Budgets for Process Studies: A-RIP and LESFMIP Perspectives

Jonathon S. Wright • Shenglong Zhang • Yuanrui Chen
Department of Earth System Science, Tsinghua University

APARC Reanalysis Intercomparison Project
Contributions welcome!

Topics include:

- Monsoons and extreme events
- Teleconnections
- Stratosphere-troposphere coupling
- Polar vortex dynamics
- Atmospheric composition
- Aerosols and air quality
- Contact me:
  jswright@tsinghua.edu.cn

Joint special issue in ACP & WCD


Special issue

Articles / Special issue

Search

The SPARC Reanalysis Intercomparison Project (S-RIP) Phase 2 (ACP/WCD inter-journal SI)

Editor(s): ACP co-editors | Coordinators: Gabriele Stiller and Peter Haynes | Co-organizers: Gloria Manney, Jonathon Wright, and Masatomo Fujiwara

Special issue jointly organized between Atmospheric Chemistry and Physics and Weather and Climate Dynamics

what a reanalysis is:

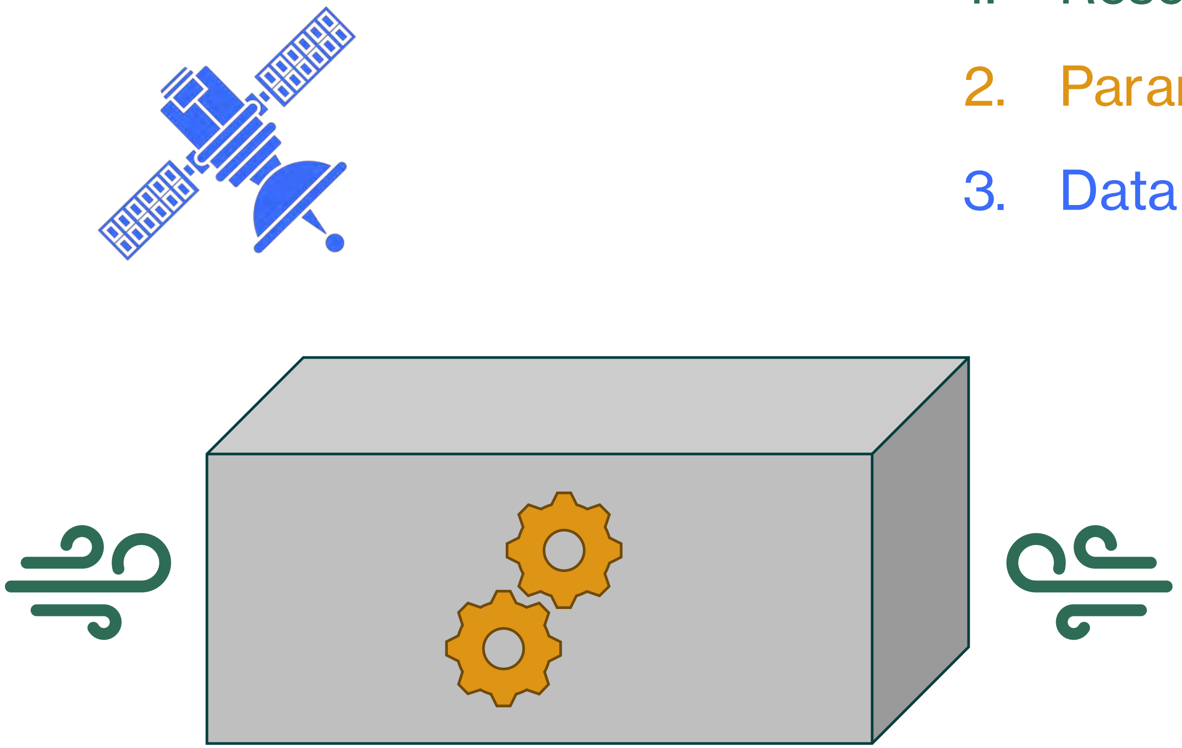
a best estimate

what a reanalysis is not:
observations

The Problem:

In a reanalysis grid cell, energy changes due to:

1. Resolved transport (advection)
2. Parameterized physics (convection, radiation…)
3. Data Assimilation



Energy is not conserved!

what a reanalysis is not:

conservative

what a reanalysis is:

complete

A Solution:

Dry static energy

$$s = c_p T + gz$$

The standard approach using reanalysis products (Yanai et al. 1973):

$$Q_1 \equiv \frac{\partial \overline{s}}{\partial t} + \overline{\nabla \cdot (\mathbf{v}s)} + \frac{\partial \overline{\omega s}}{\partial p} = Q + \frac{\partial}{\partial p}\overline{s'\omega'}$$

But reanalyses now support:

$$\frac{\partial \overline{s}}{\partial t} + \nabla \cdot (\overline{\mathbf{v}s}) + \frac{\partial \overline{\omega s}}{\partial p} = Q_{\mathrm{phy}} + Q_{\mathrm{asm}} + \frac{\partial}{\partial p}\overline{s'\omega'}$$

output from reanalysis model

residual

compute transports from reanalysis fields

compute from forecast vs analysis fields

We have constructed similar budgets for specific humidity, momentum, ozone...

Account for assimilation effects

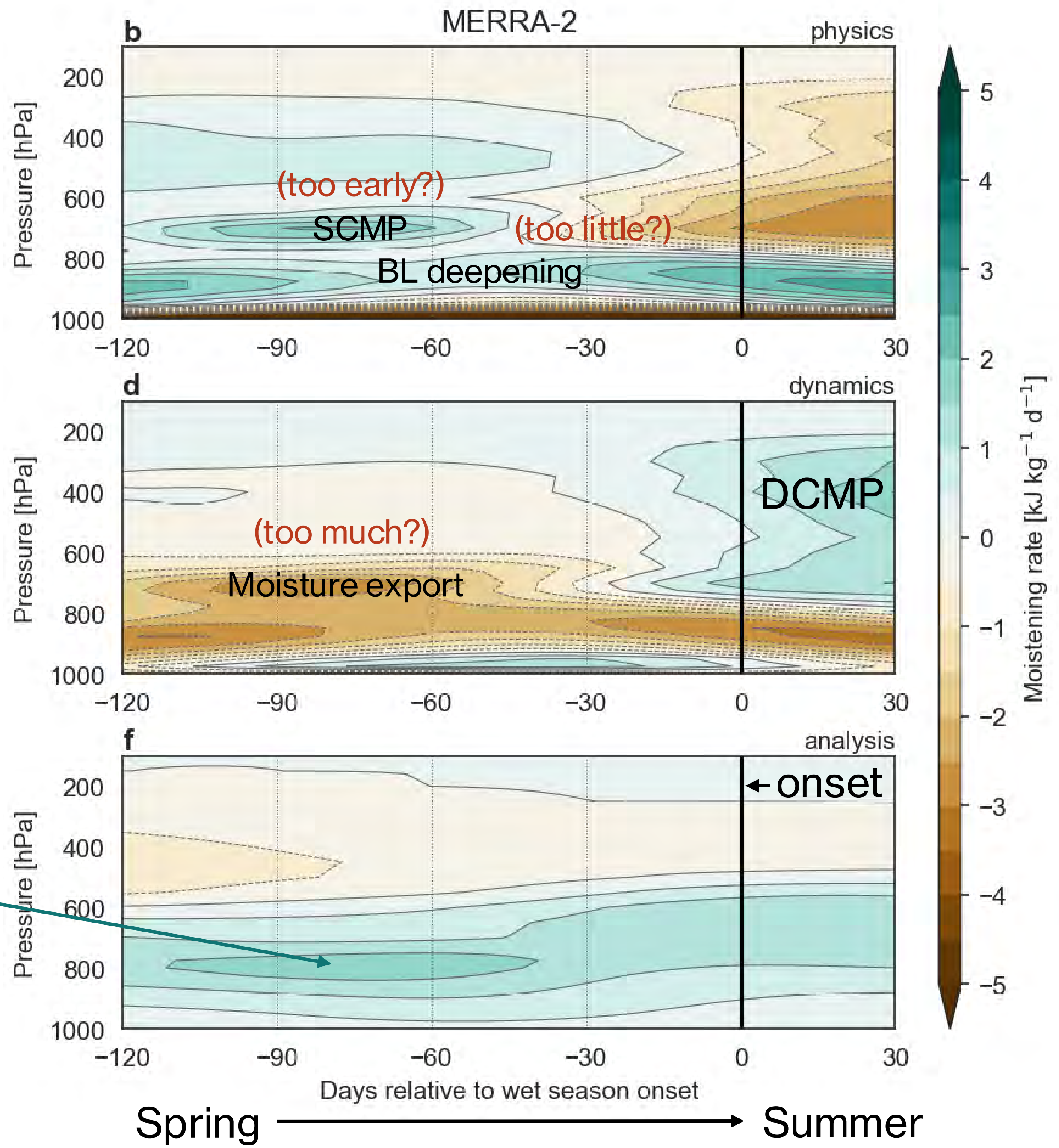
[poster with more details next Wednesday @ BACO-25]

Example:
Southern Amazon

Where the rainforest summons the rainy season

1. Rainforest ET exported during dry season
2. Late dry season increase in ET and T_{sfc}
3. Shallow convection preconditioning
4. Deep convection moisture pump and wet season onset

The lower troposphere above the Southern Amazon rainforest is too dry in MERRA-2, requiring a large assimilation increment in water vapor to support the dry-to-wet season transition.



