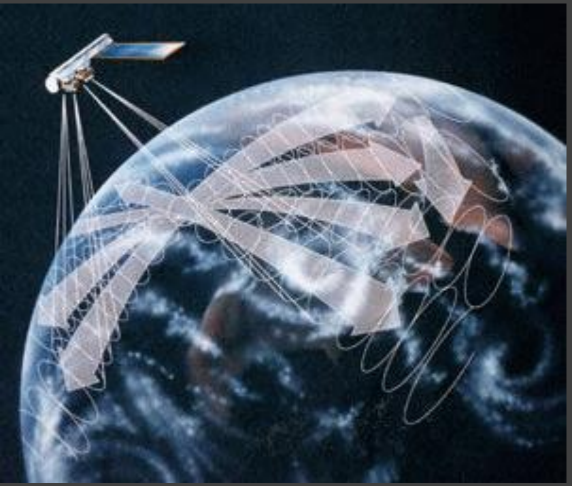

# CERES Angular Distribution Model Working Group Report

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CERES Science Team Meeting, Oct 1-3, 2024
Lawrence Livermore National Laboratory, Livermore, VA

# Outline

- Sensitivity of CERES ADMs to different climate states
- Impact of Terra orbital drifting on SW CERES ADMs

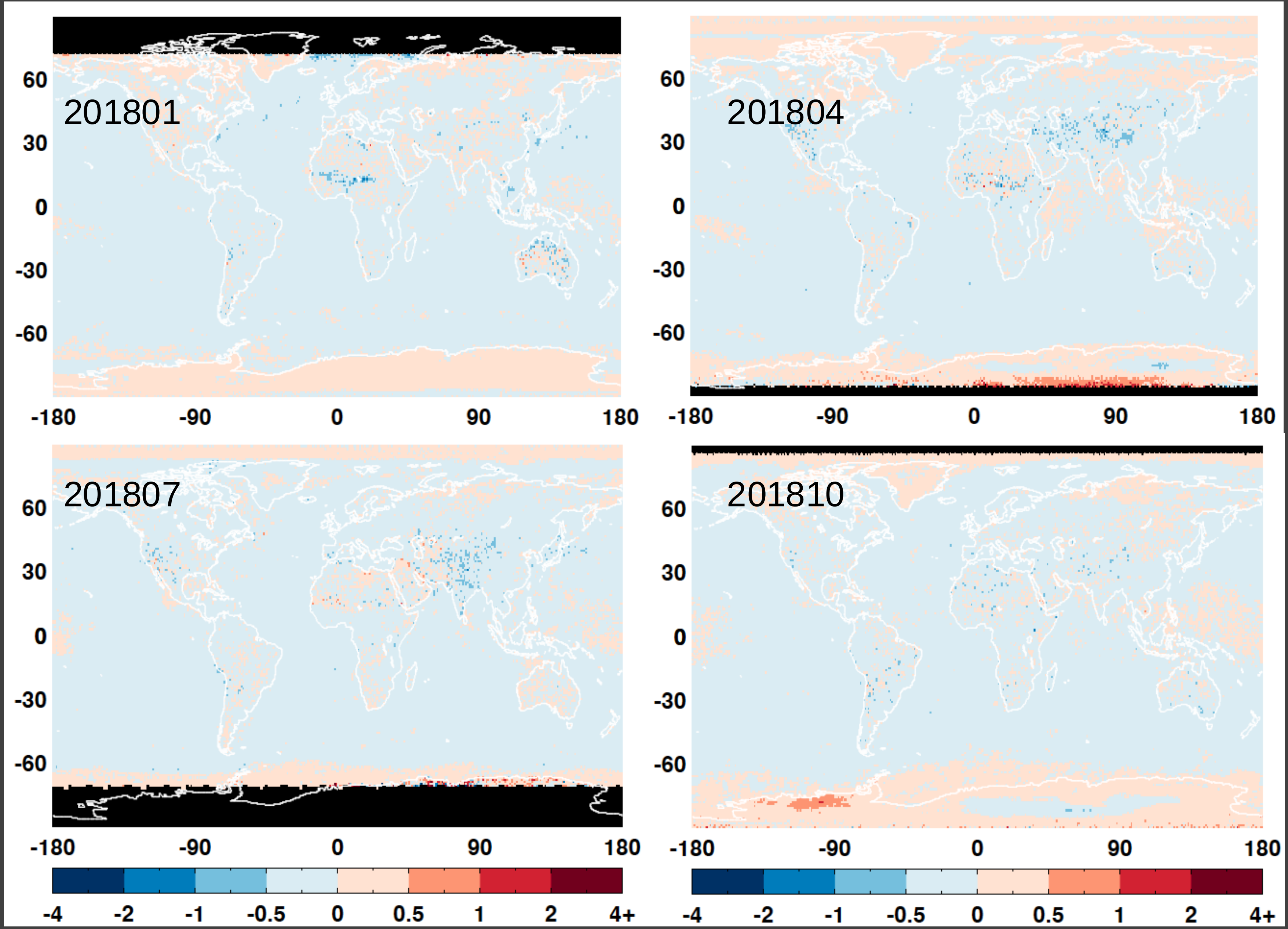
# Sensitivity of CERES ADMs to different climate states

# How resilient are ADMs to climate variability and change?

- As the mean climate state shifts, can the Terra/Aqua ADMs constructed using data taken in the early 2000s be used for flux inversion now and in the coming decades?

- Using data taken during different ENSO phases to test ADM sensitivity to climate variability:
  - Use the NOAA Physical Sciences Laboratory Multivariate ENSO Index (MEI) v2 to characterize ENSO phase for data selection to build ADMs.
  - Build a set of “El Niño SW ADMs” and a set of “La Niña SW ADMs”.
  - LW ADMs use Ed4 ADM approach.
  - SW ADMs over ocean/land use TRMM ADM approach to mitigate the sampling limitation; using MEI > 0.5 for the “El Niño ADMs” and MEI < 0 for the “La Niña ADMs“.
  - SW ADMs over snow are modified to achieve sampling symmetric by using MEI > 0 for the “El Niño ADMs” and MEI < 0 for the “La Niña ADMs”, and by using different numbers of months for the two ADMs.

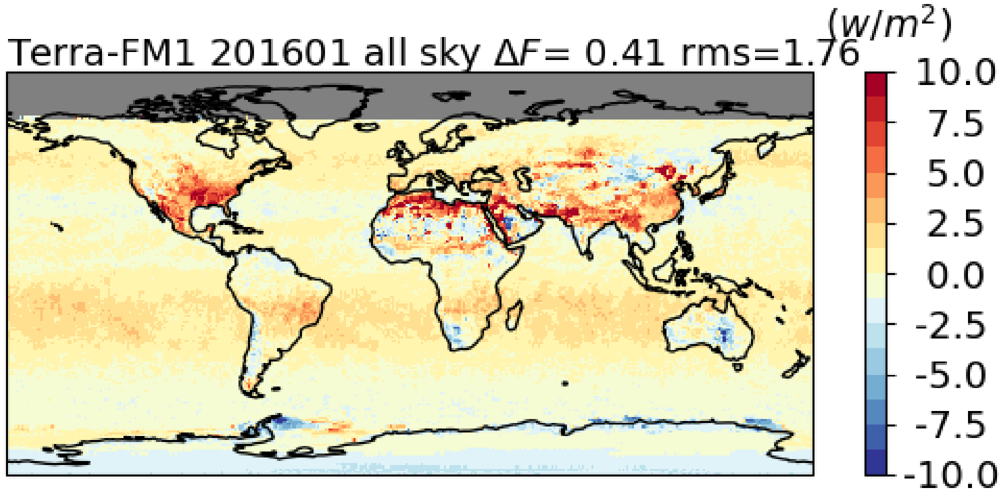
# Terra all-sky daytime LW flux difference: El Niño - La Niña ADMs



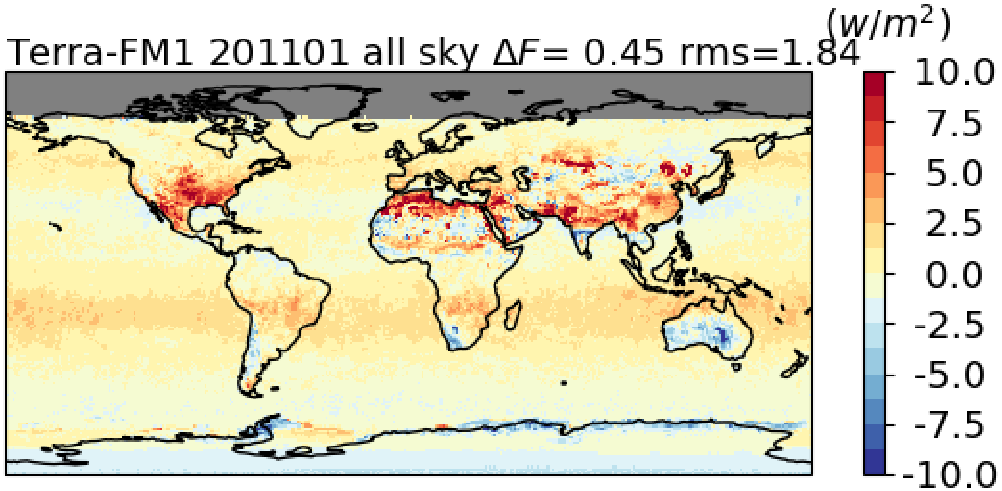

| | All-sky bias ($W\ m^{-2}$, %) | All-sky RMS |
|---|---|---|
| 201801 | 0.13 (0.06%) | 1.08 (0.45%) |
| 201804 | 0.13 (0.05%) | 1.17 (0.48%) |
| 201807 | 0.14 (0.06%) | 1.17 (0.47%) |
| 201810 | 0.12 (0.05%) | 1.09 (0.45%) |

LW ADMs constructed using data taken during El Niño phase and La Niña phase have a minimum impact on flux.

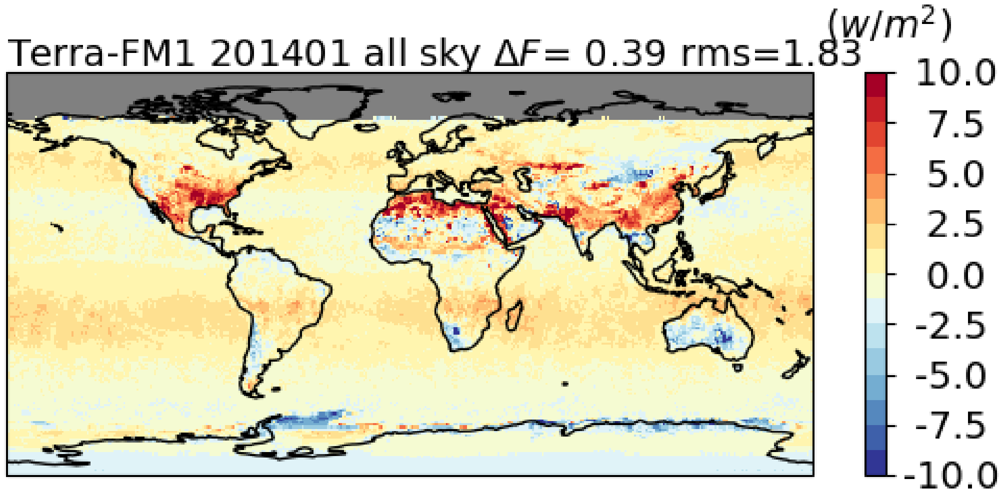
# SW flux differences from these two sets of ADMs show no dependence on the ENSO phase (flux by "El Niño ADMs" – flux by "La Niña ADMs")




MEI= 2.0



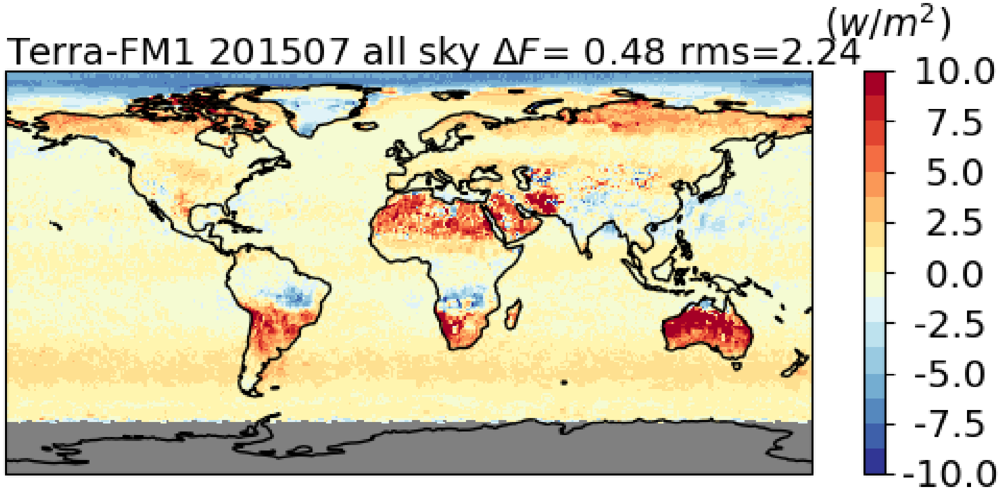

MEI= -1.8



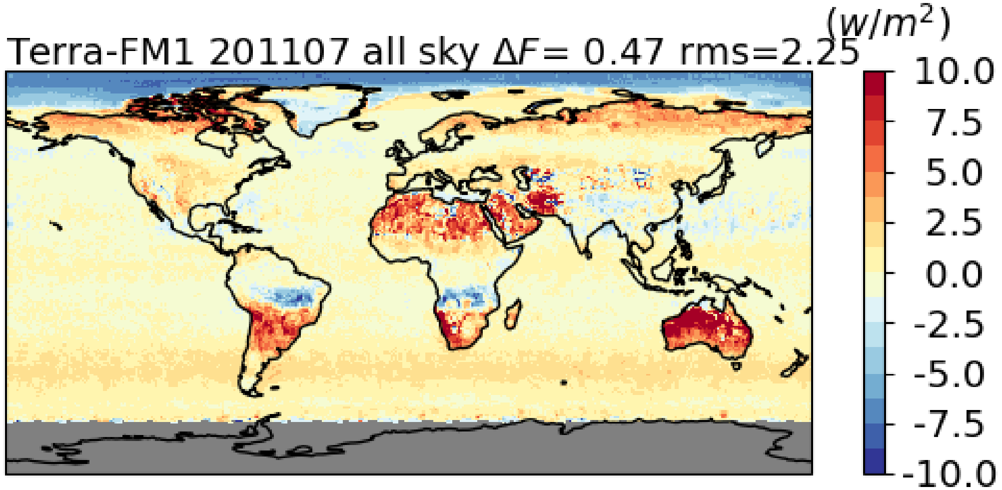

MEI= -0.5

- Flux shows regional differences.
- Flux difference patterns are similar for El Niño, La Niña, and neutral phases.

