
SEASONAL AND HEMISPHERIC DEPENDENCE OF THE GLOBAL MONSOON
RESPONSE TO MAJOR EXTRATROPICAL ERUPTIONS IN THE CESM LME
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MOTIVATION AND SCIENCE QUESTIONS

- Monsoon regions are among Earth's most populous and agriculturally productive regions.
- Recent work *(Liu et al. 2016)* identifies a dependence of the monsoon response on the hemisphere of an eruption; but the mechanisms of monsoon disruption and influence of eruption latitude are not well understood. Questions also exist regarding the dependence of the response on eruption season *(Stevenson et al. 2017)*.

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Science Questions:

1) Over the last millennium, what have been the global-scale responses to volcanic eruptions (as a function of eruption hemisphere and season) and what monsoon responses have accompanied them? *(to isolate forced response compositing/ensemble are essential)*

2) What are the root causes of the hemispheric dependence of monsoon responses? What role is played asymmetries in forcing versus those in the climate response? Do **energetic** (*Frierson et al. 2013*) or **thermodynamic** influences appear to be operating?

3) What influence does the season of eruption have on the climate response and what does it suggest regarding our ability to accurately simulate the last millennium?

TAKE HOME POINTS

- **Strong hemispherically coherent monsoon responses exist in YEAR0/1 (eruption yr, yr after):** Characterized by 1) a global mean water cycle weakening and 2) significant ITCZ displacement+monsoon weakening in hemisphere of eruption, strengthening in opposing hemisphere. This effect has been particularly strong for NH eruptions over the last millennium due to the high latitude of NH eruptions.

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- **The responses are consistent with hypotheses based on energetic influences on the ITCZ:** strengthening of deep convection and upper level divergence of dry static energy in the opposing hemisphere, enhancing DSE transport into the eruption hemisphere (compensating for cooling) and inducing anomalous subsidence in monsoon regions. *Near-symmetric rainfall response to symmetric forcing, despite other large intrinsic asymmetries in the climate response.*

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- **Responses after YEAR0 are linked to the response of internal modes:** These depend strongly on the magnitude, hemisphere, and season of the eruption. Our knowledge of these for LM is often poor and this limits our ability to accurately simulate the last millennium.

METHODS: THE CESM LAST MILLENNIUM ENSEMBLE (LME)

- **Part 1: Compositing LM eruptions: CESM Last Millennium Ensemble;** 850-2005; 2° atmosphere/land; 1° ocean; 13 full-forcing members (**Gao et al. 2008 v1 volcanic forcing**, solar, orbital, GHG, LULC); initialized from a 1300-yr control run using 850 forcings

- **Part 2: Targeted Laki simulations: SH Laki and 6-months lagged NH/SH Laki eruptions**: same model configuration as LME; **Volcanic loading from Gao et al. 2008 but mirrored in latitude.** ~8 members of each type initialized from LME at 1750, run through 1770. During this period the only large eruption is that of Laki: late 1761 (1783 in nature).

CLIMATE VARIABILITY AND CHANGE SINCE 850 CE

An Ensemble Approach with the Community Earth System Model

BY BETTE L. OTTO-BLIESNER, ESTHER C. BRADY, JOHN FASULLO, ALEXANDRA JAHN, LAURA LANDRUM, SAMANTHA STEVENSON, NAN ROSENBLOOM, ANDREW MAI, AND GARY STRAND

The Community Earth System Model-Last Millennium Ensemble (CESM-LME) modeling project gives the research community a resource for better understanding both proxy records and climate variability and change since 850 CE.

Otto-Bliesner et al. 2016, BAMS

METHODS: LME VOLCANIC FORCING: SEASON AND EVOLUTION

- **Gao et al. 2008 v1** reconstruction used for LME volcanic forcing is based on ice core deposition in Greenland and Antarctica.
- The approach is limited in its ability to resolve the season and latitude of eruptions in addition to their transient evolution.
- Aside from a few eruptions where the exact eruption date is known, eruptions are assumed to begin in April and follow a common evolution over time.
- These uncertainties can underlie significant discrepancies between YEAR0 responses in the LME and nature *(Stevenson et al. 2017, PNAS)*.

STEVENSON ET AL.

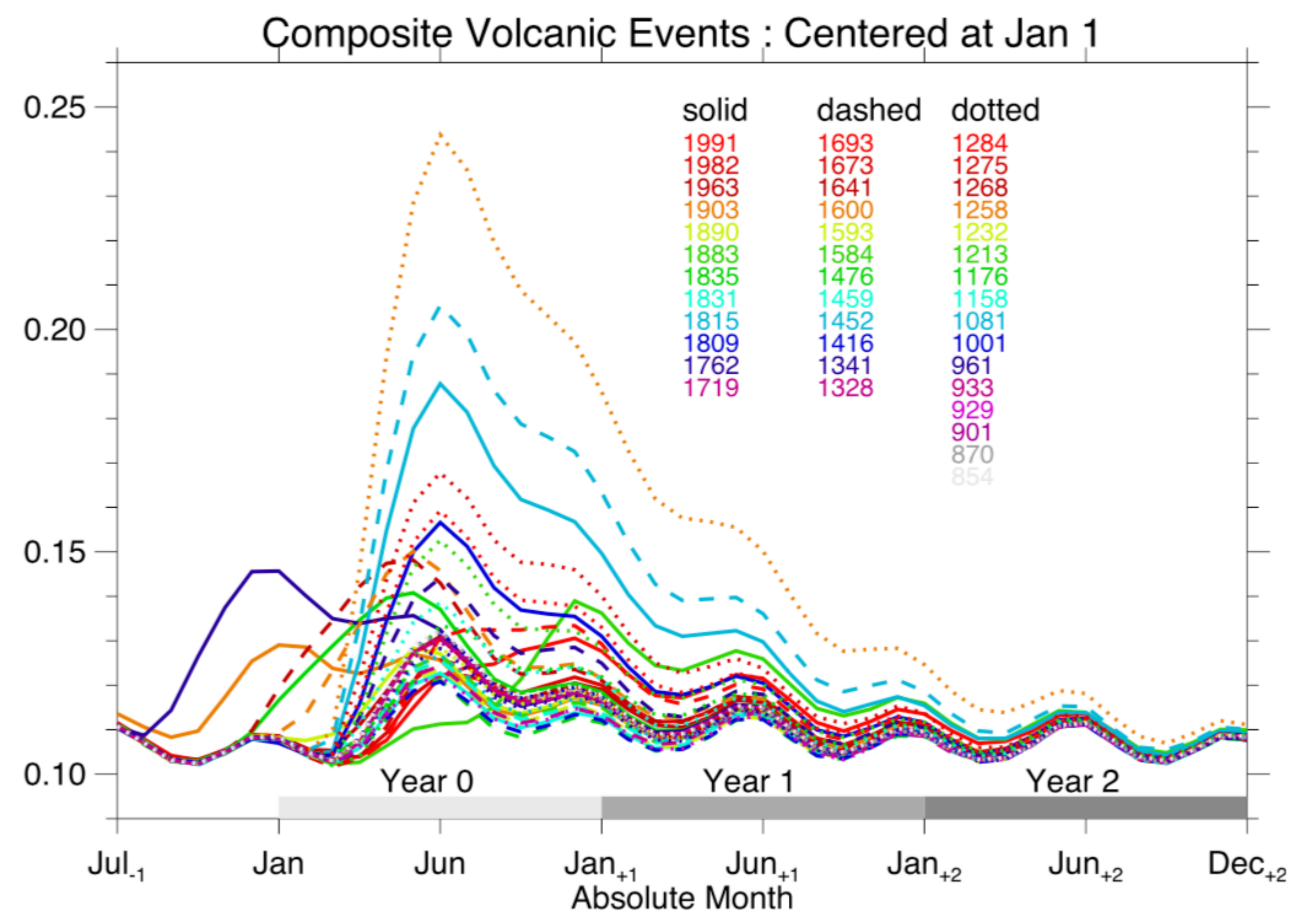
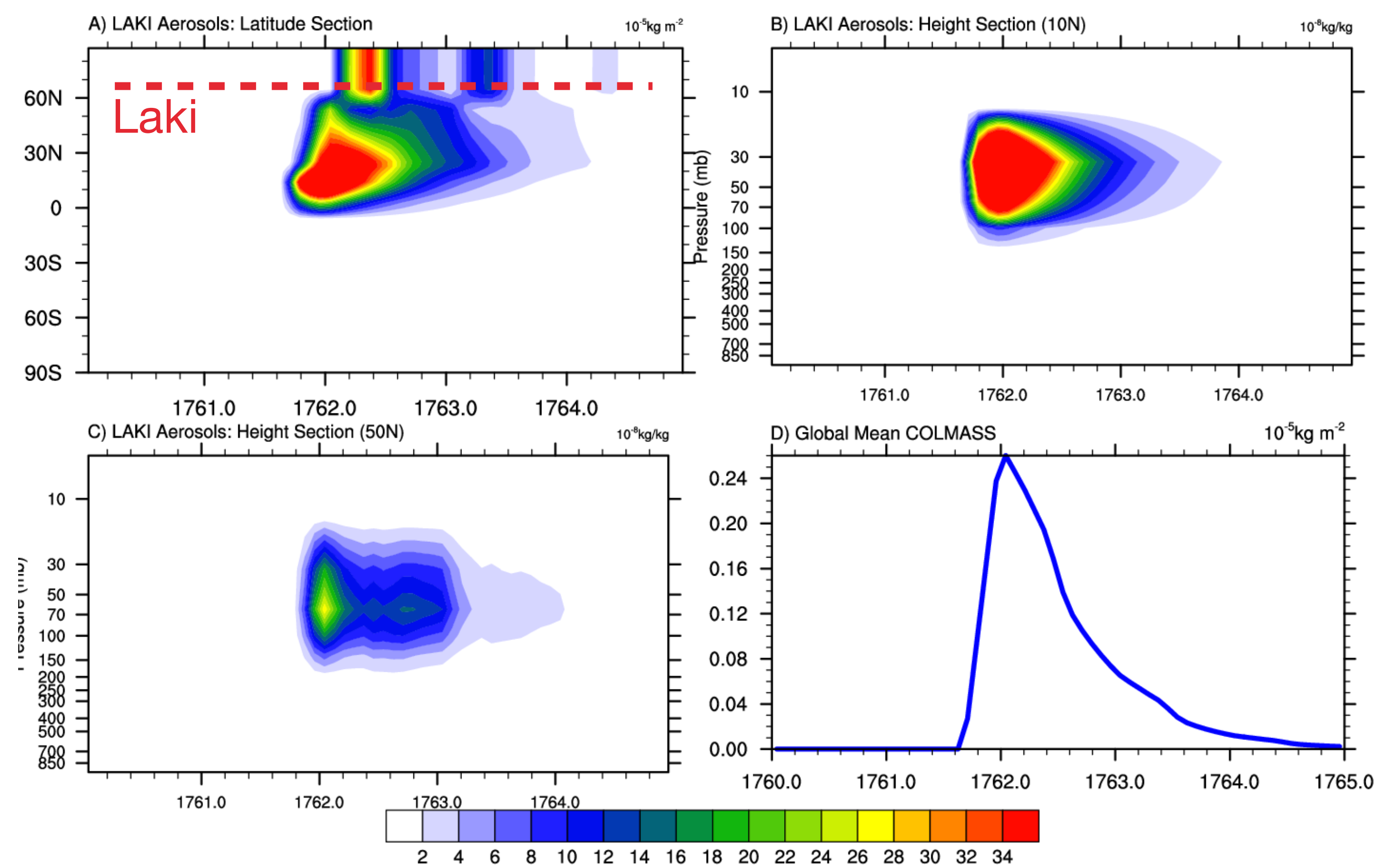


FIG. 1. Composite clear-sky albedo for all LME eruptions, averaged over ocean regions from 30°S to 30°N. Eruptions occurring after 1700 are represented by solid lines, eruptions occurring between 1300 and 1699 by dashed lines, and eruptions occurring before 1300 by dotted lines. The eruption year indicated here is the year in which the albedo reaches its peak; this is the year referred to as year 0 in subsequent analyses.

Stevenson et al. 2016, J. Clim.

