ATMOSPHERIC WATER BUDGETS OVER TROPICAL OCEANS

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INTRODUCTION

Tropical ocean regions contribute to a substantial portion of the global hydrological cycle. This study looks at the relationships between evaporation, water vapor convergence and precipitation for two separate purposes.

- Product Assessment: Because water vapor convergence and evaporation must balance precipitation over oceanic grid boxes, independent observation of precipitation and evaporation together with water vapor divergence from Reanalysis products provides a solid foundation for estimating the quality of current state-of-the-art products.
- Climate sensitivity: because smaller oceanic boxes show significant seasonal and interannual variability, changes in the precipitation can be related to changes in the large scale circulation or dynamic (leading to changes in water vapor divergence) or changes in the thermodynamics (leading to changes in local evaporation). Analyzing this behavior in 5 distinct regions provides a reference frame for regional versus globally representative results.

Observationally-derived **SeaFlux** evaporation and **GPROF TMI** precipitation data were selected. These are both GEWEX reference products and are being readied for reprocessing using common ancillary data. Moisture fluxes algorithms are still in their infancy. Initially ERA-Interim (Dee et al. 2011) and MERRA reanalyses (Rienecker et al. 2011) were evaluated to determine how they compared. While similar, ERA-Interim data was chosen for over MERRA in this study, due to the spurious trends present in MERRA precipitation data (Trenberth et al. 2011). Conclusions would not change significantly had MERRA moisture fluxes been used.

Box climatologies are examined to determine how changes in SST, wind and specific humidity impact regional moisture budgets.

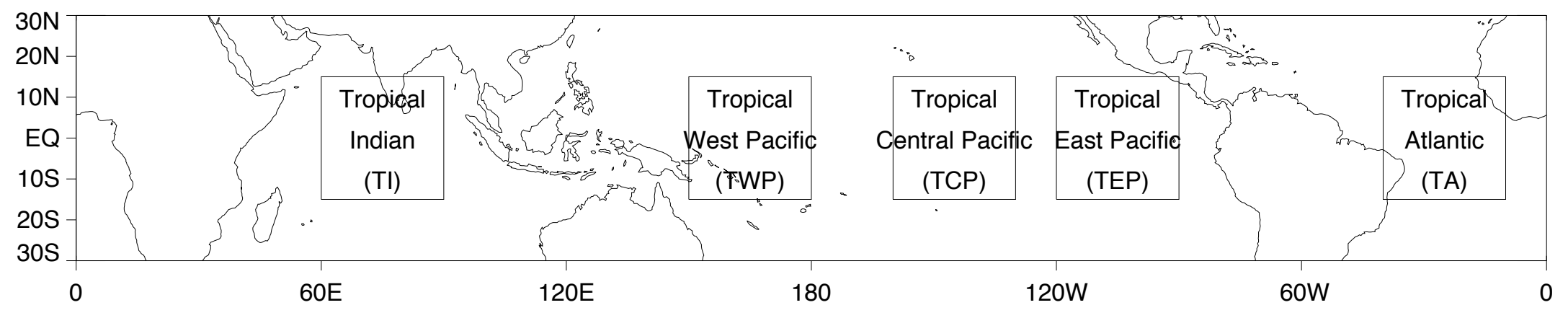

Figure 1 The five tropical boxes selected.

Table1 Data products used to obtain evaporation, precipitation and pressure level data.

Data Type	Acronym	Data Description	Resolution
Reanalysis	ERA	European Reanalysis Assessment Interim (ECMWF)	0.75°x0.75° 6-hourly
Reanalysis	MERRA	Modern Era Retrospective-analysis for Research and Applications (NASA)	0.67°x0.5° 6-hourly
Precipitation	GPROF	Goddard PROFiling Algorithm TMI Version 7 (GPROF2010)	0.25°x0.25° daily
Evaporation	SeaFlux	Satellite-based data set of surface turbulent fluxes over the global oceans.	0.25°x0.25° 3-hourly

Calculating Atmospheric Divergence

Evaporation, precipitation and atmospheric divergence are related according to the following balance equation for water vapor (Peixoto and Oort 1992).

$$\frac{\partial W}{\partial t} + \Delta \cdot \frac{1}{g}\int_0^{p0} qV\,dp = E - P$$

Reanalysis data for the pressure levels between 1000 hPa and 200 hPa were used to determine atmospheric divergence from the time-averaged vertically integrated total column water vapor.

$$W = \frac{1}{g}\int_0^{p0} q\,dp$$

Figure 2 shows the monthly divergence (and E-P) for tropical oceans between 30°S and 30°N. Generally the ERA and MERRA data exhibit similar variability and are closely related, especially after 2002. The earlier period's discrepancy may be due to the ATOVS transition which creates a bias in MERRA precipitation data (Bosilovich et al. 2011).

