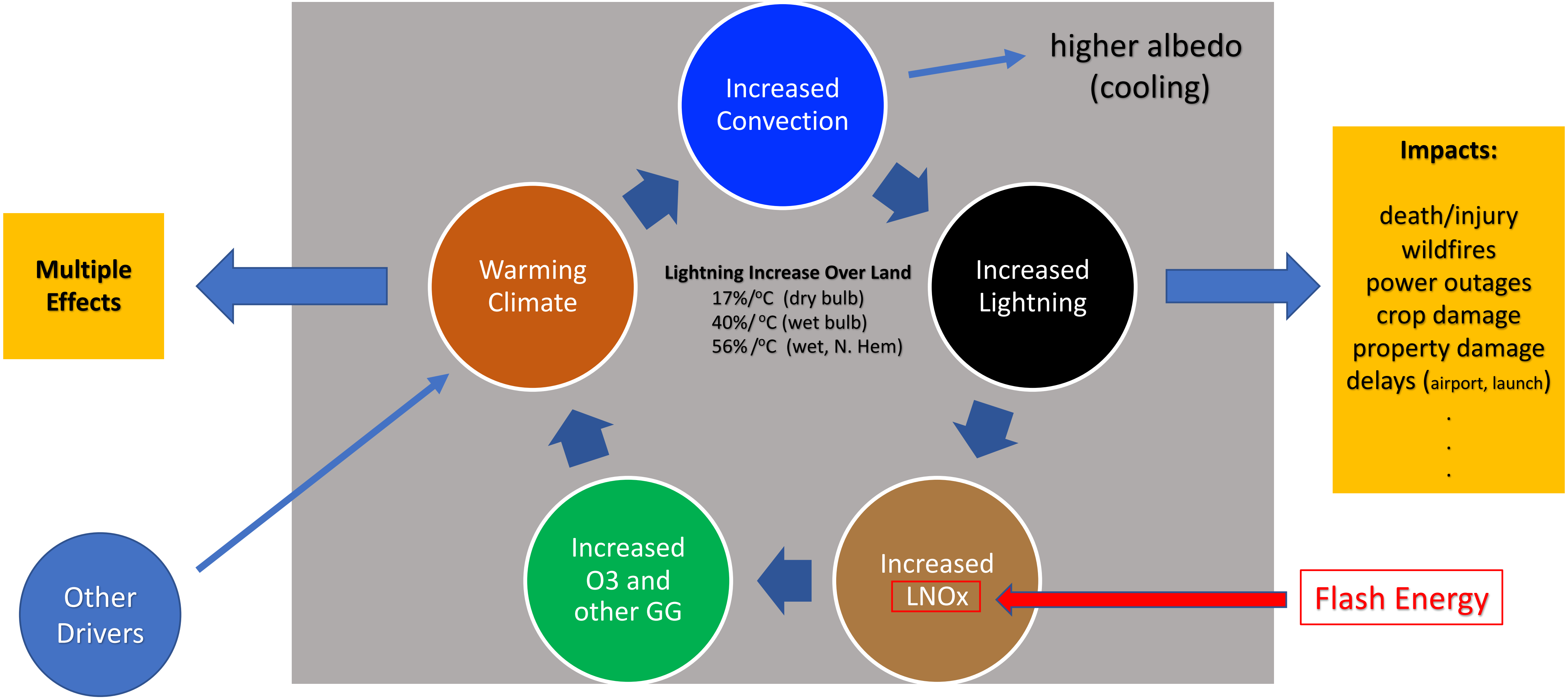
Lightning Flash Energetics

William Koshak
NASA Marshall Space Flight Center (MSFC), Huntsville, AL

Bolide Meeting, 6 February 2019
Lockheed Martin Advanced Technology Center (LMATC)
Palo Alto, California

Flash Energy is Important

Lightning/Climate Interaction



Koshak, NASA/MSFC

LNO_x Production P in moles:

$$P = \left[\frac{Y}{N_A}\right] E = \left[\frac{Y}{\beta N_A}\right] Q\ , \qquad Q \text{ in Joules}$$

$Y \sim 10^{17}\ molecules\ J^{-1}$ (Thermochemical Yield)

$N_A = 6.022 \times 10^{23}\ molecules\ mol^{-1}$ (Avogadro's Number)

$\beta \sim 1.35997 \times 10^{-22} \Rightarrow$ ave $P = 250$ moles/flash over 1st 10 mo of 2018 reference year

Flash Energy E when $P = 250$ moles is:

$$E = \frac{N_A P}{Y} = 1,505,500,000\ J \sim 1.5\ GJ$$

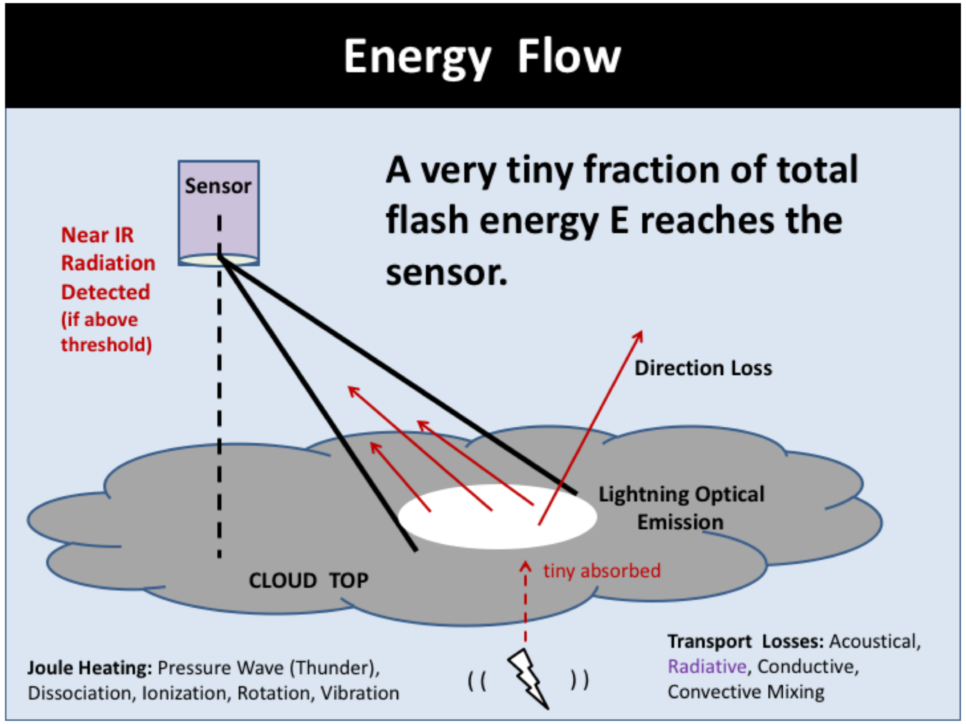
Two Optical Energy Metrics

Sensor-Intercepted Energy

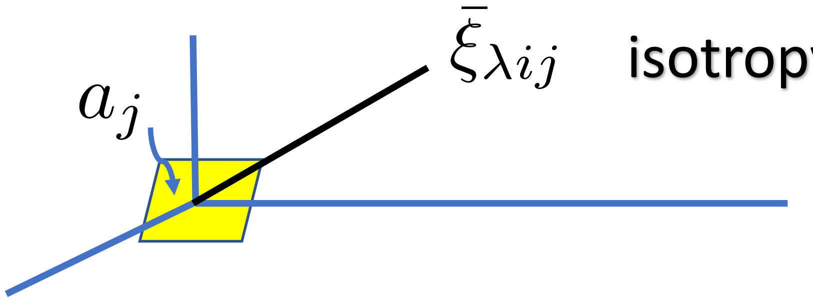
$$Q = \sum_{i=1}^{m} \sum_{j=1}^{n} A_j \Delta\lambda_j \Delta\omega_j \bar{\xi}_{\lambda ij} \qquad (\text{in fJ}) \qquad [GLM]$$