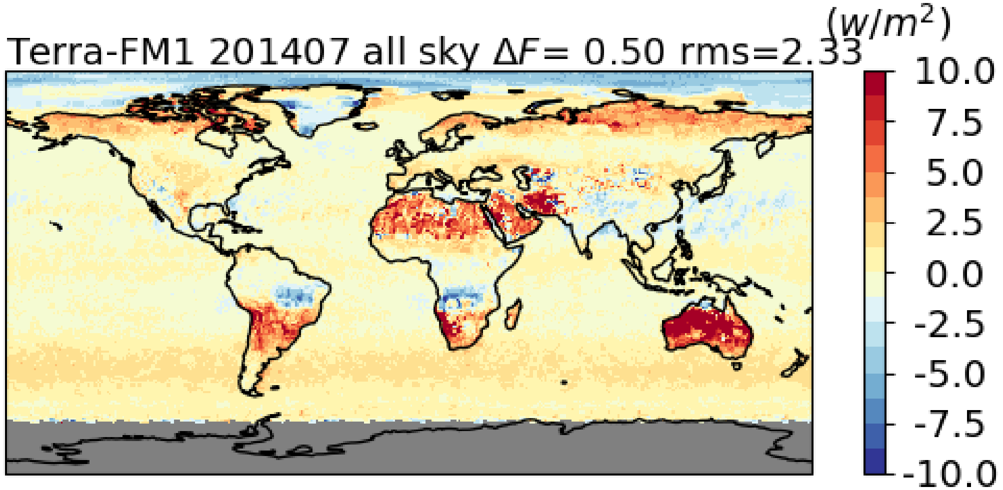
# SW flux differences from these two sets of ADMs show no dependence on the ENSO phase (flux by "El Niño ADMs" – flux by "La Niña ADMs")




MEI= 1.7




MEI= -0.9




MEI= 0.3

- Flux shows regional differences.
- Flux difference patterns are similar for El Niño, La Niña, and neutral phases.

# SW flux consistency using MISR measurements over snow/ice

- Broadband SW radiances derived from multiangle observations measured by MISR instrument.
- SW fluxes are inverted from the multi-angles SW radiances by the two sets of ADMs.
- Flux consistencies are evaluated.

| SW Flux ADM Error | Clear | Single Cloud Layer | Multi-Cloud Layer | All |
|---|---|---|---|---|
| $\Psi_{ADM}$ (%) (Ed. 4 snow/ice ADMs) | 3.8 | 5.9 | 5.8 | 5.5 |
| $\Psi_{ADM}$ (%) (El Nino snow/ice ADMs) | 4.9 | 6.4 | 6.2 | 6.1 |
| $\Psi_{ADM}$ (%) (La Nina snow/ice ADMs) | 5.0 | 6.3 | 6.0 | 6.0 |

the El Niño and La Niña ADMs have nearly the same uncertainty.

# Flux by direct integration

- For the ”La Niña ADMs” and “El Niño ADMs”, respectively, construct two sets of regional (10ºx10º) all-sky ADMs for each season (DJF, MAM, JJA and SON).

  (1) ADMs based on observed radiances

$$R_o(\theta_o, \theta, \phi) = \frac{\pi I_o(\theta_o, \theta, \phi)}{F_o(\theta_o, \theta, \phi)}, \text{ where } F_o = \int_0^{2\pi} \int_0^{\pi/2} I_o(\theta_o, \theta, \phi) cos\theta sin\theta d\theta d\phi$$

  (2) ADMs based on ADM-predicted radiances

$$\hat{R}(\theta_o, \theta, \phi) = \frac{\pi \hat{I}(\theta_o, \theta, \phi)}{\hat{F}(\theta_o, \theta, \phi)}, \quad \text{where } \hat{F} = \int_0^{2\pi} \int_0^{\pi/2} \hat{I}(\theta_o, \theta, \phi) cos\theta sin\theta d\theta d\phi$$

- Both sets of ADMs have the same sampling.

- How “La Niña ADMs” based flux differ from “El Niño ADMs” based flux
- How “La Niña ADMs” based flux differ from observed-ADM based flux
- How “El Niño ADMs” based flux differ from observed-ADM based flux

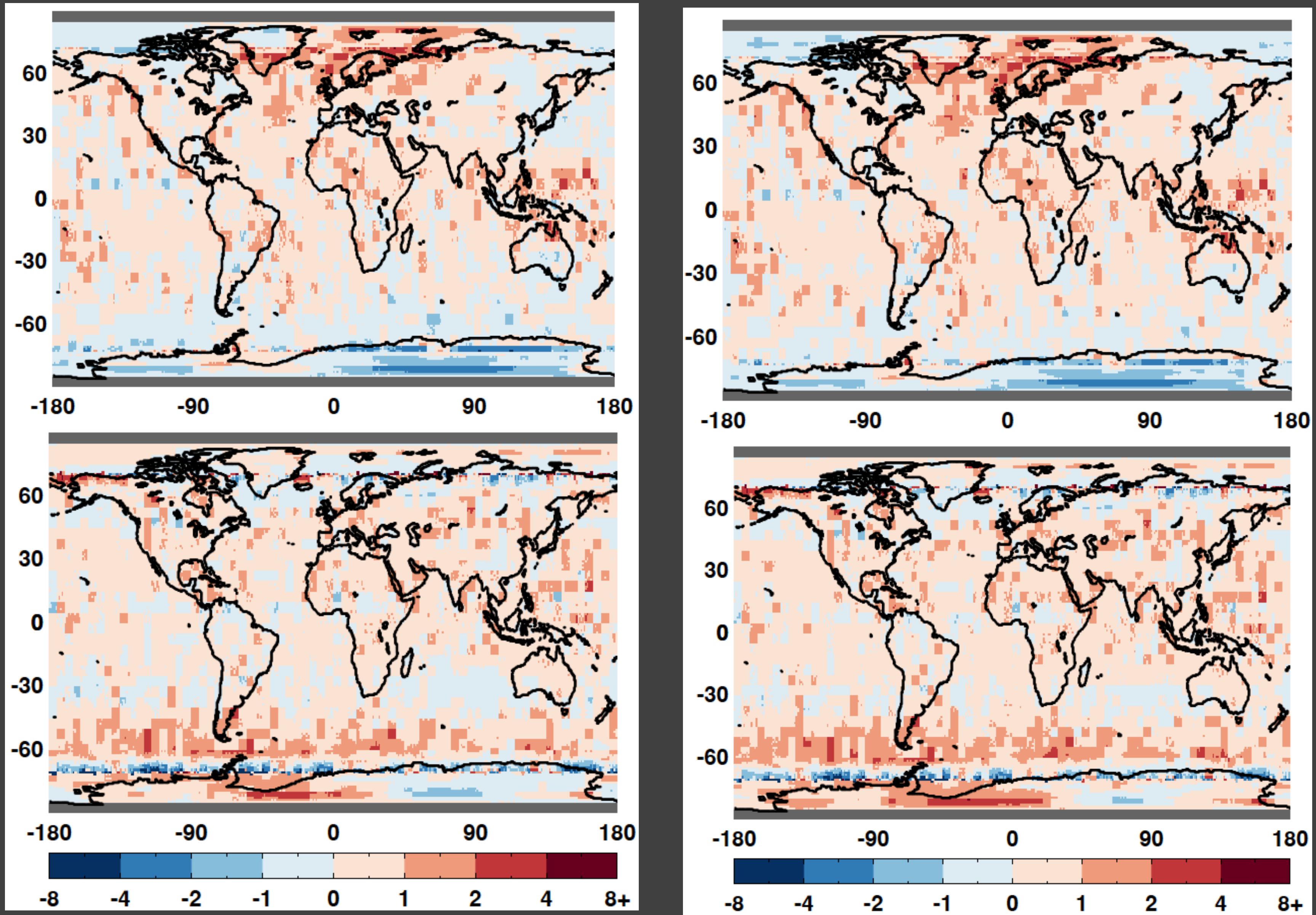
# Direct integration LW flux error for 2002 Terra FM1
# (flux from predicted radiance ADM – flux from observed radiance ADM)

using La Nina ADMs

using El Nino ADMs

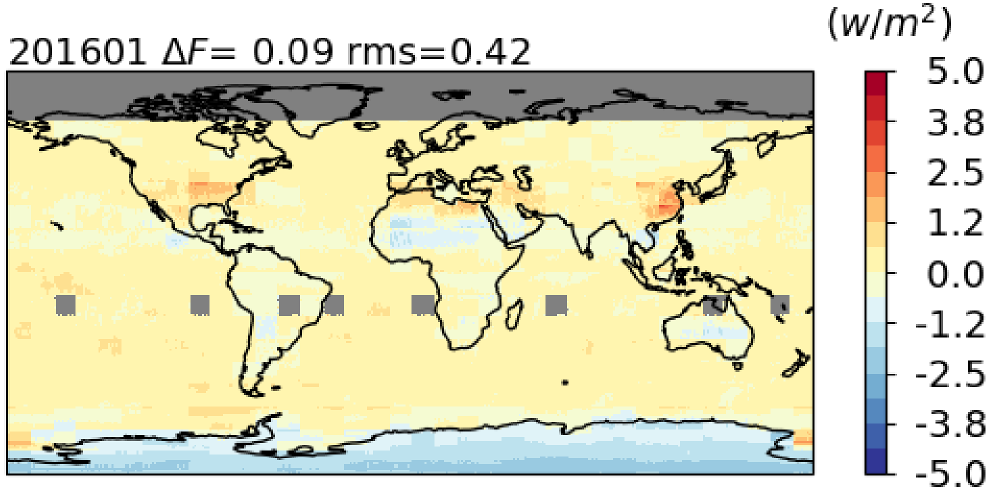
Jan

Jul

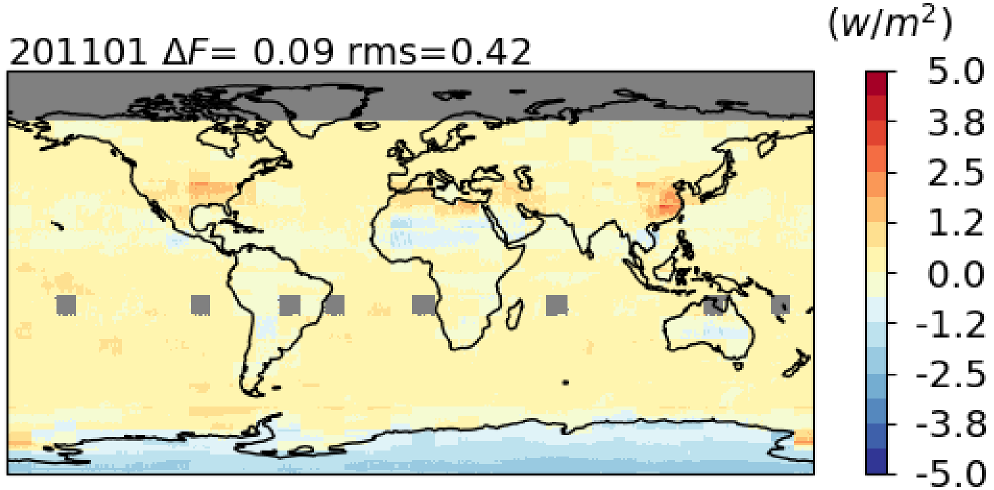



| | La Nina | El Nino |
|---|---|---|
| Jan | 0.27 (0.67) | 0.36 (0.70) |
| Jul | 0.34 (0.74) | 0.43 (0.78) |

