Evaluation of the diurnal cycle of precipitation, surface thermodynamics, and surface fluxes in the ECMWF model using LBA data

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[1] The mean diurnal cycle of precipitation, near-surface thermodynamics and surface fluxes from short-term forecasts of the ECMWF model are compared with corresponding observations from the Large-Scale Biosphere-Atmosphere Experiment in the Amazonia wet season campaign in 1999 in Rondônia. Precipitation starts about 2 hours after sunrise in the model, several hours earlier than observed, because the model does not simulate well the morning growth of the nonprecipitating convective boundary layer. However, the mean daily precipitation during the wet season compares well with observed rainfall. On most days, maximum early afternoon temperature and cloud base height are lower in the model than observed. Maximum equivalent potential temperature is close to that observed. The model surface evaporative fraction is higher than observed and rises to near unity in the late afternoon. Work is in progress to evaluate and integrate the parameterizations for shallow and deep convection. *INDEX TERMS:* 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3314 Meteorology and Atmospheric Dynamics: Convective processes; 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; *KEYWORDS:* convective parameterization, precipitation, diurnal cycle, Amazonia.

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1. Introduction

[2] The Wet Season Atmospheric Mesoscale Campaign (WETAMC) of the Large-Scale Biosphere-Atmosphere (LBA) Experiment in Amazonia in January and February 1999 afforded an excellent opportunity to study the diurnal cycle of convection over land in the deep tropics [*Silva Dias et al.*, 2002]. Surface mesonet sites and flux towers measured the diurnal thermodynamic cycle and the surface energy balance, while tethered balloons and rawinsondes probed the atmosphere above. For ground validation of the Tropical Rainfall Measuring Mission (TRMM) satellite, two Doppler radars mapped the structure of evolving convective systems, and four rain gage networks were installed within the scan of the ground radars [*Rutledge et al.*, 2000]. Since the European Centre for Medium-Range Weather Forecasts (ECMWF) was closely monitoring the experiment, we took the opportunity to evaluate the surface thermodynamic cycle and diurnal cycle of precipitation in the ECMWF forecast system, using both the model operational at that time and the current operational model, which has a new land-surface scheme [*Van den Hurk et al.*, 2000]. Earlier studies over the Mississippi basin had shown that the ECMWF model, used in the Centre's first reanalysis [*Gibson et al.*, 1997], had deficiencies in the diurnal cycle of precipitation (it rained too early in the day), although the daily precipitation totals had only a slight high bias [*Betts et al.*, 1998, 1999]. In this paper we shall show a similar diurnal error over land in the tropics. Precipitation starts in the model only about 2 hours after sunrise, and it is clear from the LBA observations that this is because the morning growth of the convective boundary layer (CBL), which delays the onset of convective precipitation over the Amazon till near local noon, is not modeled correctly.

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2. Data and Model Products

2.1. Data Used

[3] The data for this comparison were collected at a pasture site located near Ouro Preto d'Oeste, Rondônia, Brazil (10.75°S, 62.37°W; about 30 km northwest of Ji-Parana) during the wet season months of January and February 1999 as part of the LBA/TRMM/WETAMC campaign. The site is part of a large deforested area (>250 km^2) dominated by a short grass (*Brachiaria brizantha*) with isolated palm and hardwood trees scattered throughout the landscape. At this site a micromet tower, eddy correlation instrumentation, and a gas analyzer measured the surface meteorology and energy balance components. For the comparison here we use hourly averaged data from the analysis of *Betts et al.*, [2002]. A tethered balloon system and a rawinsonde measured profiles up through the CBL and atmosphere, while the structure of the convection nearby was mapped by two Doppler radars [*Rutledge et al.*,

Table 1. Surface Diurnal Composites

Composite Name	Days Included (UTC)	Mean Daily Observed	Precipitation (mm), ECMWF Model
1, East 20°–28°	20–28	5.7	8.5
2, West 29°–38°	29–38	6.9	4.9
3, East 39°–52°	39–52	7.5	7.3
4, West 53°–59°	53–59	10.1	10.7
5, WET-8 days	20, 24, 30, 31, 38, 42, 44, 48 (afternoon rainband)	8.9	8.4
All days	20–59	7.4	7.6

2000; *Rickenbach et al.*, 2002; *Cifelli et al.*, 2002]. The estimates of precipitation that we shall use here come from averaging the four rain gage networks, which were established to help calibrate the TRMM radars [*Rickenbach et al.*, 2002]. These four networks were in a northwest to southeast line with the nearest group ~25 km east of the pasture site. Representative precipitation estimates are notoriously difficult, and we use these rain gage networks until the precipitation analyses of the TRMM science team are complete.

2.2. Model Simulations

[4] The model outputs used for comparison were 12- to 36-hour short-range forecasts, run at a triangular truncation of T319 and a vertical resolution of 60 levels, from each daily 1200 (UTC) analysis. The forecast model was the operational ECMWF model in the fall of 2000, which includes the tiled land-surface scheme (TESSEL) [*Van den Hurk et al.*, 2000] and recent revisions to the convection, radiation, and cloud schemes described by *Gregory et al.*, [2000]. The analyses were from the operational model in early 1999, which included the earlier land-surface model of *Viterbo and Beljaars* [1995]. We also made, however, the comparison using forecasts using the 1999 operational model and found the results were not substantially different, so we only present here the comparison from forecasts with the more recent land surface scheme. Model data were extracted every time step at the model grid point in Rondônia (10.85°S, 61.87°W) closest to the field measurement site (10.75°S, 62.37°W), which we shall hereinafter refer to as the Abracos pasture site (after a previous field experiment there with that name). This specific model grid point has 76% tall vegetation (evergreen broadleaf trees) and 24% low vegetation (tall grass), which is a lower percent of grass than in the region close to the pasture site. However, during the rainy season, the surface fluxes are similar over pasture and forest.