Increments can help to:

- Identify where, when, and (sometimes) why reanalyses differ from obs, models, other reanalyses…
- Improve budget allocation and process understanding
- Distinguish real trends from changes in assimilated obs
- Enrich trajectory-based source attribution
- Clarify assimilation effects around extreme events
- Deepen reanalysis–model comparisons

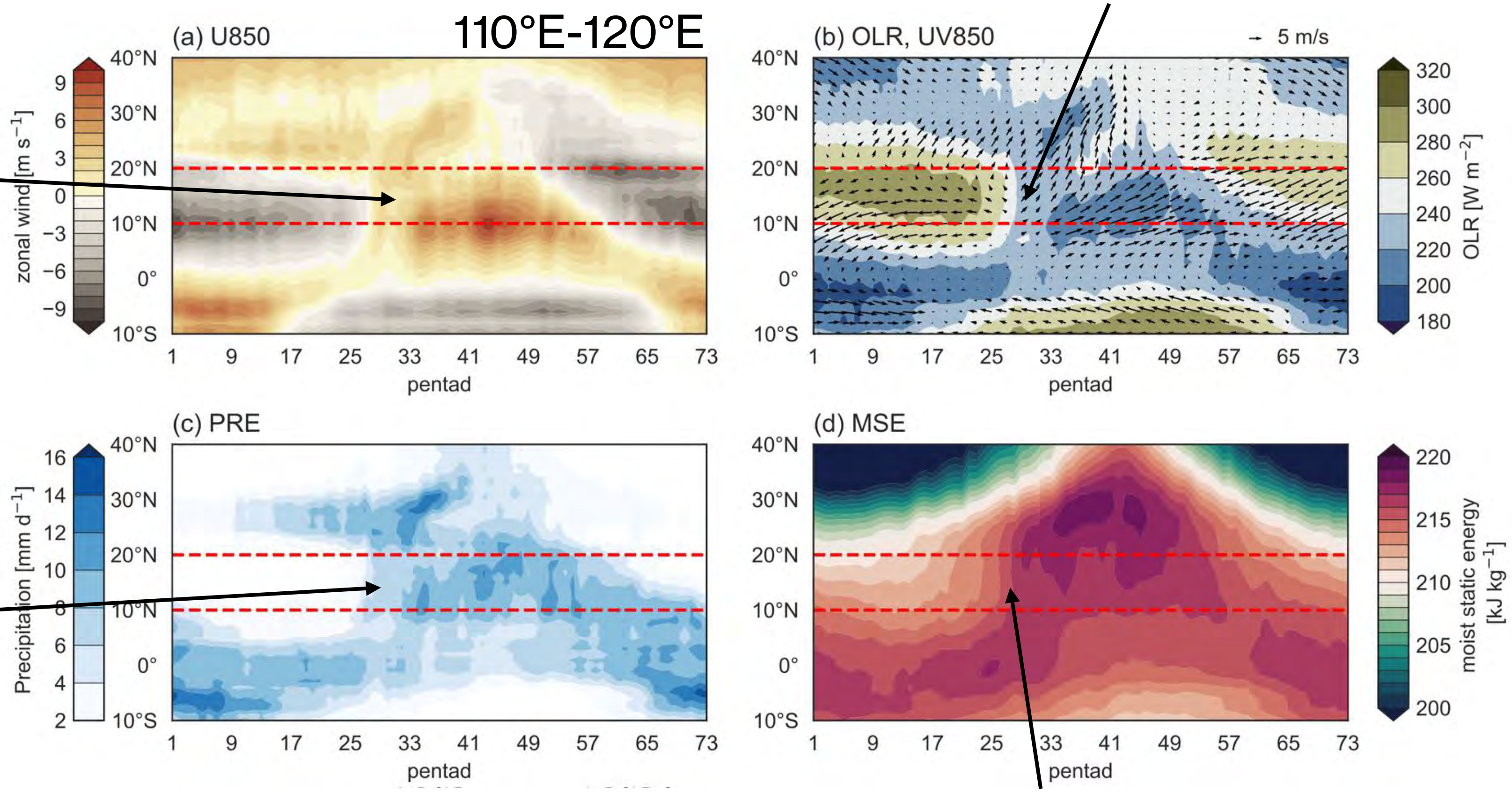
…but…

Application:
South China Sea Summer Monsoon

Harbinger of rains to come

Regional-scale deep convection causes decrease in OLR

Onset often defined by reversal of lower tropospheric zonal winds



Large increase in rainfall in late April to early May

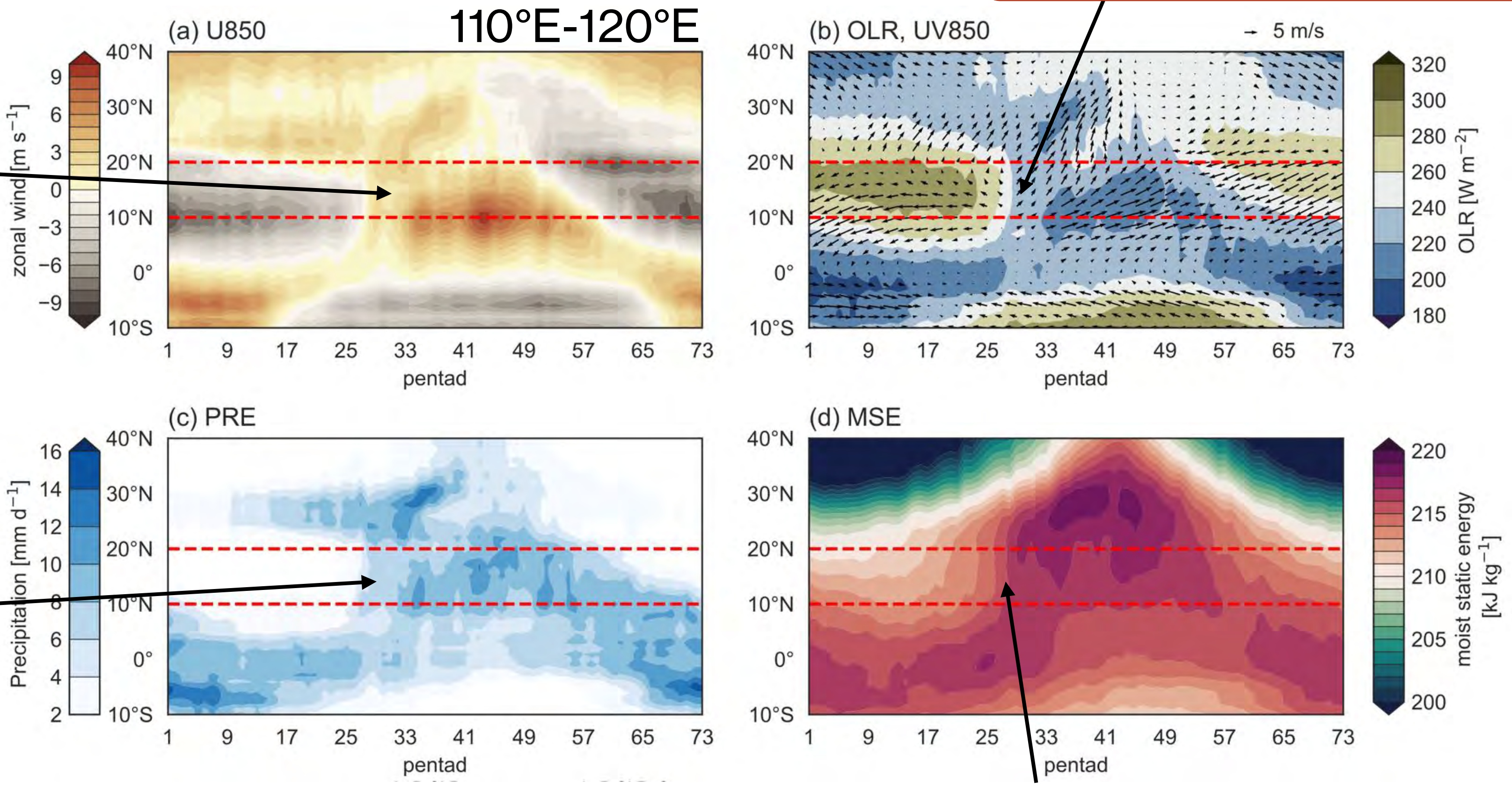
Sharp increase in moist static energy

Application:
South China Sea Summer Monsoon

Harbinger of rains to come

Regional-scale deep convection causes decrease in OLR

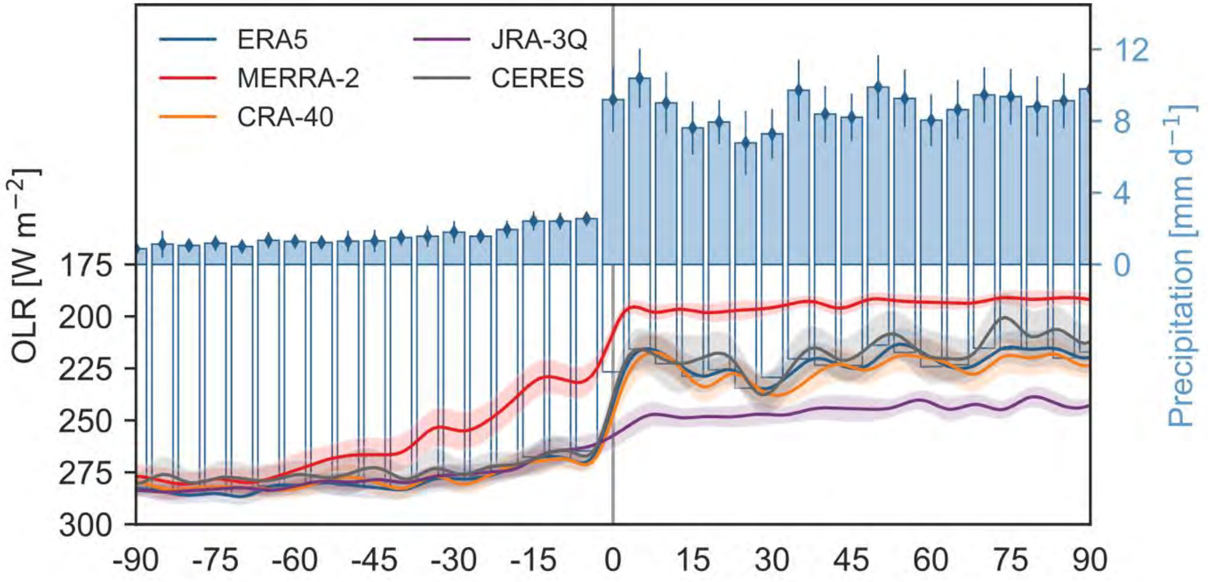
Onset often defined by reversal of lower tropospheric zonal winds