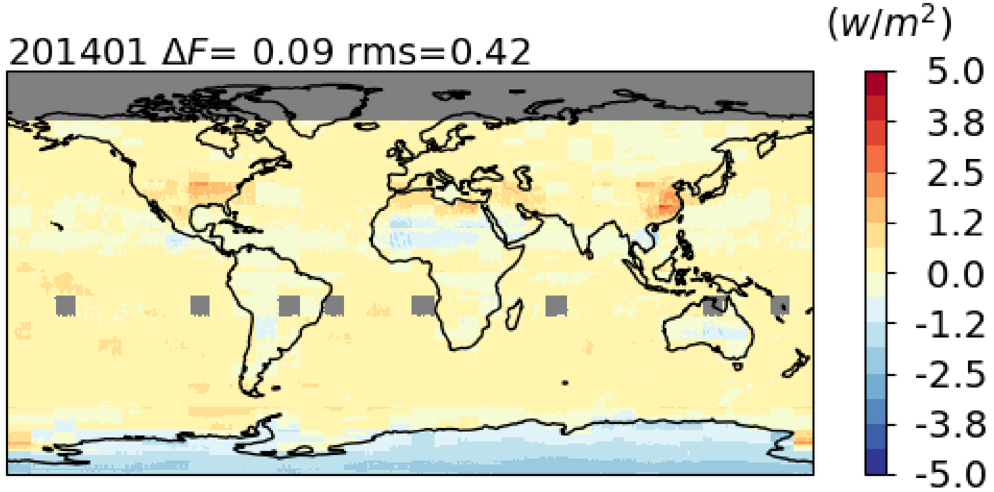
# Flux (by direct integration) differences show no dependence on the ENSO phase (flux by “El Niño ADMs” – flux by “La Nina ADMs”)




MEI= **2.0**



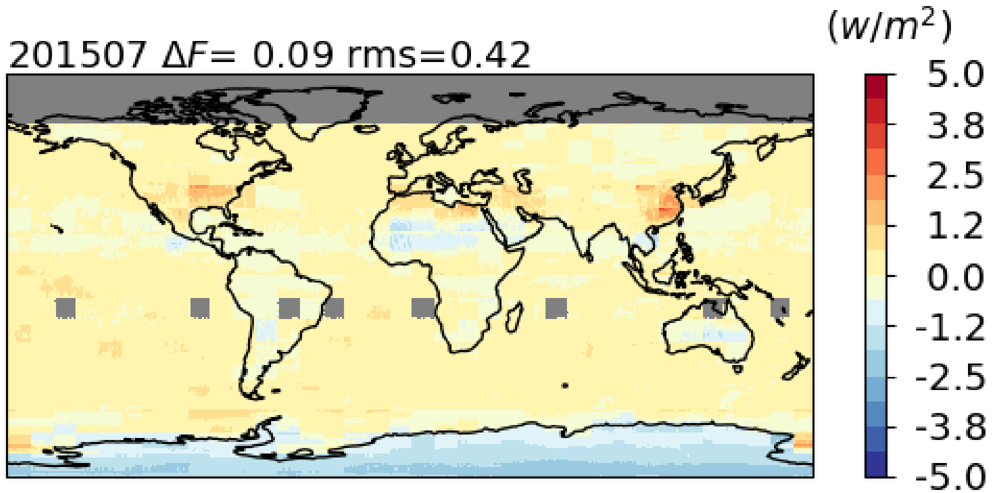

MEI= **-1.8**



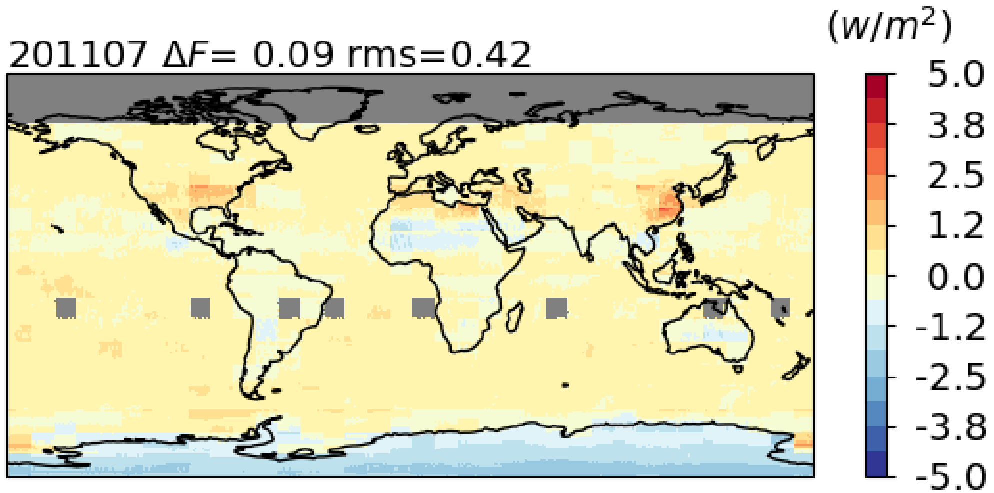

MEI= -0.5

- Flux shows regional differences.
- Flux difference patterns are similar for El Niño, La Niña, and neutral phases.

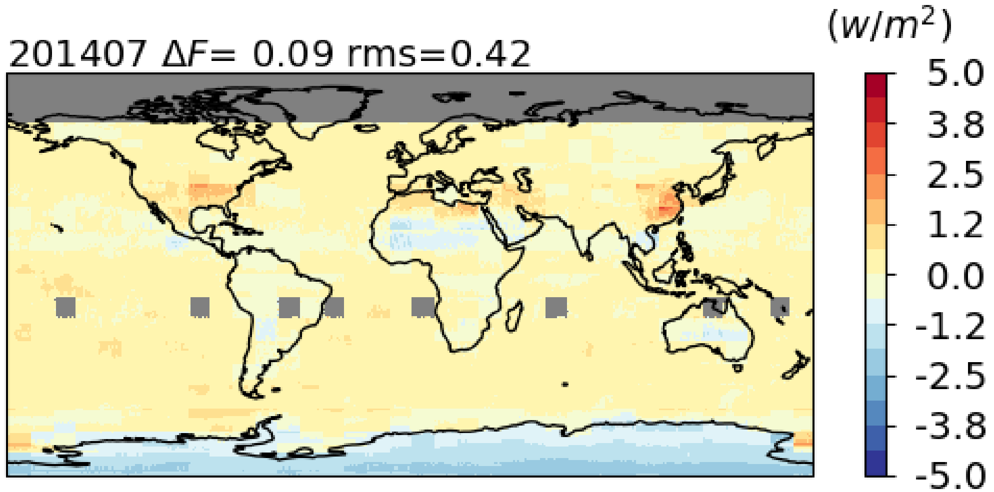
# Flux (by direct integration) differences show no dependence on the ENSO phase (flux by "El Niño ADMs" – flux by "La Nina ADMs")




MEI= **1.7**



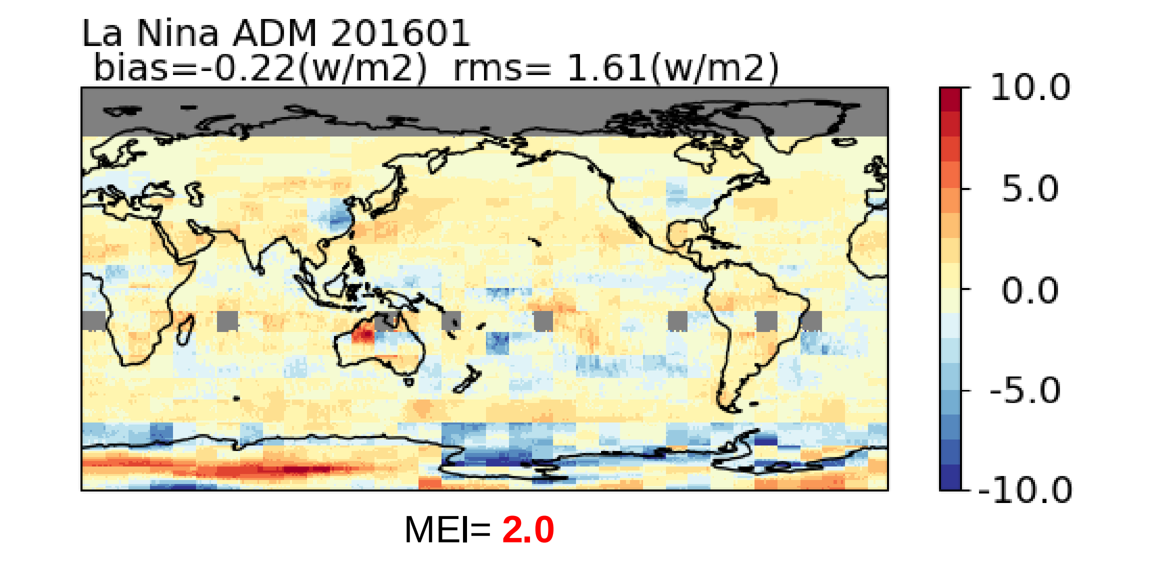

MEI= **-0.9**

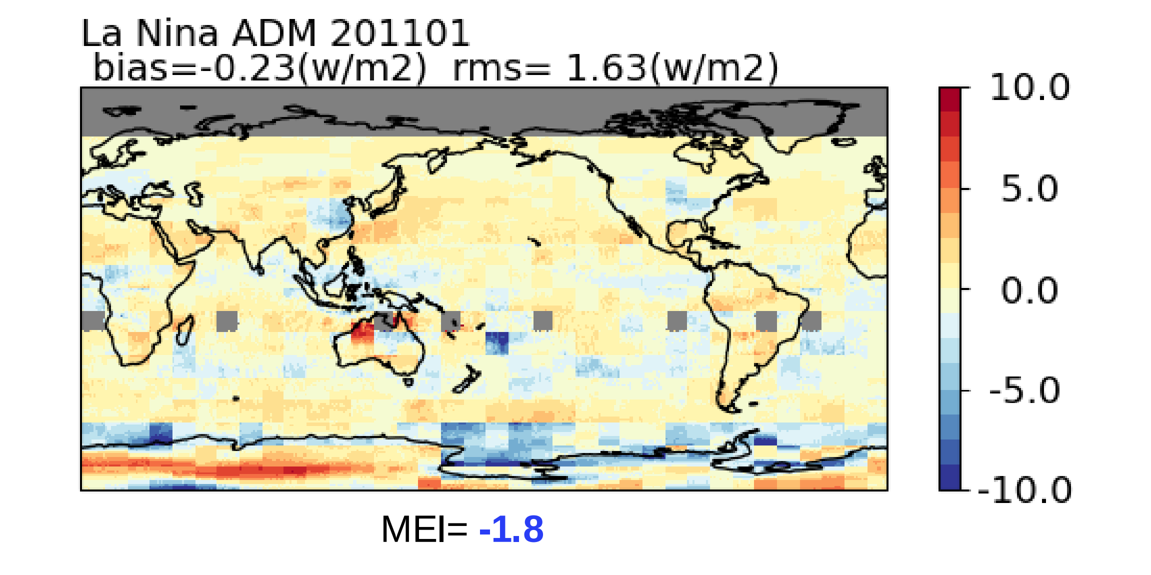


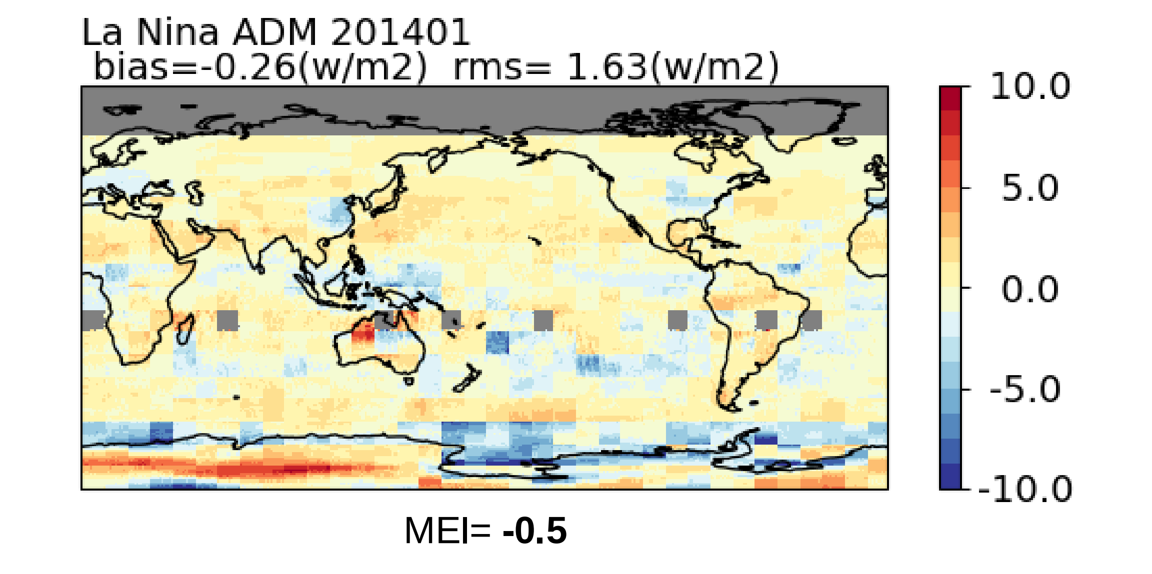

MEI= 0.3

- Flux shows regional differences.
- Flux difference patterns are similar for El Niño, La Niña, and neutral phases.

