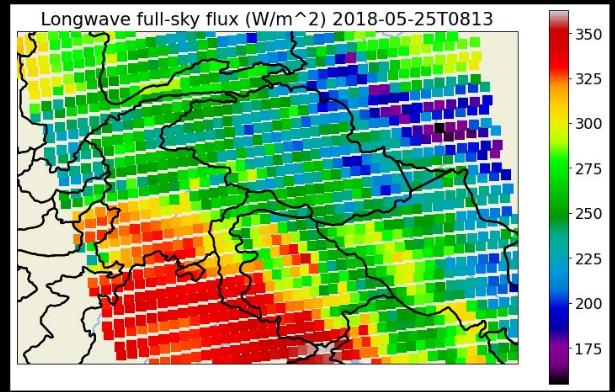
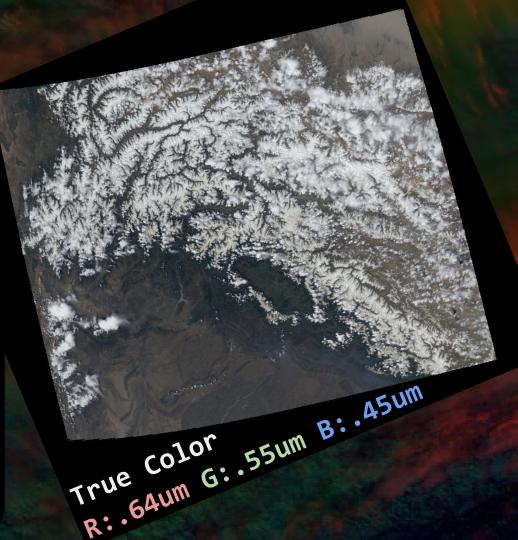
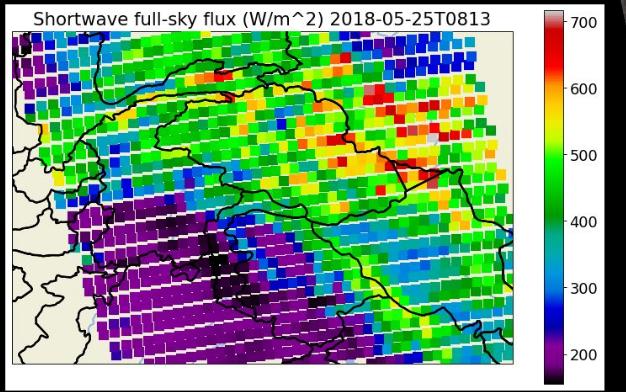
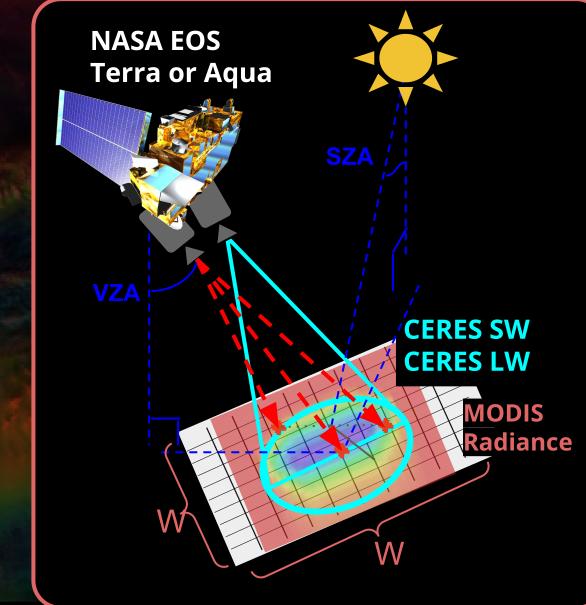


# A Deep Learning approach to Estimate CERES Broadband Flux with 1km MODIS Pixels.

AES 690 - Final Presentation - Mitchell Dodson

Goal: develop a **data-driven deep learning model** to characterize the relationship between EOS-MODIS' 36 spectral radiance bands, the sun/pixel/satellite viewing geometry, and the full-sky broadband radiative flux observed by the EOS-CERES instrument over a diverse set of regions.



# Data pipeline overview:

1

Use the LARC downloader to acquire CERES SSF data over a series of desired regions and time periods.

2

Select fields, restrict valid viewing geometry, and apply other constraints, then call `get_ceres_swath.py`, which extracts, subsets, and preprocesses CERES footprints, then groups them into individual overpasses per region and satellite. These are stored with their meta-info in a new pickle file.

3

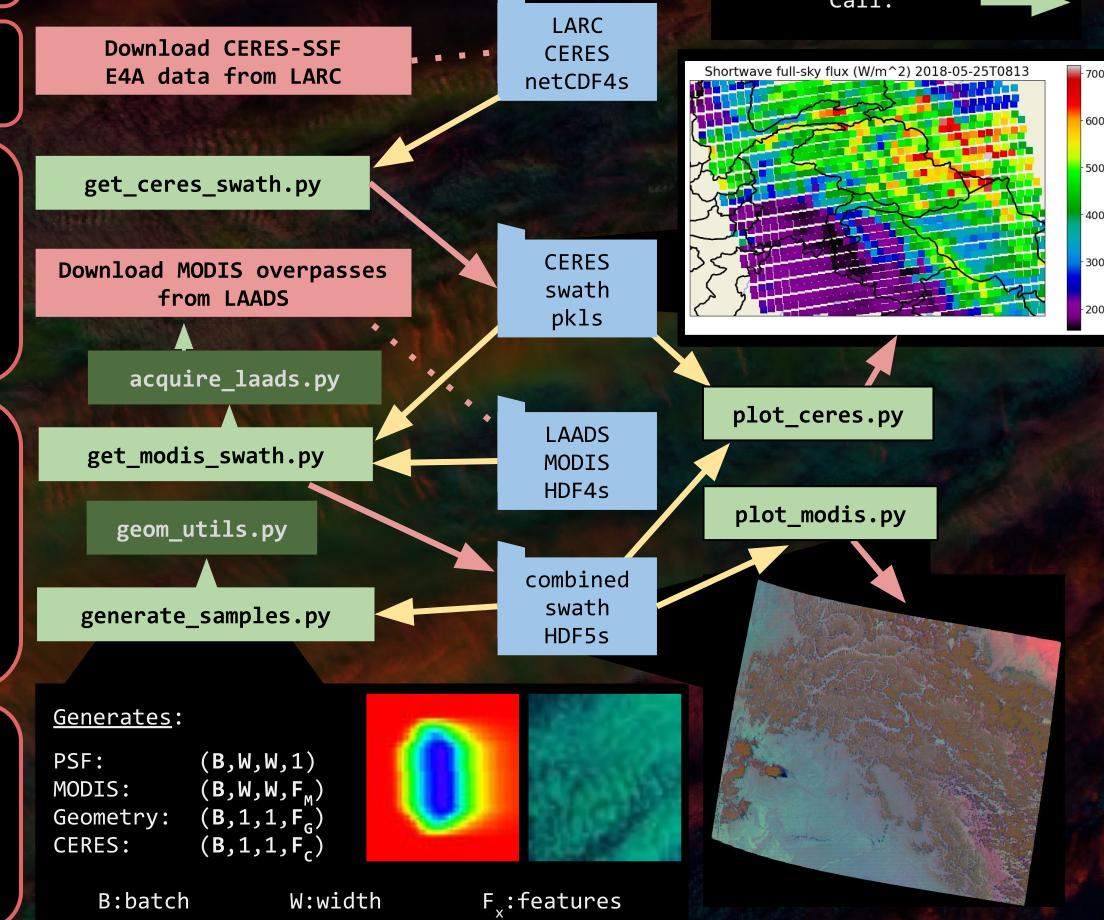
Select a series of MODIS bands to extract, and set file storage parameters in `get_modis_swath.py`, then run the script to download MxD021KM and MxD03 1b granules from LAADS corresponding to each swath. Extract the desired bands in range of the CERES data, and combine the MODIS and CERES data for each overpass in a custom ‘swath’ HDF5.

4

`generate_samples.py` loads several swath HDF5s concurrently, extracts CERES footprints and surrounding MODIS tiles, then calculates the CERES point spread function over each sub-domain. Samples from the loaded swaths’ PSFs, MODIS/CERES data, and viewing geometry are interleaved and yielded as tensors.

