GLM Product Evaluation and Highlights of My Research at CICS

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Overview of my research visit

- “Japanese Government Short-Term Overseas Fellowship Program” sponsored by the National Personnel Authority of Japan
  - Period: Nov. 5, 2018 - Nov. 3, 2019

- NESDIS accepted me at CICS, based on the framework of the NESDIS-JMA high-level letter exchange on information exchange regarding GOES-R Series & Himawari-8/9

- Research topics: GLM & NOAA’s advanced efforts on satellites

I deeply appreciate NESDIS’s giving me this great opportunity

Contents

1. Overview of JMA and Himawari satellites

What JMA is

Japan’s national meteorological service, whose ultimate goals are

Safety of transportation

Prevention and mitigation of natural disasters

Development and prosperity of industry

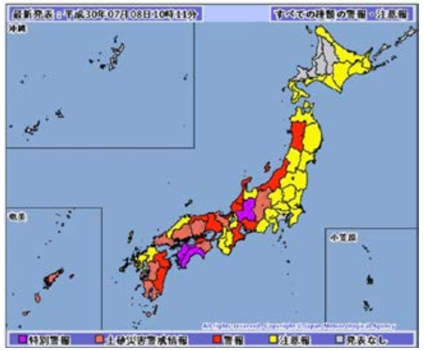
International cooperation

prescribed by the Meteorological Service Act.

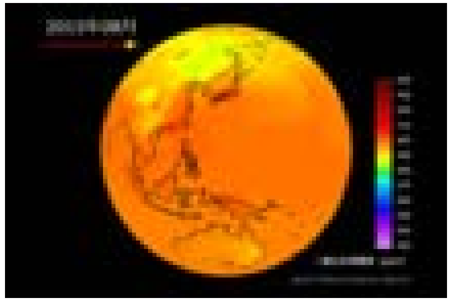
What JMA does

- Weather observations

- Weather forecasts and warnings



- Aviation & marine weather services



- Climate & global environment services

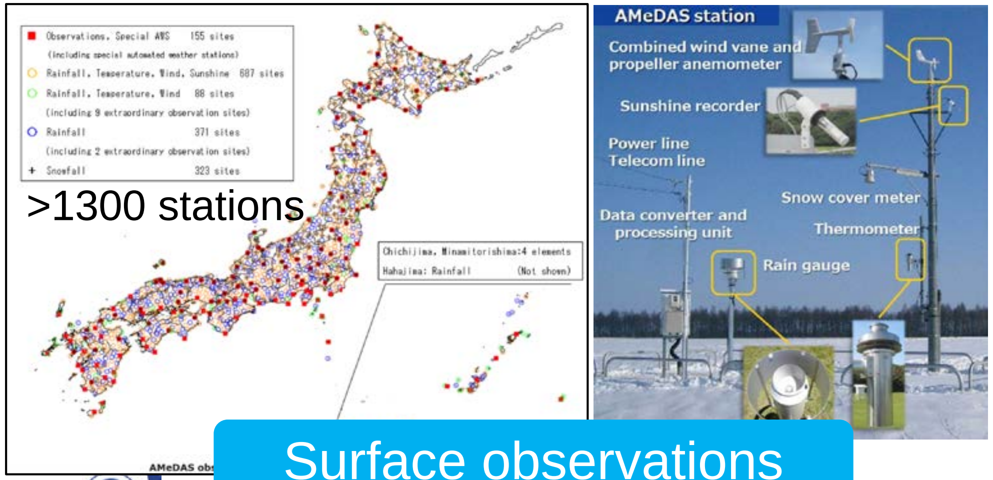
- Monitoring seismic & volcanic activity & tsunamis

JMA’s weather observation systems

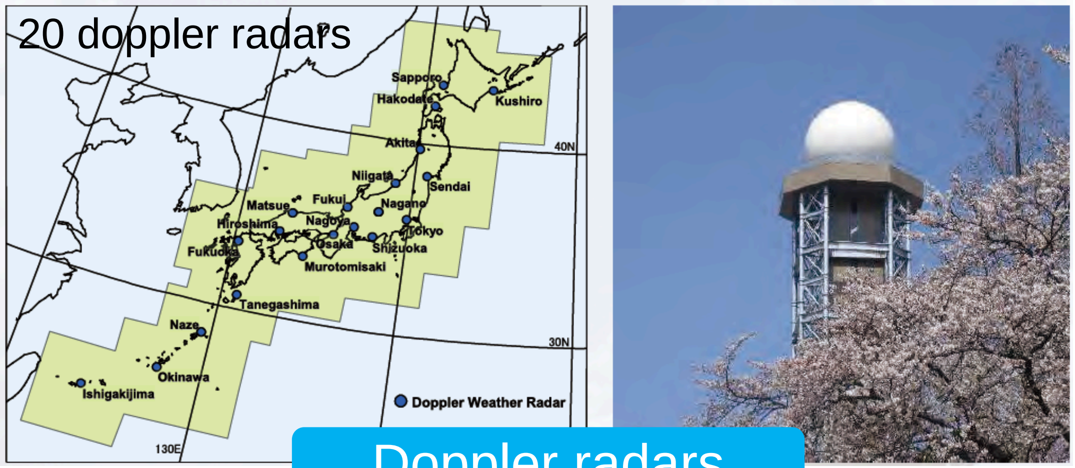
Upper air observations

Geostationary satellites

Observations for Aviation



Surface observations



Doppler radars

JMA’s weather prediction system

32	Japan Meteorological Agency Japan	Cray XC50, Xeon Platinum 8160 24C 2.1GHz, Aries interconnect Cray Inc./Hitachi	135,792	5,730.5	9,125.2	1,354
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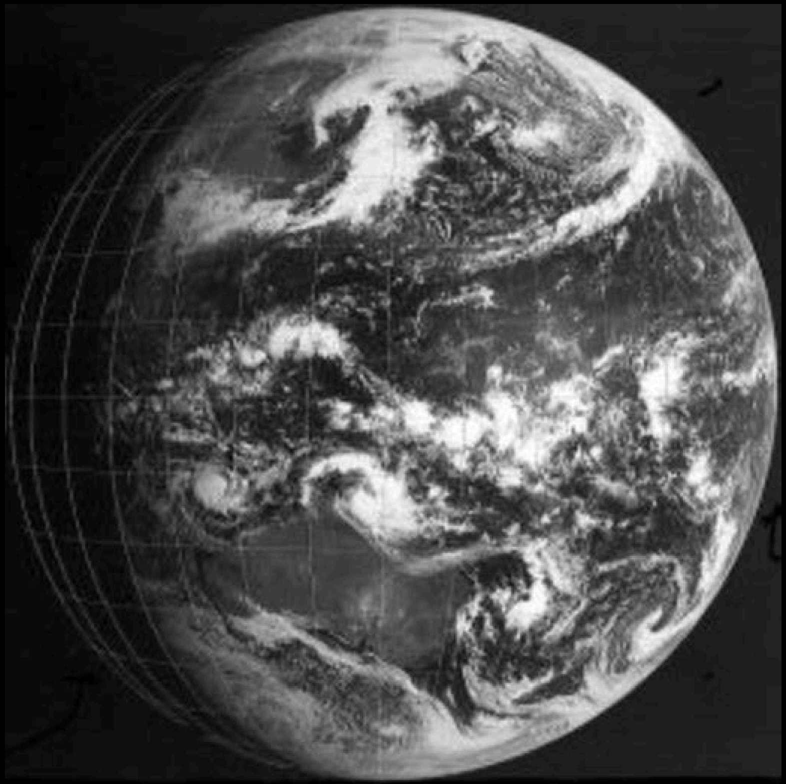
https://www.top500.org/lists/2019/06/

JMA’s world-class operational supercomputer system runs global & regional models.

	Global Spectral Model (GSM)	Meso-Scale Model (MSM)	Local Forecast Model (LFM)	Global Ensemble (GEPS)	Meso-scale Ensemble (MEPS)	Seasonal Ensemble (CPS2)
Forecast domain	Global 	Regional 	Regional 	Global 	Regional 	Global (Coupled) 
Horizontal resolution	TL959 (0.1875 deg)	5km	2km	TL479 / TL319 (0.375 / 0.5625 deg)	5km	Atmos: 1.125 deg Ocean: 0.3-0.5x1 deg

Himawari series satellites



April 6, 1978

July 14, 1977

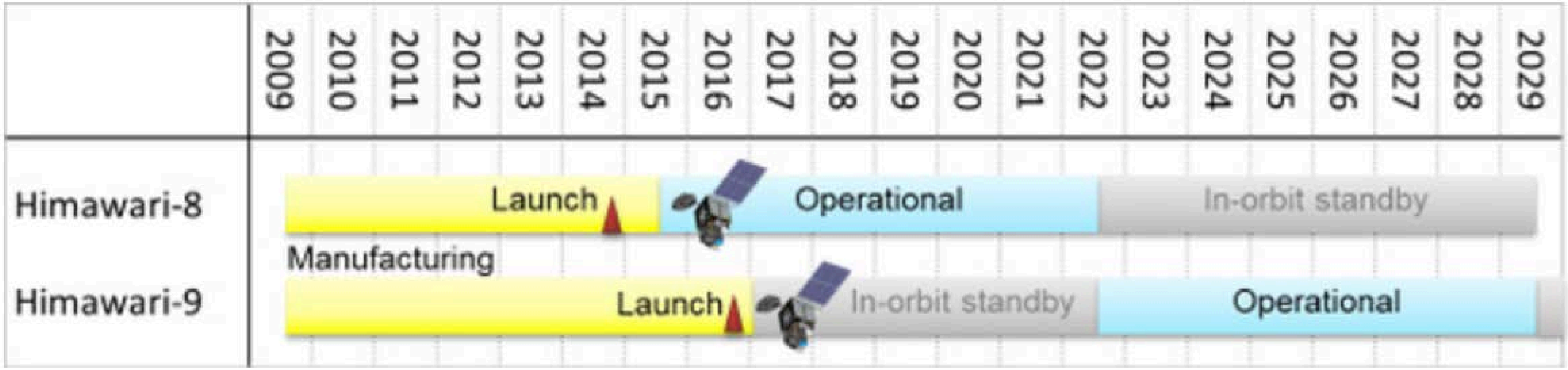
Satellite	Obs period
GMS (Himawari)	1978 – 1981
GMS-2 (Himawari-2)	1981 – 1984
GMS-3 (Himawari-3)	1984 – 1989
GMS-4 (Himawari-4)	1989 – 1995
GMS-5 (Himawari-5)	1995 – 2003
GOES-9	2003 – 2005
MTSAT-1R (Himawari-6)	2005 – 2010
MTSAT-2 (Himawari-7)	2010 – 2015
Himawari-8	2015 – (2022)
Himawari-9	(2022) – (2029)

Covering the Asia-Pacific region for over 40 years

Himawari-8 and -9

The latest generation of Himawari series satellites.

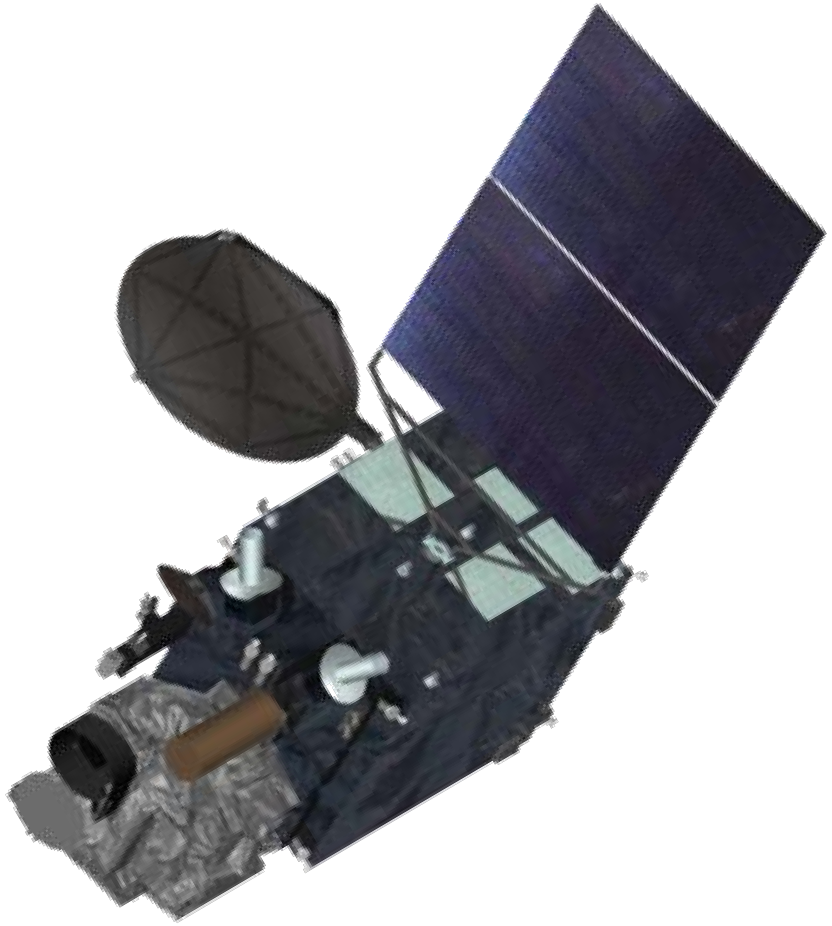
- Himawari-8 in operation since 2015.
- Himawari-9 on standby in orbit, and scheduled to be operational in 2022.
- Compose a twin satellite system until 2029.



AHI aboard Himawari-8/9

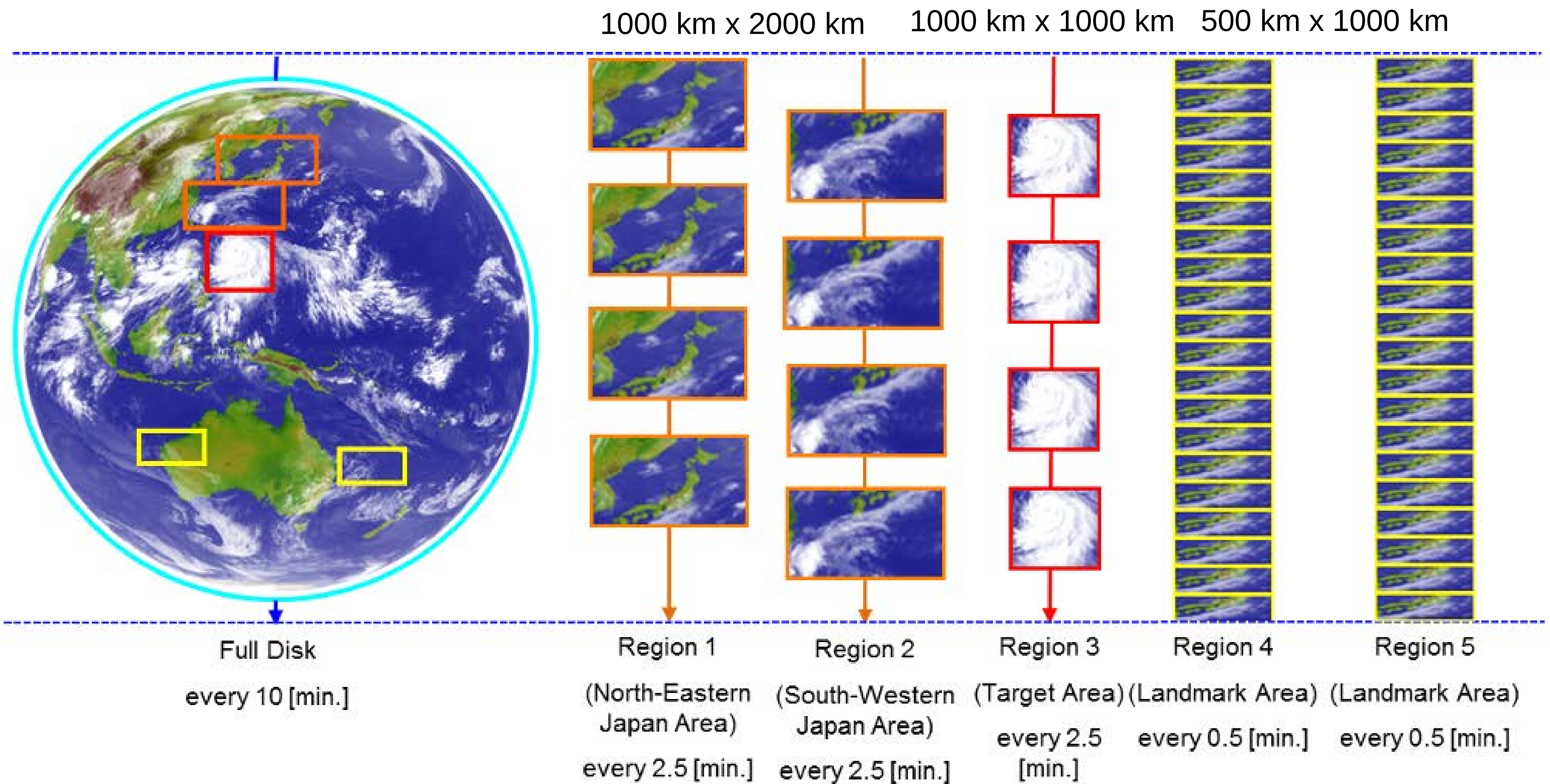
Himawari-8/9 each carry the Advanced Himawari Imager (AHI), an ABI-class 16-spectral-band imaging instrument.

