Water Cycle Variability over the Global Oceans: Wet-get-Wetter, Dry-get-Drier Regimes in Reanalyses and Observations

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Background

- Extensive literature on water cycle response to a warming planet: *Mitchell et al, 1987; Emori & Brown, 2005; Held & Soden, 2006; Allan & Soden, 2007; Allan et al, 2010; Muller&O'Gorman, 2011; Liu & Allan, 2013.*

- Investigations have relied heavily on CMIP model simulations and emphasized anthropogenic forcing responses. Limited supporting observations (e.g. GPCP precipitation).

Here we attempt to broaden that knowledge base somewhat by examining a spectrum of reanalysis products and folding in new satellite-based ocean evaporation estimates. We'll examine…

- Current reanalysis ocean moisture budgets and the problems of data assimilation in less than perfect models and some adjustments to fields.
- Stratifying E and P changes by regimes of vertically-integrated moisture convergence / divergence, $-\widehat{\nabla \cdot qV}$.
- Differences across reanalysis types (AMIPs→ Reanalyses → Satellite-based retrievals (GPCP2.3, SeaFlux CDR).

A Hierarchy of Global Observational / Reanalysis Data Sets

←More Observationally Constrained

Better space / time sampling, duration →

AGCMs w/ Specified SSTs (AMIPs) GEOS, ERA-20CM Ensembles

Incorporate best historical estimates of SST, sea ice, radiative forcing
Atmospheric "weather noise" is inconsistent with specified SST so sfc fluxes can be wrong sign (e.g. Indian Ocean Monsoon, high latitude oceans). Averaging over ensemble members helps isolate SST-forced signal.

Reduced Observational Reanalyses: NOAA 20CR v2c, CERA-20C, JRA-55C

Incorporate observed Sfc Press (20CR), Marine Winds (CERA-20C) and other conventional data (JRA-55C) to recover much of the true internal atmospheric variability or weather "noise".

Comprehensive Reanalyses ERA-I, MERRA-2, JRA-55

Full suite of observational constraints- both conventional and remote sensing.
But… substantial uncertainties owing to evolving satellite observing system.

