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**El Niño Related Tropical Land Surface Water and Energy Response in
MERRA-2**

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ABSTRACT

Though El Niño events each have distinct evolutionary character they typically provide systematic large scale forcing for warming and increased drought frequency across the tropical continents. We assess this response in the MERRA-2 reanalysis and in a ten-member model AMIP ensemble. The lagged response (3-4 months) of mean tropical land temperature to El Niño warming in the Pacific Ocean is well represented. MERRA-2 reproduces the patterns of precipitation in the tropical regions, while the AMIP ensemble reproduces some regional responses similar to observed, and some regions are not simulating the response well. Model skill is dependent on event forcing strength and temporal proximity to the peak of the sea surface warming.

A composite approach centered on maximum Niño3.4 SSTs and lag relationships to energy fluxes and transports is used to identify mechanisms supporting tropical land warming. The composite necessarily moderates weather scale variability of the individual events, while retaining the systematic features across all events. We find that reduced continental upward motions lead to reduced cloudiness and more shortwave radiation at the surface, as well as reduced precipitation. The increased shortwave heating at the land surface, along with reduced soil moisture leads to warmer surface temperature, more sensible heating and warming of the lower troposphere.

While the composite provides a broad picture of the mechanisms governing the hydrologic response to El Niño forcing, the regional and temporal response can vary substantially for any given event. The 2015-16 El Niño, one of the strongest events, demonstrates some of the forced response noted in the composite, but with shifts in the evolution that depart from the composite, demonstrating the limitations of the composite and individuality of El Niño.

45

46 **1. Introduction**

47 El Niño Southern Oscillation (ENSO, see Appendix for full list of acronyms) has far
48 reaching systematic influence on the global atmospheric circulation (Oort and Yienger 1996;
49 Alexander et al. 2002), energetics (Mayer and Haimberger 2012; Mayer et al. 2013; Trenberth and
50 Fasullo 2013); and regional hydrological variability (Ropelewski and Halpert 1987; Dai and
51 Wigley 2000; Trenberth et al. 2002; Gu et al. 2007; Miralles et al. 2014). The remote response to
52 ocean temperatures related to ENSO has been well documented in observations, as well as in
53 coupled and forced atmospheric models. In a multi-model sensitivity experiment, Schubert et al.
54 (2016) summarize regional land precipitation responses around the Earth to global SST patterns
55 noting the linkages of many regions to ENSO. Pathways by which tropical oceans create remote
56 responses are fundamentally dynamic in nature (Walker 1924; Hoskins and Karoly 1981;
57 Alexander et al. 2002; Trenberth et al. 2002; Alexander et al. 2009). Relative to El Niño local SST
58 warming and tropical convection, remote oceanic regions of descending motion show reductions
59 in clouds and increasing surface radiative forcing, predominantly from the shortwave (Stephens et
60 al. 2018).

61 In the case of El Niño, warming in the eastern and central Equatorial Pacific precedes
62 broader remote ocean warming (Klein et al. 1999; Yu and Rienecker 1999; Alexander et al. 2002,
63 Mayer et al. 2013). Tropospheric temperatures over the global tropics rise in response to warm
64 SST events within a period of a couple months; deep convective mixing of moist entropy
65 throughout the troposphere providing a heat source that is dispersed longitudinally by inertia-
66 gravity wave propagation (Charney 1963; Yulaeva and Wallace 1994; Sobel et al. 2002). Widely
67 dispersed tropospheric warmth spreads over tropical land (Chiang and Lintner 2005). Reductions
68 in moisture transport to land and associated reductions in precipitation and evapotranspiration

predominantly result from these diabatically-driven circulation anomalies (Gu et al. 2007; Miralles et al. 2014). With the complexity of the response and diversity of any given El Niño event, there are many outstanding questions regarding the El Niño remote response and the redistribution of heat. Here we are focused on one aspect of SST-driven climate effects—El Niño-related changes in the land surface energy balance within the tropical belt which we take as within 30 degrees latitude of the equator.

A notable aspect of these adjustments between the land and ocean domains is that land surface temperatures tend to be amplified over those of the global ocean (Chiang and Lintner 2005; Dommenges 2009; Tyrrell et al. 2015)—this amplification factor being typically about 1.2-1.5 over that of SSTs is close to upper tropospheric warmth dynamically spread over the tropics in response to El Niño events. Modeling studies by Tyrrell et al. (2015) suggest that amplified land warming associated with shorter-term interannual climate variability appears to behave in similar fashion to that occurring in model simulations of greenhouse gas-induced climate change (Manabe et al. 1991; Lambert and Chiang 2007; Sutton et al. 2007; Joshi et al. 2008; Fasullo 2010; Lambert et al. 2011). Sutton et al. (2007) employed the IPCC AR4 modeling suite to study relaxation to equilibrium after changes in doubled CO₂ forcing experiments, emphasizing the important role that surface moisture availability plays in adjustments. They particularly noted the opposite change in Bowen ratio response over the land versus ocean. Increased sensible heat flux loss over land exceeded that of latent heat flux (0.86 and 0.83 Wm⁻², respectively). This result lends support to the analysis of Chiang and Lintner (2005) who concluded from mechanistic modeling studies of the 1997/98 El Niño that sensible heat flux regulates the warming over land. On the other hand, Compo and Sardeshmukh (2009) argue that observed multi-decadal temperature over land can be replicated by AMIP experiments forced by observed SSTs and that enhanced downward longwave radiation from a warmer, moister troposphere is a primary surface warming agent.

In further modeling studies using specified SST and slab ocean models, Tyrrell et al. (2015) also place emphasis on the delayed tropospheric warming accompanying remote ocean SST changes that act to require adjustments in the land surface energy balance. Their results indicate a prominent role for downward longwave flux from a moistened lower troposphere, a result consistent with that of Compo and Sardeshmukh (2009). However, they also noted more cloudiness and a reduced shortwave flux into the land surface, a result at odds with the previously noted studies. Clearly the role of different mechanisms controlling the tropical land surface energy balance changes needs further examination.

While surface observations confirm the relationship of ocean and land surface temperatures and precipitation, many of the studies relating tropical land warming and drying to the ocean temperatures are conducted with atmospheric or coupled numerical model ensemble simulations. Here, we will use the MERRA-2 reanalysis to provide additional information, surface fluxes in particular, that are not easily observed in order to evaluate the atmospheric circulation and land response over tropical continents to El Niño; we also use a ten member AMIP ensemble with the MERRA-2 model to distinguish the model simulated response from the analyzed atmospheric response in the reanalysis. Reanalysis quality broadly depends on the availability of observations assimilated into the system (e.g. Bosilovich et al. 2011; 2015), which may be challenging for tropical land areas where in-situ observations are fewer than in the northern mid latitudes. This necessitates an evaluation of monthly mean SST, T2m and precipitation anomaly behavior in comparison to available observations. We then analyze a composite of El Niño events, examining the evolution of radiative and turbulent energy fluxes and related quantities. This is done for tropical land mean values with additional diagnostics to highlight regional contributions to the global tropical signals. We then use pentad MERRA-2 data to examine more closely the lag

relationships to SST warming. Finally, we examine the 2015/16 El Niño, withheld from the composite analysis, to put this extreme event in context with composite results.

2. Data

a. MERRA-2

The MERRA-2 reanalysis (Gelaro et al. 2017) is a state-of-the-art global data product that includes numerous diagnostics (for example vertically integrated transport, cloud free radiation and surface fluxes) that can be used to investigate El Niño heating response, especially in the energy and water budgets. A preponderance of atmospheric satellite and in situ observations are assimilated in MERRA-2 (McCarty et al. 2016). Numerous model physics advancements have been included (Molod et al. 2015). The assimilation of atmospheric mass (including water vapor) is constrained to balance at the global scale (Takacs et al. 2016) which provides continuity of the mass through data assimilation. The climatology of the MERRA-2 data is discussed by Bosilovich et al. (2015) while Collow et al. (2017) provide some discussions on ENSO and SST forcing.

In the MERRA-2 reanalysis, observation-corrected precipitation is input to force the land surface parameterization, rather than the model simulated precipitation (Reichle et al. 2017 provide details on the observation-corrected precipitation). The benefit here is that surface heat fluxes, temperature and soil moisture are more closely constrained by the observed precipitation. However, the atmospheric model's precipitation can be different and related to physical processes (e.g. convergence). This is an important consideration in evaluating the land coupling to the atmosphere. Substantial biases exist in the MERRA-2 model-generated tropical precipitation (Bosilovich et al. 2017). Such biases are common in reanalyses (Trenberth et al. 2011; Bosilovich et al. 2008). We will identify whether observation-corrected precipitation or model-generated precipitation is used in subsequent analysis of the data, as the choice of which depends on if the forcing on the land surface or the atmospheric condensation is more relevant to the discussion.

Lim et al. (2017) used MERRA-2 and ocean reanalyses to evaluate the tropical Pacific Ocean evolution of the strongest El Niño case studies in the ocean and atmosphere. The MERRA-2 representation of El Niño events was validated against cloud and precipitation observations. Each event is unique, though the evolution of the SST, clouds, convection and precipitation in the tropical Pacific are similarly connected. Even with a thorough dissection of each event, in the atmosphere and the ocean, the authors note that there is still more to be done to complete the understanding of the events.

b. M2AMIP

To help evaluate the model processes response to SST, as it differs from the assimilated state fields, a numerical model integration was carried out, following the MERRA-2 atmospheric model set up exactly (Molod et al. 2015), including its climate forcing data (Collow et al. 2017). Ten simulation members were made to allow for an ensemble of global simulations, using the observed SST, aerosol, and solar forcing that was used in MERRA-2. The data formats and output variables are identical to MERRA-2. Collow et al. (2017) evaluates the M2AMIP ENSO connection to the continental United States regional climate. Here we focus on tropical land El Niño response, incorporating the ensemble mean of the experiment into the comparison to consider the role that the prescribed SSTs has in governing the background model used in MERRA-2.

c. ERA5

The latest reanalysis from ECMWF, ERA5, includes physics and analysis updates (Hersbach et al. 2018) and will provide a point of comparison for the MERRA-2 evaluation. All ECMWF reanalysis products have characteristically produced superior near surface air temperature owing to the analysis of surface meteorology stations (Simmons et al. 2017) which is continued in ERA5 at one hourly frequency (Hersbach et al. 2018). In addition to the significant

advancement in data assimilation, ERA5 also includes model improvements in radiation, land and convection processes.

d. Observations

One purpose of this study is to evaluate the MERRA-2 reanalysis and M2AMIP model capability to replicate El Niño and to use their unique data to better understand the subsequent warming and drying of the tropical land areas. Several key quantities in this process have very good quality observational climate data records to compare with the model-generated quantities. The MERRA-2 land surface air temperature is influenced by the observational data assimilation and the input observation-corrected precipitation forcing, though the model land parameterizations play a role.

For surface air temperature, CRU time series version 4.01 (Harris and Jones 2017; Harris et al. 2014) provides land station data set gridded to $\frac{1}{2}$ degree spatial resolution with monthly means up to near current times, using quality control algorithms that have developed over decades. In precipitation, GPCP covers the globe and encompasses the modern satellite era by merging satellite and gauge observations to provide a continuous and consistent record of precipitation. While the resolution is somewhat coarser than current reanalysis systems, the high quality and global coverage are useful characteristics in evaluating large scale modeling processes. The most recent version (2.3) includes several quality advancements over previous processing of the observations (Adler et al. 2017).

Because we are interested in the warming of the land surface during the life cycle of El Niño, the clouds over the land surface would likewise be closely related to the land surface response. Cloud observations and their comparison to model quantities are often uncertain owing to fundamental differences in the measured and modeled structural formulations. Using ISCCP HX satellite radiance, cloud and surface information (Rossow and Schiffer 1999; Young et al.

2018), SRB provides the surface radiation and clear sky estimates to determine the cloud radiative effect at a resolution of 1 degree (Stackhouse et al. 2011; Zhang et al. 2014 and 2019). CERES Surface-EBAF (Edition 4; Kato et al. 2018) also provides estimates of the radiative effect using MODIS and CERES observations. In this way, the surface radiative effect can serve as a method to determine the influence of clouds on the land surface. Here, SRB (Release 4.0 – Integrated Product) provides surface short wave radiative flux estimates for 1983 through 2015, while CERES EBAF (Edition 4.0) is available from 2000 to the present (CERES 2018).

3. Time series

While steps were taken in the development of the MERRA-2 model and data assimilation to mitigate excessive unrealistic impact of water vapor assimilation and variations in the water vapor observing system, there were notable instances of changes apparent in the time varying global water vapor (Bosilovich et al. 2017; Robertson et al. 2016). For example, test experiments without AIRS radiance assimilation demonstrated that MERRA-2's already high precipitation over global land surfaces increases even more as AIRS is included. Tropical continental (30S-30N, land only) precipitation produced by MERRA-2 (Figure 1a), does not increase sharply after AIRS introduction (November 2002) but does suggest larger interannual variability. ERA5 tends to have higher correlation to GPCP than MERRA-2, and a smaller bias. After 1998, MERRA-2 and ERA5 track closely to the GPCP anomalies. Interestingly, the M2AMIP mean precipitation high bias is similar to that of MERRA-2, but the interannual variability amplitude more closely follows GPCP, and is as well correlated as ERA5.

