Sensitivity of CERES Angular Distribution Models to ENSO Phase

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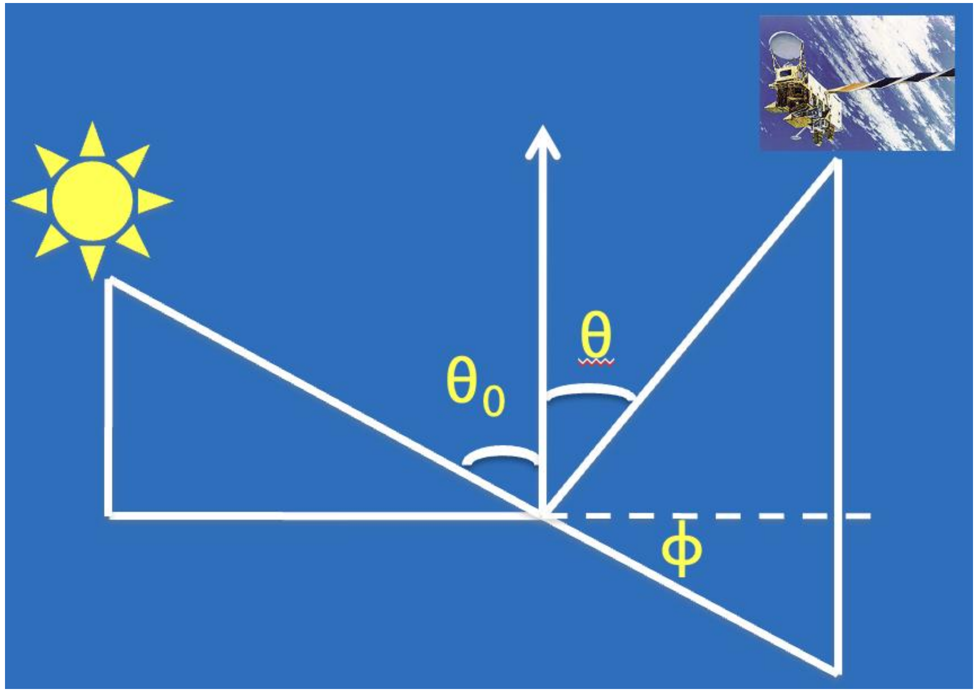
Introduction

- CERES instruments onboard Terra and Aqua measure broadband radiances.
- Scene-dependent Angular Distribution Models (ADMs) are used to convert CERES radiances to irradiances.
- ADMs account for the angular dependence in the observed radiance field, which is a strong function of the physical and optical characteristics of the scene (e.g., surface type, cloud fraction, cloud/aerosol optical depth, cloud phase, etc…) and solar zenith angle.
- CERES ADMs are developed from rotating azimuth plane (RAP) and cross-track scan data from Terra and Aqua satellites for the static period between 2000-2005. The ADMs from this static period are used to produce the fluxes given for the whole CERES period (2000 – present).
- Are ADMs developed from a static period appropriate to calculate fluxes for other periods in the presence of climate variability and change?

Methodology

- For every scene type, bin observed radiances over all relative azimuth (**φ**), viewing (**θ**) and solar zenith angles (**θ_o**) and calculate the mean radiance ($\hat{I}$) for all bins.



- Ratio of isotropic flux to the integrated radiance over the angular space gives the anisotropic factor (*R*):

$$R(\theta_0, \theta, \phi) = \frac{\pi \hat{I}(\theta_0, \theta, \phi)}{\int_0^{2\pi} \int_0^{\frac{\pi}{2}} \hat{I}(\theta_0, \theta, \phi) cos\theta sin\theta d\theta d\phi} = \frac{\pi \hat{I}(\theta_0, \theta, \phi)}{\hat{F}(\theta_0)}$$

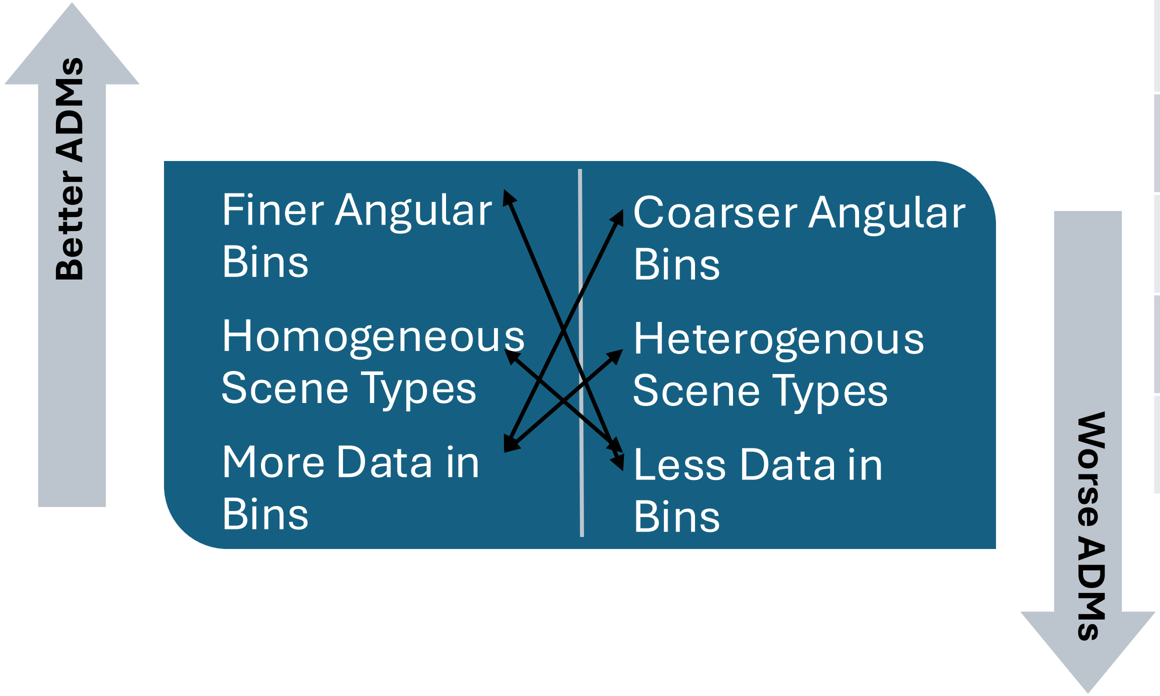
- For each radiance measurement, first determine the scene type, then apply scene type dependent anisotropic factor (i.e., the ADM) to observed radiance to derive TOA flux:

$$F(\theta_0) = \frac{\pi I_o(\theta_0, \theta, \phi)}{R(\theta_0, \theta, \phi)}$$

ENSO Climate Variability

- Leverage ENSO variability during the ADM development period (2000-2005) to investigate ADM sensitivity to climate variability.

- Develop two sets of ADMs: La Niña ADMs and El Niño ADMs.