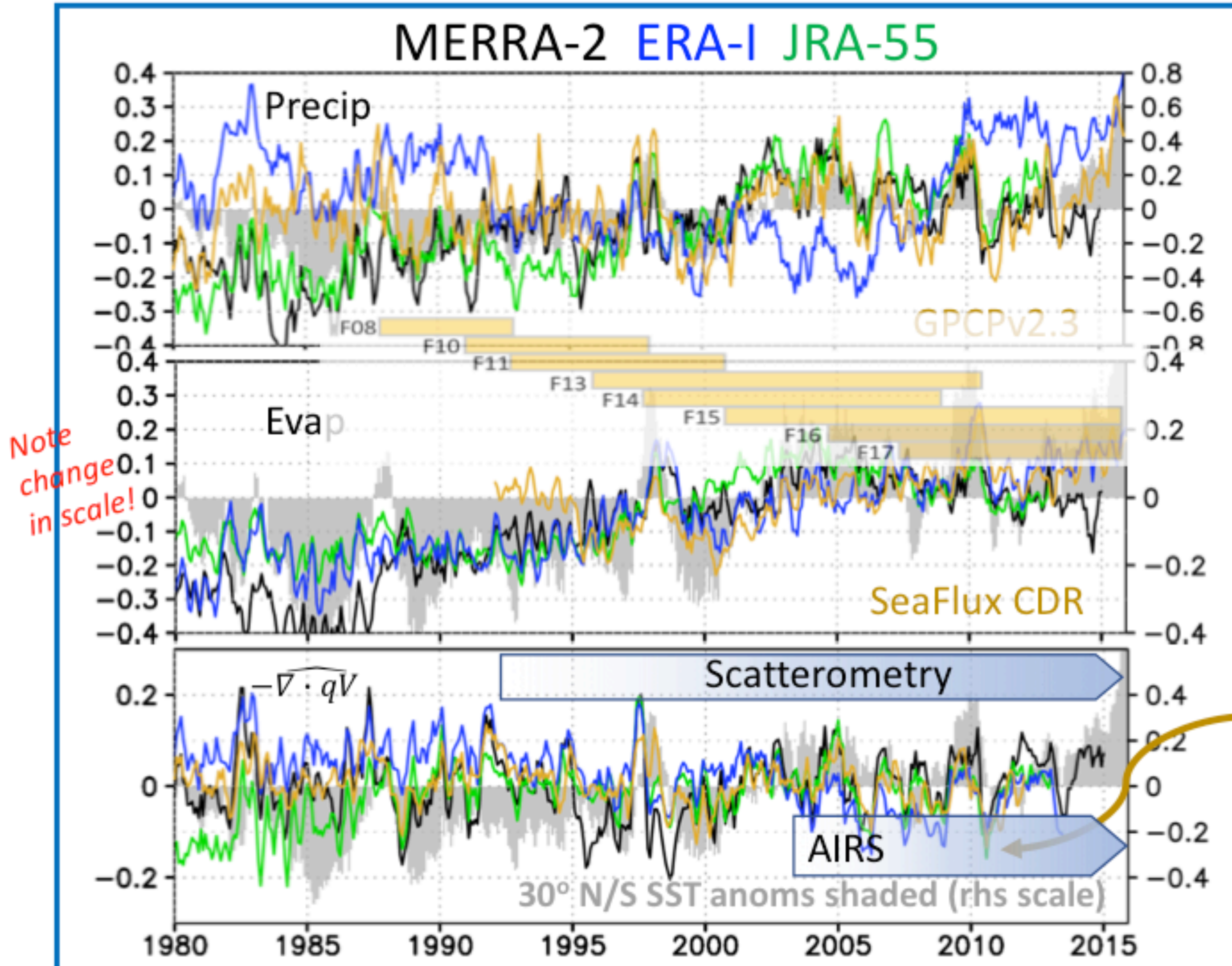
Satellite Retrievals GPCP, SeaFlux, …

Global coverage. Passive & active microwave. Short record (1987-present).

In situ Measurements ICOADS, IVAD, Research Cruises

Ships, buoys offer direct measurements. Sparse data coverage (esp south of 30S.
Changes in measurement techniques (e.g. shipboard anemometer height).

Reanalysis Ocean Flux Anomalies (30°N/S, mm d^{-1})



- Significant uncertainty in decadal variations and trends.
- More coherence in interannual variations
- Influence of SSMI passive microwave data availability evident (MERRA-2, ERA-I)