Key:

- Download:
- Generate:
- Utilize:
- Call:



# Acquired regional data:

Using the described data pipeline, I acquired every third available EOS Terra and Aqua swath in the 3 years between Jan 1, 2018 and Dec 31, 2020, within the regional boundaries described below, for a total of about 2,600 overpasses, each of which contain about 300 individual samples on average.

( neus )--				
Label	Min	Max	Avg	Std
lat	34.263	42.930	38.566	2.414
lon	-77.322	-71.226	-74.367	1.493
vza	3.196	29.845	17.103	7.317
sza	37.378	46.063	41.750	2.078
swflux	90.989	611.449	282.029	120.906
lwflux	159.813	285.003	236.770	27.402
pct_clr	0.407	93.280	34.357	28.979
pct_ll1	0.758	99.300	51.161	33.039
pct_ll2	0.000	93.300	14.463	23.803
l1_cod	0.261	85.039	12.805	13.646
l2_cod	0.000	72.005	3.399	8.280
aer_land_pct	0.071	12.461	1.178	2.274
aod_land	0.000	0.380	0.037	0.063
aer_ocean_pct	0.006	65.302	7.309	14.265
aod_ocean	0.000	0.304	0.024	0.045
aod_ocean_small	0.000	0.180	0.015	0.028

## Northeast United States

lat ∈ [34,43] lon ∈ [-69,-79]  
Swath count: 532

( idn )--				
Label	Min	Max	Avg	Std
lat	-4.915	4.570	-0.170	2.646
lon	122.493	127.521	124.999	1.212
vza	3.631	29.836	17.166	7.275
sza	24.370	32.308	28.293	1.766
swflux	76.795	750.847	255.039	142.570
lwflux	129.861	291.400	237.621	33.949
pct_clr	0.370	96.402	33.312	28.465
pct_ll1	0.139	99.266	42.657	31.592
pct_ll2	0.000	97.317	24.029	28.747
l1_cod	0.119	88.985	7.904	11.022
l2_cod	0.000	75.253	3.334	7.609
aer_land_pct	0.000	66.529	2.391	7.737
aod_land	0.000	0.476	0.028	0.074
aer_ocean_pct	0.000	73.113	9.976	18.050
aod_ocean	0.000	0.317	0.035	0.056
aod_ocean_small	0.000	0.199	0.022	0.034

## Indonesia

lat ∈ [-5,5] lon ∈ [120,130]  
Swath count: 493

( alk )--				
Label	Min	Max	Avg	Std
lat	58.017	60.926	59.490	0.834
lon	-159.497	-154.426	-156.955	1.397
vza	6.192	27.520	16.523	5.521
sza	50.844	53.976	52.441	0.822
swflux	144.629	485.575	326.102	71.836
lwflux	183.409	252.280	219.779	15.006
pct_clr	1.557	76.016	25.339	19.179
pct_ll1	1.941	97.623	60.437	28.288
pct_ll2	0.000	81.810	14.198	20.830
l1_cod	1.684	71.662	17.545	13.079
l2_cod	0.000	54.584	4.973	8.809
aer_land_pct	0.008	35.277	5.602	7.379
aod_land	0.000	0.242	0.043	0.056
aer_ocean_pct	0.000	32.833	1.176	4.748
aod_ocean	0.000	0.161	0.008	0.027
aod_ocean_small	0.000	0.116	0.006	0.020

## Alaska

lat ∈ [58,61] lon ∈ [-160,-154]  
Swath count: 383

( seus )--				
Label	Min	Max	Avg	Std
lat	34.040	37.989	36.052	1.129
lon	-89.262	-85.598	-87.429	0.988
vza	6.326	29.145	17.635	6.152
sza	37.417	41.794	39.648	1.031
swflux	173.794	525.623	314.402	79.409
lwflux	188.285	277.697	242.395	20.083
pct_clr	6.995	80.235	38.927	19.716
pct_ll1	1.329	90.458	47.711	25.542
pct_ll2	0.003	74.999	13.343	19.167
l1_cod	1.436	58.629	13.910	18.614
l2_cod	0.000	48.194	4.084	7.625
aer_land_pct	0.313	14.549	4.637	3.751
aod_land	0.002	0.357	0.082	0.078
aer_ocean_pct	0.000	0.000	0.000	0.000
aod_ocean	0.000	0.000	0.000	0.000
aod_ocean_small	0.000	0.000	0.000	0.000

## Southeast United States

lat ∈ [34,38] lon ∈ [-90,-85]  
Swath count: 356

( hkh )--				
Label	Min	Max	Avg	Std
lat	32.033	37.975	35.050	1.691
lon	71.428	77.224	74.422	1.463
vza	3.056	29.836	16.732	7.363
sza	35.610	42.123	38.904	1.502
swflux	150.927	661.060	345.650	113.011
lwflux	168.895	312.938	244.834	30.726
pct_clr	1.460	97.151	41.651	27.731
pct_ll1	0.154	97.405	41.977	29.464
pct_ll2	0.000	89.662	16.353	22.979
l1_cod	0.254	74.625	9.265	9.618
l2_cod	0.000	61.636	3.812	7.255
aer_land_pct	0.000	81.474	13.372	22.328
aod_land	0.000	1.043	0.128	0.197
aer_ocean_pct	0.000	0.000	0.000	0.000
aod_ocean	0.000	0.000	0.000	0.000
aod_ocean_small	0.000	0.000	0.000	0.000

## Hindu Kush Himalayas

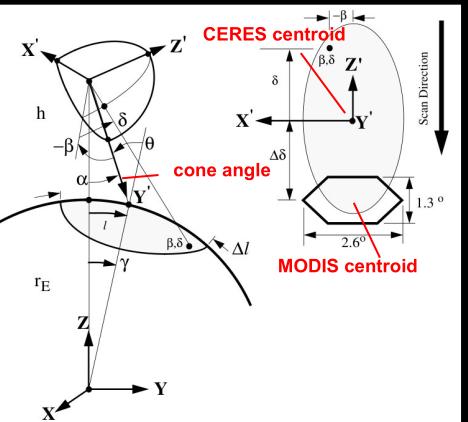
lat ∈ [32,38] lon ∈ [69,79]  
Swath count: 520

( azn )--				
Label	Min	Max	Avg	Std
lat	-7.978	-3.014	-5.503	1.419
lon	-69.103	-65.659	-67.383	0.910
vza	5.146	29.637	17.302	6.608
sza	26.745	31.586	29.156	1.095
swflux	171.321	693.881	342.504	110.928
lwflux	155.151	277.341	236.693	26.385
pct_clr	1.191	84.800	30.260	21.657
pct_ll1	1.094	97.671	52.261	28.037
pct_ll2	0.000	91.002	17.472	23.435
l1_cod	0.966	70.073	10.730	10.726
l2_cod	0.000	61.328	4.526	8.378
aer_land_pct	0.179	76.433	16.845	17.728
aod_land	0.002	0.525	0.135	0.122
aer_ocean_pct	0.000	0.000	0.000	0.000
aod_ocean	0.000	0.000	0.000	0.000
aod_ocean_small	0.000	0.000	0.000	0.000

## Amazon Rainforest

lat ∈ [-3,-8] lon ∈ [-65,-70]  
Swath count: 305

# Challenge: Point Spread Function



Equatorial geometry of the observation, and MODIS/CERES centroid offset schematic

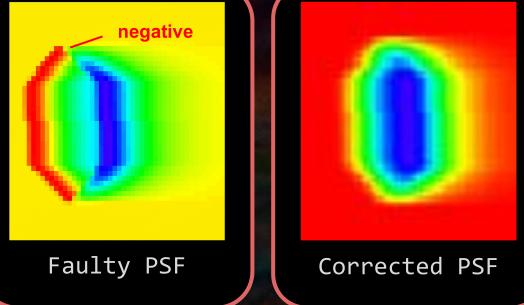
One related challenge that is still yet to be resolved is that the orientation of the MODIS grid centroid relative to the CERES footprint centroid is determined by the time derivative of CERES' cross-track scan elevation  $\alpha$  (satellite viewing cone angle), which alternates between cross-track sweeps, as diagrammed by the figure to the right.