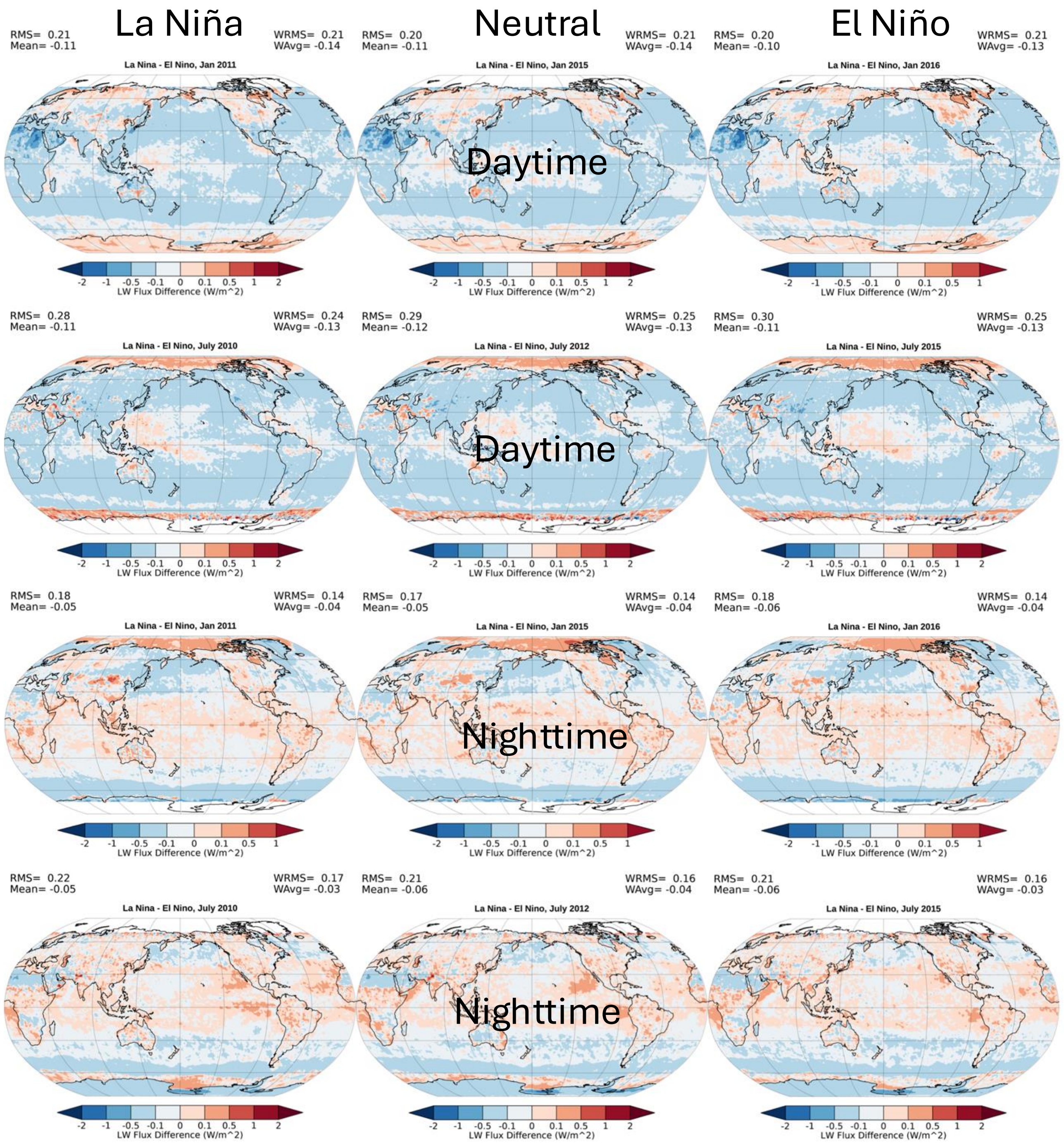
Multivariate ENSO Index :

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000				-0.9	-0.9	-1.2	-0.6*	-0.1	-0.3	-0.5*	-0.9*	-0.8*
2001	-0.8*	-0.9*	-0.8*	-0.6	-0.5	-0.7	0	0.4	-0.1	-0.2	-0.3	0.1
2002	0.1	-0.3	-0.2	-0.4	-0.1	0.3	0.4	1	0.9	0.8*	0.8*	0.9*
2003	0.8*	0.6*	0.5*	-0.1	-0.6	-0.1	0	0.1	0.2	0.3	0.3	
2004	0.2	0		-0.2	-0.5	-0.4	0.5*	0.8	0.6	0.4	0.6	0.5
2005	0.1			0.1	0.2							

- CERES Edition 4 methodology is used for LW and snow/ice SW ADMs, while the simpler CERES TRMM methodology is adopted for ocean and land SW ADMs.