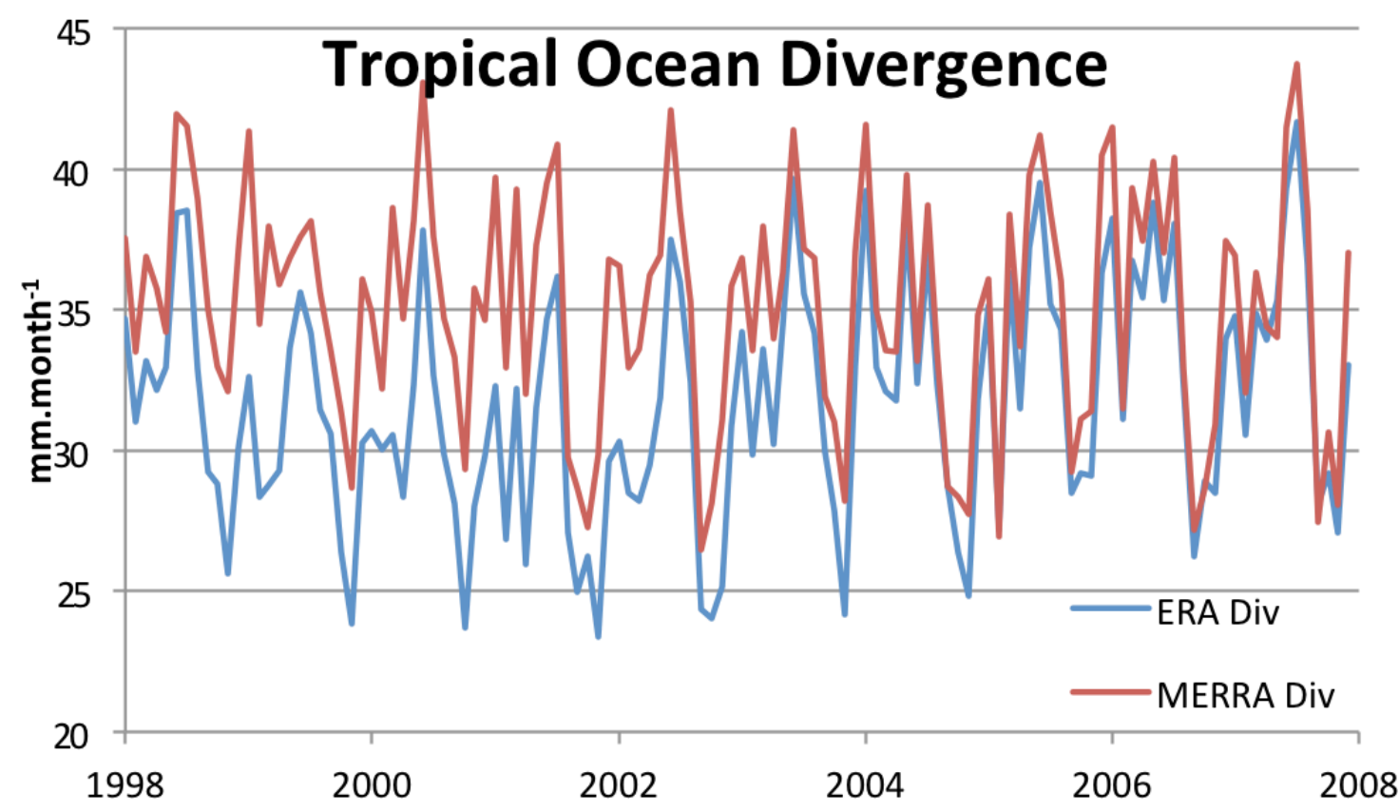

Figure 2 Monthly average divergence for tropical (30°S - 30°N) oceans, 1998 - 2007.