Total Upward Energy (from cloud-top surface)

$$\Gamma_\lambda = \sum_{i=1}^{m} \sum_{j=1}^{n} \pi \bar{\xi}_{\lambda ij} a_j \qquad (\text{in mJ } nm^{-1}) \qquad [LIS]$$



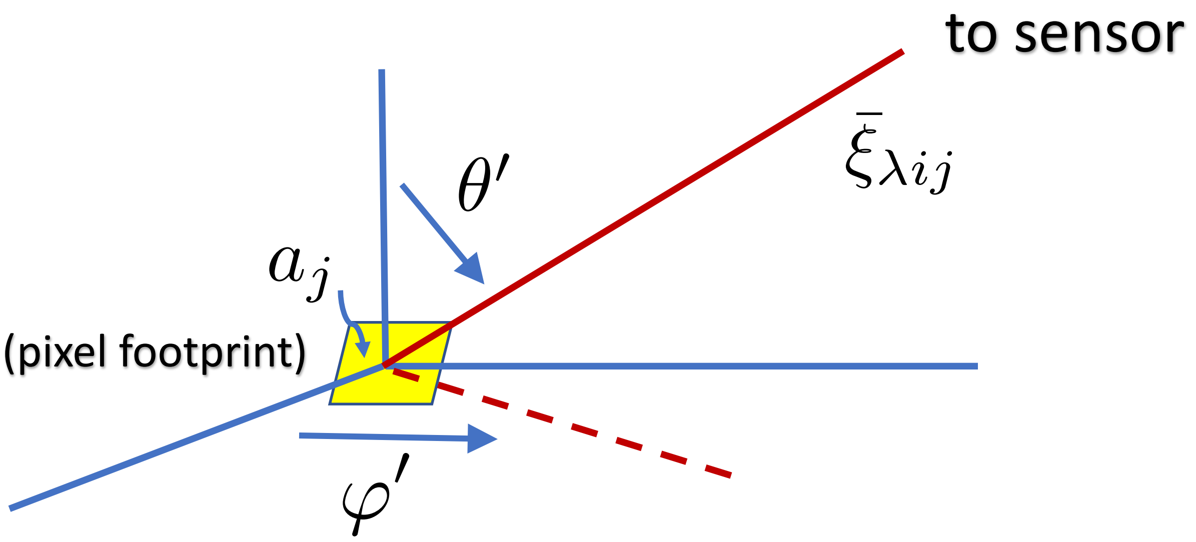
sum upward flux from each event



isotropy assumed

Koshak, NASA/MSFC

isotropy assumed



LIS

$$J_{\lambda ij} = \int_{2\pi} \cos\theta' \bar{\xi}_{\lambda ij} d\Omega' = \bar{\xi}_{\lambda ij} \int_0^{2\pi} \int_0^{\pi/2} \cos\theta' \sin\theta' d\theta' d\varphi'$$

$$\Rightarrow \quad J_{\lambda ij} = \pi \bar{\xi}_{\lambda ij} \quad (\mu J\ m^{-2} nm^{-1})$$

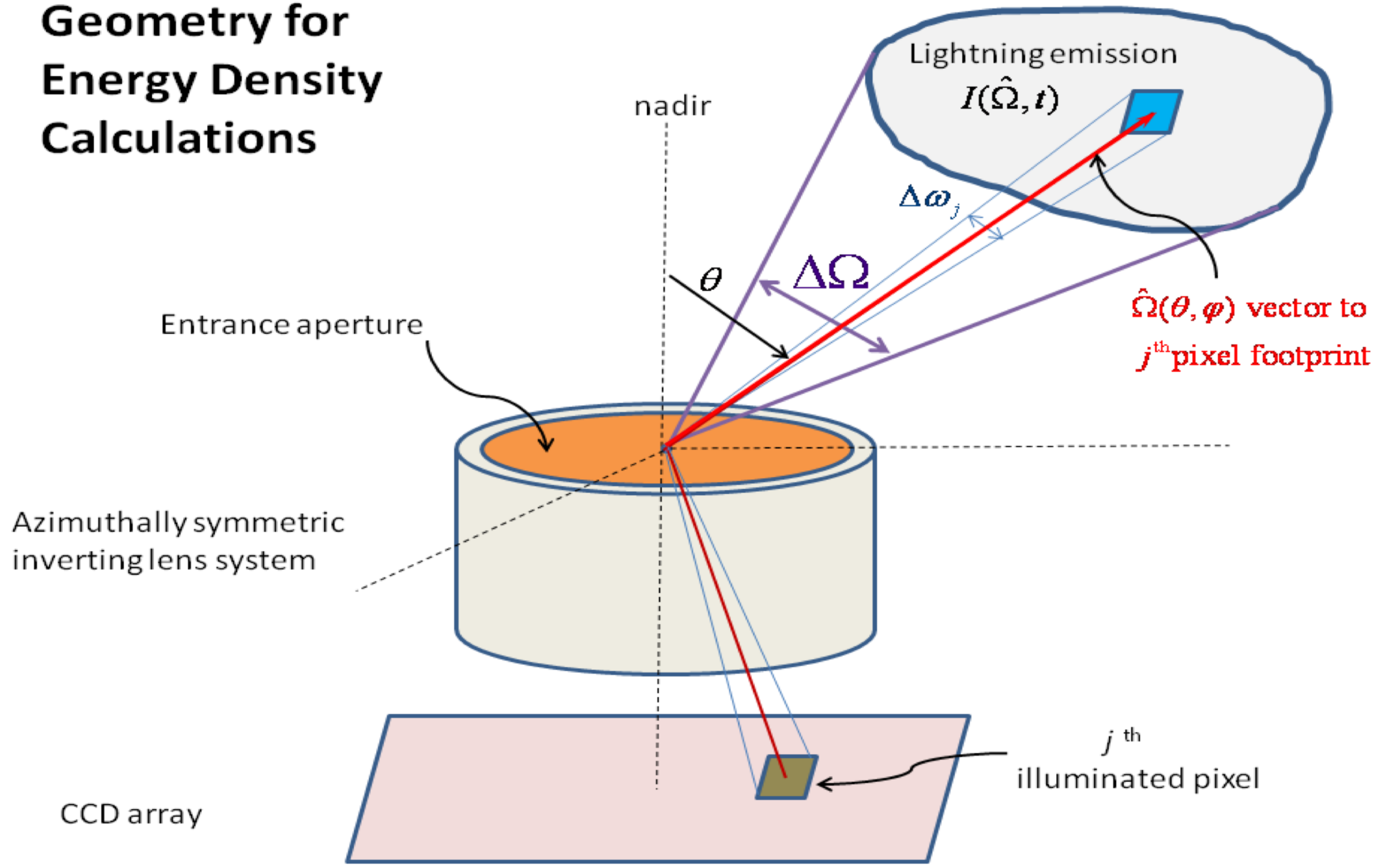
[Upward time-integrated spectral flux density from j^{th} pixel footprint for i^{th} frame]

$$\Rightarrow \quad \Gamma_\lambda = \sum_{i=1}^{m} \sum_{j=1}^{n} J_{\lambda ij} a_j = \sum_{i=1}^{m} \sum_{j=1}^{n} \pi \bar{\xi}_{\lambda ij} a_j$$