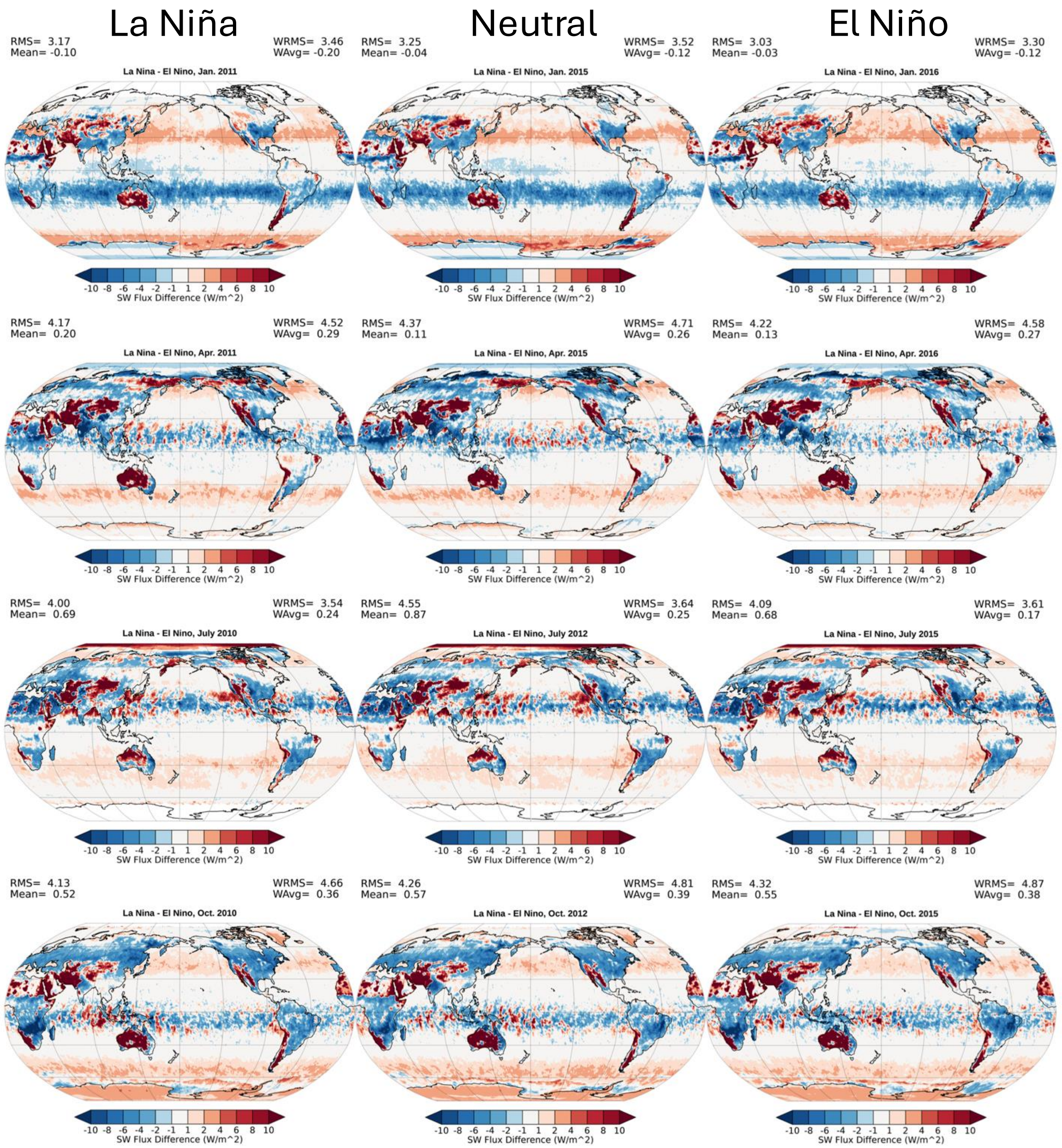
Longwave Flux Differences

- Difference between LW fluxes computed from La Niña ADMs and El Niño ADMs is small for both daytime (0.21-0.25 W*m^{-2}) and nighttime (0.14-0.17 W*m^{-2}).
- Differences display similar spatial patterns despite undergoing distinct phases of ENSO.



Shortwave Flux Differences

- Differences between SW fluxes computed from La Niña ADMs and El Niño ADMs are large for all seasons (3.30-4.87 W*m^{-2}).
- Differences display similar spatial patterns despite undergoing distinct phases of ENSO.



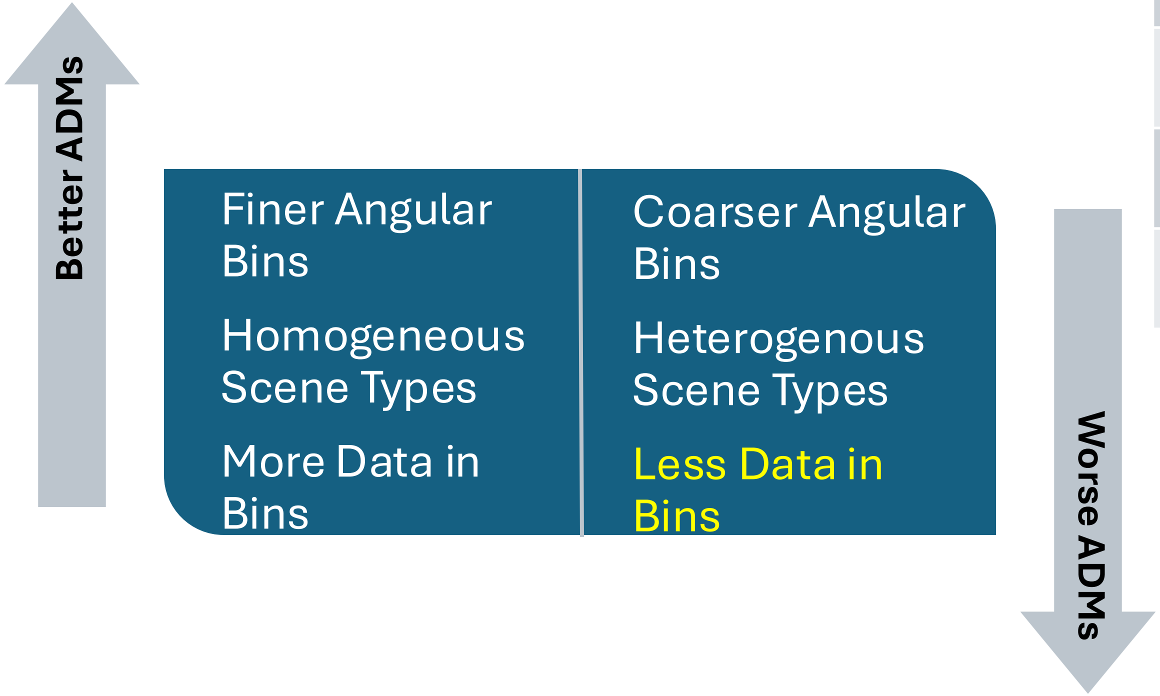
Impacts of Seasonality on ADM Development

- Data used for the development of La Niña and El Niño ADMs is seasonally asymmetric.

- Does the seasonal asymmetry influence the flux differences between the two sets of ENSO ADMs?

Multivariate ENSO Index :