Despite being specified in the ATBD, the derivative quantity isn't included in the CERES SSF data product. Since the above geometry is entirely calculated from relative geodetic values, it also cannot be directly inferred from the data.

Implementing the CERES point spread function (PSF) over the co-located MODIS domain has presented a major development challenge. The algorithm to do so is specified in CERES ATBD subsystem 4.4, which I vectorized and implemented in `generate_samples.py` and `geom_utils.py`.

One issue I encountered is that the analytic equation approximating the PSF (specified to the right) was producing a result with very negative values near the aft border of the oblong CERES centroid.

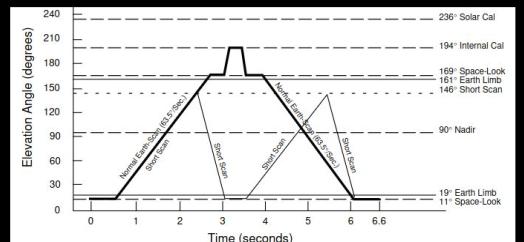
I found that the cause of the error was that the ' $\xi$ ' angle in the formula is assumed to be in radians rather than degrees, despite having been bounded and scaled previously by values in degrees.



$$F(\xi) = 1 - (1 + a_1 + a_2)e^{-c_1\xi} \\ + e^{-6.35465\xi}[a_1 \cos(1.90282\xi) + b_1 \sin(1.90282\xi)] \\ + e^{-4.61598\xi}[a_2 \cos(5.83072\xi) + b_2 \sin(5.83072\xi)]$$

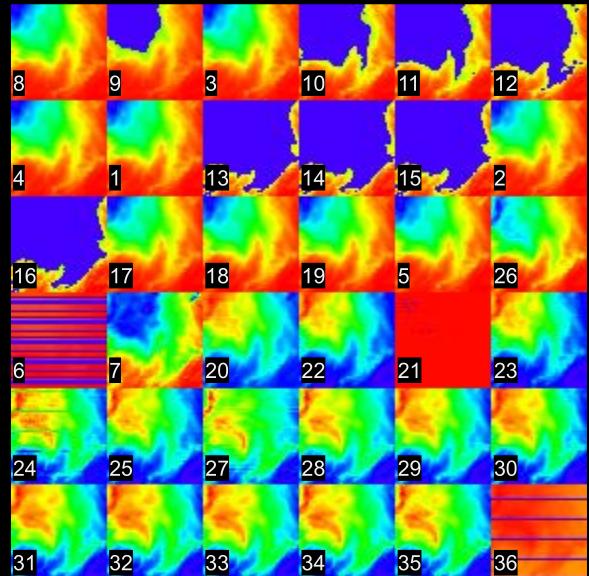
$$\begin{aligned} a_1 &= 1.84205 & a_2 &= -0.22502 \\ b_1 &= 1.47034 & b_2 &= 0.45904 \\ c_1 &= 1.98412 \end{aligned}$$

Empirical convolution equation  
(silently given in radians)

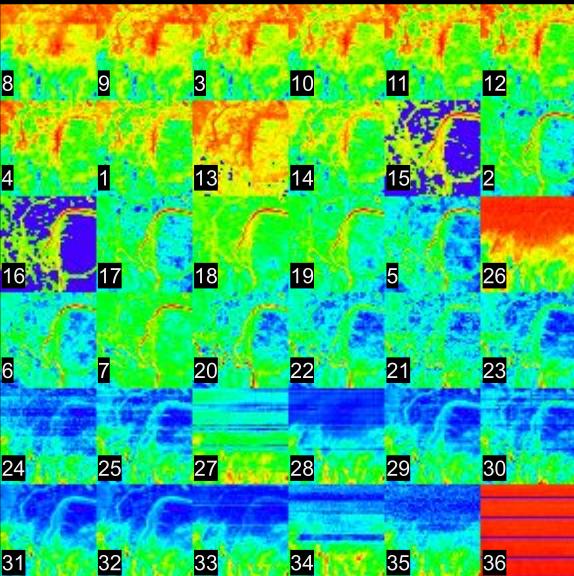


CERES' alternating scan direction

# Challenge: Band striping



The 36 MODIS bands on Aqua,  
in order of increasing wavelength



The 36 MODIS bands on TERRA,  
in order of increasing wavelength

## MODIS Collection 6a band quality seriously affected model predictions

Aqua has at least 1 dead scanner on 3 channels: 5, 6, and 36, and noise/cross-talk in bands 6, 21, 26, 29, and 30.  
Terra has dead detectors in channels 5 and 36, and noise/cross-talk issues in bands 2, 6, 27, 29, 30, 33, 34, and 36.  
<https://mcst.gsfc.nasa.gov/time-dependent-list-non-functional-or-noisy-detectors>

```
# Land/Cloud/Aerosols Boundaries
1, 620-670, 21.8, 128
2, 841-876, 24.7, 201

# Land/Cloud/Aerosols Properties
3, 459-479, 35.3, 243
4, 545-565, 29.0, 228
5, 1230-1250, 5.4, 74
6, 1628-1652, 7.3, 275
7, 2105-2155, 1.0, 110

# Ocean Color/Phytoplankton
8, 405-420, 44.9, 880
9, 438-448, 41.9, 838
10, 483-493, 32.1, 802
11, 526-536, 27.9, 754
12, 546-556, 21.0, 750
13, 662-672, 9.5, 910
14, 673-683, 8.7, 1087
15, 743-753, 10.2, 586
16, 862-877, 6.2, 516

# Atmospheric Water Vapor
17, 890-920, 10.0, 167
18, 931-941, 3.6, 57
19, 915-965, 15.0, 250

# Cirrus Clouds Water Vapor
26, 1360-1390, 6.00, 150

# Surface/Cloud Temperature
20, 3660-3840, 0.45(300K), 0.05
21, 3929-3989, 2.38(335K), 0.20
22, 3929-3989, 0.67(300K), 0.07
23, 4020-4080, 0.79(300K), 0.07

# Atmospheric Temperature
24, 4433-4498, 0.17(250K), 0.25
25, 4482-4549, 0.59(275K), 0.25

# Water Vapor
27, 6535-6895, 1.16(240K), 0.25
28, 7175-7475, 2.18(250K), 0.25

# Cloud Properties
29, 8400-8700, 9.58(300K), 0.05

# Ozone
30, 9580-9880, 3.69(250K), 0.25

# Surface/Cloud Temperature
31, 10780-11280, 9.55(300K), 0.05
32, 11770-12270, 8.94(300K), 0.05

# Cloud Top Altitude
33, 13185-13485, 4.52(260K), 0.25
34, 13485-13785, 3.76(250K), 0.25
35, 13785-14085, 3.11(240K), 0.25
36, 14085-14385, 2.08(220K), 0.35
```

## ceda: convolutional encoder disaggregator

### Description:

The model consists of a 6-layer pixel-wise encoder, and separate 2-layer pixel-wise decoders for longwave and shortwave predictions. Two different model pathways generate separate predictions by aggregating with the PSF before decoding, or by decoding then aggregating. The result is averaged for the bulk prediction.

