Interactive comment on **"Land–atmosphere interactions in the tropics"** ***by*** **Pierre Gentine et al.**

Anonymous Referee #1

Received and published: 17 March 2019

General comments:

The authors present a nice review of a topic that has not been properly reviewed before - the specific range of land-atmosphere interactions in the tropics. Most published work including reviews have focused on the subtropics and summertime mid-latitudes. This is a welcome addition to the literature. The topic will draw a diverse readership with different interests and expertise.

The authors need to be sure they are not jumping in at too technical a level or assuming too much foreknowledge of the readers. Also, the paper could use more homogenization in style and level of detail - it is clear that different authors wrote different parts. It needs to be made more even throughout.

Response: we thank the reviewer for the comment: we have now tried to homogenize the different paragraphs so that it would flow better.

In Sec 3.2 and later in Sec 5 the problem that LSMs have representing water stress and GPP should explicitly mention root access to groundwater / shallow water tables in tropical lowlands and plains - a process that is not present in most models with their very shallow soils. This is hinted at, but there should be explicit statement regarding the link between tropical phenology and hydrology.

Response: Indeed, this is a very good comment, we now include a more complete discussion of this issue, in particular citing Maxwell and Condon 2016

Specific comments:

L133: A comma after "initiation"

Response: corrected

L195-196: The equivalence drawn between turbulent carbon fluxes and GPP needs a little explaining for non-expert readers.

Response: we have replaced this with carbon fluxes to avoid any confusion

L242: The work of Tawfik and colleagues (10.1002/2013GL057984, 10.1175/JHM-D- 14-0117.1, 10.1175/JHM-D-14-0118.1) is highly germane here as well.

Response: indeed, this is correct, and has been added (Tawfik et al., 2014, 2015a,b)

Figure 1: Please give the date and time of the image (a la Fig 14), and the domain (lon and lat range) - also a scale superimposed on the figure would be helpful to understand the size of the clouds.

Response: we could not find the same figure but extracted a similar figure from the earth observatory including the scale.

L250-259: I suggest this paragraph be reordered, grouping the density/buoyancy pro- cesses (thermals, radiative destabilization, cold pools) and references first, and then the dynamically forced vertical motions (circulations, wave activity).

Response: This is a good point of the reviewer. This paragraph has been modified accordingly. We have included cold pools in both thermodynamical and dynamical processes

L260-268: Propagating convection should also be mentioned here - I am thinking of work by Nieto-Ferreira and Rickenbach, for instance.

Response: this reference has now been added

L277: A glitch in the citation software for the Lintner reference.

Response: thank you this has now been corrected.

Figure 3 is not referenced anywhere - please remove.

Response: we now reference this Figure when discussing the weak temperature gradient

L326: "Section XX".

Response: there was an issue in the referencing, we have now replaced this by section 4.2

L338: Remove reference to Figures 4-8 - they do not correspond exactly to what is said in this sentence, and they get referenced properly later.

Response: these references have been removed

Figure 4: Need to explain that it is lambda*P that is shown, not P.

Response: indeed this is a good point: we now say: in units of energy (W/m^2, by multiplying it by the latent heat of vaporization)