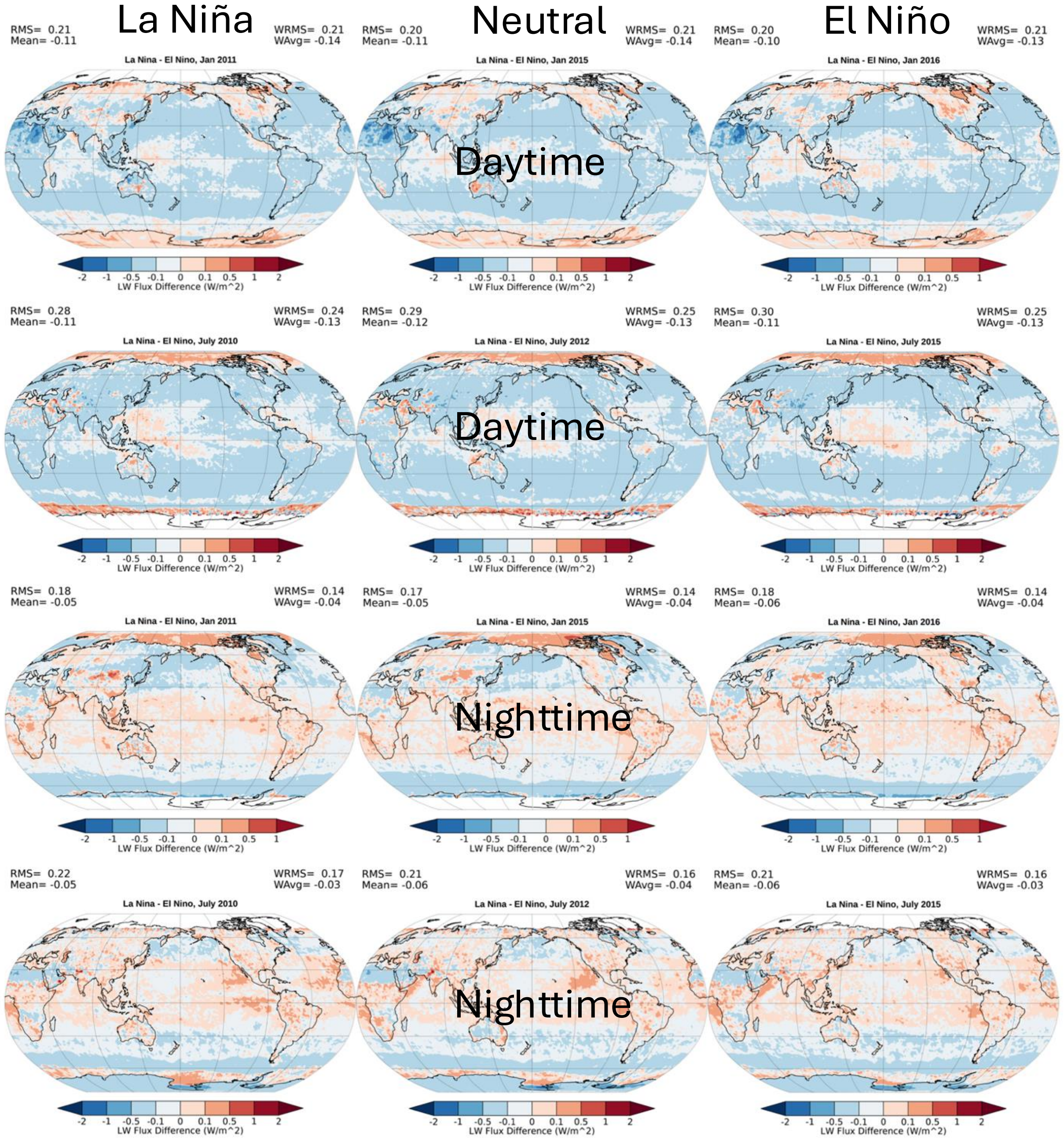
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000				-0.9	-0.9	-1.2	-0.6*	-0.1	-0.3	-0.5*	-0.9*	-0.8*
2001	-0.8*	-0.9*	-0.8*	-0.6	-0.5	-0.7	0	0.4	-0.1	-0.2	-0.3	0.1
2002	0.1	-0.3	-0.2	-0.4	-0.1	0.3	0.4	1	0.9	0.8*	0.8*	0.9*
2003	0.8*	0.6*	0.5*	-0.1	-0.6	-0.1	0	0.1	0.2	0.3	0.3	
2004	0.2	0		-0.2	-0.5	-0.4	0.5*	0.8	0.6	0.4	0.6	0.5
2005	0.1			0.1	0.2							



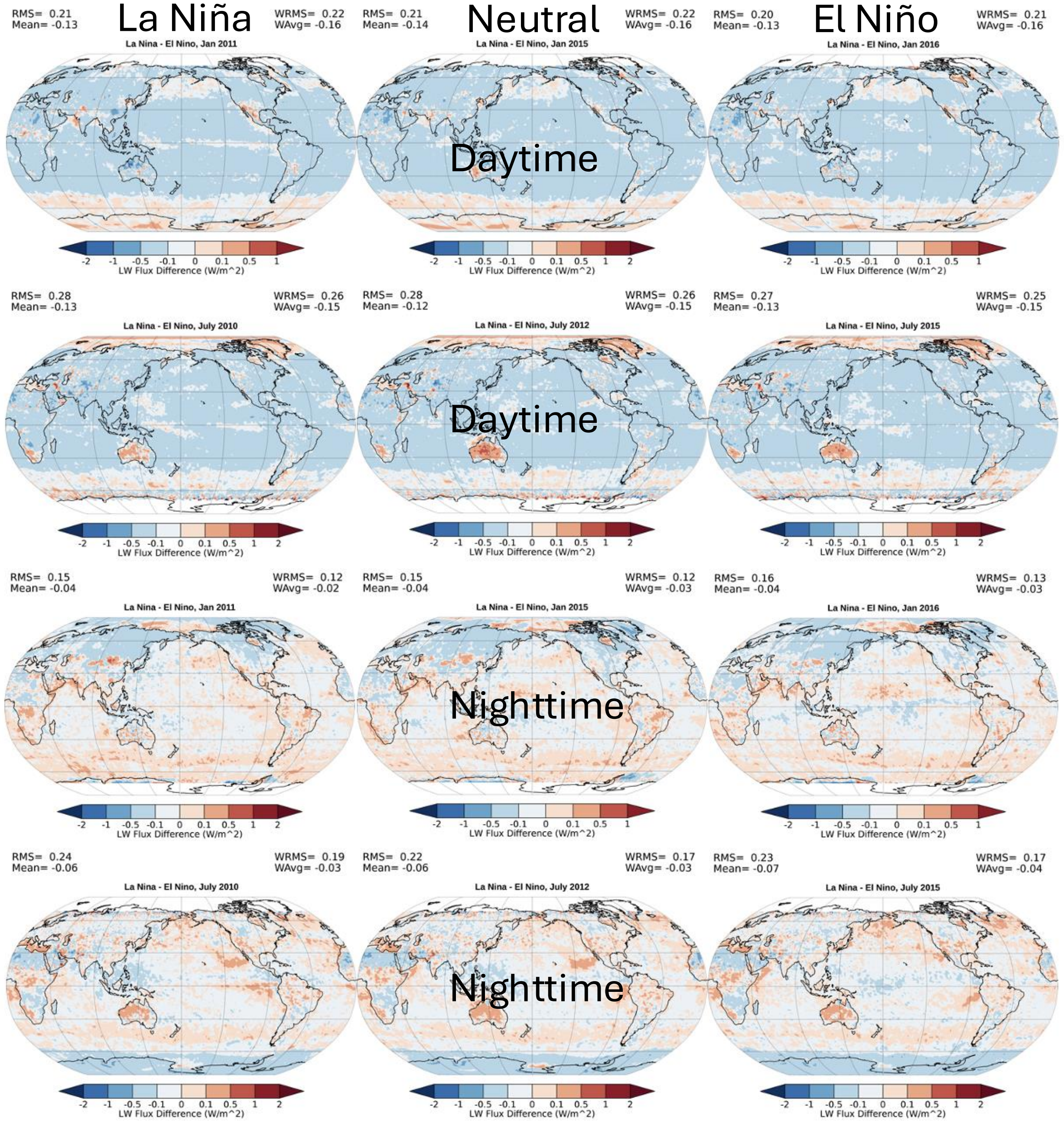
If seasonality has no influence, then differences should be larger!