3. Results

3.1. Composites by Lower Tropospheric Wind Regime

[5] Composites are useful for the comparison between model and surface observations as they average over several days and the individual small-scale convective events within them and give a picture of the mean diurnal cycle, more representative perhaps of the 60×60 km grid square used in this global forecast model. We group the 40 days (from day of year 20 to 59) for which we have data at the pasture site, into the five groups shown in Table 1. The first four groups correspond to the surface easterly and westerly regimes in the analysis of *Rickenbach et al.* [2002]. The fifth group is a composite of eight selected days, when a strong rainband passed directly over the measurement site in the mid-afternoon. We show this as a separate group, since strong convective downdrafts in the afternoon produce such a distinct modification to the diurnal cycle, in order to see whether this feature is reproduced in the model. Columns 3 and 4 compare the mean daily observed and model precipitation. Daily "observed" precipitation was defined by first taking the mean of the TRMM rain gages in four networks and then averaging these four means [see *Betts et al.*, 2002]. This basic grouping by the sequence of lower tropospheric easterly and westerly components also represents a time progression of the rainy season. For the entire 40-day period (column 4) the mean daily precipitation for the TRMM rain gage networks is 7.4 mm, in close agreement with the model's 7.6 mm. However, the model does not reproduce well the increasing temporal trend of precipitation of the first four composites, and on a daily basis, the correlation between model and rain gage observations is poor (not shown).

3.2. Diurnal Cycle of Precipitation

[6] Despite reasonable agreement in mean precipitation during the rainy season, the current ECMWF model has a clear error in its diurnal cycle of precipitation over Rondônia, as shown in Figure 1 (left). This first composite is color-coded with easterly (in red) or westerly (in green) winds in the lower troposphere, and the group of days (in blue) when a convective rainband passed over the site in the afternoon (about 1400 (LST), i.e., 1800 UTC). On the left is the current ECMWF model using TESSEL as its land-surface model and a convective available potential energy closure for deep convection [*Gregory et al.*, 2000]. Every model composite has a rainfall peak just after 1200 UTC, ~2 hours after sunrise, which is not observed in any of the composites on the right, derived from an average of four TRMM rain gage network networks in Rondônia. Most days have afternoon rainfall maxima, some have rain also at night, while all have a rainfall minimum in the morning for the period 1200–1400 UTC (0800–1000 LST). This is also the time when the TRMM radars show a minimum in both fractional rain area and conditional rain intensity [*Rickenbach et al.*, 2002]. We will discuss in section 4 the reasons why the model convective parameterizations produce a precipitation maximum in the morning at a time when, in reality, rainfall is a minimum. The model produces a secondary rainfall maximum in late afternoon. For the WET-8 rainband composite this peak is slightly higher than for the other composites, consistent with the observations (although the model peak is later in time and broader). For the last westerly composite (53–59) the model is consistent with the data in having a weaker diurnal cycle of precipitation, including more precipitation at night.

[7] This diurnal precipitation structure is a large-scale feature of the model over the Amazon region. Figure 1 (lower panels) shows the deviation of 6-hour averages of precipitation from the daily total taken from 24- to 48-hour forecasts with the operational model for 1–7 February 1999. The four panels show the rainfall anomaly from the 7-day all-day average for