Large increase in rainfall in late April to early May

Sharp increase in moist static energy

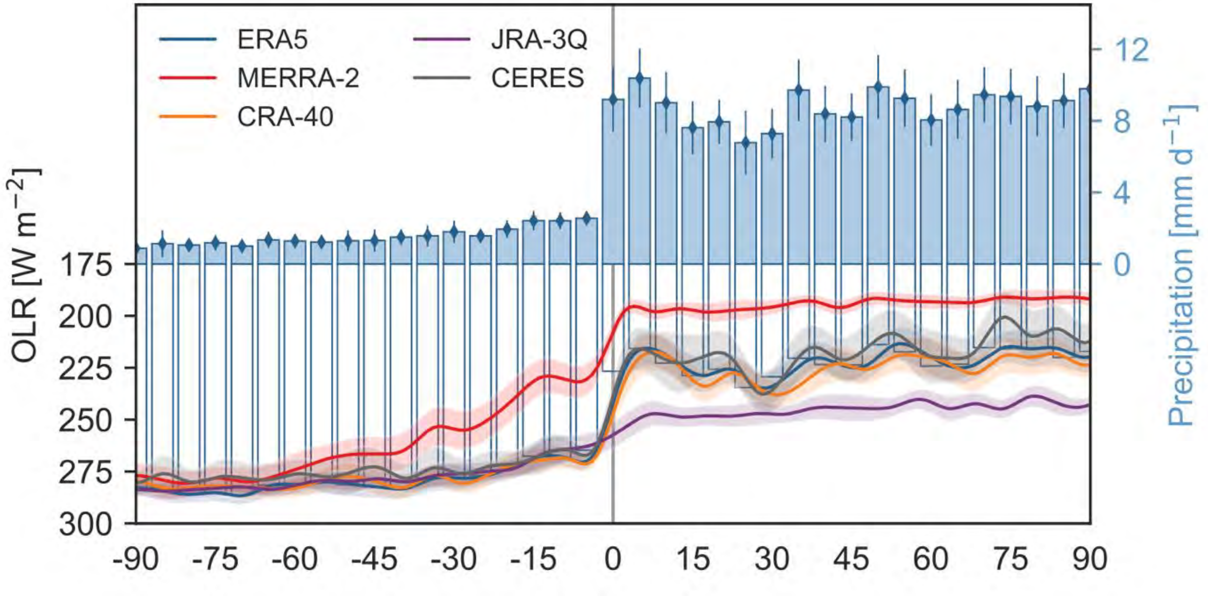
Application:
South China Sea Summer Monsoon



Vertically-integrated dry static energy equation:

$$c_p \frac{\partial \langle T \rangle}{\partial t} + \nabla_h \cdot \langle \mathbf{v} s \rangle \approx L_v P + Q_{\mathrm{R}} + H$$

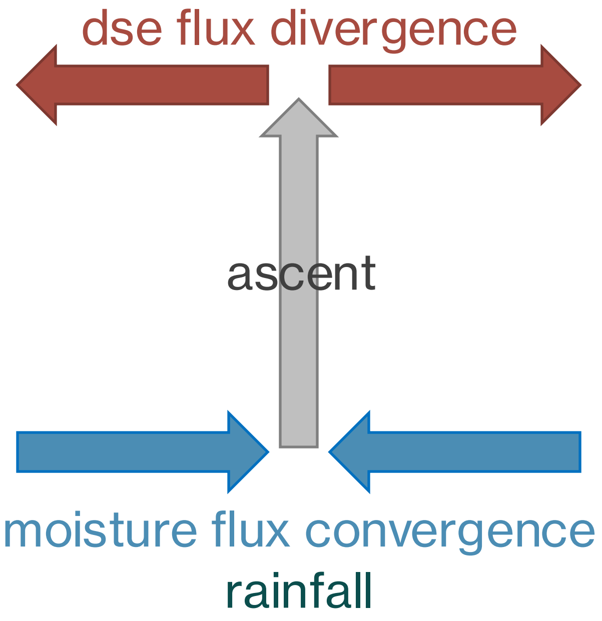
Application:
South China Sea Summer Monsoon



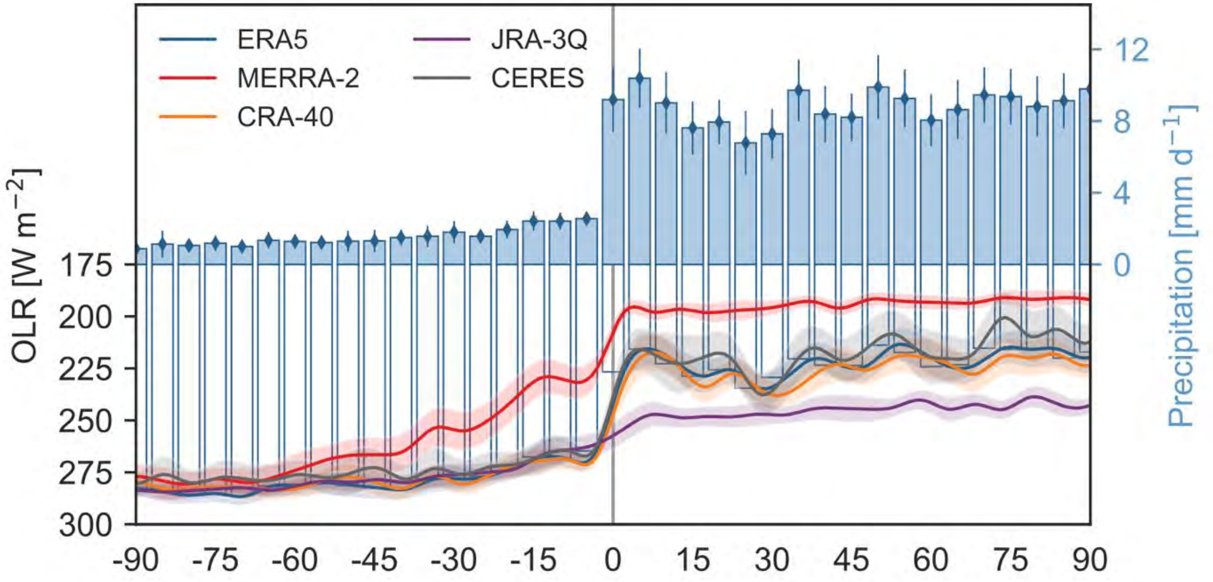
Vertically-integrated dry static energy equation:

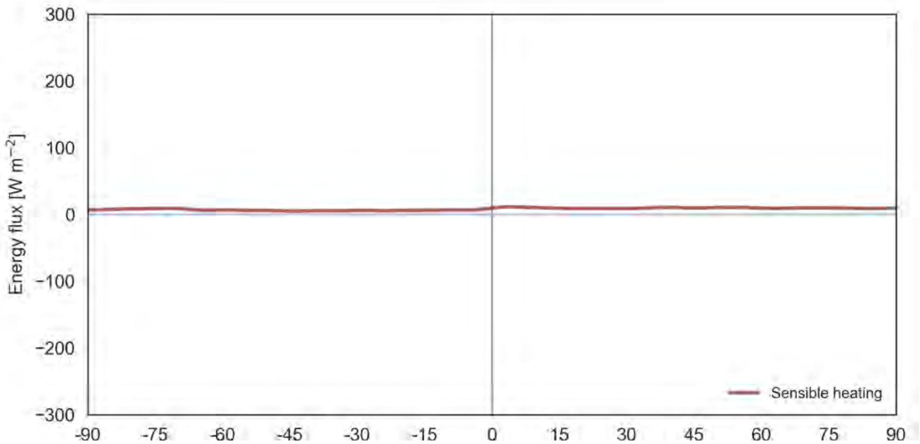
$$c_p \frac{\partial \langle T \rangle}{\partial t} + \boxed{\nabla_h \cdot \langle \mathbf{v} s \rangle} \approx L_v P + Q_{\mathrm{R}} + H$$

Target is vertically-integrated DSE flux divergence.



Application:
South China Sea Summer Monsoon





Vertically-integrated dry static energy equation:

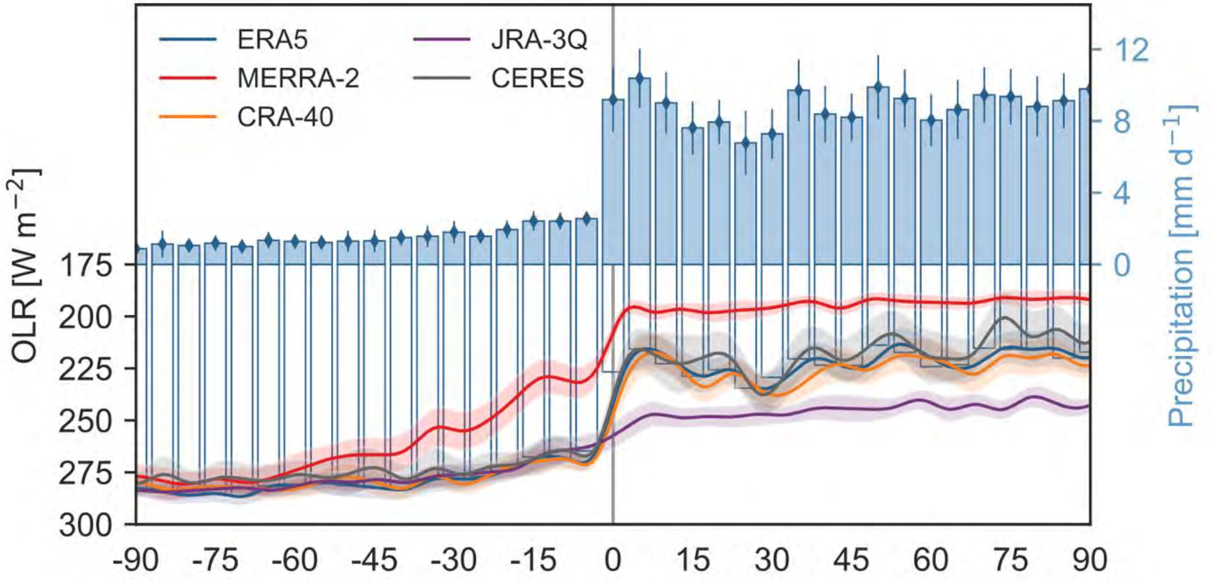
$$c_p \frac{\partial \langle T \rangle}{\partial t} + \nabla_h \cdot \langle \mathbf{v} s \rangle \approx L_v P + Q_{\mathrm{R}} + H$$