Longwave Flux Differences

Asymmetrical

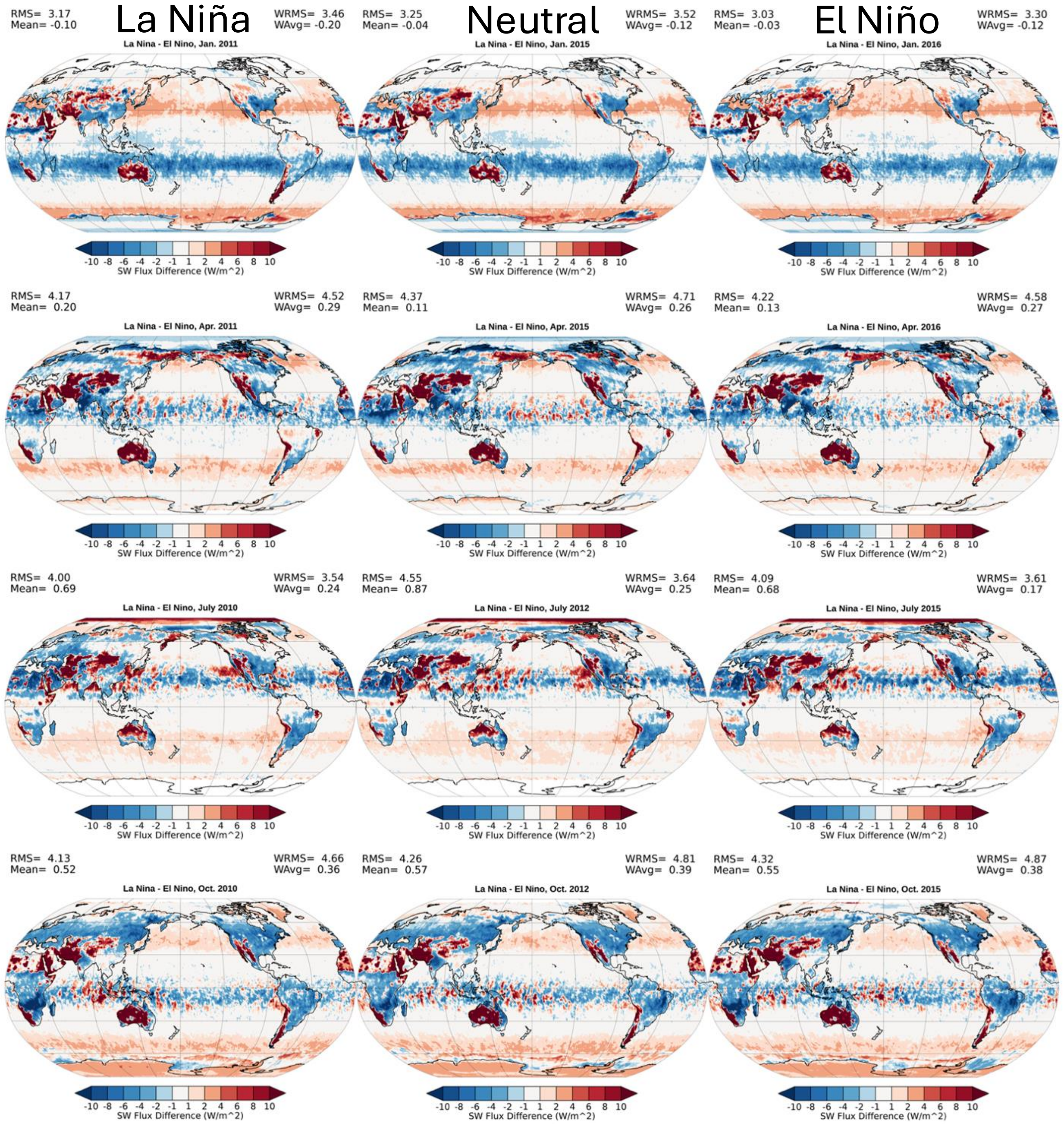


Symmetrical

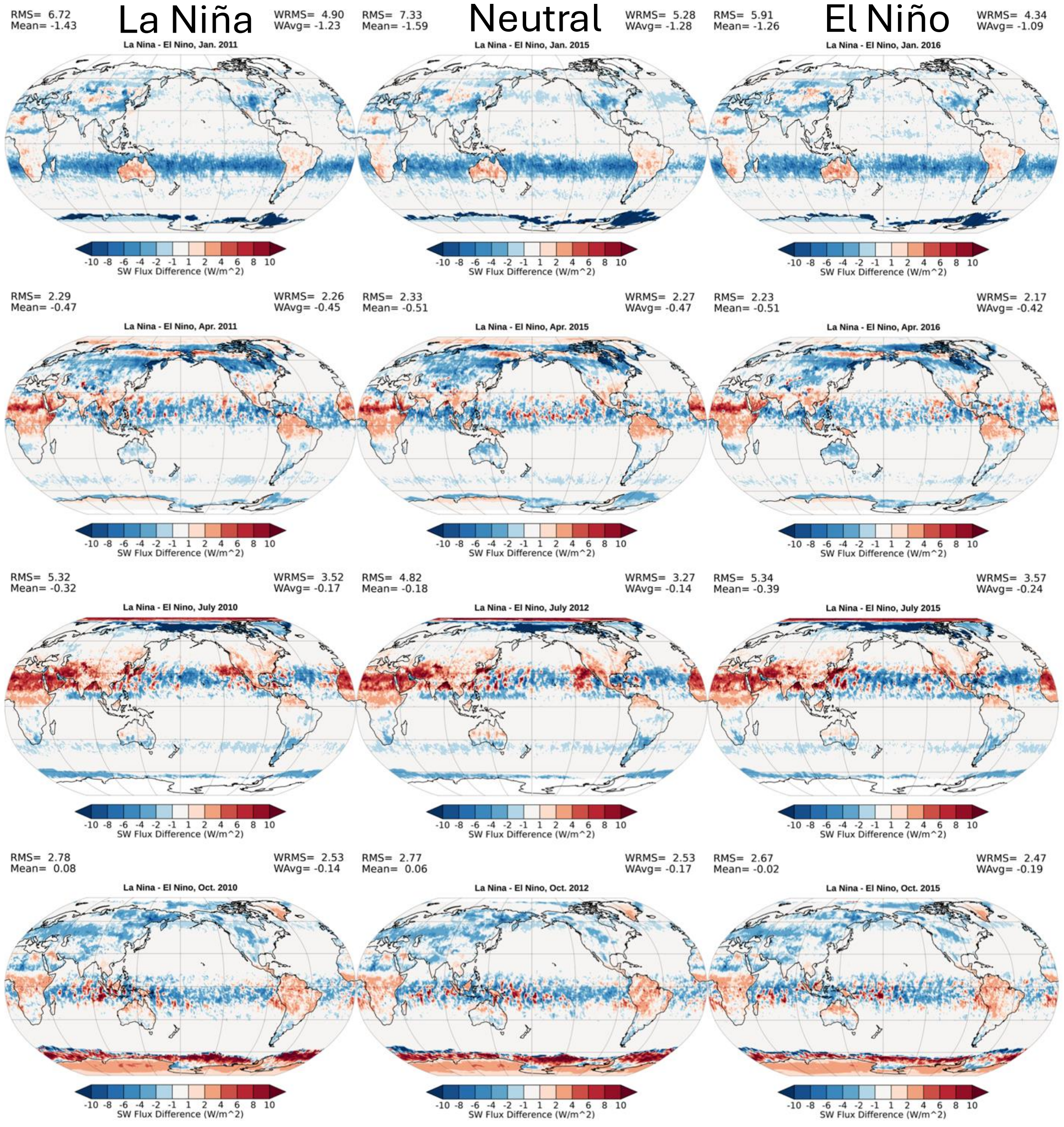


Shortwave Flux Differences

Asymmetrical



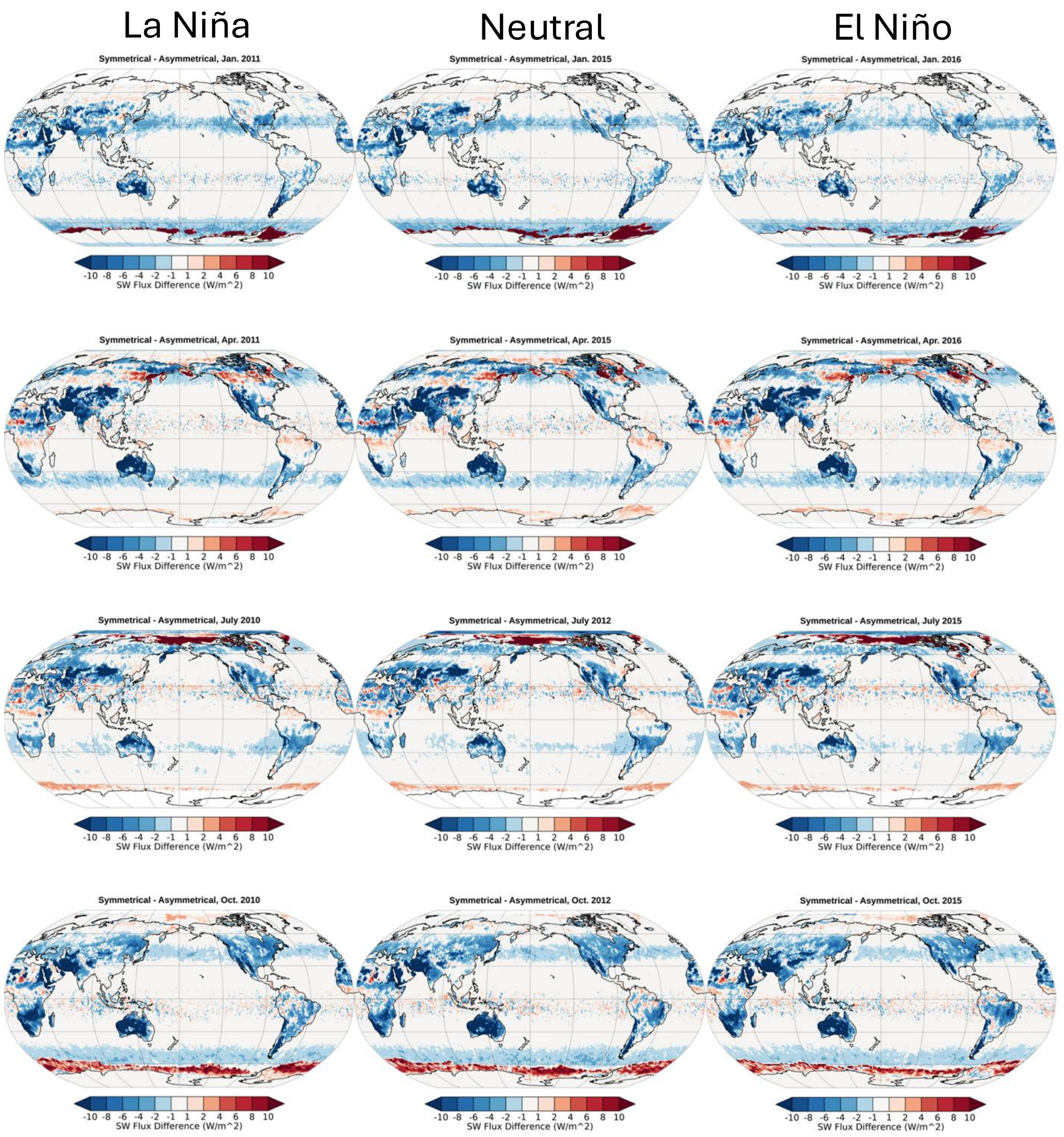
Symmetrical



Impact of Seasonality on ADM Development

- Blue (red) regions indicate the seasonally symmetric ENSO ADMs have smaller (larger) SW flux differences than the seasonally asymmetric ENSO ADMs.

- Symmetric case generally has smaller differences except over sea ice regions.



Additional Lines of Evidence

Direct Integration

- Integrate cross-track and RAP radiance measurements composited in 3-month intervals (DJF, MAM, JJA, SON) over a 5° latitude x 5° longitude (10° latitude x 10° longitude) region for LW (SW).

$$F_{LW} = 2\pi \int_0^{\frac{\pi}{2}} I_o(\theta_v) \cos\theta_v \sin\theta_v d\theta_v$$

$$F_{SW}(\theta_o) = \int_0^{2\pi} \int_0^{\frac{\pi}{2}} I_o(\theta_o, \theta_v, \varphi) \cos\theta_v \sin\theta_v d\theta_v d\varphi$$

- Compare LW flux given by La Niña and El Niño ADMs, respectively, with the observed direct integration (DI) approach.

- For SW fluxes, the standard DI approach cannot be applied since the sun-synchronous orbit of Terra introduces a strong correlation between latitude and solar zenith and relative azimuth angles. Instead, DI ADMs are developed:

$$R_o(\theta_o, \theta_v, \varphi, \text{reg}) = \frac{\pi I_o(\theta_o,\theta_v,\varphi,\text{reg})}{\int_0^{2\pi} \int_0^{\frac{\pi}{2}} I_o(\theta_o,\theta_v,\varphi,\text{reg}) \cos\theta_v \sin\theta_v d\theta_v d\varphi}$$