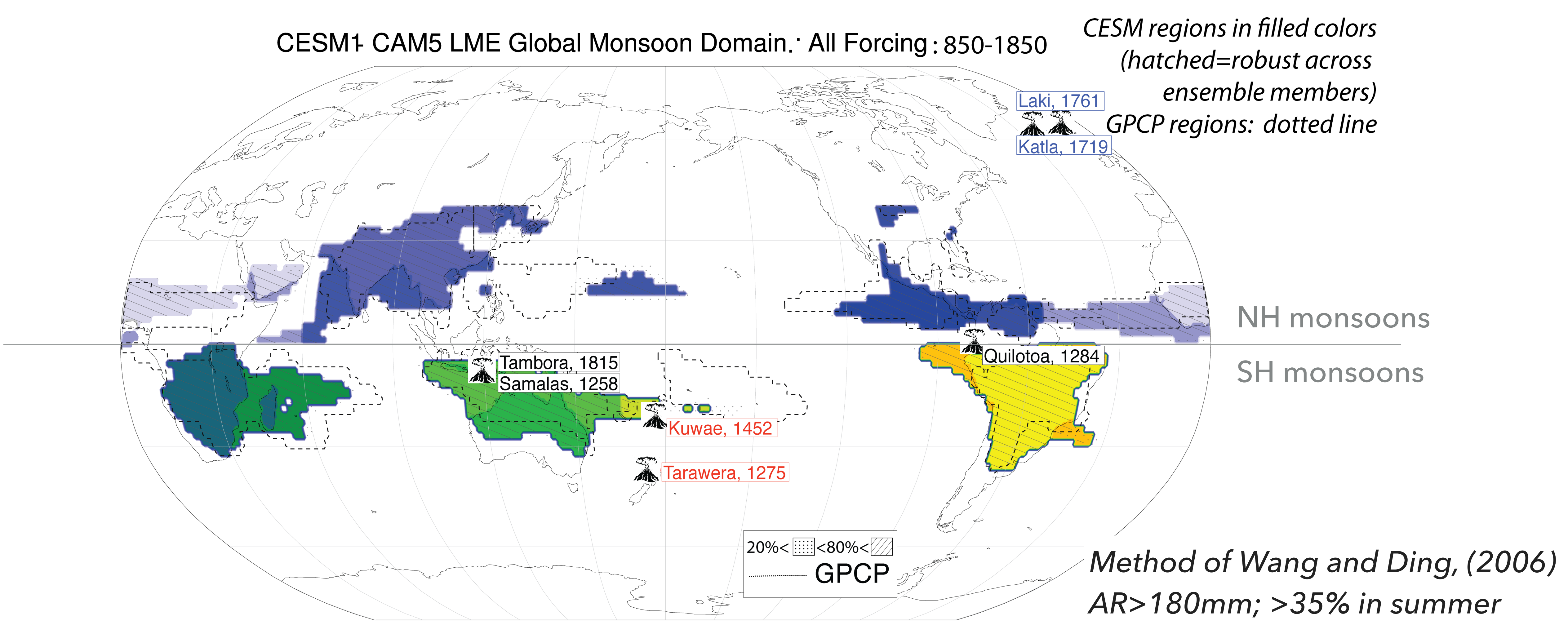
METHODS: LME VOLCANIC FORCING: LATITUDE

- Gao et al. 2008 v1 reconstruction latitudinal structure disagrees with dates and known locations of some major eruptions.
- For example, following the Laki eruption (at 64N) in late 1761 (should be 1783) peak aerosol burdens exist at low latitudes (10N) in the reconstruction.
- It is very likely that the latitudinal and seasonal structure of volcanic forcing in the reconstruction contains significant error.



What are the implications for modeling the climate response?

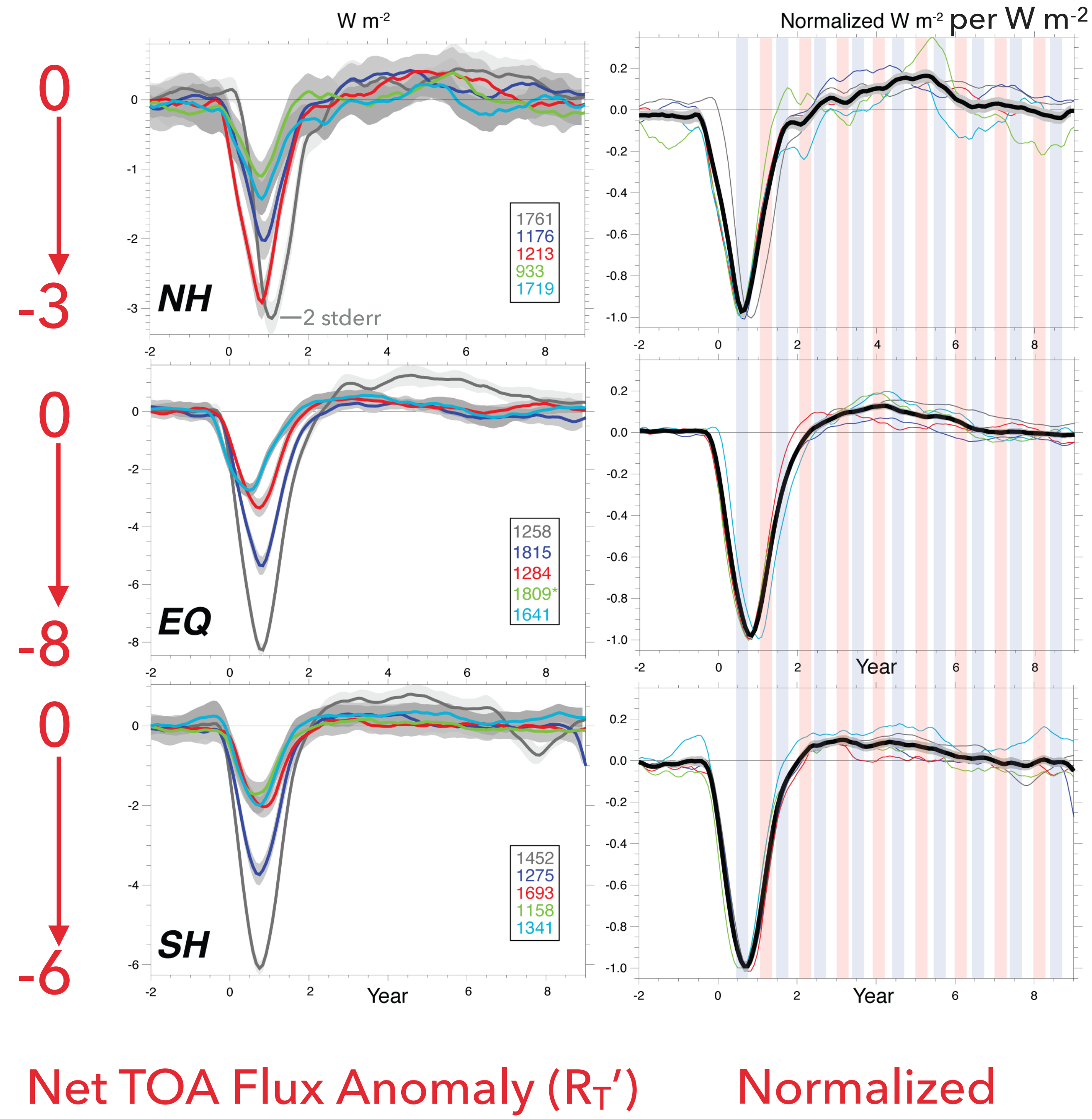
METHODS: GLOBAL MONSOON IN THE CESM



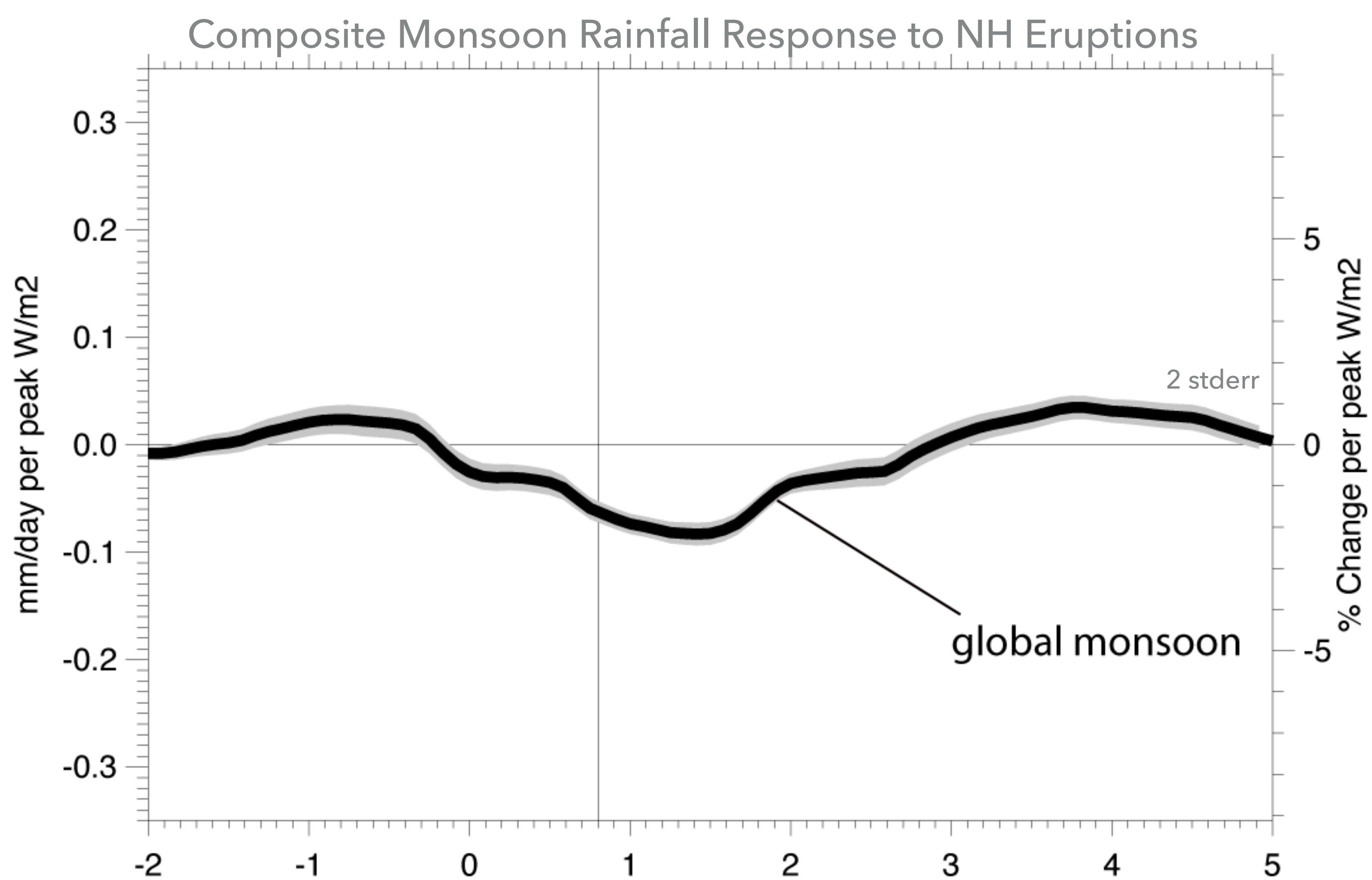
- **Monsoon regions in CESM (colors)** compare favorably with satellite obs (GPCP, dot), with main discrepancy in western Pacific Ocean monsoons (SPCZ, WPO absent from CESM, biases 🔗double ITCZ).
- Known major eruptions also shown for SH, EQ and NH. Other eruption locations are unknown.

METHODS: IDENTIFYING AND COMPOSITING ERUPTION RESPONSES IN LME

- **Eruptions:** identified by clear-sky albedo anomalies over 30S-30N ocean (~constant sfc. albedo).
- **Eruption Types**: SH/EQ/NH based on difference between |0-30N| - |0-30S| clear-sky albedo over ocean > 0.1. Events not categorized as either SH/NH are EQ.
- **Events used**: 5 strongest eruptions of each type are normalized and composited (to increase S/N, 5•13 members=85 events).
- **Normalization:** (to address the wide range of intensities) based on peak ensemble mean Earth energy imbalance for each eruption.



LME RESULTS: LARGE-SCALE WATER CYCLE RESPONSE



- **Global Mean:** detectible weakening in YEAR 0/1 of about 2% per Wm^{-2}.