Band	Himawari-8/AHI			GOES-R/ABI		MTSAT-2/IMAGER	
	Wave length	Spatial resolution	Bit depth	Wave length	Spatial resolution	Wave length	Spatial resolution
1	0.47 μm	1km	11	0.47 μm	1km		
2	0.51 μm	1km	11				
3	0.64 μm	0.5km	11	0.64 μm	0.5km	0.68 μm	1km
4	0.86 μm	1km	11	0.86 μm	1km		
				1.38 μm	2km		
5	1.6 μm	2km	11	1.61 μm	1km		
6	2.3 μm	2km	11	2.26 μm	2km		
7	3.9 μm	2km	14	3.90 μm	2km	3.7 μm	4km
8	6.2 μm	2km	11	6.15 μm	2km	6.8 μm	4km
9	6.9 μm	2km	11	7.00 μm	2km		
10	7.3 μm	2km	12	7.40 μm	2km		
11	8.6 μm	2km	12	8.50 μm	2km		
12	9.6 μm	2km	12	9.70 μm	2km		
13	10.4 μm	2km	12	10.3 μm	2km	10.8 μm	4km
14	11.2 μm	2km	12	11.2 μm	2km		
15	12.4 μm	2km	12	12.3 μm	2km	12.0 μm	4km
16	13.3 μm	2km	11	13.3 μm	2km		



AHI frequent observations

AHI generates a full disk image every 10 minutes, while providing regional observations with 2.5 min and 30 sec intervals.



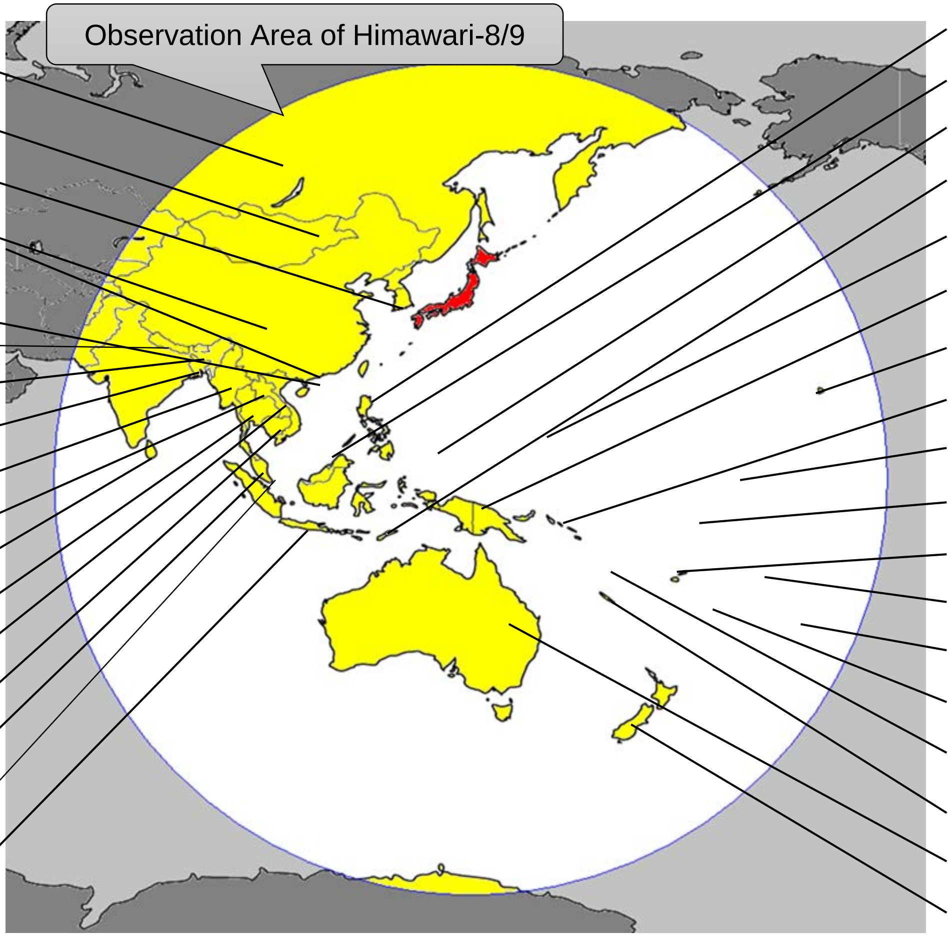
National weather services using Himawari-8

HimawariCast
32 users

HimawariCloud
21 users and
NESDIS & EUMETSAT

Web service
42 areas including
Timor-Leste & Cook Islands

- Russia
- Mongolia
- Korea
- China
- Hong Kong, China
- Macau
- Nepal
- Bhutan
- Bangladesh
- Myanmar
- Laos
- Sri Lanka
- Thailand
- Vietnam
- Cambodia
- Malaysia
- Singapore
- Indonesia



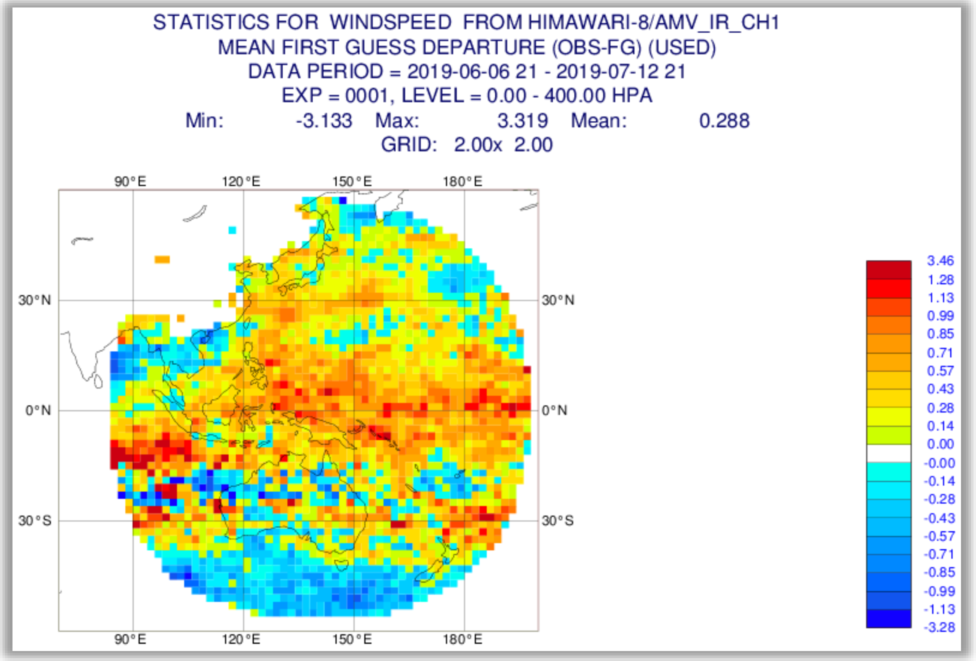
- Philippines
- Brunei
- Palau
- Timor-Leste
- Micronesia
- Papua New Guinea
- Hawaii (USA)
- Solomon Islands
- Kiribati
- Tuvalu
- Fiji
- Samoa
- Cook Islands
- Tonga
- Vanuatu
- New Caledonia (Fr.)
- Australia
- New Zealand

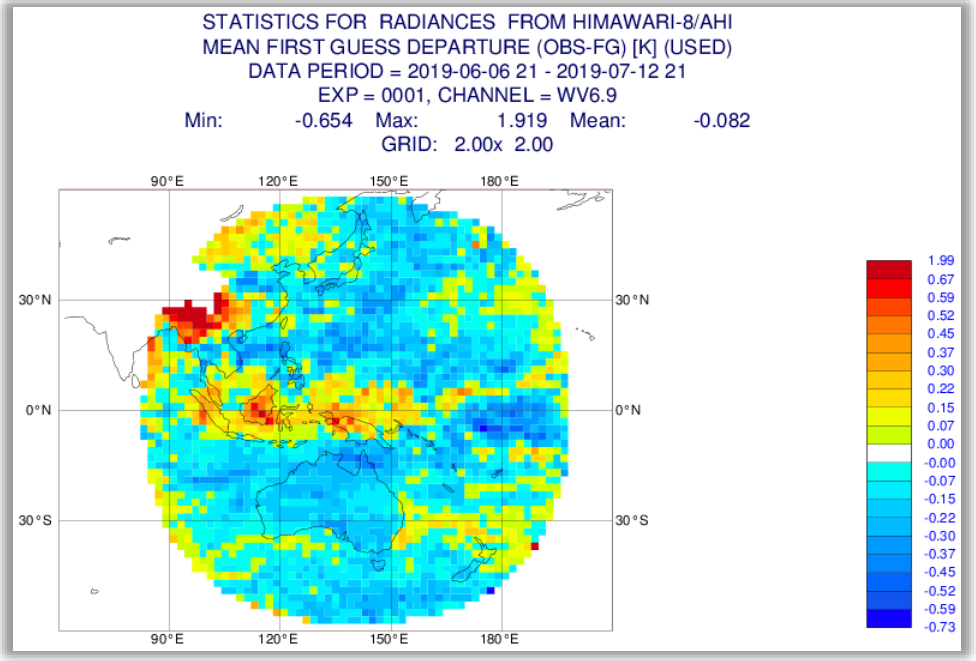
(As of May 2018)

Himawari-8 products for NWP centers

The Himawari-8 AMV & CSR products are provided to NWP centers via the WMO Global Telecommunication System (GTS).

AMV and CSR data used in ECMWF's assimilation system





ECMWF Website: https://www.ecmwf.int/en/forecasts/quality-our-forecasts/monitoring-observing-system#Satellite

Next Himawari planning

- Himawari-8/9 will complete the observation operation in 2029.
- JMA has undertaken feasibility studies of their follow-on satellites.

Vision for WIGOS 2040 (Geostationary core instruments)	**Missions (to be) implemented by satellite operators**			
	USA	**Europe**	**China**	**Korea**
Multi-spectral VIS/IR imagery with rapid repeat cycles	GOES-R series/ ABI	MTG I series [2021[2]]/ FCI	FY-4 series/ AGRI	GK-2A/AMI
IR hyperspectral sounders		MTG S series [2023[2]]/ IRS	FY-4 series/ GIIRS	
Lightning mappers	GOES-R series/ GLM	MTG I series [2021[2]]/ LI	FY-4 series/ LMI	
UV/VIS/NIR sounders	TEMPO [2022[1]]	MTG S series [2023[2]]/ UVN (Sentinel-4)		GK-2B [2020[3]]/ GEMS

[ ] indicate planned launch year based on:
[1] NASA's press release (July 22, 2019)
[2] EUMETSAT's website (as of July 2019)
[3] CGMS-47 KMA-WP-01 (May 2019)

2. Highlights of my research at CICS

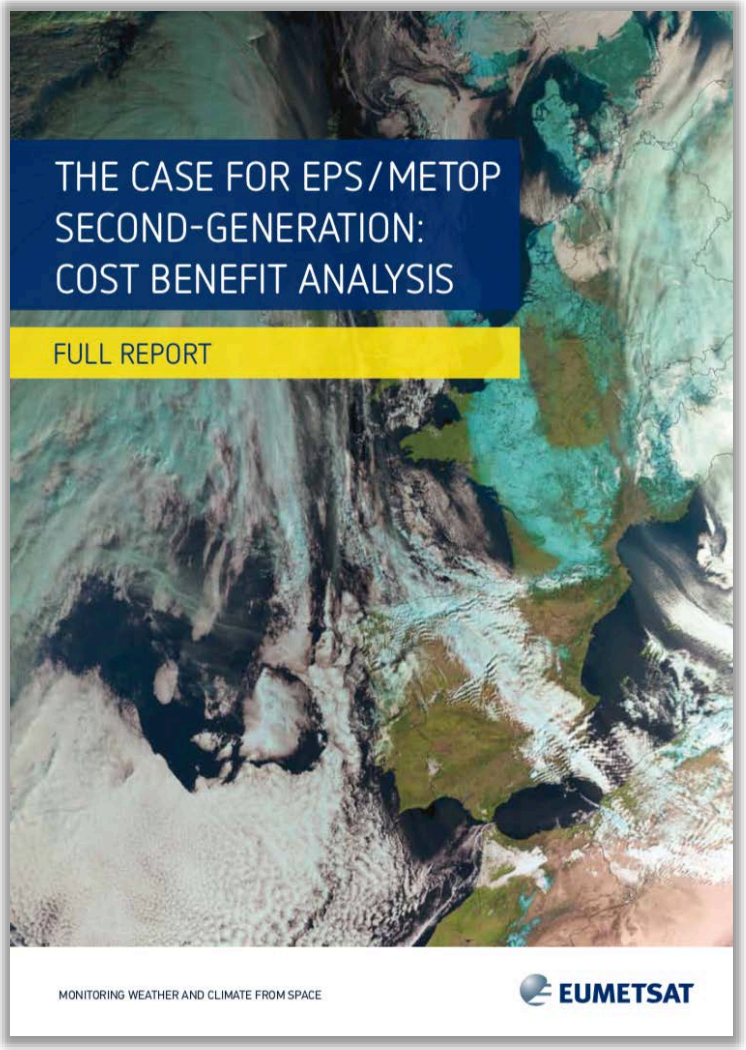
Highlights of my research at CICS

- **Study on GLM**
  - Space system & data processing (with GOES-R Data Book)
  - Product evaluation
  - Data use in NOAA
- **Study on cost benefit analysis (CBA) of weather satellites**
  - Existing Metop-SG CBA & JPSS CBA
  - Trial CBA for a hypothetical IR sounder on Himawari
- **Study on NOAA's approach for commercial satellites**
  - Commercial Weather Data Pilot (with NOAA's report to the Congress)
  - Weather Research and Forecasting Innovation Act of 2017
- **Study on NOAA's Cooperative Institutes**
  - General framework (with CI Handbook)
  - Research activities (with CICS annual report)

Metop-SG CBA

- Socio-economic benefits of **weather information** in Europe was assessed for three benefit areas:
  - Protection of Property and Infrastructure
  - Added Value to the European Economy
  - Private Use by European citizens
- Socio-economic benefits of **Metop-SG** was estimated by prorating the weather information benefits based on Metop contribution to forecast skill

Value of weather info. X **Contribution to forecast** = **Value of Metop-SG**



EUMETSAT (2014)