### Inputs:

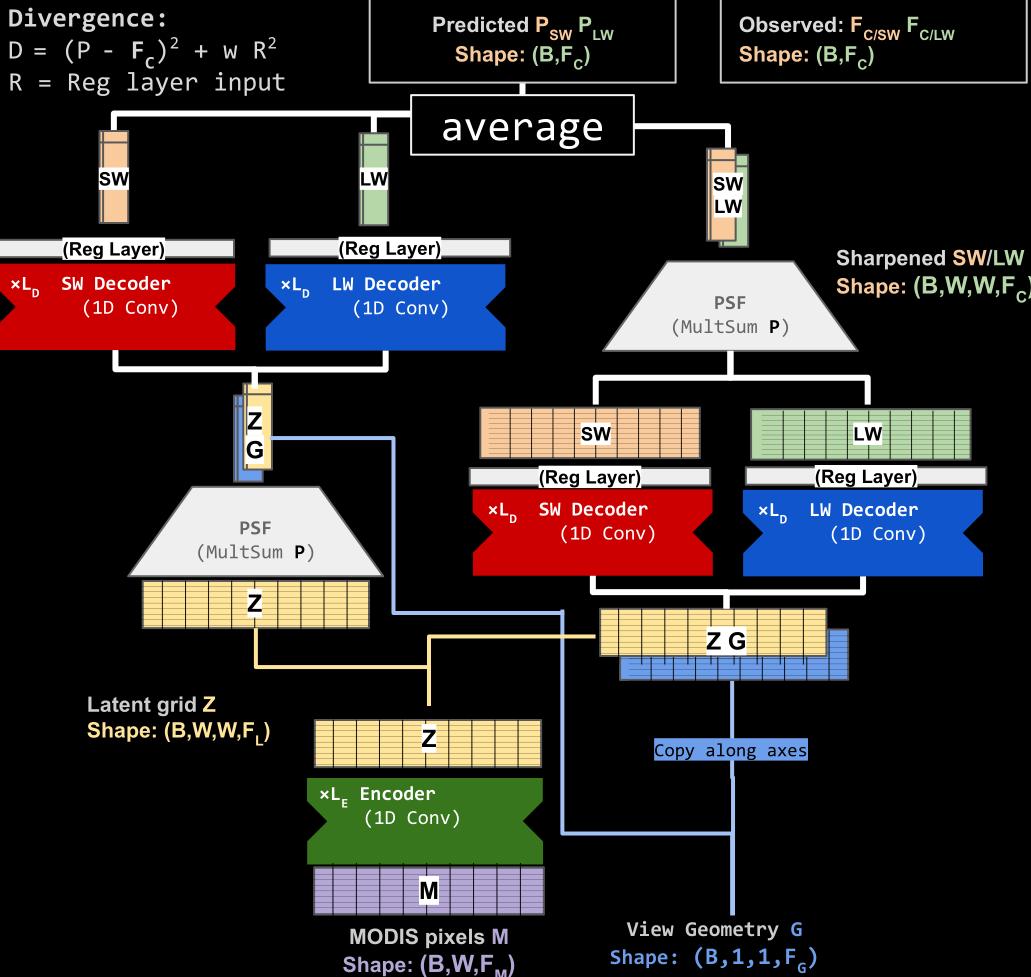
1.  $M := (B, W, W, F_M)$ ;  $F_M$  bands  
MODIS reflectance or brightness temperature.
2.  $G := (B, 1, 1, F_G)$ ;  $F_G := (\text{sol\_zen}, \text{sat\_zen}, \text{rel\_azi})$   
Viewing geometry (constant for small grid).
3.  $P := (B, W, W, 1)$   
2D PSF distribution over the MODIS domain

### Outputs:

Full-scene and sharpened SW/LW flux predictions.

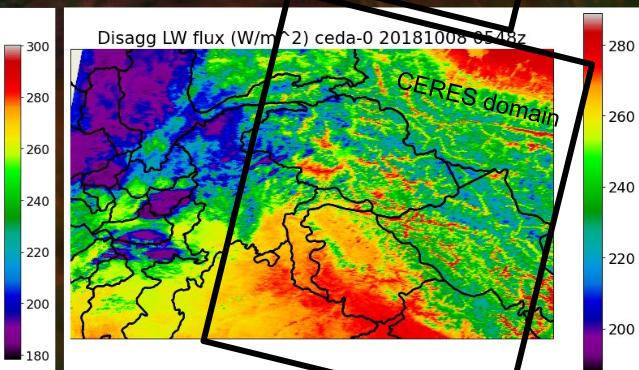
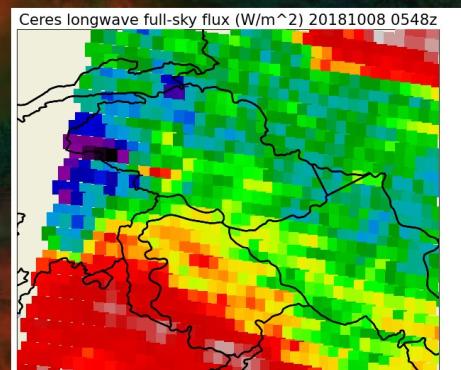
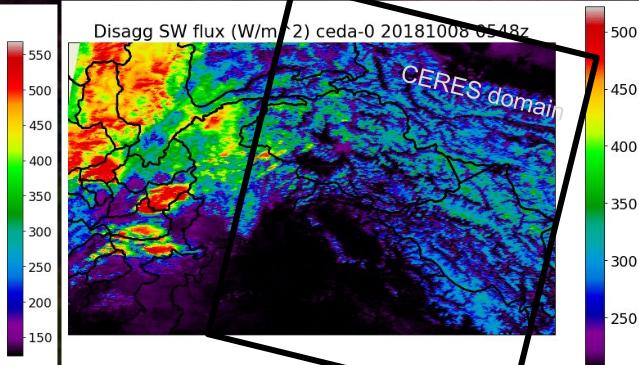
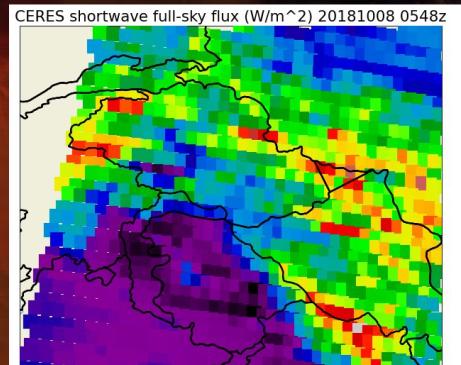
### Properties:

- Each output's decoder shares weights between the aggregate/decode and decode/aggregate branches.
- Full model is pixel-wise, so accepts an image with any grid size as an input.
- Decoder outputs are regularized during training with a penalty on squared distance from 0.
- PSF can be set to 1 during inference.



# Hindu Kush Himalayas

(Aqua; October 8, 2018)



## Cloud phase RGB:

**RED : 1.38μm**

High glaciated  
clouds

**GREEN : 0.64μm**

Visible  
reflectance

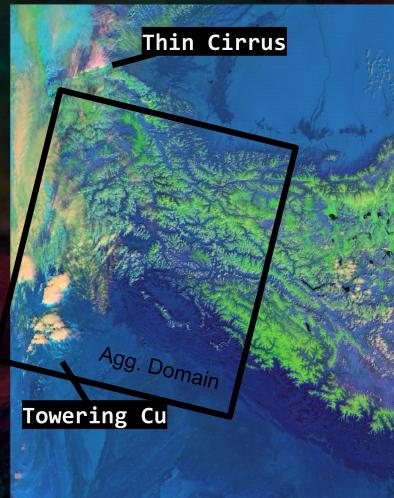
**BLUE : 1.61μm**

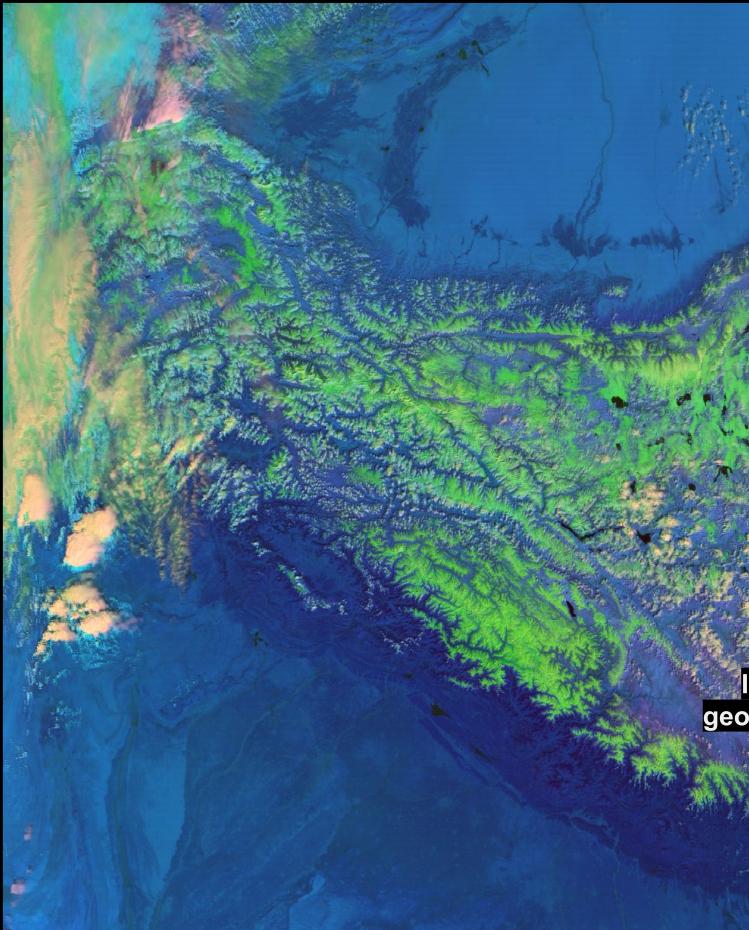
Cloud phase  
(bright if water)