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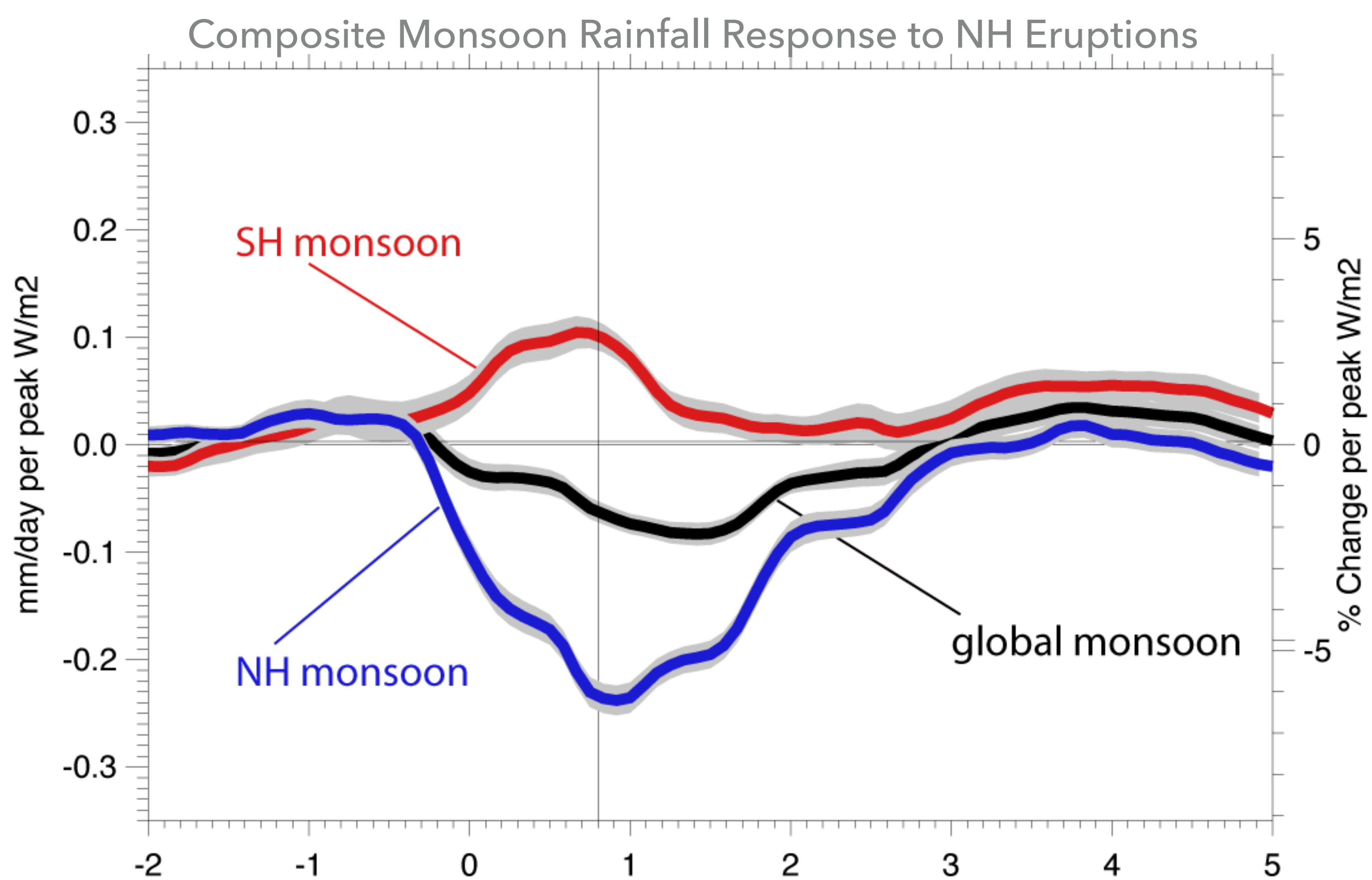

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- **Hemispheric Structure**: Differences between hemispheric components are many times greater than the global mean response. Need to understand.

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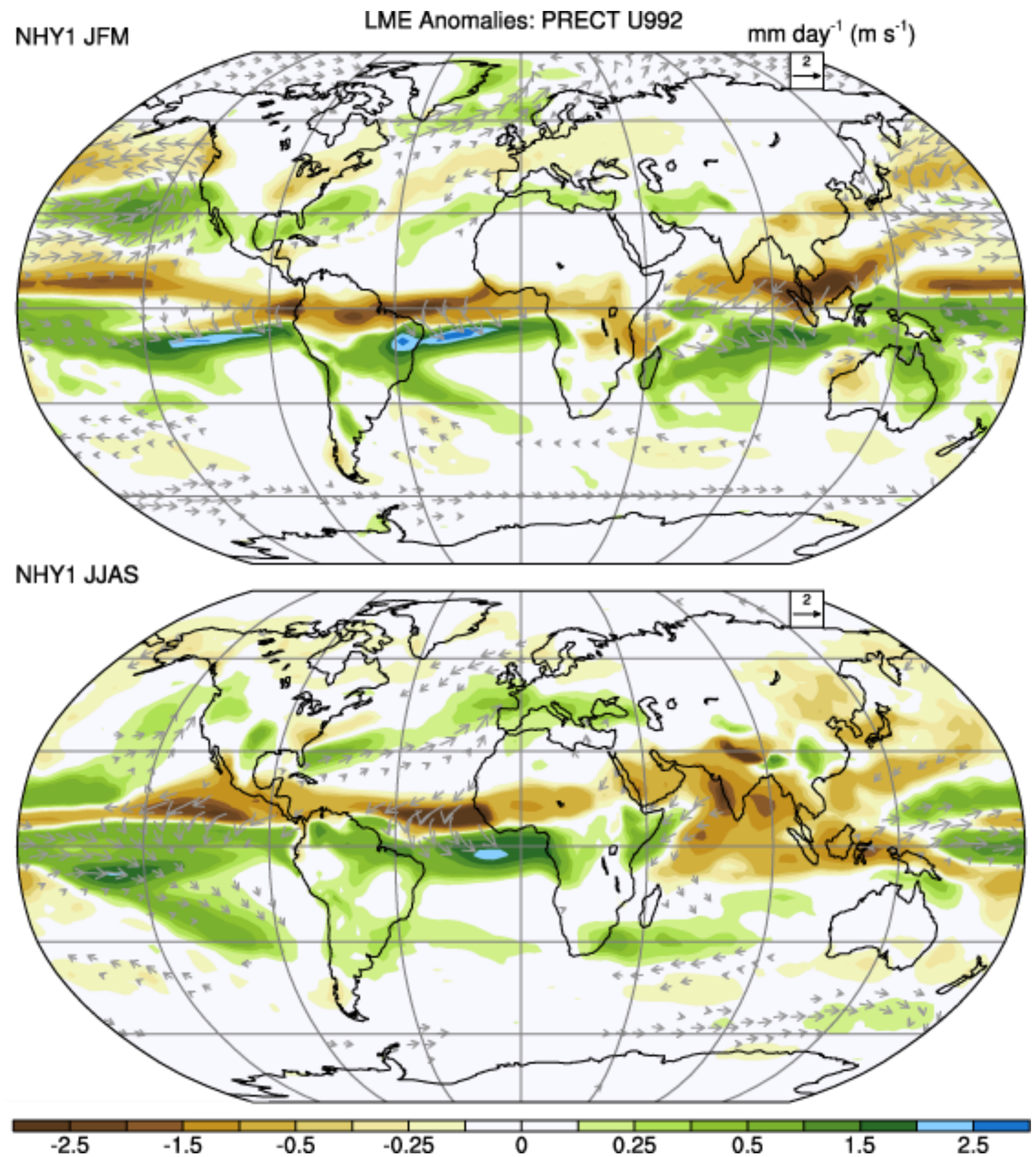

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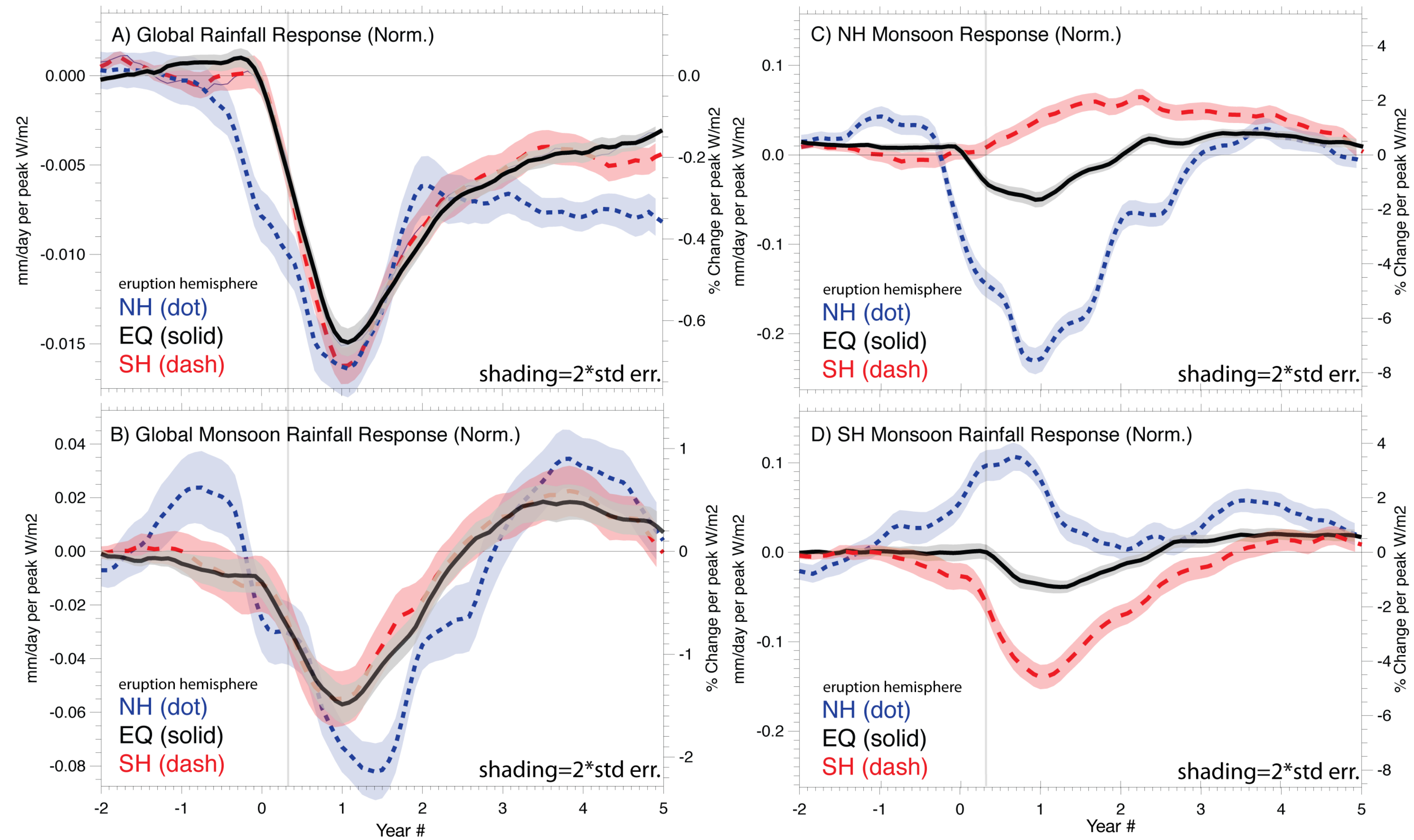
- **Hemispheric Structure**: Differences between hemispheric components are many times greater than the global mean response. Need to understand.