Koshak, NASA/MSFC

Geometry for Energy Density Calculations

LIS



Front Lens Incident solid - angle - averaged spectral energy density (in $\mu J \ m^{-2} sr^{-1} \mu m^{-1}$) :

$$\left\langle \xi_\lambda(\hat{\Omega}) \right\rangle = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \int_{t_o}^{t_m} I_\lambda(\hat{\Omega}, t) dt d\Omega$$

Koshak, NASA/MSFC

LIS

$$\left\langle \xi_\lambda(\hat{\Omega}) \right\rangle = \frac{1}{\Delta\Omega}\int_{\Delta\Omega}\left[\int_{t_o}^{t_m} I_\lambda(\hat{\Omega},t)dt\right]d\Omega = \frac{1}{\Delta\Omega}\int_{\Delta\Omega}\left[\sum_{i=1}^{m}\int_{t_{i-1}}^{t_i} I_\lambda(\hat{\Omega},t)dt\right]d\Omega = \frac{1}{\Delta\Omega}\int_{\Delta\Omega}\left[\sum_{i=1}^{m}\xi_{\lambda i}(\hat{\Omega})\right]d\Omega$$

$$= \frac{1}{\Delta\Omega}\sum_{i=1}^{m}\left[\int_{\Delta\Omega}\xi_{\lambda i}(\hat{\Omega})d\Omega\right] = \frac{1}{\Delta\Omega}\sum_{i=1}^{m}\left[\sum_{j=1}^{n}\int_{\Delta\omega_j}\xi_{\lambda i}(\hat{\Omega})d\Omega\right] = \frac{1}{\Delta\Omega}\sum_{i=1}^{m}\sum_{j=1}^{n}\Delta\omega_j\bar{\xi}_{\lambda ij} \simeq \frac{\Delta\omega}{\Delta\Omega}\sum_{i=1}^{m}\sum_{j=1}^{n}\bar{\xi}_{\lambda ij}$$

Hence:

$$\boxed{\left\langle \xi_\lambda(\hat{\Omega}) \right\rangle \simeq \frac{1}{n}\sum_{i=1}^{m}\sum_{j=1}^{n}\bar{\xi}_{\lambda ij}}$$

Solid Angle Averaged Spectral Energy Density

(in $\mu J\ m^{-2} sr^{-1} \mu m^{-1}$)

where:

$i = 1, ..., m$ ($m =$ # frames covered by the flash)

$j = 1, ..., n$ ($n =$ # pixels illuminated by the flash $\neq$ # of EVENTS!, in general)

$\xi_{\lambda i}(\hat{\Omega}) \equiv \int_{t_{i-1}}^{t_i} I_\lambda(\hat{\Omega},t)dt$ = spectral energy density function in i^{th} frame

$\bar{\xi}_{\lambda ij} \equiv \frac{1}{\Delta\omega_j}\int_{\Delta\omega_j}\xi_{\lambda i}(\hat{\Omega})d\Omega$ = mean spectral energy density heading toward j^{th} pixel in i^{th} frame

$\Delta\Omega = \sum_{j=1}^{n}\Delta\omega_j = n\Delta\omega =$ flash solid angle; $\Delta\omega \equiv \frac{1}{n}\sum_{j=1}^{n}\Delta\omega_j =$ mean pixel solid angle in the flash

LIS

By correcting the HDF data product $\zeta_{\lambda ij}(c_L)$, one can estimate the true incidence:

$$\bar{\xi}_{\lambda ij} \cong \frac{0.985\zeta_{\lambda ij}(c_L)}{F_j}$$

So put all the pieces together:

$$\left\langle \xi_\lambda(\hat{\Omega}) \right\rangle \simeq \frac{1}{n}\sum_{i=1}^{m}\sum_{j=1}^{n}\bar{\xi}_{\lambda ij} \quad \simeq \quad \frac{1}{n}\sum_{i=1}^{m}\sum_{j=1}^{n}\frac{0.985\zeta_{\lambda ij}(c_L)}{F_j}$$

$$\Phi_\lambda \equiv \sum_{i=1}^{m}\sum_{j=1}^{n}\zeta_{\lambda ij}(c)$$

But, a flash is fairly localized to one boresight region so that $F_j \simeq \bar{F}$:

$$\left\langle \xi_\lambda(\hat{\Omega}) \right\rangle \simeq \frac{0.985}{n\bar{F}}\sum_{i=1}^{m}\sum_{j=1}^{n}\zeta_{\lambda ij}(c_L) = \frac{0.985}{n\bar{F}}\Phi_\lambda$$

Hence:

$$\boxed{\Phi_\lambda \simeq \frac{n\bar{F}}{0.985}\left\langle \xi_\lambda(\hat{\Omega}) \right\rangle}$$

So data product generally overestimates true incidence by about a factor of n.
At max boresight the correction is n(0.82)/0.985 = 0.832n

Summary (from OTD/LIS)

Heritage Flash Amplitude Baseline Computed by Koshak Using Raw Data Results from Various Investigators

Raw Data Source	Koshak OTD CONUS 1999-2000 Z = 3 weighting Resolution Model	Koshak OTD CONUS 1999-2000 data weighting Resolution Model	Buechler & Christian LIS GLOBAL 1998-Jul 2001 Pre-boost Resolution Model	Buechler & Christian LIS GLOBAL Sep 2001-2013 Post-boost Resolution Model	Buechler & Christian LIS GLOBAL 1998-Jul 2001 Pre-boost Res: data 22.6 km^2	Buechler & Christian LIS GLOBAL Sep 2001-2013 Post-boost Res: data 25.3 km^2	Beirle et al. LIS GLOBAL 1998-2012 both Pre- & Post- Res: BC data 24.7 km^2
Koshak Computation	79.8	72.8	55.7	57.9	67.9	**59.9**	60.3

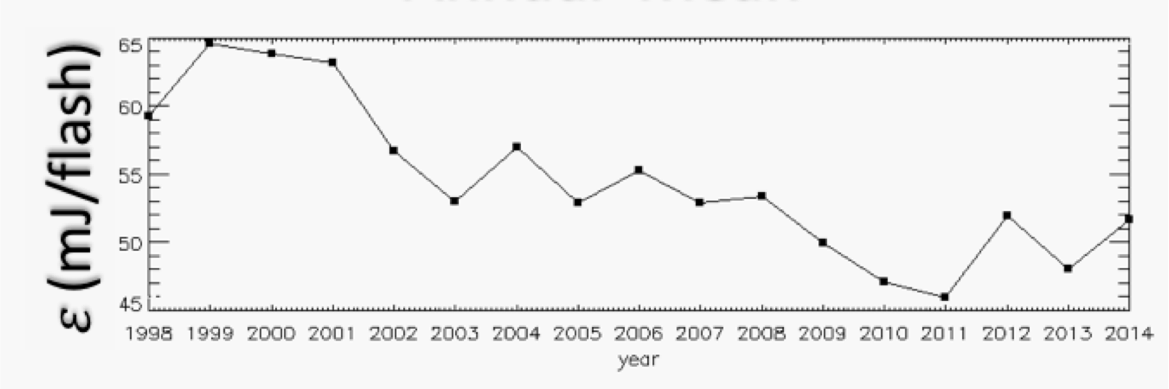
- OTD: poor sensitivity, only CONUS stats done, Z estimate … not best to use.
- More data in LIS Post-Boost than in Pre-boost … so Post-Boost better sample size
- Buechler & Christian study has 1 more year of data than the Beirle et al. study, and more specific mean event footprints (since Beirle didn't separate out Pre-boost from Post-boost).
- So best estimate currently is 6th column above (bolded).