- Scaled P-ET from an ensemble Land Sfc Models forced with obs precip & near Sfc meteorology (Robertson et al, 2016)

Adjustment Strategy to Minimize Reanalysis Artifacts from Evolving Satellite Data Record

Since models have imperfect physics and the accuracy and availability of assimilated observations evolves in time, biases in the reanalysis budget terms (model physics) arise. We employ simple a adjustment strategy.

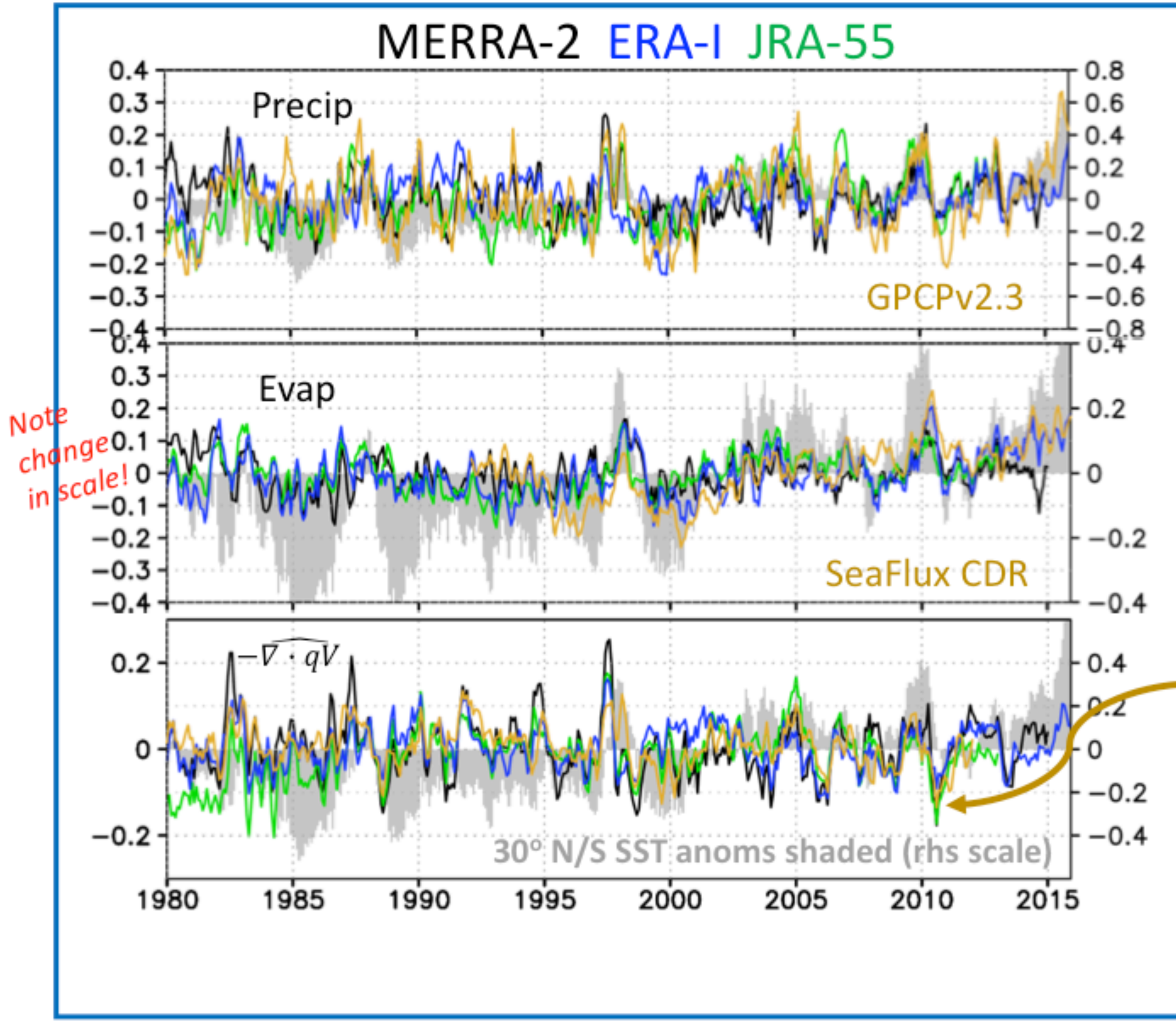
Model Physics + Model Dynamics + Analysis Increment = Reanalysis Tendency