Shortwave cloud radiative effect at the ground surface (SWgCRE) is computed as the all sky net shortwave radiation minus the clear sky net shortwave radiation, so that positive anomalies indicate reduced cloudiness and more warming of the land surface. The reanalyses and model means SWgCRE anomalies in Figure 1b are biased strongly relative to SRB values towards more

clouds with ERA5 values showing more clouds than both observation data sets for tropical land. While the MERRA-2 mean SWgCRE is between the means of the observations (included in the legend of Figure 1), the interannual variations after 2002 may be related to variations in observations (for example AIRS and SSM/I, see McCarty et al. 2016). A general decreasing trend (after 2000) is somewhat captured by MERRA-2 and ERA5, but not M2AMIP (or in the CERES EBAF record). The reduction of surface shortwave radiation attenuated by cloud effects during El Niño events is apparent, but also varies between the observations and numerical systems.

The time series of tropical continental near surface air temperature anomalies (Figure 1c) demonstrates two dominant signals: an apparent global warming trend and ENSO. In subsequent analysis, we will focus on the ENSO signal, as the global warming signal should be addressed with longer time series of observations and reanalyses (e.g. Compo and Shardashmukh 2009). Both MERRA-2 and M2AMIP represent a reasonable surface temperature response to ENSO over the tropical lands, despite some interannual variations occurring stronger than observed. ERA5 variations track the CRU observations well, owing to the analysis of surface air temperature and water vapor observations (Hersbach et al., 2018).

From here forward, we will emphasize the processes in MERRA-2 and M2AMIP with a focus on the continental global monsoon regions in the tropical (30S-30N) latitude band. The global monsoon regions are defined as in Wang et al. (2012) (see their figure 1, and here in Figure 2). The definition uses the amplitude of the seasonal precipitation variations for monsoon development, and Wang et al. (2012) note that the monsoon precipitation is also affected by ENSO. This partitioning of the land area provides focus on the hydrological response and drought of the land areas during El Niño. Figure 3a-c compares the SST averaged over the Niño 3.4 region (170W-120W by 5S-5N) with the area averaged tropical land near surface air temperature in the global monsoon areas. In this figure (and in the remainder of the paper, with any exceptions noted),

the time series have been detrended to emphasize ENSO variability and the relationship between the SST and continental near surface air temperature and other properties.

Comparing HadISST (Rayner et al. 2003) with CRU tropical continental air temperature observations, the land response to El Niño warming varies in magnitude from event to event. This is to be expected, as essentially each El Niño is different, despite attempts to classify them by similar characteristics (e.g. Trenberth and Smith 2006 and Pillai et al. 2017). However, major El Niño events generally lead to tropical continental warming within a few months. Computing lead and lag correlations from monthly means (Figure 3d), the CRU air temperatures reach a peak warming 3 months after the peak SST warming, though the lag correlation value at 4 months after is very close to that peak. MERRA-2 and M2AMIP (Figure 3b and c) tend to follow the same relationship, though; both systems have generally higher continental air temperature correlations to the Niño 3.4 temperature anomalies (Figure 3d). The shape of the lead / lag curve (Figure 3d) is much the same in each system, and the significant positive correlations demonstrate the systematic El Niño SST controls on land surface temperatures. While acknowledging that so-called Central Pacific or “Modoki” El Niño events may originate from somewhat different processes than Eastern Pacific counterparts (e.g. Kao and Yu, 2009; Hu et al, 2016), a compositing approach provides a compact way of examining first order characteristics and evolution of these events.

4. Composite El Niño

In order to composite El Niño events, we first determine a central time, when the event is at its peak (will also be referred to as $M=0$). Using the monthly mean MERRA-2 SSTs, area averaged for the Niño 3.4 region (170W-120W, 5S-5N), we remove the mean annual cycle (base period 1981-2010) and then average for 3-month seasonal anomalies. The peak seasonal anomaly for each event (if $>1K$) is used in the composite El Niño. Peak dates and anomalies are listed in Table 1. The composite mean is developed for 25 months beginning at the month $M=-12$ relative

to the M=0 month, ending at M=+12 months. The DJF 2015/16 event is excluded, in order to compare the composite to that event (section 5b). Note that by compositing only warm events, averaging the 25-month anomalies does not yield zero-mean in the composite figures. This compositing of 2-year periods also helps mitigate the influence of discontinuities in the data. Statistical significance and composite standard deviation are presented in the composite time series. These statistics help focus the interpretation of the results.

a. Tropical Composite

Niño 3.4 SST and tropical land global monsoon area 2m air and mid-tropospheric temperature time series composites are given in Figure 4. Shading indicates the envelope of one standard deviation of the composite average for Niño 3.4 SST and T2m. Note MERRA-2 and M2AMIP use the same SST data. The peak land temperature response, as shown above with correlations, occurs in the 3-4-month time frame, after the peak of Niño 3.4 anomalies. Initial land warming slows through the SST peak month before again warming rapidly. MERRA-2 warming of tropical continental surface air temperature exceeds that in CRU observations and is perhaps a little earlier. On the other hand, MERRA-2 mid-tropospheric temperatures are cooler than ERA5, but the timing of the warming in both composites is similar (Figure 4a and b). Mid-tropospheric temperature maxima generally follow close to those of T2m, lagging T2m by one month for MERRA-2. The M2AMIP has a smoother time evolution owing to the ensemble simulation. Its land response is driven by the atmospheric modeling, and maintains a similar evolution of the land temperatures as CRU. For all three cases, the amplitude of mid-tropospheric warming in the six months preceding the T2m maximum exceeds that of the near surface. This is consistent with behavior reported by Chiang and Lintner, 2005; Fasullo, 2010 and Tyrell et al, 2014.

Figure 5 shows the SWgCRE and precipitation composite evolution for the tropical land areas. A double maximum (minimum) is apparent in the SWgCRE (precipitation) time series. The

initial reduction in precipitation and associated cloudiness occurs at $M=-4$ to -6 months. Following this SWgCRE weakens near $M=0$ as precipitation deficits also weaken somewhat. A second maximum in SWgCRE and precipitation reduction occurs at $M=3$ to 4 months in the observations and in MERRA-2. For each of these two phases SWgCRE changes coincide closely with the precipitation changes, with a suggestion that SWgCRE leads the precipitation. The entire sequence is somewhat weaker in M2AMIP and the second maximum occurs much earlier ($M=0$).

Figure 6 and 7 provide regional structure of temperature and precipitation anomalies at three times in the composite complementing the time series in Figure 4. At $M=-4$ as near-equatorial SSTs have already cooled west of the dateline and are rapidly warming over the eastern tropical Pacific, near surface warming is widespread over the Indo-Pacific rim countries and most of Australia. Only weak mid-level warming is present in the southeastern subtropical Pacific; yet, other regions of the subtropics at 500hPa have already started to cool, especially in the Southern Hemisphere where a band of mid-level cold anomalies stretches from the subtropical south America southeastward around the globe. MERRA-2 and ERA5 agree on this spatial structure, but it is largely absent in the M2AMIP simulations. Oceanic precipitation has migrated eastward over the tropical Pacific (Figure 7) and, consistent with SST declines just south of the Maritime continent, predominantly negative precipitation anomalies have developed over that region, parts of Africa, India and Australia. These decreases in precipitation over the Indo-Pacific rim land areas before the El Niño have been well documented (e.g. Ropelewski and Halpert, 1987; Curtis and Adler, 2003). While MERRA-2 is representing this feature compared to GPCP, the M2AMIP simulation also develops a strong decrease on precipitation toward the north, into the Maritime continent. This precipitation decrease in the Maritime continent is evident in MERRA-2 and GPCP at $M=-3$ (not shown), indicating the simulated response in M2AMIP is occurring earlier than observed.

307 By $M=0$, when Niño 3.4 SST anomalies peak, MERRA-2 continues to agree with CRU
 308 showing surface warming in Australia and large parts of Africa. The surface temperature anomaly
 309 pattern across Southeast Asia is well reproduced in MERRA-2 but across the interior of South
 310 America the warming is too large compared to CRU. In the mid-troposphere, a quadrupole
 311 temperature pattern is close to its mature state; warm T500 anomalies sit astride the T2m anomalies
 312 in the eastern tropical Pacific Ocean while negative anomalies are present to the west over western
 313 Australia and southern Asia. This pattern reflects the movement of precipitation and vertical
 314 mixing of moist enthalpy and dynamical response to deep convective heating from the Indo-Pacific
 315 region eastward toward the dateline. Prominent negative T500 anomalies are now at their peak
 316 over the Maritime Continent, Australia and southern Africa (Figure 6), consistent with reduced
 317 precipitation over this region. There is now a resurgence of precipitation over equatorial western
 318 Indian Ocean and East Africa with continued suppressed precipitation over most of Australia. This
 319 anomaly pattern is likely due not only to delayed Indian Ocean SST forcing by El Niño but also
 320 by the remnants of a positive Indian Ocean Zonal Mode SST, IOZM, (Saji and Yamagata, 2003)
 321 structure that occurs preferentially during El Niño events (Cai et al, 2011). The 1997 El Niño
 322 event was accompanied by a very strong positive IOZM event (Webster et al, 1999) which may
 323 heavily weight the composite, but 1987, 1994 and 2006 also experienced significant positive
 324 IOZM events. The M2AMIP ensemble replicates MERRA-2 temperature and precipitation
 325 anomalies over the land surface except that the magnitudes are generally slightly weaker. In
 326 particular, M2AMIP produces too much warming in South America while ENSO is building.
 327 African temperature anomalies in M2AMIP are also not as strong as in MERRA-2 and CRU as El
 328 Niño builds. After the peak, warm temperatures occur everywhere, except the Sahara, which is
 329 observed to be cooling.

At M=4 months, the mean tropical land has reached maximum warm anomalies (Figure 4), but at this point not all regions are in phase with the mean. Southeast Asia, Africa and central South America have all increased surface temperature anomalies. In the mid troposphere, anomalous warmth has been dispersed over the entire tropical band but a dipole maximum of T500 remains in the eastern Pacific with its easternmost extent now over South America. However, Australia land temperatures have decreased substantially (Figure 6) in the presence of a return to positive precipitation anomalies; (the remaining warm anomalies in the extreme north are included in the global monsoon area). The wet regime in areas surrounding the Caribbean has diminished in intensity. MERRA-2 follows the progression of the observations well in most of the continents, including the cooling in Australia. Africa, however, warms more than observations. The M2AMIP handles the warming regions at M=4 well, but also maintains a warm anomaly through all of Australia, instead of cooling as observed.

These results show that the global mean temperature evolution (Figure 4) results from combined regional responses that can differ in evolution according to whether they are primarily under the influence of adjacent El Niño SST forcing (S. America) or to SST and circulation anomalies that develop in concert with far field adjustments during El Niño (e.g. Australia, East Africa and other Indo-Pacific rim regions). MERRA-2 compares reasonably with the observed precipitation anomalies, for land and ocean, with some regional higher intensity owing to its higher resolution (as compared to the GPCP data). The M2AMIP anomalies are smoother than observed (related to the ensemble averaging) and generally comparable, although some regions are not well represented (Australia after the peak in Niño3.4).

The spatial patterns in MERRA-2 and M2AMIP are positively correlated to the GPCP observed anomalies (Figure 8). The observational analysis in MERRA-2 provides substantial improvements in the representation of the precipitation across the composite time periods

(compared to the AMIP simulations), including the times when the SST forcing is weak, and also over continental regions. The influence of El Niño SSTs leads to peak positive correlation in M2AMIP larger than most other months, but this benefit is limited to the few months nearest the peak SST anomalies and less prominent over tropical land areas.

These initial evaluations show that MERRA-2 global and even most regional tropical land and responses correspond well to observations; M2AMIP comparisons too are reasonable though somewhat less successful in the details of precipitation pattern change.

b. Energy Fluxes

The foregoing consistency check between observation, reanalysis and AMIP temperature and precipitation relationships provides confidence that we can now use these tools to pursue interpreting the role of various fluxes in determining moisture and temperature changes. Figures 9a-d show anomalous downward motion and increased shortwave radiation at the surface, as the precipitation is reduced and temperatures rise, across tropical land areas. Reduced total cloudiness occurs over tropical land extend from $M=-8$ to $M=8$ months, though a substantial recovery toward climatological values is present during $M=-3$ to $M=0$. The surface warming which is an integrated response to all fluxes begins in earnest after the first increase in SWgCRE, strongly suggesting the importance of cloudiness reductions in the land surface energy budget during El Niño events. The SWgCRE evolution is also tightly correlated to that of mid-tropospheric vertical motion (Figure 9c-d) with downward vertical motion anomalies leading reductions in cloudiness. These vertical motion changes represent dynamical linkages to the SST-induced convection over the tropical Pacific, the Niño 3.4 region and to other regions where the Walker and Hadley circulations are perturbed by anomalous convective heating.