Figures 5-10: These can be made easier to read. Please confine the zonal range to 95°W-165°E, stack the maps in 4 rows, instead of 2x2, so they are not so distorted, include the units prominently in caption, not just hidden in the Y axis label of panel e. Also, this paper clearly defines Tropics as within 15° latitude of the equator, but these maps stop around 12° - why?
Response: We have now modified the maps so they do not look as distorted
L374: This is misleading - the plot appears to have a steady annual cycle of precipitation because of the meridional averaging. There is in fact locally distinct seasonalities in precipitation in most locations - a point that is mentioned later. Please note here the effect of the meridional averaging.
Response: This is an excellent point, indeed we now add the fact that those are regional averages.
L405: I find the reference to "moist static energy flux" here and in Fig 10 to be clumsy. I know what the authors are trying to say. To my mind, MSE naturally includes the "gz" term. So this statement seems to include orographic forcing (upslope flows) which I believe is not the intention here as this is all locally calculated neglecting horizontal motions over terrain.
Response: Here we are discussing the flux and not the state so that there should be no change due to gz when computed at a given level.
L428: This should be Fig 11, not Fig 3.
Response: corrected
L430-432: As phrased, this is not a sentence.
Response: this has been corrected to: "However, water is typically not limiting for low-canopy species, as relative humidity is high and VPD is low, leading to low stress on understory conductance"
Discussion of Fig 12: It is a nice figure, but it is not clear that moisture stress is essen- tially VPD - this can be clarified in the text. In fact, the whole discussion (L434 onward) is a bit circular and muddled - it could be said much more clearly and more succinctly.
Response: in fact, the moisture stress should not just be VPD but rather plant water status/water potential which reflects the interaction of hydraulics (typically not too limiting for tropical rainforest species as recently demonstrated by Liu et al., 2019) and VPD. This is now clarified in the text
Liu, H., Gleason, S. M., Hao, G., Hua, L., He, P., Goldstein, G., & Ye, Q. (2019). Hydraulic traits are coordinated with maximum plant height at the global scale. *Science Advances*, *5*(2), eaav1332. https://doi.org/10.1126/sciadv.aav1332
L479-480: The first reference should be to Dawson (1993; 10.1007/BF00317442) - his work was seminal.
Response: indeed, this is completely correct and has been added now
L484-486: Don't need to cite the same paper for each phrase. There are several places where the same references are repeated unnecessarily, sentence by sentence.
Response: Indeed, we have removed the reference to Kennedy et al, 2017
L502: Change "one" to "two".
Response: corrected
Figure 13 would benefit from a schematic diagram that illustrates the contrasts between wet and dry seasons.
Response: this is a good point from the reviewer. We now emphasize that this schematic was in the dry season. Wet season is more complicated (e.g. mesoscale convective systems).
L567: Change "inspired in" to "inspired by". L580: "aerosol" -> "aerosols"
L588: Change "is clear" to "are clear". L605: "out-weight" -> "outweigh"
L624: Change "i.e. Manaus" to "e.g., from Manaus". L625: "lighting" -> "lightning"
Response: those have all been corrected.
L647: Section number should be 4.1.
Response: there was an issue with the referencing. This has now been corrected.
Figure 14: Again, a scale would be a helpful addition.
Response: this has been corrected
Sec 4.1.1: This is a complete departure in style from the tone of the rest of the pa- per. The rest of the paper provides synopses and literature reviews on the various topics, but this is a singular specific conceptual model presented in detail and in vacuo. Spracken et al. (2012; 10.1038/nature11390), Makarieva et al (2013; 10.1175/JHM- D-12-0190.1) and Gimeno (2014; 10.1002/2014WR015477) come to mind as relevant publications

on this topic that could provide context - there are certainly others. But this section needs to be made to fit better with the rest of the manuscript.

Response: this section has been rewritten to better fit the rest of the paper.

Figure 15: The blue line looks about the same color as the black line - needs to be more distinct. And what is the dashed black line that cuts the corner around about x_c?

Response: this has been corrected

Sec 4.1.3: There is other relevant literature that informs this topic, e.g., Dirmeyer et al. (10.1175/JHM557.1; 10.1016/j.jhydrol.2008.11.016; 10.1175/JHM-D-13-053.1), Keys et al. (2012; 10.5194/bg-9-733-2012), Hoyos et al. (2018; 10.1007/s00382-017-3653- 6), to name a few. This section is relatively weak and terse compared to others - there is more than can be said for such a review.

Response: the reviewer is correct and this has been corrected and adjusted.

Figure 17 cited out of order, after Fig 18 - and the second occurrence of the word "continental" can be removed from the caption. L790: "west" -> "wet"

Response: those have been corrected

L806: "researches" -> "research"

Response: corrected

L873-: This is new material not discussed earlier - in fact, this mention of climate change responses seems tacked on as a means to exit the paper. It should probably be covered in the core of the manuscript if it is to be mentioned here.

Response: the conclusion has been rewritten

***Interactive comment on* "Land–atmosphere interactions in the tropics" *by* Pierre Gentine et al.**

Anonymous Referee #2

Received and published: 1 April 2019

Review of "Land-Atmosphere Interactions in the tropics"

The authors present new perspectives based on recent literature, emphasizing the role of surface radiation in biosphere-atmosphere interactions and the water cycle. This is a much needed shift in focus toward (shallower) clouds and aerosols and their coupling to the surface water balance. A central part of this coupling, and a focus of the review, is on transpiration and its connection to clouds and aerosols via surface radiation and photosynthesis. These are important yet often overlooked topics for a wide range of current research problems from Earth system modeling to monitoring changes in the water cycle. The review gives a balanced discussion of observations, theory, and mod- eling, including new techniques to constrain the photosynthesis-water cycle connection from observations. Thus I believe this review will be a valuable contribution.