MERRA-2: Principal Component Analysis applied to anomalies in vertically-integrated q, wind speed increments is used to remove signals related to obvious satellite changes.

JRA-55: Higher frequency data (periods < 2yrs) are combined with low-frequency filtered JRA-55C (uses conventional data only- RAOB, Sfc, Marine, Aircraft) that is free of satellite change-induced signals.

ERA-I: EOF modes of ERA-I data (periods < 2yrs) are examined and those (1-3) with obvious relationship to satellite system changes are removed.

Adjusted Reanalysis Ocean Flux Anomalies (30°N/S, mm d^{-1})



- Improved agreement among the reanalyses and between each reanalysis and independent GPCP, SeaFlux and LSM P-ET data
- Scaled P-ET from an ensemble Land Sfc Models forced with obs precip & near Sfc meteorology (Robertson et al, 2016)

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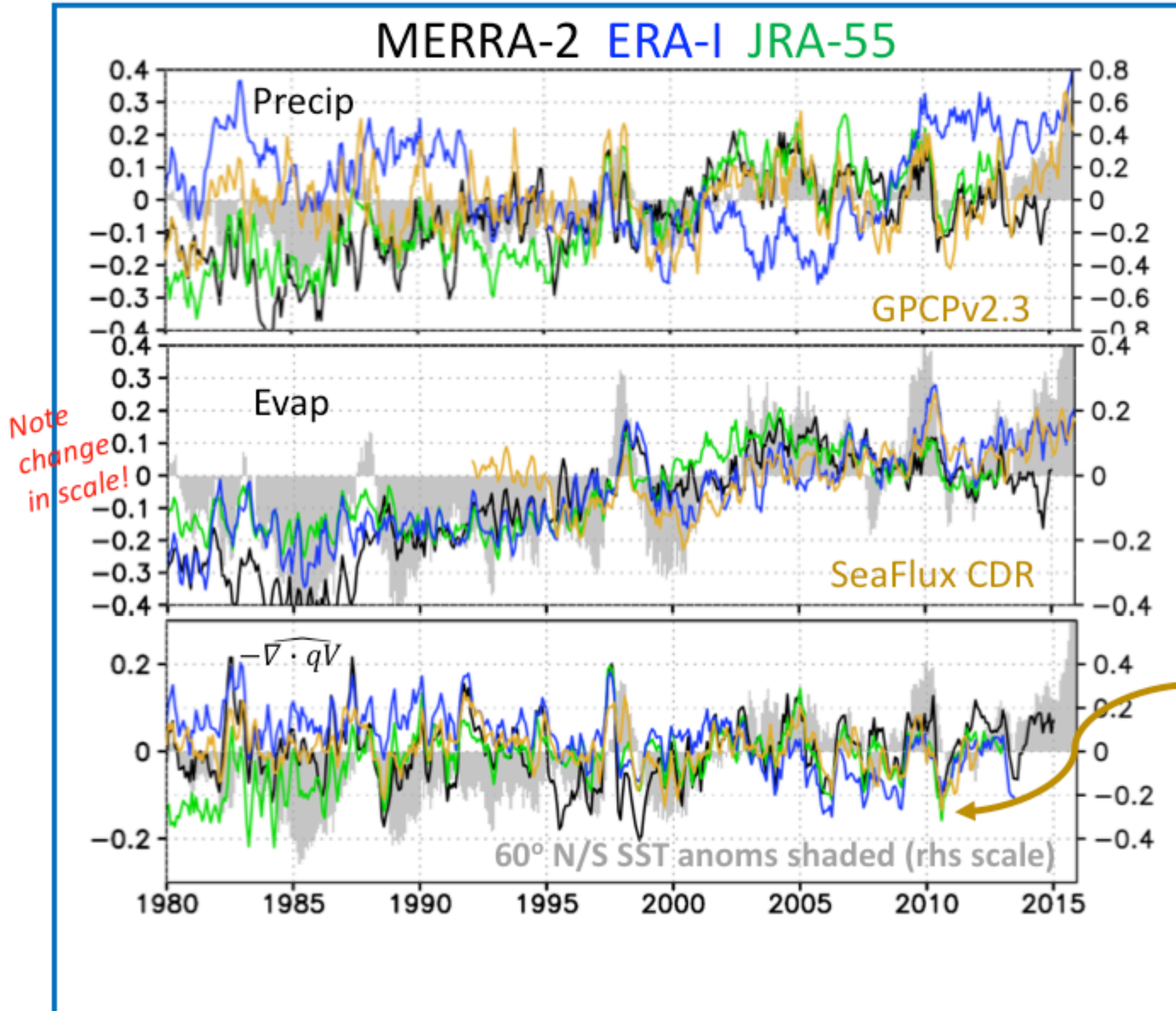

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Inter-related Mechanisms Govern Changes in the Hydrologic Cycle

- Clausius-Clapeyron / "thermodynamic scaling" (~ 7% $deg^{-1}\delta SST$) strongly constrains atmospheric water holding capacity.
- Radiative convective balance → δP, δE ~ 2% $deg^{-1}\,\delta SST$) globally.
- As noted by Held & Soden, 2006; Chou et al, 2007; Allan et al, 2010), under the assumption of small changes in circulation relative to SST-induced humidity changes, the expectations for hydrologic cycle change,

  $\delta(E-P) = \nabla \cdot \widehat{\delta(qV)}$ can be approximated by

  $\delta(E-P)/(E-P) \approx \alpha\delta SST \approx 7\%\, deg^{-1}\delta SST.$

So regional changes in E, P and moisture transport would scale at the C-C rate. *But we know that dynamical changes are a significant hallmark of interannual to decadal variability.*

Analysis Methodology

- To isolate tropical wet & dry (~ ascending & descending) regimes, monthly $-\widehat{\nabla \cdot qV}$ values from each ocean gridpoint (30° N/S) were sorted into 0.5 mmd^{-1} resolution bins forming histograms. This was done for each reanalysis data set.