Climatologically in MERRA-2 (not shown), there is net energy export from tropical land regions associated with mean moisture convergence but a dominant export of dry static energy

(DSE) and kinetic energy (KE). El Niño-related dynamical changes weaken these energy flows yielding reduced flux convergence of moisture, correspondingly reduced divergence of (DSE + KE); little or no net energy export anomaly through the peak of El Niño results (Figure 10a). These circulation and energy transport anomalies are consistent with tropical land precipitation reductions (Figure 5) which correlate strongly with mid-tropospheric vertical velocity (ω_{500}) changes. Note that the spread in MERRA-2 transports among composite events reduces the statistical significance. The M2AMIP ensemble shows similar relationships except that the slight recovery of the transports toward climatological values occurs about three months earlier.

Though SWgCRE relates closely to surface temperature changes, other surface energy budget components provide significant contributions. In response to reduced precipitation and altered shortwave forcing, surface soil moisture and evaporation begin a steady decrease after M=-9 and sensible heat flux increases, communicating this thermal energy surplus to the overlying boundary layer (Figure 9e-f). Sensible heat flux variations are strongly correlated with both surface and near-surface air temperature, but lead these temperatures as well as downward longwave flux increases by about 1-2 months (Figure 9e,g). The evaporation response lags the precipitation as soil moisture storage is depleted (Figures 9a, 10c). Individually, the surface longwave flux components are contemporaneously correlated to surface temperature. Unlike SWgCRE which exhibits two maxima dynamically coupled to vertical velocity, the downward longwave radiation has a single maximum that tracks surface temperature (and the upward longwave radiation). These relationships are replicated in the M2AMIP results, albeit with smaller magnitudes.

This analysis suggests a pathway for SST / convectively-induced free tropospheric temperature anomalies directly controlling near surface land temperatures: The dynamically induced precipitation reductions, allied cloud reduction and increased shortwave radiation drive

subsequent surface temperature and sensible heat flux increases. Surface upward and downward LW fluxes act with the sensible heat flux to keep T_s and T_{2m} strongly coupled. Since turbulent processes dominating land PBL structure operate on sub-diurnal time scales (not shown) the 850hPa temperature also correlates closely with T_s and T_{2m} .

The mid-tropospheric temperature increases act to offset the destabilizing effects of boundary layer temperature rise and, in conjunction with reduced moisture flux convergence, suppress precipitation. However, these temperature increases are dynamically tied to reduced upward motion and cloudiness and increased SW forcing of surface temperature. M2AMIP results, where the SST forcing is the most significant observational input data, show similar though more muted connections as MERRA-2.

One expects these global tropical flux relationships to have substantial regional / temporal granularity as evidenced by Figures 6 and 7. In the remainder of this section we explore the contributions of processes in two different regions to the tropical land signal. Then in section 5, we will use MERRA-2 data at pentad frequencies to better test the lag relationships.

c. South America

El Niño impacts on South American precipitation anomalies (global monsoon region, as in Figure 2) via teleconnections associated with Walker Circulation variations have been widely documented (Kousky et al, 1984; Ropelewski and Halpert, 1987; Grimm, 2003). In MERRA-2, land temperature closely follows the timing of precipitation (observation-corrected) decreases (Figure 11a). T_s , T_{2m} , and downward longwave flux are all strongly correlated and lead T_{500} , ω and $SWgCRE$ by 1-3 months. More shortwave radiation is reaching the surface (Figure 11c) owing to reduced cloud effects which, along with downward longwave, sustains the warming against sensible heat losses (Figure 11e) that increase nearly 5 Wm^{-2} in the six months before $M=0$. Downward longwave radiation at the surface correlates highly with surface outgoing longwave

radiation yielding a net cooling effect for the surface, and that cooling effect continues during El Niño.

The reduced cloud effect in M2AMIP is also closely related to reduced upward vertical motions and precipitation (Figures 11b,d) and T2m also leads T500. In MERRA-2, the increase in SWgCRE and decrease of upward motion at M=0 is apparent, but also shows more composite variance, leading to limited statistical significance.

While the M2AMIP experiment exhibits several features similar to MERRA-2, there are some key differences worth noting. In South America for example, the anomalies tend to be more pronounced closer to the time of the peak Niño3.4 SST anomaly. This is related to the inter-ensemble variability when the forcing is still developing. In the model, the lowest precipitation deficit leads the warm temperatures by 2 months (Figure 11b). In general, the M2AMIP El Niño signal starts later than the reanalysis and ends earlier, emphasizing the model's response to the strongest SST forcing, but diminished in the buildup and decay phase when SST forcing is weaker.

d. Australia

While we have primarily focused on global monsoon areas, Australia only has a small area that by definition registers as global monsoon; yet the whole continent has strong connection to El Niño in this composite (Figure 6 and Figure 7). Here, we expand the composite El Niño Australia region to consider the whole continent. The precipitation deficit in MERRA-2 (using the observation corrections), the anomalous downward motion, and reduction in cloudiness all begin as much as 6 months before the peak in Niño 3.4 SSTs (Figure 12 c). The surface responds to the cloud and precipitation reductions with reduced evaporation (Figure 13) and more sensible heating. Surface warming follows these forcings, but somewhat abruptly stops just after the peak in El Niño SSTs (M=0), when continental anomalous upward vertical motion and precipitation positive anomalies return and temperature anomalies drop to near zero. Note that downward longwave

radiation decreases sharply until $M=-4$ and remains anomalously low until $M=0$, this at a time when $T2m$ is increasing. The strong correlation between $-\omega$ (Figure 12c) and downward surface LW radiation (Figure 12g) is evidence of how strongly the El Niño-altered circulation controls atmospheric temperature and moisture changes. In contrast to South America where $T2m$ and downward LW are tightly correlated, for Australia we see the $T2m$ maximum ($M=-1$) leading downward LW ($M=3$) by four months. Also, in contrast to the sequence over South America, here $T500$ is decreasing with time before $M=0$ as $T2m$ is increasing. $T2m$ and $T500$ variation are anticorrelated. This tropospheric cooling is in response to the eastward shift of convection from the Indo-Pacific region into the central Pacific Ocean and, in conjunction with the loss of lower tropospheric moisture, controls the anomalous decrease of downward longwave radiation.

Previously, Figure 6 and Figure 7 showed significant disagreement between the M2AMIP and observations in Australia with warming onset too late, and maintaining the anomalously warm temperature beyond when MERRA-2 has returned to normal. In Figure 12a and b, the M2AMIP precipitation continues reduced for some time after the Niño 3.4 peak SST and recovers more slowly than does the MERRA-2 observation-corrected precipitation. SWgCRE and vertical motions agree with the precipitation anomaly and the reduction of surface soil water anomalies (Figure 13) is contributing to the increase in sensible heat flux and extension of the surface air temperature warm anomalies far beyond $M=0$. We suspect that the poor M2AMIP simulation over Australia is linked to the fact that biases in precipitation and air-sea interaction over the Indo-Pacific region remain persistent both in AGCMs and in coupled models (Wu and Kirtman, 2005; Bollasina and Nigam, 2009). The cold $T500$ anomalies in the SH subtropics (Figure 6) that are weakly reproduced in M2AMIP at $M=-4$ and completely gone at $M=0$ west of the dateline are evidence of this deficient Indo-Pacific circulation response in M2AMIP.

Our analysis here has highlighted two regions with distinct responses to El Niño. Responses in other localities may have additional complexity. For example, the disparate climatic regimes over Africa are linked to the semi-annual cycle and the complicating influence of Atlantic SSTs and the African Monsoonal system. The seasonality of the Asian Monsoon and the influence of IOZM mean that the response of South Asia and the Maritime Continent to ENSO likely have even more complex regime structure. A more detailed treatment of these local contributions to the global signal is warranted.

5. High Frequency and Individual El Niño Variability

To this point the discussion has focused on the monthly composite El Niño, in which relationships are inherently related to seasonal and longer time scale variability. The composite average minimizes internal atmospheric variability as well as random differences among El Niño events, retaining any consistent response to evolving far-field tropical SST anomalies. In addition, this analysis allowed comparison to AMIP experiments and comparison across several long duration observational and reanalysis data. In order to refine the global tropical lag relationships and connections, we now evaluate the composite in MERRA-2 with pentad time series (M2AMIP ensemble data were not saved at such high frequency). We compute pentads from MERRA-2's hourly data collections and composite the same El Niño events averaging 5 days data for 73 pentads per year (with leap days averaged into the 12th pentad of each year). As in the monthly composite, a climatological annual cycle (1981-2010) is removed from the pentad time series, and the variables are detrended before making the composite mean. The pentad composite time series contains more variability. In the next section, we present the pentad composite evolution, but first, we test the higher frequency relationships of the physical quantities that contribute to the tropical land surface warming and drying.

a. *High Frequency Variability*

Figure 14 shows the lead/lag correlations for several quantities as related to the land surface temperature and precipitation/evaporation. The time correlations are computed for 101 pentads (+/- 8 months) relative to the pentad with peak Niño 3.4 SST. Lead/lag correlations are determined by shifting the first variable listed, relative to the second. In this way, we highlight the modes of variation between the relevant quantities during the evolution of El Niño. For example, 500 hPa vertical velocity and SWgCRE correlate most strongly at zero lag, indicating a mode of rapid response of one to the other. Given the large-scale change over the composite El Niño, this represents the cloud responding to the dynamical variations represented in vertical velocity.

On the other hand, SWgCRE leads surface temperature (T_s) even out to leads of 100 days (~3 months), suggesting the effects of persistent radiative forcing. However, there is a maximum correlation at a lead of 25 days. The surface temperature leads sensible heating, but with a broad peak correlation with an approximate lead of 15-10 days. This contributes to a rapid response of T_{850} to the surface temperature, which correlate to 0.99 at lag zero indicating strong mixing within the planetary boundary layer. Surface temperature does have a low frequency leading correlation with T_{500} , but their correlation is declining at zero lag. These results show the importance of multiple temporal scales (weather to interannual) governing the nature of the surface warming as the circulation reduces clouds over land, increases the shortwave and warms the surface and the lower troposphere.

The water cycle is strongly coupled to these processes. In Figure 14b, as could be expected, precipitation (model-generated) is highly correlated with vertical motion at zero lag. Precipitation that forces soil moisture (note for MERRA-2 this is the observation-corrected precipitation) leads evaporation, primarily at longer lead times. This reflects the influence of the soil water storage on the evaporation and the time it takes to deplete the soil water and warm the surface, as the soil

wetness also has a peak correlation leading the evaporation (by 15 days). Surface temperature is already increasing by the time evaporation is decreasing.

b. 2015-2016 El Niño

The 2015/16 El Niño produced tropical ocean temperatures as high as the warmest previous events in recent records (Santoso et al., 2017). A significant portion of the globe (12%) experienced drought conditions, some of the highest in modern records, related to El Niño influence (Dunn et al. 2017). Here, pentad resolution data permits closer examination of how one particular event, in this case the extreme 2015/16 El Niño, evolves compared to the composite (Figure 15) and the contributions from various regions (Figure 16). The 2015-16 El Niño is approximately 1K warmer (its peak occurs 9NOV2015 using the MERRA-2 SST pentad anomalies) than the composite Niño 3.4 temperature, while warmer than the composite throughout the entire 2-year period of the composite (Figure 15a). Tropical land 2m air temperature in 2015 is warm for the 6 months leading up to the Niño 3.4 peak, but then drops dramatically before warming again 3 months after the peak. When the land is warm, it is much warmer than the composite El Niño (more than 1 standard deviation). Early rises in T2m are driven by South America and, after M=-1, by Australia and tropical S. Asia (Figure 16a). Negative precipitation anomalies in the months leading up to the peak of El Niño (Figure 15b) are followed by a recovery punctuated by episodic spikes of positive anomalies near M=2 and M=4. Regionally, South America experiences the largest reduction in precipitation on average during the 2015-16 El Niño (Figure 16b). Record breaking temperatures and drought occurred in Amazonia, but also a significant wet/dry dipole in precipitation occurred (Jiménez-Muñoz et al. 2016). Australia and Tropical South Asia have much weaker, but predominantly negative, precipitation anomalies in the six months prior to M=0, but little T2m response. Conversely, Africa in 2016 becomes sporadically wetter and cooler than average just before M=0 and is the only region with T2m cooling and anomalously low sensible heat flux

during the peak of El Niño, $M=-3$ to $M=3$ (Figure 16c). It is the temporary peak in precipitation over all regions centered near $M=2$, along with a brief spike in South American precipitation that drives the drop in $T2m$ and $T850$ during this period. Though the 2015/16 sequence of events is “noisy” compared to the composite mean (Figure 15), the relationships are similar over tropical land as a whole; precipitation correlates well with vertical velocity and $-SWgCRE$ variations, at least on seasonal time scales, and is consistent with changes in latent and sensible heat flux.