Metop-SG benefit assessment

BENEFIT AREA	MINIMUM	LIKELY
Protection of Property and Infrastructure	€1.3 billion/year	€5.5 billion/year
Added Value to the European Economy	€10 billion/year	€41 billion/year
Private Use by European Citizens	€4 billion/y[illegible]	[illegible]
TOTAL (rounded)	**€15 billion[illegible]**	[illegible]

TABLE 1: SUMMARY OF ESTIMATED ANNUAL BENEFITS (

Annual socio-economic benefits of weather information mainly based on Hallegatte, S. (2012) etc

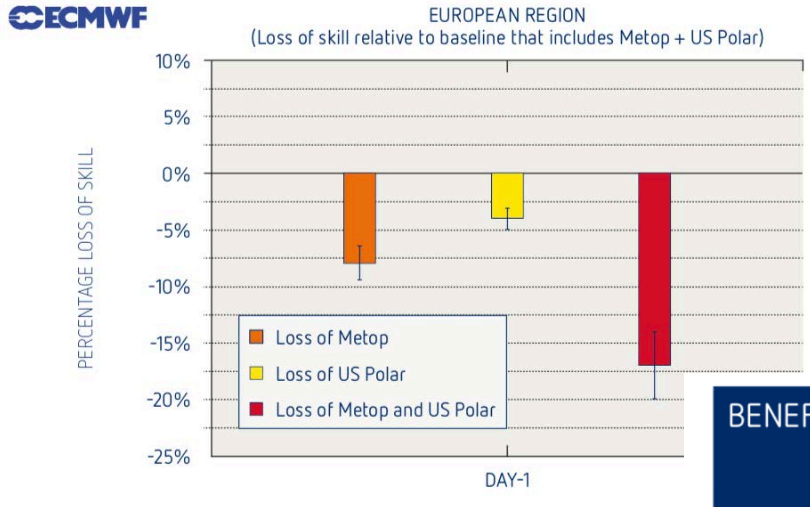


FIGURE 8: IMPACT OF POLAR OBSERVATIONS ON DAY-1 FORECAST ACCURACY

Metop contribution to forecast skill 8 % based on ECMWF's data denial experiments

Metop-SG benefits for 20 years

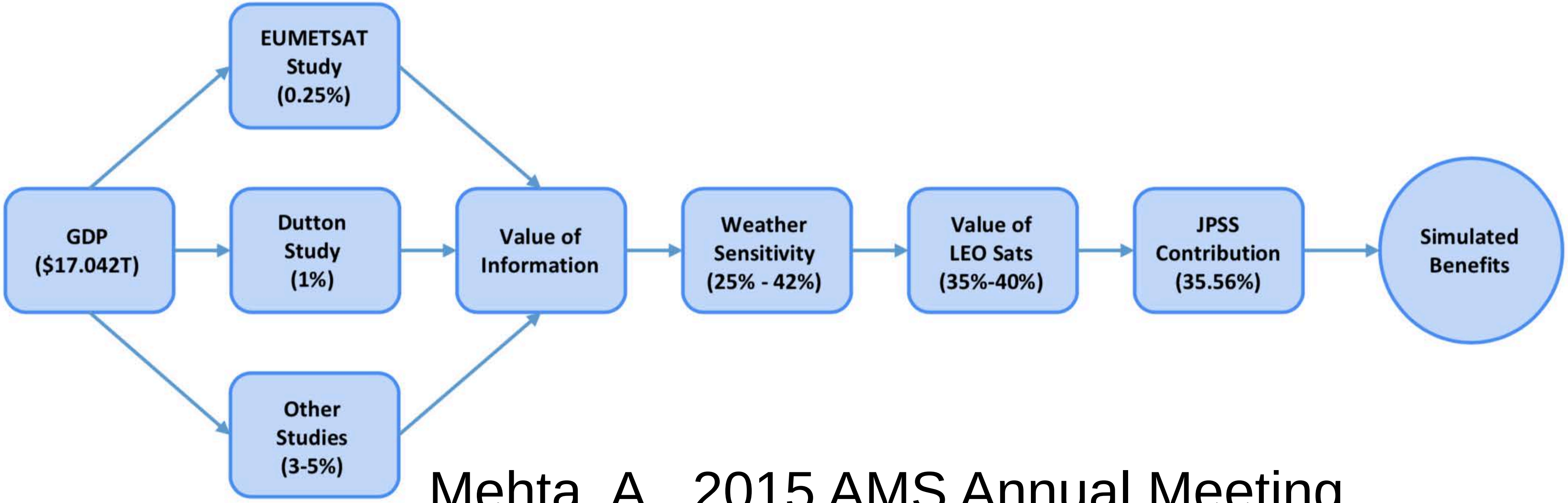
BENEFIT AREAS	SOCIO-ECONOMIC BENEFIT[35] (over 20 years of EPS/Metop-SG)	
	MINIMUM	LIKELY
Protection of Property and Infrastructure	€1.5 billion	€6.0 billion
Added Value to the European Economy	€11.3 billion	€45.2 billion
Private Use by European citizens[36]	€3.0 billion	€11.5 billion
TOTAL (rounded)	**€16 billion**	**€63 billion**

TABLE 2: ESTIMATED SOCIO-ECONOMIC BENEFITS OF EPS/METOP-SG OBSERVATIONS DUE TO THEIR POSITIVE IMPACT ON FORECASTING

B/C = 5 ~ 20
where C = ~€3 billion

JPSS benefit assessment

- Benefit of weather information was assessed by top down analysis using GDP and assumed parameters
- JPSS contribution to weather forecasts assessed by the WMO OSCAR database



Mehta, A., 2015 AMS Annual Meeting

CBA for a “hypothetical” IR sounder on Himawari

- Socio-economic **benefits of weather information in Japan** was estimated **by scaling those of Europe**:
  - Protection of Property and Infrastructure -> proportional to GDP
  - Added Value to the European Economy -> proportional to GDP
  - Private Use by European citizens -> proportional to # of households

- B/C is derived as a function of a hypothetical IR sounder contribution to forecast skill.
  - Life time and life cycle cost of the hypothetical IR sounder were assumed to be the same with the Himawari-8/9 system

Benefit analysis in Japan

- Annual benefit of weather information

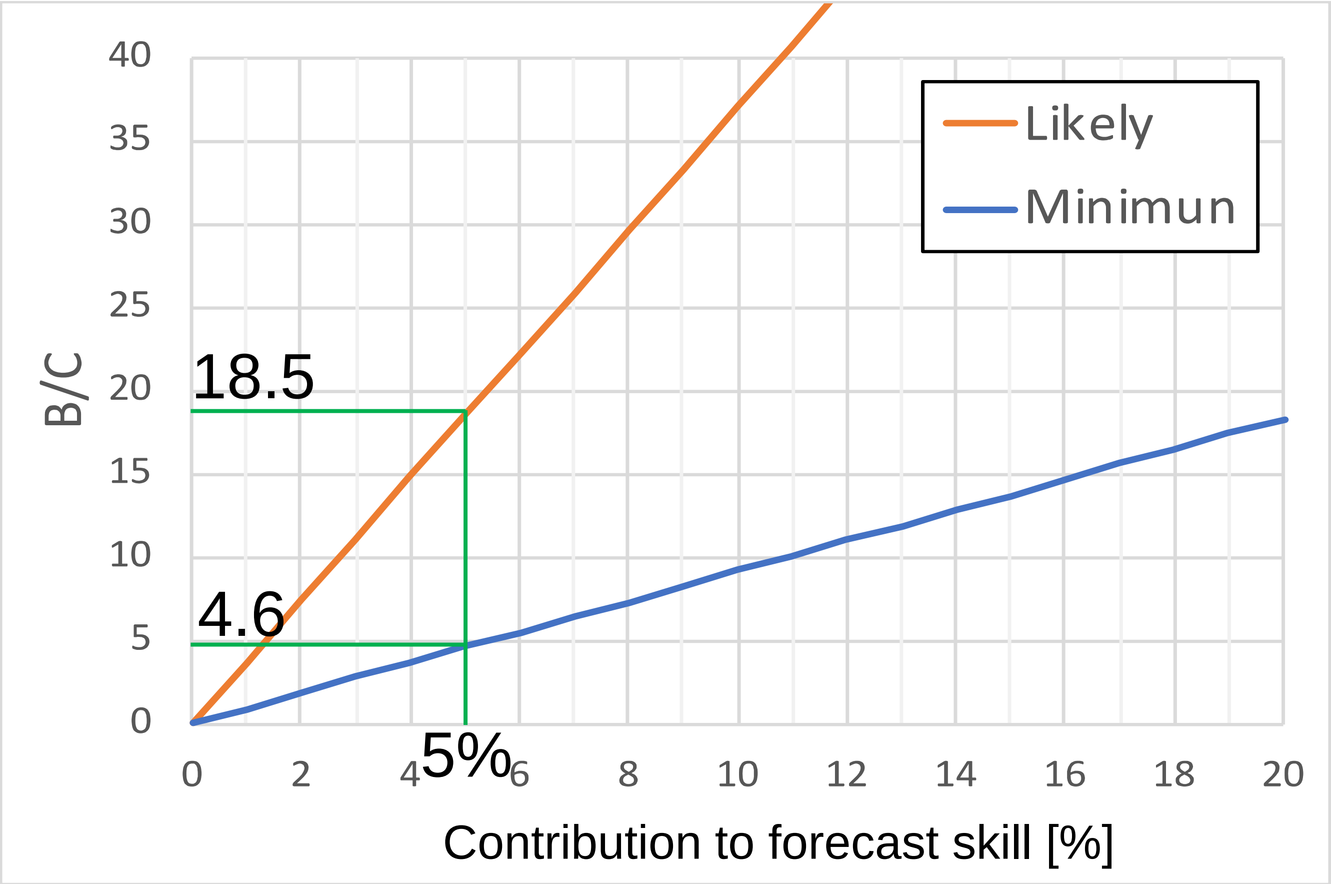
Benefit area		Minimum	Likely	Derivation
Protection of Property and Infrastructure	B_a	58.2	246.4	=[Value in EU27]x[GDP ratio JP/EU27]
Added Value to the European Economy	B_b	448.0	1836.7	=[Value in EU27]x[GDP ratio JP/EU27]
Private Use by European citizens	B_c	133.6	501.1	=[Value in EU27]x[# household ratio JP/EU27]x[exchange ratio ¥/€]
Total		**639**	**2584**	Unit: billion JPY/Year

- Benefit of the hypothetical sounder for a 15-year mission life cycle

$$= f \sum_{t=1}^{15} \frac{\{\boldsymbol{B_a}(1+g)^{t-1} + \boldsymbol{B_b}(1+g)^{t-1} + \boldsymbol{B_c}\}}{(1+r)^{t-1}}$$

f: contribution to forecast skill
g: Annual GDP increase rate (1%)
r: Annual discount rate (4%)

CBA result of the hypothetical IR sounder



- B/C = 4.6~18.5, for a contribution of 5%
- A reasonable contribution can be determined by OSSE

For refining this CBA

- More realistic benefit assessment
  - Benefits of weather information must be dependent on countries
  - ➢ Benefits in Japan would not be derived correctly by scaling European result. (e.g. Typhoons need to be considered for Japan)
  - ➢ Bottom-up approach is required

  - Contribution to forecast skill is determined by numerical experiments (e.g. OSSE)

- More realistic cost assessment

3. GLM product evaluation

This work was conducted in coordination with the GLM science team at CICS led by Dr. Scott Rudlosky

Geostationary Lightning Mapper (GLM)

- Optical lightning sensor aboard GOES-R Serie satellites
- Continuous & hemispherical coverage (up to 54 deg N/S)
- Detection of both intra-cloud (IC) and cloud-to-ground (CG) lightning
    - No discrimination between IC & CG

GLM sensor design parameters	
# of CCD pixels	1372 x 1300
Frame rate	2 ms
Ground sample distance	8 km (Nadir) 14 km (FOV edge)
Wavelength	777.4 nm

Image: GOES-R Series Data Book

GLM Level 2 product

- **Event:** Pixel-level detection exceeding the threshold in one frame
- **Group:** 1 or more events in adjacent pixels in one frame
- **Flash:** 1 or more groups separated by less than 330 ms and 16.5 km

GLM Level 2 product maturity		
Status	GOES-16	GOES-17
Launch	Nov 19, 2016	Mar 1, 2018
Beta	June 9, 2017	Oct 3, 2018
Provisional	Jan 19, 2018	Dec 20, 2018
Full	Nov 1, 2018	

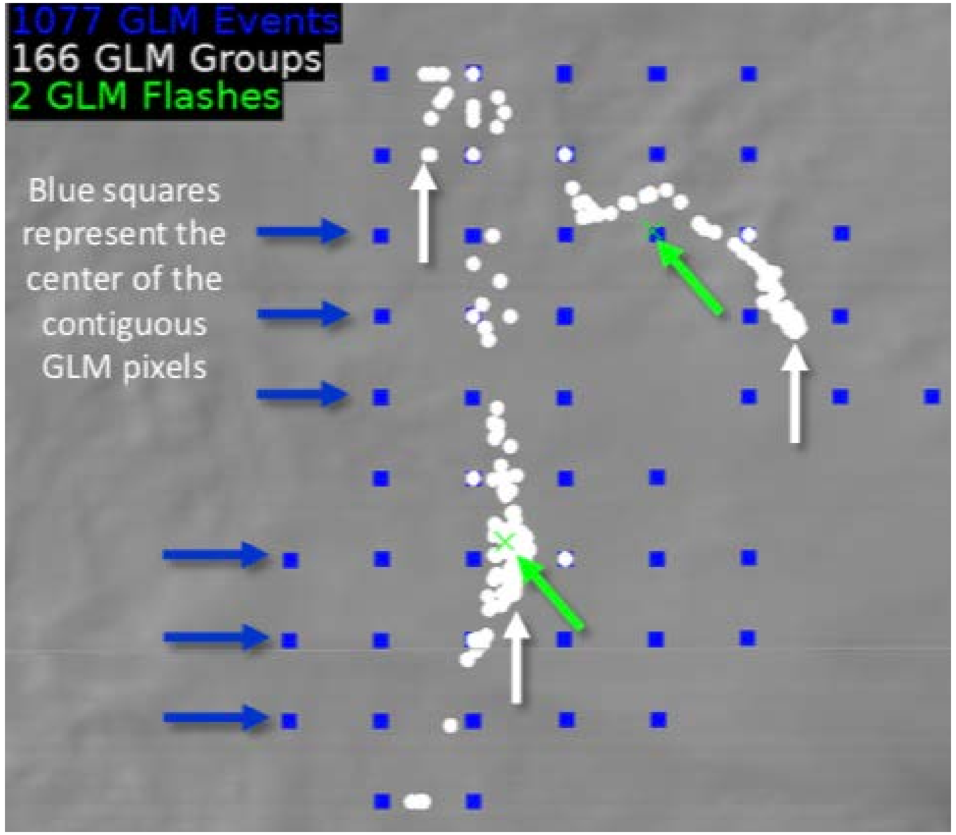


Image: GLM Definitions and Detection Method Quick Guide

GLM L2 product evaluation

A: Flash geographical distribution

B: Flash detection efficiency

- B-1: GLM vs GLD360
- B-2: GLM vs ENTLN

C: Group timing & location

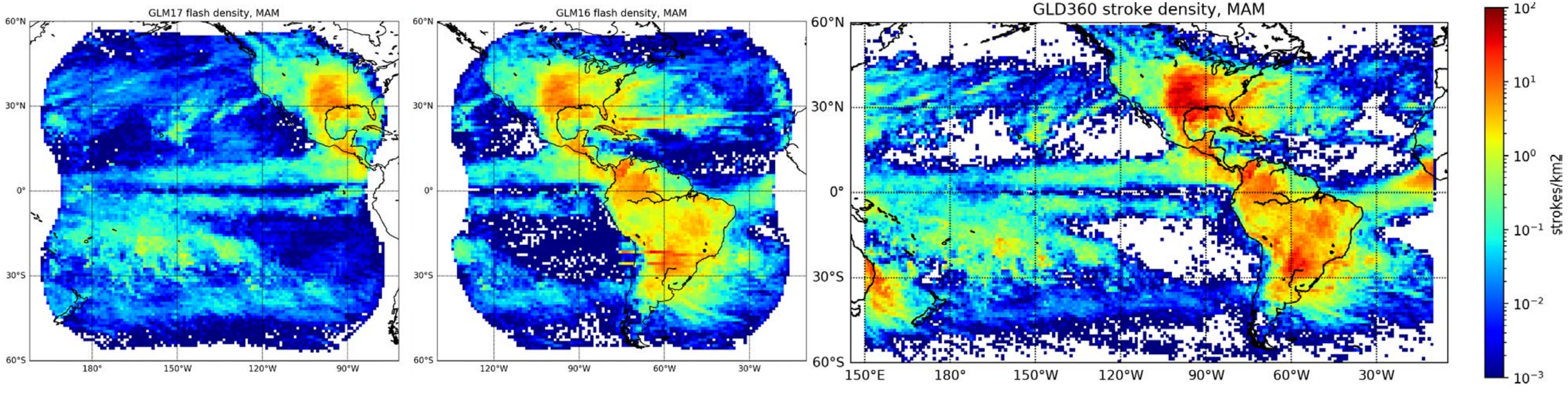
A: Flash geographical distribution

Flash density maps (MAM 2019)