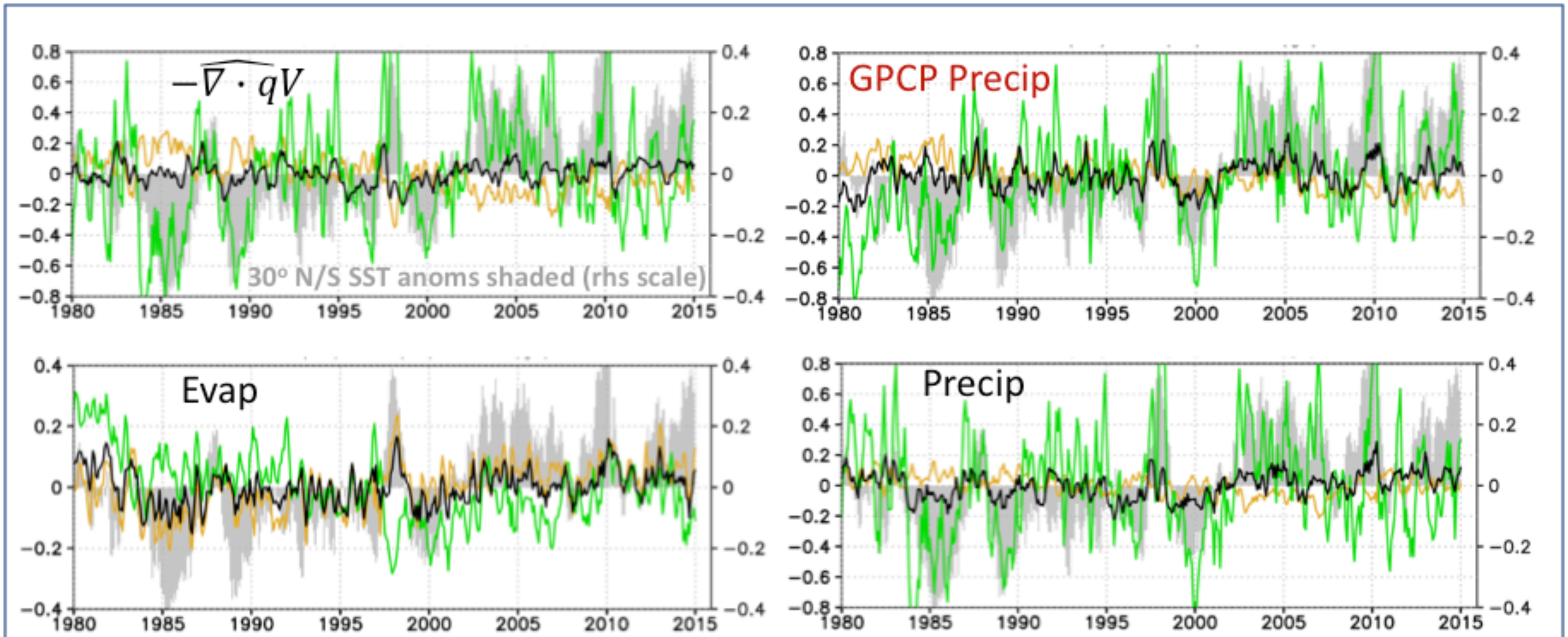
- P and E were then stratified according to the $-\widehat{\nabla \cdot qV}$ bins into which they fell. ($-\widehat{\nabla \cdot qV}$ from Merra-2 was used to bin GPCP V2.3 precip and SeaFlux CDR evaporation.)

- Climatological values defined over the period 1990-2010 were removed to examine temporal variability.

MERRA-2 Adjusted Moisture Budget Anomalies Stratified By Moisture Convergence / Divergence Regions

$-\widehat{\nabla \cdot qV}$, P and E time series anomalies (mm d^{-1}) are area-averages over the ***Convergent***, ***Divergent*** and ***Entire*** extent of 30°N/S ocean domain.