Interestingly, while $T2m$ and $T850$ warm along with the surface and the turbulent heating increases following precipitation declines in the 2015 event, $T500$ only rises after $M=0$ (Figure 15d), completely at odds with the low level warming in the developing months. Australia is the dominant contributor to this mid-level cool anomaly (Figure 16d) and this coolness, while extreme, follows the evolution of the composite prior to $M=0$. This behavior contrasts in general with that of S. America which warms at mid-levels beginning at $M=-6$ and cools after $M=3$. The exceptional warming at mid-levels afterward at $M=3$ to $M=5$ is driven initially by the Tropical South Asian and Africa regions and sustained by changes over Australia. We suspect this warming is due to the relaxation of cold SSTs in the Indo-Pacific region and return toward climatological precipitation there. A strongly positive IOZM event (cold eastern, warm western equatorial Indian Ocean SST) develops during late 2015 (https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/DMI/). Saji and Yamagata (2003) and Cai et al. (2011) make note of equivalent barotropic wave structures over the Indo-Pacific subtropics during El Niño that get augmented by positive IOZM events. These flow patterns are consistent with the late 2015 mid-level coolness over Australia and Tropical S. Asia seen in Figure 16d.

These results emphasize that the composite provides general guidance on the dominant circulation, flux processes and tropical land temperature response during typical El Niño events, at least on a tropical average basis. But as evidenced by the high frequency variations and

intermittent spikes in the time series (e.g. the tropical mean precipitation increase near $T=2$) even one of the strongest El Niño events in the last 35 years can manifest land/atmosphere processes through the lifecycle that differ significantly from the composite El Niño. Weather-scale events, intraseasonal variability and especially internal atmospheric variability can add significant variance to flux processes.

6. Summary and conclusions

In this work we have sought to better understand how various components of the tropical land surface energy balance adjust during the evolution of typical El Niño events. Using a compositing technique, and centering the composite members on the time of the Niño 3.4 SST maxima allowed us to identify the role of various processes leading to predominant drought and warming. Preliminary observational assessment justified the use of MERRA-2 reanalysis and AMIP fluxes and related variables over the ± 12 month period.

In MERRA-2, we find that dynamical effects of atmospheric teleconnections embodied in Walker / Hadley dislocations during El Niño couple via tropospheric vertical motion changes both to SWgCRE, precipitation anomalies, and eventually other components of the surface energy balance (Figure 9). These changes are consistent with reduced moisture import from ocean to land and with weakened DSE+KE export (but with a partial recovery near $M=0$). Individually these fluxes are consistent with arguments outlined in Lambert et al. (2011) for SST-driven changes, but the for El Niño events the present results indicate little evidence of increased net energy export. However, it should be noted that the inter-event spread of time variations of the tropical continental energy fluxes across the range of El Niño events is large (as evidenced by low statistical significance). We suspect the partial recovery in moisture transport near $M=0$ is tied to the relaxation of the downward component of the Walker circulation and increased precipitation anomalies over much of Eastern Africa (Figure 7). A complicating factor in this partial recovery

of is the tendency for positive phasing of the IOZM with El Niño which though important for increasing East African rainfall also tends to produce drought over southern Australia.

From a global tropic perspective the quadrupole pattern of warming over the eastern Pacific and cooling over the Indo-Pacific (dominantly in the SH) during the developing and mature stages of El Niño is accompanied by distinctive regional surface energy flux changes. Over South America Ts, T2m and downward LW are in phase, while for Australia a reduction in downward LW maximizes at M=3, some four months after T2m and Ts anomalies reach their peak. The anomalous downward motion, reduced precipitation and increased Ts, T2m, Hs and SWgCRE over Australia during growth stages of El Niño (Figure 12) occurs with a cold troposphere (Figure 6) linked to reduced precipitation and associated dynamical heating over the Indo-Pacific region (Figure 7). In contrast, South America has similar upper-level anomalous downward motion and surface flux changes that occur at and after El Niño maturity, but in the presence of tropospheric warmth that has now spread throughout the equatorial region between M=0 and M=4. This sequence of events and processes is more in line with the dynamical picture argued by earlier papers (e.g. Lambert and Chiang 2007; Joshi et al, 2008; Tyrrell et al. 2014). We find that globally, Ts and T2m lag relationships to mid-tropospheric warmth are ambiguous; T500 lags Ts increases in MERRA-2 (Figures 4b, 14) but the timing is ill-defined. On the other hand the CRU T2m and ERA5 lag relationship is reversed (Figure 4a), but also ill-defined. As noted earlier though, T500 increases prior to the time of T2m maximum are larger than those near the surface. So mid-tropospheric warming, anomalous descent and increased SW absorption are all linked.

In terms of the surface energy budget fluxes, we also find a significant role for sensible heat flux increases which act to offset SWgCRE and downward longwave effects in the face of reduced precipitation and LE. Because sensible heat flux increases warm the overlying near surface air (and ultimately the PBL), we interpret the increases in downward LW as responding

more to this turbulent energy transport than being coupled to the mid-tropospheric temperature by virtue of changes in heat transport. Figure 9 suggests that the tropical land surface integrates sustained SW anomalous forcing and that the sensible heat flux anomalies couple T_s , T_{2m} and downward LW. Correlations of T_s with T_{850} are stronger than with T_{500} (Figure 14), supporting this view. This interpretation is consistent with the results of surface flux process sensitivity tests in Chiang and Lintner (2005) that showed that constraining sensible heating drastically distorted the surface temperature response. The significant increases in SH seen in our study also echo the results of Sutton et al. (2007) who found reduced moisture transport to land and significant increases in sensible heat flux in the face of SST increases in a global warming scenario.

CS09 on the other hand find a dominant role for T_s forcing by downward longwave. In trying to reconcile our results with theirs we first note that their study involves changes on decadal time scales which greatly diminishes the average El Niño signal and precludes resolving life cycle effects. Furthermore, their domain encompasses global land whereas ours is a tropical subset. But as in the present study CS09 also find a significant role for SW forcing of T_s that relates to mid-tropospheric vertical motion changes. As we argue above, since turbulent processes typically couple surface and PBL temperature strongly, a significant component of their T_s , downward LW down correlation due to this coupling may mask the intrinsic importance of the SW and cloud effects on T_s .

The M2AMIP ensemble reproduces many of the changes in fluxes in a tropical mean sense (Figure 9). While the nature of the teleconnection changes and the effects on flux changes over South America can be reproduced approximately, the Indo-Pacific Basin and the adjacent continents are much more of a challenge because of strong two-way coupling of the ocean / atmosphere system there. Consequently, the equatorially trapped atmospheric response to deep convective heating variations over the SST warm pool (and associated equivalent barotropic

waves) is problematic in AMIP experiments. The model responds more closely to SSTA observations closer to the peak of El Niño SSTs. This likely results from AMIP experiment ensembles averaging out internal atmospheric variability, enhancing SST-forced signals.

Compositing approaches have both merits and drawbacks—one prominent shortcoming being the associated blurring of different El Niño flavors into one mean event. In comparing the 2015/16 event to the composite mean, significant weather variations were also noted, including the significant effect of a significant temporary spike in precipitation a few months after $M=0$. However, the distinct difference in response to El Niño between Australia and South America was still in evidence. To the extent that lagged, far-field ocean warming effects are present (Klein et al, 1999; Alexander et al, 2002) relating systematically to Niño 3.4 at $M=0$, they are captured by the compositing method and implicit in lag relationships between flux quantities.

In this composite, we have not attempted to separate so-called eastern Pacific vs central Pacific events (Kao and Yu, 2009; Hu et al. 2016). Nor have we attempted to control for the variable presence of the IOZM or cross equatorial SSTA in the Atlantic widely known to affect Brazilian hydrometeorology. This may explain to some extent the ambiguities in some of the regional time series shown here. Longer time series of reanalyses may allow more events that would permit adequate sampling and stratification to address these factors. Nevertheless, the present study identifies the sequence of processes important to global tropical land response to El Niño forcing. Regional and local response to ENSO events is a significant challenge in sub-seasonal to seasonal forecasting as well and continued efforts to understand the hydrometeorological responses to this continuum of events remains important work.

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669

7. Appendix: Acronyms

671	AIRS Atmospheric Infrared Sounder
672	AMIP Atmospheric Model Intercomparison Project
673	AMSU Advanced Microwave Sounding Unit
674	CERES Cloud's and the Earth's Radiant Energy System
675	CPCU Climate Prediction Center Unified precipitation data
676	CRU Climate Research Unit
677	DSE Dry Static Energy
678	EBAF Energy Balanced and Filled
679	ECMWF European Centre for Medium Range Weather Forecasts
680	ERA5 ECWMF Reanalysis 5
681	GPCP Global Precipitation Climatology Project
682	HadISST Hadley Centre Sea Ice and Sea Surface Temperature
683	ISCCP International Satellite Cloud Comparison Project
684	IOZM Indian Ocean Zonal Mode
685	MERRA Modern Era Retrospective-analysis for Research and Applications
686	M2AMIP MERRA-2 Atmospheric Model Intercomparison Project ensemble experiment
687	MSU Microwave Sounding Unit
688	NASA National Aeronautics and Space Administration
689	Niño 3.4 refers to the index based on SST and region of the tropical Pacific Ocean defined in the
690	text
691	SRB Surface Radiation Budget
692	SSM/I Special Sensor Microwave Imager
693	SWgCRE Shortwave Ground Cloud Radiative Effect (all sky minus clear sky)
694	Ts, T850, T500 Temperature at the surface, 850 hPa and 500hPa respectively
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9. Tables

Table 1 Coordinates and magnitude of the Niño3.4 temperature anomalies that are the center times included in the composite El Niño.

Mon-Year	SST Anomaly (K)
DEC1982	1.8
AUG1987	1.4
JAN1992	1.8
DEC1994	1.1
DEC1997	1.9
NOV2002	1.2
NOV2006	1.1
DEC2009	1.2

10. List of Figures

Figure 1 Comparison of anomalies of tropical (a) precipitation, (b) surface shortwave cloud radiative effect (SWCRE), and (c) near surface air temperature over land (30S-30N) regions for MERRA-2, M2AMIP, and ERA5 data with observations from CERES/SRB, GPCP and CRU, respectively. The anomalies remove the common mean annual cycle period (2000-2014), and have a 12-month running mean applied. The time averaged mean of the data is reported in the legend.

Figure 2 Global monsoon areas (blue shaded regions) as defined by MERRA-2 seasonal amplitude of precipitation using the method developed by Wang et al. (2012). The bold continental outlines depict regions that will be evaluated more closely.

Figure 3 Time series of Niño 3.4 SST and near surface tropical continental air temperature (T2m) in global monsoon areas for a) HadISST and CRU observations, b) MERRA-2 and c) M2AMIP sea surface temperature (Ts). MERRA-2 and M2AMIP SSTs are from the same source, which is documented by Bosilovich et al. (2015). The time series data have been deseasonalized, detrended and then filtered with a 12-month running mean. The lead/lag correlations of these time series (d), are computed from the monthly mean time series. Units are Kelvin, except for correlations which are dimensionless.

Figure 4 El Niño composite anomalies for Niño 3.4 SST (black) and all tropical lands identified in global monsoon regions 2m air temperature (red, T2m). The solid line indicates the composite average and shading indicates ± 1 standard deviation. Units are K, and the scales are color coded to each corresponding line. The dashed red lines indicate 500 hPa temperature anomalies (where ERA5 reanalysis is shown for comparison purposes in the observations panel). M2AMIP uses the same prescribed SST as MERRA-2, while the

observations are from HadISST. Dots indicate anomalies significantly different from zero (using t-test at 90% confidence).

Figure 5 As in Figure 4, except for absorbed shortwave radiation cloud radiative effect (SWgCRE, made negative so the lower values correspond to less cloud, black) and precipitation (Prec, red), where units are Wm^{-2} for SWgCRE and mm day^{-1} for precipitation. Note that the MERRA-2 precipitation is derived from the atmospheric model prediction.

Figure 6 Monthly mean 2m temperature (K) El Niño composite anomalies for CRU (top), MERRA-2 (middle) and M2AMIP (bottom) in color shading. Corresponding 500 hPa temperature anomalies are contoured (at 0.5K intervals), where ERA5 reanalysis 500 hPa height anomalies are included with CRU observations. The columns represent the composite El Niño at 4 months before the peak (left), the month of the peak (center) and 4 months after the peak (right). As in the time series composite, these fields have been deseasonalized and detrended.

Figure 7 Monthly mean precipitation (mm day^{-1}) El Niño composite anomalies for GPCP (top), MERRA-2 (middle) and M2AMIP (bottom). The columns represent the composite El Niño at 4 months before the peak (left), the month of the peak (center) and 4 months after the peak (right). As in the time series composite, these fields have been deseasonalized and detrended. MERRA-2 is its modeled precipitation.

Figure 8 Spatial anomaly correlation in the tropics (30S-30N) of GPCP with MERRA-2 and M2AMIP precipitation for El Niño composite averages. MERRA-2 and M2AMIP are interpolated to GPCP's grid to compute the correlation. Solid lines represent all tropics while dashed is land only correlations.