# Flux (by direct integration) errors show no dependence on the ENSO phase (flux by “La Niña ADMs” – flux from observed radiance ADM)

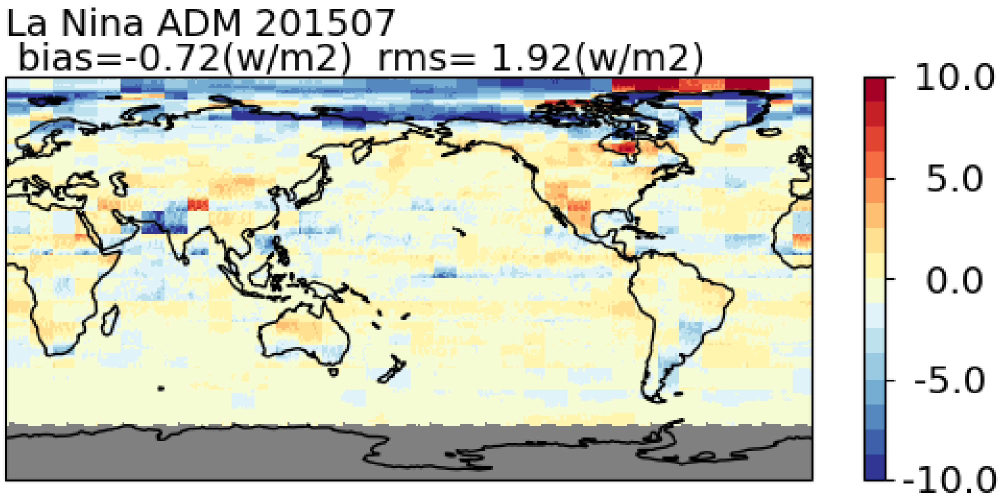


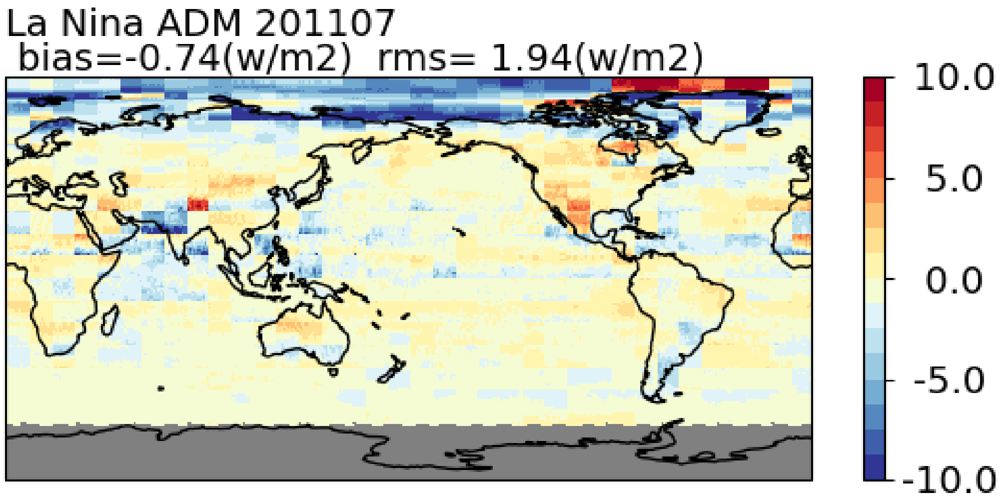




- Errors show regional differences.
- Error patterns are similar for El Niño, La Niña, and neutral phases.

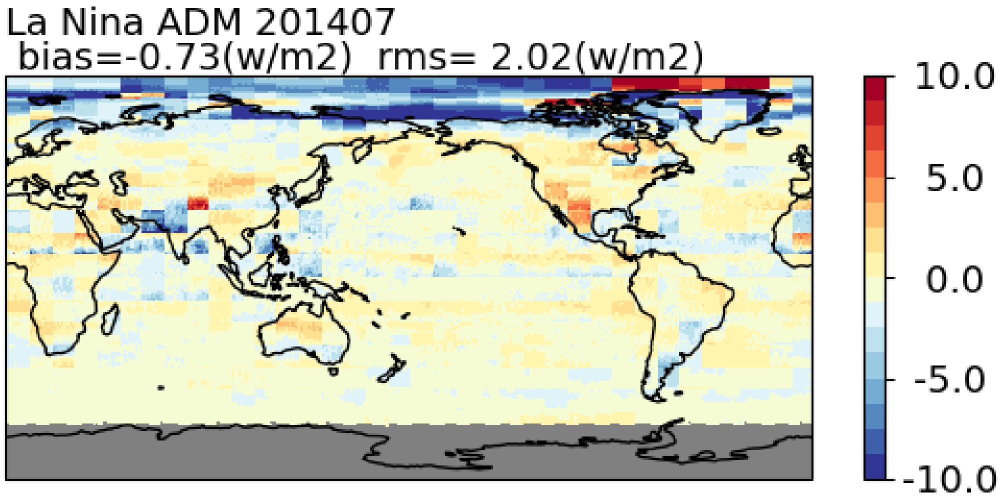
# Flux (by direct integration) errors show no dependence on the ENSO phase (flux by "La Niña ADMs" – flux from observed radiance ADM)



MEI= 1.7



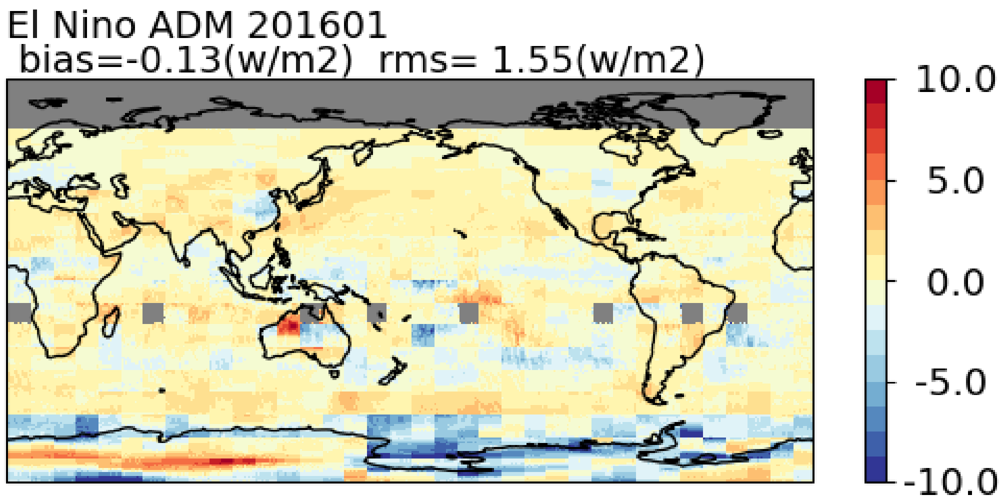
MEI= -0.9



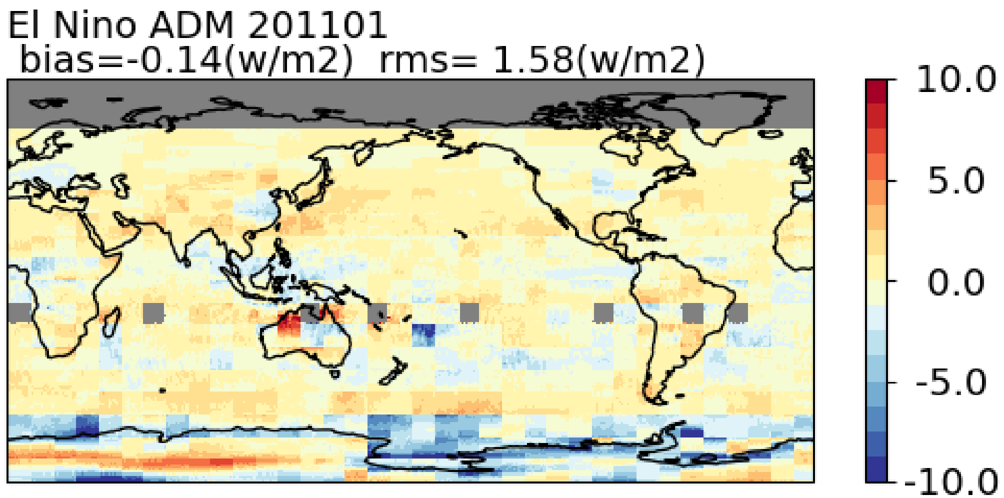
MEI= 0.3

- Errors show regional differences.
- Error patterns are similar for El Niño, La Niña, and neutral phases.

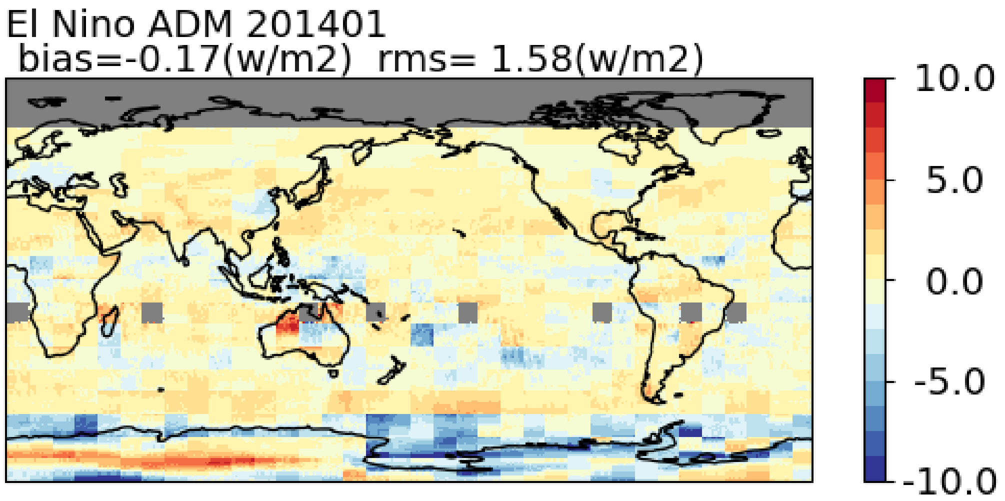
# Flux (by direct integration) errors show no dependence on the ENSO phase
## (flux by "El Niño ADMs" – flux from observed radiance ADM)




MEI= **2.0**



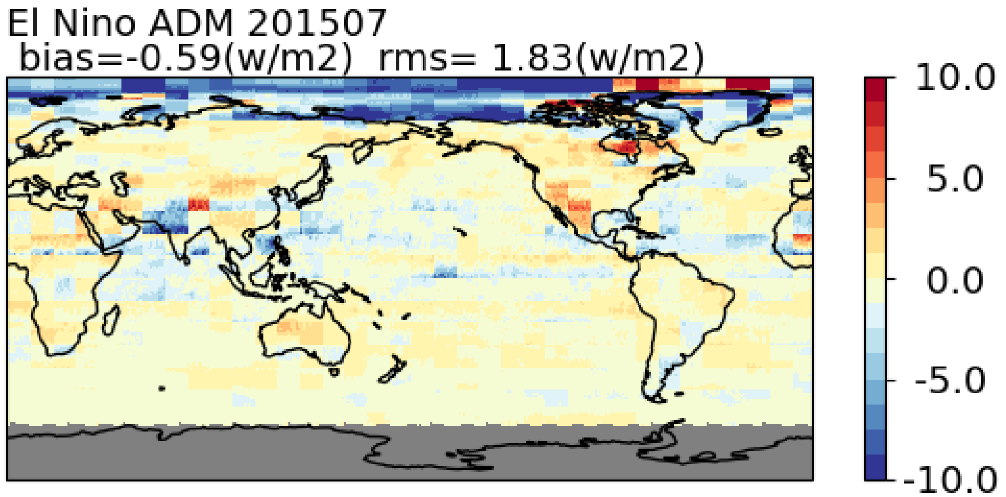

MEI= **-1.8**



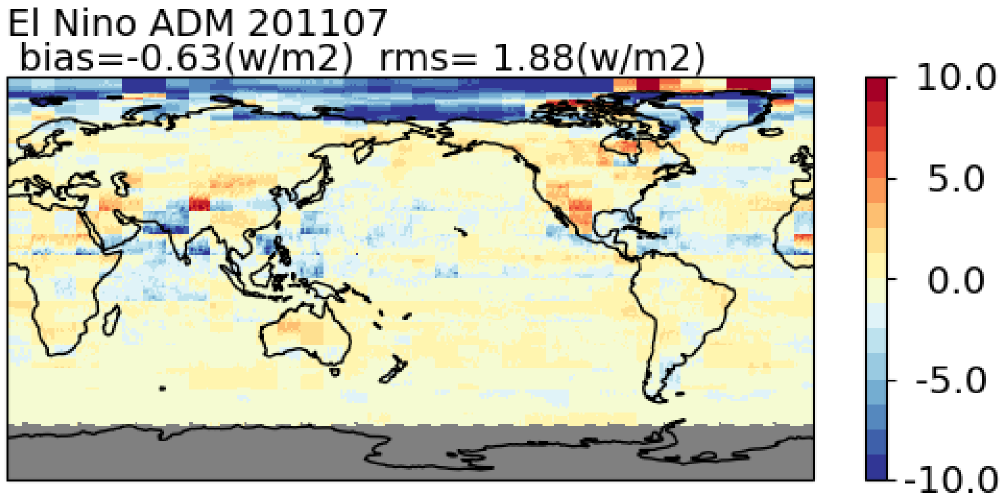

MEI= **-0.5**

- Errors show regional differences.
- Error patterns are similar for El Niño, La Niña, and neutral phases.