GLM17 flashes

GLM16 flashes

GLD360 strokes

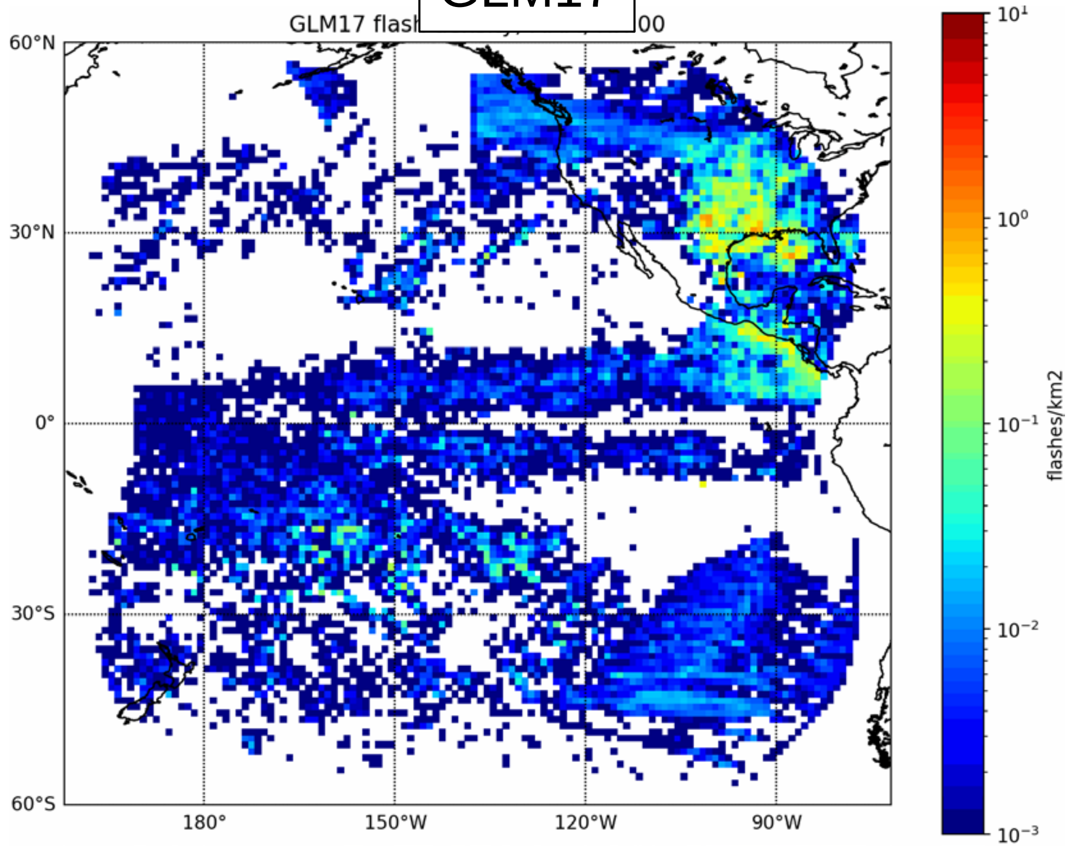


- Generally consistent with each other
- GLM false detections (e.g. GLM16's Bahama bars)

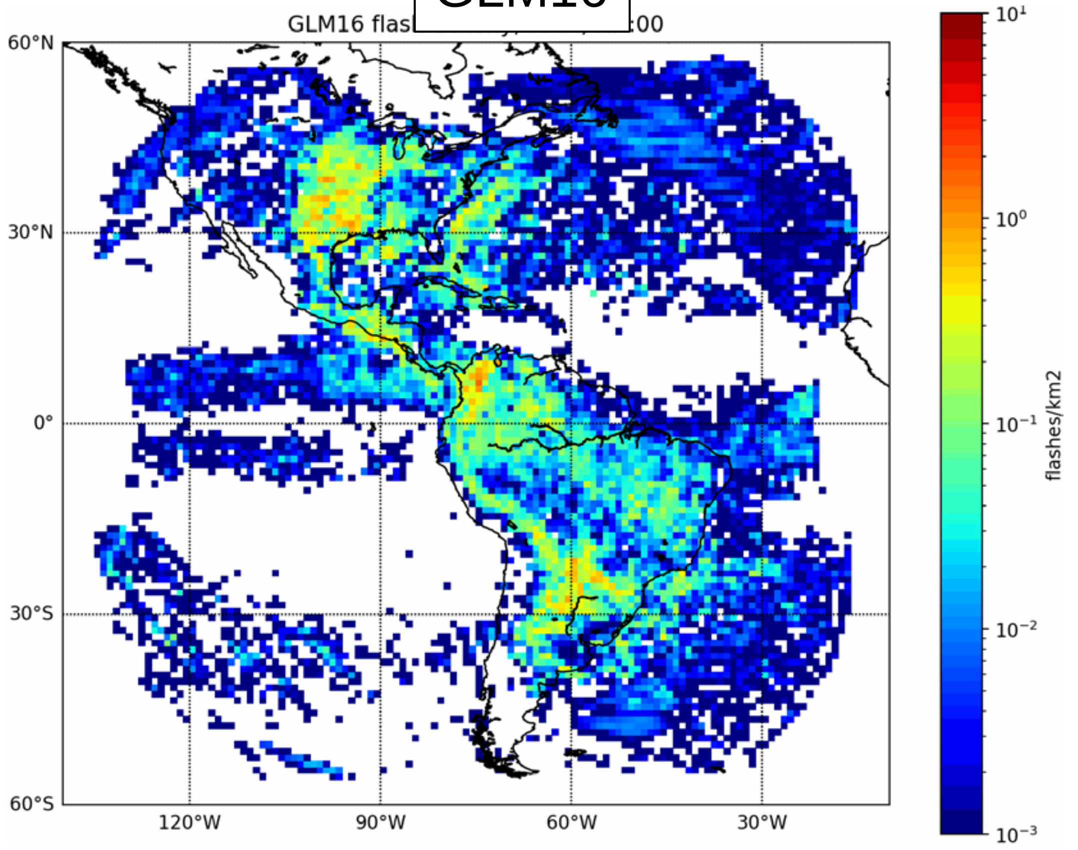
GLM false flashes (MAM 2019)

Flash density hourly variation in nadir local time

GLM17



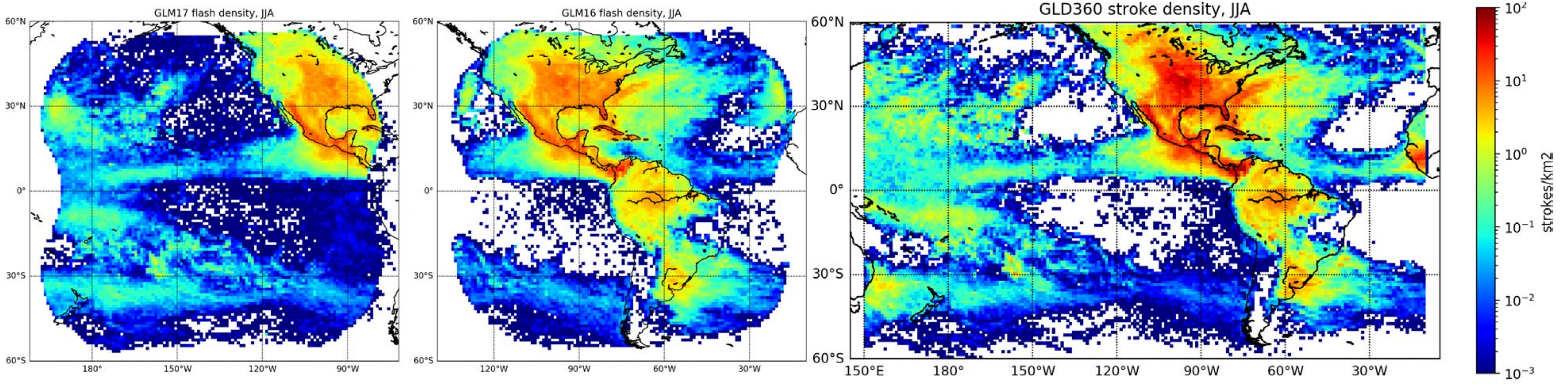
GLM16



- Bahama bars (daytime), Solar intrusions (midnight), Solar glints (morning/evening)
- Westward moving daytime artifacts (GLM17 > GLM16)

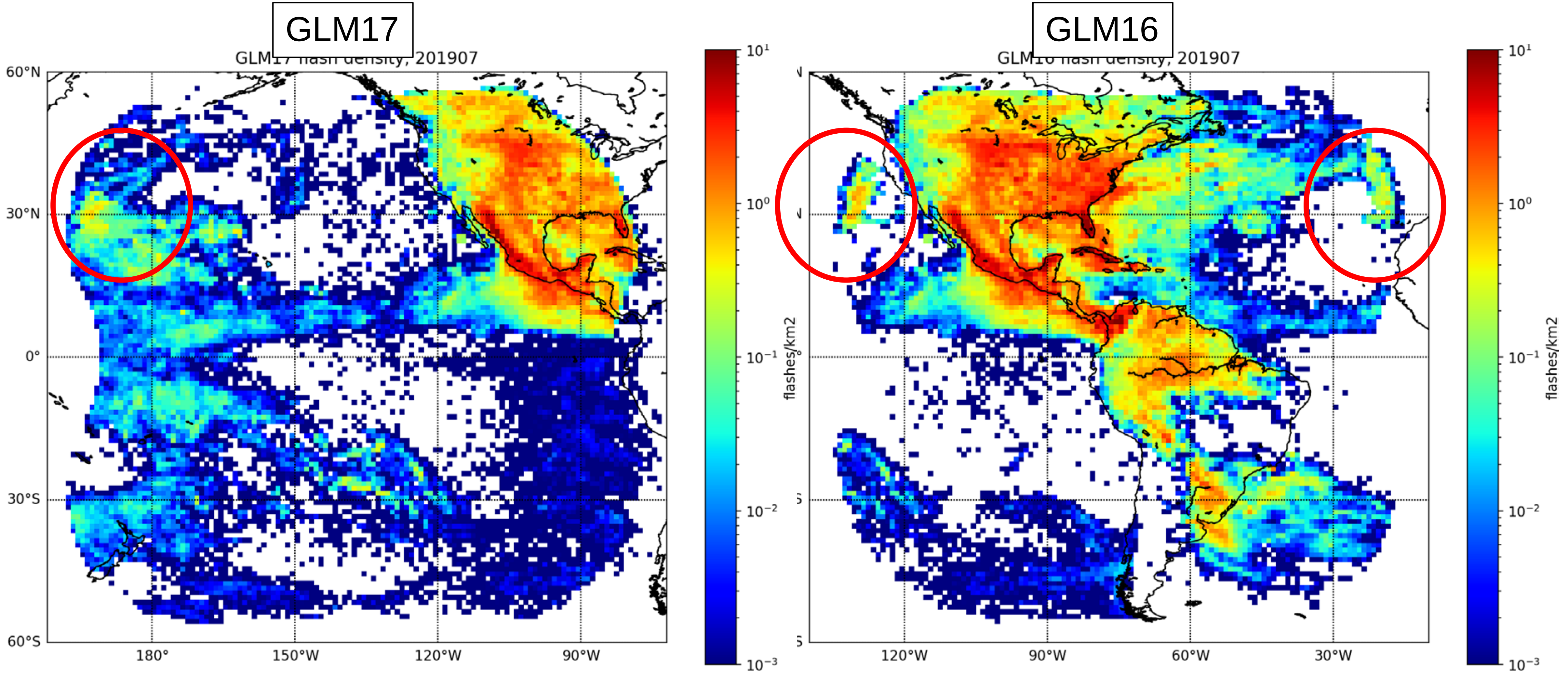
Flash density maps (JJA 2019)

GLM17 flashes | GLM16 flashes | GLD360 strokes



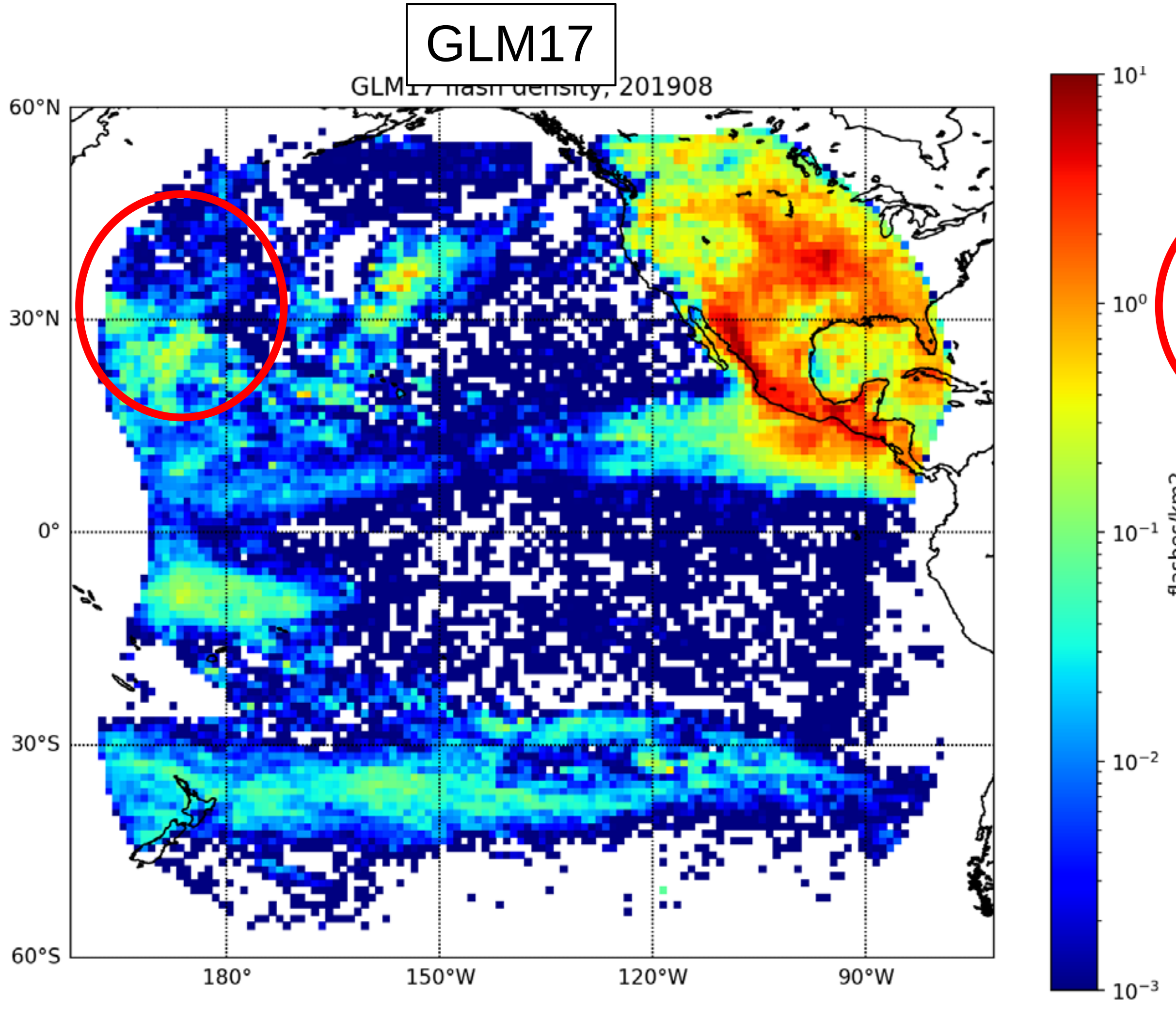
- False detections reduced by updating ground processing for G16 & G17
  - Contrast Leakage Algorithm activated (Apr. 30) to reduce jitter noise
  - 2nd-level Threshold Algorithm updated (Apr. 30) to reduce Bahama bars
  - Blooming Filter activated (Jul 25) to reduce solar glints and intrusions