Observed DI ADM

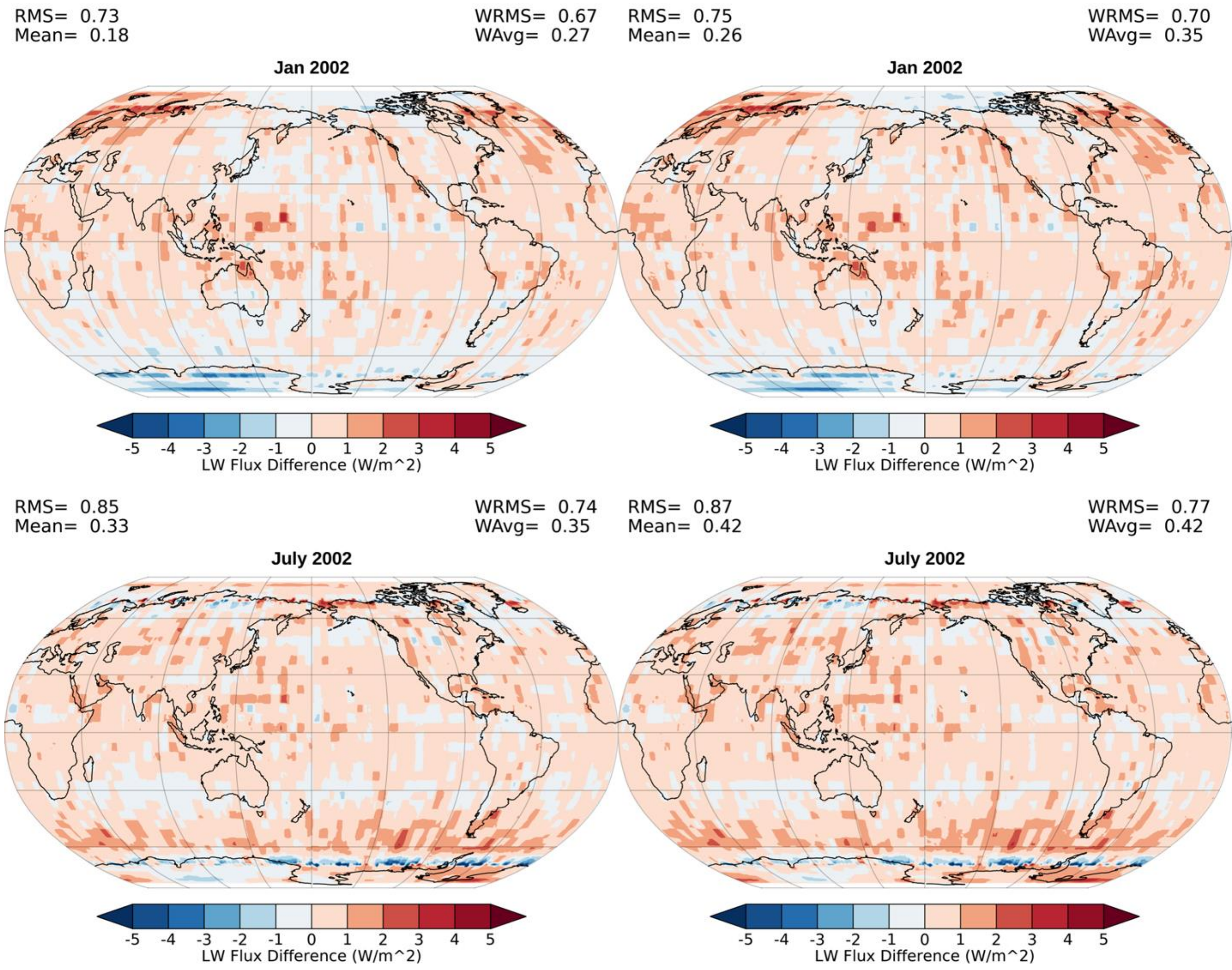
$$\hat{R}(\theta_o, \theta_v, \varphi, \text{reg}) = \frac{\pi \hat{I}(\theta_o,\theta_v,\varphi,\text{reg})}{\int_0^{2\pi} \int_0^{\frac{\pi}{2}} \hat{I}_j(\theta_o,\theta_v,\varphi,\text{reg}) \cos\theta_v \sin\theta_v d\theta_v d\varphi}$$

ENSO DI ADM

DI Longwave Flux Differences

- LW fluxes computed from La Niña ADMs and El Niño ADMs display similar differences relative to that given by DI approach (0.67-0.77 W*m^{-2}). Very similar spatial patterns.

- ENSO ADMs tend to overestimate LW fluxes relative to the observed DI approach. El Niño ADMs overestimate LW fluxes slightly more than La Niña ADMs.



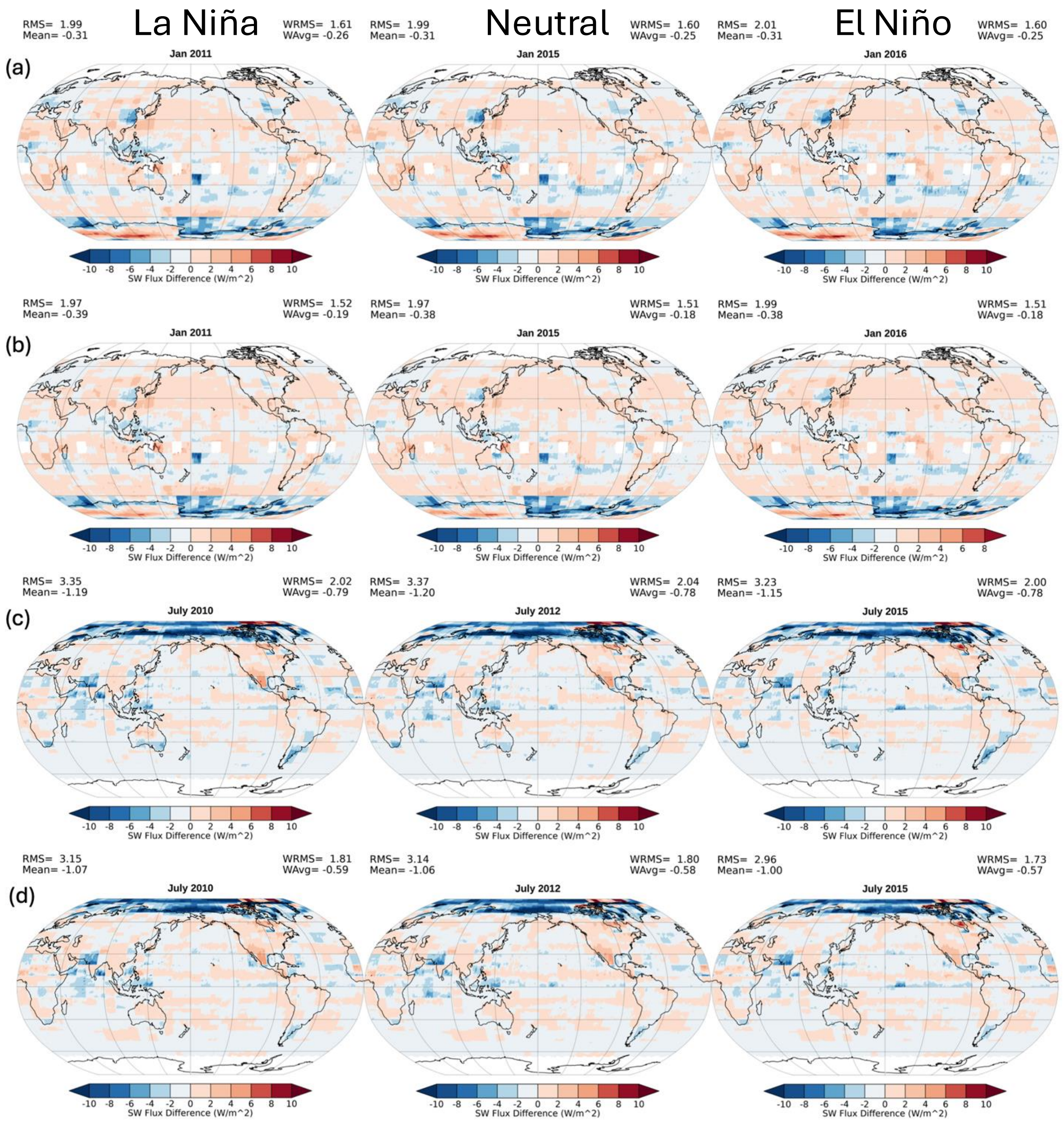
DI Shortwave Flux Differences

- SW fluxes computed from La Niña ADMs and El Niño ADMs display similar differences relative to that given by the observed DI ADMs (1.51-2.04 W*m^{-2}).