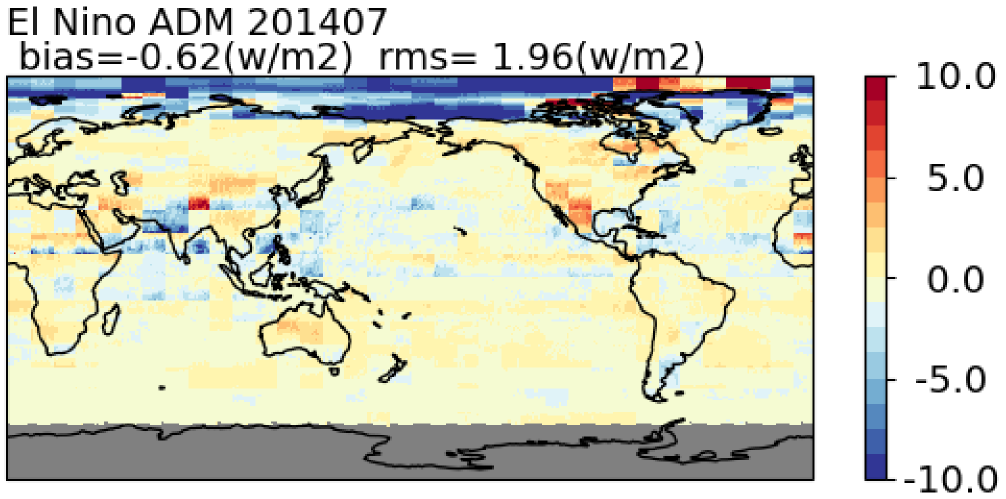
# Flux (by direct integration) errors show no dependence on the ENSO phase (flux by “El Niño ADMs” – flux from observed radiance ADM)




MEI= **1.7**




MEI= **-0.9**

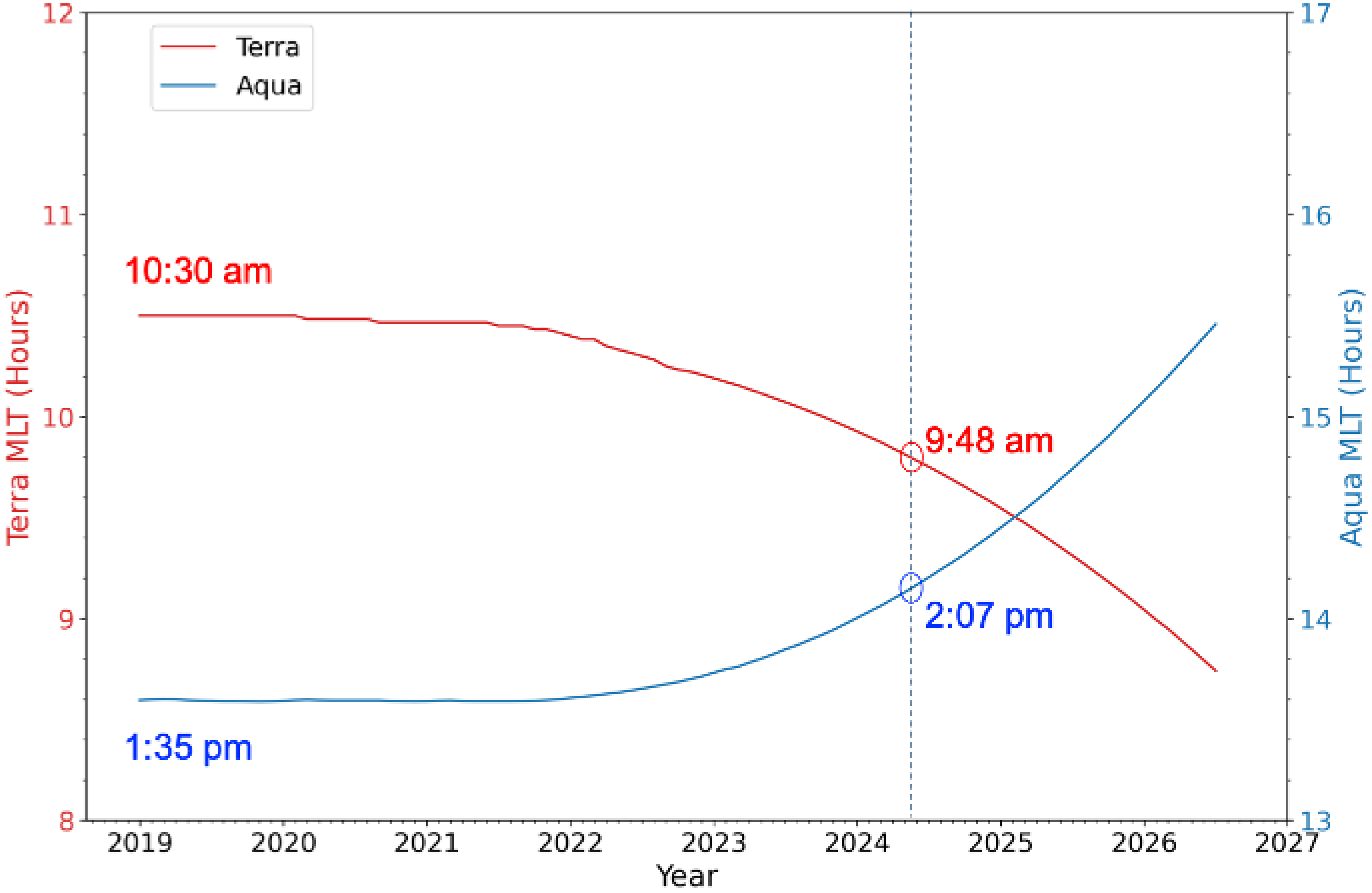



MEI= 0.3

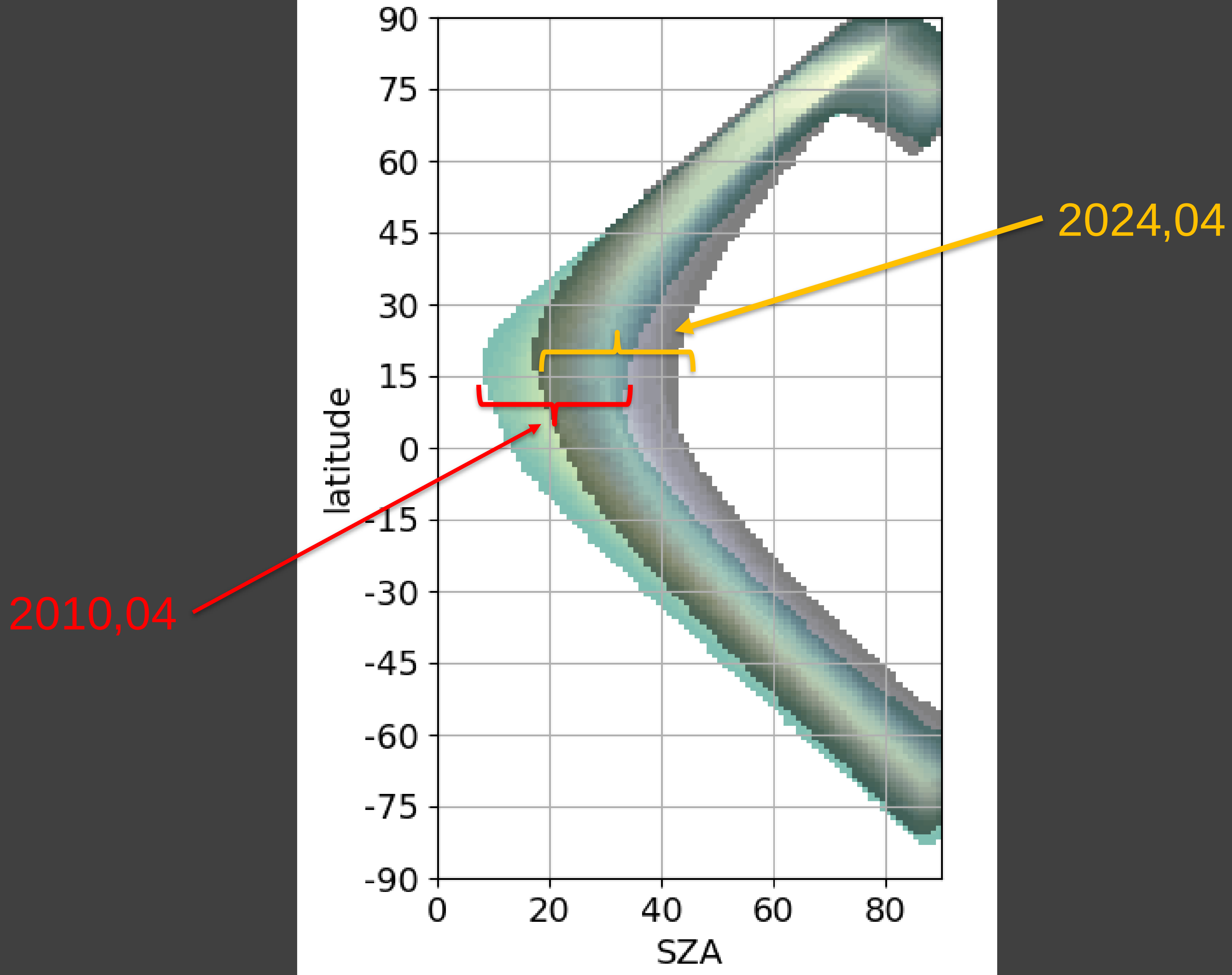
- Errors show regional differences.
- Error patterns are similar for El Niño, La Niña, and neutral phases.

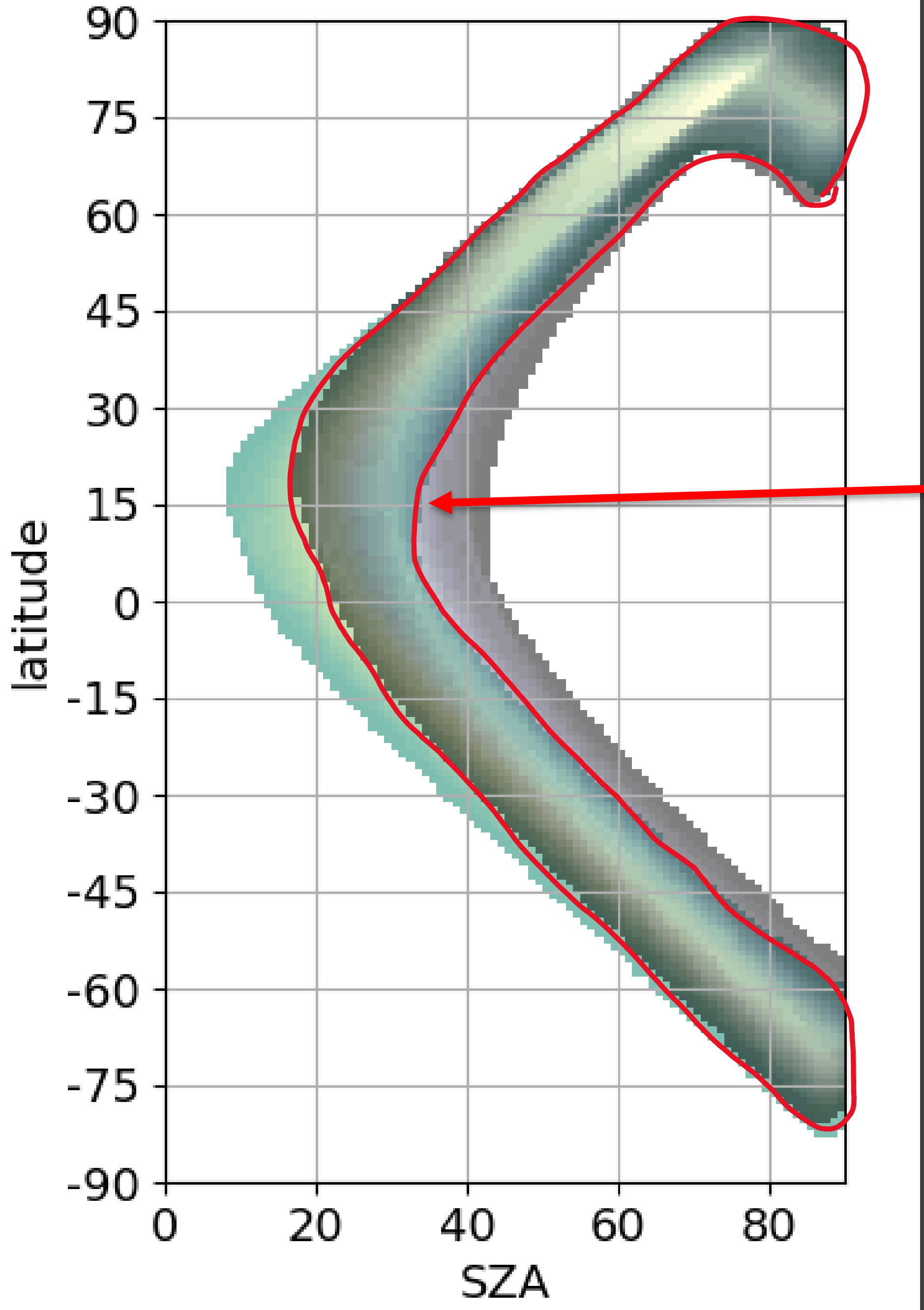
# Impact of Terra orbital drifting on SW CERES ADMs