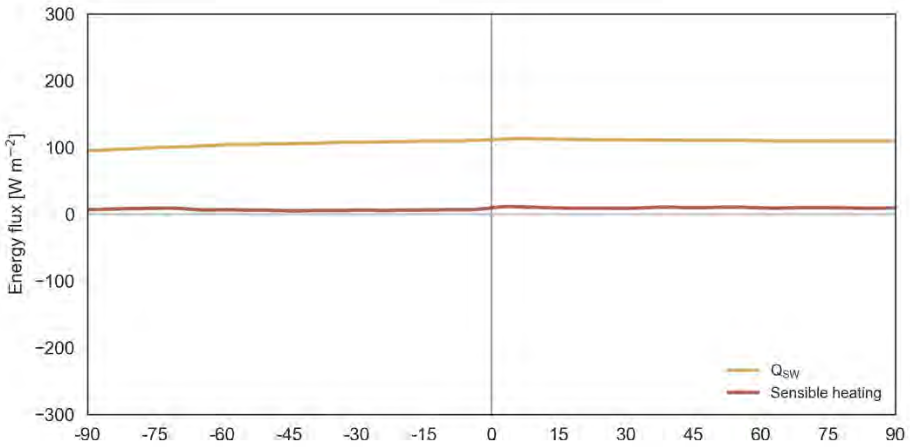
Target is vertically-integrated DSE flux divergence.
Which terms matter?

$$c_p \frac{\partial \langle T \rangle}{\partial t} + \nabla_h \cdot \langle \mathbf{v} s \rangle \approx L_v P + Q_{\mathrm{R}} + \boldsymbol{H}$$

Changes in sensible heat flux are small because the surface is wet and seasonal variations in SST are small

Application:
South China Sea Summer Monsoon





Vertically-integrated dry static energy equation:

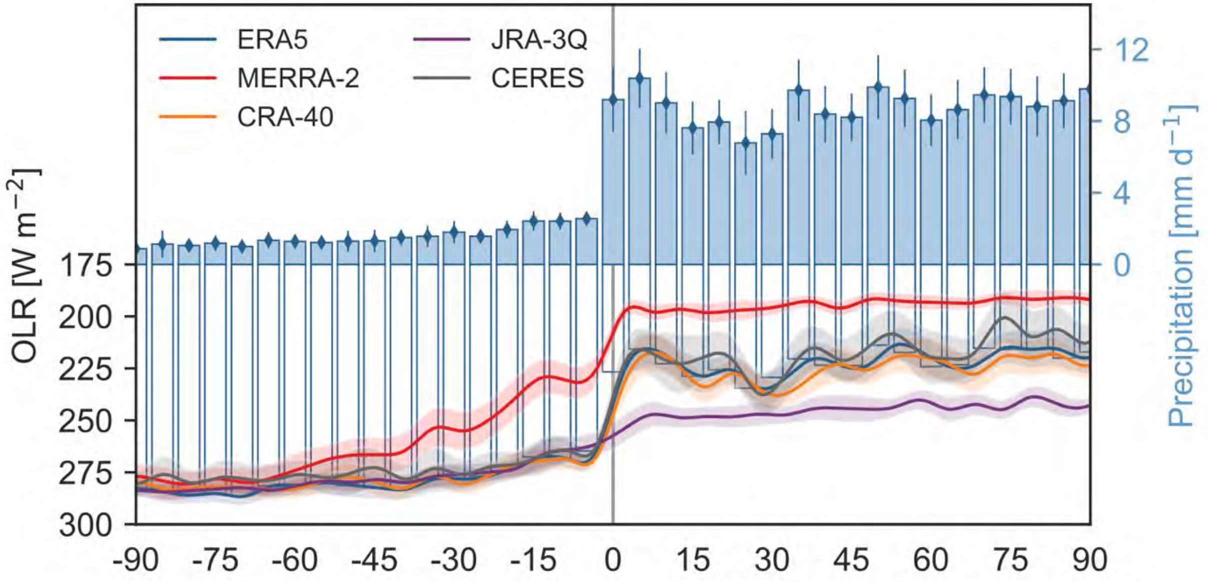
$$c_p \frac{\partial \langle T \rangle}{\partial t} + \nabla_h \cdot \langle \mathbf{v} s \rangle \approx L_v P + Q_{\mathrm{R}}$$

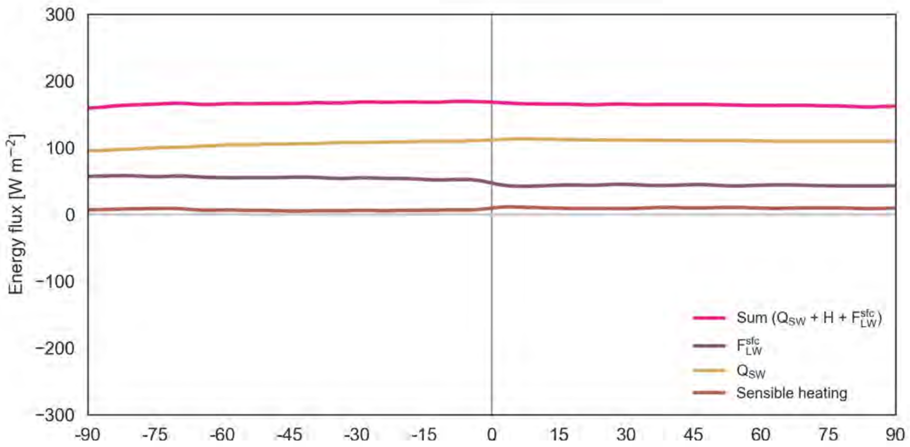
Target is vertically-integrated DSE flux divergence.
Which terms matter?

$$Q_{\mathrm{R}} = Q_{\mathrm{LW}} + Q_{\mathrm{SW}}$$

Column-integrated shortwave heating changes little if changes in surface flux balance changes in TOA flux

Application:
South China Sea Summer Monsoon





Vertically-integrated dry static energy equation:

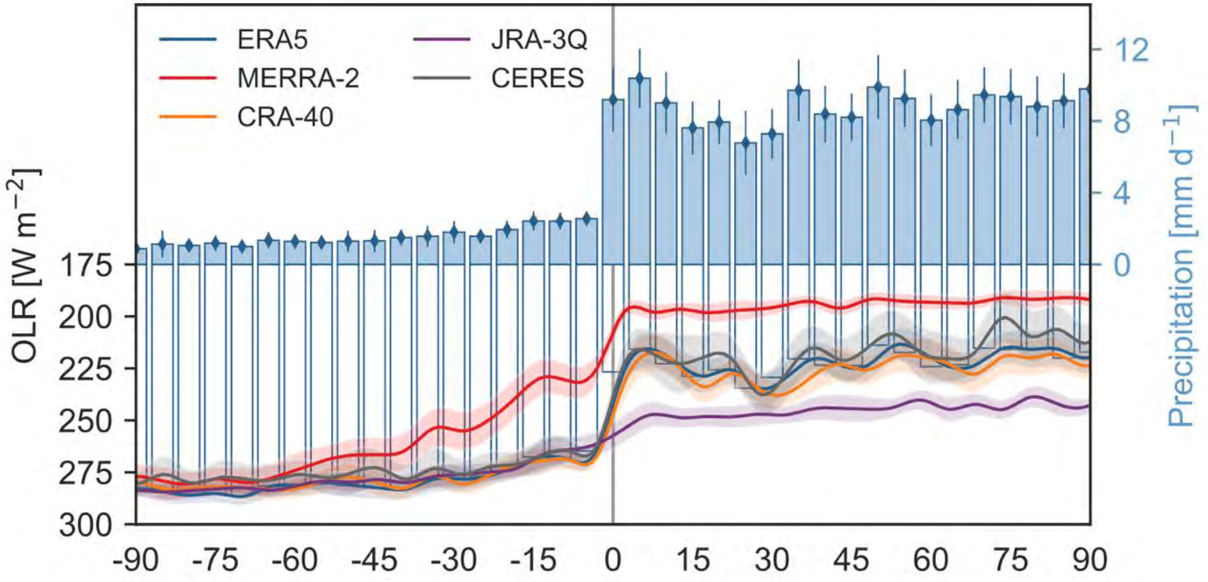
$$c_p \frac{\partial \langle T \rangle}{\partial t} + \nabla_h \cdot \langle \mathbf{v} s \rangle \approx L_v P + Q_{\mathrm{LW}}$$

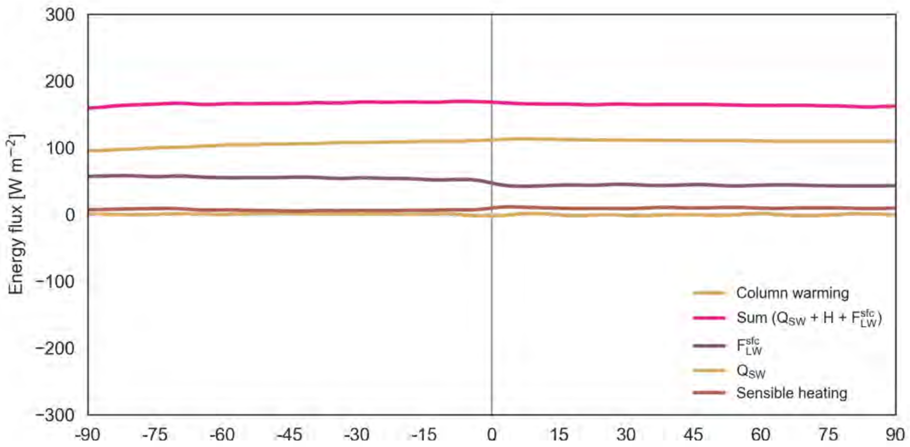
Target is vertically-integrated DSE flux divergence.
Which terms matter?

$$Q_{\mathrm{LW}} = \left(F^{\mathrm{sfc}}_{\mathrm{LW}\uparrow} - F^{\mathrm{TOA}}_{\mathrm{LW}\uparrow} \right)$$

Net surface LW flux should change little due to small changes in SST and large surface air humidity.