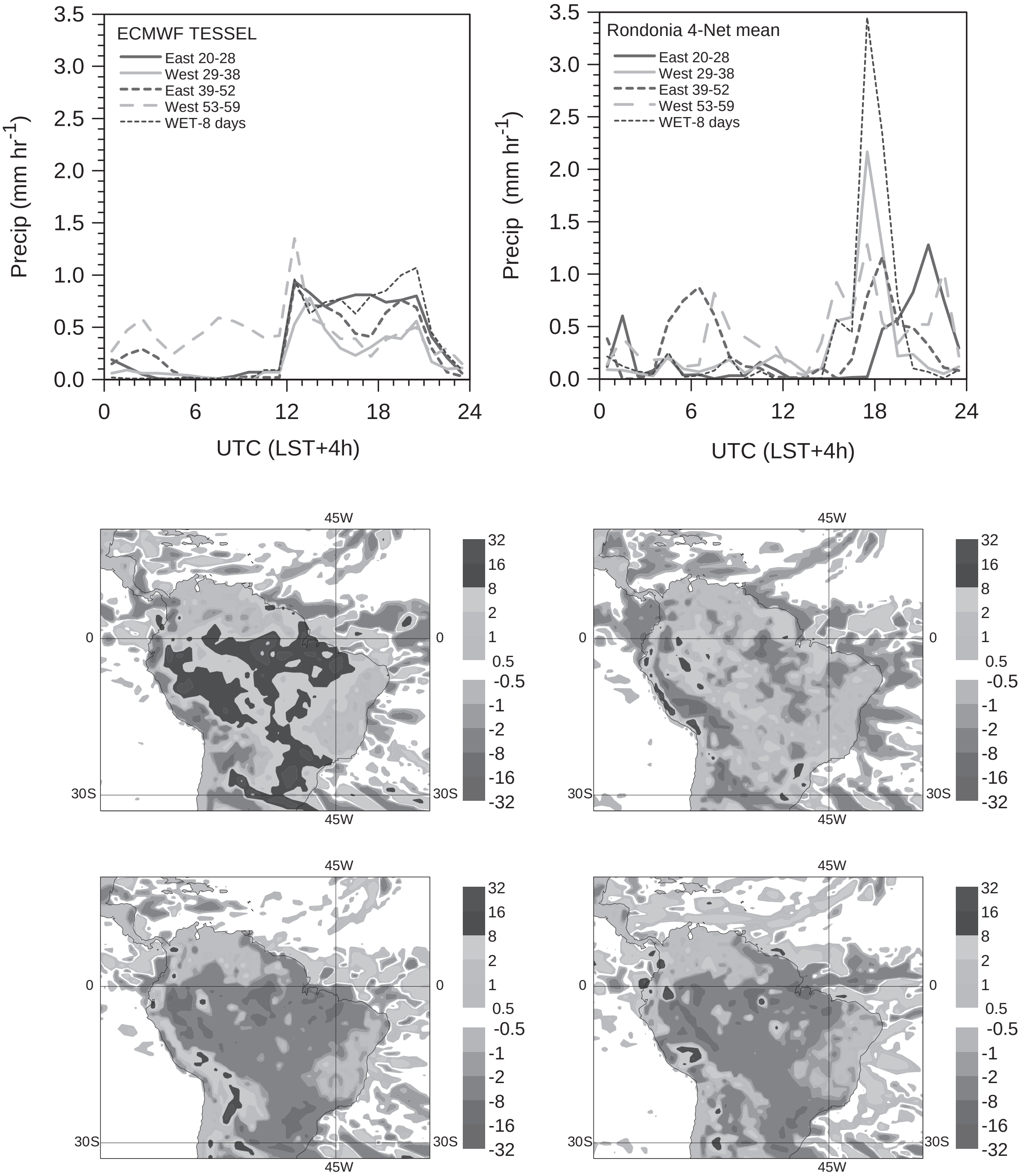

Figure 1. (top left) Mean diurnal cycle of precipitation over Rondônia for five convective classifications for current ECMWF model; (top right) observed mean diurnal cycle of precipitation over Rondônia, an average of four rain gage networks. (lower panels) Diurnal cycle of precipitation anomaly from daily total over South America from operational ECMWF model for 1–7 February 1999. Shown are the 6-hour averages from 1200–1800 UTC (8–14 LST (center left), 1800-0000 UTC (center right), 0000–0600 UTC (bottom left), 0600–1200 UTC (bottom right). The units are mm d^{-1}. See color version of this figure at back of this issue.

rainfall occurring between 1200–1800 UTC (8–14 LST, center left), 1800–0000 UTC (center right), 0000–0600 UTC (bottom left), and 0600–1200 UTC (bottom right). The units are mm d^{-1}. Observations [e.g., *Negri et al.*, 2002] suggest that the relative maximum of precipitation should occur in the local afternoon (i.e., 1800–0000 UTC), while the model exhibits a strong maximum earlier than that in the 1200–1800 UTC period. It is probable that this type of model behavior will influence the large-scale dynamics of the model in the tropics.

3.3. Comparison of Surface Thermodynamic Cycle

[8] Figure 2 compares the mean surface thermodynamic cycles of potential temperature θ, mixing ratio q, equivalent

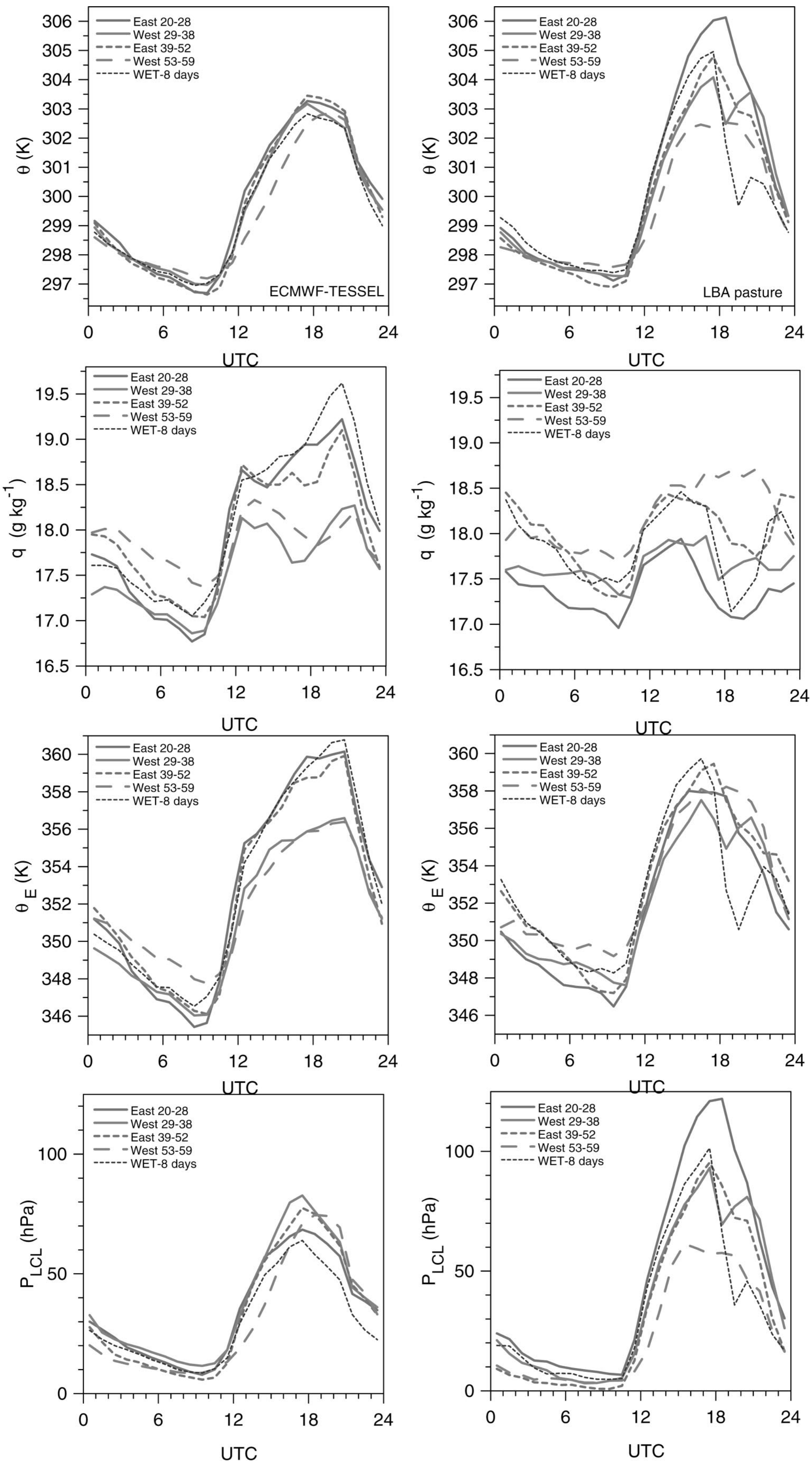

Figure 2. Comparison of surface thermodynamic cycle in ECMWF model (left) with LBA pasture site (right). See color version of this figure at back of this issue.