# Terra and Aqua Mean Local Equatorial Crossing Times (MLTs)

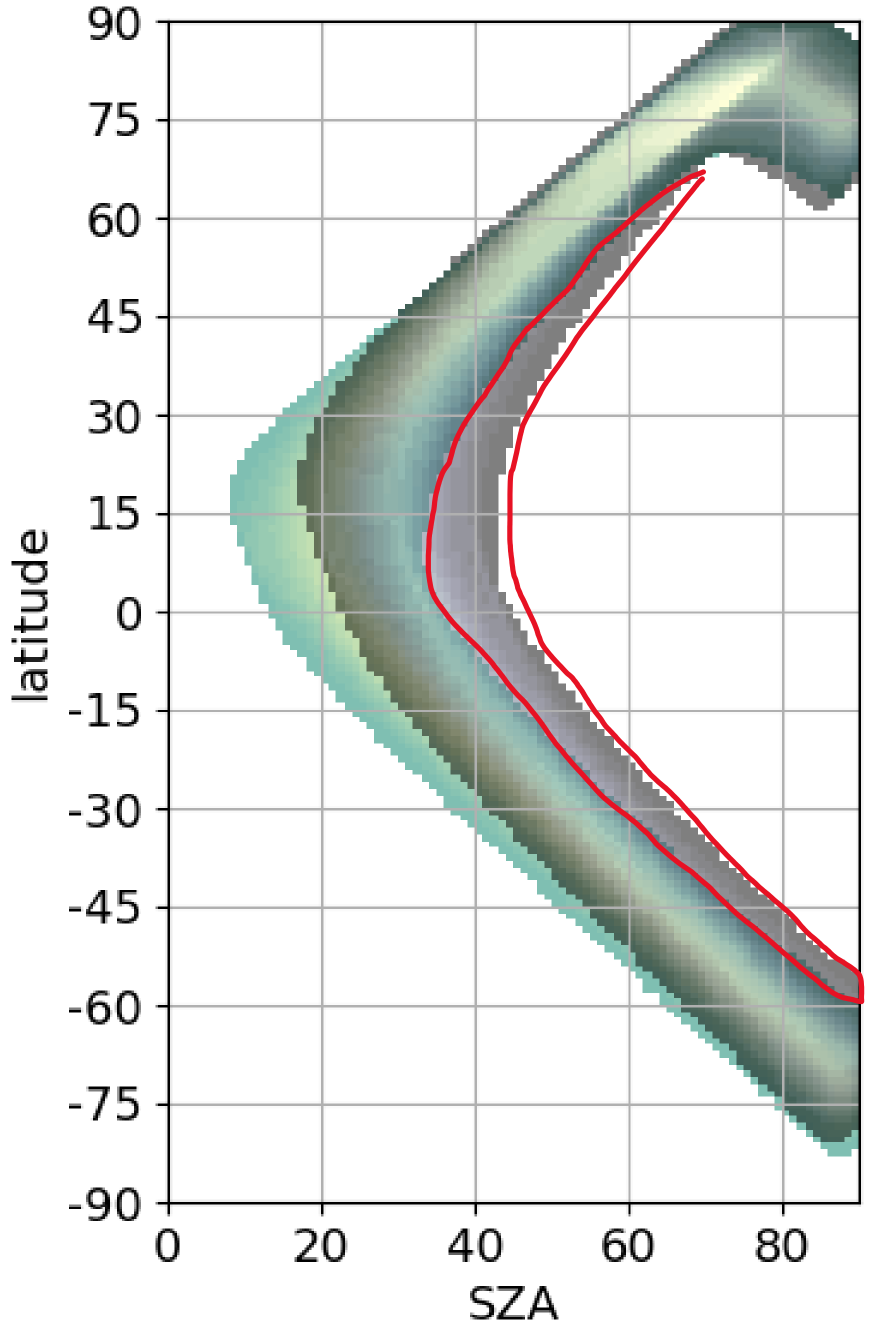



- **MLT updates available at: https://terra.nasa.gov & https://aqua.nasa.gov**


2024,04
2010,04
latitude
SZA
90
75
60
45
30
15
0
-15
-30
-45
-60
-75
-90
0
20
40
60
80



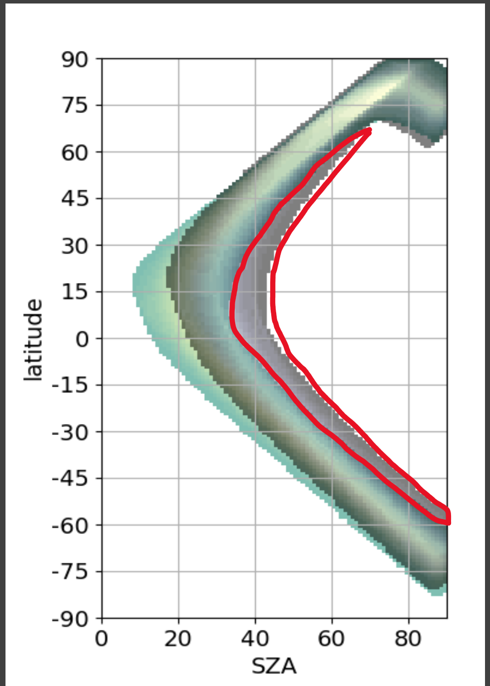

SZAs are seen in both Apr 2010 and Apr 2024



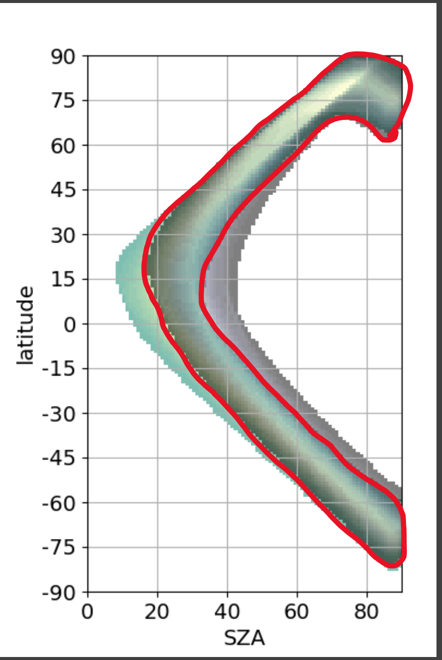

Larger SZAs are not seen in Apr 2010.

# ADMs

- Terra Edition 4 ADMs were constructed from cross-track and RAPS data from April 2000 to May 2005.
- A set of new SW ADMs is constructed by adding additional ~2.5 years of Terra-FM2 RAPS data from Nov 2021 to Apr 2024.
- Compare fluxes derived from the two sets of ADMs for data with larger SZA not seen as in Apr 2010.