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ATMOSPHERIC MOISTURE IN THE TROPICAL BOXES

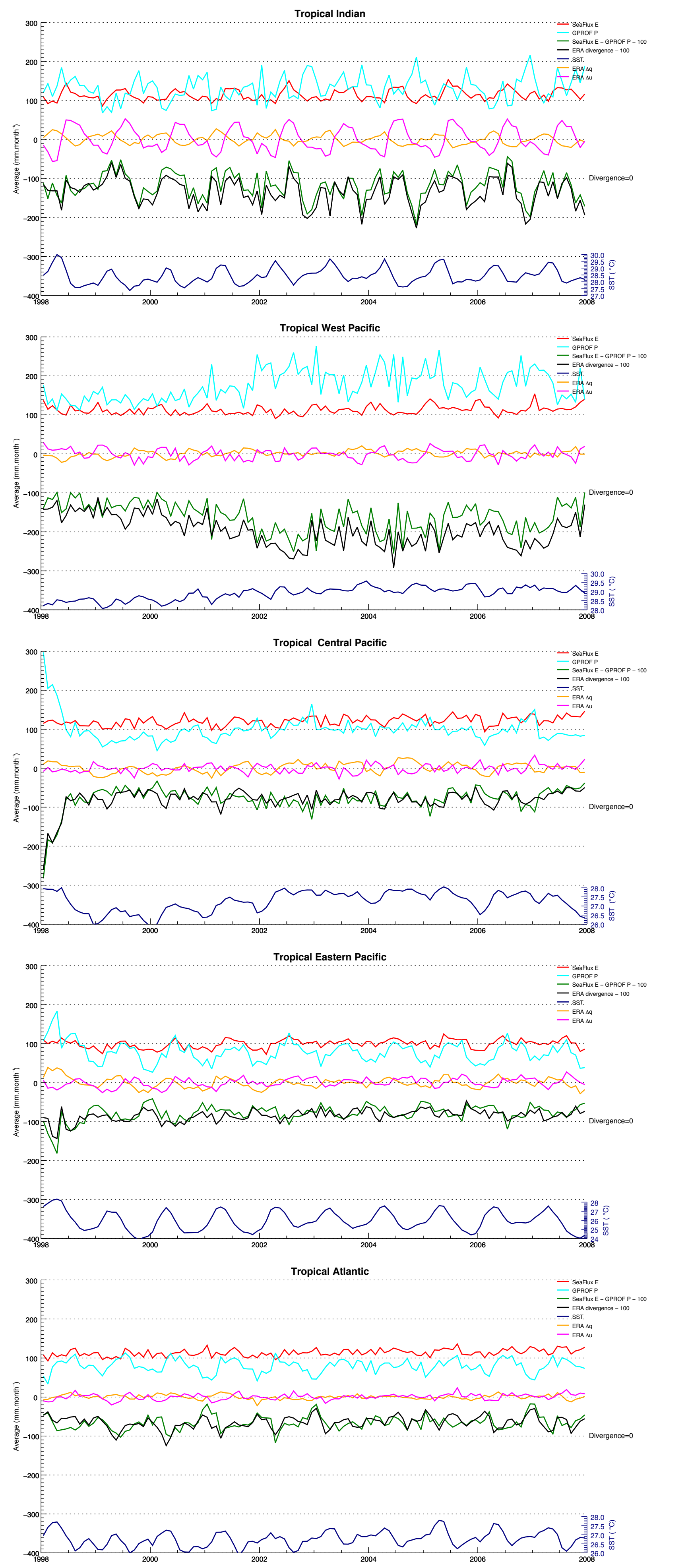

Figure 3 Monthly averages for SST, specific humidity (Δq) derived evaporation, wind (Δu) derived evaporation, evaporation, precipitation and divergence or E-P.

Tropical Indian Ocean

- SST has pronounced seasonality
- Δq mimics SST
- Δu inversely related to SST and Δq, more variable than Δq
- E variability correlated with Δu,
- P more variable than E
- Convergence into region as P > E
- ERA divergence and E-P well correlated, anticorrelated with P
- Seasonal variability in P related to moisture convergence
- No discernable trends in P, E or SST

Tropical West Pacific Ocean

- SST has weak semiannual seasonality
- High SSTs with little variability
- Curve in SST trend
- Some correspondence between SST and Δq
- Δu variability > Δq
- E increases slightly but Δq and Δu do not change, and SSTs late cooling
- P>>E, convergence dominates West Pacific Warm Pool
- E-P shows less convergence than ERA divergence
- Peak in SST, P and convergence, 2002 – 2005, not seen in E