potential temperature θ_E, and pressure height to the lifting condensation level P_{LCL}, between the ECMWF model on the left and the pasture site observations on the right. Overall, the model biases are rather small, typically cooler and wetter in the daytime. As a result, the model has a lower mean P_{LCL}, corresponding to a lower mean cloud base, and rather little bias in mean θ_E. In the model the earlier onset of precipitation in the diurnal cycle is producing a cooler and moister boundary layer (BL) in the daytime by the evaporation of falling precipitation. A distinct break in the model diurnal cycle can be seen, particularly in q and θ_E profiles, at 1200 UTC with the onset of rain. Unlike the data, the model shows little variability in maximum temperature. The model does show some differences in the q structure between easterly and westerly wind regimes (although the convective parameterizations are not directly aware of wind shear). The easterly regimes are wetter, with a higher afternoon θ_E than the westerly regimes, and do not show a morning fall of q. However, this is not in agreement with the observations, which show the morning fall of q for the easterly regime and mean q increasing from beginning to end of the period (consistent with the mean precipitation increase). The θ_E comparison of the WET-8 rainband composite shows that the model does not represent the unsaturated downdraft process, which brings low θ_E air down to the surface. Unlike the downward spike in the data at the time of the rainfall maximum, the model has a θ_E maximum at the time of its rainfall maximum, which is later at 2000 UTC. The P_{LCL} comparison shows a much larger variation in the data, with the model resembling most closely the low-cloud-base case of the last westerly regime, which has more frequent weaker showers and the weakest diurnal cycle of rainfall. It is clear that the mechanisms, by which the model convective parameterizations for shallow and deep convection are producing precipitation and modifying the BL, while they produce a plausible diurnal cycle of cloud base and θ_E, do not reproduce in detail the variability observed over Rondônia in these composites. The morning onset of precipitation is too early, which truncates the growth of the shallow cumulus BL, and the unsaturated downdraft process seems largely missing. It seems likely that improving the diurnal evolution of the CBL, so that the morning transition to deep convection is delayed, may significantly improve the model over land in the tropics.

3.4. Comparison of Surface Fluxes

[9] Figure 3 compares the surface energy balance for the ECMWF model (on left) for the five composites with that measured by an eddy flux tower at the LBA pasture site [*Betts et al.*, 2002]. For the last westerly composite (long dashed), only 3 days of data are available at the tower, so the comparison is not exact. The net radiation (R_n) in the model is slightly higher in the model and has noticeable jumps every 3 hours. This is a model artifact. The cloud field, although it is computed at every time step, is only updated every 3 hours in the shortwave calculation (where it plays a major role in determining the incoming shortwave). All composites are similar in R_n, except for the last West 53–59 composite, which has more cloud cover. This suggests the model cloud cover is less variable than observed. The latent heat flux (LE) in the model is higher than observed, and the sensible heat flux (H) a little lower than observed, giving a higher evaporative fraction (see section 3.5). The ground flux in the model is similar to that observed, although somewhat discontinuous every 3 hours, when the cloud field is updated in the radiation calculation.

3.5. Surface Evaporative Fraction

[10] We define evaporative fraction as EF = LE/(LE + H). Figure 4 shows the daytime diurnal cycle for the model, and observations are quite different. The flux tower observations are quite flat in EF, and symmetrical about local noon with a value in the range 0.7–0.75, typical of grassland with high soil moisture in both tropics [*Garstang and Fitzgarrald*, 1999] and midlatitudes [*Kim and Verma*, 1990; *Betts and Ball*, 1995]. This implies decreasing surface conductance in the afternoon, as observed in Rondônia at both forest and pasture sites [*Wright et al.*, 1996]. The model, however, has a somewhat higher EF around 0.8 in the morning (local noon is near 1600 UTC) and then climbs steadily toward 1.0 before sunset. This suggests the model surface conductance is higher than observed and does not decrease in the afternoon, or perhaps that there is too much evaporation from the model surface water reservoir, which is itself large because the model grid point has a high percent of forest. The jump in model EF at 1800 UTC is consistent with the sharp fall of R_n, when the cloud field is updated.

4. Discussion and Conclusions

[11] These comparisons raise more questions than we can as yet answer. Our motivation was to understand in more detail (and then correct) the error in the diurnal cycle of precipitation seen in Figure 1 (left). We have made some progress in understanding the early onset of precipitation in the model. The diurnal evolution of the tropical BL involves the tight interaction of many processes. At dawn the layer near the surface is generally saturated and stabilized by precipitation late in the previous day and by radiative cooling at night [see *Betts et al.*, 2002]. The surface sensible and latent heat fluxes are trapped initially in a shallow stable layer less than 400 m deep, and so initially, θ and q rise rapidly in a shallow growing mixed layer. This process is reasonably represented in the model, but only 2 hours after sunrise, model representation and reality separate. At the Abracos pasture site, a shallow cumulus layer deepens rapidly once the nocturnal BL is penetrated, since the atmosphere above 950 hPa is conditionally very unstable and transports the large surface evaporation up and out of the subcloud layer. In the easterly wind regimes, mixed layer q even starts to fall around 1300–1400 UTC (0900–1000 LST) as a result of this upward transport of moisture into nonprecipitating clouds (*Betts et al.* [2001] and Figure 3). The developing cumulus grow deep enough to produce the first radar echoes about 1500 UTC (1100 LST), and the first showers often form near local noon. Organized convective bands typically take till around 1800 UTC (1400 LST) to develop in this Rondônia region [*Silva Dias et al.*, 2002]. The model convective parameterizations do not describe this growing cumulus BL stage at all well. In fact, as soon as the surface heating in the model breaks though the nocturnal BL ~2 hours after sunrise, the deep convective parameterization "sees" the deep conditionally unstable atmosphere, calculates a convective cloud top in the upper troposphere, and produces convective rain (see Figure 1 (left)), computing a timescale for the process from a CAPE (convective available potential energy) closure. Although the shallow cloud parameterization (which has its own closure, based on moist static energy balance in the subcloud layer in a single time step) is activated intermittently, most of the morning a growing shallow cumulus BL phase is by-passed in the model. We note that calculating cloud top, or