Figure 9 Tropical global monsoon land areas (30S-30N) composite El Niño anomaly time series for MERRA-2 (left) and M2AMIP (right) for several key quantities listed on the figure. The solid line indicates the composite average and shading indicates ± 1 standard deviation of the composite mean. Scales are color coded for each line. Dots indicate anomalies significantly different from zero (at 90% confidence). The variables are near surface air temperature (T2m), precipitation, SWgCRE, vertical velocity ($-\omega_{500}$, directed positive for upward motion, at the 500hPa level), surface temperature (Ts), sensible heat flux (Hs), downward longwave radiation ($LW_{\downarrow}$) and net surface longwave radiation (LW_{net} , directed downward positive).

Figure 10 As in Figure 9, except for additional quantities: dry static energy (DSE) divergence ($\nabla \cdot C_p T + \nabla \cdot gZ + \nabla \cdot KE$), heating due to water vapor divergence ($\nabla \cdot Lq_v$), surface evaporation (Evap) and surface soil wetness.

Figure 11 South America global monsoon region composite El Niño anomaly time series for MERRA-2 (left) and M2AMIP (right) for several key quantities. Vertical velocity ($-\omega_{500}$) is directed positive for upward motion, determined at the 500hPa level. The solid line indicates the composite average and shading indicates ± 1 standard deviation of the composite mean. Scales are color coded for each line. Red dashed lines in the top row indicate the 500mb Temperature (T500). Dots indicate anomalies significantly different from zero (at 90% confidence).

Figure 12 Australia (land only) composite El Niño anomaly time series for MERRA-2 (left) and M2AMIP (right) for several key quantities. Vertical velocity ($-\omega_{500}$) is directed positive for upward motion, determined at the 500hPa level. The solid line indicates the composite average and shading indicates ± 1 standard deviation. Red dashed lines in the top row

973 indicate the 500mb Temperature (T500). Scales are color coded for each line. Dots indicate
 974 anomalies significantly different from zero (at 90% confidence).

975 Figure 13 Australia (land only) composite El Niño anomaly time series for MERRA-2 (left) and
 976 M2AMIP (right) for evaporation (black, mm day⁻¹) and surface soil wetness (red, m³ m⁻³).
 977 The solid line indicates the composite average and shading indicates ± 1 standard
 978 deviation. Scales are color coded for each line. Dots indicate anomalies significantly
 979 different from zero (at 90% confidence).

980 Figure 14 Tropical land global monsoon region lead lag correlations for a) surface temperature
 981 variables and b) water cycle variables. The correlations are developed by from the
 982 MERRA-2 pentad time series, with leading correlations as negative days and lag
 983 correlations are positive days for pairs of variables x:y, where the first variable (x) is
 984 computed as leading or lagging the second variable (y). Correlation units are
 985 dimensionless, and the values are computed over 101 data points (8 months of pentads)
 986 and values of 0.26 are significant at 99% confidence.

987 Figure 15 The Niño 3.4 region SST composite with the 2015-16 event is presented in panel (a).
 988 Tropical land global monsoon regions composite El Niño (b-f) for the MERRA-2 pentad
 989 time series (solid lines with shaded ensemble standard deviation) compared to the 2015-
 990 2016 El Niño (dashed line) for several key quantities (where LE is surface latent heat,
 991 SfcNet is the net flux of energy into the surface and TPW is total precipitable water). Black
 992 variables are scaled on the left axis and red variables are scaled on the right axis.

993 Figure 16 Tropical land regions composite El Niño for the MERRA-2 pentad time series (dashed
 994 lines) compared to the 2015-2016 El Niño (solid lines) for 2m air temperature (a, T2m),
 995 modeled precipitation (b, Prec), surface sensible heat (c, Hs) and mid-tropospheric

996 temperature at 500 hPa (d, T500) over the main tropical regions (colors match the those in
997 the figure title).

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11. Figures

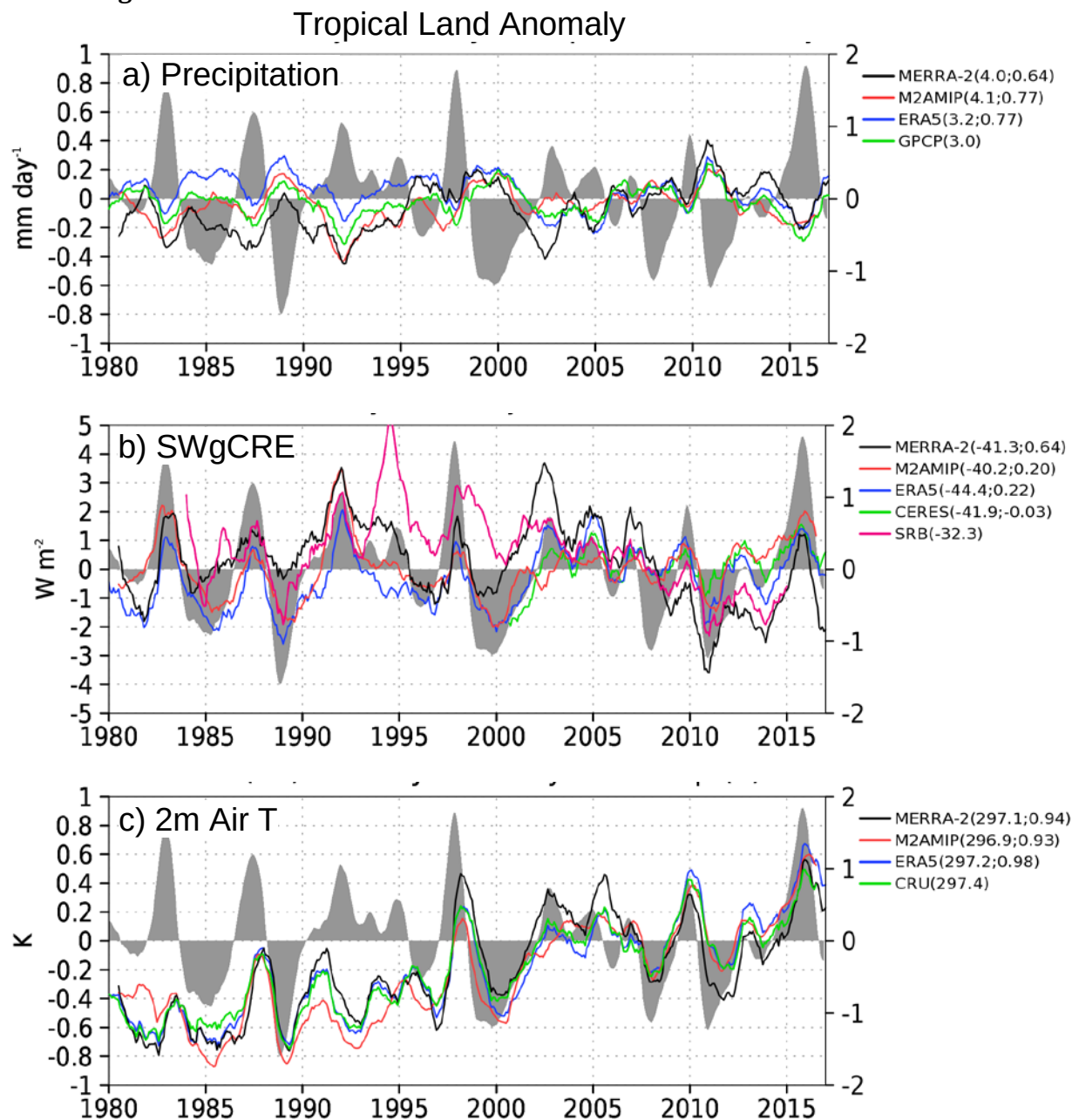


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Tropical Land Sub-regions and Global Monsoon Areas

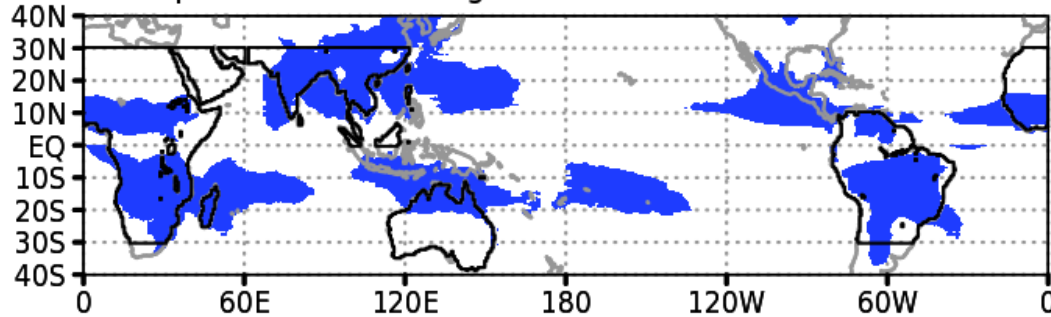


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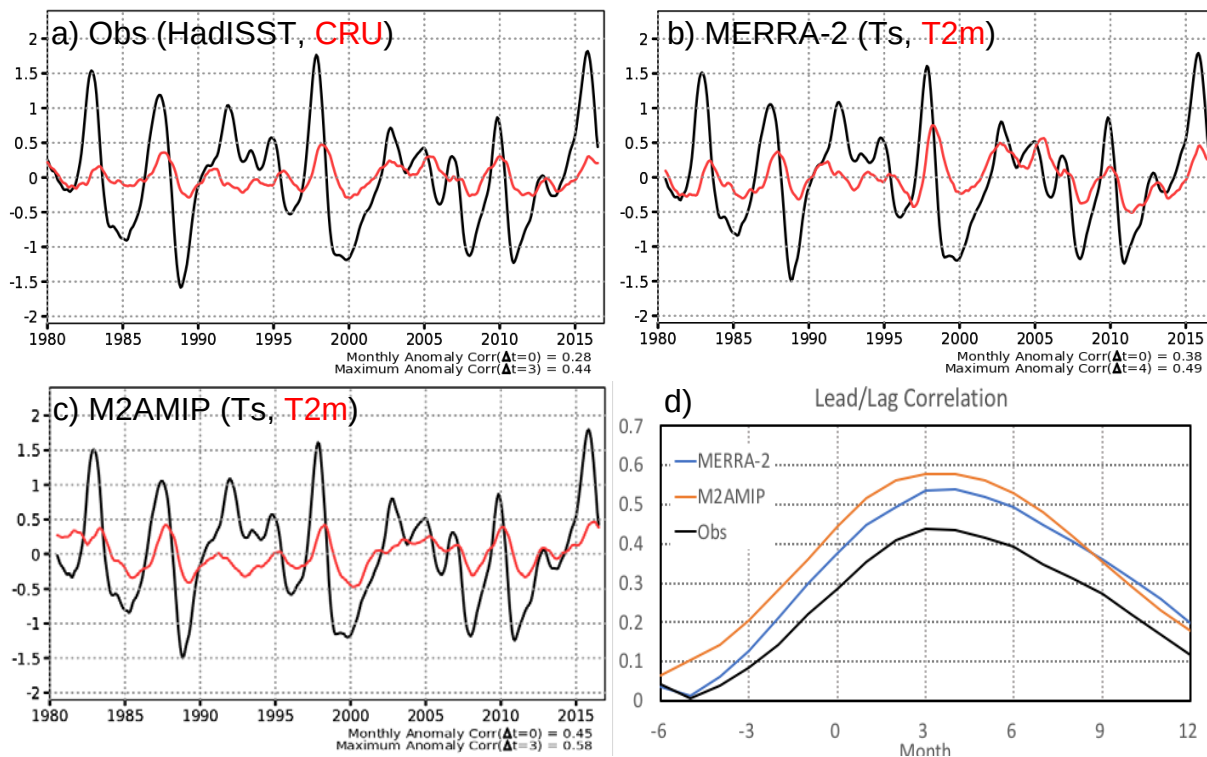