LME RESULTS: RAINFALL RESPONSE ASYMMETRIES

per W/m2 NH eruptions induce:

- (A) a similar weakening of global rainfall in yrs 0-2
- (B) a stronger global monsoon response
- (C,D) much greater weakening (~60%) of the NH monsoon by NH eruptions than of the SH monsoons by SH eruptions

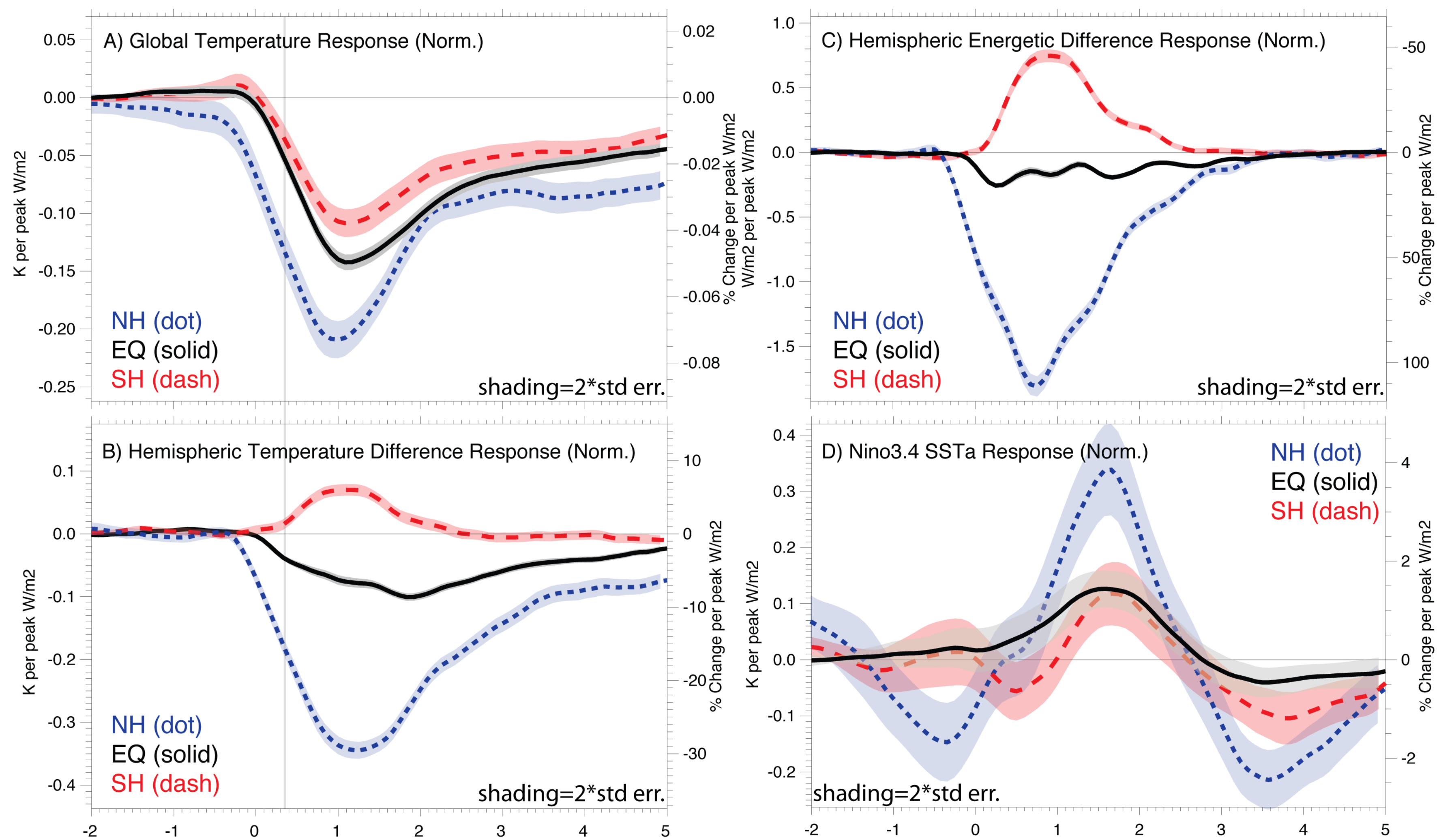


Does the greater sensitivity of the NH monsoons to NH eruptions reflect an intrinsic property of the climate system? or something else?

LME RESULTS: LARGE-SCALE RESPONSE ASYMMETRIES

per W/m2; NH eruptions induce:

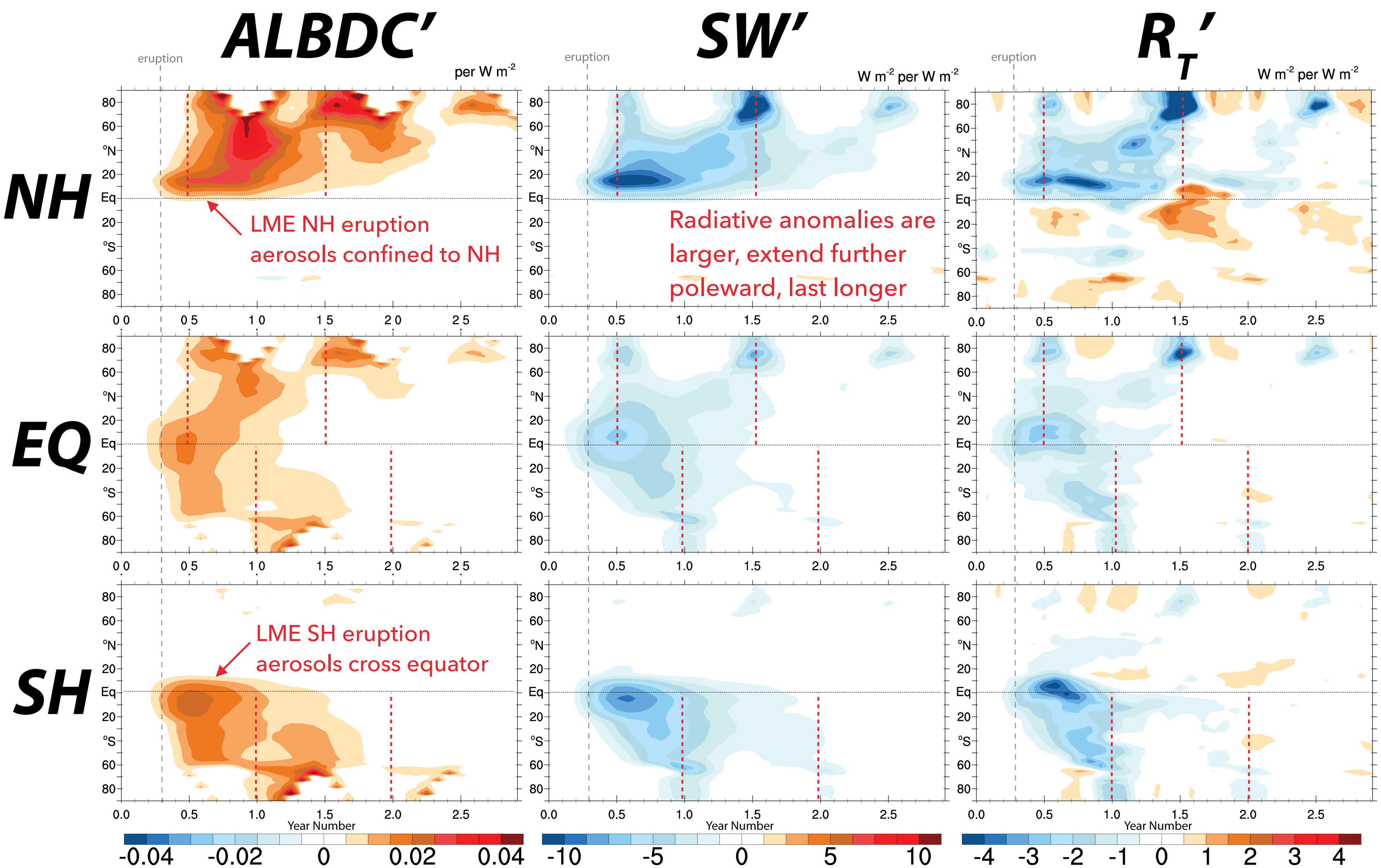
- (A) stronger global mean norm. sfc. T response (less ocean buffer)
- (B) larger inter-hemispheric T_S' contrast
- (C) larger hem. R_T' contrast (forcing asymmetries/ cryospheric response)
- D) stronger ENSO response (caution: normalized)



Broad intrinsic hemispheric asymmetries characterize the climate responses.

LME RESULTS: ERUPTION ENERGETIC ASYMMETRIES

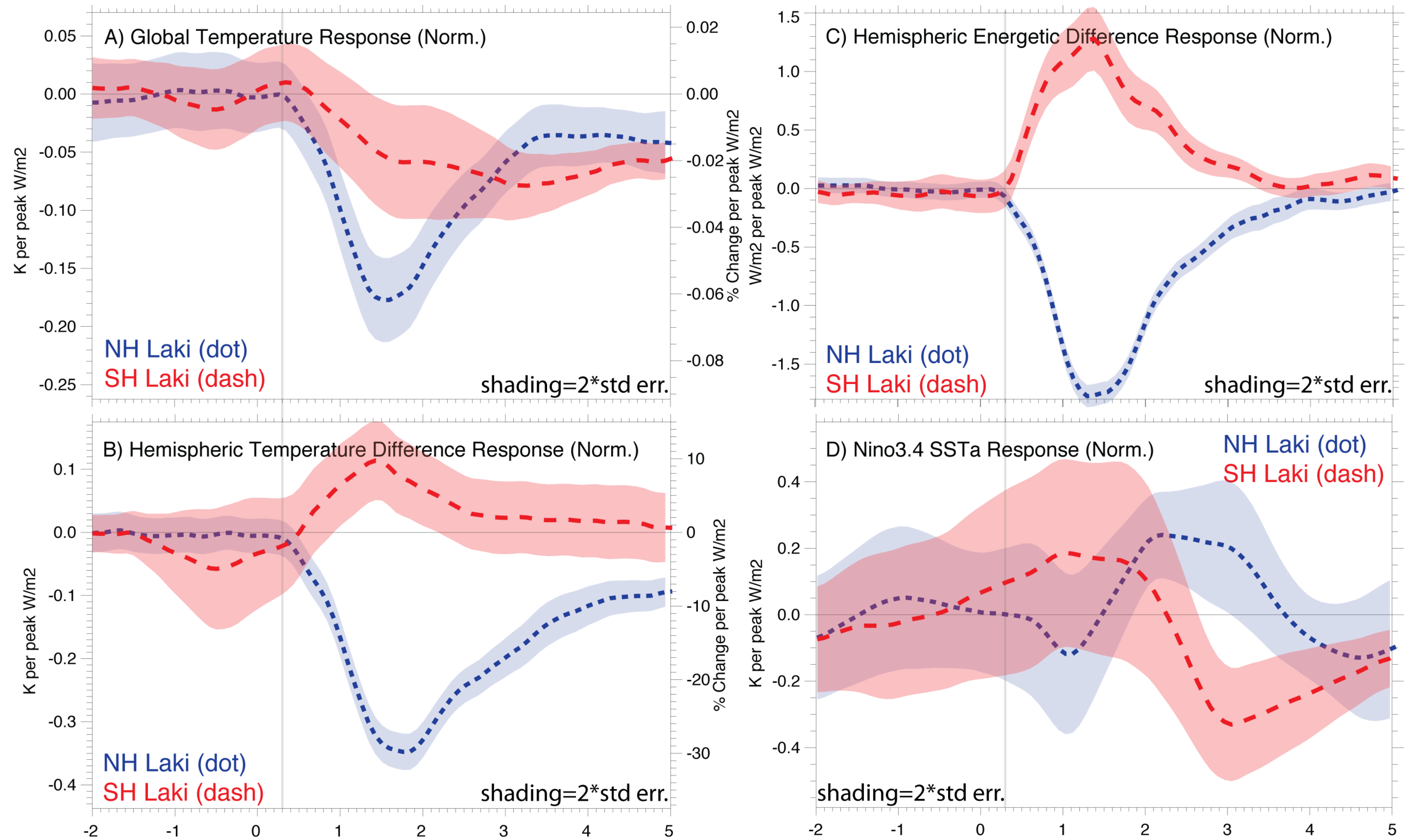
- Regional increases in norm. clear-sky albedo are stronger for NH/SH eruptions; EQ eruptions span both hems (dilute)
- Normalized top of atmosphere (TOA) SW and net flux (R_T) anomalies more symmetric for EQ eruptions; also weighted by solar insolation (align with summer maxima, dashed)



If the aerosol distributions were symmetric, would the monsoon response be as well?

