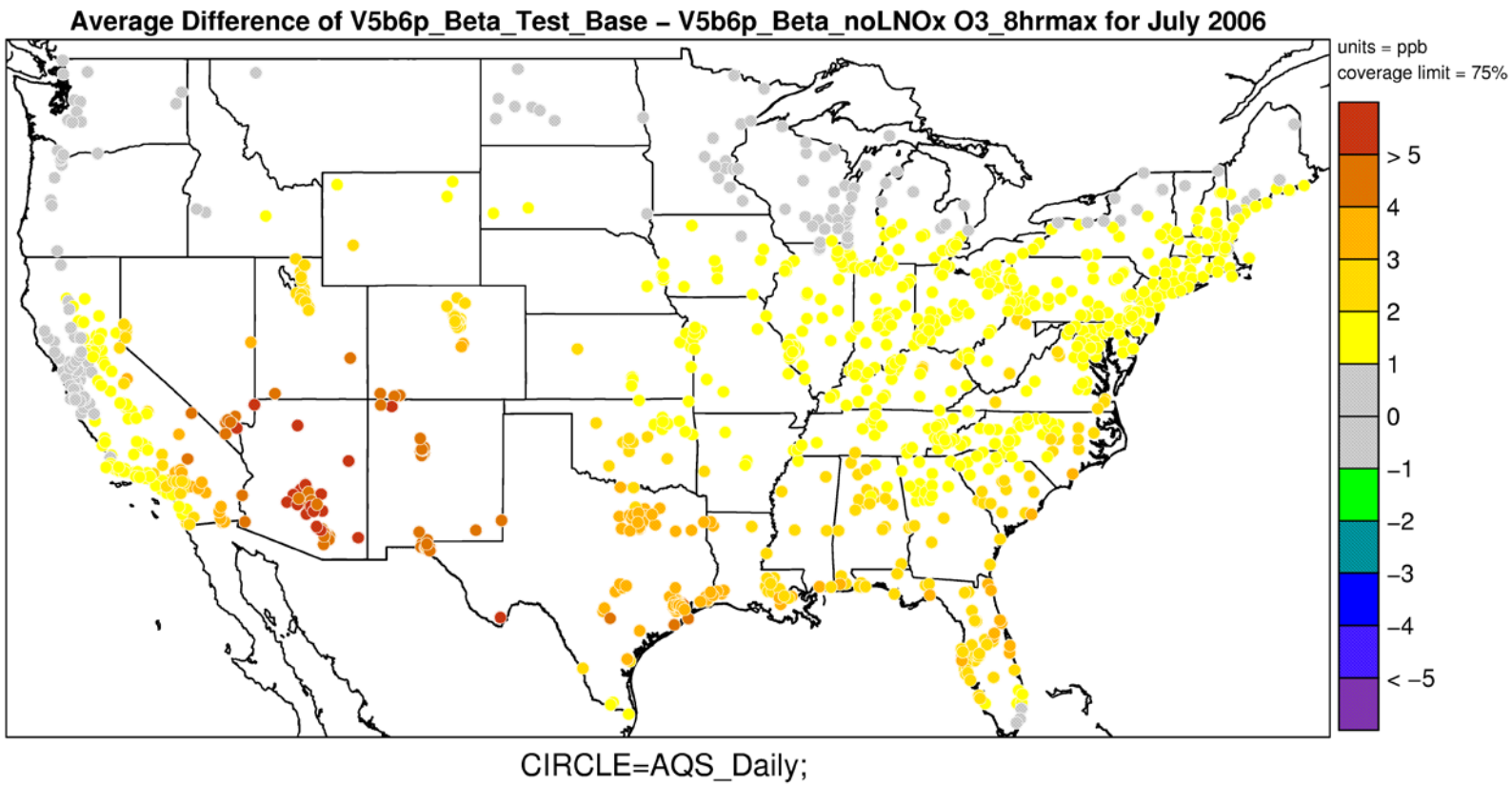


Mean summer 2006 enhancement of 