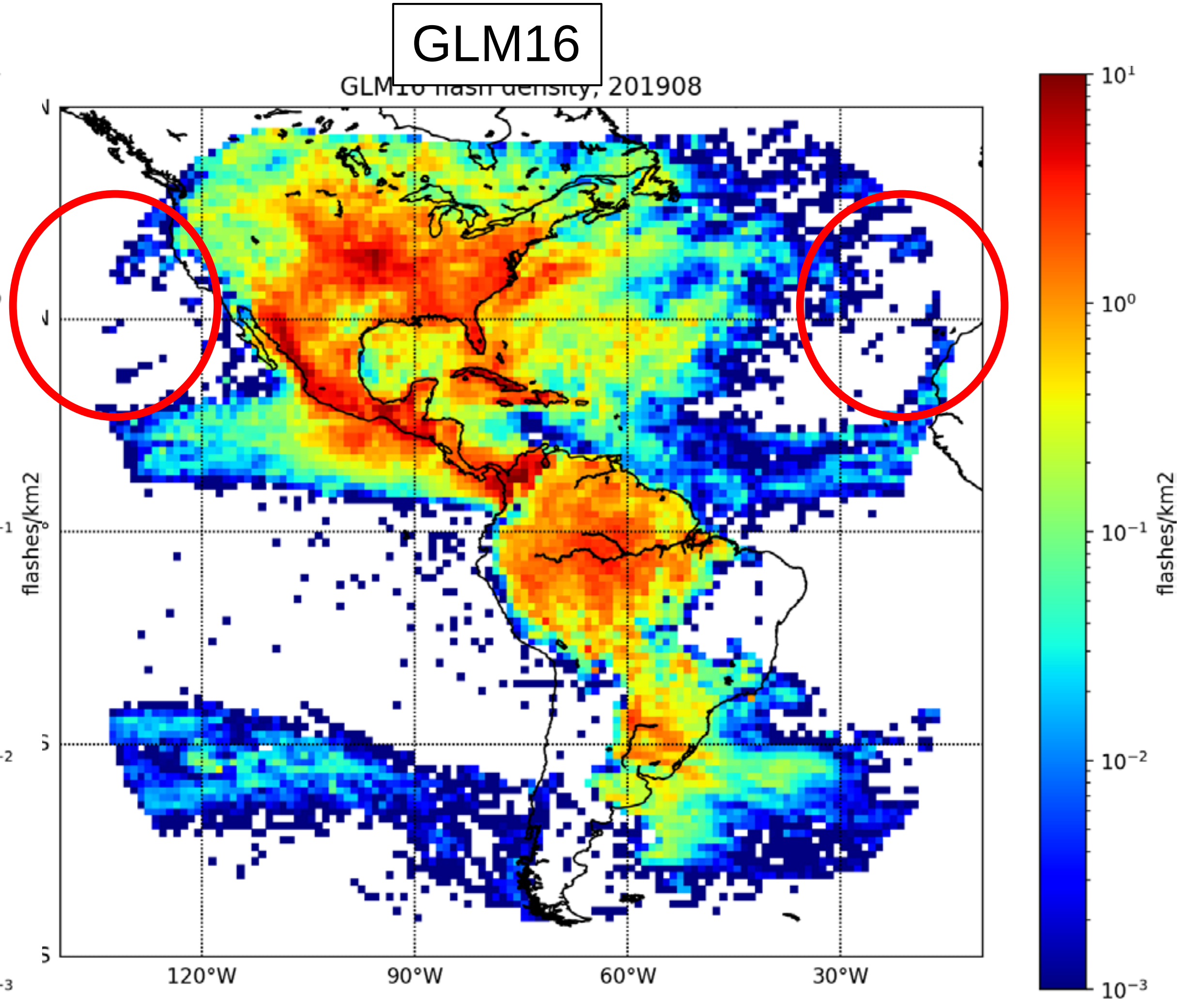
Before Blooming Filter activated (Jul. 2019)



Solar glints are apparent

After Blooming Filter activated (Aug. 2019)





Solar glints are mitigated by Blooming Filter

B: Flash detection efficiency

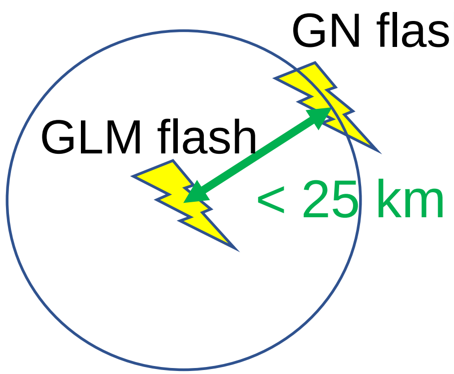
Flash detection efficiency

- Flash detection efficiency (DE) indicates the ability to detect flashes
- GLM DE relative to a ground-based network (GN)

$$\text{GLM DE} = \frac{\text{\# GN flashes detected by GLM}}{\text{Total \# GN flashes}}$$

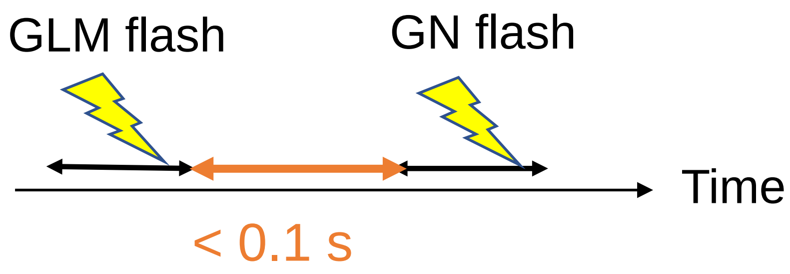
- Detection criteria: flash separation less than 25 km and 0.1 s.

Spatial separation



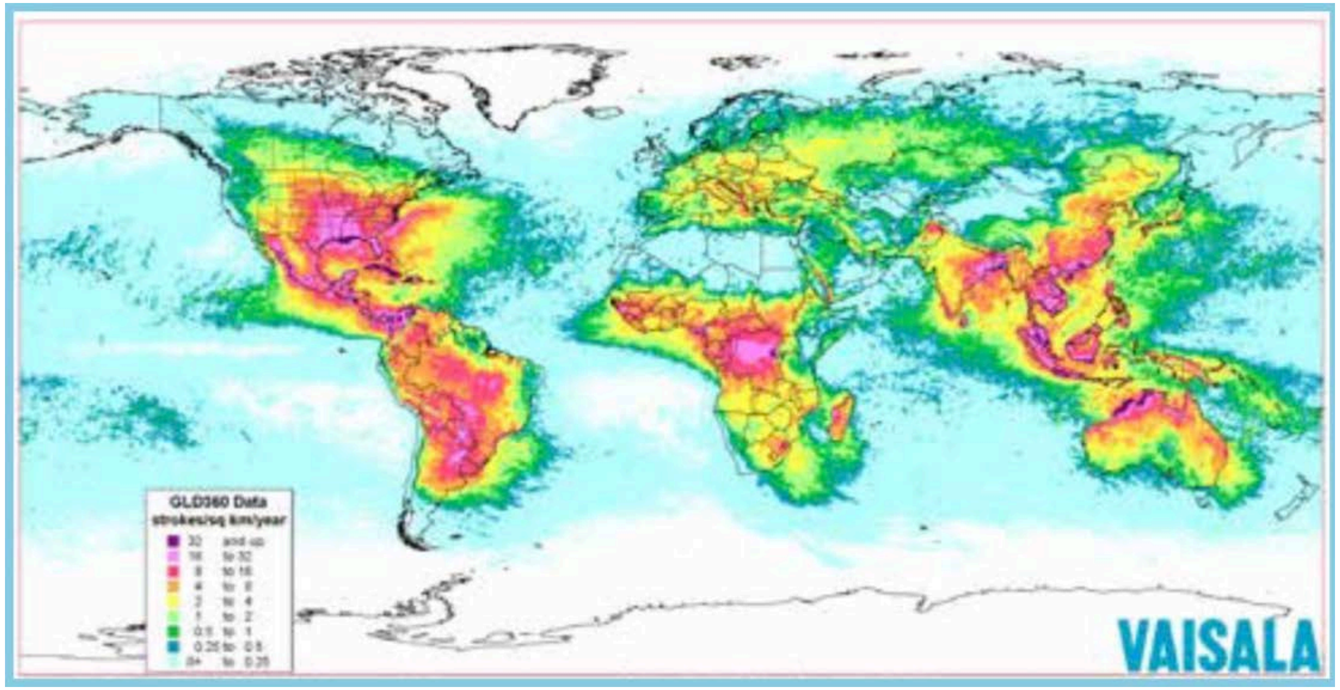
AND

Temporal separation



B-1: GLM DE relative to GLD360

- GLM16 & GLM17 DE for overall FOV were examined using GLD360
- GLD360 is designed to globally detect >80 % CG with VLF sensors



GLD360 stroke density for May 2011 to May 2015 (Vaisala, 2015)

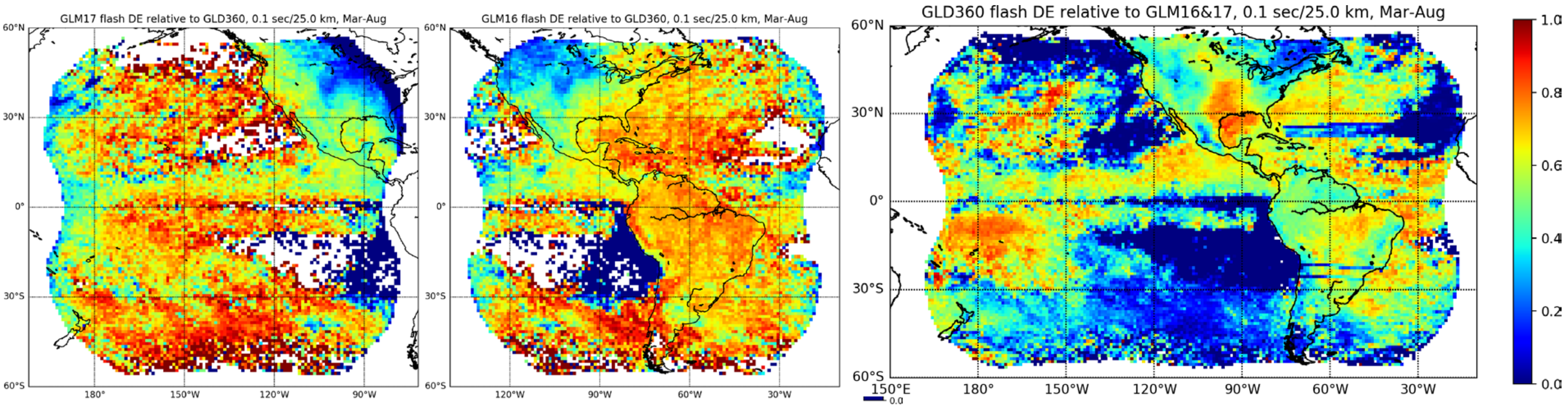
Acknowledgement:
GLD360 used in this study were provided by Vaisala.

GLM DE relative to GLD360 (Mar-Aug, 2019)

GLM17 DE

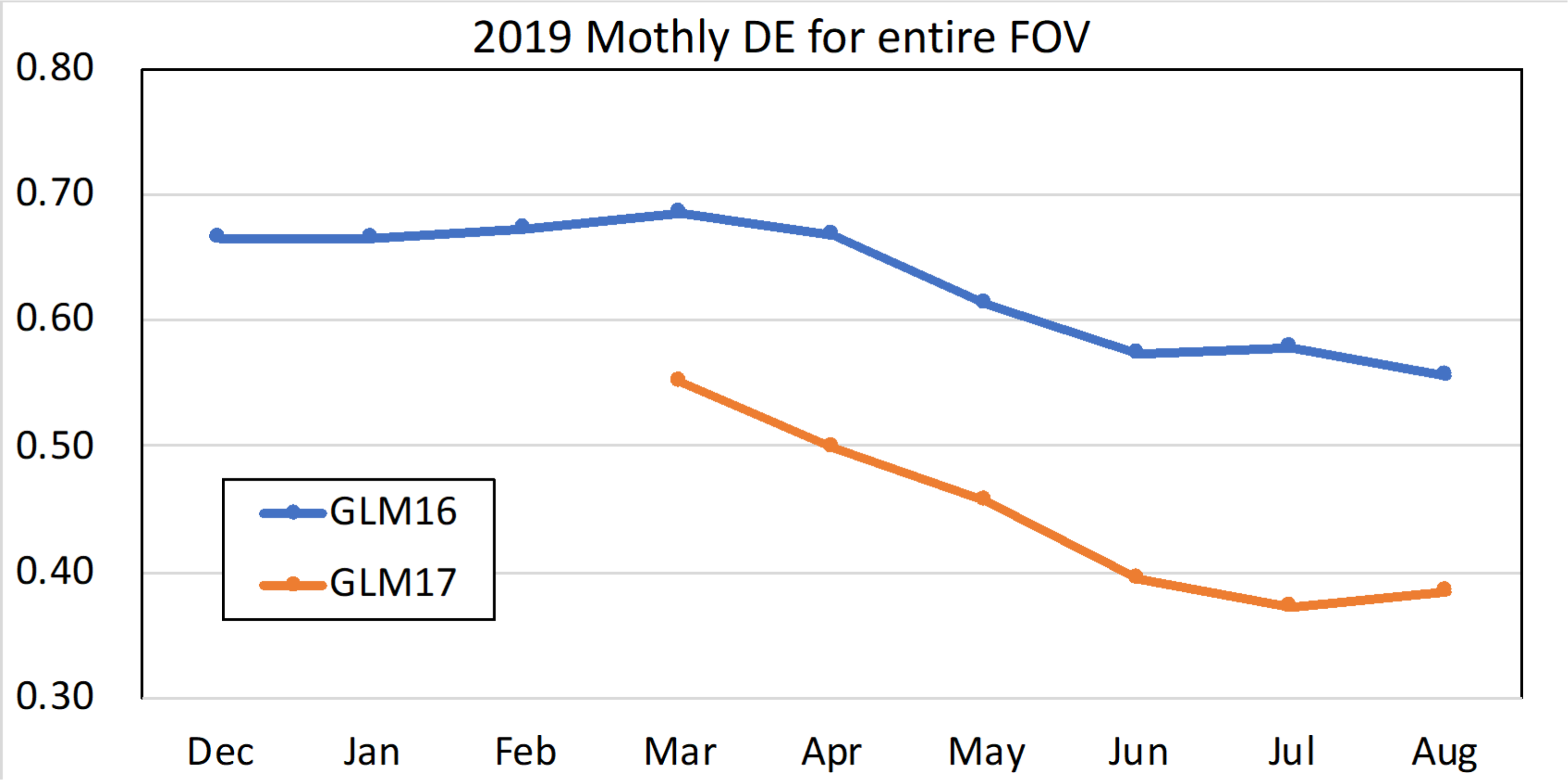
GLM16 DE

GLD360 DE



- GLM DEs are maximized over the oceans and the South America
- GLM DE depression over high-boresight-angle CONUS (GLM16: NW, GLM17: NE)
- GLD360 pixels with DE < ~30% generally coincide with GLM false detections

DE Monthly variation



- GLM16/17 DE decreases in spring & summer, when lightning activity increases over CONUS.
- Note: DE is dependent on matching criteria (larger criteria, larger DE)
  - Need to focus on variance/difference rather than absolute values

B-2: GLM DE relative to ENTLN

- GLM16 DE variance was examined using ENTLN flashes.
  - IC/CG difference & diurnal variation
- ENTLN is
  - Earth Networks Total Lightning Network
  - Designed to detect both IC & CG with wideband (1Hz to 12MHz) sensors
  - High IC detection efficiency over CONUS.