Tropical Central Pacific Ocean

- SST shows little seasonality and increases after early El Niño peak
- Niño 3.4 signal in SSTs
- Δq and Δu display a similar range of variability
- E varies similar to SST and Δq
- E increases after El Niño event
- E generally exceeds P, region of divergence
- P variability has similar range to E, excluding El Niño
- Niño 3.4 signal in P
- E-P is larger than ERA divergence term at times
- El Niño event dramatically increased convergence, P and SST, not E

Tropical East Pacific Ocean

- SST has pronounced seasonal variability, also seen in Δq
- Δq variability slightly greater than Δu
- E less variable than P and driven by both Δq and Δu
- P strong seasonal cycle, lags SST by 3 months
- E-P more variable than ERA divergence, correlate well though
- Divergence occurs on average but seasonal
- Convergence and P increase in NH summer
- 1998 El Niño event increases SST, Δq, P and convergence
- No trends

Tropical Atlantic Ocean

- SST has semiannual seasonal cycle is strongest at start of the year
- Variability of Δq and Δu is minimal
- E increases slightly, but no trend seen in SST
- Divergence region as E>P
- P seasonality associated with peak in NH summer
- E-P varies more than ERA divergence
- E-P and ERA divergence not well correlated, some large discrepancies

TROPICAL BOXES MOISTURE COVARIANCES

Calculating Evaporation Over Oceans

Evaporation in the tropics is primarily driven by wind and Sea Surface Temperature (SST). The speed and specific humidity of air above the ocean surface affect how much moisture can be supplied by the oceans to balance atmospheric moisture. This relationship is commonly quantified using the bulk aerodynamic formula for evaporation (E),

$$E = \rho_a C_q u_x (q_0 - q_a),$$

where air density (ρ_a), transfer coefficient (C_q), 10 m wind (u_x), surface specific humidity (q_0) and specific humidity at 10 m (q_a). However, 2 m q_a was used due to a lack of 10 m data.

The specific humidity component of the bulk aerodynamic formula is closely related to SST from which q_0 is determined. The change in the specific humidity (Δq) variables on evaporation was determined by using mean u to calculate the change in evaporation, and similarly Δu was determined by using mean q. Additionally, the u_x variable is obtained from the horizontal u (westerly) and v (southerly) winds.

These aforementioned components of evaporation are interrelated, and their relationship with precipitation and divergence is of interest. A correlation matrix of the variables that influence the atmospheric moisture for tropical oceans is presented in Table 2. ENSO and Hadley circulation changes also affect tropical climates, and therefore these indices are included too.

Table 2 Correlation matrix of the monthly averaged evaporation, precipitation and related variables for the five tropical boxes, 1998 – 2007.

TI	HadUp	Δq	SST	ENSO	Δu	u10m	v10m	$\Delta q+\Delta u$	ERA E	SFlux E	ERA P	GPROF P	ObsE-P
Δq	0.31	*											
SST	0.00	0.81	*										
ENSO	-0.16	0.09	0.31	*									
Δu	-0.16	-0.80	-0.60	-0.09	*								
u10m	0.11	-0.04	0.04	-0.20	0.40	*							
v10m	-0.10	-0.60	-0.30	-0.08	0.85	0.47	*						
$\Delta q+\Delta u$	-0.05	-0.55	-0.38	-0.08	0.94	0.54	0.84	*					
ERA E	-0.08	-0.51	-0.35	-0.08	0.91	0.51	0.81	0.97	*				
SFlux E	-0.05	-0.50	-0.28	0.01	0.82	0.40	0.71	0.86	0.90	*			
ERA P	-0.85	-0.24	-0.08	0.08	0.08	-0.24	-0.05	-0.02	0.05	-0.06	*		
GPROF P	-0.85	-0.34	-0.12	0.26	0.15	-0.25	-0.03	0.02	0.06	0.00	0.91	*	
ObsE-P	0.79	0.20	0.10	-0.15	0.11	0.31	0.24	0.27	0.25	0.34	-0.85	-0.92	*
ERAdiv	0.74	0.02	-0.06	-0.13	0.32	0.45	0.41	0.46	0.42	0.47	-0.86	-0.82	0.93