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Tropical Land Anomaly

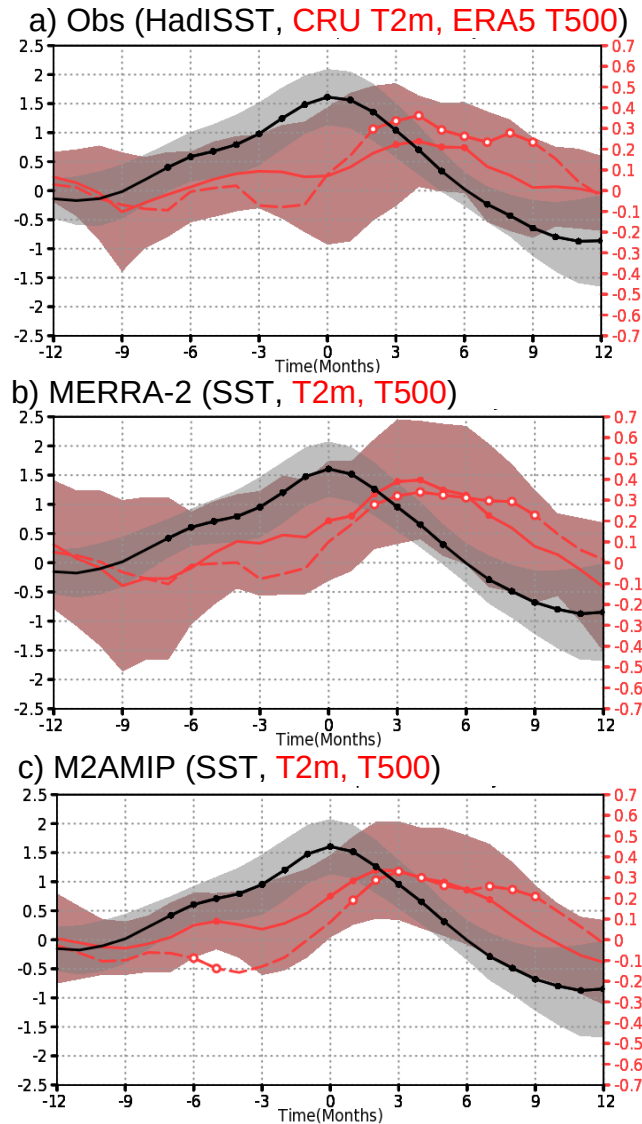
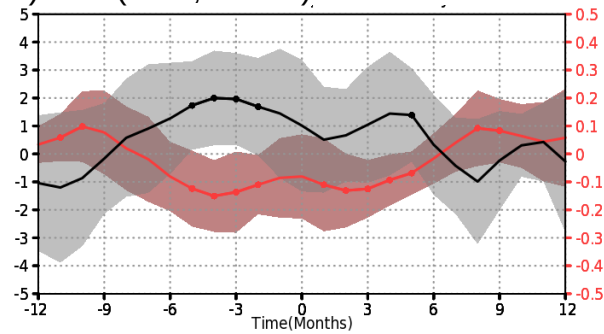


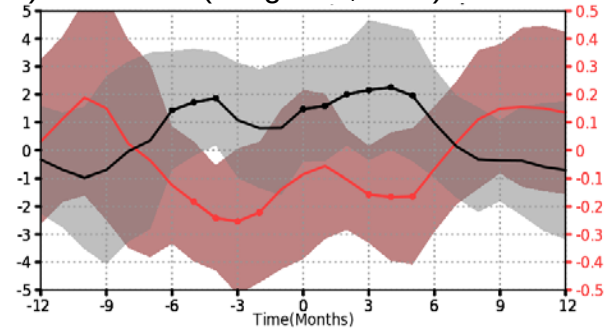
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Tropical Land SWgCRE, Prec Anomaly

a) Obs (SRB, GPCP)



b) MERRA-2 (SWgCRE, Prec)



c) M2AMIP (SWgCRE, Prec)

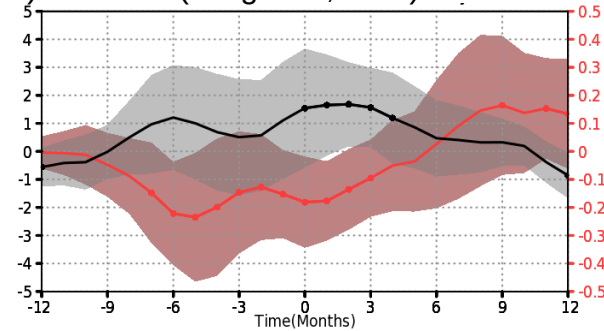
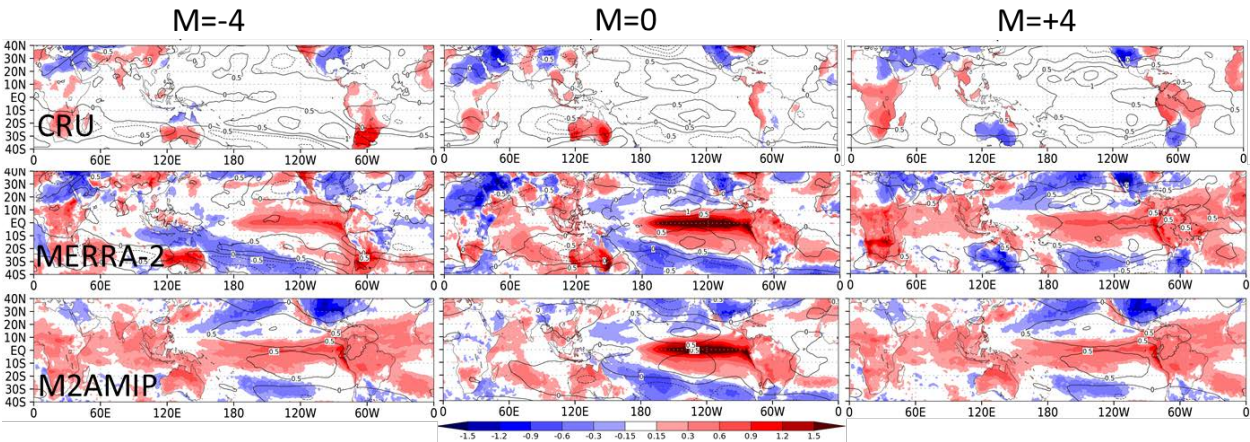


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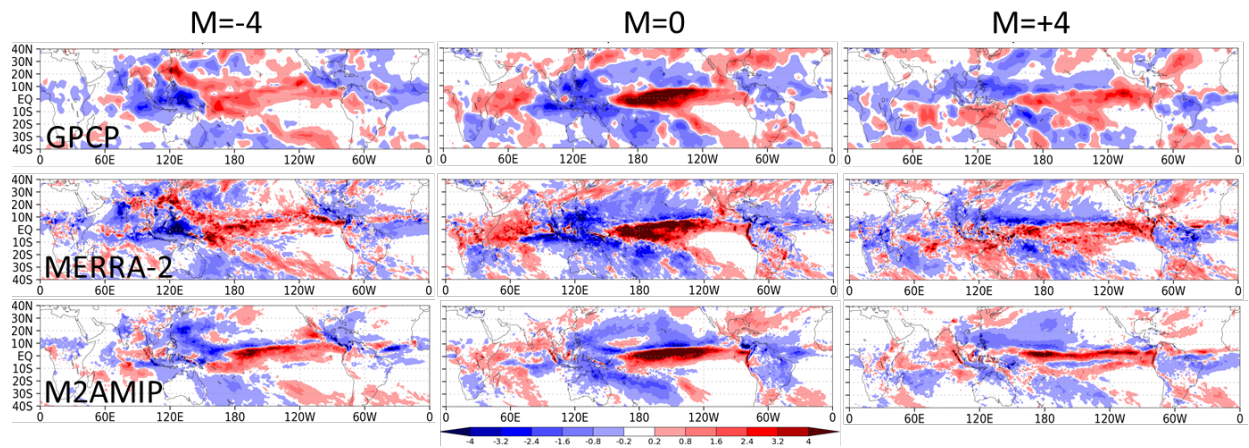
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Figure 7 Monthly mean precipitation (mm day^{-1}) El Niño composite anomalies for GPCP (top), MERRA-2 (middle) and M2AMIP (bottom). The columns represent the composite El Niño at 4 months before the peak (left), the month of the peak (center) and 4 months after the peak (right). As in the time series composite, these fields have been deseasonalized and detrended. MERRA-2 is its modeled precipitation.

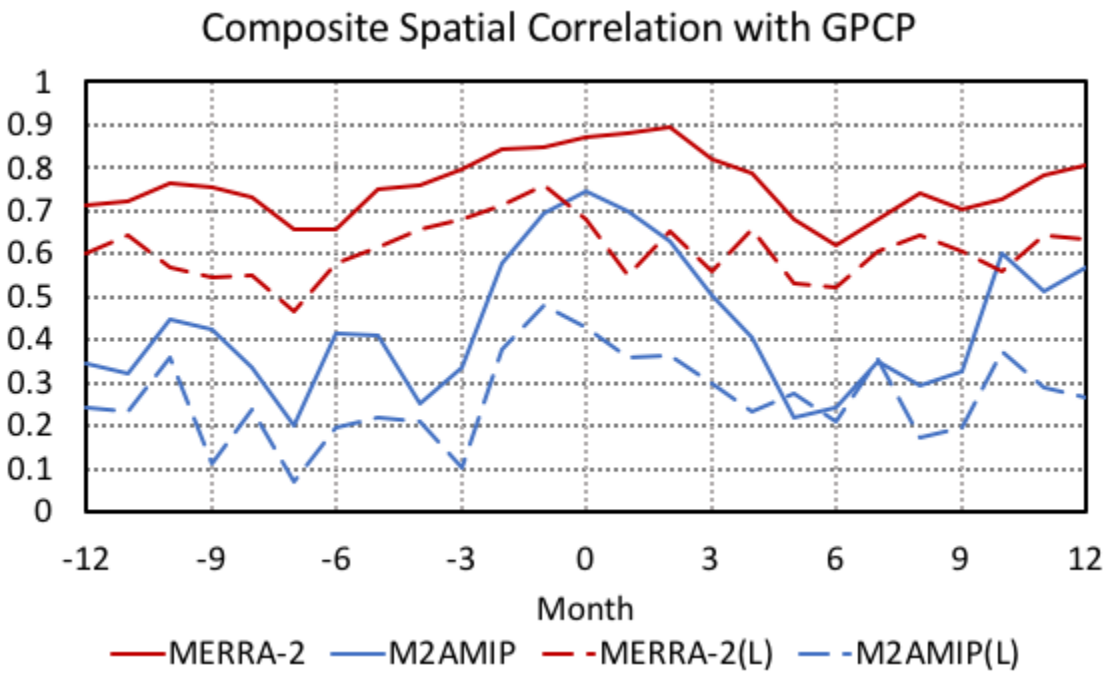


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Tropical Land (30S-30N) Composite El Niño Anomaly MERRA-2 M2AMIP

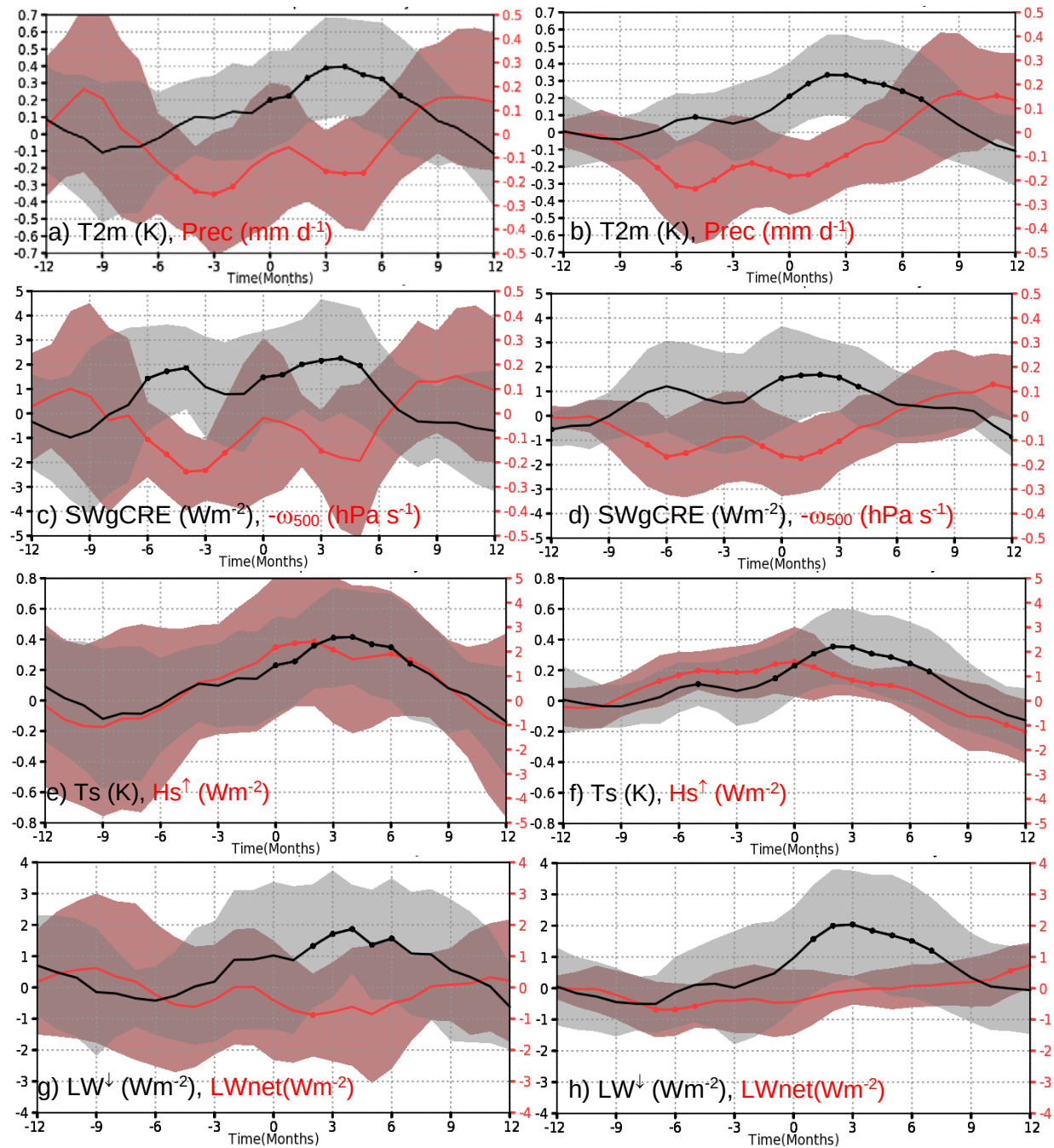


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Tropical Land (30S-30N) Composite El Niño Anomaly