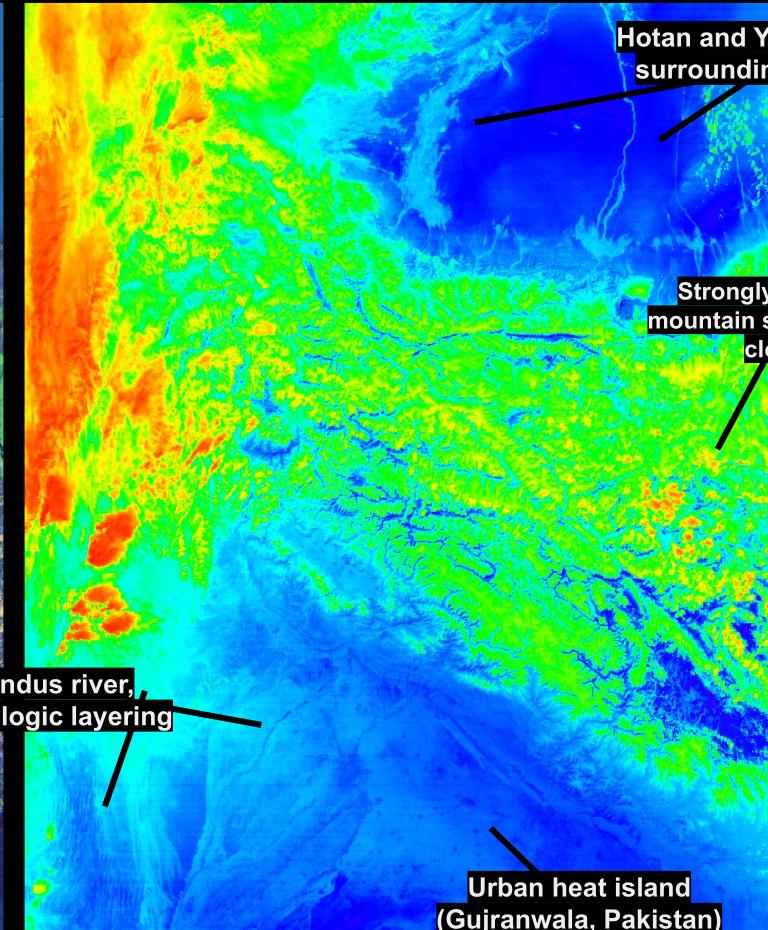
Pakistan

India





Day cloud phase RGB



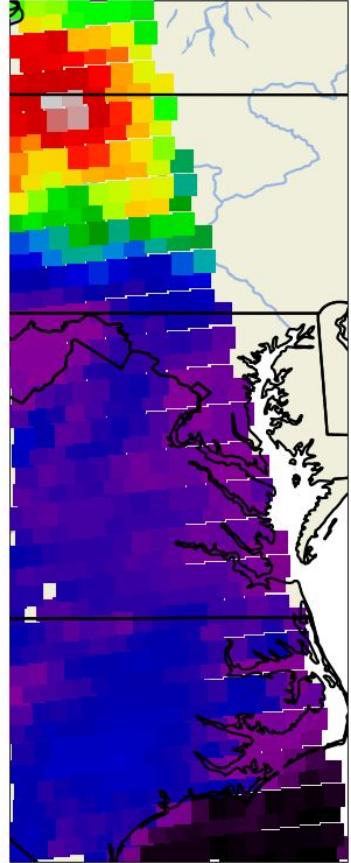
Longwave Flux Prediction

# Northeast US: Shortwave predictions

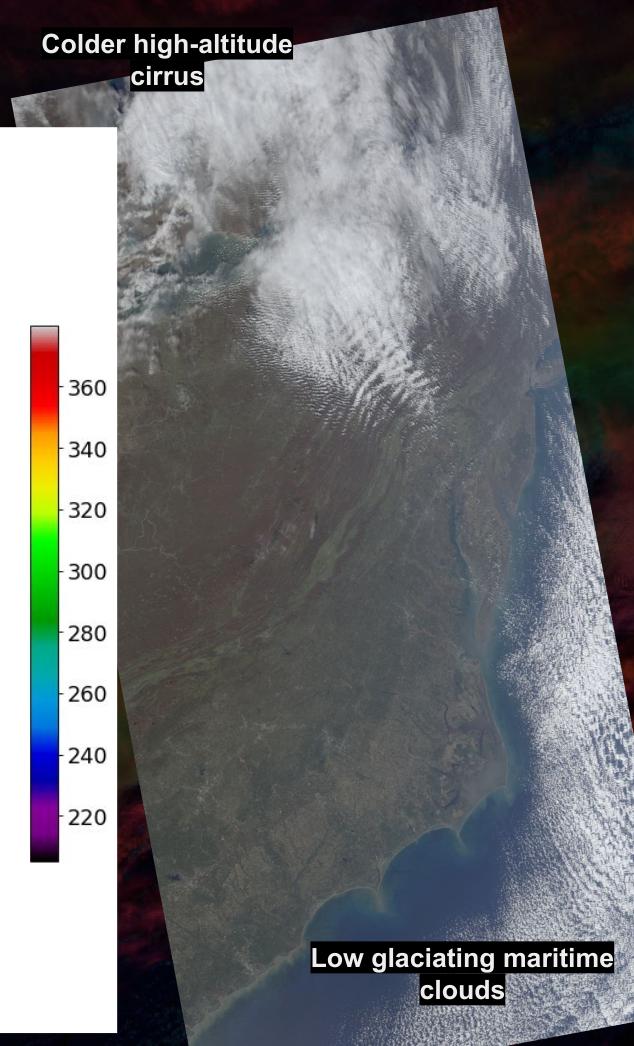
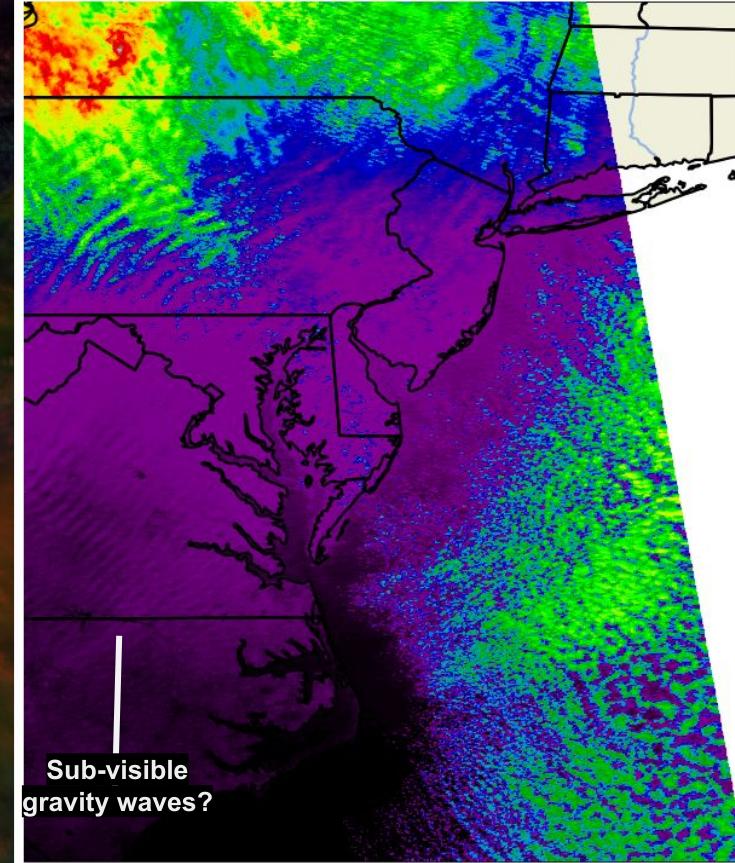
(Terra; November 2, 2020)