Application:
South China Sea Summer Monsoon





Vertically-integrated dry static energy equation:

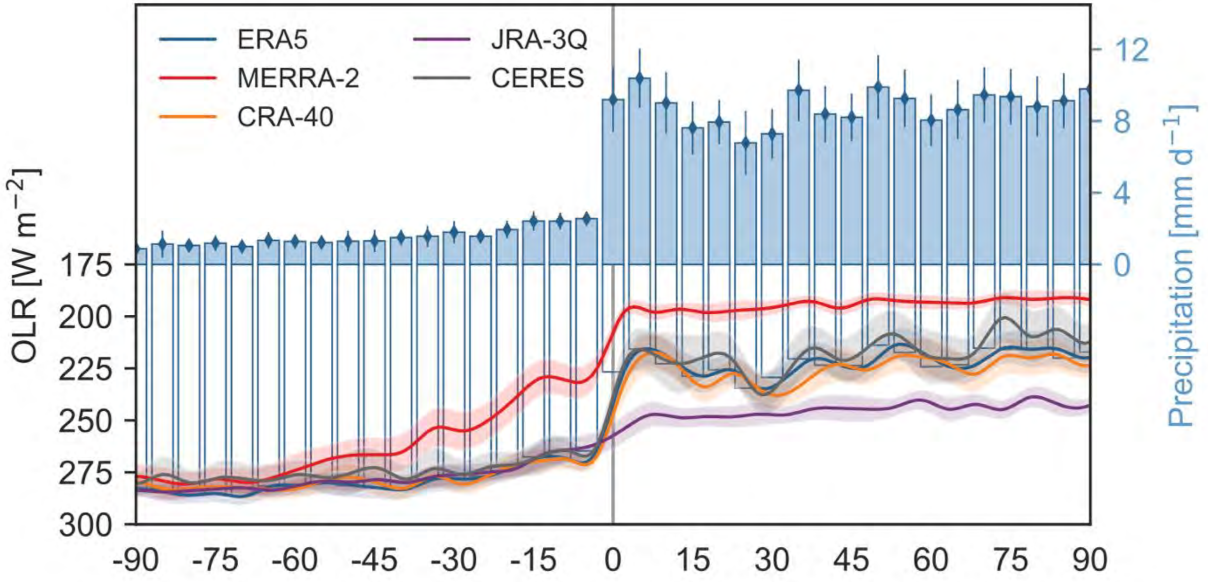
$$c_p \frac{\partial \langle T \rangle}{\partial t} + \nabla_h \cdot \langle \mathbf{v} s \rangle \approx L_v P - \mathrm{OLR}$$

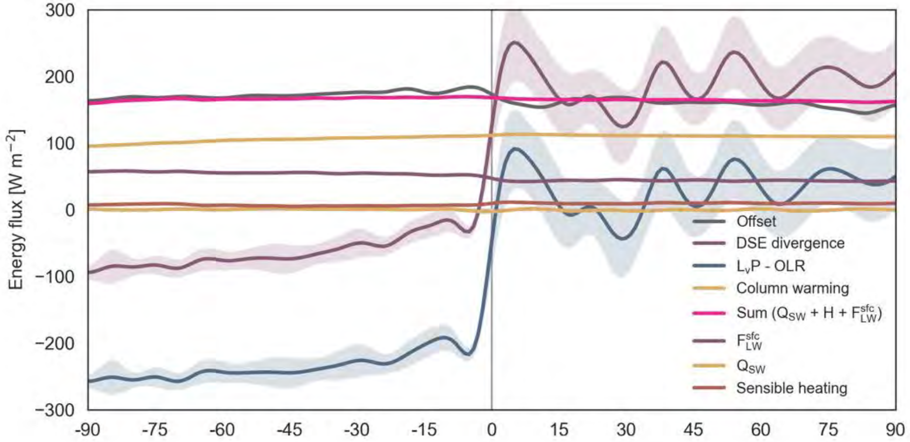
Target is vertically-integrated DSE flux divergence.
Which terms matter?

$$c_p \frac{\partial \langle T \rangle}{\partial t} + \nabla_h \cdot \langle \mathbf{v} s \rangle \approx L_v P - \mathrm{OLR}$$

Small Coriolis term means only very large (~10,000 km) circulations can accumulate available potential energy

Application:
South China Sea Summer Monsoon



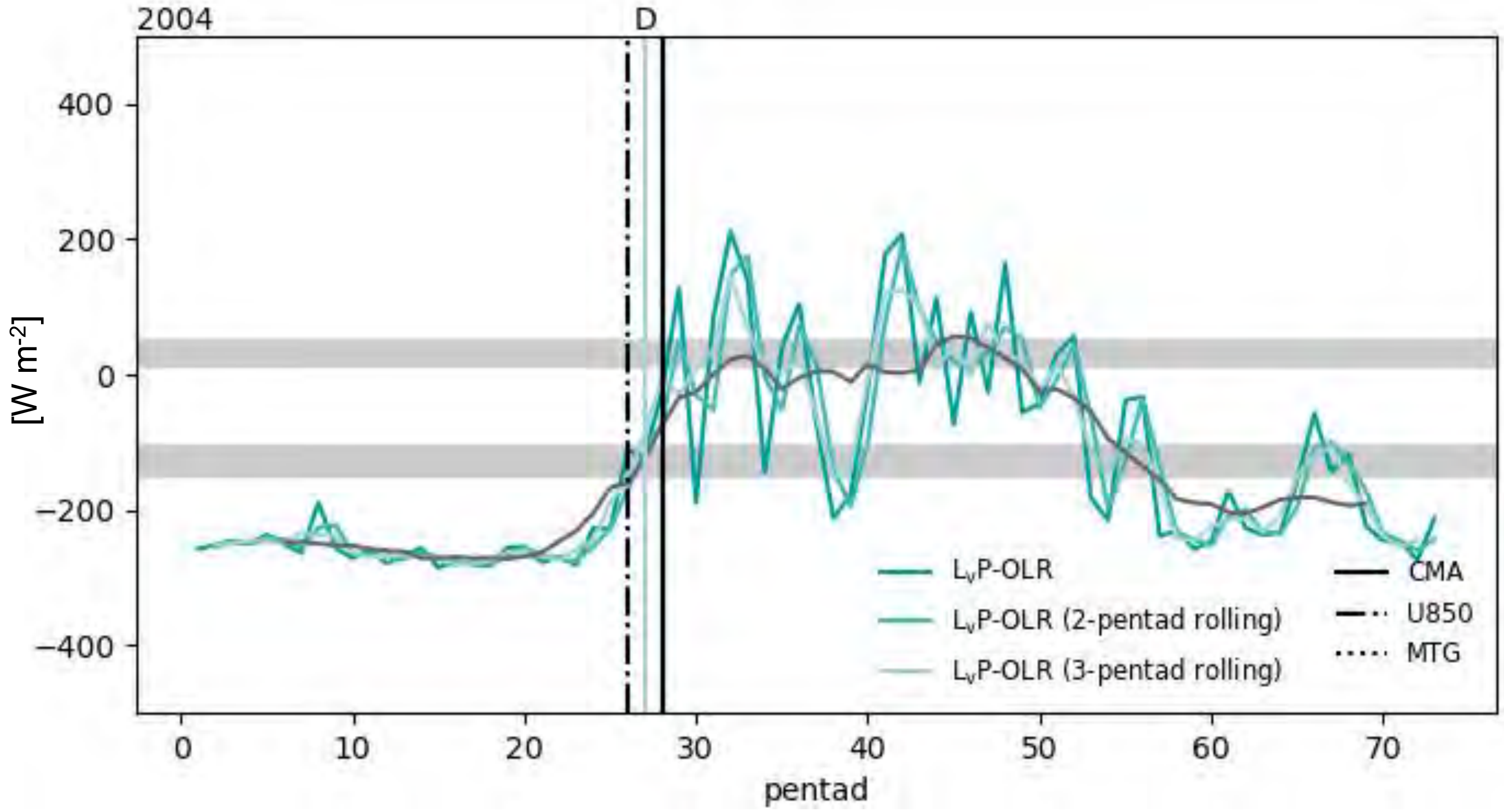


Vertically-integrated dry static energy equation:

$$\nabla_h \cdot \langle \mathbf{v} s \rangle \approx L_v P - \mathrm{OLR}$$

We can track the initiation and variability of the monsoon overturning circulation from precipitation and OLR, both of which are readily observable!