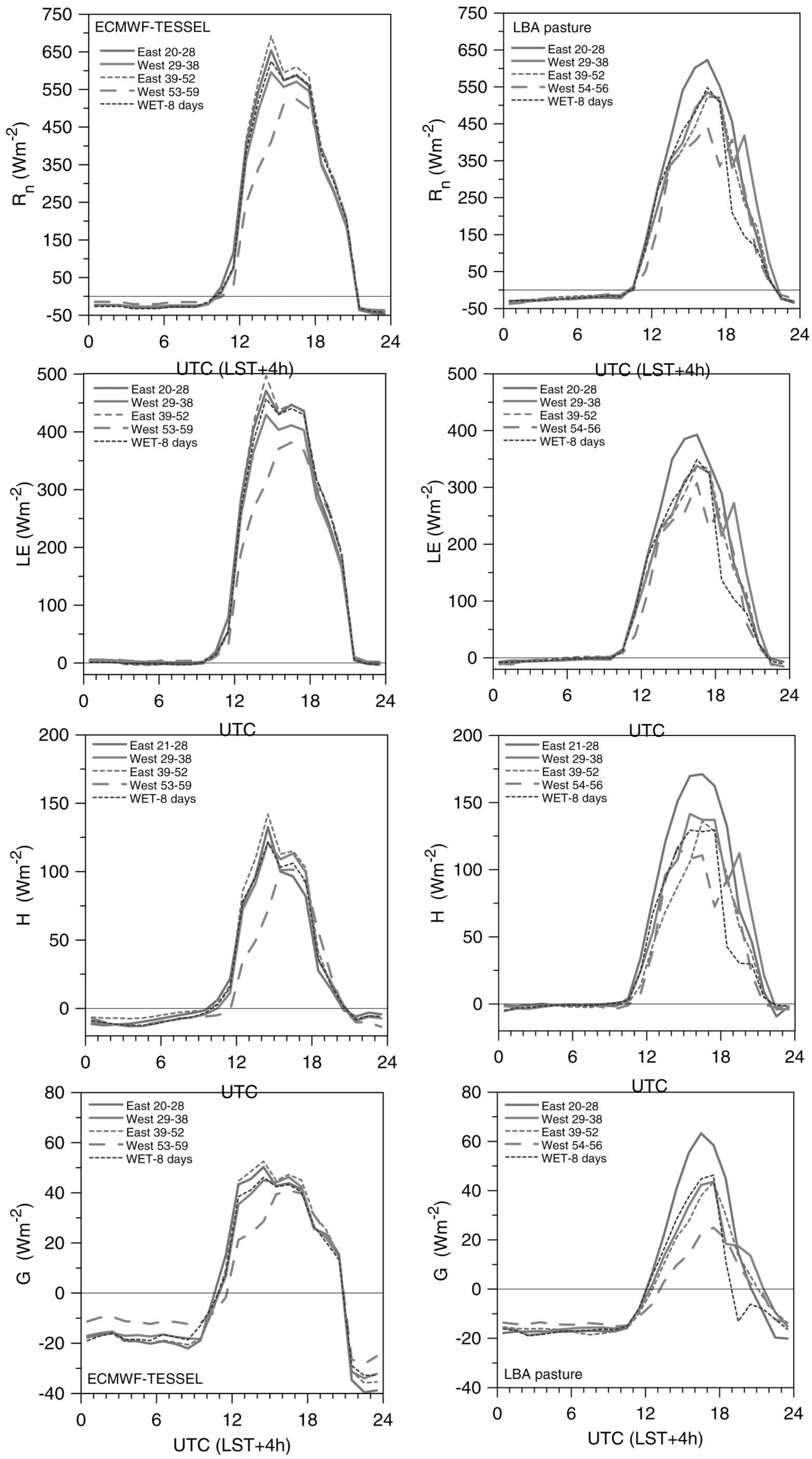

Figure 3. Comparison of surface fluxes in ECMWF model (left) with LBA pasture site (right). See color version of this figure at back of this issue.