Colder high-altitude  
cirrus

wave full-sky flux ( $\text{W/m}^2$ ) 20201102 18



Disagg SW flux ( $\text{W/m}^2$ ) ceda-0 20201102 1829z

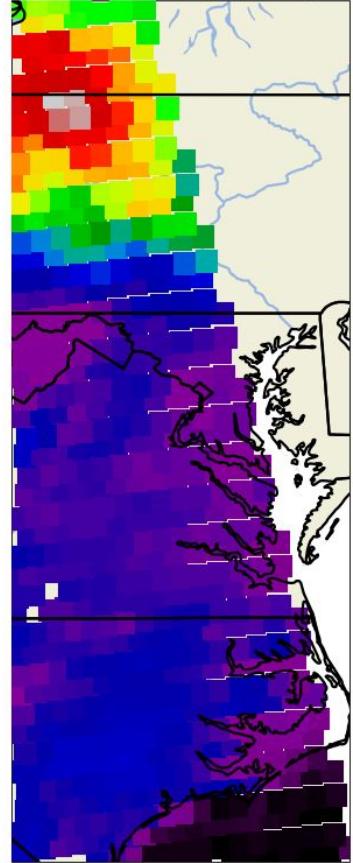


# Northeast US: Shortwave predictions

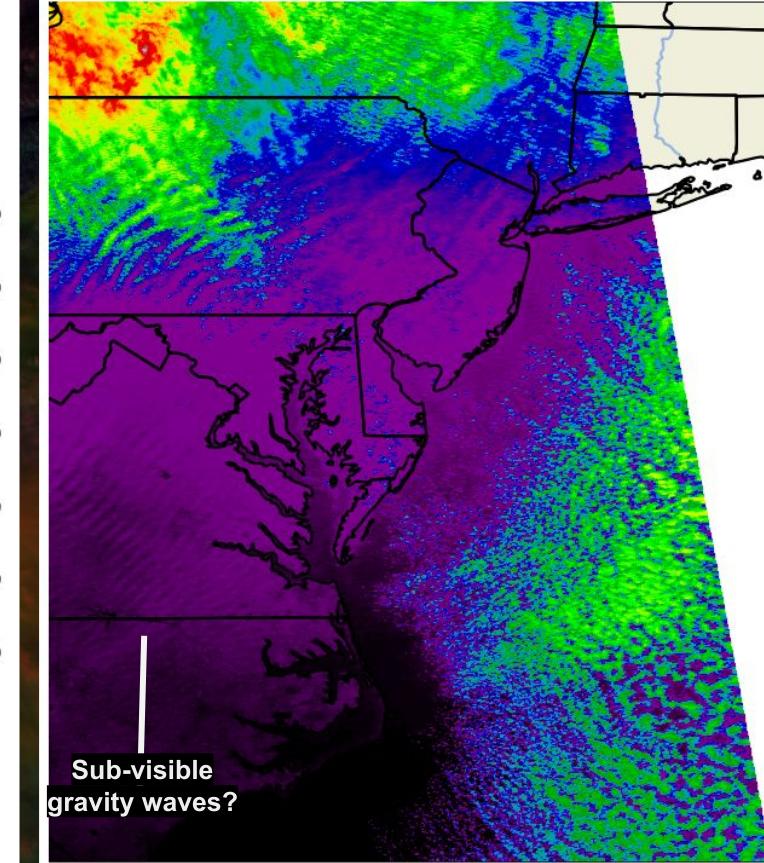
(Terra; November 2, 2020)

Colder high-altitude  
cirrus

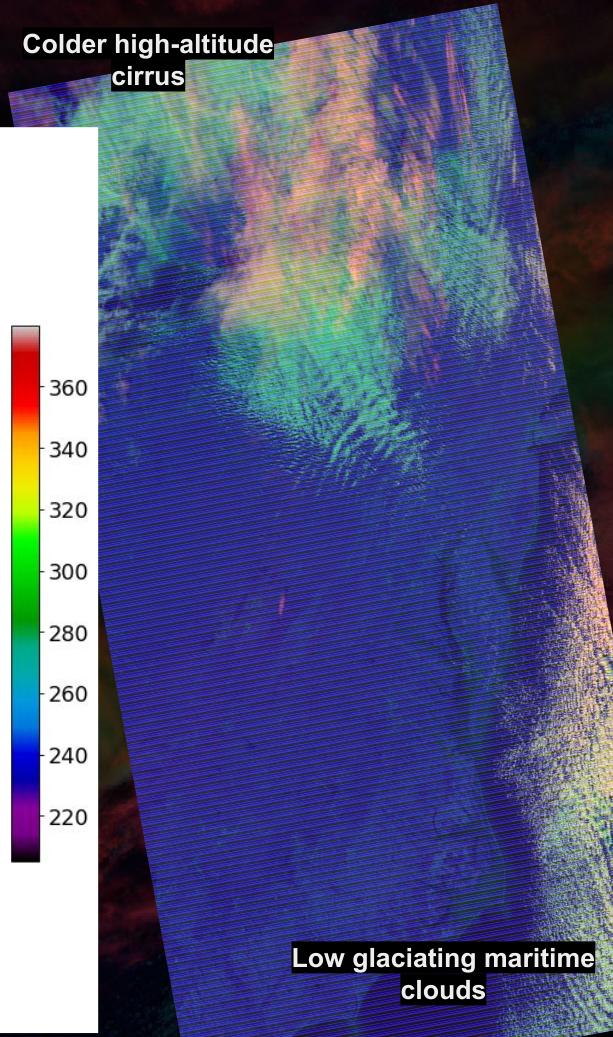
wave full-sky flux ( $\text{W/m}^2$ ) 20201102 18