NH VS SH LAKI RESULTS: LARGE SCALE RESPONSES

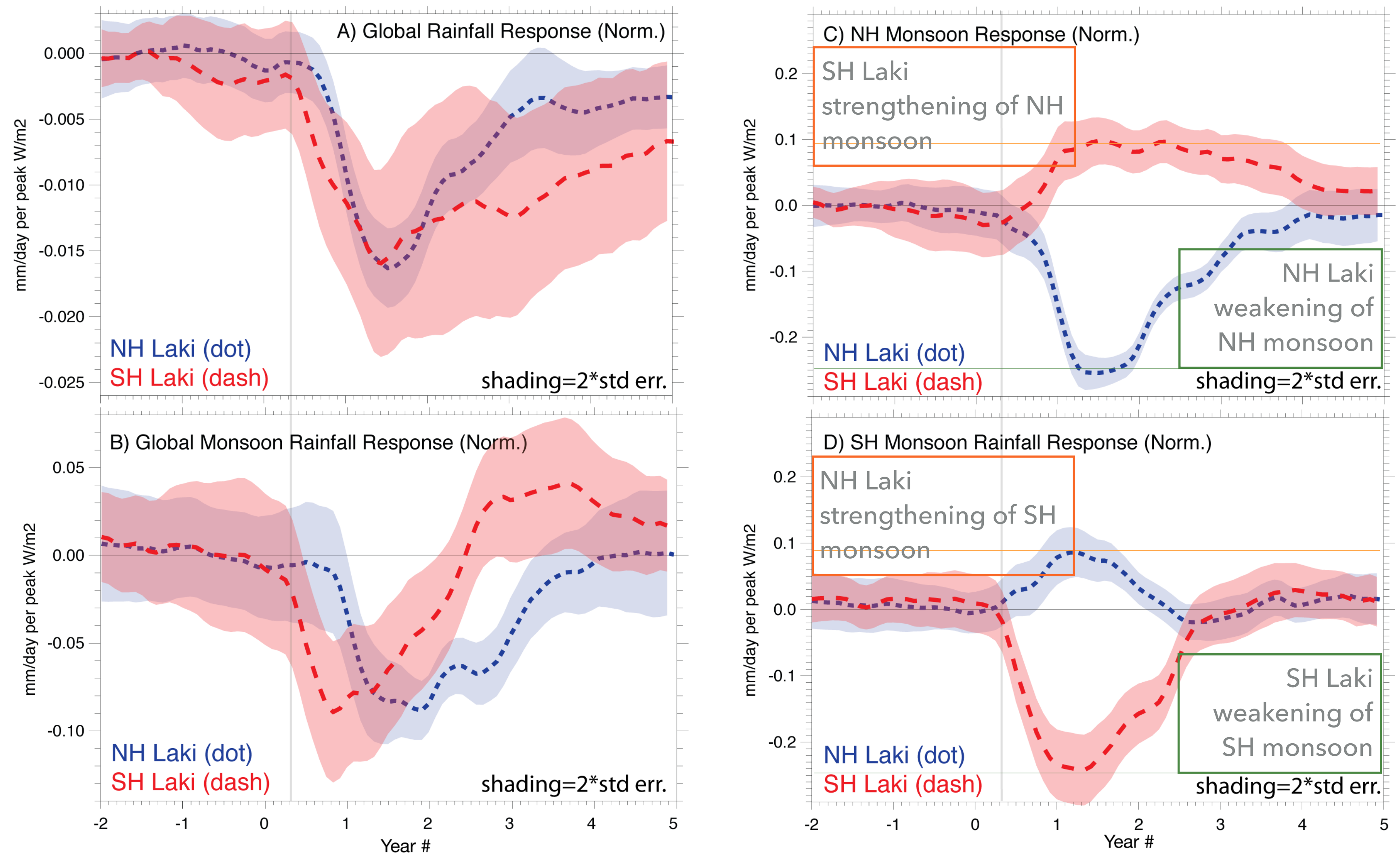
- NH Laki exhibits a much stronger YEAR1 climate response in many large-scale fields including:
  - global Ts (~2x>)
  - hemispheric Ts diff.(~3x>)
  - surface albedo (not shown)
- R_T' hemispheric contrast is comparable (~1.4 Wm^{-2}) due to offsetting LW responses.
- ENSO responses are quite different.



Many of the broad hemispheric asymmetries are apparent in the climate response, even with symmetric forcing. What about the monsoon response?

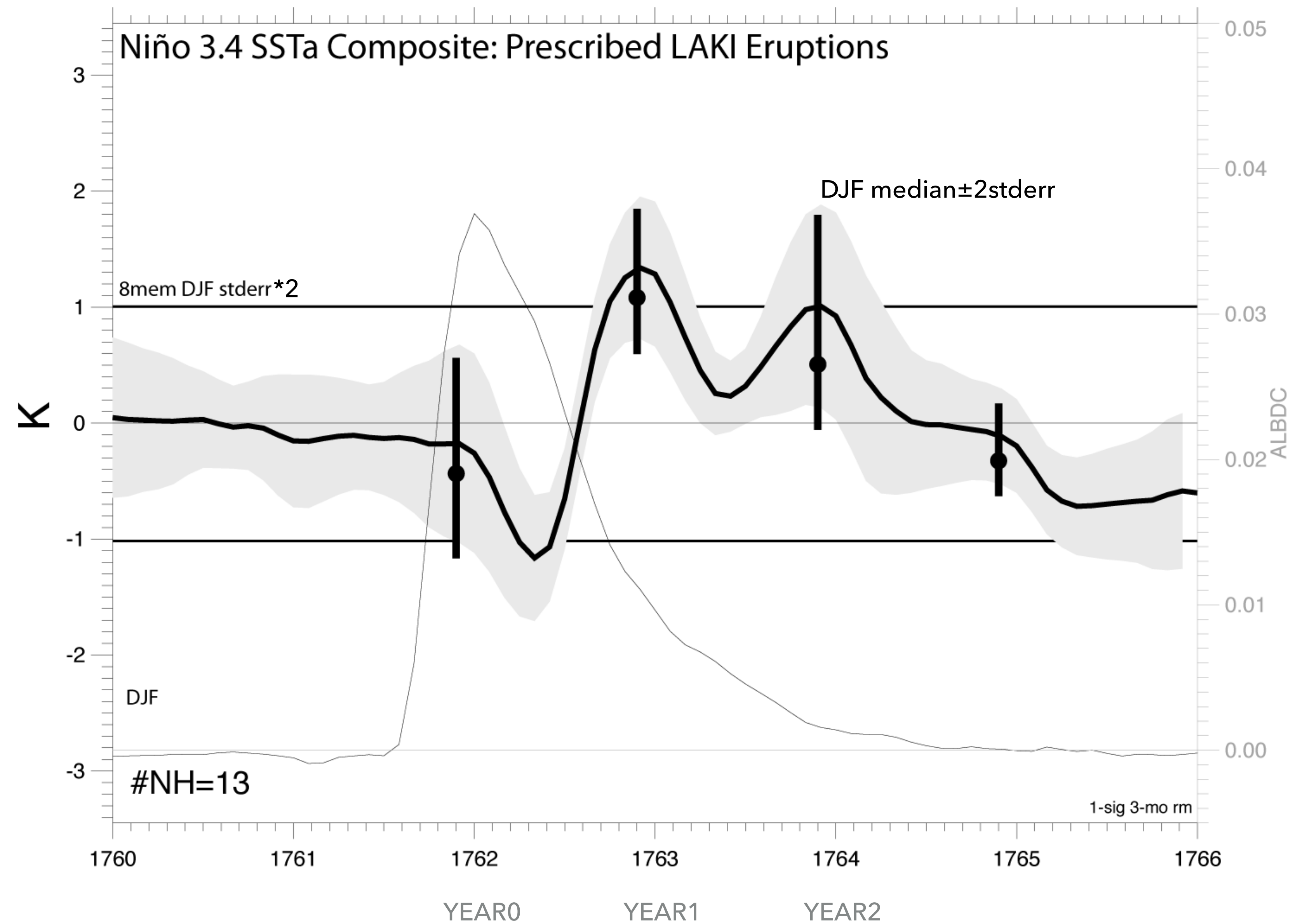
NH VS SH LAKI RESULTS: PRECIPITATION RESPONSES

- A) Global rainfall anomalies in YEAR1 are well within the ensemble spread.
- B) Global monsoon response is also comparable (shifted sooner for SH as DJF is first summer impacted)
- C/D) **Monsoon response is symmetric: SH Laki responses are similar to NH Laki responses** ∴The asymmetric response of the NH and SH monsoon in the LME is largely not an intrinsic response of the monsoon systems but instead reflects the differing character of the forcing.