Application:
South China Sea Summer Monsoon



First pentad for which:

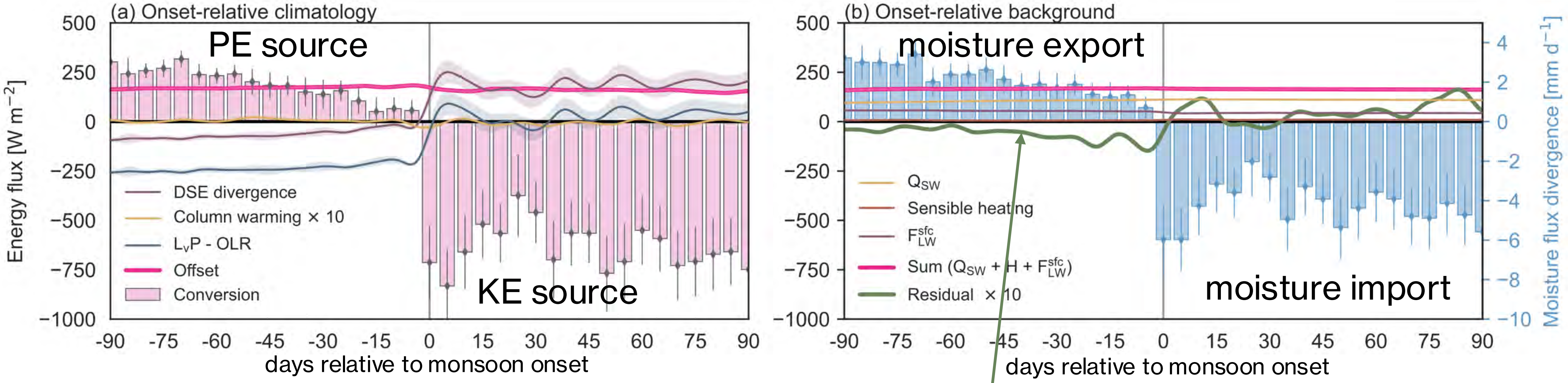
1. Pentad mean and slow annual cycle both exceed the median
2. Subsequent local maximum exceeds the 75th percentile
3. No pentad mean between onset and subsequent local maximum falls below the median
4. Annual cycle time series consistently increases from onset to its peak

Application:
South China Sea Summer Monsoon

Vertically-integrated dry static energy equation:

$$\nabla_h \cdot \langle \mathbf{v} s \rangle \approx L_v P - \mathrm{OLR}$$

- Energy conversion drives the monsoon
- Moisture flux convergence sustains it

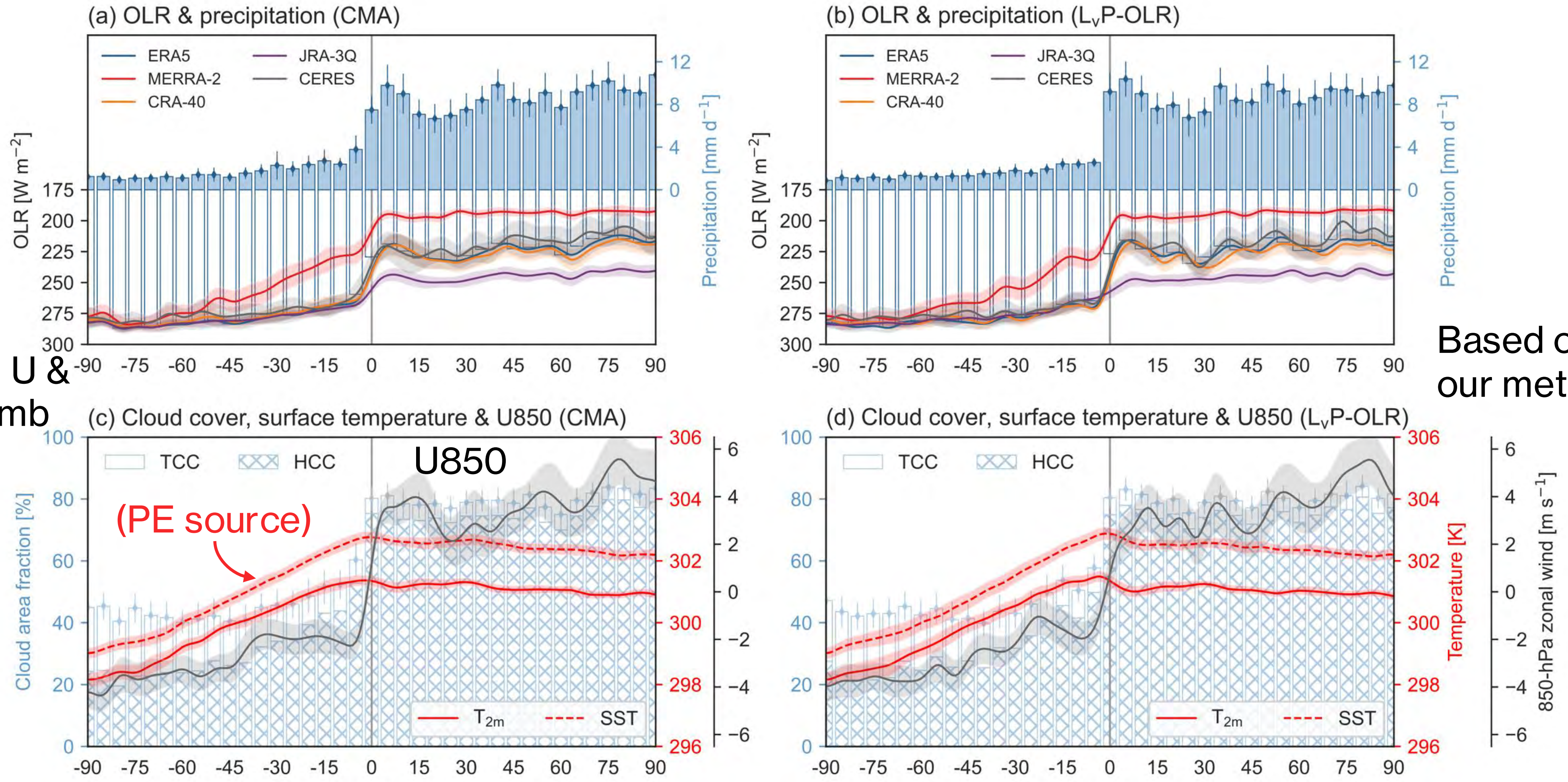


The residual (data assimilation) has a significant negative correlation with energy conversion

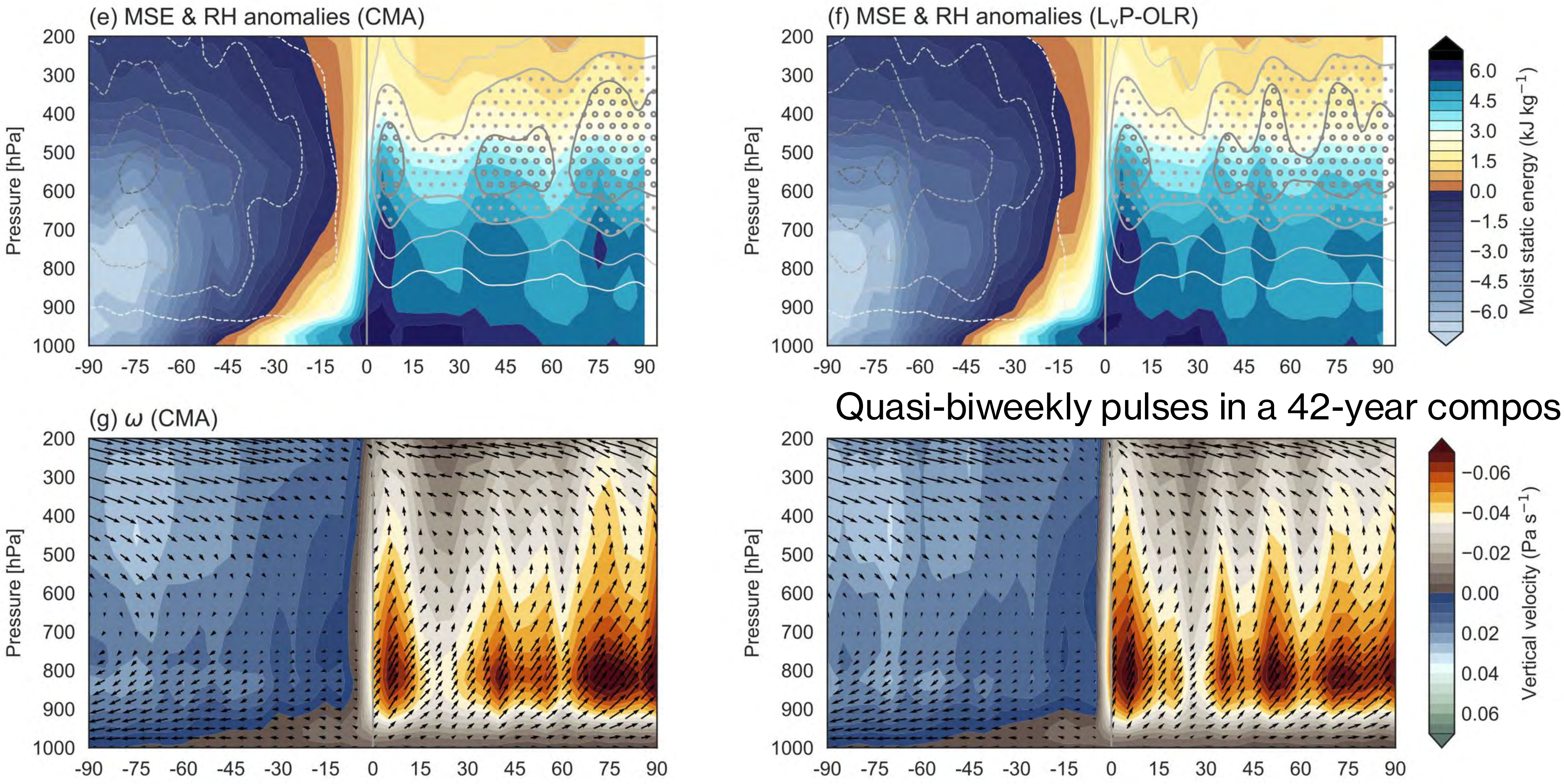
Application:
South China Sea Summer Monsoon