TWP	HadUp	Δq	SST	ENSO	Δu	u10m	v10m	$\Delta q+\Delta u$	ERA E	SFlux E	ERA P	GPROF P	ObsE-P
Δq	-0.23	*											
SST	-0.52	0.68	*										
ENSO	0.04	-0.13	0.07	*									
Δu	0.07	-0.66	-0.43	0.26	*								
u10m	-0.49	0.40	0.33	0.09	-0.22	*							
v10m	-0.22	0.34	0.16	-0.12	-0.58	-0.06	*						
$\Delta q+\Delta u$	-0.08	-0.11	-0.05	0.25	0.82	0.01	-0.50	*					
ERA E	-0.06	0.07	0.00	0.24	0.62	0.04	-0.29	0.87	*				
SFlux E	0.01	-0.02	-0.02	0.23	0.67	0.01	-0.52	0.86	0.89	*			
ERA P	-0.91	0.08	0.44	-0.03	0.02	0.35	0.25	0.09	0.12	0.00	*		
GPROF P	-0.83	-0.01	0.41	0.12	0.23	0.56	-0.14	0.29	0.22	0.20	0.82	*	
ObsE-P	0.86	-0.06	-0.39	-0.02	0.03	-0.56	-0.10	0.00	0.05	0.13	-0.86	-0.96	*
ERAdiv	0.91	-0.09	-0.55	-0.04	0.10	-0.47	-0.25	0.07	0.11	0.18	-0.94	-0.84	0.90

TCP	HadUp	Δq	SST	ENSO	Δu	u10m	v10m	$\Delta q+\Delta u$	ERA E	SFlux E	ERA P	GPROF P	ObsE-P
Δq	0.16	*											
SST	-0.25	0.70	*										
ENSO	-0.36	0.35	0.51	*									
Δu	-0.31	-0.55	-0.30	-0.06	*								
u10m	-0.06	0.61	0.40	0.30	-0.78	*							
v10m	0.71	0.46	-0.01	-0.23	-0.33	0.07	*						
$\Delta q+\Delta u$	-0.11	0.62	0.50	0.34	0.31	-0.05	0.21	*					
ERA E	0.06	0.67	0.47	0.32	0.17	0.03	0.34	0.92	*				
SFlux E	0.14	0.42	0.12	0.10	0.35	-0.21	0.41	0.81	0.88	*			
ERA P	-0.76	0.17	0.53	0.46	0.04	0.37	-0.53	0.23	0.18	-0.05	*		
GPROF P	-0.58	0.45	0.49	0.51	-0.08	0.55	-0.21	0.43	0.40	0.18	0.84	*	
ObsE-P	0.62	-0.26	-0.42	-0.43	0.27	-0.62	0.40	-0.05	0.02	0.29	-0.86	-0.93	*
ERAdiv	0.70	-0.08	-0.33	-0.41	0.17	-0.53	0.56	0.06	0.11	0.35	-0.91	-0.75	0.88

TEP	HadUp	Δq	SST	ENSO	Δu	u10m	v10m	$\Delta q+\Delta u$	ERA E	SFlux E	ERA P	GPROF P	ObsE-P
Δq	-0.63	*											
SST	-0.43	0.81	*										
ENSO	-0.28	0.36	0.34	*									
Δu	-0.22	-0.28	-0.53	0.05	*								
u10m	-0.37	0.27	-0.18	0.02	0.14	*							
v10m	-0.28	-0.16	-0.58	-0.12	0.75	0.56	*						
$\Delta q+\Delta u$	-0.72	0.67	0.30	0.36	0.53	0.34	0.44	*					
ERA E	-0.72	0.66	0.29	0.35	0.48	0.35	0.45	0.96	*				
SFlux E	-0.66	0.56	0.27	0.26	0.52	0.18	0.43	0.89	0.93	*			
ERA P	-0.86	0.68	0.47	0.14	0.09	0.40	0.22	0.67	0.70	0.58	*		
GPROF P	-0.81	0.65	0.30	0.33	0.28	0.54	0.37	0.79	0.80	0.66	0.87	*	
ObsE-P	0.72	-0.53	-0.18	-0.19	-0.09	-0.67	-0.33	-0.53	-0.53	-0.32	-0.81	-0.92	*
ERAdiv	0.55	-0.41	-0.34	-0.05	0.25	-0.25	0.07	-0.16	-0.21	-0.06	-0.73	-0.61	0.74