Response: we thank the reviewer for the positive assessment of our manuscript.

There are some relatively minor edits and clarifications needed, along with a few sug gestions below.

Some of section 4 on WTG approximation could be put into a broader context as a way to study multiscale interactions by parameterizing the larger scales. The discussion of the literature on WTG certainly raises awareness of the challenges in linking the larger and smaller scales and provides a way to gain understanding. The motivation for think- ing about nonlocal coupling could be clarified slightly, since I don't think the authors are arguing for nonlocal coupling as being dominant over or even separate from the other. For feedbacks, it seems less clear a priori which scales should be most important for future change in the water cycle; and from a model development perspective, the un- known still centers largely on local or subgrid scale processes (e.g. the diurnal cycle of clouds), although the interactions of the 'nonlocal' and 'local' processes are certainly part of that unknown. It seems the challenge is to make progress on modeling the multiscale and multicomponent system, and in gaining some understanding (and ca- pability of observing) the overall behaviors of the complex system related to water cycle extremes. This sort of discussion would help wrap up the review in the conclusions.

Response: this is a good point from the reviewer. We now correct this in the conclusion and expand the discussion regarding key challenges.

Technical comments/clarifications:

133 their initiation [and] the role of surface [processes]

Response: a comma was missing

201 – A little more background on the WECANN product would be helpful, specifically what other observations it uses besides SIF in deriving the surface fluxes (if any).

Response: this has been corrected.

203 plausible interannual [variability]

Response: this has been corrected

231 'The distinction between shallow and deep convection remains elusive' - Elusive may not be the right word; perhaps 'imprecise', 'subjective', or 'contextual' would work better

Response: we replaced elusive by imprecise

277 Fix citation: {Lintner:2017gm}.

Response: this has been corrected

299 One key concept in tropical climate is the Weak Temperature Gradient (WTG) - This could be set up a bit more with another sentence or two, depending on page limits.
Response: we have better connected those sentences and the paragraph.
310 - “In addition it is relatively straightforward” - nec- essary?
Response: this has been corrected as indeed it is useless to say so
326 as discussed in Section XX.
Response: this has been corrected, there was incorrect referencing to the section
335 ‘upscale to larger scale.’ - Redundant?
Response: indeed, this has been removed
“In what follows, we evaluate climatologies of evapotranspiration” - Maybe give some idea of what the reader should expect to learn?
Response: We have extended this sentence by: “in order to understand the typical seasonal cycles of those carbon, energy and water fluxes across the continental tropics.”
Fig. 4 "over the wet part of the Amazon (top left), the Savanna region of Brazil (top right), " - Some readers may confuse the titles Amazon (wet) and Amazon (dry) for wet and dry seasons as opposed to regions. Perhaps replace with Amazon (rainforest) / Amazon (Savanna) or Amazon (rainforest) / Amazon (Cerrado), and then in the caption make the connection between those regions and wet vs dry climates.
Response: the figure legend has been corrected as indeed it was confusing
347 – Perhaps be more specific to ET components here “canopy evaporation (of inter- cepted rain)”
Response: this has been corrected as suggested
Fig. 5 Could you set the aspect ratio of the panels to make this less stretched out and easier to read? i.e., make the axes labels consistent and crop the ocean regions. I recommend stacking all the panels vertically so that panel 3 has the same longitude axis as the seasonal plots. That way we get a clear picture of how variable the SE Asian/Indonesian region is due to the topography (as noted in the text).
Response: yes we corrected this for all figures from Figure 5 to 10
Fig. 5 could be better integrated with the text - perhaps add references around line 367 ‘the topography and the distribution of island land masses leads to strong local variability [Fig. 5e]’
Response: yes we corrected, as suggested by the reviewer.
392-395 – “The seasonal pattern of ET resembles GPP...” - this section could use minor editing by breaking up the sentences and expanding to be more specific and clear.
Response: we have cut down this sentence and clarified it as: “Indeed, the seasonality reflects 1) the seasonality of water availability in drier, water-limited regions or 2) the seasonality of surface radiation in the wetter, more energy-limited portion of the Amazon.”
389 "regions (Figure 5). GPP is maximized during the wet season in South America, as GPP is" - The text moves on to GPP without much transition here; perhaps add a transition sentence.
Response: we now better introduce the sentence by adding: “Integrated over the entire tropical latitudinal band, precipitation is highest in DJF and MAM when the wet season extends over most of the Amazon and adjacent savanna regions (**Error! Reference source not found.**). This seasonal cycle of precipitation largely determines the seasonal cycle of GPP. GPP”
404 It would help to define “moist static energy flux” as LH+SH
Response: indeed we have added LE+H now