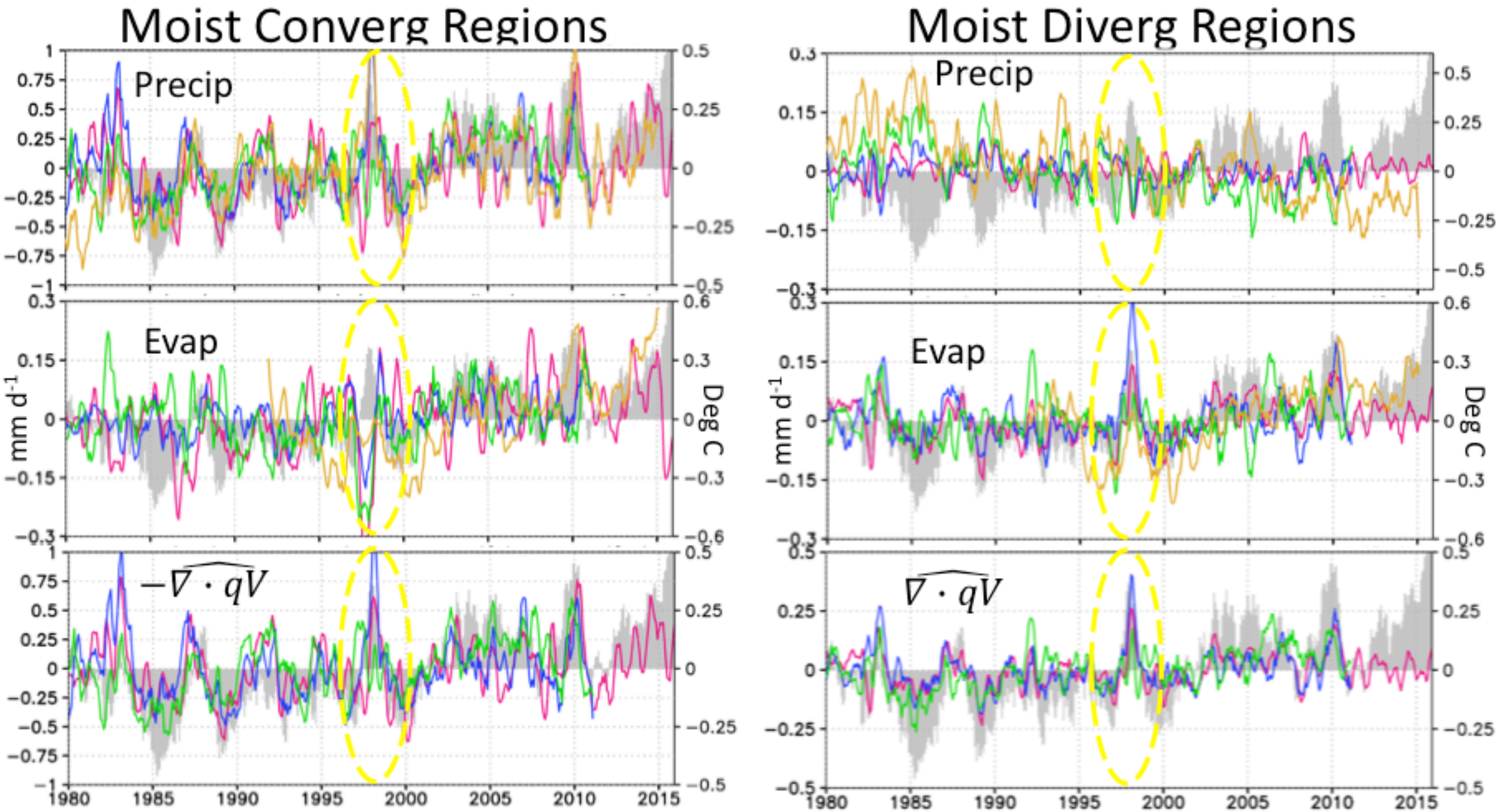
ENSO warm events and their frequency are major drivers: Increased moisture convergence & precip in wet regions and moisture divergence and evap in dry regions. The opposite holds for ENSO cold events.