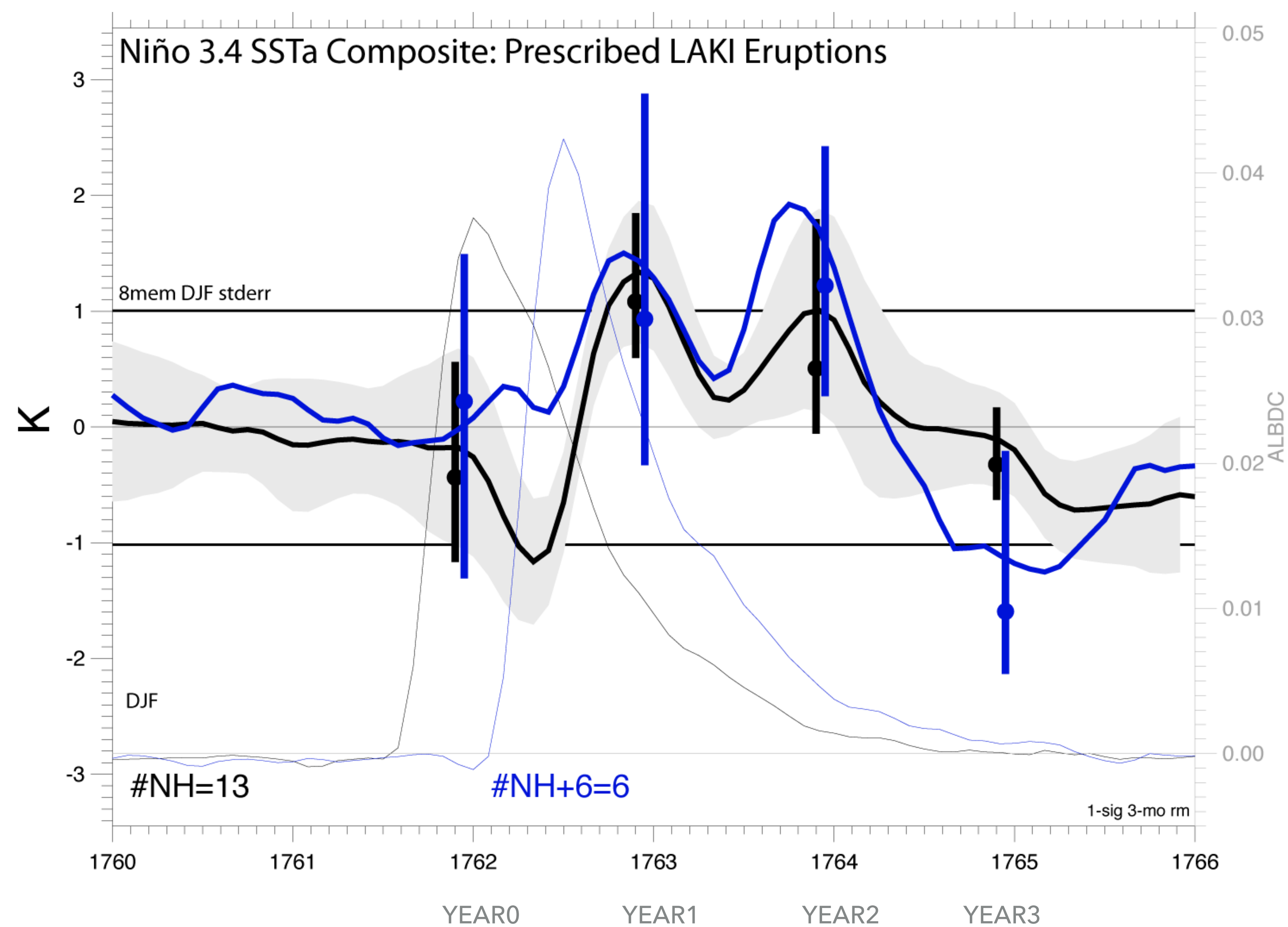
NH VS SH LAKI RESULTS: ENSO

- NH LAKI: YEAR 1/2 El Niño



NH VS SH LAKI RESULTS: ENSO

- NH LAKI: YEAR 1/2 El Niño
- NH+6 LAKI: YEAR1/2 El Niño, YEAR3 La Niña



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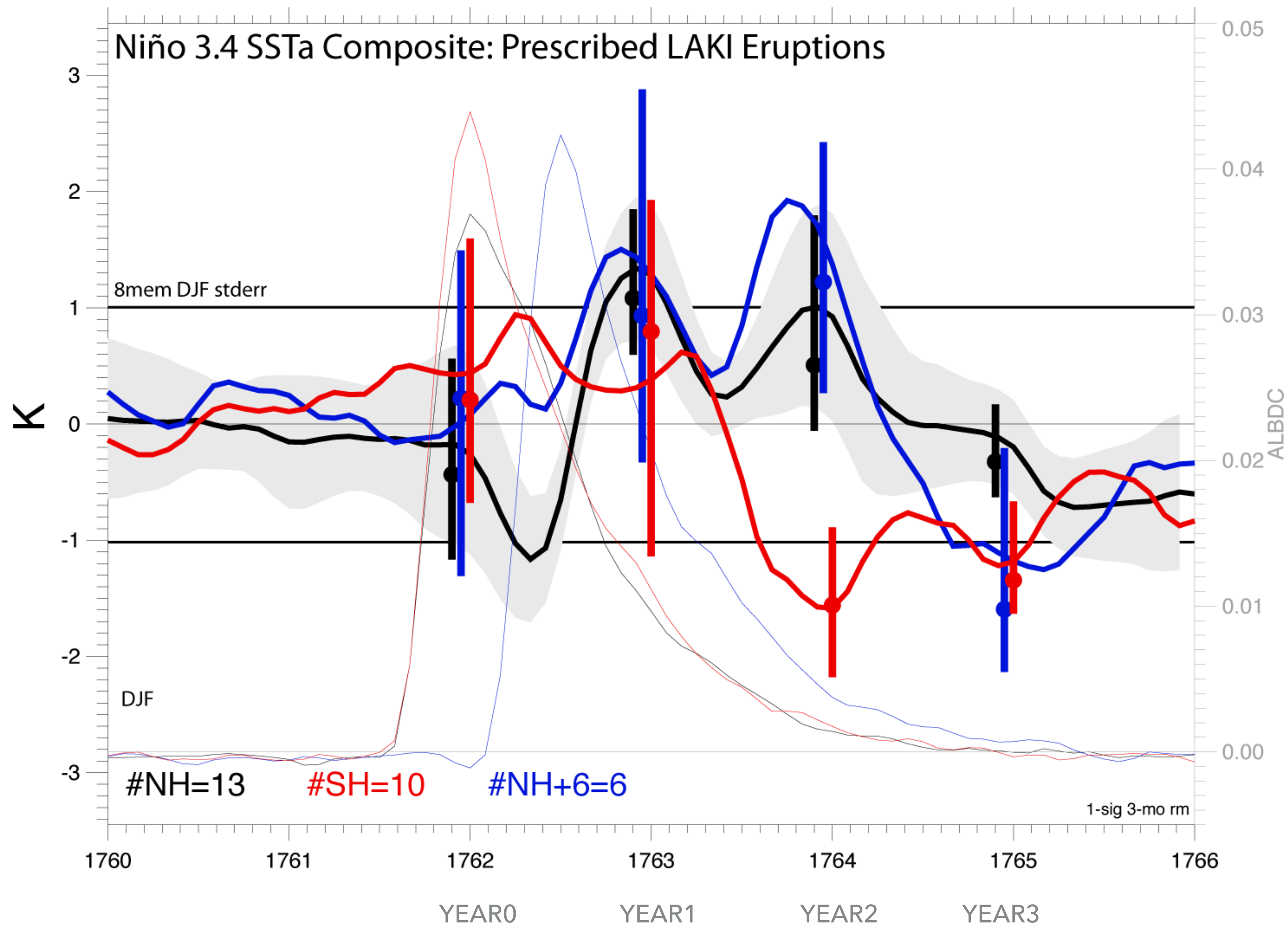
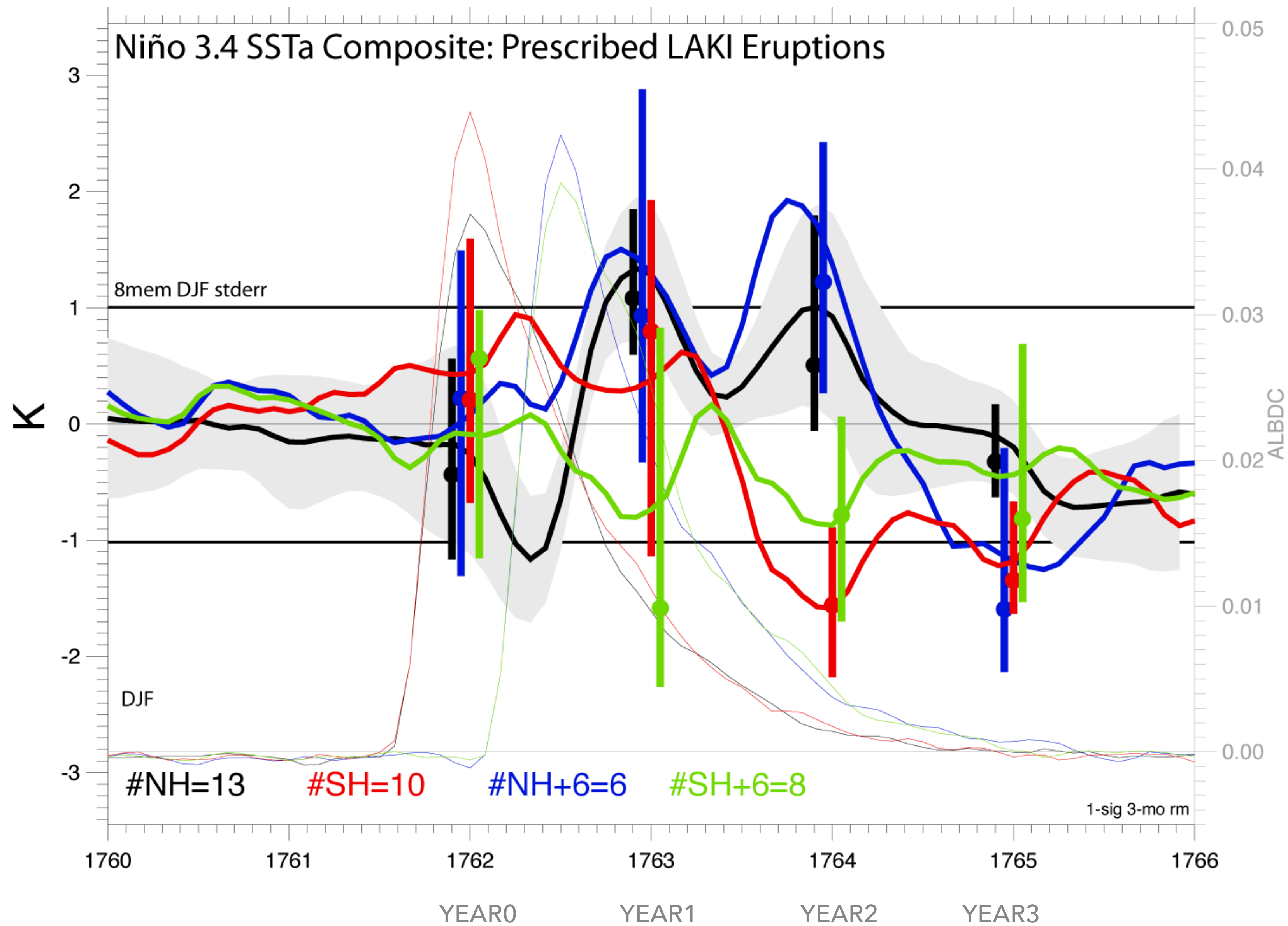
- NH LAKI: YEAR 1/2 El Niño
- NH+6 LAKI: YEAR1/2 El Niño, YEAR3 La Niña
- SH LAKI: YEAR1 El Niño, YEAR2/3 La Niña



NH VS SH LAKI RESULTS: ENSO

- NH LAKI: YEAR 1/2 El Niño
- NH+6 LAKI: YEAR1/2 El Niño, YEAR3 La Niña
- SH LAKI: YEAR1 El Niño, YEAR2/3 La Niña
- SH+6 LAKI: YEAR1/2 La Niña or neutral, no El Niño

∴ **Strong YEAR1/2 dependence of ENSO on eruption hemisphere and season.**



CONCLUSIONS

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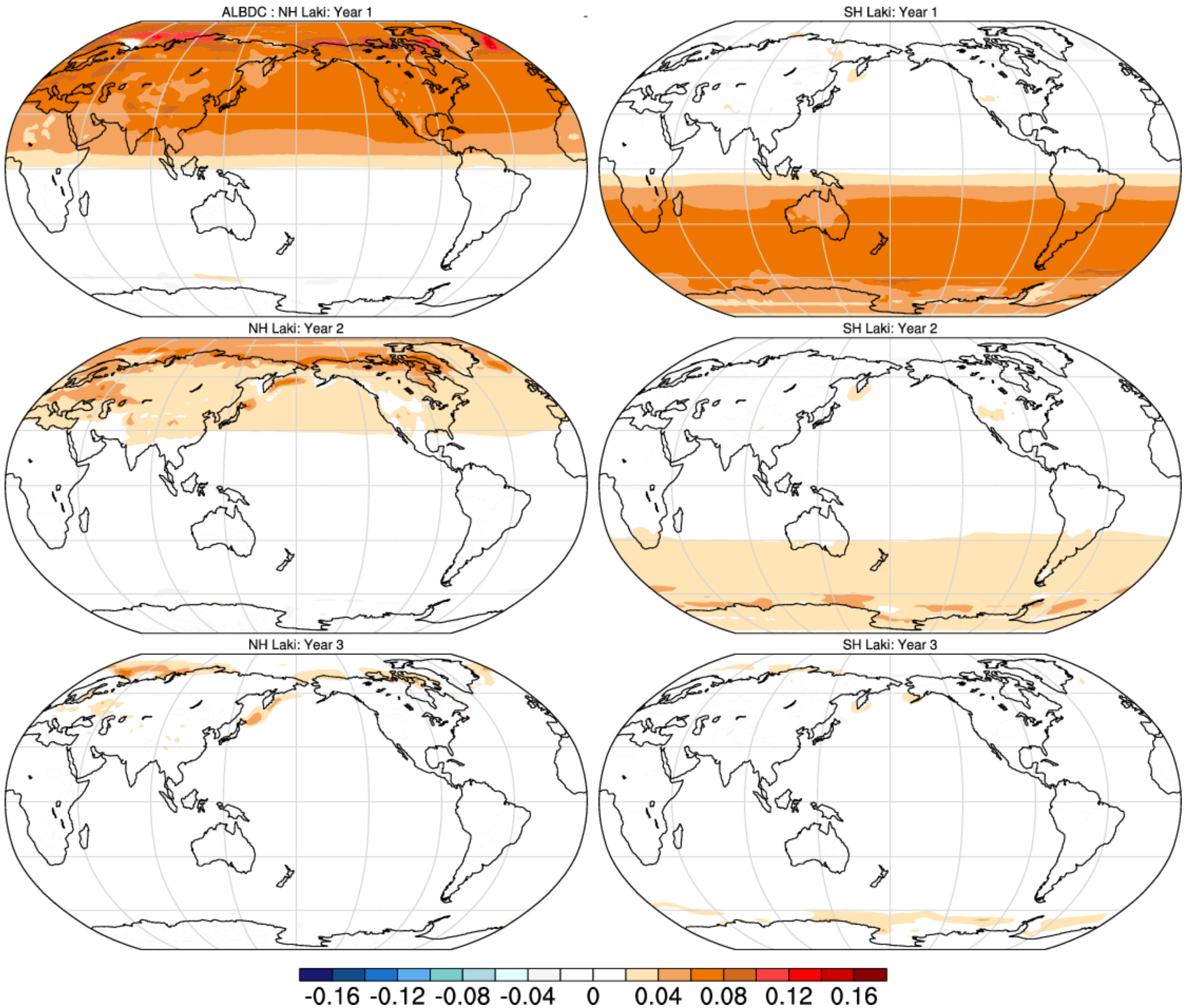
END