8-hr maxO3 in CMAQ v4.7.1 due to LNO_x

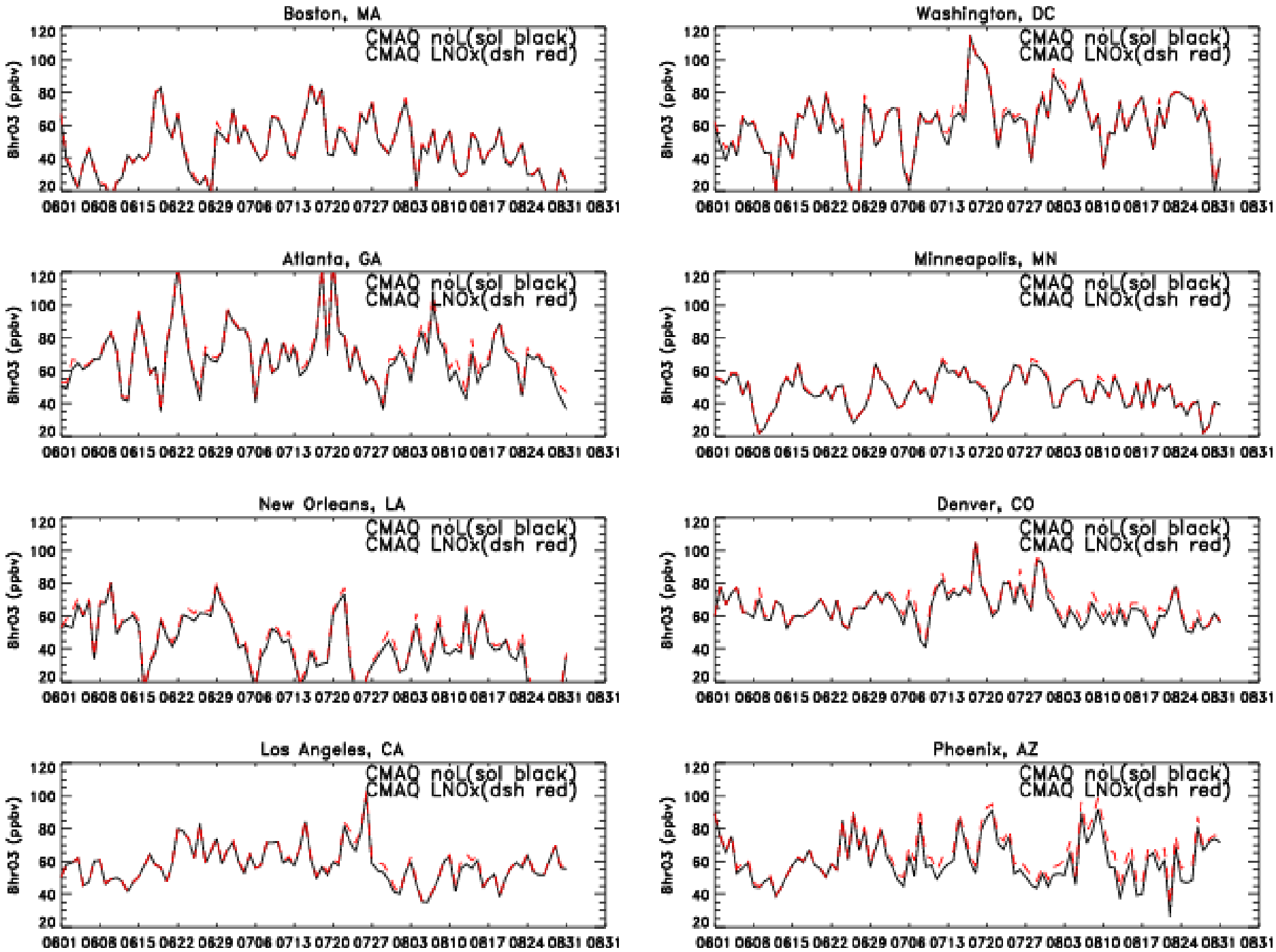