Acknowledgement:
ENTLN data used in this study were provided by Earth Networks, Inc.

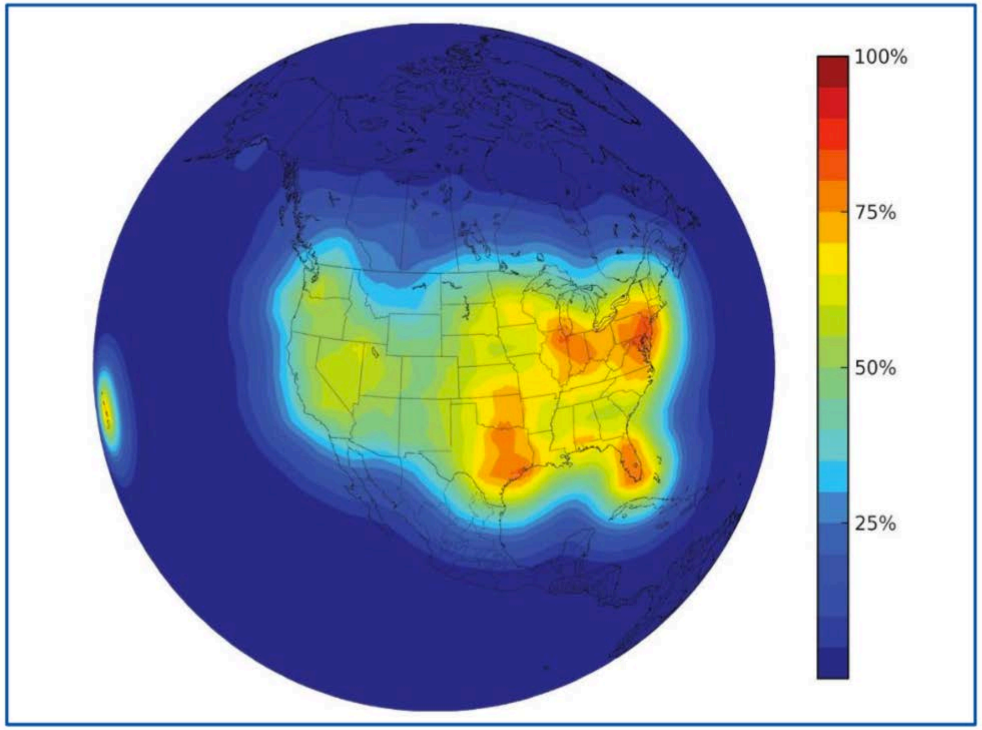
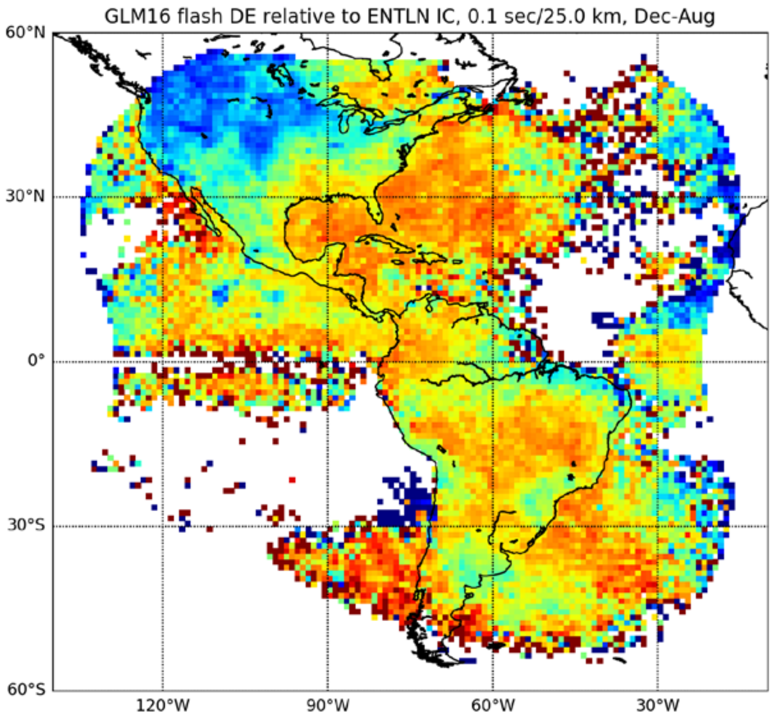


Figure 3: Estimated IC detection efficiency map for ENTLN in U.S.

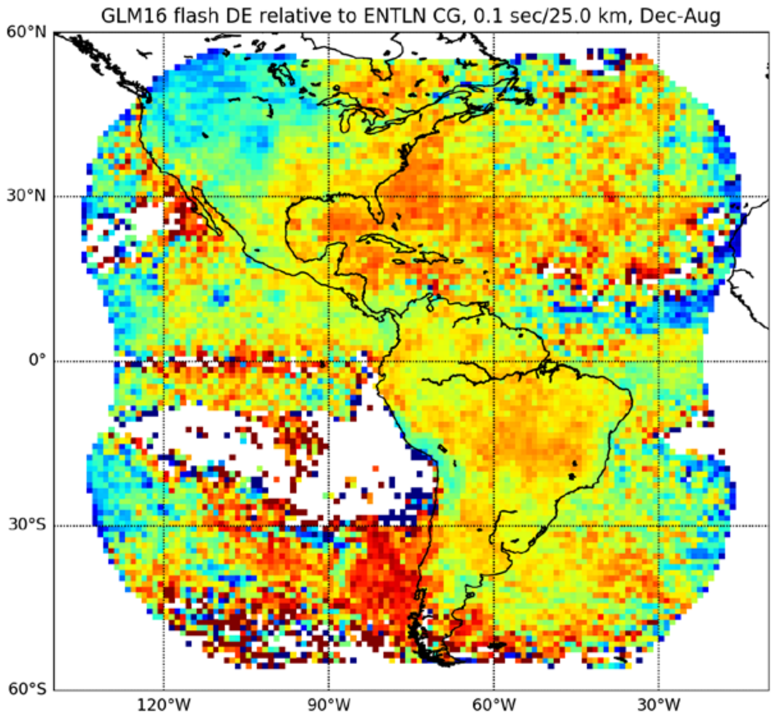
Estimated ENTLN IC DE (Liu and Heckman, 2012)

GLM16 DE for ENTLN IC & CG (Dec-Aug, 2019)

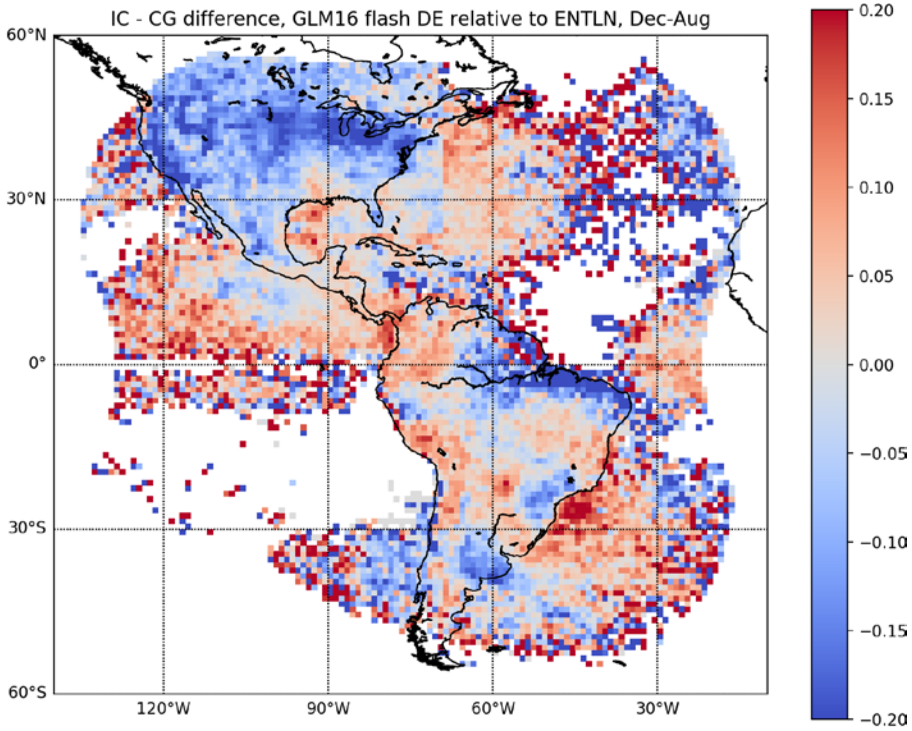
GLM DE for IC (DE_{IC})



GLM DE for CG (DE_{CG})

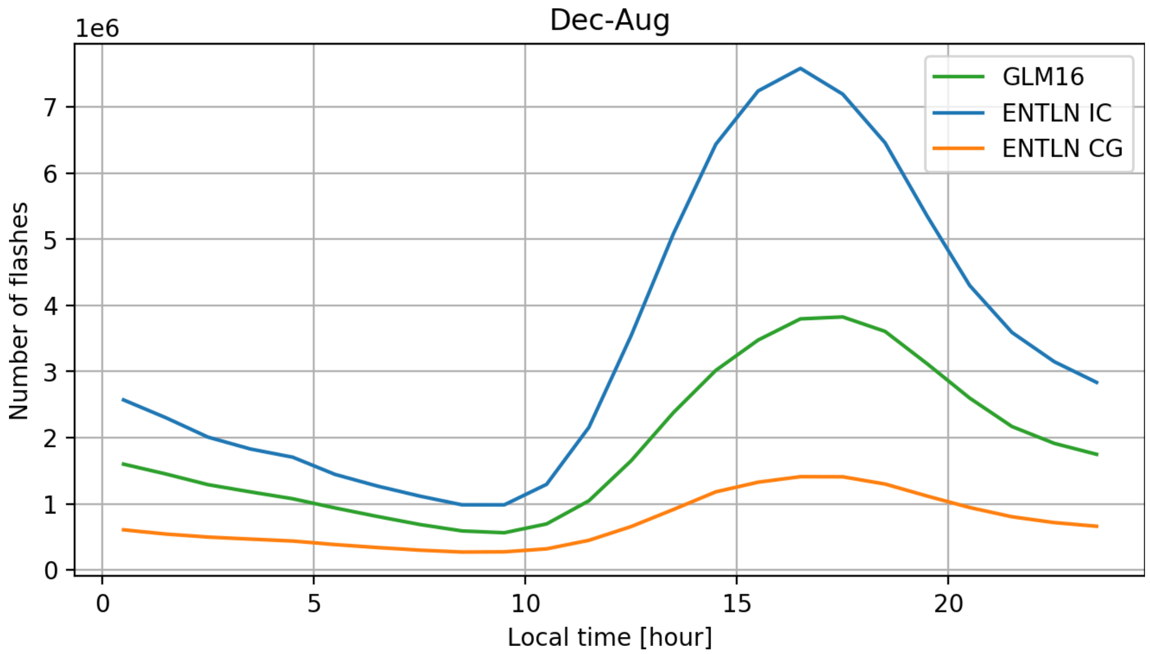


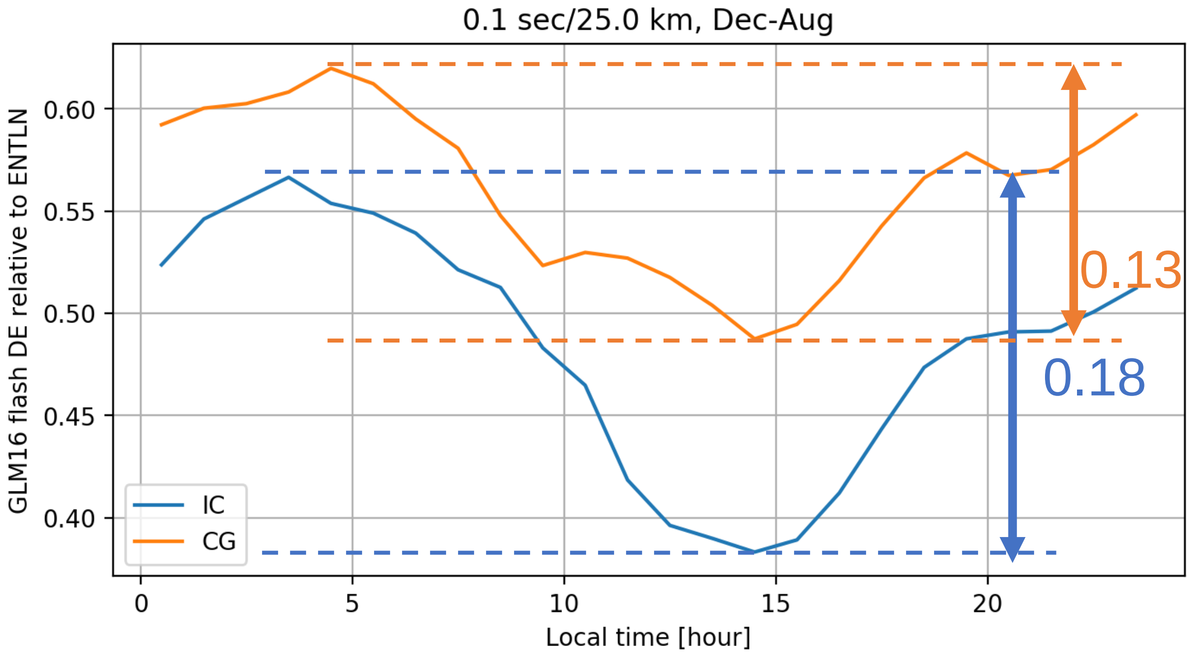
DE_{IC} - DE_{CG}



- DE depression over NW CONUS is more clear for IC
- DE_{IC} < DE_{CG} over CONUS