Disagg SW flux ( $\text{W/m}^2$ ) ceda-0 20201102 1829z



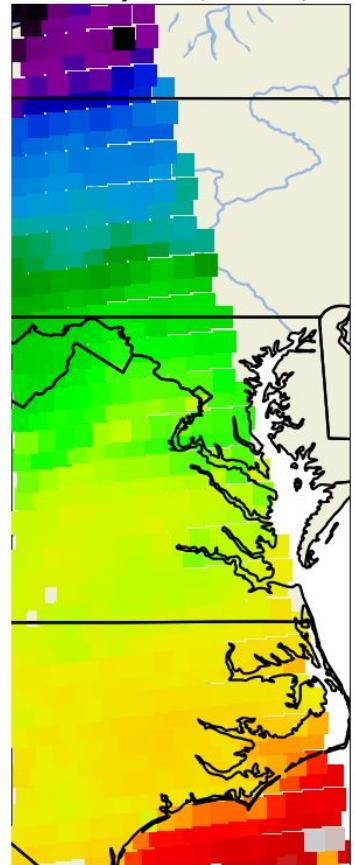
Low glaciating maritime  
clouds



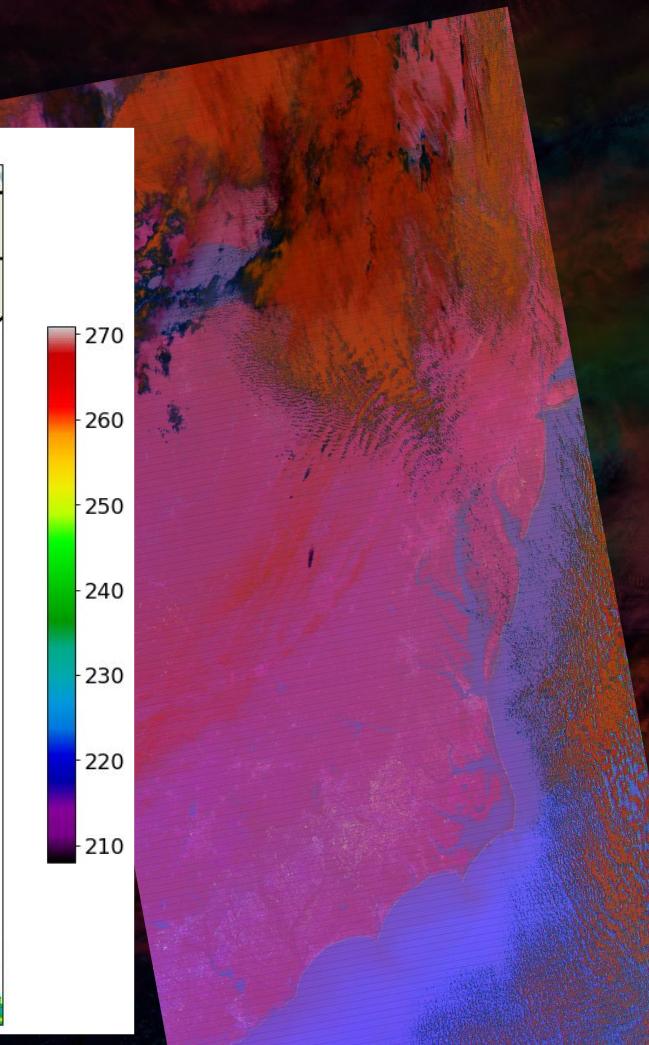
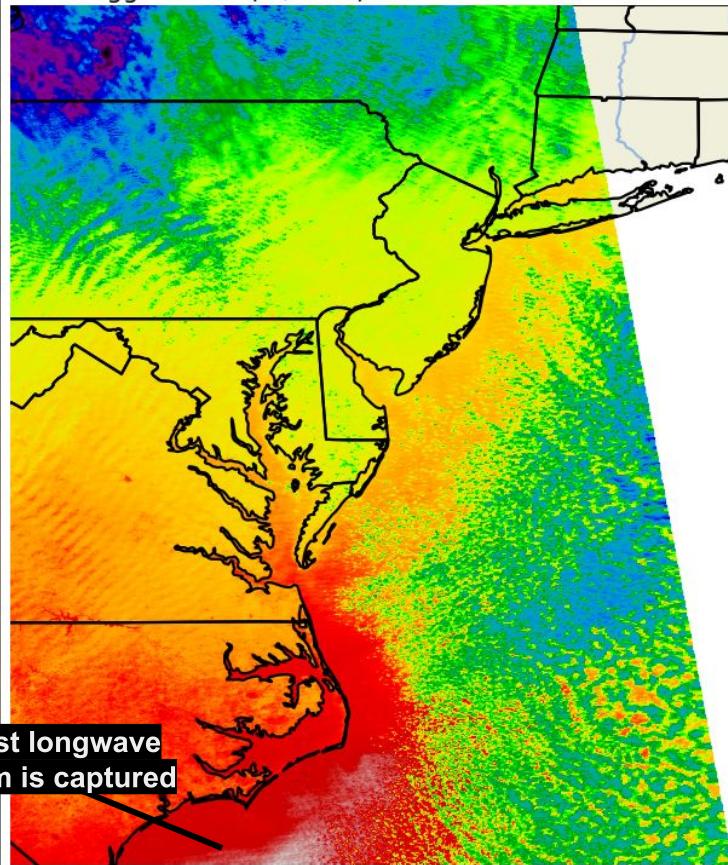
# Northeast US: Longwave predictions

(Terra; November 2, 2020)

wave full-sky flux ( $\text{W/m}^2$ ) 20201102 18



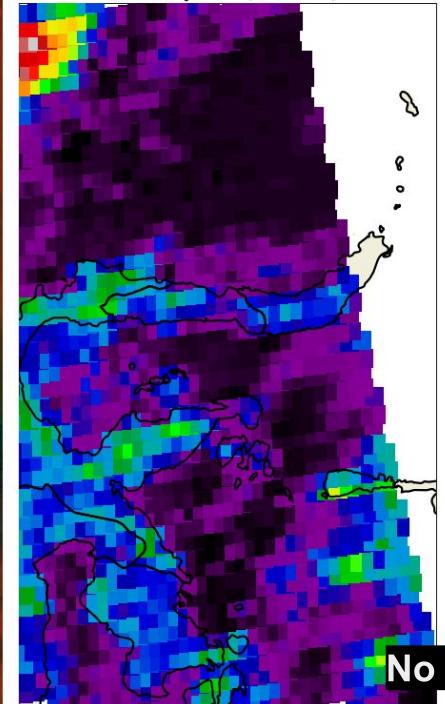
Disagg LW flux ( $\text{W/m}^2$ ) ceda-0 20201102 1829z



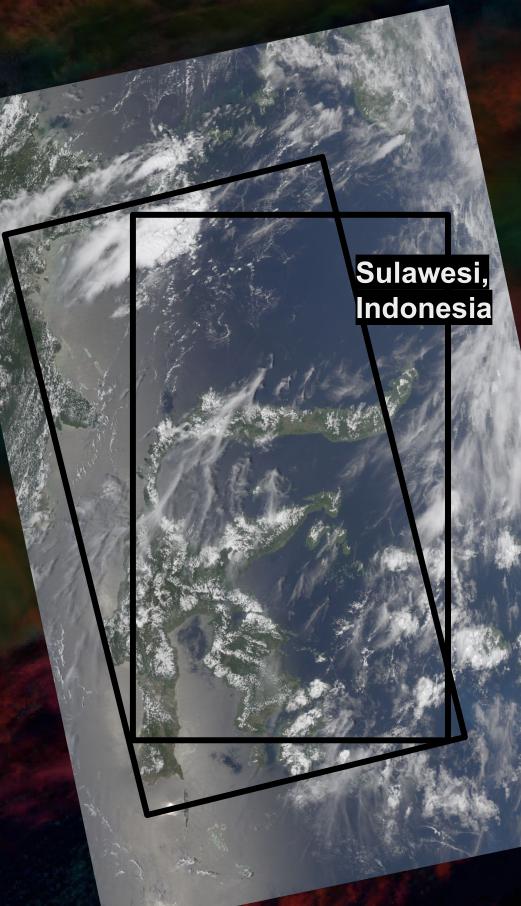
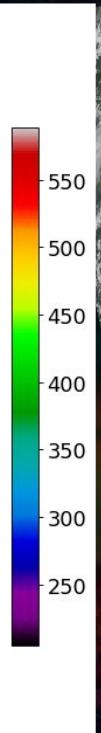
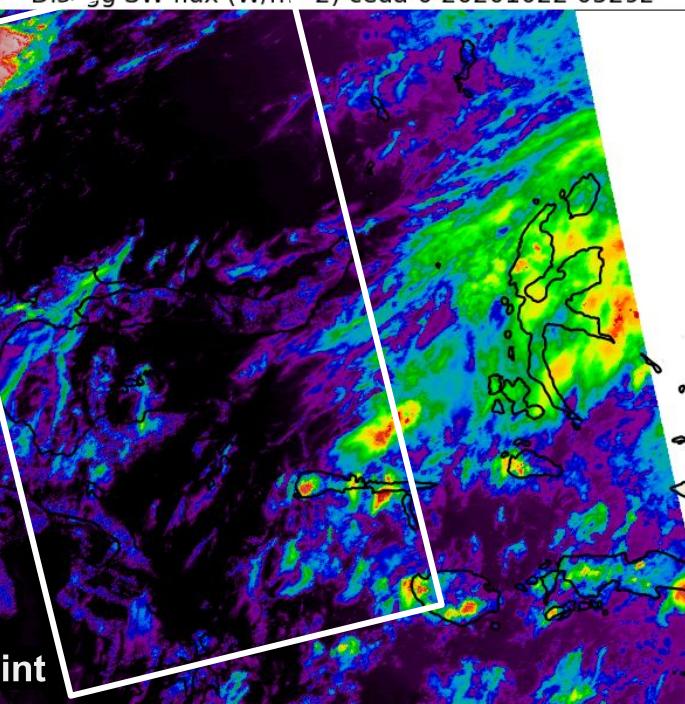
# Indonesia: Shortwave predictions