$$\left\langle \xi_\lambda(\hat{\Omega}) \right\rangle \sim 60 \frac{\mu J}{m^2 sr\ nm}$$

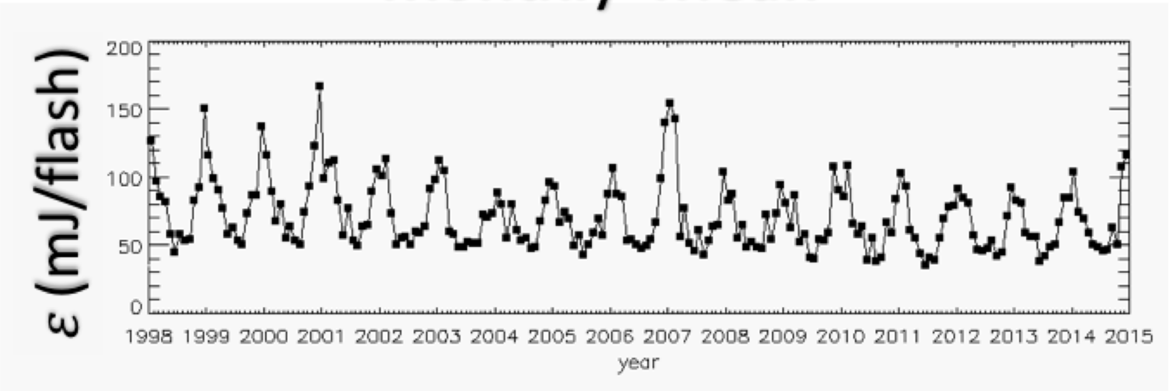
Long-Term Trend of TRMM/LIS Mean CONUS Upward Flash Optical Energy Ɛ

LIS

Annual Mean



Monthly Mean



➡ Trends down to 2011, then trends up.

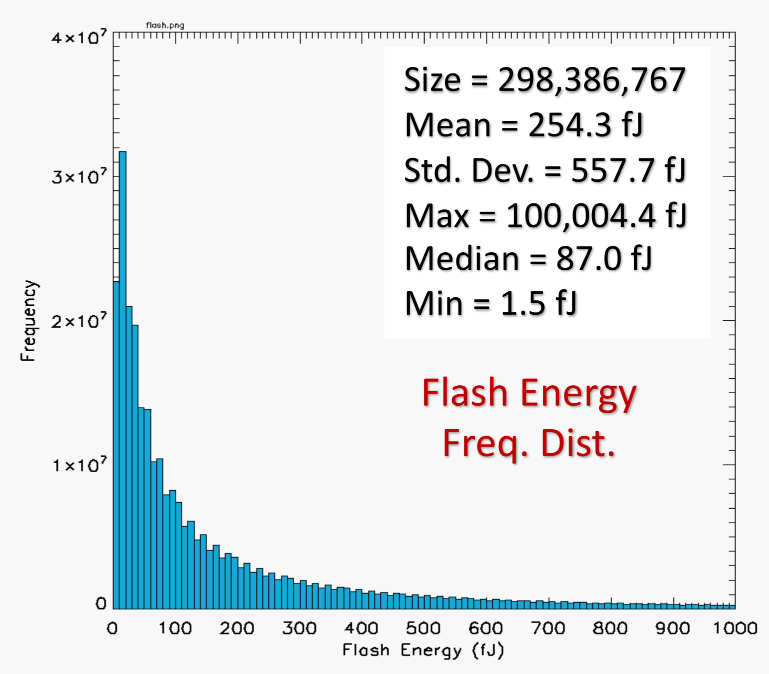
$$\varepsilon = \frac{1}{N_o}\sum_{k=1}^{N_o}\Gamma_{\lambda k}\Delta\lambda$$

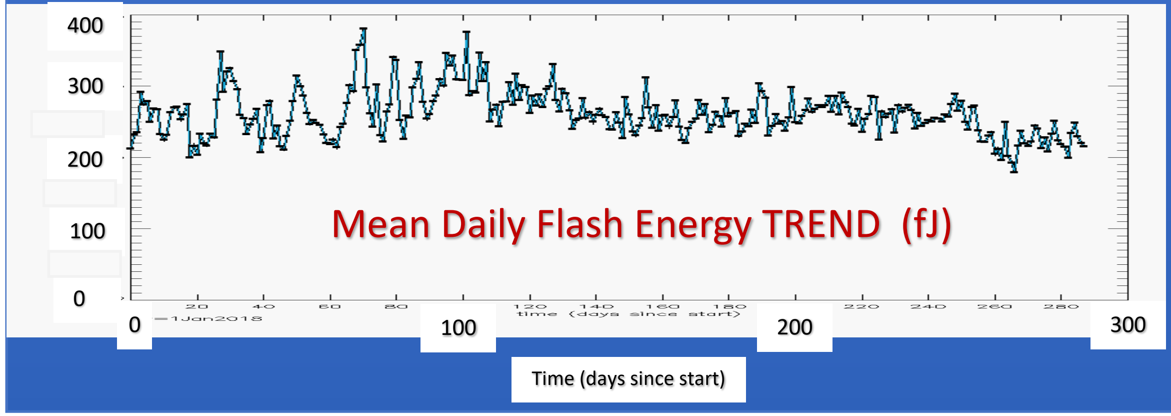
➡ Oscillates! ... with peak in Winter.