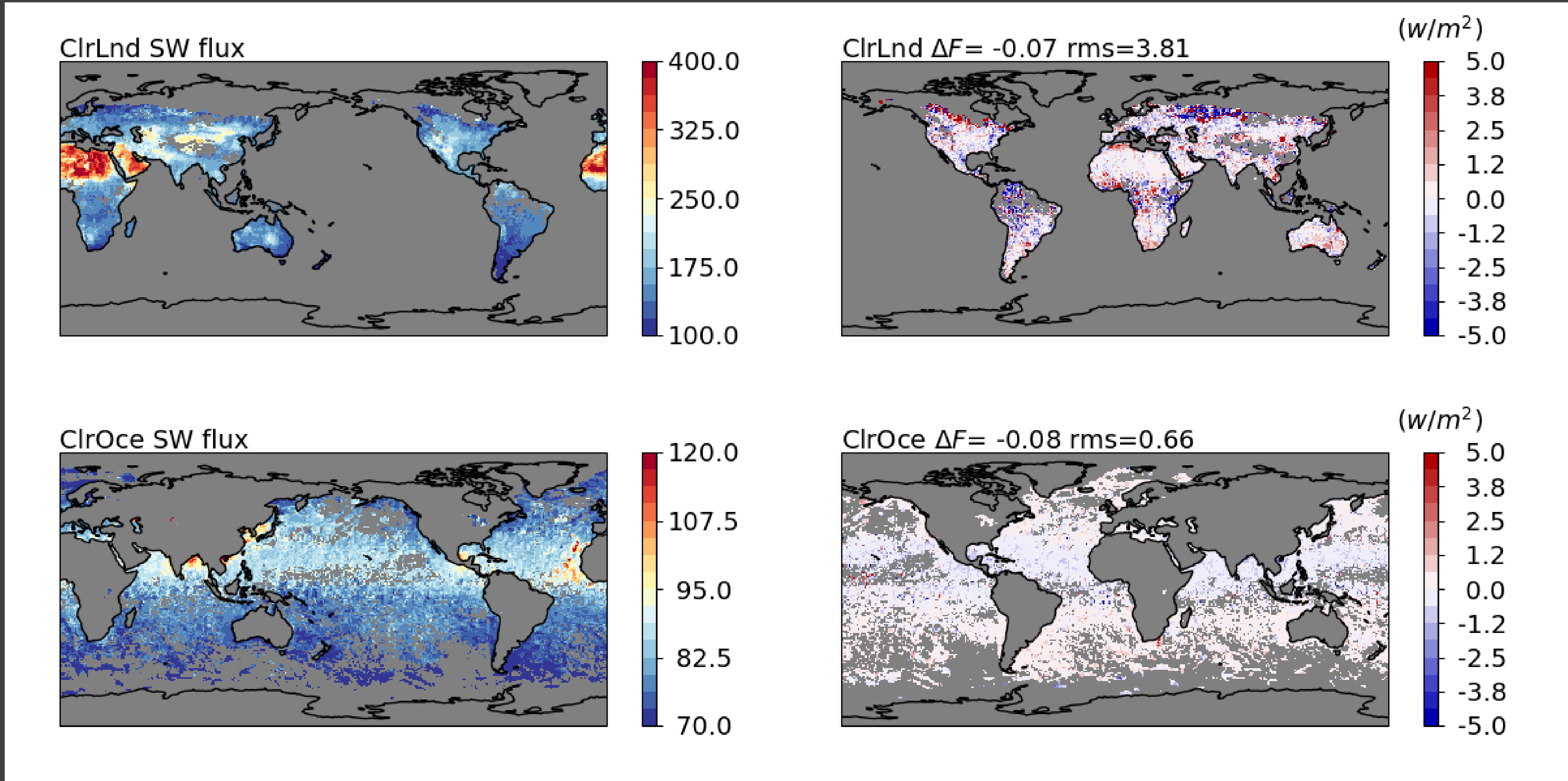


# Fluxes and differences for data with SZAs covered in both Apr 2010 and Apr 2024




## By Ed4 ADMs

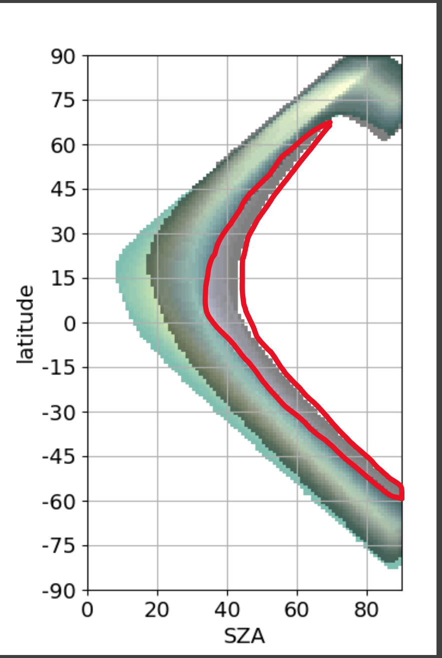
## New ADMs- Ed4 ADMs

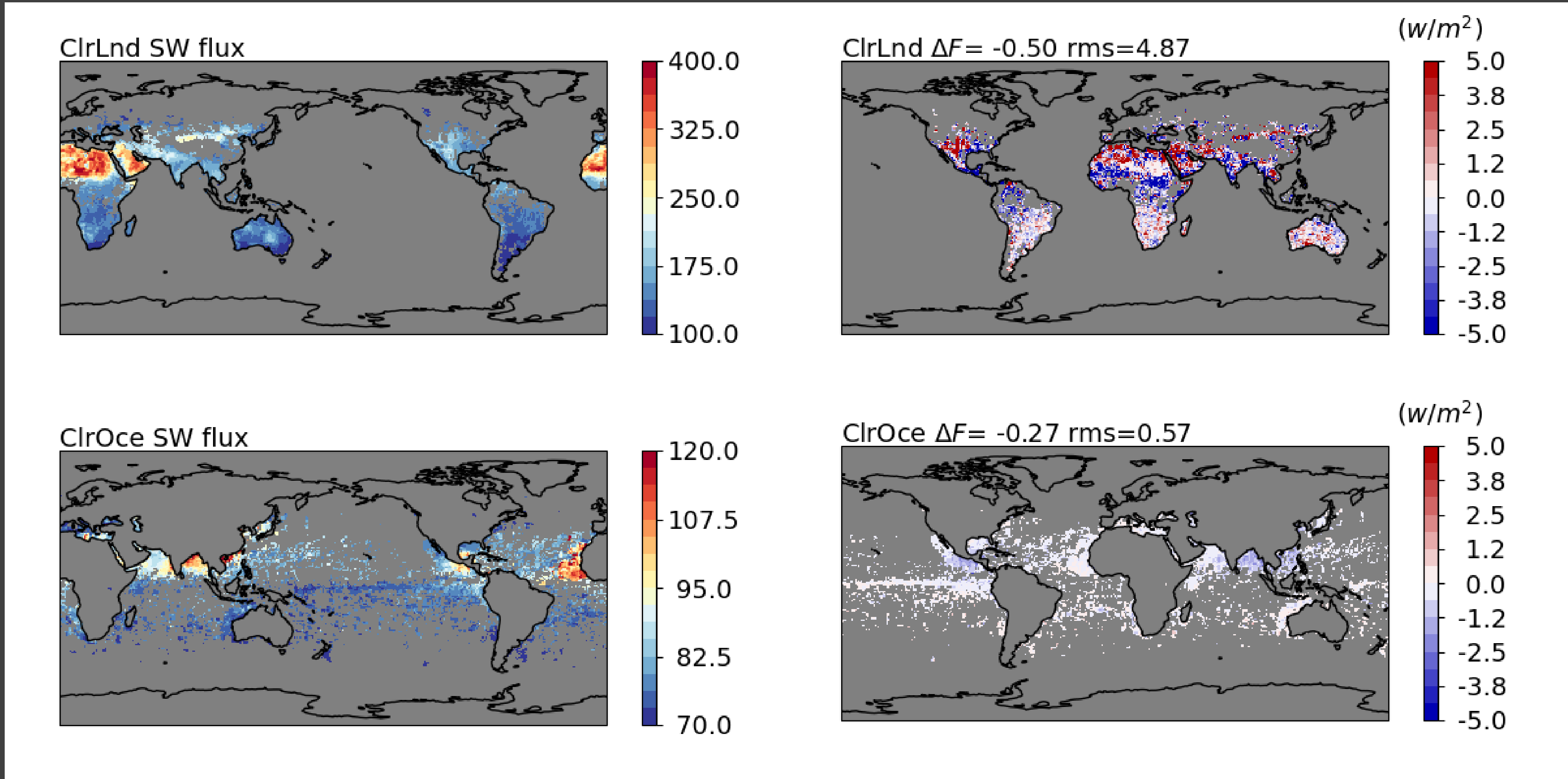


# Fluxes and differences for larger SZAs not covered in Apr 2010

## By Ed4 ADMs

## New ADMs- Ed4 ADMs



# Why do we see large differences in clear-sky land for larger SZAs not seen in Apr 2010

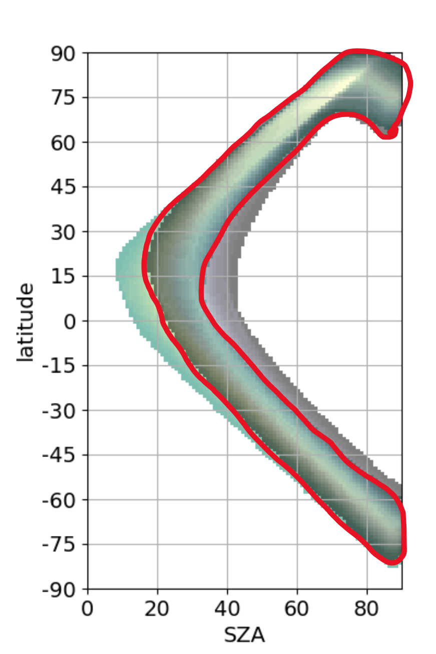
- Within each 1x1-degree region, ADMs are available for SZA-NDVI bins.

| example | SZA bins | | | | ADM selection | | |
|---|---|---|---|---|---|---|---|
| | Bin1 | Bin2 | Bin2 | Bin4 | Step1 | Step2 | step3 |
| Ed4 | $\Delta I_1$ | $\Delta I_2$ | | | $\min(\Delta I_1, \Delta I_2)$ | Searching neighboring grids by $\min(\Delta I_1, \Delta I_2, \ldots, \Delta I_n)$ | TRMM |
| new ADM | $\Delta I_1$ | $\Delta I_2$ | $\Delta I_3$ | $\Delta I_4$ | $\min(\Delta I_1, \Delta I_2, \Delta I_3, \Delta I_4)$ | | |

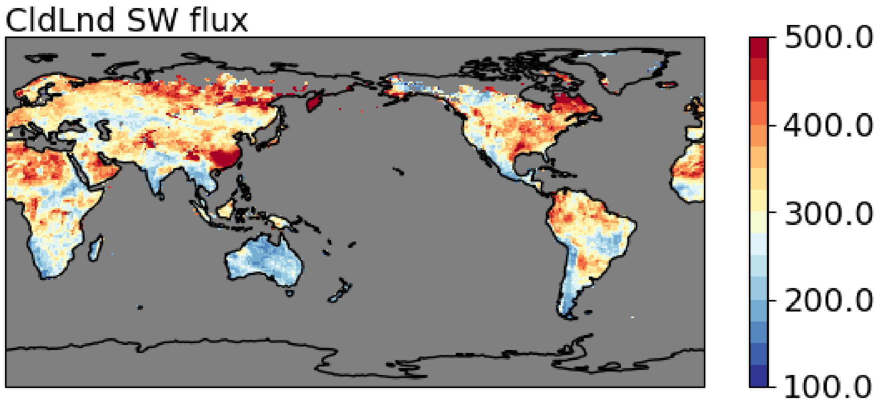
where, $\Delta I_j$ is the radiance difference between observed and ADM-predicted

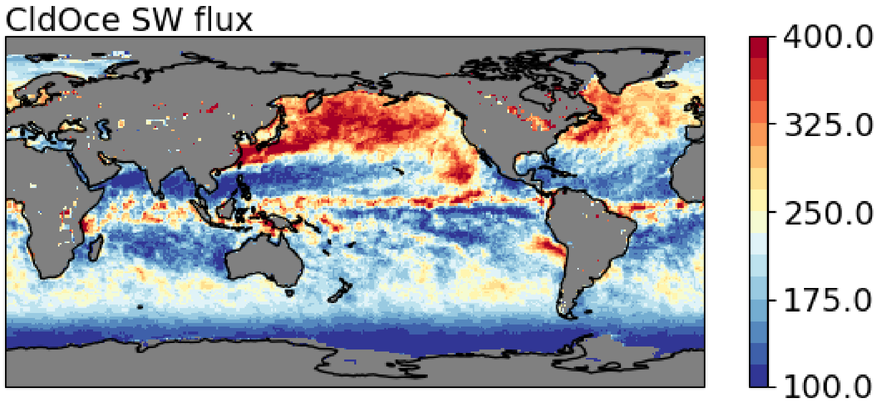
- Given an observations with a large SZA,
- For Ed4, $\Delta I_3$ and $\Delta I_4$ are not available, Step 1 fails automatically, Steps 2 and 3 are used instead.
- For new ADM, $\Delta I_1$ *to* $\Delta I_4$ are available in Step1.
- The flux differences are caused by Ed4 using Steps 2 and 3 and new ADM using Step1.