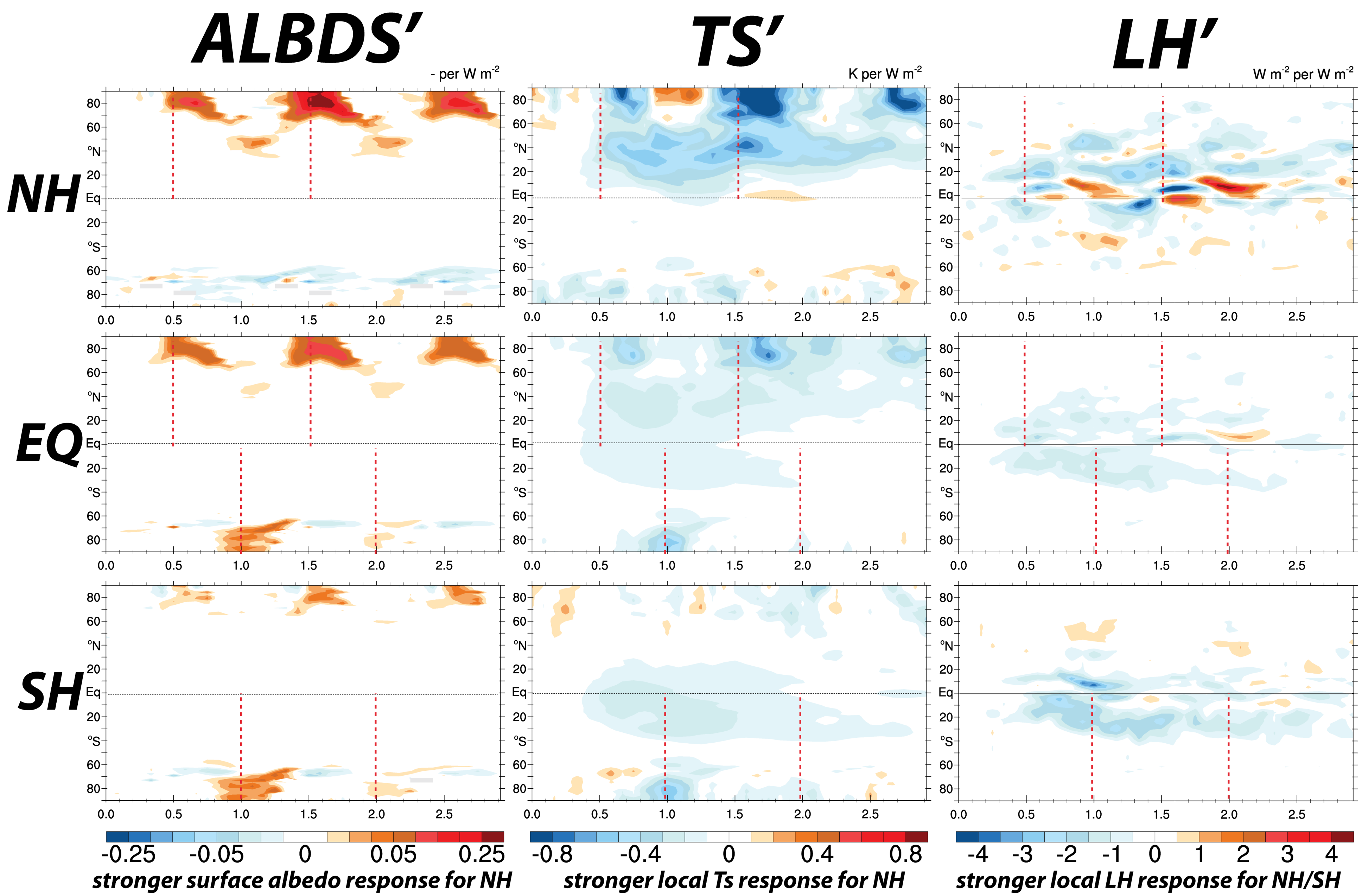
FORCING: NH & SH LAKI ERUPTIONS

- Basic features of clear-sky albedo anomalies are shared by the NH/SH Laki eruptions.
- Land-sea contrasts and cloud masking modulate those anomalies, resulting in slightly different net solar flux perturbations.
- Thermal response contrasts further modulate those responses and result in modest differences in the net TOA flux response.



LME RESULTS: INTRINSIC ASYMMETRIES

- NH eruptions induce greater surface albedo (ALBDS) and temperature (TS) responses (summer)
- Lower NH ocean extent leads to stronger surface expression (less of a moderating influence by the ocean)

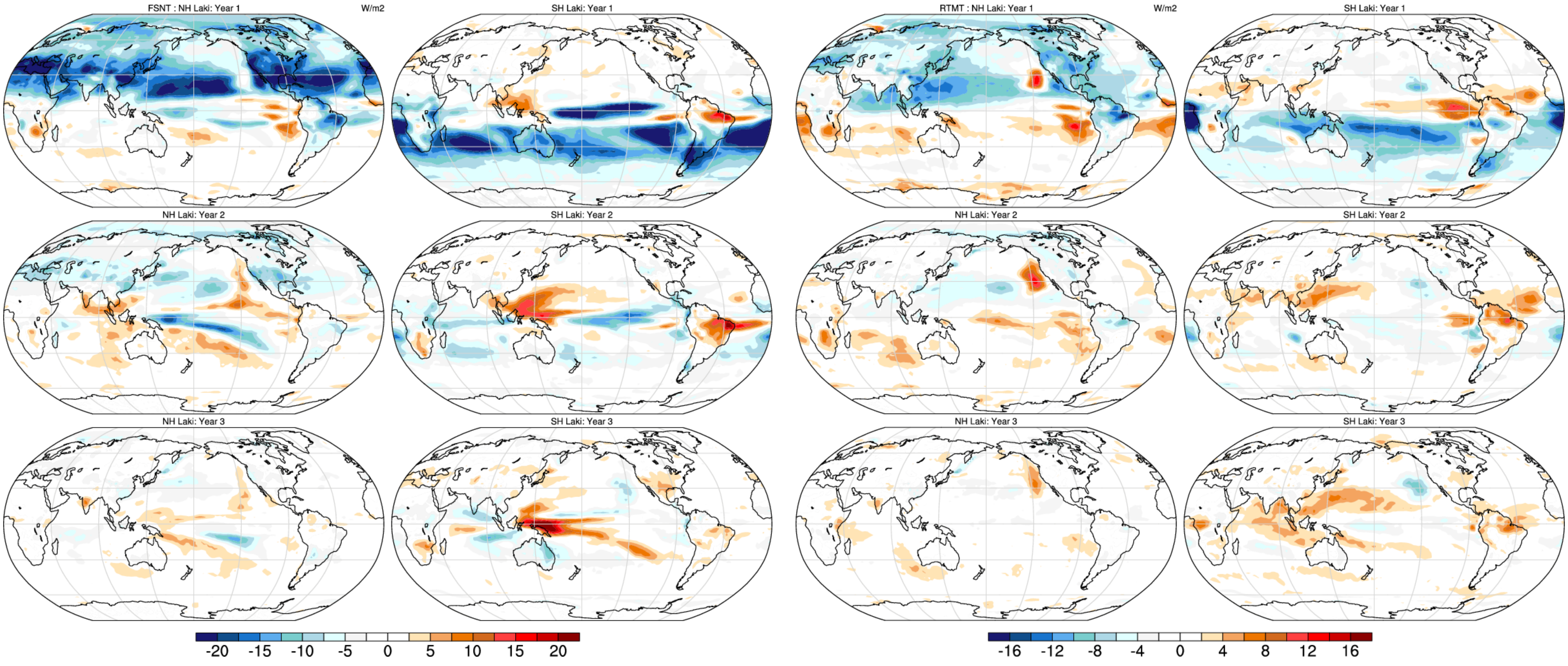


Are these and related asymmetries responsible for the asymmetric monsoon responses of the last millennium?

FORCING: NH & SH LAKI ERUPTIONS

FSNT R_T

NH SH NH SH



AMDV-GLOBAL MONSOON CONNECTIONS

- Monerie et al. 2019; warm phases associated with strong North Africa/ India monsoons, weak South American
- mediated by change in circulation driven by Pacific/Walker Cell interactions and inter hemispheric temperature gradient
- tropical component of SSTa changes is key though NATL also plays a role
- influence is not linearly related to warming

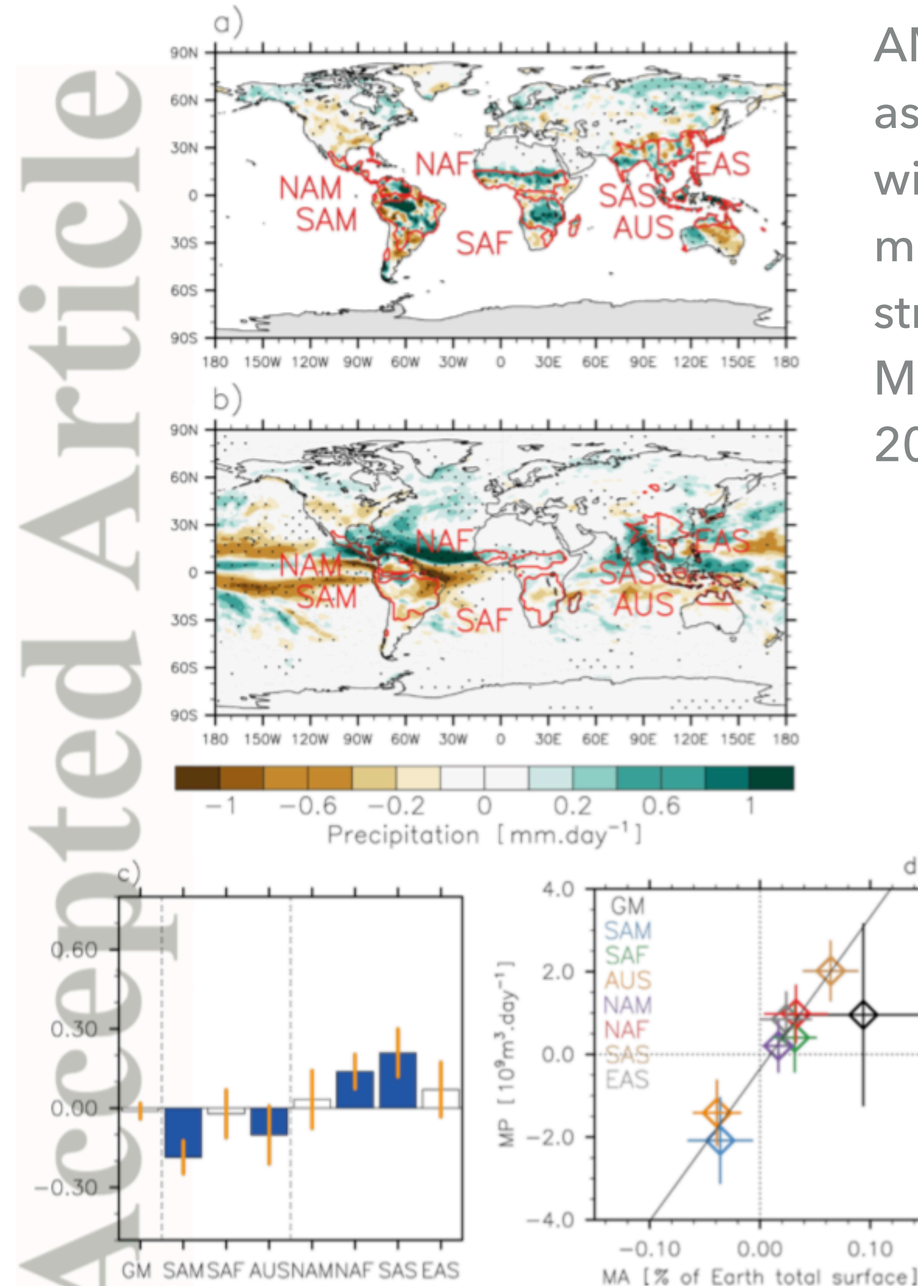


Figure 1: (a) Observed precipitation (mm.day^{-1}; GPCC; (Schneider et al., 2014)) regressed onto the AMV index (ERSST;(Huang et al., 2015)) (See the method in the supplementary material). (b)

AMV association with regional monsoon strength from Monerie et al. 2019, fig 1.