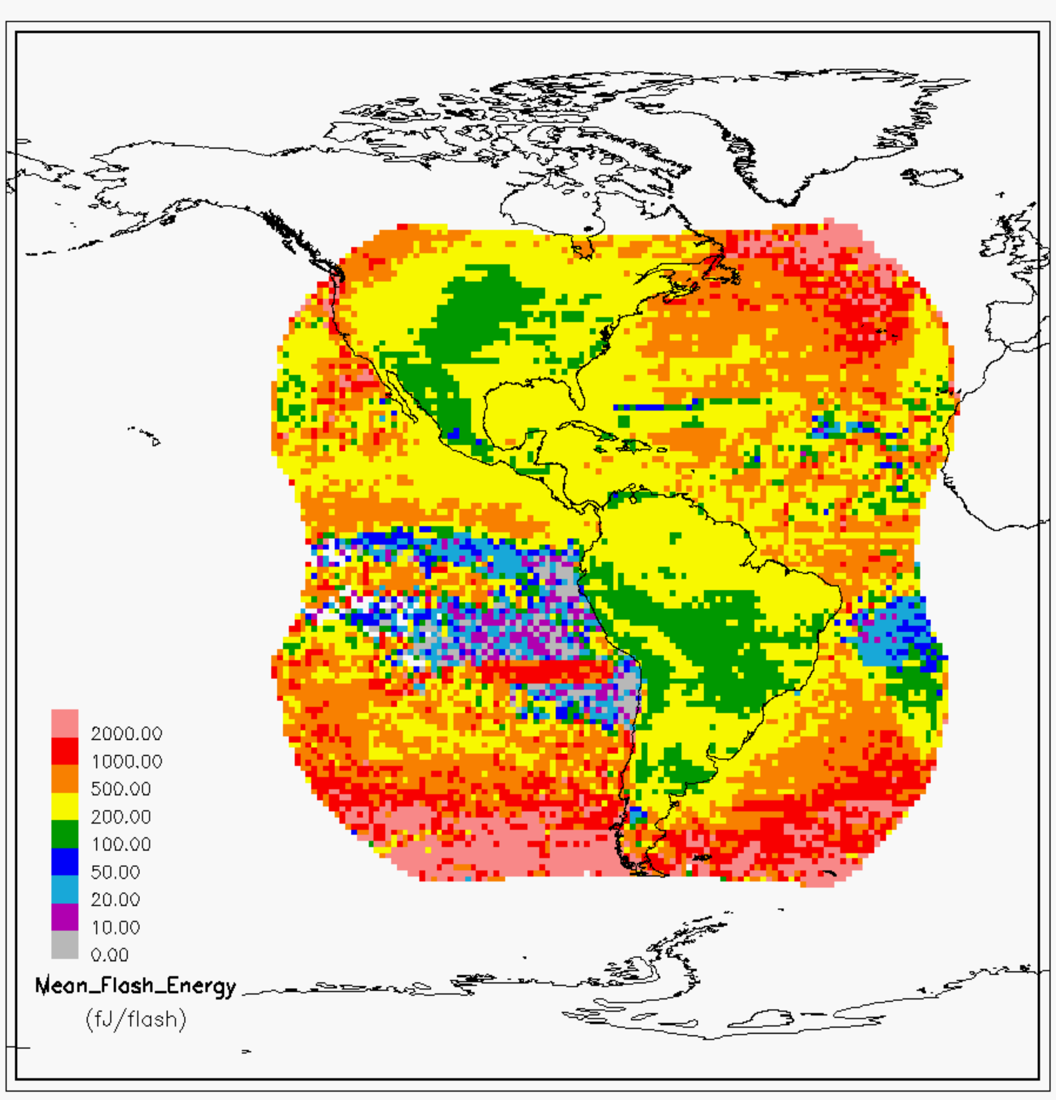
Koshak, W. J, Lightning NOx estimates from space-based lightning imagers, 16th Annual CMAS Conference, Chapel Hill, NC, October 23-25, 2017