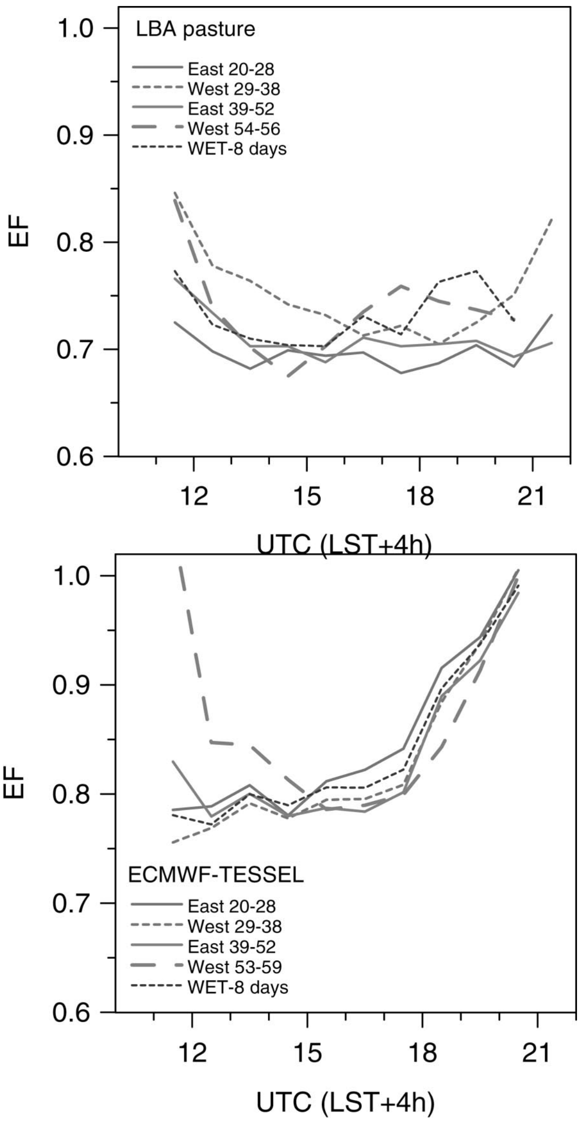

Figure 4. Daytime evaporative fraction for composites, observed and in ECMWF model. See color version of this figure at back of this issue.

the depth of the CBL, during this morning growth phase is a challenging problem in a numerical model, as the tropical atmosphere over Rondônia in the rainy season is so conditionally unstable from 900 to 600 hPa. The reason is that unless there is a strong inversion as in the trade winds, the depth of the CBL, as it evolves, is determined by mixing or entrainment processes between the clouds and their surroundings. As yet, no suitable general formulation of this entrainment process has been found, which will give the depth of the growing CBL in the very unstable atmosphere of the tropics over land. It seems clear also that most large-scale models, including the ECMWF model, are deficient in the way they separate convection and clouds into separate parameterizations. Rather than the continuum of convection seen in nature, in the model the growing convective BL is broken into a dry convective process and a shallow cloud process; and furthermore, shallow and deep convection are computed with two separate parameterizations with distinct closures.

[12] The near-surface diurnal cycle of the thermodynamic variables and the surface fluxes are influenced by the evaporation of falling precipitation, which occurs too early in the model. Cloud-base and near-surface temperature are lower than observed in the model in the early afternoon by about 1K and 20 hPa. These biases are, however, small by global model standards. Interestingly enough, the model comes within $\pm$2K of replicating the maximum afternoon θ_E observed of around 358 K, although there is no evidence that the model represents well the convective downdraft process, which can be seen to bring low θ_E air into the subcloud layer. The daytime diurnal cycle of mixing ratio in the model is within $\pm$0.5 g kg^{-1} of observations, which is also good for the moist tropical BL, although the detailed differences seen between the composites are not reproduced. The high bias of the model EF is probably influenced in the morning by the early precipitation. This fills the model surface water reservoir, which evaporates unimpeded by stomatal control. The afternoon rise of EF implies that the model does not reproduce the afternoon fall of surface conductance that has been deduced from observations.

[13] The infrequent update of the cloud fields in the radiation calculation is causing some discontinuities at time steps every 3 hours, which can be seen in the surface fluxes. Even the onset of precipitation after 1200 UTC appears influenced by the rapid rise of θ_E at this time step, when the net radiation jumps. A simple solution, with some computational cost, is more frequent cloud updates.

[14] We conclude that although the model diurnal cycle of the near-surface thermodynamics is quite close to that observed, it is being produced in the model by a different mix of boundary layer and surface processes, primarily more rainfall evaporation and less shallow cumulus convection than is generally observed. Consequently, the model diurnal cycle most closely resembles the westerly wind regime in late February, when showers were more frequent. It is our belief that the LBA will provide us with the data sets to systematically improve and unify the model convective parameterizations, until they simulate reality more closely. We have begun an extensive exploration of the impact of changing different components in the ECMWF convection schemes, their closures and the sequence in which the schemes are called by the model, as a first step toward developing a more robust representation of tropical convection over land.

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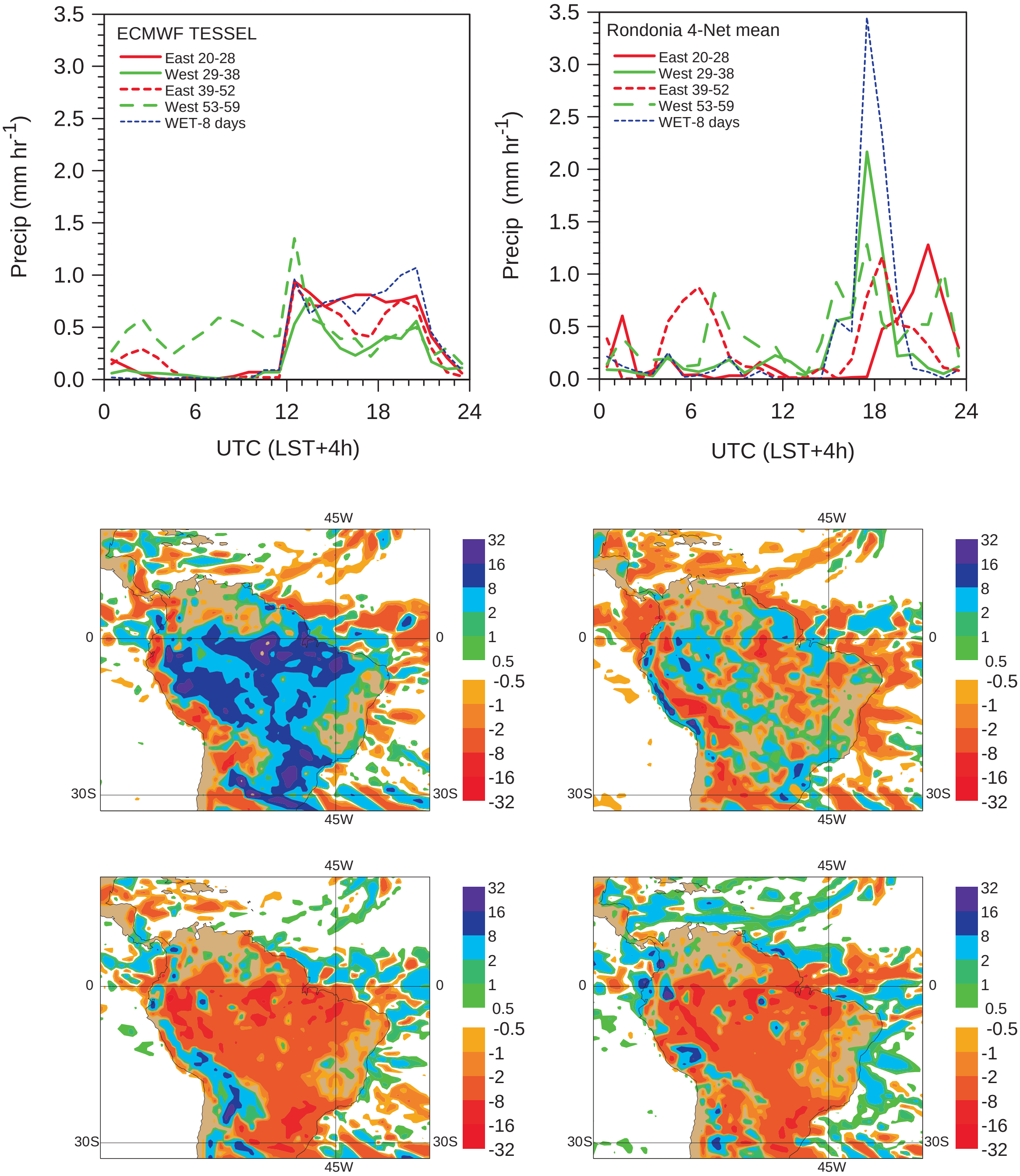