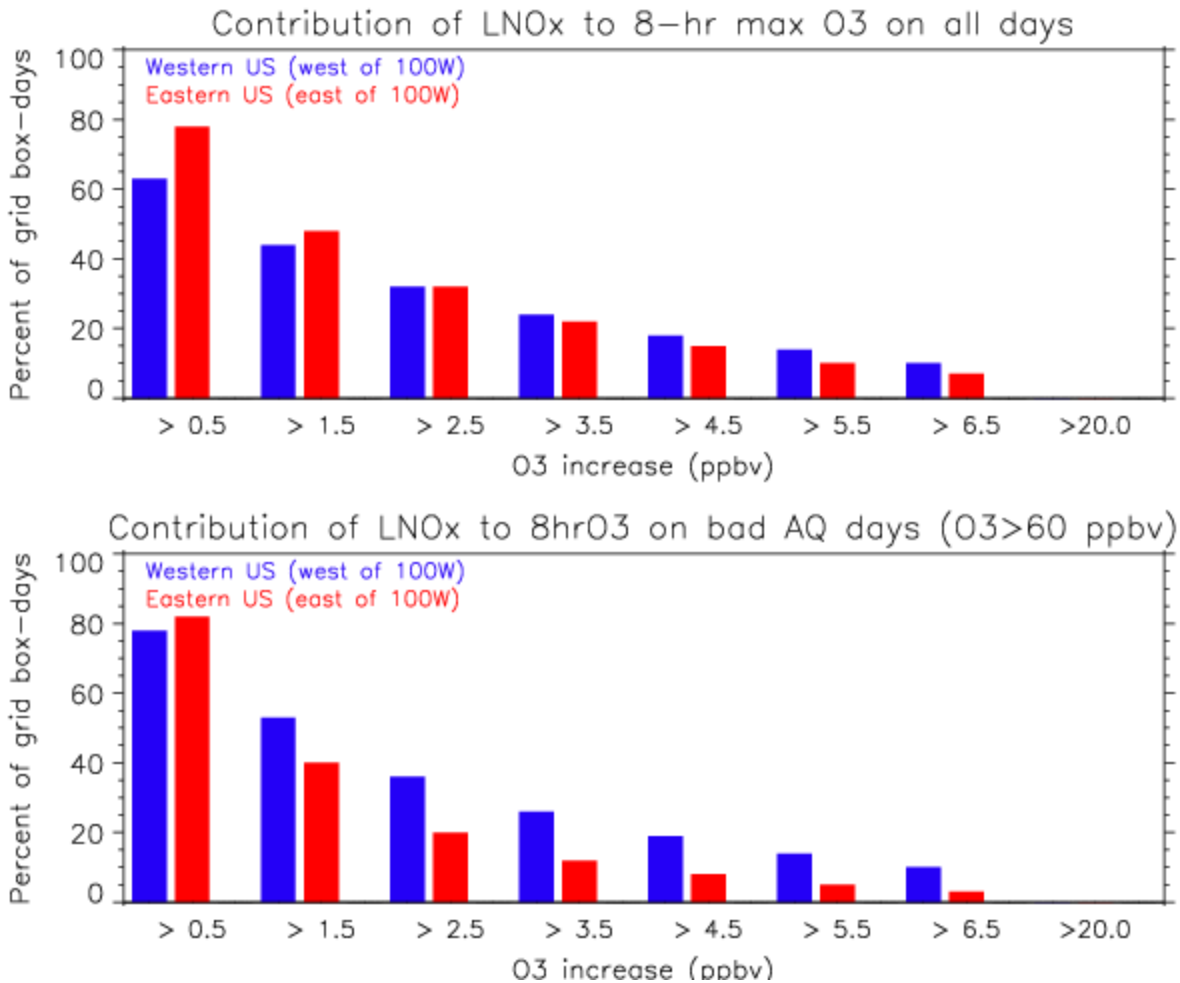
O_3 enhancement (ppbv)