(Aqua; October 22, 2020)

shortwave full-sky flux ( $\text{W/m}^2$ ) 20201022 0529z



Disagg SW flux ( $\text{W/m}^2$ ) ceda-0 20201022 0529z

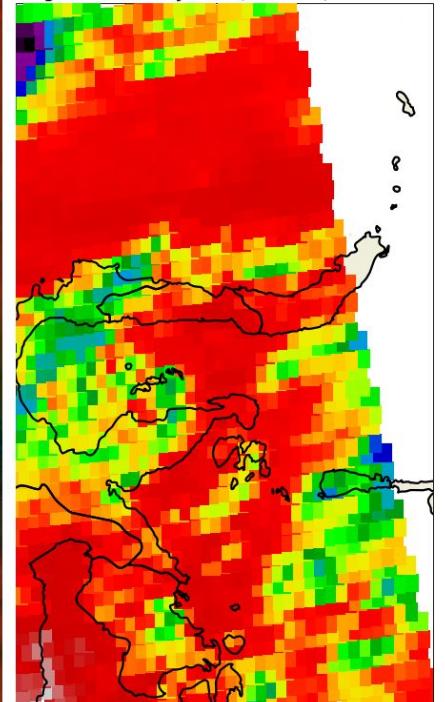


Sulawesi,  
Indonesia

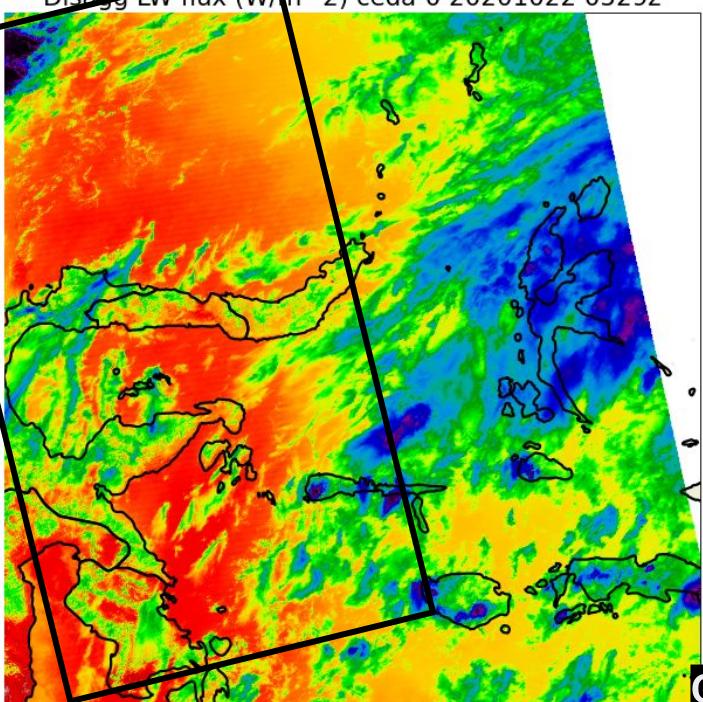
# Indonesia: Longwave predictions

(Aqua; October 22, 2020)

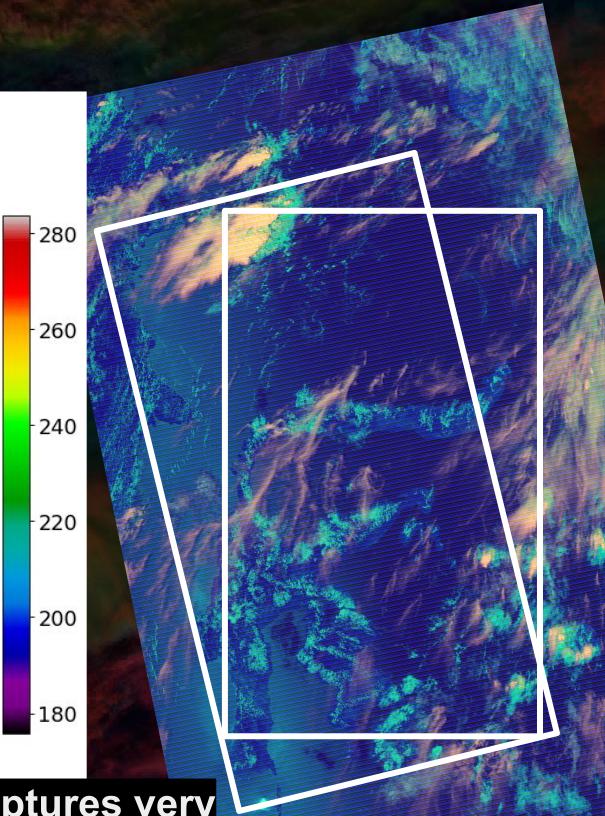
longwave full-sky flux ( $\text{W/m}^2$ ) 20201022 0529z



Disagg LW flux ( $\text{W/m}^2$ ) ceda-0 20201022 0529z



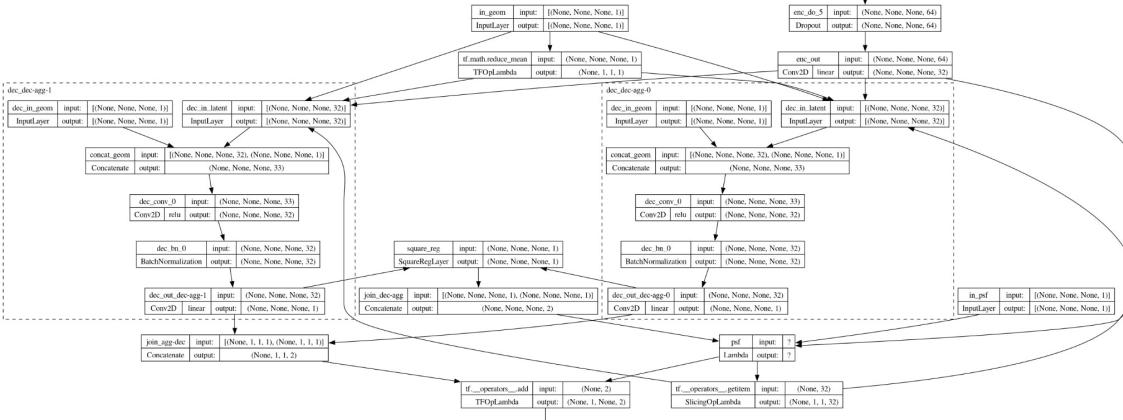
Captures very  
thin cirrus



Questions?

# ceda-0 architecture

(convolutional encoder-disaggregator)



# Model training plan

## Data Source:

The data tensors yielded by `generate_samples.gen_swaths_samples` are structured as tuples:  $((M, G, P), C)$ , each containing  $B$  batch samples:

$M := (B, W, W, F_M)$  MODIS reflectance or brightness temperature in  $F_M$  bands  
 $G := (B, 1, 1, F_G)$  Full-footprint viewing geometry  $F_G := (\text{sol\_zen}, \text{sat\_zen}, \text{rel\_azi})$   
 $P := (B, W, W, 1)$  2D PSF probability distribution over the MODIS domain  
 $C := (B, 1, 1, F_C)$  CERES footprint over the MODIS domain  $F_C := (\text{lw\_flux}, \text{sw\_flux})$

The generator also provides options for linear normalization, and for constraining the parameters and sources of the data it returns.

The full dataset includes observations from 2 different sensors, which were collected over 6 distinct regions having widely varying characteristics.

These statistical sub-populations may make the flux prediction significantly more complex, so I will train separate models using stratified sampling techniques on subsets of the data.

The basic model architecture consists of a sequence of 1D convolutions over the MODIS pixels to produce an independent latent representation of the radiance. The latent domain is concatenated with the viewing geometry (which is the same for all the pixels). Next, a second sequence of pixel-wise convolutional layers decodes the intermediate data to pixel-wise SW/LW predictions. Finally, the predictions are aggregated by a weighted sum over the PSF, and the loss is calculated with the result relative to the CERES footprints over the domain.

If time allows, I will experiment with applying the PSF aggregation to the latent grid before concatenating the resulting vector with the viewing geometry, and decoding with a simple multi-layer perceptron.

Since the entire model is pixel-wise, the full range of its predictions can be evaluated by modulating a single vector of input features. As such, it will also be interesting to see how predictions change with respect to the viewing geometry and MODIS spectral response.

## Model training plan:

First, do a broad random search of model hyper-parameters on the simplest possible task (ie, a single region/season/satellite combination)

Then, using the most promising learning rate schedule and regularization method:

1. Train a large and small model on each individual region, using only one satellite.
2. Train a large and small model combining all swaths, seasons, and satellites.

Finally, evaluate each of the models on unseen data from all of the input sub-populations.

## Base Model Architecture:

$L_D$  and  $L_E$  are pixel-wise convolution layers.

### Divergence:

$$D = (P - F_C)^2$$