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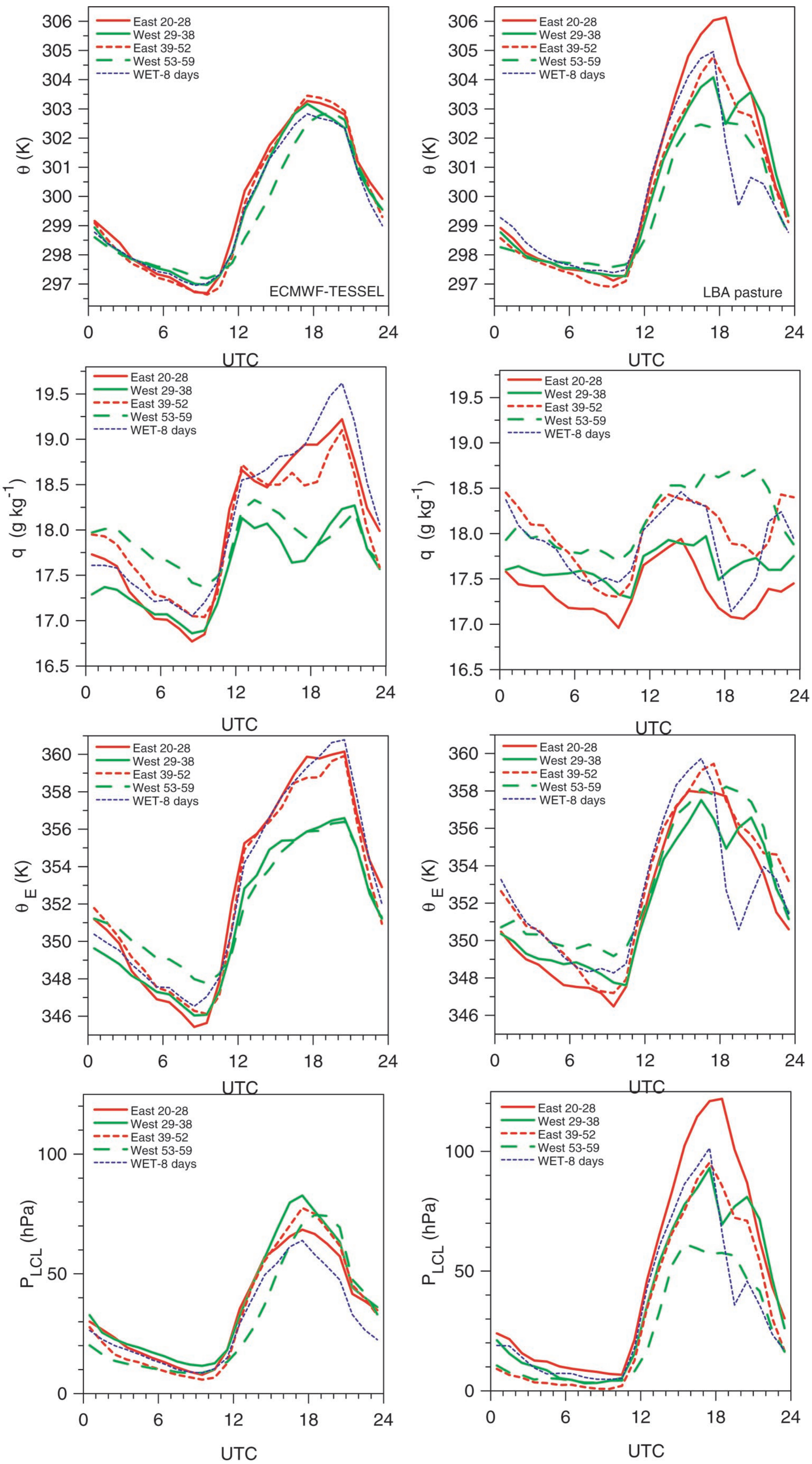