Impact of Lightning NO on Monthly Average Surface O_3 during the summer of 2006



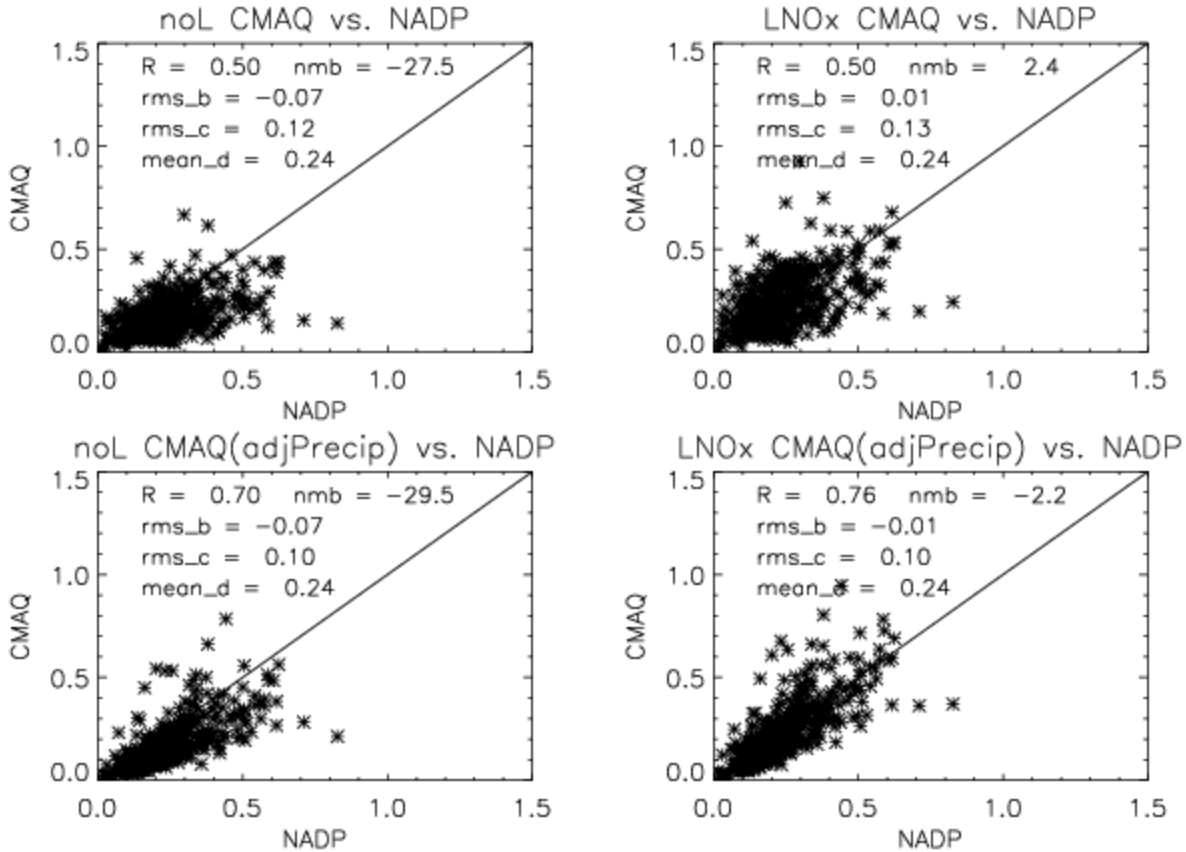
Calculated by Wyat Appel using v5.0 of CMAQ


Boston, MA
Washington, DC
Atlanta, GA
Minneapolis, MN
New Orleans, LA
Denver, CO
Los Angeles, CA
Phoenix, AZ
CMAQ noL(sol black)
CMAQ LNOx(dsh red)
8hrO3 (ppbv)
120
100
80
60
40
20
0601 0608 0615 0622 0629 0706 0713 0720 0727 0803 0810 0817 0824 0831 0831



In general, the contribution of LNO_x to 8hrO3 decreases on bad AQ days over the eastern U.S.

EastUS scatterplot: summer 2006 wet dep of oxN (nitrate)