Based on U & θ_e @ 850mb

Based on our method

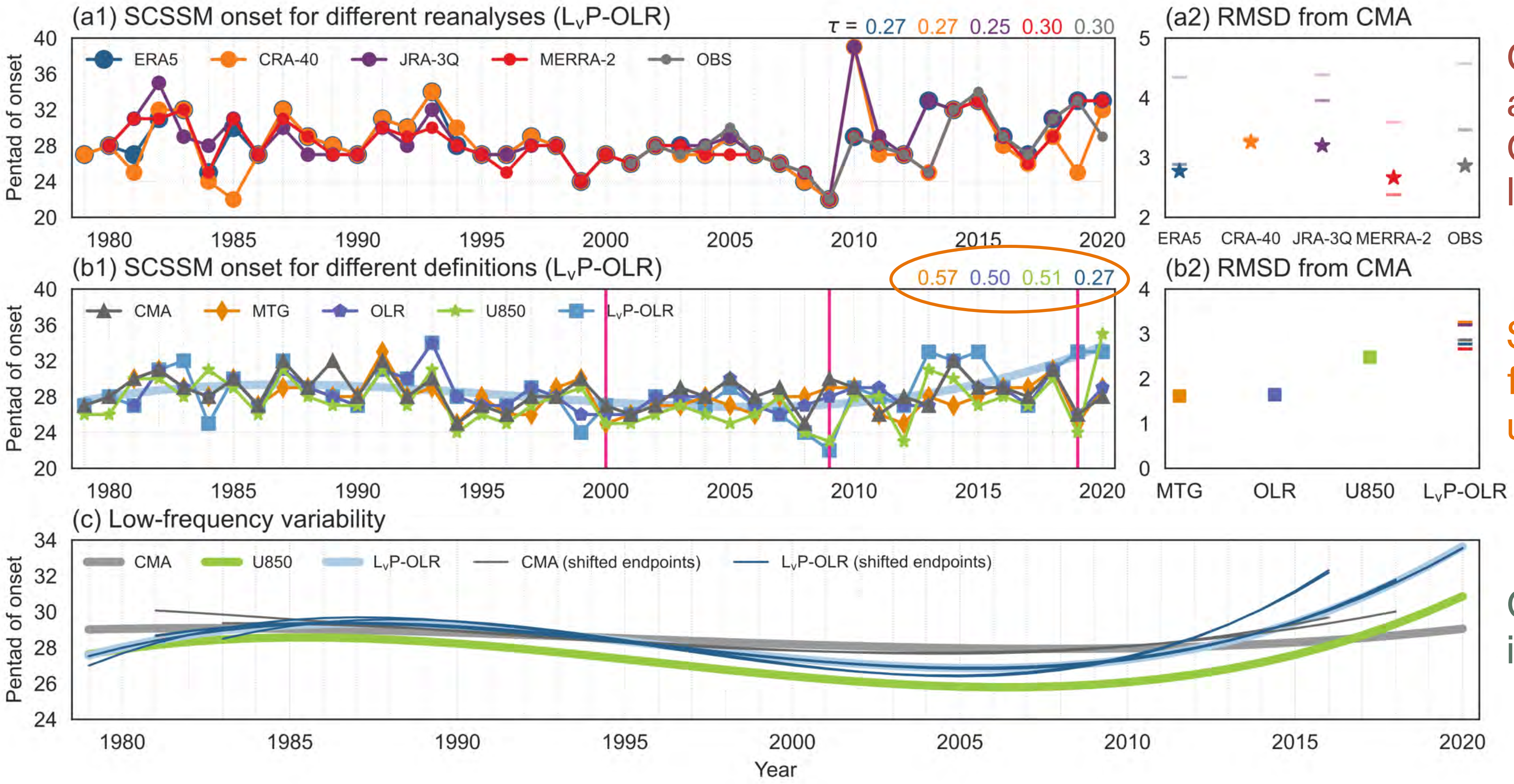


Application:
South China Sea Summer Monsoon



Quasi-biweekly pulses in a 42-year composite!

Application:
South China Sea Summer Monsoon

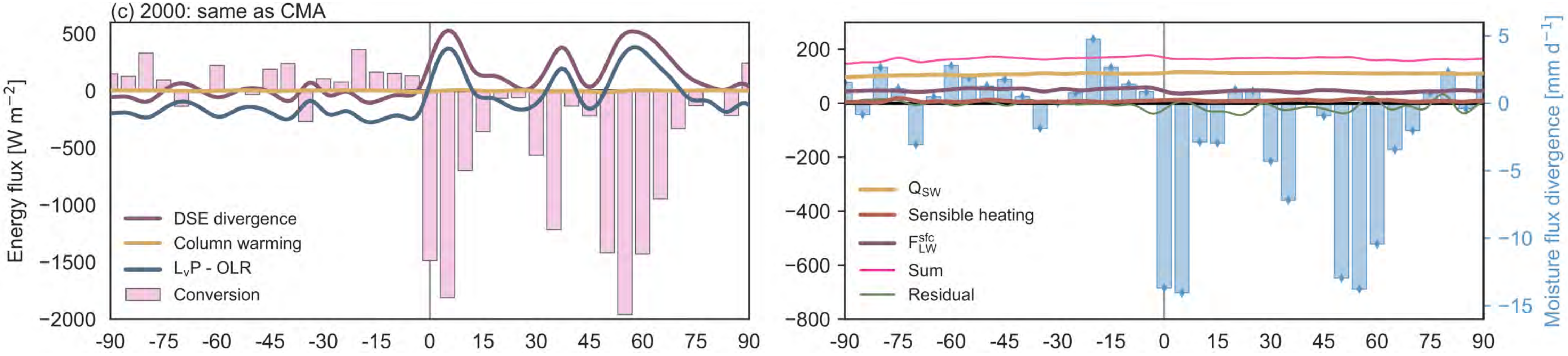


Good agreement among different P and OLR products despite large biases in both

Statistically distinct from current widely-used methods

Clear signatures of interdecadal variability

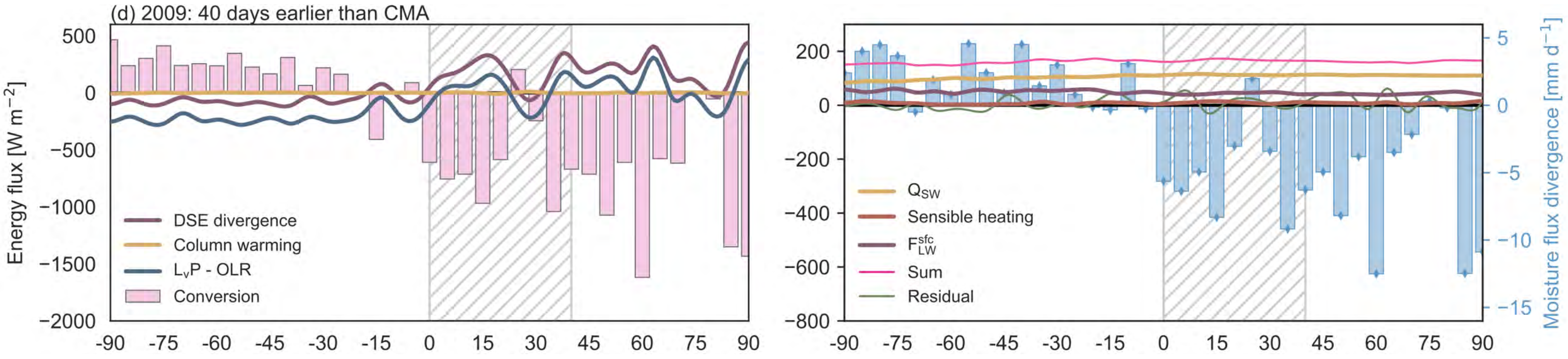
Application:
South China Sea Summer Monsoon



In 2000, all methods identified the same onset:

- Clear initiation of the wet season by a strong ISV event

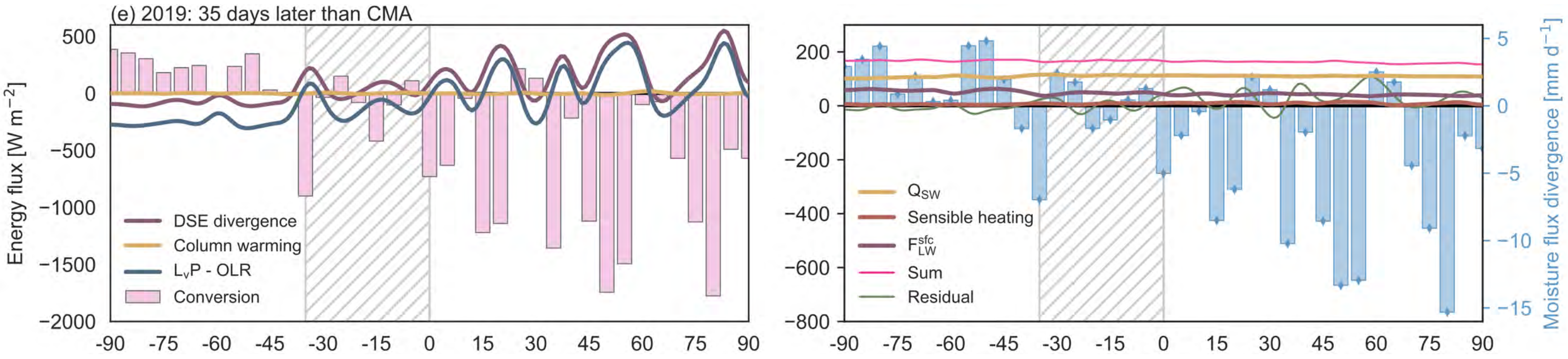
Application:
South China Sea Summer Monsoon



In 2009, our method identifies a much earlier onset date than most approaches:

- Sustained large-scale transition occurred earlier than 25 April (pentad 24)
- Early onset is consistent with our target criteria
- Many methods disallow onset before pentad 24; in our approach, the slow annual cycle criterion eliminates early transient events without enforcing a strict cutoff