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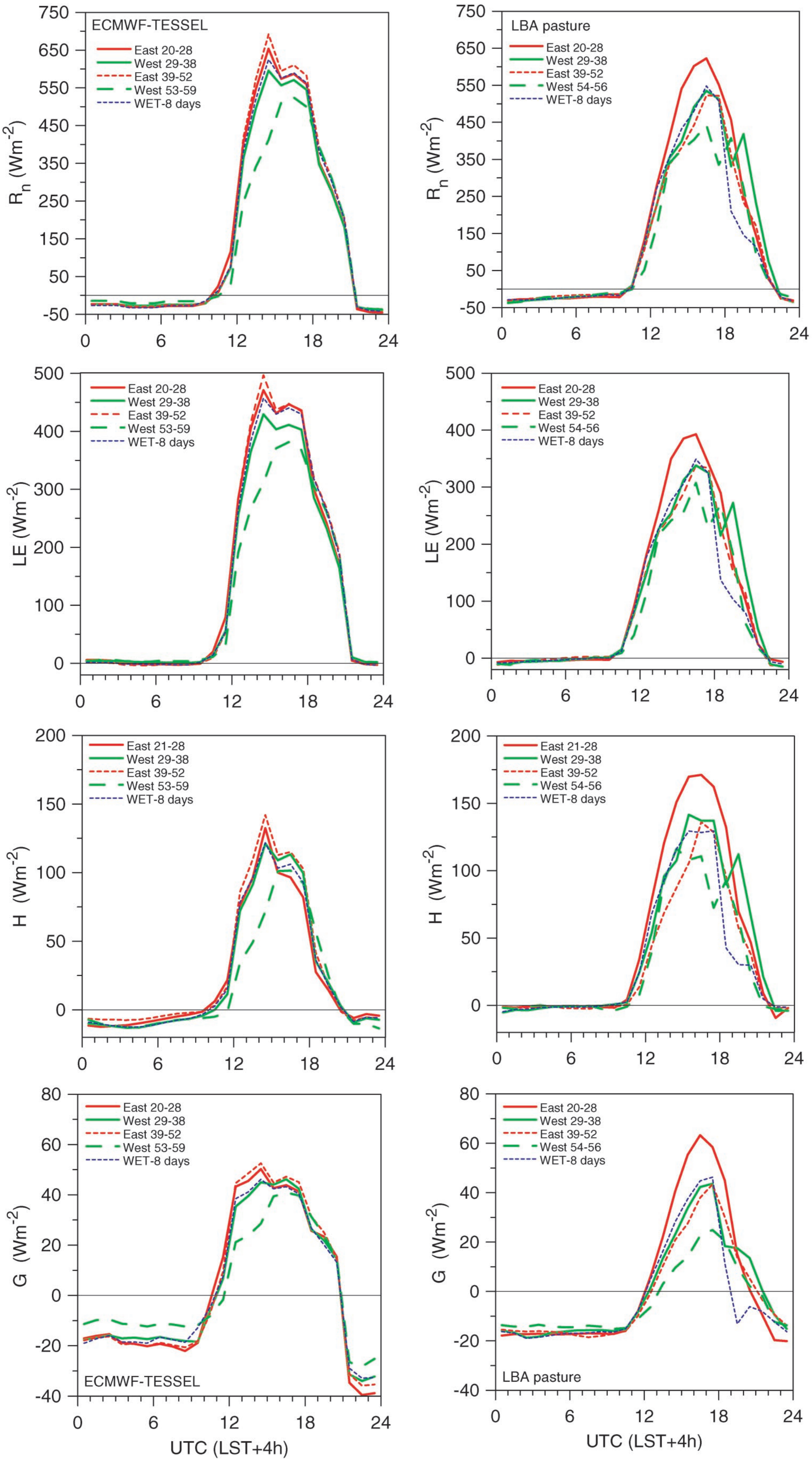

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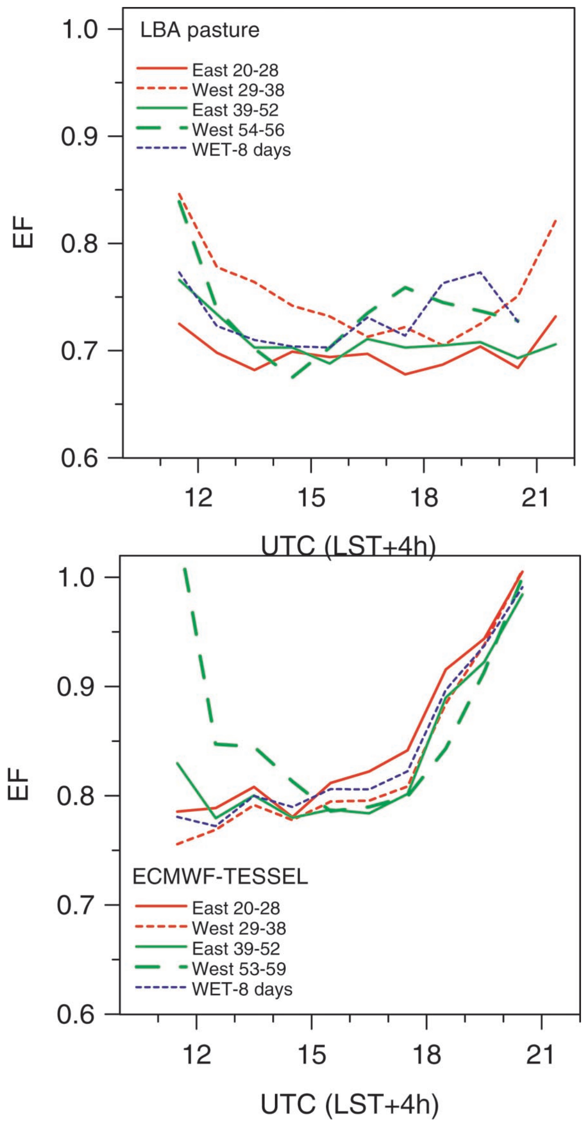

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