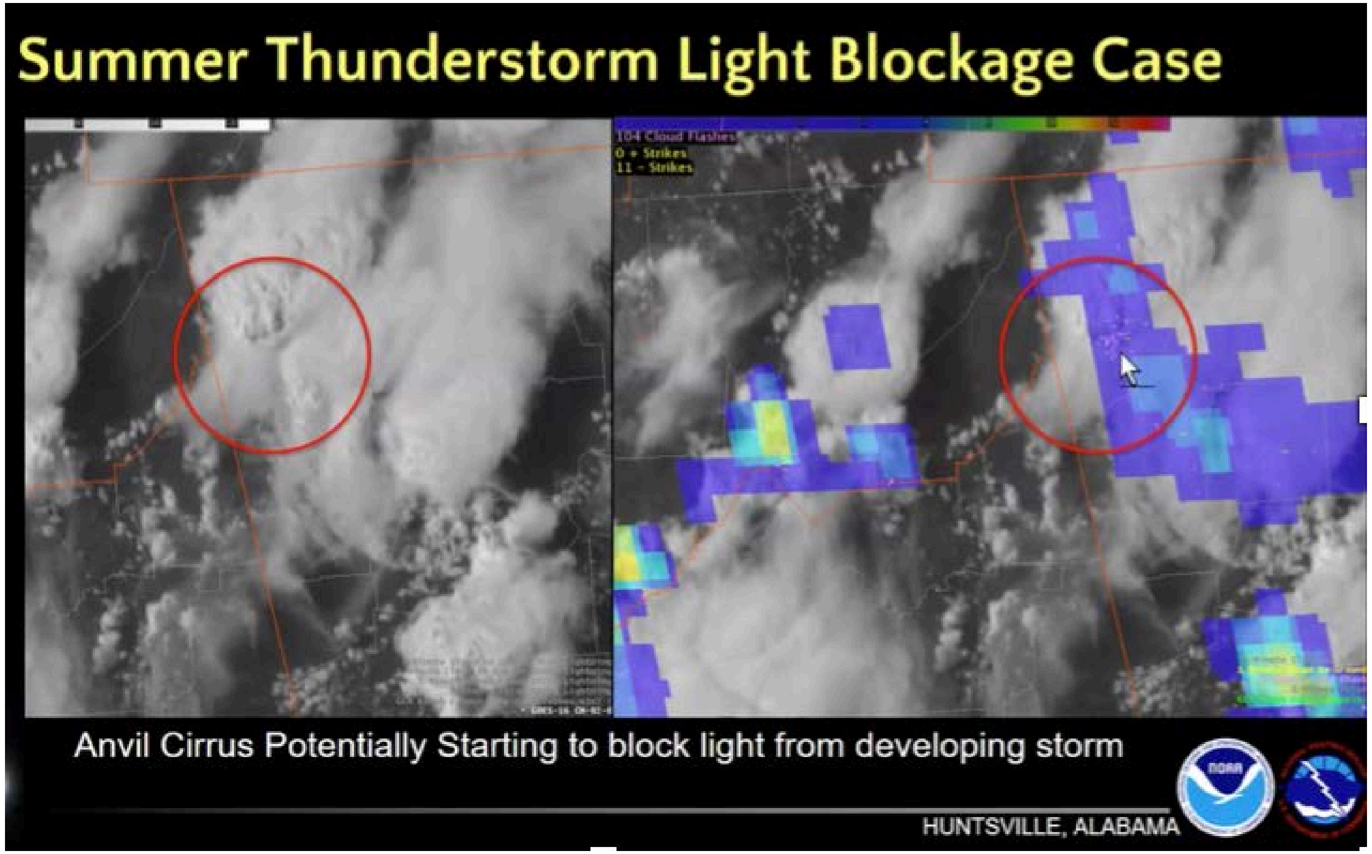
Diurnal variation over CONUS





- GLM and ENTLN flashes are maximized in the late afternoon (17-18 local time), associated with day-time thermal convections.
- GLM DE decreases during the daytime
  - Peak-to-peak diurnal variation of GLM DE is larger for IC (0.18) than CG (0.13)

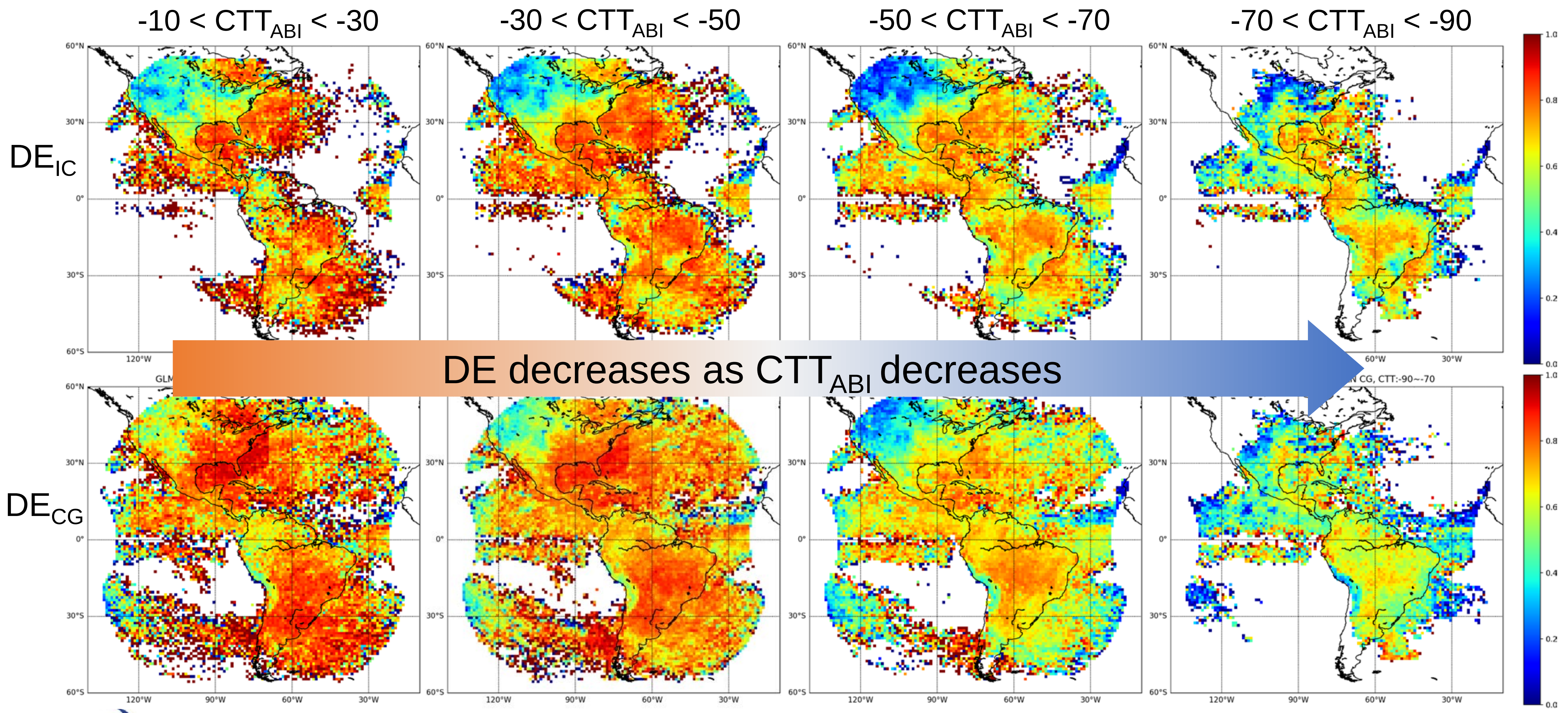
Cloud light blockage effect



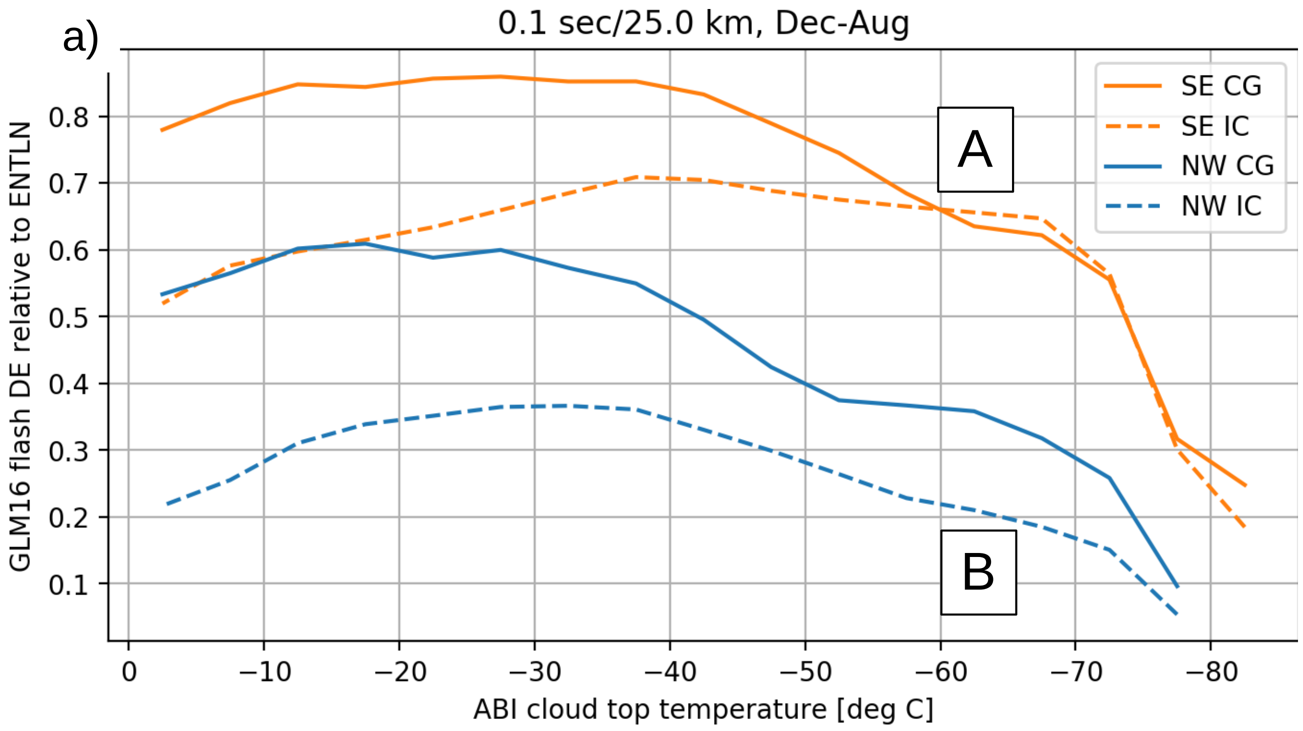
Dr. Stano's report at the 2019 AMS annual meeting:
https://ams.confex.com/ams/2019Annual/meetingapp.cgi/Person/88040

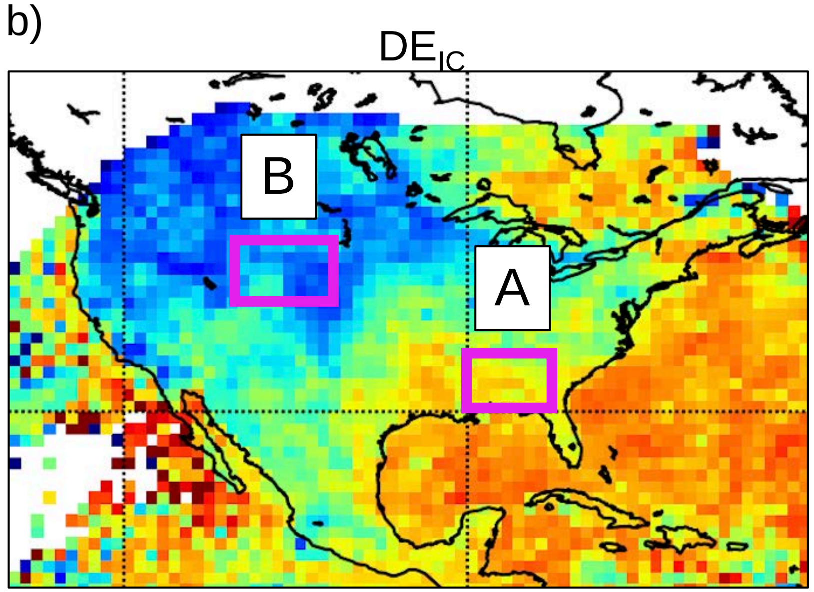
- GLM's flash underestimation due to cloud light blockage was reported in evaluation efforts.
- GLM DE dependence on cloud development was examined using the ABI cloud top temperature product (CTT_{ABI}).

Dependence on cloud top temperature



Local analysis over CONUS

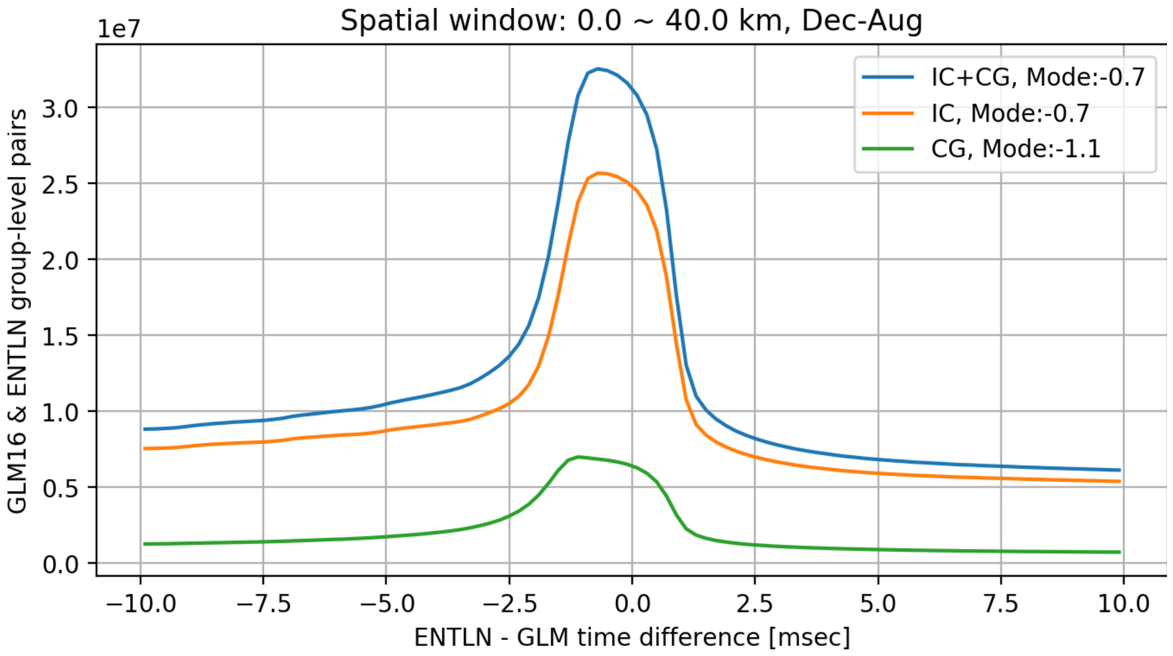




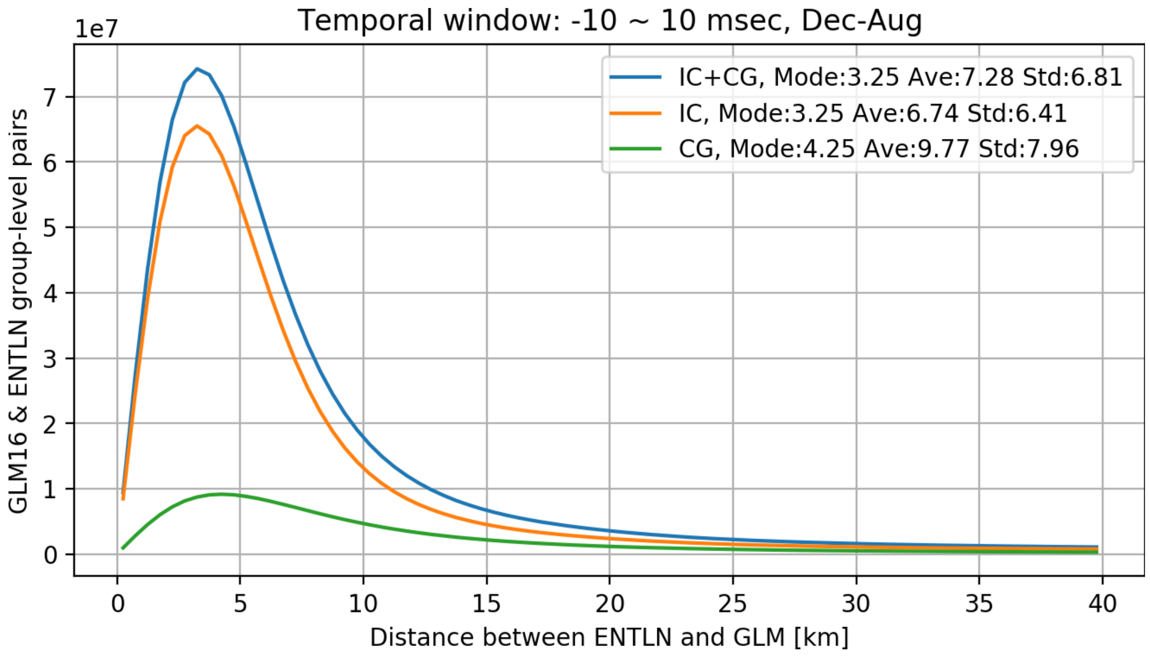
- GLM DE decreases as CTT_{ABI} decreases to ~0.2 (A) & ~0.1 (B)
- DE difference between IC and CG becomes small as CTT_{ABI} decreases