# Fluxes and differences for SZAs covered in both Apr 2010 and Apr 2024

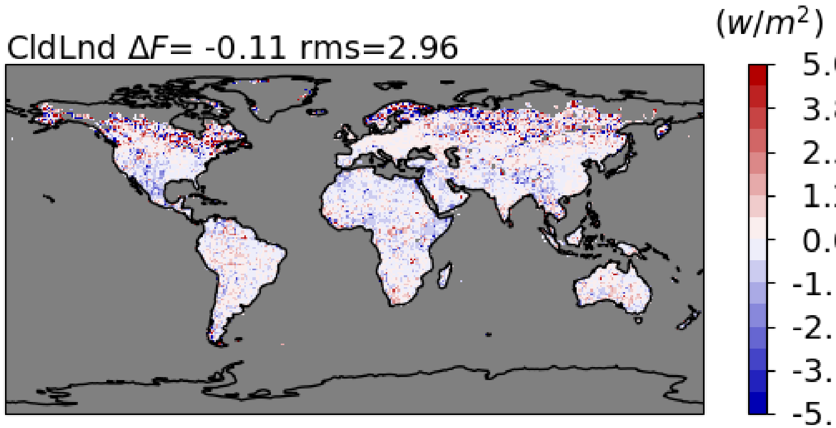


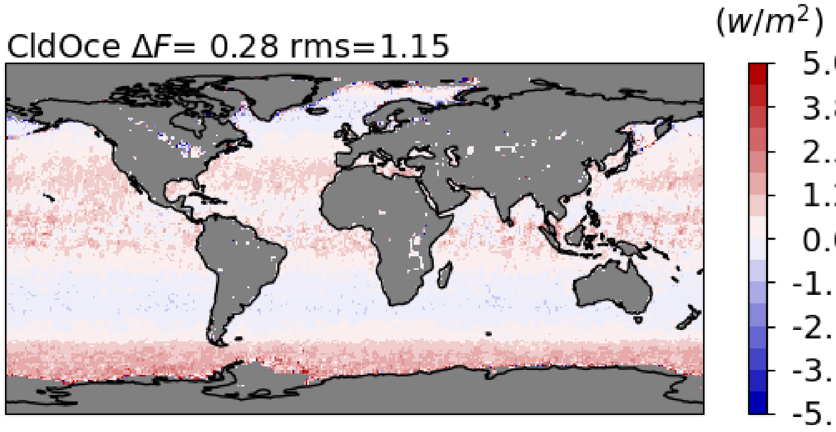

## By Ed4 ADMs



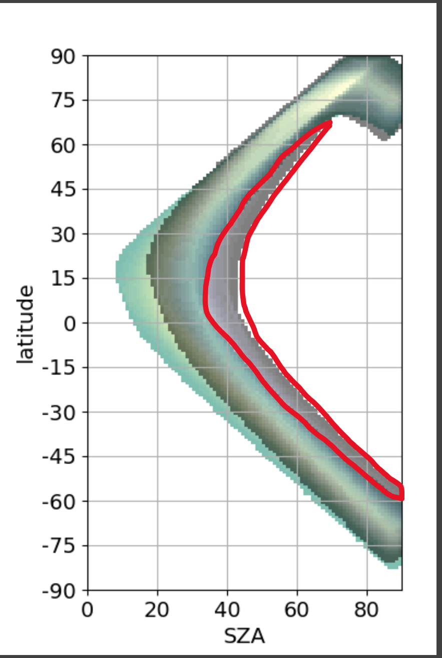




## New ADMs- Ed4 ADMs



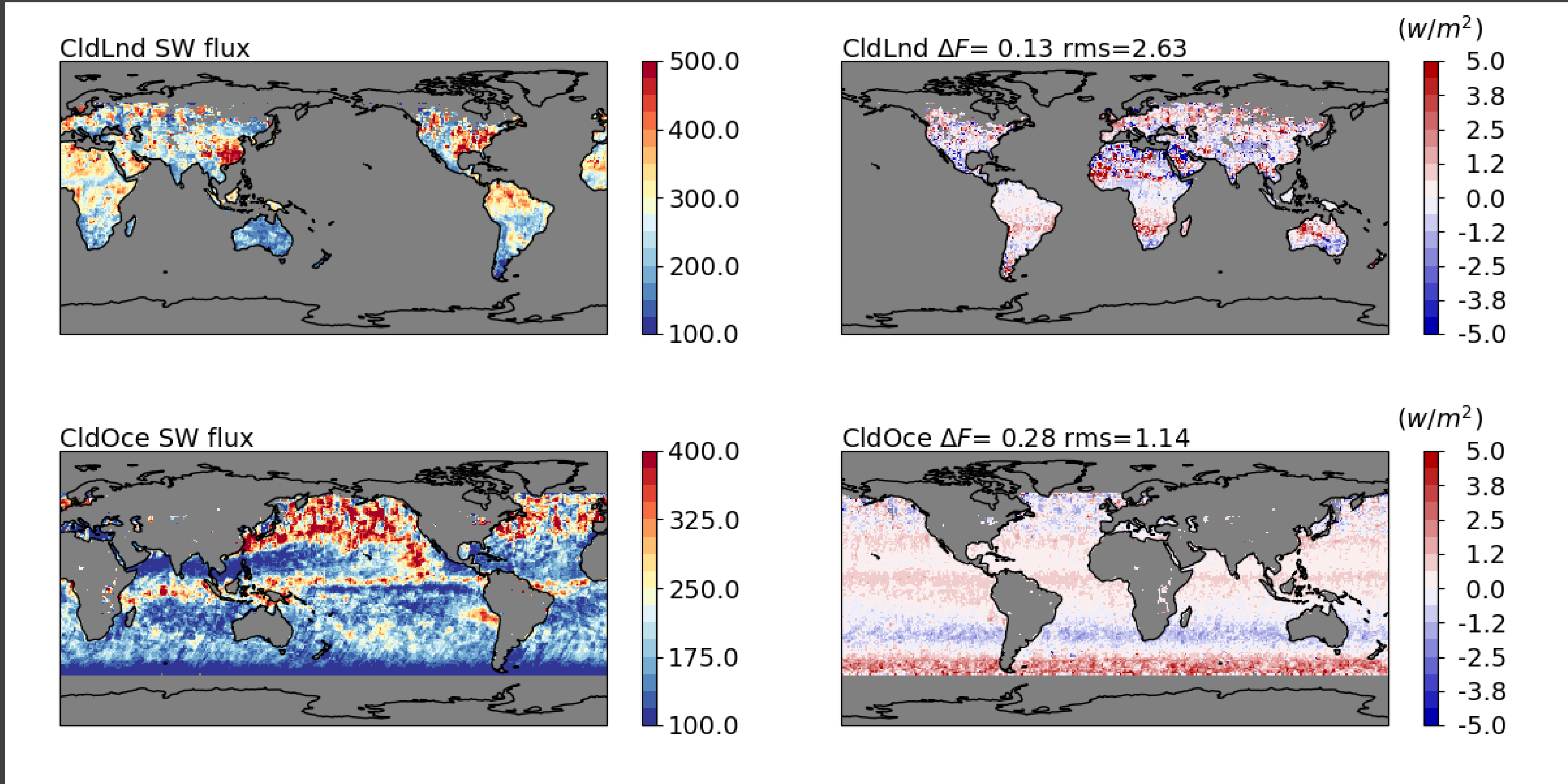



# Fluxes and differences for large SZAs not covered in Apr 2010

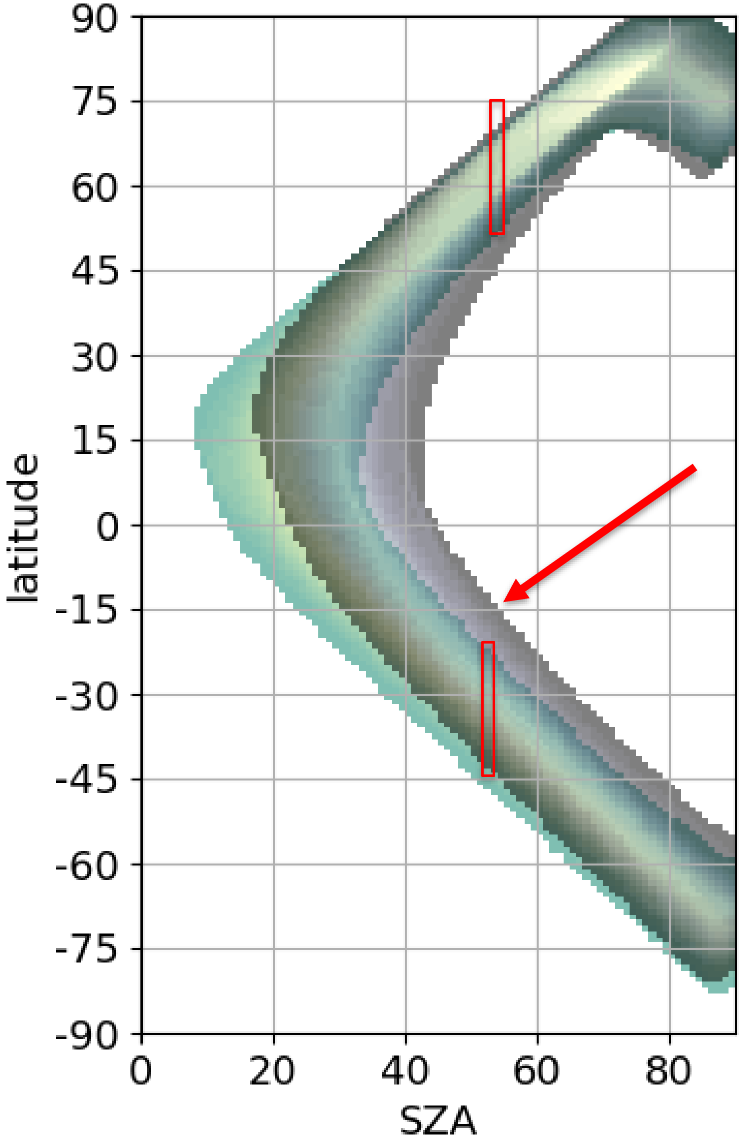



By Ed4 ADMs

New ADMs- Ed4 ADMs



# Why do we see large differences in cloudy-sky ocean for larger SZAs not seen in Apr 2010




- SZA correlates to latitude.
- For a scene with a larger SZA, the selected Ed4 ADM is constructed with observations including data over higher latitude regions.
- The selected new ADM is constructed within the same latitude range for the scene.

For example,
In Ed4, the flux for an observation at 15S with SZA=55 deg. is inverted by an ADM constructed by observations within ~25-45S and ~50-65N, instead of observations around 15S.

# Summary

- Using data taken during different ENSO phases to test SW and LW ADM sensitivity to climate variability.
- LW ADMs constructed using data taken during El Niño phase and La Niña phase have a minimum impact on flux.
- SW fluxes inverted from El Niño and La Niña ADMs show consistent regional difference features that are independent of the ENSO phase of each month.
- Flux inverted by the direct integration from El Niño and La Niña ADMs show consistent regional difference features that are independent of the ENSO phase of each month.
- Adding RAPS data during Terra orbital drifting period has noticeable impact on flux inversion for clear sky over land and cloud sky over ocean, and less impact for clear sky over ocean and cloudy sky over land.

# Additional slides

# Direct Integration for SW Flux

- Construct two sets of regional (10° X 10°) all-sky ADMs by season (e.g. DJF, MAM, JJA, and SON) from
  - CERES measured radiances $I_o \rightarrow F(\theta_0) = \dfrac{\pi I_o(\theta_0, \theta, \phi)}{R(\theta_0, \theta, \phi)}$
  - ADM predicted radiances $\hat{I} \rightarrow R(\theta_0, \theta, \phi) = \dfrac{\pi \hat{I}(\theta_0, \theta, \phi)}{\hat{F}(\theta_0)}$
- Both sets of regional all-sky ADMs have the same sampling
- Apply regional ADMs to cross track data of the middle month of the season to determine the fluxes
- Compare fluxes derived from these two sets of ADMs

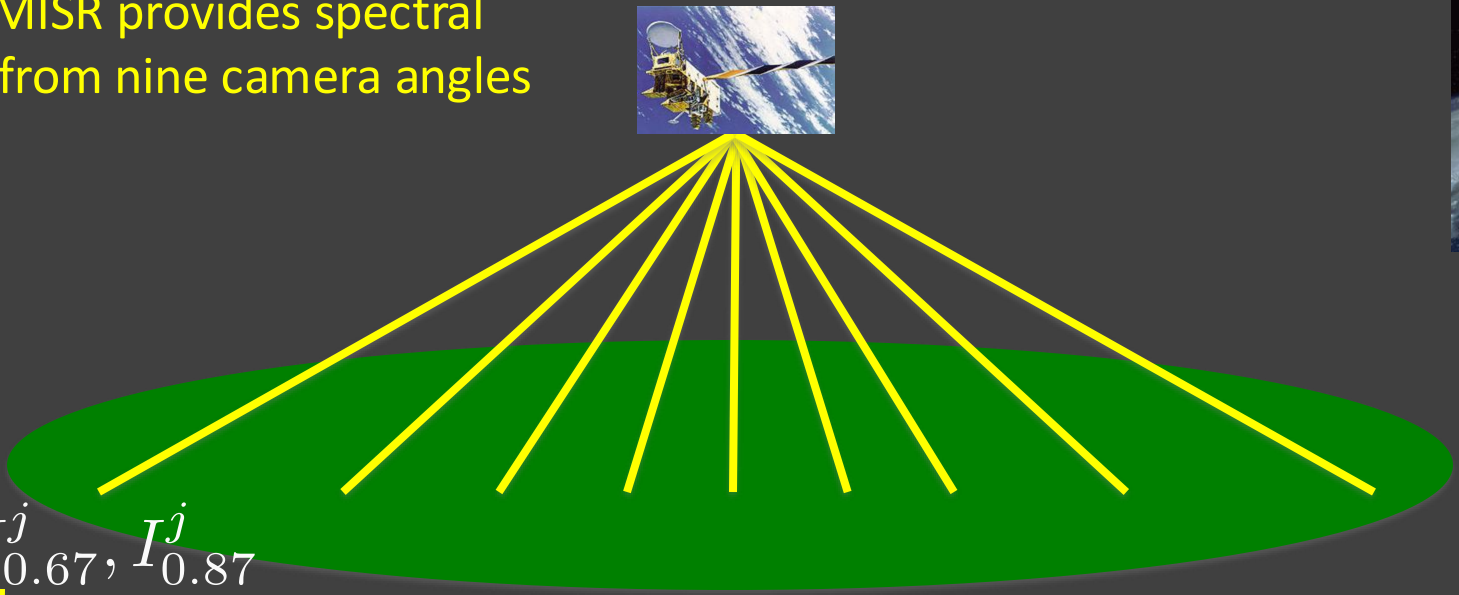
# Direct integration for LW flux

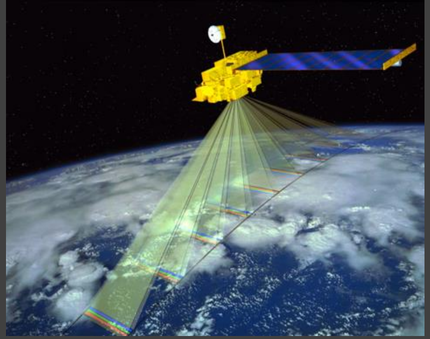
- Direct integration (DI) calculates the regional ($10^o$ x $10^o$) seasonal (DJF, MAM, JJA, SON) all-sky fluxes by directly integrating the CERES measured radiances ($I_o$) from both cross-track and RAPS measurements:

$$F(\theta_0) = \int_0^{2\pi} \int_0^{\pi/2} I_o(\theta_0, \theta, \phi) cos\theta sin\theta d\theta d\phi$$

- DI is done separately for daytime and nighttime observations.
- LW flux error is assessed by comparing the averaged ADM-derived TOA LW fluxes with the fluxes derived from DI.
- Weight the daytime and nighttime flux error by fraction of daylight at each latitude for each month to derive the 24h-averaged flux error.

For a CERES footprint, MISR provides spectral radiance measurements from nine camera angles





$$I_{0.45}^{j}, I_{0.67}^{j}, I_{0.87}^{j}$$

$$I_{sw}^{j} = c_0 + c_1 I_{0.45}^{j} + c_2 I_{0.67}^{j} + c_3 I_{0.87}^{j}$$

$$I_{sw}^{j}$$

CERES ADM

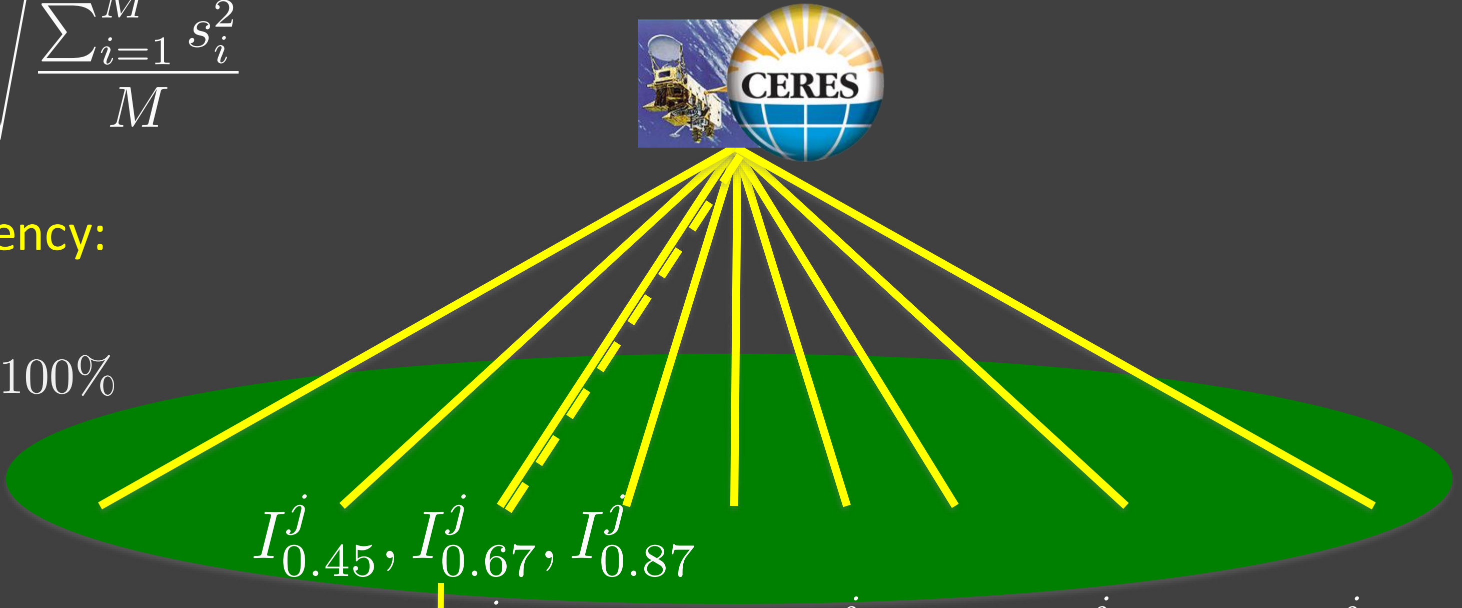
$$F_{sw}^{j} \longrightarrow \overline{F_{sw}} = \frac{\sum_{j=1}^{9} F_{sw}^{j}}{9} \longrightarrow s = \sqrt{\frac{\sum_{j=1}^{n} (F_{sw}^{j} - \overline{F_{sw}})^2}{n-1}}$$

For M CERES footprints, we calculate the mean standard deviation:

$$\overline{\sigma} = \sqrt{\frac{\sum_{i=1}^{M} s_i^2}{M}}$$

and the overall relative consistency:

$$CV_T = \left( \frac{\sqrt{\frac{1}{M}\sum_{i=1}^{M} s_i^2}}{\frac{1}{M}\sum_{i=1}^{M} \overline{F_{sw}^i}} \right) \times 100\%$$




$$I_{0.45}^j, I_{0.67}^j, I_{0.87}^j$$

$$I_{sw}^j = c_0 + c_1 I_{0.45}^j + c_2 I_{0.67}^j + c_3 I_{0.87}^j$$

$$I_{sw}^j \; I_{sw}^c$$

CERES ADM

$$F_{sw}^j \; F_{sw}^c \longrightarrow CV_{NB} = \left( \frac{\sqrt{\frac{1}{m}\sum_{i=1}^{m}(F_{sw}^j - F_{sw}^c)^2}}{\frac{1}{m}\sum_{i=1}^{m} F_{sw}^c} \right) \times 100\%$$

$$CV_{ADM} = \sqrt{CV_T^2 - CV_{NB}^2}$$