G16 Flash Optical Energy Q

9.5 mo (2018: Jan 1 – Oct 15); ~ 300 M flashes



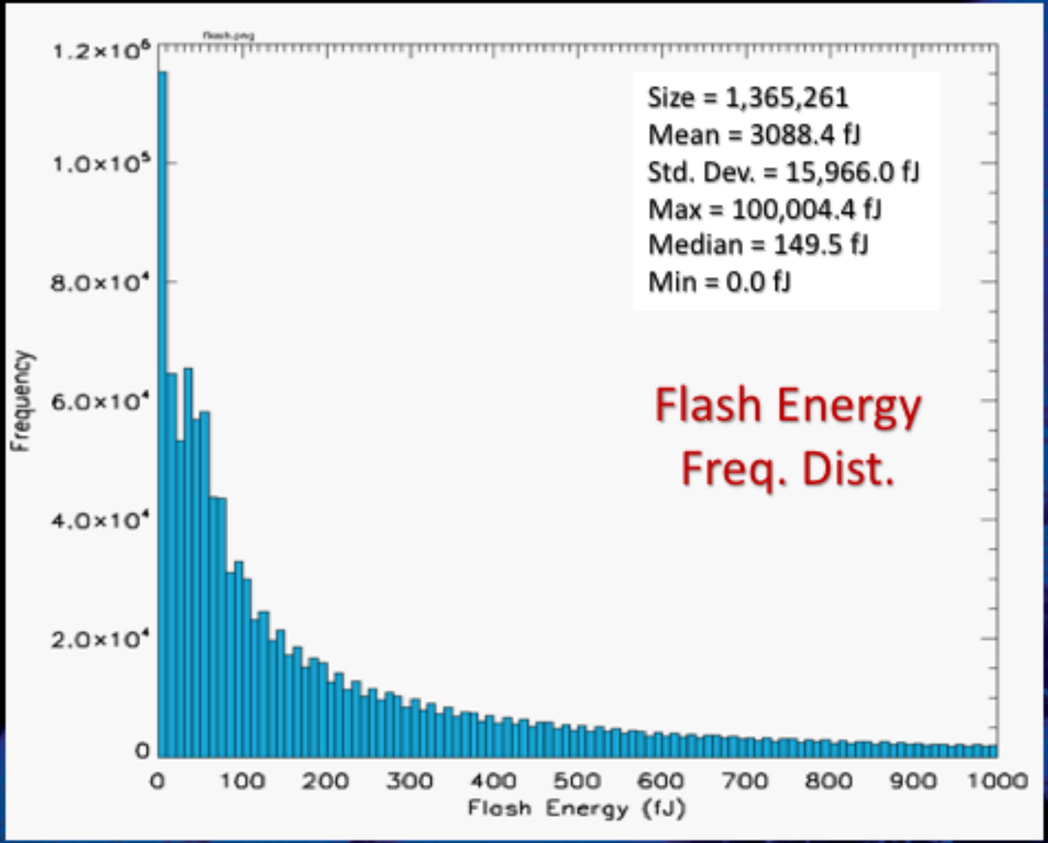




Koshak, NASA/MSFC

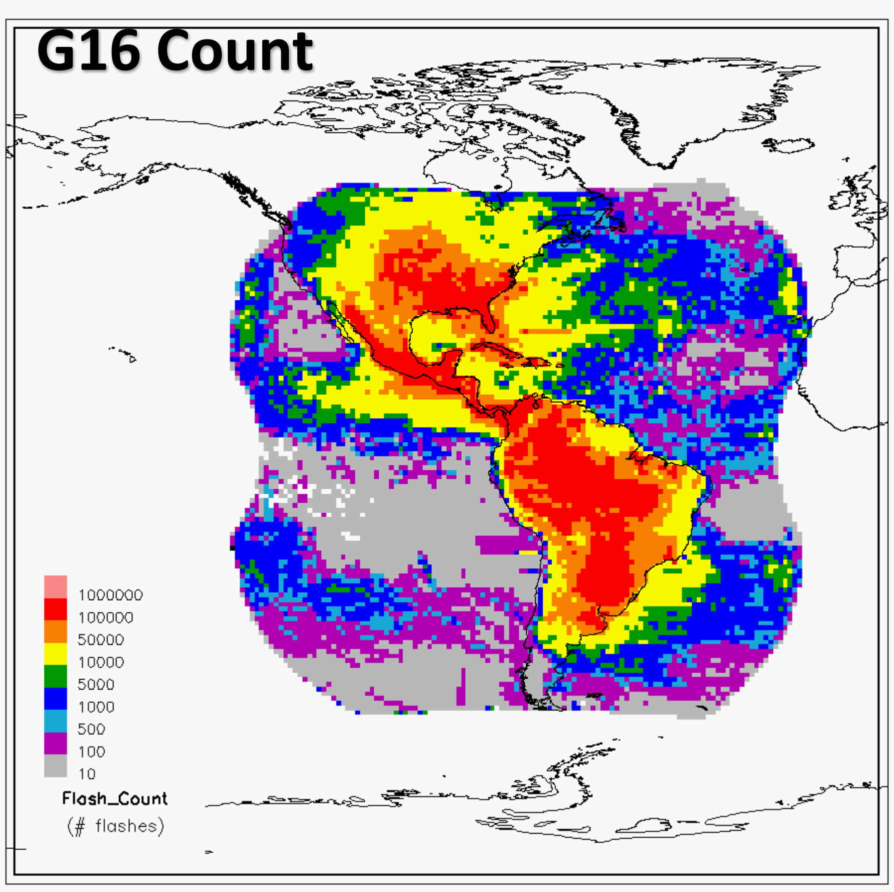
G17 Flash Optical Energy Q

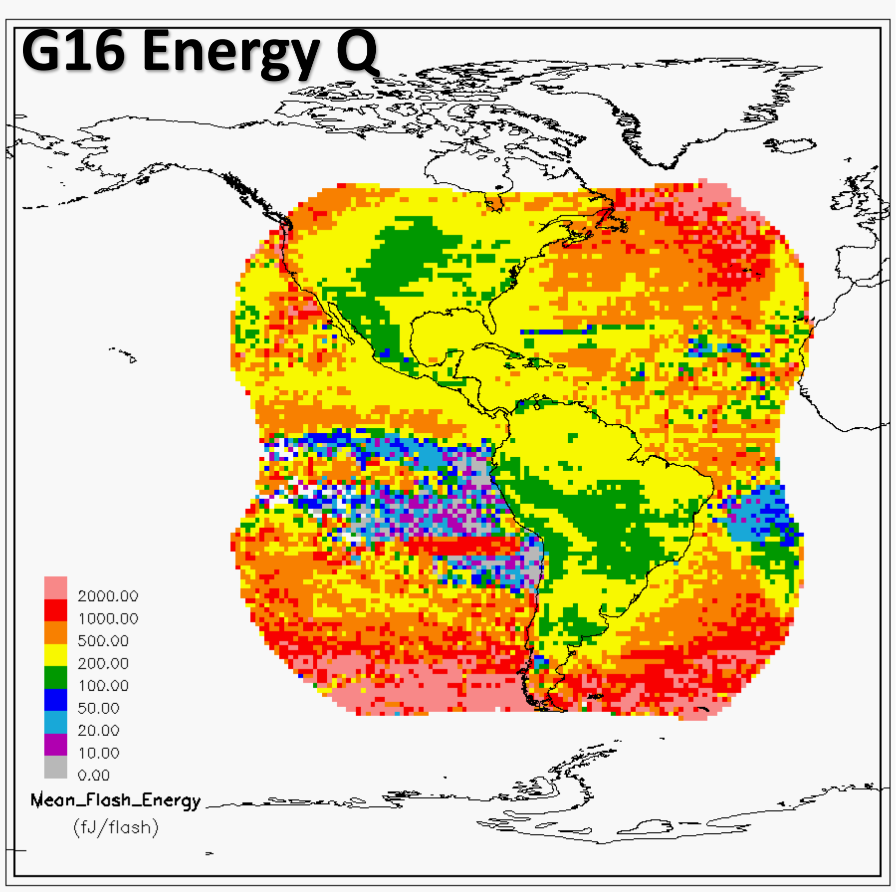
Flash Energy Trending (Koshak/MSFC)



- Dec 4-16, 2018
- ~ 1.4 M flashes
- removed flashes with flash_quality_flag ≠ 0 to help remove high-bias from blooming/glint
- Mean of 3088.4 f J is far greater than **254.3 f J** obtained from G16 Full.

NOAA's GOES-17 satellite has not been declared operational and its data are preliminary and undergoing testing. Users receiving these data through any dissemination means (including, but not limited to, PDA and GRB) assume all risk related to their use of GOES-17 data and NOAA disclaims any and all warranties, whether express or implied, including (without limitation) any implied warranties of merchantability or fitness for a particular purpose.



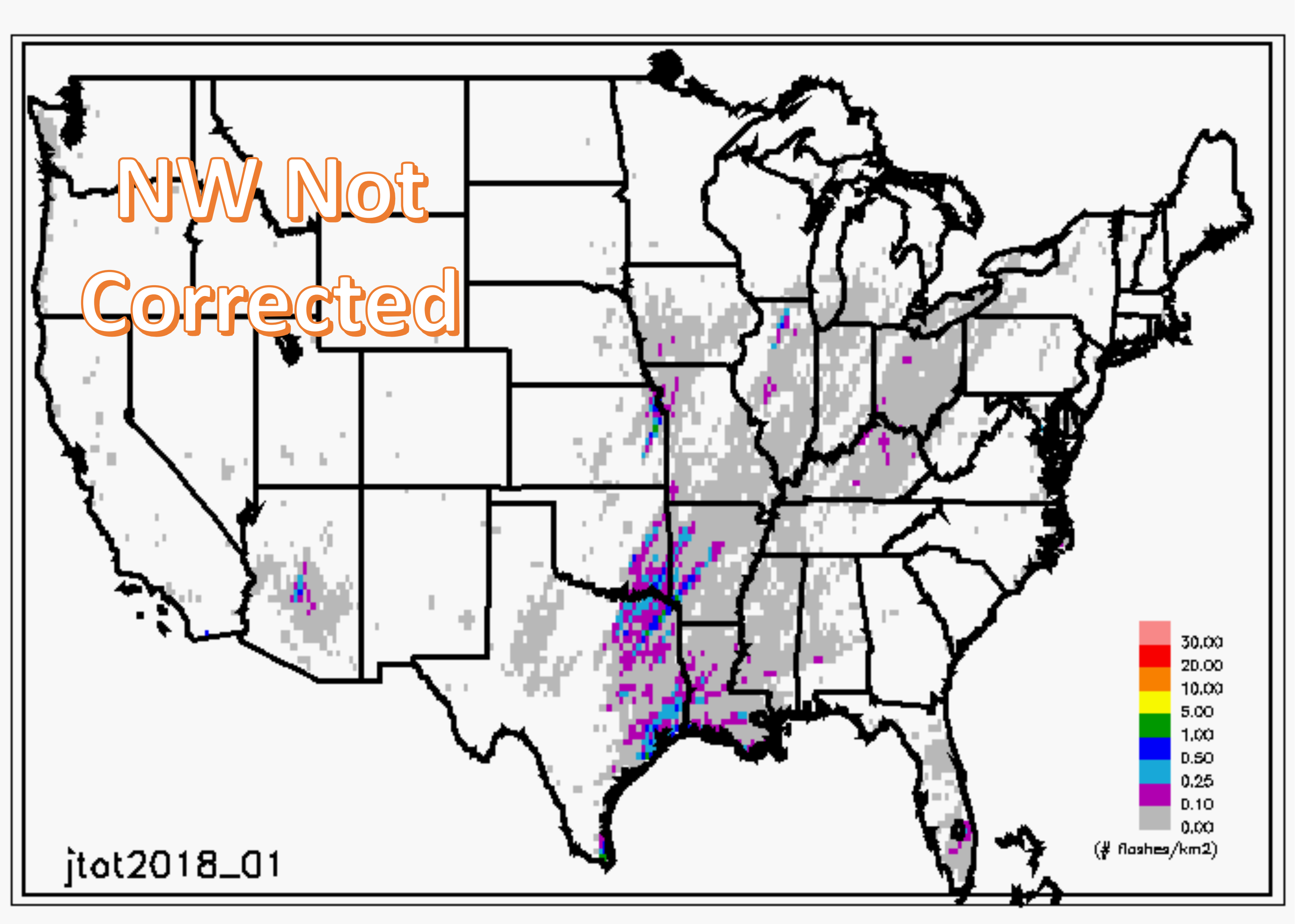


G17 Q larger than G16's because of:

- **Boresight Effect** (most G17 flashes at large boresight)
- **Ocean Effect** (most G17 flashes over ocean)
- **Statistical Effect** (G17 sample of natural lightning not as large relative to noise: glint, radiation dots)
- **Seasonal Effect** (flash energies peak in January per LIS study in Koshak, 2017)

10 mo Trend (Jan-Oct, 2018) CONUS Flash Density

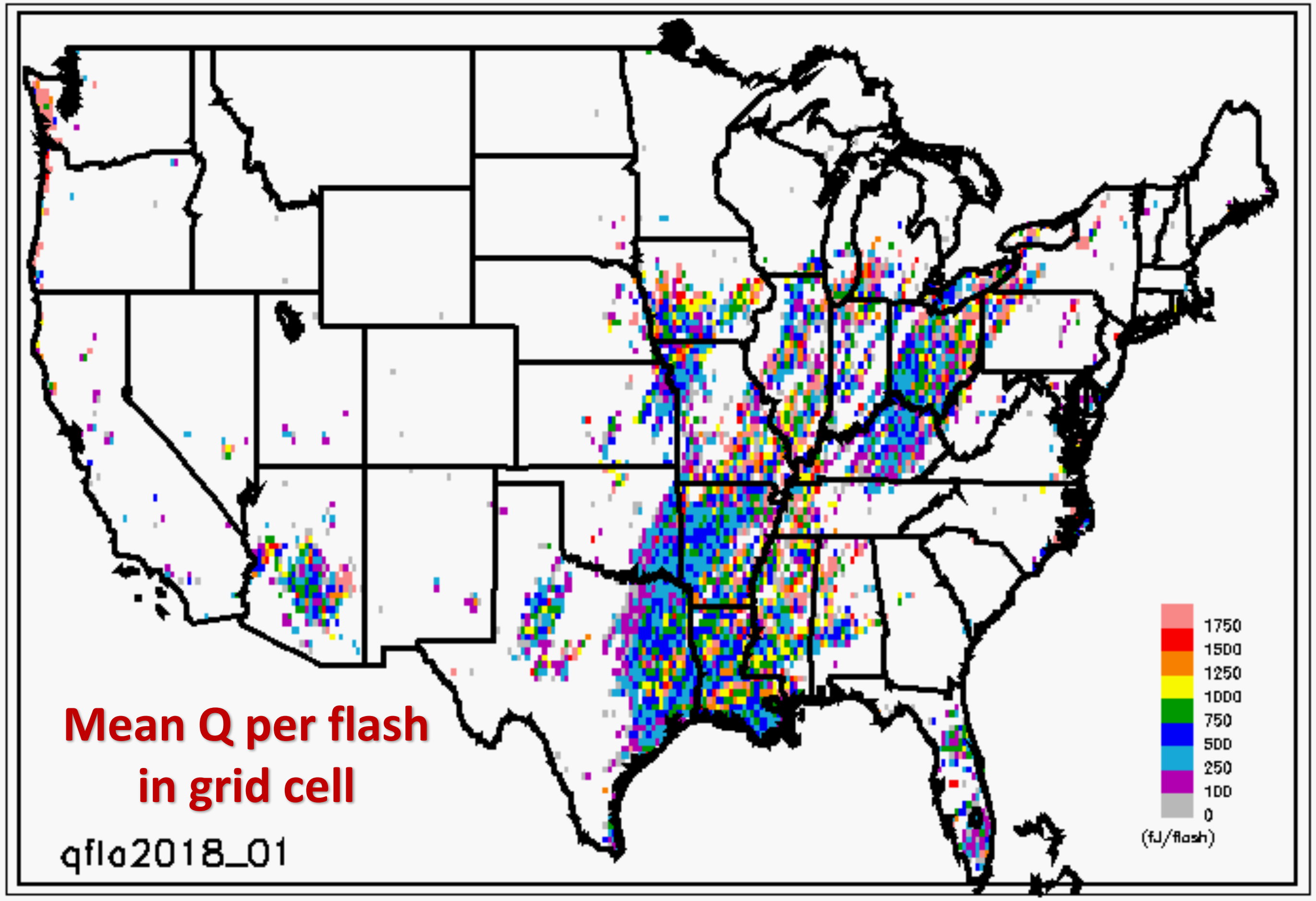
GLM-16



Koshak, NASA/MSFC

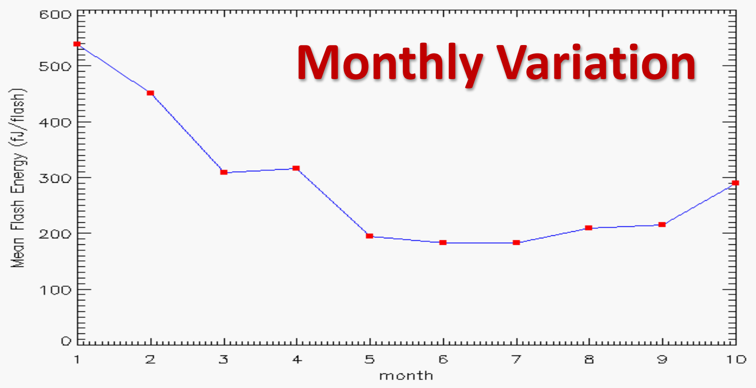
10 mo Trend (Jan-Oct, 2018) of GLM-16 CONUS Incident Flash Optical Energy Q

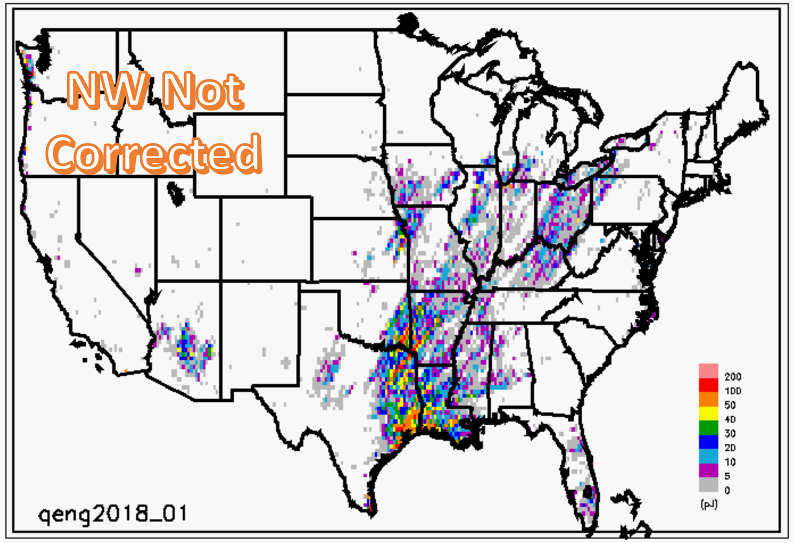
$$Q = \sum_{i=1}^{m}\sum_{j=1}^{n} q_{ij} = \sum_{i=1}^{m}\sum_{j=1}^{n} A_j \Delta\lambda_j \Delta\omega_j \bar{\xi}_{\lambda ij} \quad \text{(in f}J\text{)}$$