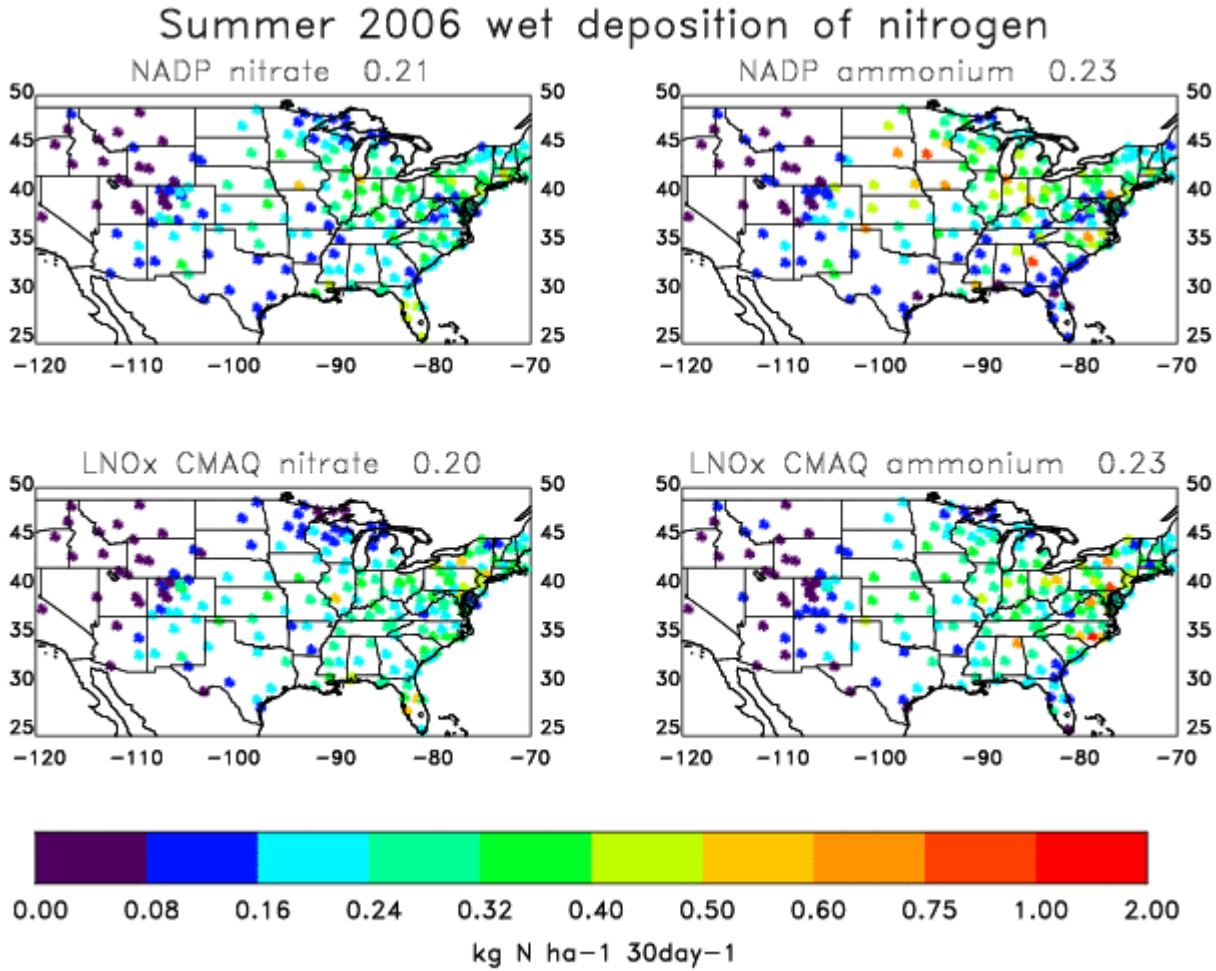


Adding LNO_x eliminates low-bias

Adjusting for precip bias leads to better fit

Eastern US: Longitudes east of 100W

Nitrate
Biases
NE: +5%
SE: +19%
West –(5-10)%



Ammonium
biases
NE: +20%
SE: +40%
West: -(20-25)%

Summary

Contribution of LNO_x to mean model column is ~25%, ranging from ~10% in the northern states to >45% along the Gulf of Mexico and in the southwestern states.

For a 500 mole per flash LNOx source, CMAQ columns have a high-bias wrt DOMINO columns over urban areas. Mean biases at other locations were generally minor after accounting for the impacts of LNOx and the averaging kernel on model columns.

LNO_x increases wet dep of nitrate by 43%, total dep of N by 10%, & changes 30% low-bias wrt NADP measurements to 2% high-bias.

On poor AQ days (O3>60 ppbv), LNO_x contributes >6.5 ppbv to 8hrO_3 at 10% of western sites and 3% of eastern sites

Adding LNOx is unlikely to improve forecasts of 8hr ozone

- Day-to-day variations in flash rate are poorly simulated in the summer (better agreement when flashes are associated with frontal passages)
- NLDN network samples CG flashes while both IC & CG flashes contribute to LNOx (geostationary measurements of total flash rate will help).

Acknowledgments

Wyat Appel & Shawn Roselle of EPA: AQMEII simulations
Kristin Foley & Jeffrey Young: Implementation of LNOx in CMAQ
L. Lamsal: DP-GC NO2 data.
OTD/LIS data are from NASA/MSFC.
NLDN data are collected by Vaisala Inc
NASA Applied Science Air Quality Program

Processing of DOMINO & CMAQ fields

- Gridded DOMINO fields created by mapping version 2.0 level 2 DOMINO fields onto 0.25°x0.25° grid.
- DOMINO retrievals over snow/ice or with cloud radiance fractions > 50% filtered out (Boersma et al., 2009)
- Mean value in each grid box obtained using algorithm that gives more weight to near-nadir pixels and to pixels with low geometric cloud fractions (Celarier and Retscher, 2009).
- CMAQ profiles extracted at location of high-quality DOMINO pixels & weighted in same manner. CMAQ output interpolated onto TM4 vertical grid (TM4 model used to obtain a priori profiles for DOMINO product) .
- When appropriate, averaging kernel is applied to tropospheric model sub-columns before weighting is performed (Allen et al., 2010; Boersma et al., 2009).
- CMAQ tropospheric NO_2 column determined by summing sub-columns within the troposphere, where the number of tropospheric layers is included in DOMINO data product.