MERRA-2

M2AMIP

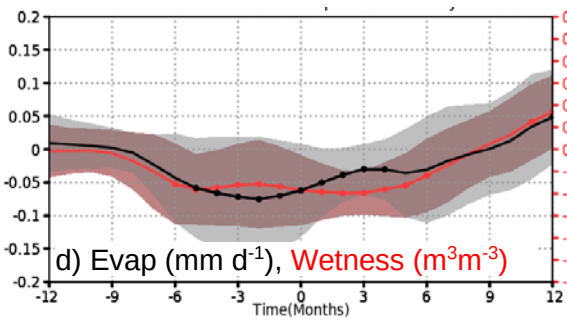
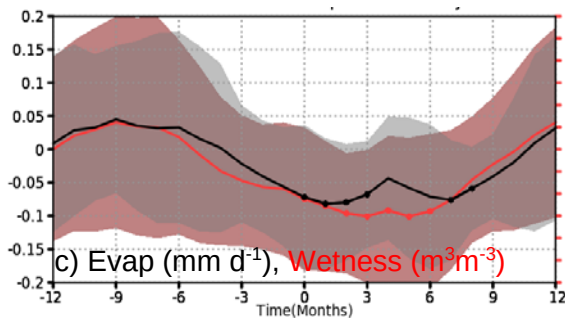
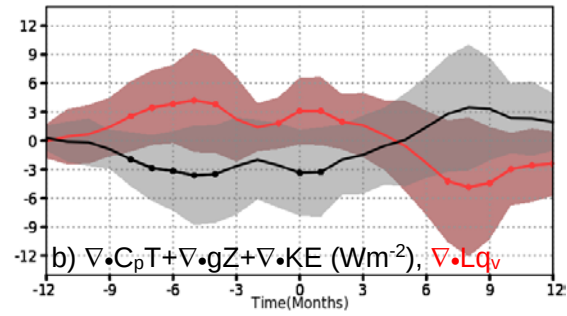
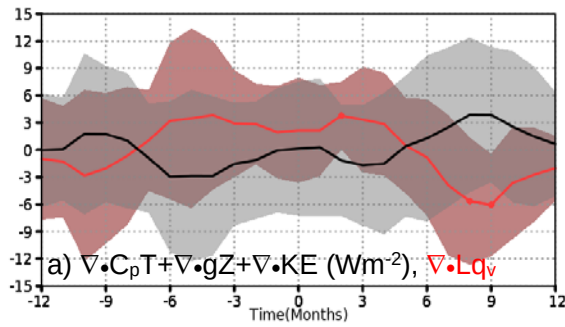


Figure 10 As in Figure 9, except for additional quantities: dry static energy (DSE) divergence ($\nabla \cdot C_p T + \nabla \cdot gZ + \nabla \cdot KE$), heating due to water vapor divergence ($\nabla \cdot Lq_v$), surface evaporation (Evap) and surface soil wetness. DSE and water vapor convergences are computed from the model output fluxes of q_v , $C_p T$ and gZ , and do not include mass corrections to the wind.

South America Composite El Niño Anomaly

MERRA-2 M2AMIP

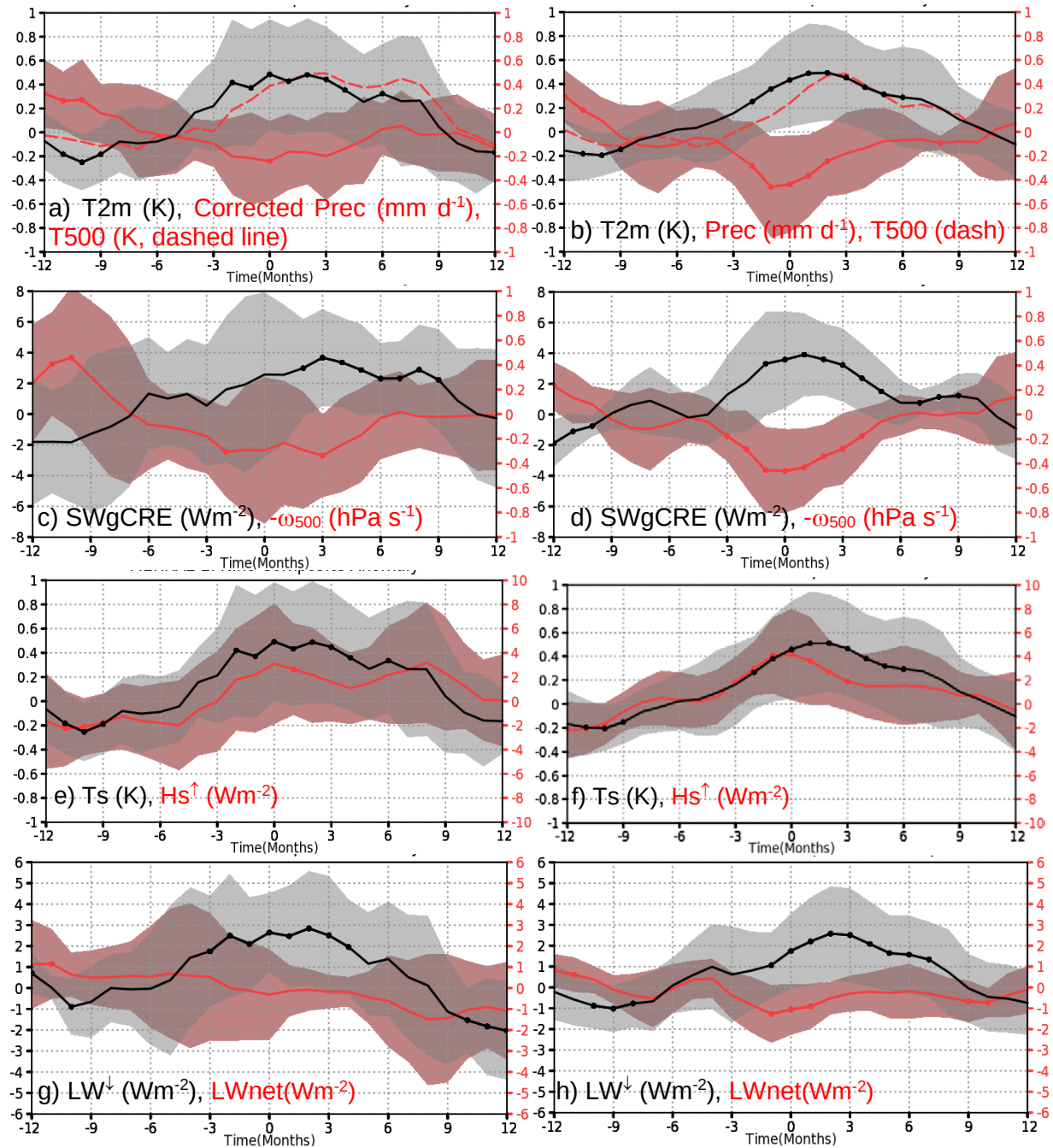


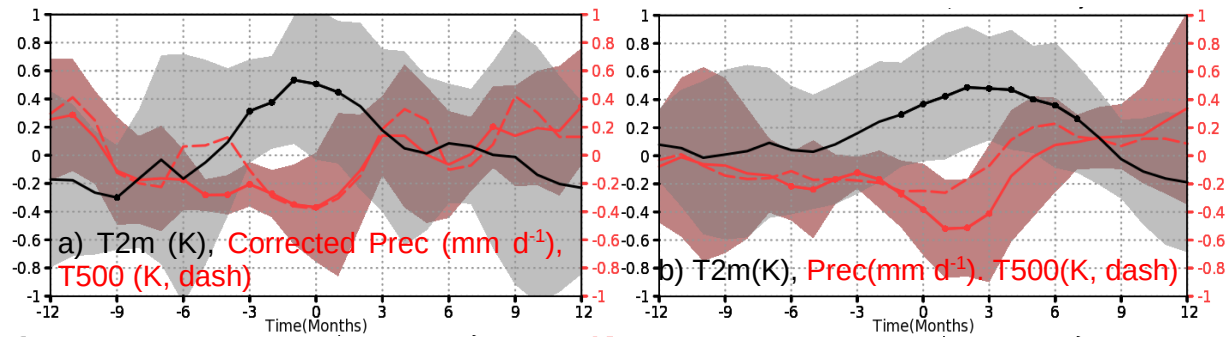
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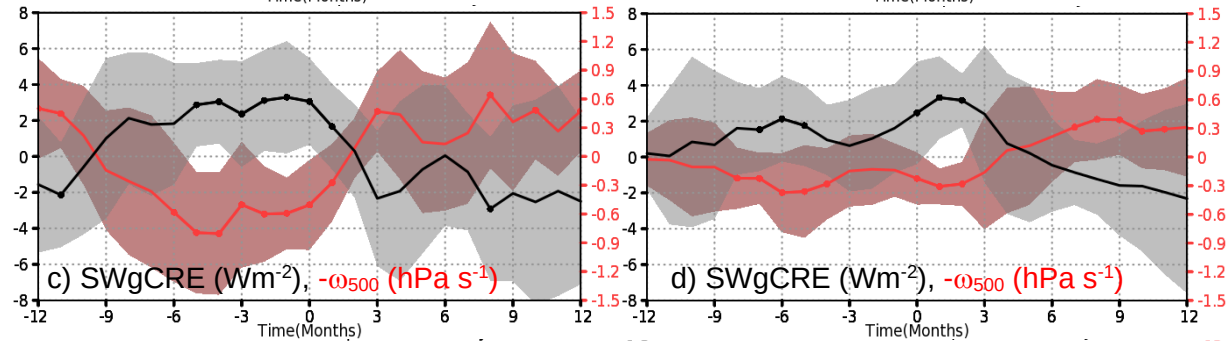
Australia Composite El Niño Anomaly

MERRA-2 M2AMIP

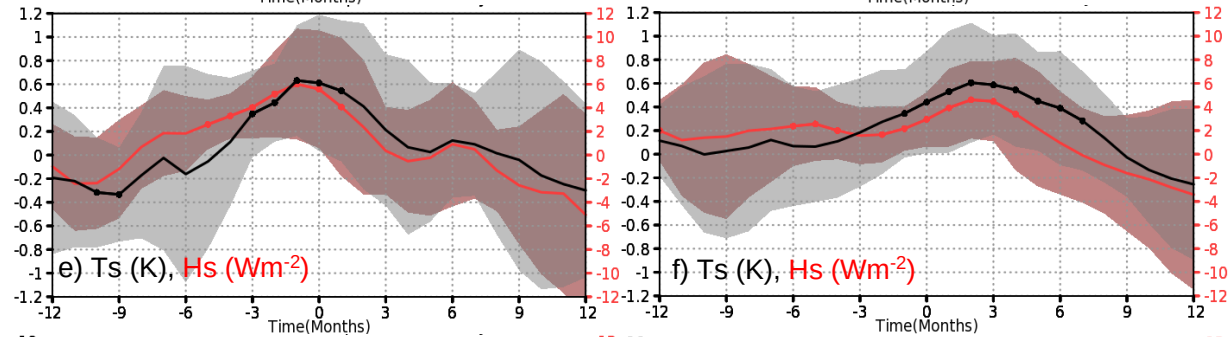
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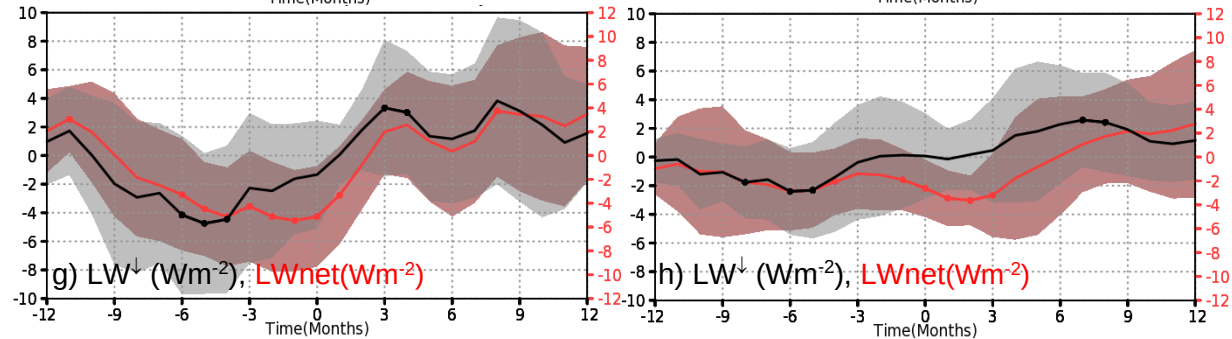


Figure 12 Australia (land only) composite El Niño anomaly time series for MERRA-2 (left) and M2AMIP (right) for several key quantities. Vertical velocity ($-\omega_{500}$) is directed positive for upward motion, determined at the 500hPa level. The solid line indicates the composite average and shading indicates ± 1 standard deviation. Red dashed lines in the top row indicate the 500mb Temperature (T500). Scales are color coded for each line. Dots indicate anomalies significantly different from zero (at 90% confidence).