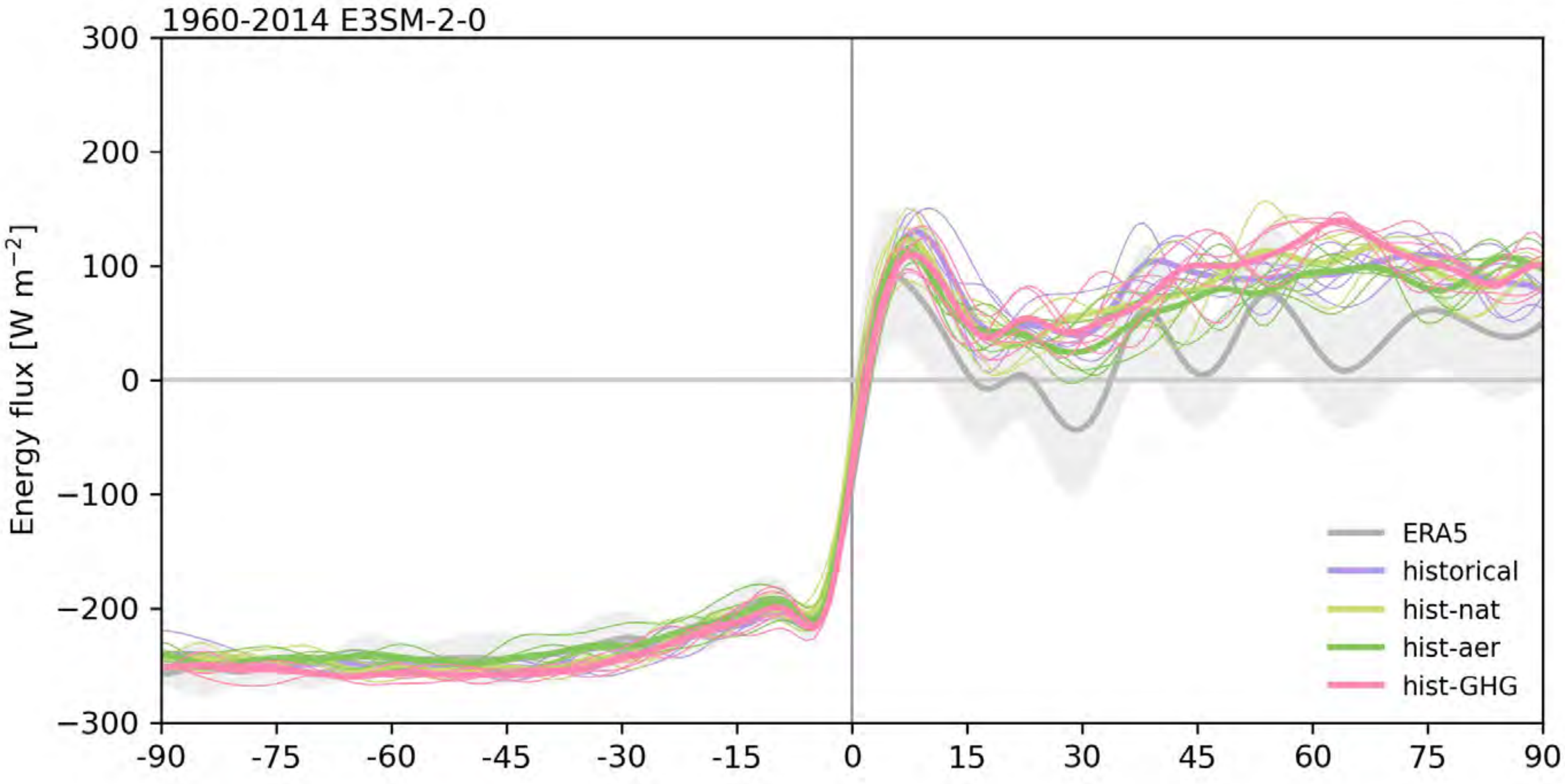
Application:
South China Sea Summer Monsoon



In 2019, our method identifies a much later onset date than U850-based approaches:

- Transient event coincides with onset identified by CMA and others
- Energy conversion, DSE divergence, and moisture convergence were not sustained
- Later onset consistent with our target criteria, but room for disagreement

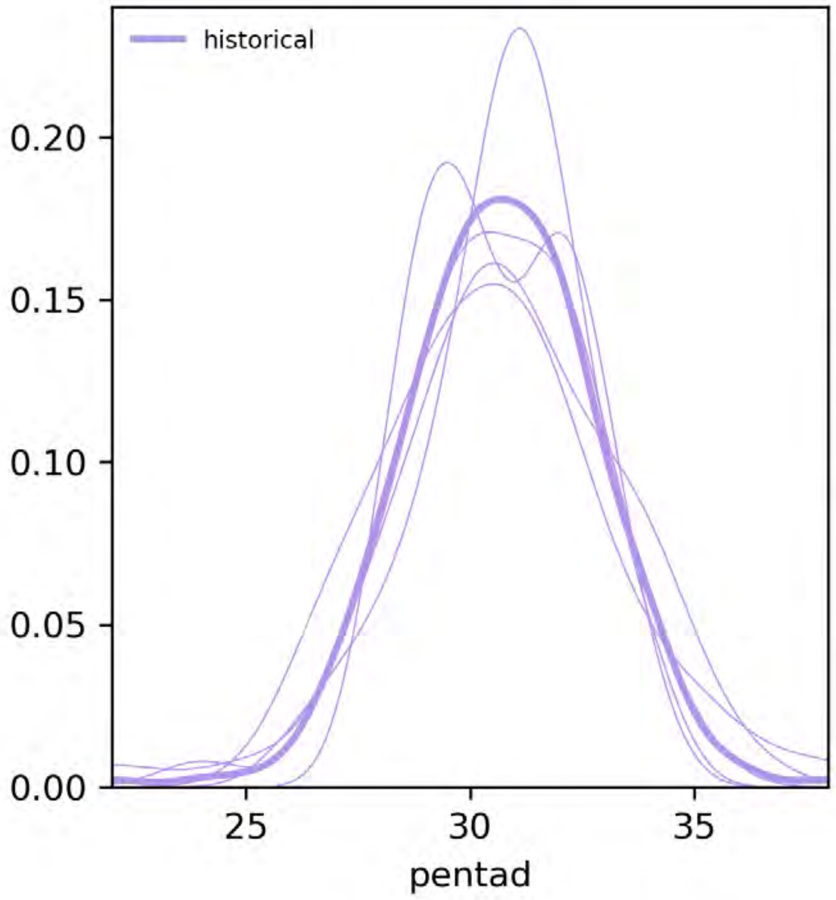
Application:
South China Sea Summer Monsoon (LESF)

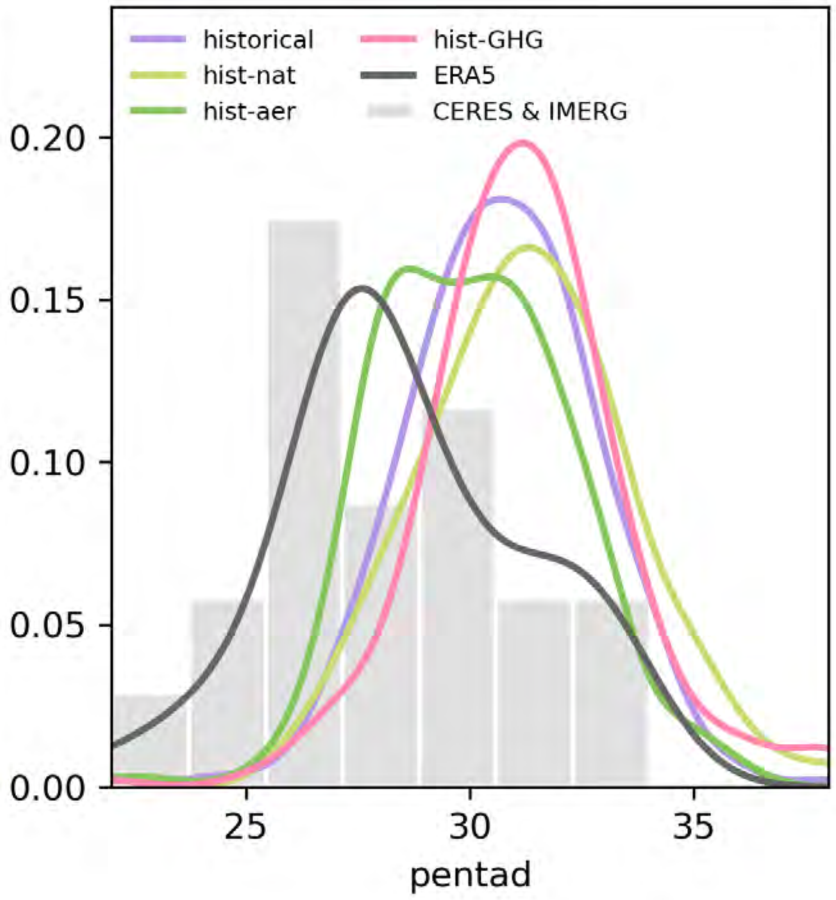


Applying this approach to large ensembles takes just seconds

- Composites for five members of each SF scenario in E3SM
- Agrees well with ERA5 in dry-to-wet transition
- Overestimates LvP-OLR in wet season
- No clear forced signal in magnitude of L_vP-OLR
- Further work needed to assess intraseasonal & interdecadal variability

Application:
South China Sea Summer Monsoon (LESF)





- Model simulates later onset than observed
- Ensemble spread shows signs of low-frequency variability
- Single-forcing experiments suggest aerosol forcing advances onset

Summary:
South China Sea Summer Monsoon

- Analysis of the vertically-integrated dry static energy budget yields a new index for the South China Sea summer monsoon overturning circulation
- Required variables are both observable and widely available as daily means for LESFMIP
- Greater year-to-year consistency sharpens focus on critical transitions (e.g. monsoon onset) in composite analysis and boosts confidence in low-frequency signal
- Composites also highlight the central role of intraseasonal variability in the SCSSM – can models capture this?
- Direct links to upper-level divergence may be useful for exploring monsoon teleconnections
- Data assimilation in ERA5 acts to damp the impacts of variations in diabatic heating on the monsoon circulation – implications for extremes?