- Both ENSO ADMs tend to underestimate the SW fluxes. La Niña ADMs tend to underestimate the SW fluxes slightly more.

- Differences display similar spatial patterns despite undergoing distinct phases of ENSO.

- La Niña (El Niño) ADMs do not perform better during La Niña (El Niño) conditions



Leveraging MISR

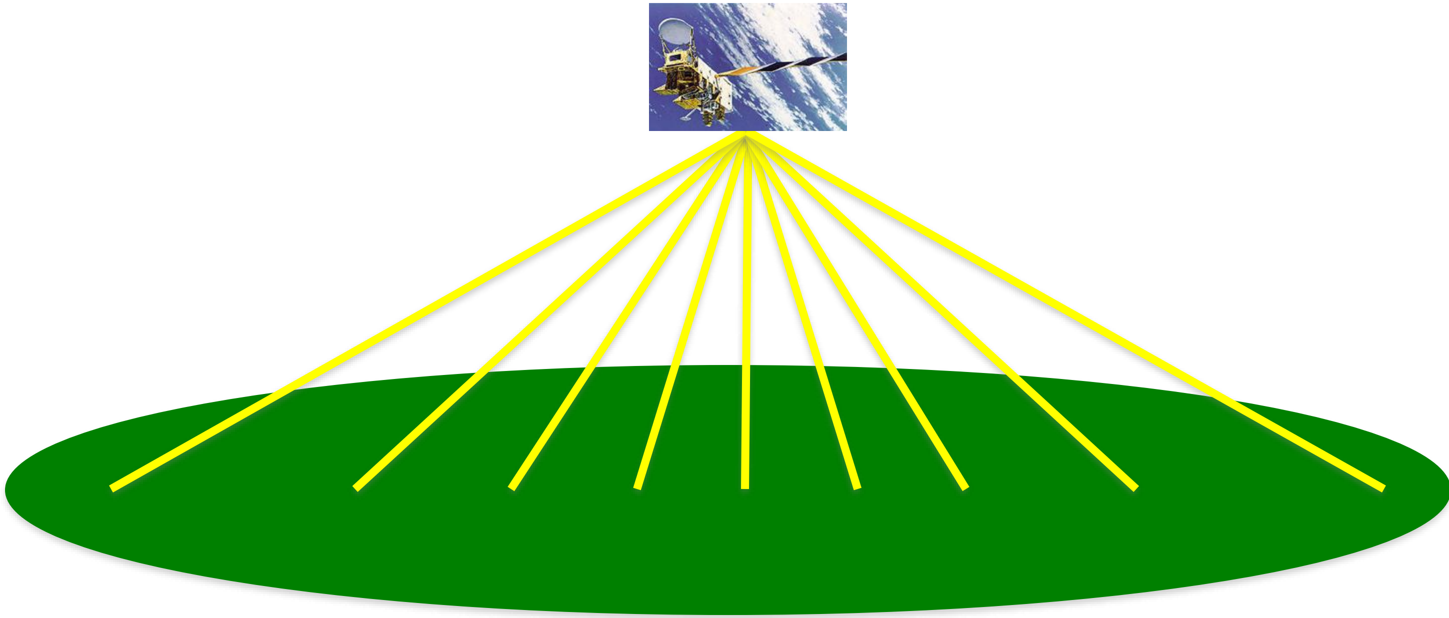
For a CERES footprint, MISR provides spectral radiance measurements from nine camera angles. Narrow-to-broadband regressions are applied to convert MISR narrowband radiances to broadband.

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

CERES ADMs

$$F_{SW}^{j}$$

$$\langle F_{SW} \rangle = \frac{\sum_{j=1}^{N} F_{SW}^{j}}{N}$$



The SW flux calculation should not be dependent on viewing geometry.

$$s = \sqrt{\frac{\sum_{j=1}^{N} \left(F_{SW}^{j} - \langle F_{SW} \rangle\right)^2}{N-1}}$$

Standard Deviation of Sample

Leveraging MISR

For *M* CERES footprints, the relative consistency of the SW TOA fluxes is given by:

$$CV_T = \frac{\sqrt{\sum_{i=1}^{M}(s_i)^2}}{\sum_{i=1}^{M}\langle F_{SW}\rangle_i} * 100\%$$

To remove the error contribution of the narrow-to-broadband regression calculate standard deviation of the MISR SW flux calculations from that given by CERES (F_{SW}^{C}) :

$$s_c = \sqrt{\frac{\sum_{j=1}^{N}\left(F_{SW}^{j} - F_{SW}^{C}\right)^2}{N-1}}$$

The contribution of the narrow-to-broadband regression to the relative consistency of the SW TOA flux is:

$$CV_{NB} = \frac{\sqrt{\sum_{i=1}^{M}\left(s_{c,i}\right)^2}}{\sum_{i=1}^{M} F_{SW,i}^{c}} * 100\%$$

The contribution of the ADMs to the relative consistency of the SW TOA flux is therefore:

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

SW Flux Consistency Test

Snow & Ice SW Flux ADM Error	Clear	Single Cloud Layer	Multi-Cloud Layer	All
Ψ_{ADM} (%) (Edition 4 ADMs)	3.82	5.94	5.81	5.55
Ψ_{ADM} (%) (Symmetrical Case; El Niño ADMs)	4.93	6.48	6.33	6.16
Ψ_{ADM} (%) (Symmetrical Case; La Niña ADMs)	5.08	6.52	6.22	6.18
Ψ_{ADM} (%) (Asymmetrical Case; El Niño ADMs)	5.05	6.47	6.20	6.15
Ψ_{ADM} (%) (Asymmetrical Case; La Niña ADMs)	4.94	6.26	5.91	5.95

- Snow and Ice El Niño and La Niña ADMs have similar SW flux ADM errors.
- Snow and Ice Edition 4 ADMs have smaller SW flux ADM error, as expected.

Summary and Conclusions

- LW flux differences are small, indicating LW ADMs have weak sensitivity to ENSO phase.

- La Niña ADMs and El Niño ADMs do produce substantial SW flux differences.
  - Symmetrical case indicates these differences are reduced when the influence of the seasonal cycle on ADM development is removed.
  - Years undergoing distinct ENSO phases display similar difference patterns indicating a weak sensitivity to ENSO phase.
  - Direct integration and SW flux consistency tests also indicate weak sensitivity to ENSO phase.

- CERES ADMs demonstrate robustness to ENSO climate variability.

- SW ADMs do demonstrate sensitivity to changes on the scale of the seasonal cycle.

- Overall, the analysis provides confidence in the reliability and robustness of CERES ADMs and thus the climate data record of CERES fluxes.