STRATOSPHERIC CONTRASTS

T50

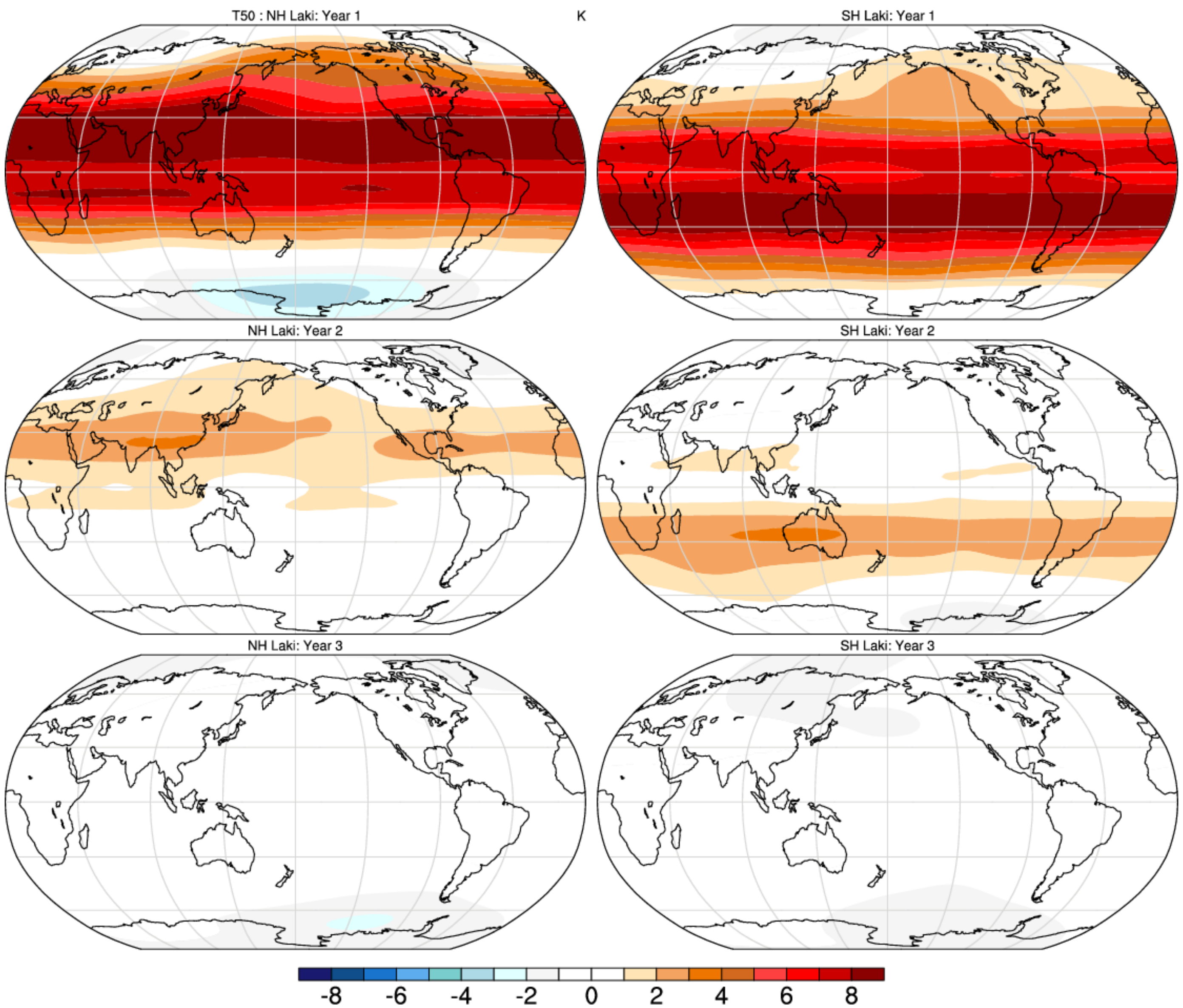
NH

SH

R_T

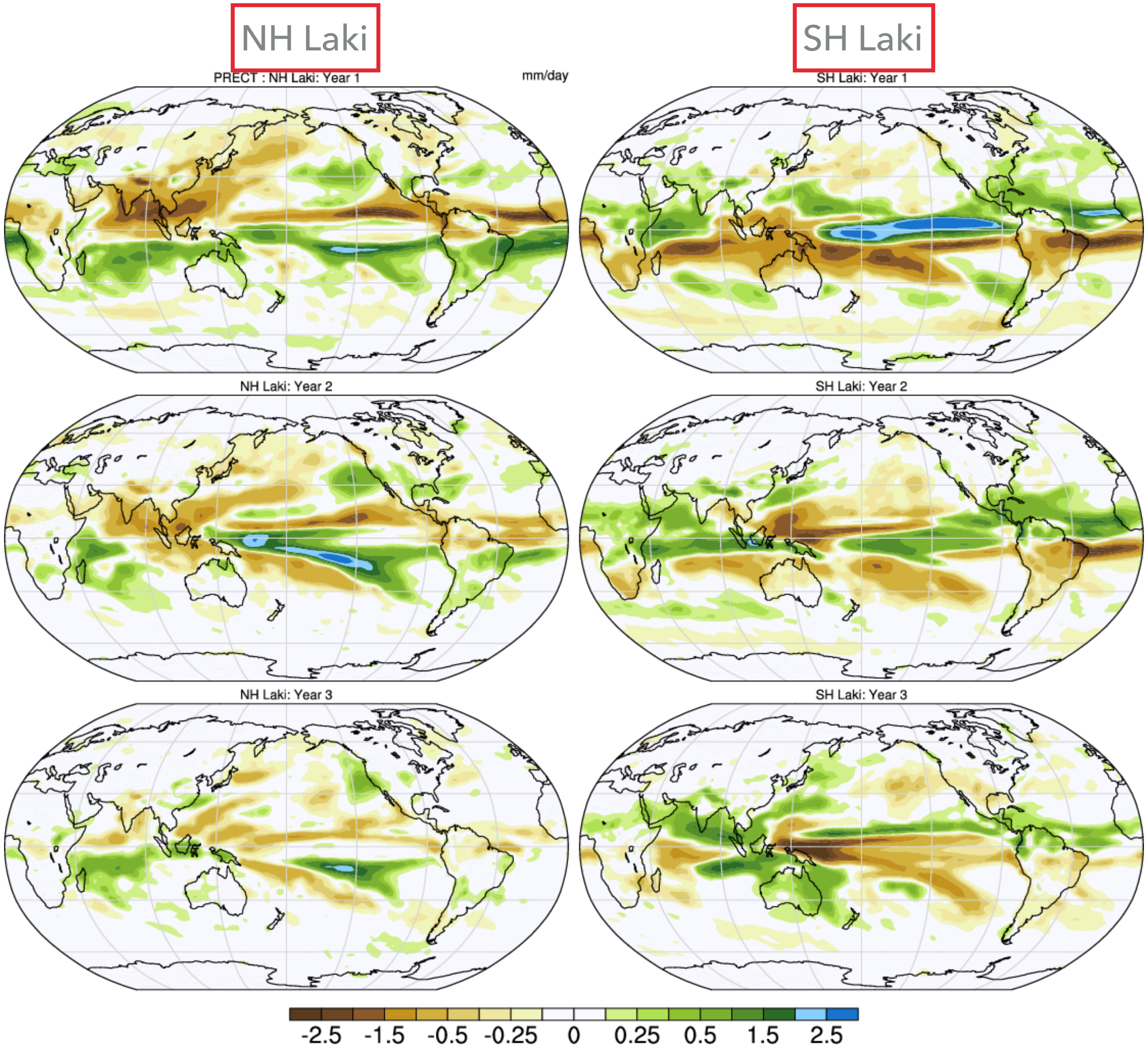
NH

SH



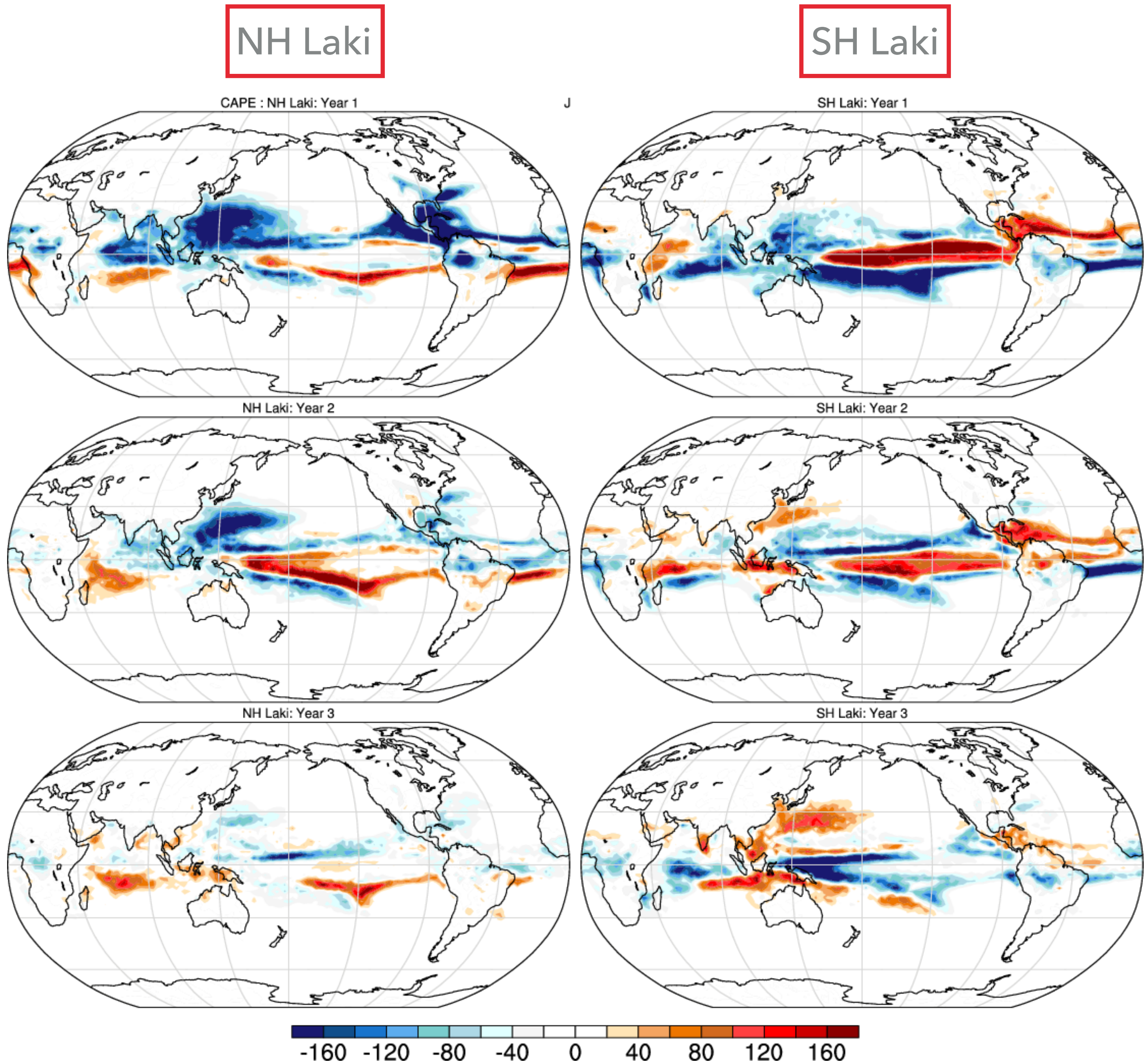
RAINFALL: NH & SH LAKI ERUPTIONS

- Changes in rainfall in year 1 are quite different on the equator.
- Diabatic heating contrasts likely arise from contrasts in the mean state and the contrast in ENSO response in years 2-3.
- Understanding the contrasts remains a work in progress.



CAPE: NH & SH LAKI ERUPTIONS

- Changes in CAPE in year 1 are also quite different on the equator.
- Diabatic heating contrasts likely arise from contrasts in the mean state and the contrast in ENSO response in years 2-3.
- Understanding the contrasts remains a work in progress.



V200: NH/EQ/SH LME ERUPTIONS

- Meridional winds at upper levels show the anomalous zonal mean divergence in the opposing hemisphere, suggesting an increase in the DSE transport to the eruption hemisphere.