$-\widehat{\nabla \cdot qV}$, P, E Anomaly Time Series 30°N/S Oceans

MERRA-2 AMIP CERA-20C 20CRv2c GPCP2.3 SeaFlux CDR δSST

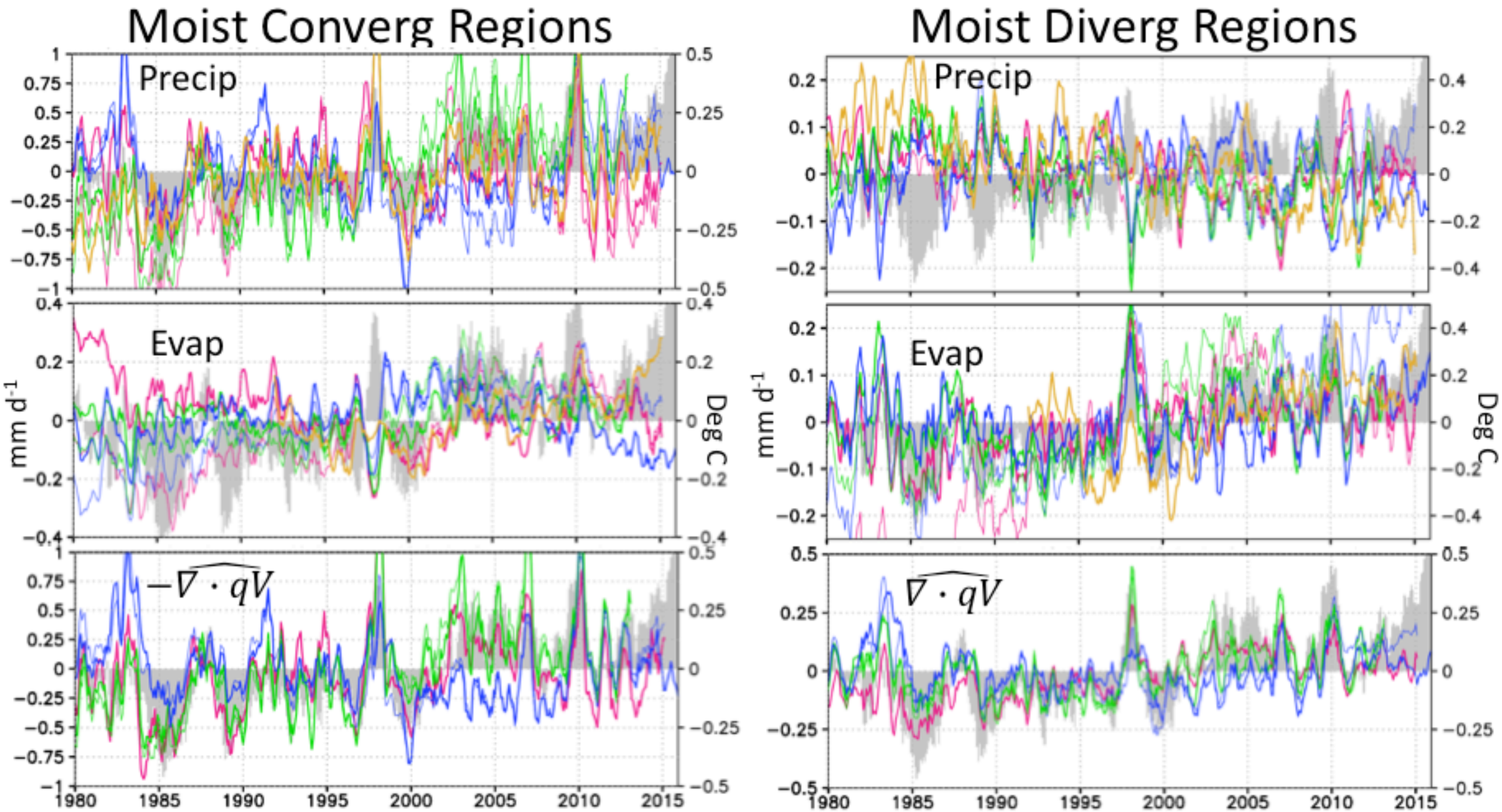
Reduced Observational Assimilation



$-\widehat{\nabla \cdot qV}$, P, E Anomaly Time Series 30°N/S Oceans

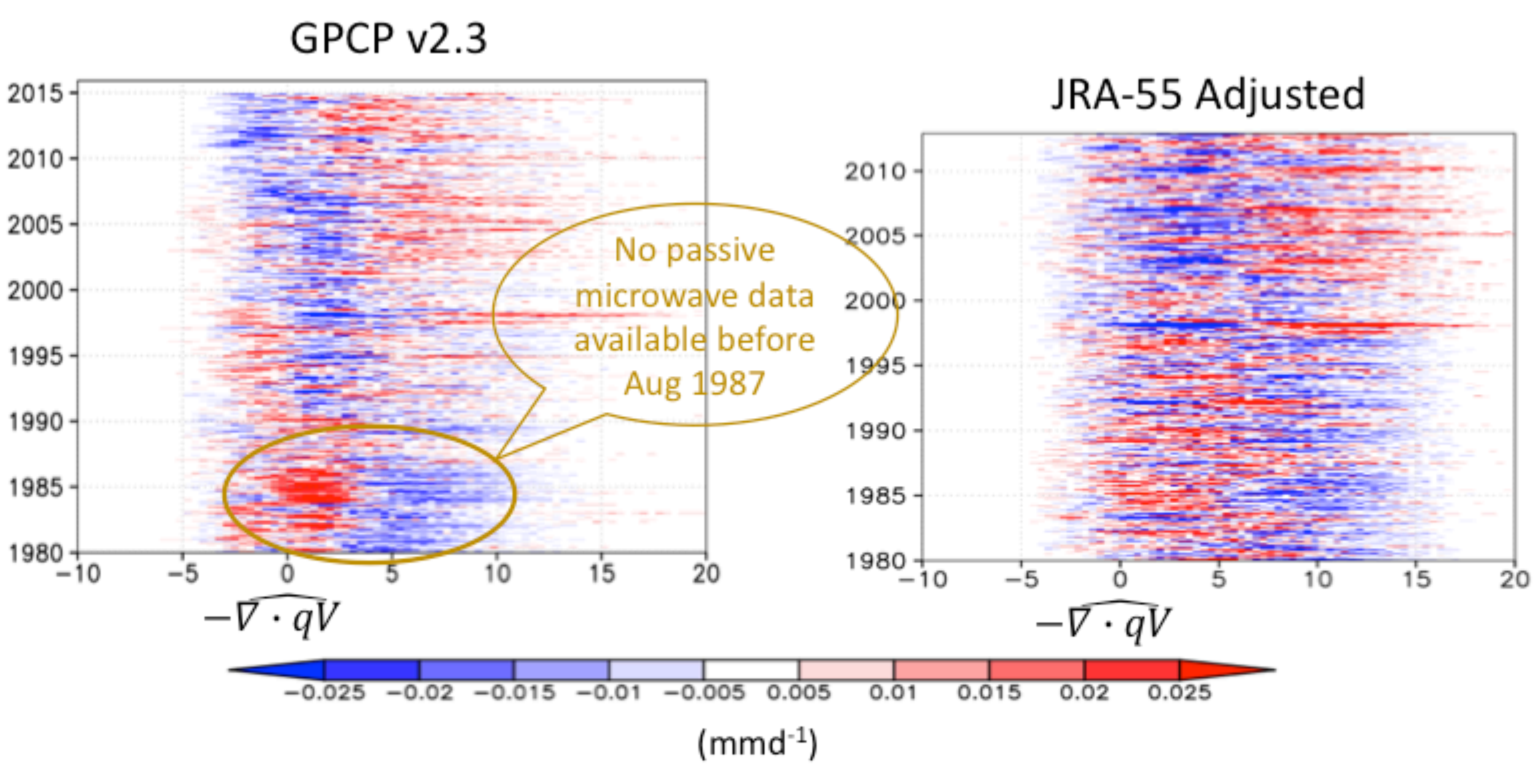
MERRA-2 ERA-I JRA-55 GPCP2.3 SeaFlux CDR δSST