Mean Q per flash in grid cell

$\bar{Q}$



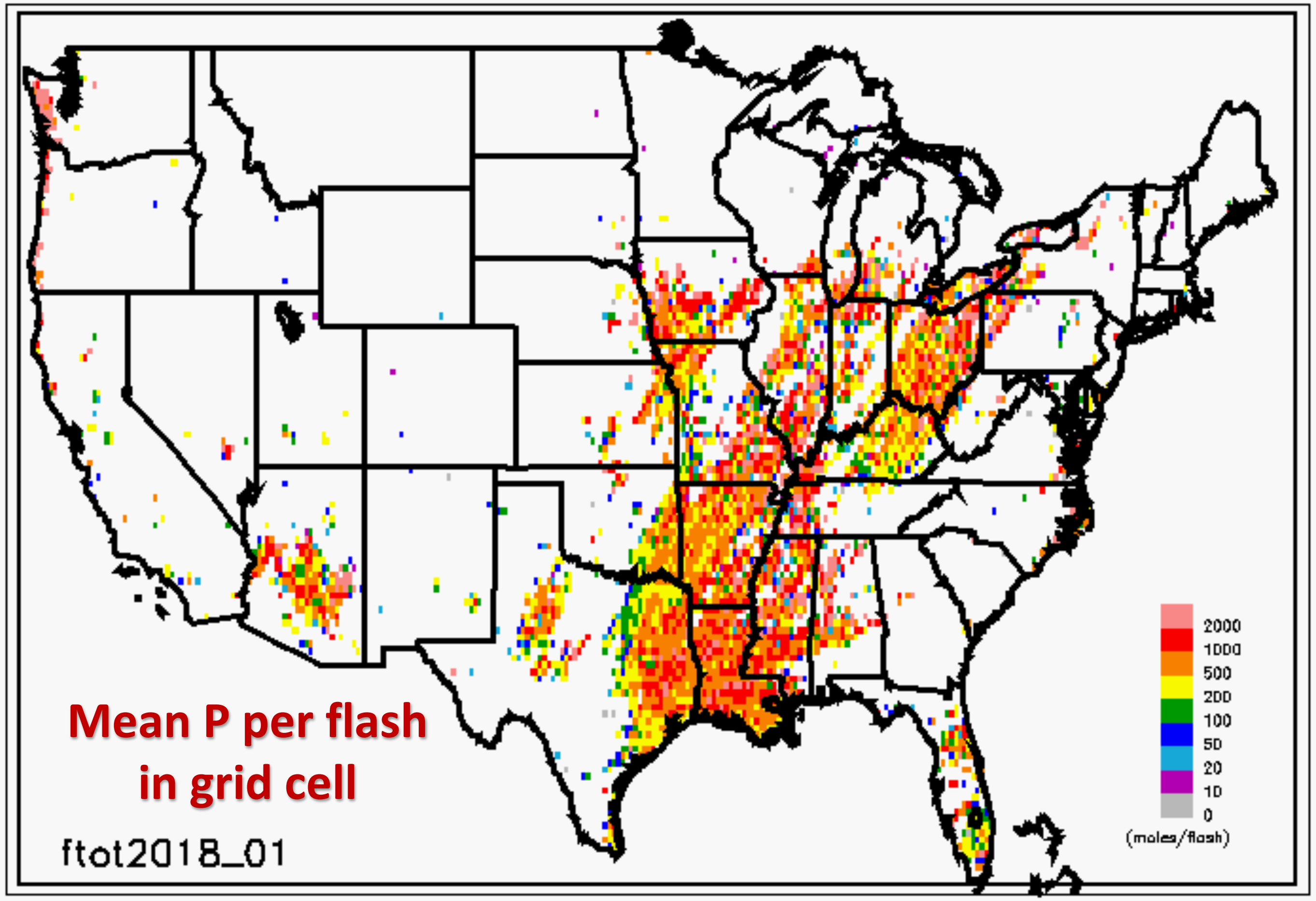


Total Q from all flashes in grid cell

Koshak, NASA/MSFC

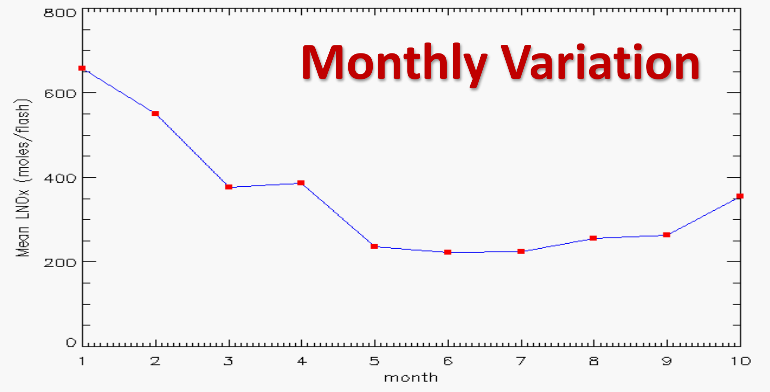
10 mo Trend (Jan-Oct, 2018) of GLM-16 CONUS LNOx Production P Estimate

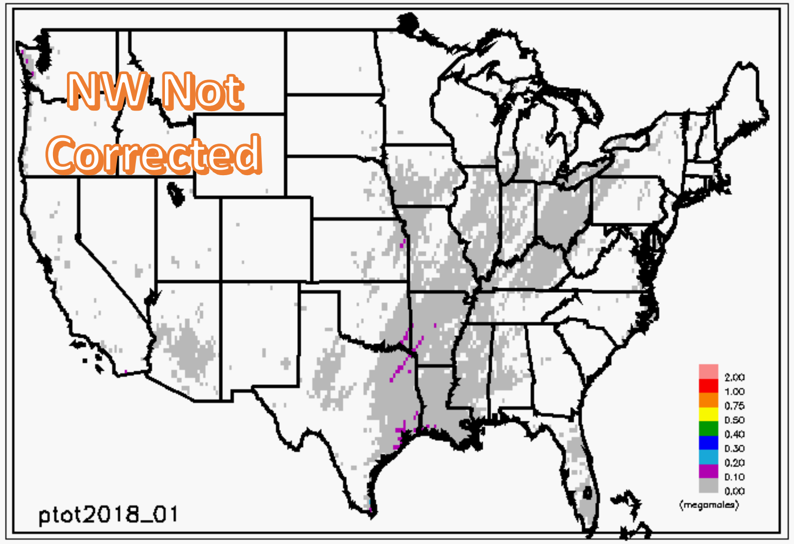
$$P = \left[\frac{Y}{\beta N_A} \right] Q \qquad \text{(in moles)}$$



Mean P per flash
in grid cell

$\bar{P}$





Total P from all flashes
in grid cell

Koshak, NASA/MSFC

Questions