TA	HadUp	Δq	SST	ENSO	Δu	u10m	v10m	$\Delta q+\Delta u$	ERA E	SFlux E	ERA P	GPROF P	ObsE-P
Δq	-0.19	*											
SST	-0.34	0.40	*										
ENSO	0.27	-0.09	0.26	*									
Δu	0.20	-0.30	-0.53	0.04	*								
u10m	0.02	0.27	-0.25	-0.03	-0.21	*							
v10m	0.33	-0.15	-0.62	-0.04	0.62	0.30	*						
$\Delta q+\Delta u$	0.06	0.44	-0.21	-0.02	0.73	-0.01	0.48	*					
ERA E	0.15	0.42	-0.24	-0.04	0.63	0.07	0.51	0.89	*				
SFlux E	0.09	0.16	-0.25	0.08	0.59	-0.06	0.32	0.67	0.72	*			
ERA P	-0.54	0.30	0.38	-0.35	-0.08	-0.02	-0.04	0.14	0.18	-0.09	*		
GPROF P	-0.22	0.35	-0.06	-0.09	0.29	0.35	0.46	0.53	0.57	0.19	0.60	*	
ObsE-P	0.30	-0.24	0.14	0.20	-0.03	-0.43	-0.40	-0.20	-0.22	0.27	-0.59	-0.87	*
ERAdiv	0.48	-0.27	-0.22	0.39	0.37	-0.27	0.08	0.15	0.16	0.40	-0.83	-0.44	0.63

HadUp – Hadley circulation uplift indices calculated from 500 hPa vertical velocities, Δq – change in evaporation due to q, SST – Sea Surface Temperatures, ENSO – Niño 3.4 indices, Δu – change in evaporation due to u, u10m – horizontal u 10 m westerly wind, v10m – horizontal v 10 m southerly wind

BOX SUMMARIES

Descriptions of the moisture climatologies for each of the tropical ocean boxes are listed below. These are based primarily on the relationships between the observation-based and reanalysis-based measures of atmospheric moisture that are described in Table 2 and Figure 3.

Tropical Indian Ocean
A region where wind, from the south, drive trends in evaporation. Southerly winds increase evaporation as they travel over warm waters. Higher specific humidities are likely associated with low winds as the ability of the atmosphere to further evaporate moisture is limited. Precipitation and convergence in this region are related to the strength of the Hadley circulation are not associated with evaporation. The monsoon season dominates the precipitation and therefore convergence in the region.

Tropical West Pacific Ocean
Winds, particularly those from the north, drive much of the evaporation in the western Pacific. This region is characterized by strong convergence that has the strongest link to Hadley circulation intensity. A weak association exists between easterly winds and convergence, with SSTs also having a small influence.

Tropical Central Pacific Ocean
Specific humidity has the closest relationship with evaporation in the central Pacific, and winds provide a secondary contribution. Evaporation exceeds precipitation resulting in divergence in this region and a weaker relationship between convergence and Hadley circulation is present. Precipitation and divergence are also correlated with SSTs, ENSO and horizontal winds.

Tropical East Pacific Ocean
Changes in both specific humidity and winds influence evaporation and precipitation due to their high correlation in this region. SSTs also affect these moisture components and as a consequence of the strong link to specific humidities, although no ENSO signal is present. The strong seasonal cycle present in SSTs perpetuates throughout the other influences on the regions moisture fluxes. Hadley circulation intensities are related to evaporation, precipitation and divergence.

Tropical Atlantic Ocean
With the exception of the relationship between southerly winds and evaporation in the Tropical Atlantic there is little to elucidate what variables circulate atmospheric moisture in the region. Despite being a region where numerous datasets showing consistent divergence on average, there is a lack of coherence in the time series, and unlike the other regions little correspondence with Hadley circulation is present.

SUMMARY

Key Results:

- The relative importance of winds (TI,TWP,TA) and SSTs (TCP), for evaporation over tropical oceans, is regionally dependent.
- Large trends in atmospheric moisture are only present in the Tropical West Pacific, where changes in precipitation and divergence occur.
- Balancing the moisture budgets over oceans is primarily dependent on precipitation due to its stronger variability (TI, TWP, TEP and TA).
- Dynamic variability appears to be more important than thermodynamic.

Future Work

- Climate change effects and their effect on atmospheric moisture as SSTs and wind speeds change.
- Determine the directional characteristics related to where moisture is being added to and removed from the tropical ocean boxes, and examine why this is occurring.
- Expand the datasets to provide global coverage and to include land regions too.