Adjusted Reanalyses (thick lines) Unadjusted (thin lines)



Anomalies of Precipitation Stratified by $-\widehat{\nabla \cdot qV}$ Bins

- Pattern of increases (decreases) of precipitation rates with time at levels of larger moisture convergence.
- Stronger interannual signals (ENSO) in JRA-55.
- Before the passive microwave era (1988 →) GPCP precipitation shifts to regions of weaker moisture convergence.



P, E Sensitivity to SST Change , % (deg C)$^{-1}$

- Precip sensitivities lie generally below (above) C-C rate in wet (dry) regions.
- Dry region Evap sensitivities accompanied by negative Precip sensitivities there.
- P-E increases in regions of moisture flux convergence are near C-C rate; but in moisture divergence regions large increases in rate of moisture export are present.

Data Set	Period	dP/dT_{wet}	dE/dT_{wet}	P - E Tend wet	dP/dT_{dry}	dE/dT_{dry}	P - E Tend dry
MERRA-2	1980 / 2015	2.5	11.8	-9.3	-7.7	10.7	18.4
(Adj)		1.8	-4.7	6.5	-2.5	13.6	16.1
(AMIP)		5.6	2.9	3.5	-2.1	32.7	34.8
JRA-55		5.3	10.0	-4.7	-9.8	17.4	26.2
(Adj)		5.2	0.3	4.9	-15.3	16.1	31.4
ERA-I		2.3	10.5	-8.2	-8.8	16.8	25.6
(Adj)		2.9	-7.0	9.9	-12.5	8.9	21.4
CERA-20C		4.0	-2.2	6.2	-13.0	16.4	29.4
20CR v2c		3.7	-0.6	4.3	-12.7	4.5	16.7
GPCP V2.3	1980-2015	5.3			-13.5		
	1988-2015	3.7			- 10.4		
SeaFlux	1991-2015		28.0			21.3	

Summary Points:

- Across all reanalyses, tropical precipitation increases with SST in moisture convergence regions with P-E increasing near C-C rate (except for raw reanalyses). I.e. adjustments seem to be reasonable.
- E and E-P in moisture divergent regions generally increase at rates far above that of C-C.
- ENSO events exert a strong influence and their decadal variability is a major source of trends / sensitivity in both reanalyses and in observations.
- Emerging new satellite E estimates from SeaFlux (and others like J-OFURO-3) show promise over previous generation products.
- Biases in existing assimilating models make them sensitive to evolving data availability that constrains them. Reduced observation reanalyses, REDOBS, (e.g. CERA-20C and JRA-55C) offer an important complement to help understand variability during the satellite era and possibly the 2nd half of the 20th Century.

THANKS!