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Australia Composite El Niño Anomaly

MERRA-2

M2AMIP

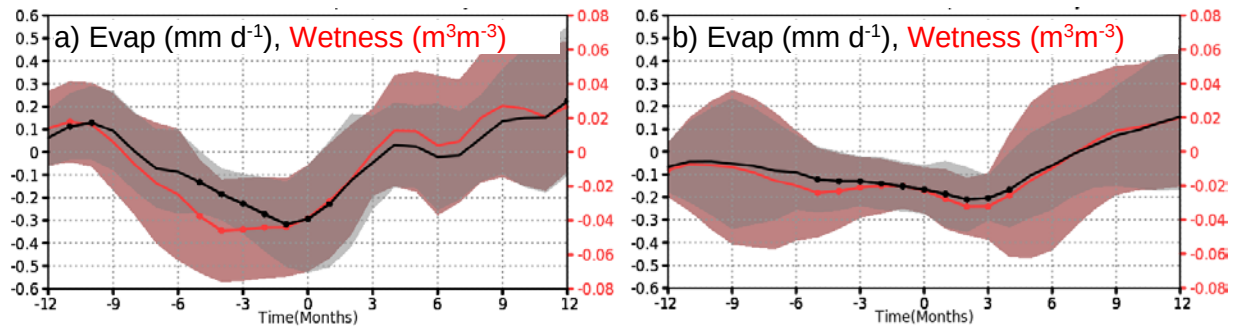


Figure 13 Australia (land only) composite El Niño anomaly time series for MERRA-2 (left) and M2AMIP (right) for evaporation (black, mm day⁻¹) and surface soil wetness (red, m³ m⁻³). The solid line indicates the composite average and shading indicates ± 1 standard deviation. Scales are color coded for each line. Dots indicate anomalies significantly different from zero (at 90% confidence).

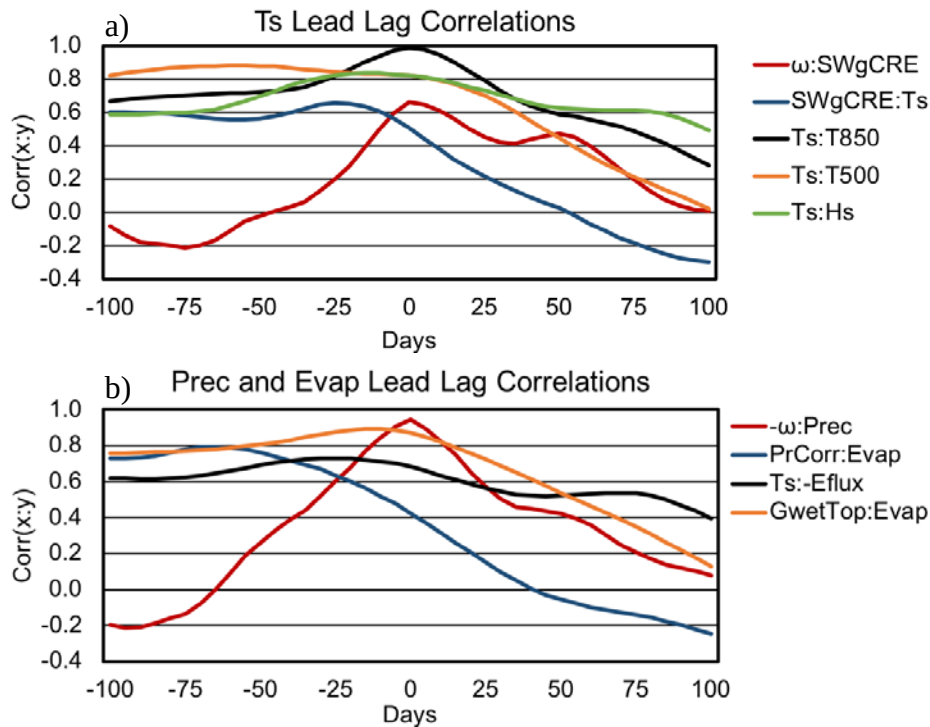


Figure 14 Tropical land global monsoon region lead lag correlations for a) surface temperature variables and b) water cycle variables. The correlations are developed by from the MERRA-2 pentad time series, with leading correlations as negative days and lag correlations are positive days for pairs of variables $x:y$, where the first variable (x) is computed as leading or lagging the second variable (y). Correlation units are dimensionless, and the values are computed over 101 data points (8 months of pentads) and values of 0.26 are significant at 99% confidence. Here, 0 days refers to contemporaneous correlation of pentads, not the $M=0$ El Niño peak.

MERRA-2 Tropical Pentad Composite El Niño Anomaly

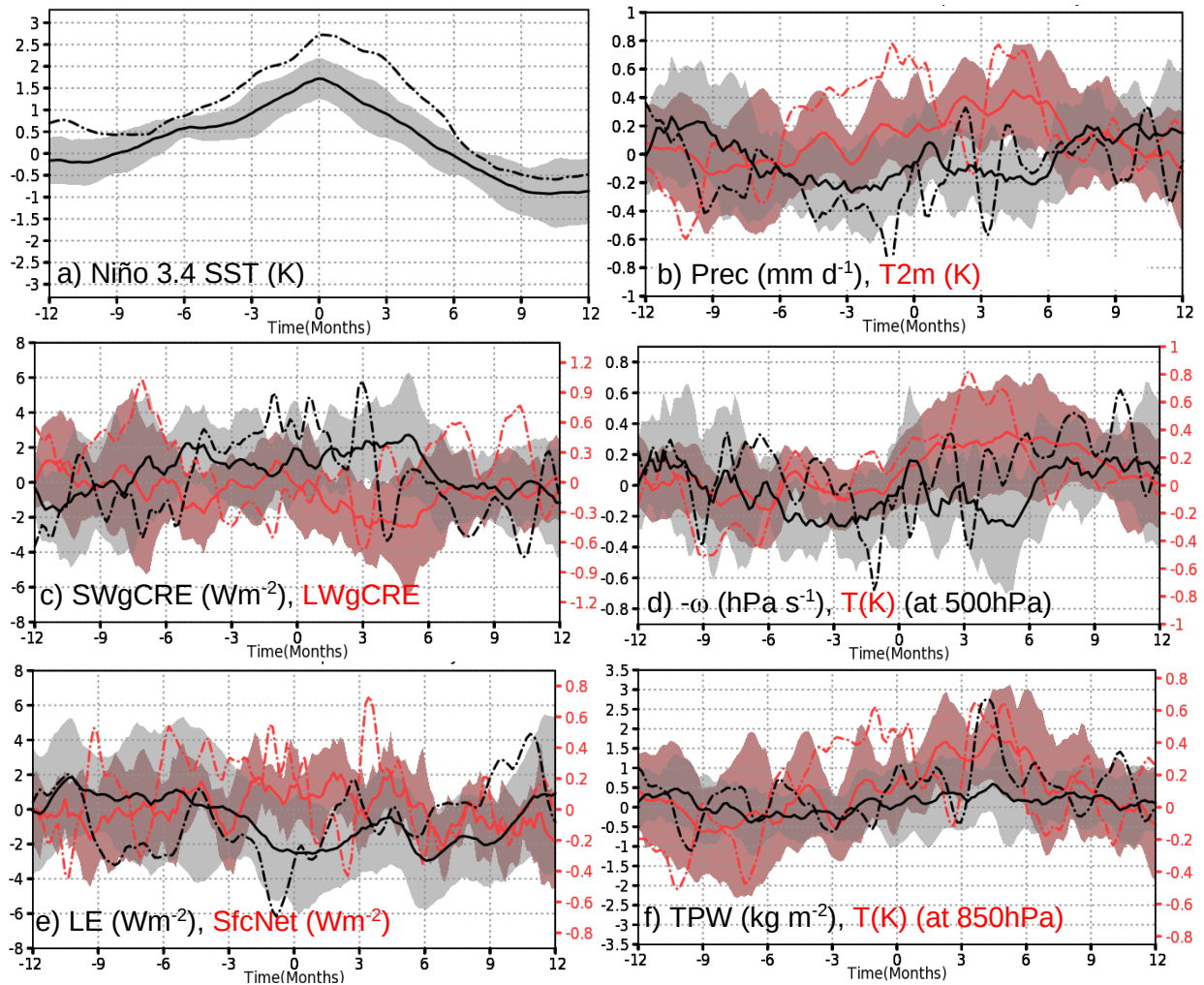


Figure 15 The Niño 3.4 region SST composite with the 2015-16 event is presented in panel (a). Tropical land global monsoon regions composite El Niño (b-f) for the MERRA-2 pentad time series (solid lines with shaded ensemble standard deviation) compared to the 2015-2016 El Niño (dashed line) for several key quantities (where LE is surface latent heat, SfcNet is the net flux of energy into the surface and TPW is total precipitable water). Black variables are scaled on the left axis and red variables are scaled on the right axis.

MERRA-2 Tropical Pentad Composite El Niño Anomaly
South America, Africa, Tropical South Asia and Australia

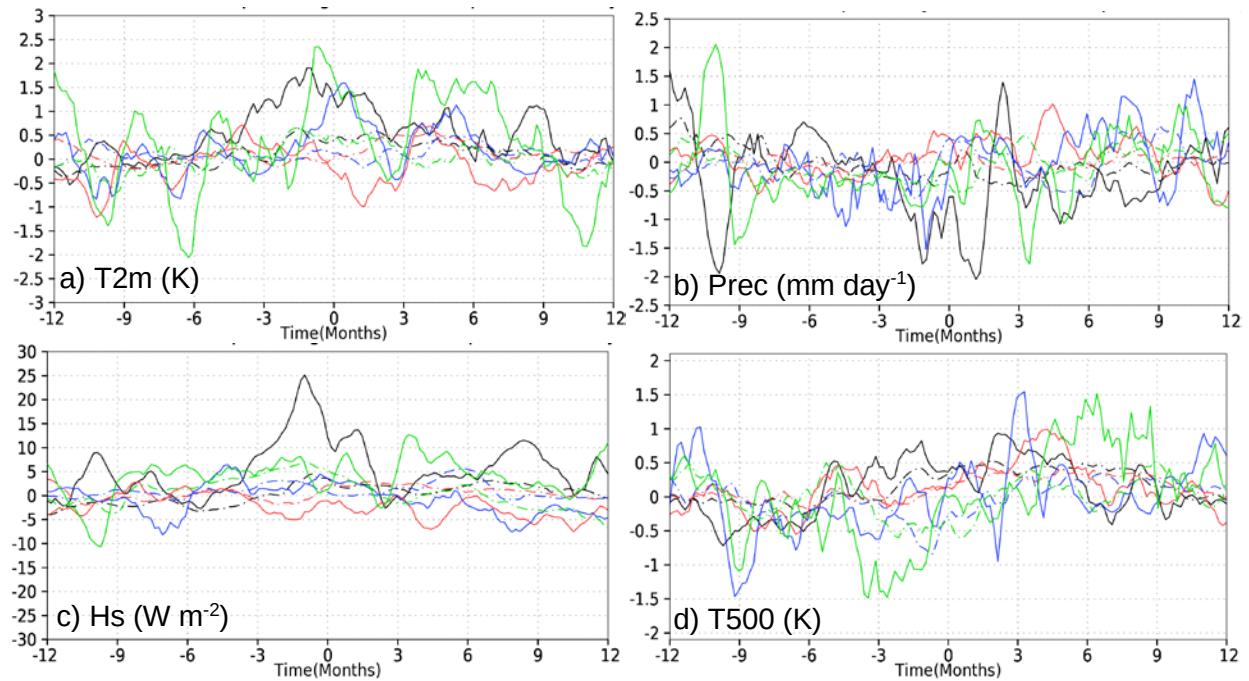


Figure 16 Tropical land regions composite El Niño for the MERRA-2 pentad time series (dashed lines) compared to the 2015-2016 El Niño (solid lines) for 2m air temperature (a, T2m), modeled precipitation (b, Prec), surface sensible heat (c, Hs) and mid-tropospheric temperature at 500 hPa (d, T500) over the main tropical regions (colors match the those in the figure title). The Australia region is for the whole continent, while the other regions are for the global monsoon areas of the respective regions.