C: Group timing & geolocation

Group timing and geolocation accuracy



ENTLN - GLM timing difference [ms]

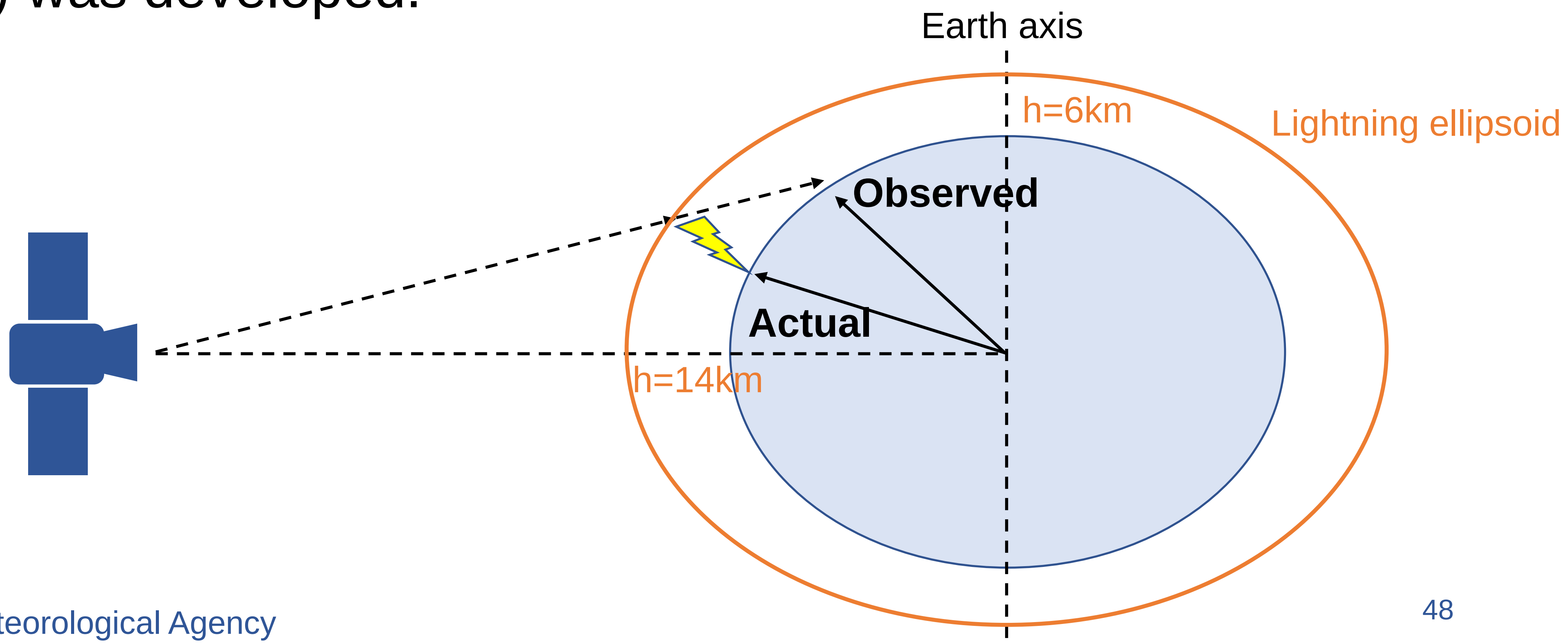


Geolocation difference [km]

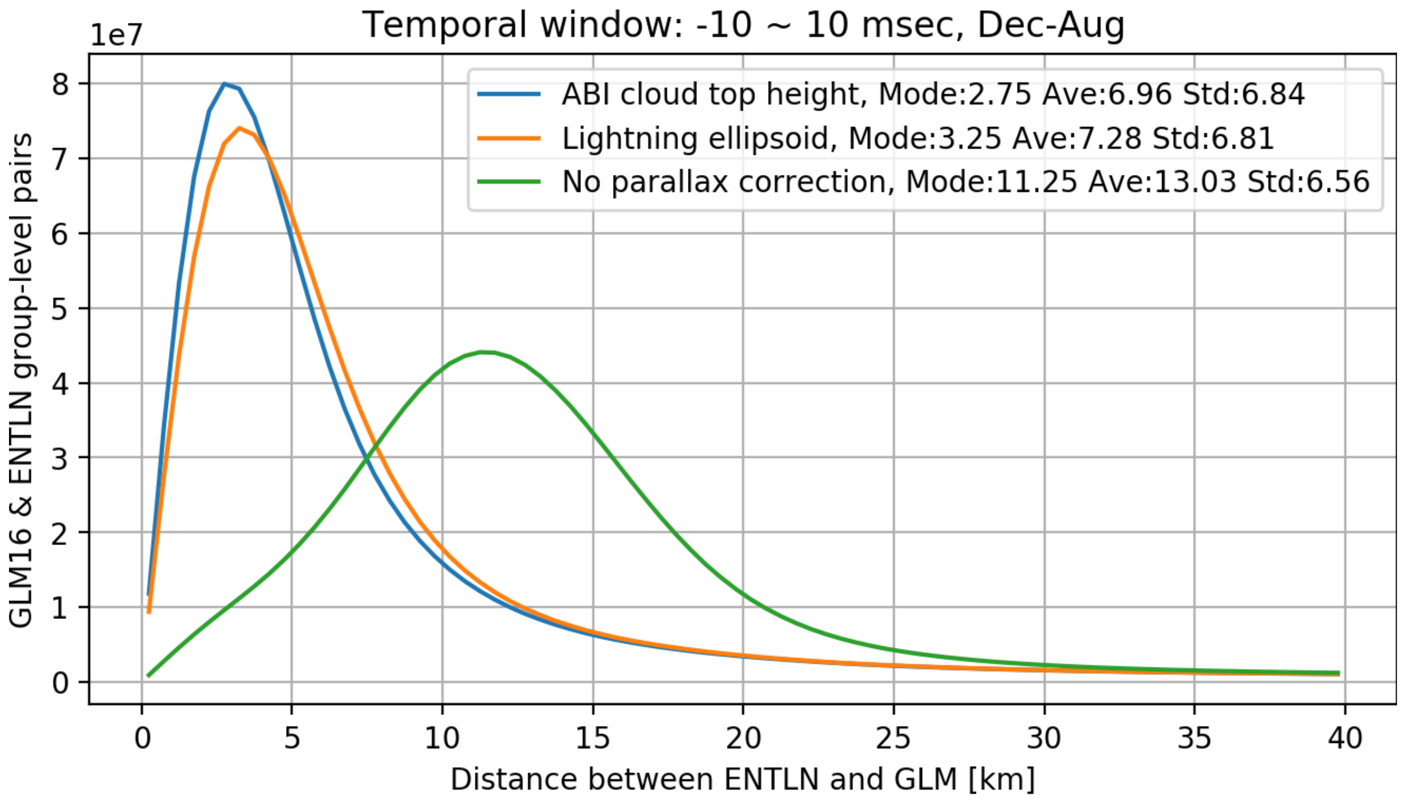
- Peak timing difference (-0.7 ms) is less than the GLM flame rate (2.0 ms).
- Peak distance (3.25 km) is less than the GLM ground sample distance (8~14 km).

New parallax correction

- Parallax in the GLM L2 product is corrected by ground processing using a static height model (lightning ellipsoid).
- A new correction method using the ABI cloud top height product (CTH_{ABI}) was developed.



Parallax correction by ABI cloud top height

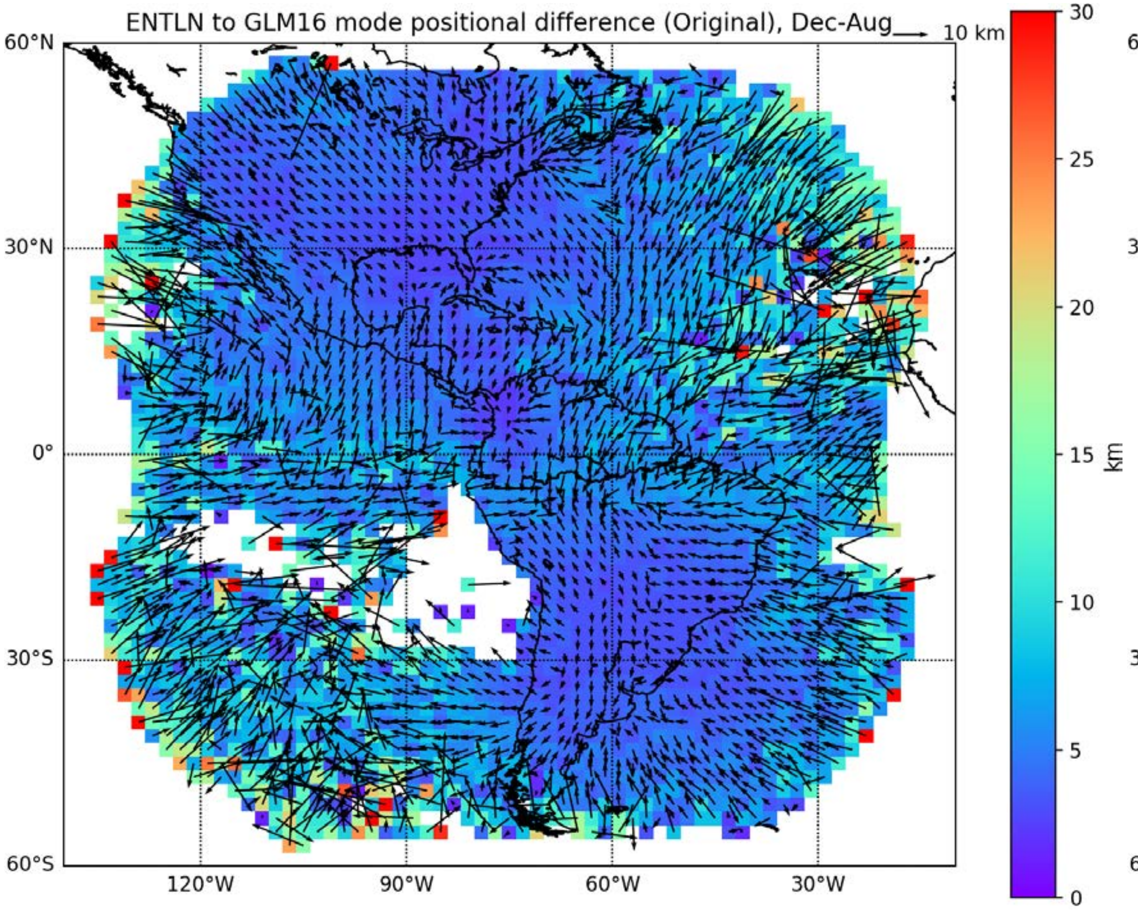


Geolocation error [km]

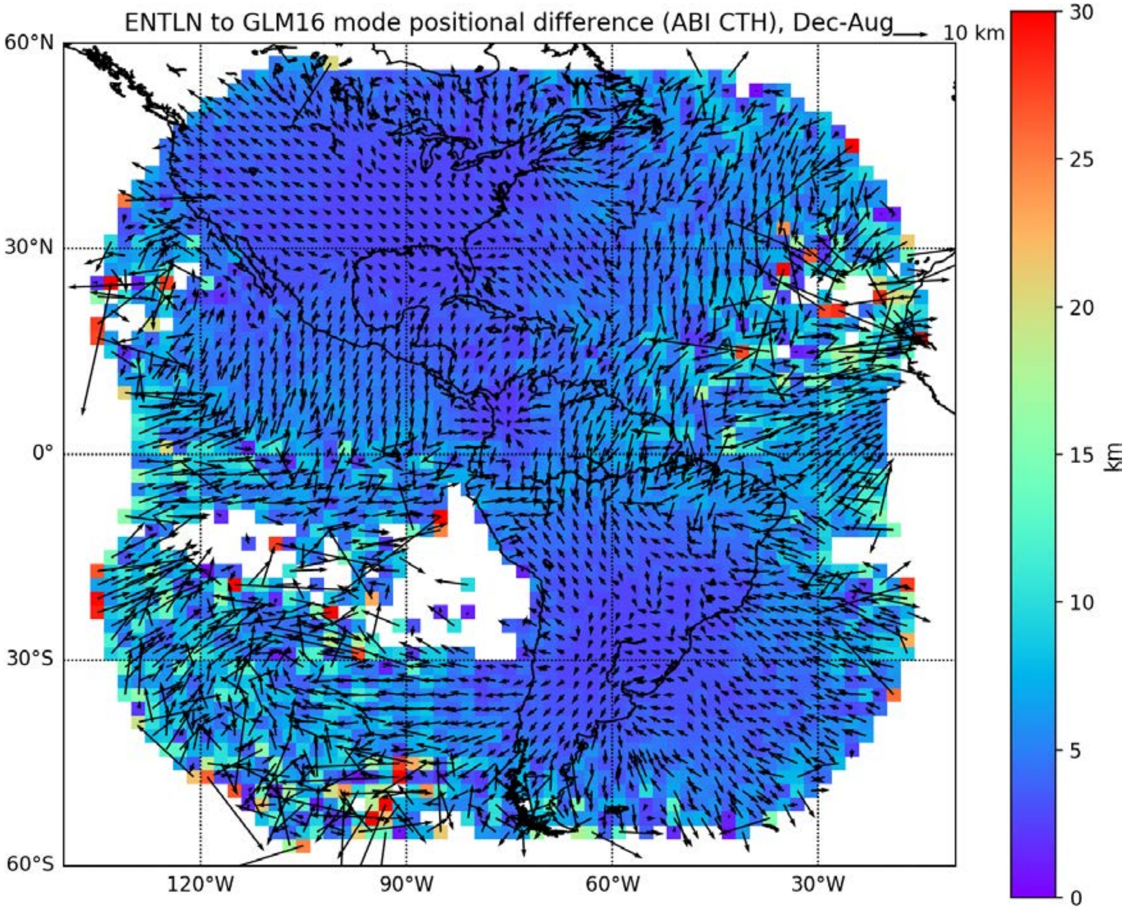
- Peak error: CTH_{ABI} (2.75 km) < Lightning Ellipsoid (3.25 km)
- Lightning Ellipsoid is a reasonable way for parallax correction

Parallax correction by ABI cloud top height

(a) Lightning ellipsoid



(b) ABI could top height



CTH_{ABI} reduces parallax location errors near the edge of FOV

Summary of GLM L2 product evaluation

A: Flash distribution analysis

- GLM flash distributions were consistent with GLD360
- Mitigation efforts significantly reduced GLM false detections

B: Flash detection efficiency (DE) analysis

- GLM’s high & broad detection capability
- DE depression over high-boresight-angle CONUS
- $DE_{IC} < DE_{GC}$ & $DE_{Day} < DE_{Night}$ over CONUS
- DE decreases as CTT_{ABI} decreases

C: Group timing & location validation

- Peak errors not exceeding GLM’s sampling rate & distance
- Further improvement of parallax correction provided by CTH_{ABI}

Thank you for your attention!

Himawari-8

GOES-17

GOES-16

Images created by RAMMB/CIRA SLIDER