419 I assume references for ‘why do most contemporary land-surface models incorrectly represent the wettest rainforest GPP and ET...” are in the prior sections? If so it may help to add a link here to refer readers back to the introduction.
Response: we have now added a link to section 3.2 discussing those challenges
422 You may mean that capturing this accurately will require better understanding?
Response: we removed this sentence that was not adding much but adding more confusion
430 remove “because” in “because relative humidity is high...”
Response: this sentence has been corrected to: “water is typically not limiting for low-canopy species, as relative humidity is high and VPD is low”
454 “build up of water stress in the soil-plant continuum” - it may help to introduce the water potential terminology a bit earlier here, since it appears in the next paragraph anyway. That terminology may help to clarify this sentence.
Response: we have entirely rewritten this paragraph which was not clear.
476 Fix “also known as...
Response: corrected
476 Regarding midday depression, there are some references on this for tropical forests (Malhi et al., 1998; Williams et al., 1998; Harris et al., 2004).
Response: those references have been added
492 “We suggest that the most critical land-atmosphere feedbacks...” - It would help to specify this a bit, as to whether it is critical for understanding, addressing ESM water cycle deficiencies, modeling dynamic vegetation in a changing climate, etc. . .
Response: our focus here was to introduce the role of shallow clouds for this section. We have now toned down the sentence.
510 longwave cooling?
Response: this was not clear, we meant nighttime longwave cooling
512 generates dew or forms dew
Response: we removed this part of the sentence which was confusing
548 - “As such the radiation feedback. . . may systematically impact clearings and de- forested regions”. I suggest expanding and editing this sentence to reflect the three ideas it contains. The first is that transpiration is able to buffer the dry season effects in these regions, stabilizing ET, so that the feedback loop involving precipitation and ET is weakened. Thus, the impact of the dry season on ET (and hence clouds) is strongest in mesoscale clearings and deforested regions. In addition, the feedback of shallower clouds and surface radiation may be more important than the feedback of deeper clouds and precipitation.
Response: this is a good suggestion and has been corrected accordingly:” Indeed, higher transpiration in the dry season (due to the higher demand which is not entirely compensated by the slight water stress) can compensate the effect of reduced rain reevaporation intercepted by the canopy. As a result the feedback loop between precipitation and ET is weakened and the impact of the dry season on ET (and hence clouds) is strongest in mesoscale clearings and deforested regions (**Error! Reference source not found.**). In addition, the feedback of shallower clouds and surface radiation may be more important than the feedback of deeper clouds and precipitation.”
564 - Here and in a few other places there is some discussion on respiration, in which the link to the water cycle may be lost for some readers as it is not as clear as for photosynthesis. Consider clarifying those connections.
Response: we have removed respiration wherever it could lead to confusion

605 “outweigh” 613 “increased lifetime” 618 “depending on the Amazonia site, from rather pristine...” ? 628 dynamics that drive

Response: those have been corrected

631 “the transition from turbulent clear convective conditions to shallow cloudy maybe modified in the future” - Do you mean changes in the frequency of the transition or nature of the transition?

Response: we have corrected this to “the frequency of the clear convective vs. shallow cloudy conditions may be modified in the future”

640 – the discussion on Maritime continent biomass burning is nice for geographical balance and is an outcome of precipitation deficits tied to El Nino. The carbon cycle impact of the burning is discussed in the review, but do you think it also has impacts on the water cycle that could be discussed here?

Response: as suggested by the reviewer we now include a discussion on the water cycle as well.

Figure 16 caption – could use a little more information on what increasing/decreasing regime mean

Response: this caption has been improved and extended

751 ‘reduced feedback strength’ - reduced relative to what?

Response: indeed this was not sufficiently clear. We have now edited this sentence to clarify it.

References Malhi Y., A. D. Nobre, J. Grace, B. Kruijt, M. G. P. Pereira, A. Culf, S. Scott, Carbon dioxide transfer over a Central Amazonian rain forest. Journal of Geophysi- cal Research-Atmospheres 103, 31593-31612 (1998); published online EpubDec 27 (10.1029/98jd02647).

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Williams M., Y. Malhi, A. D. Nobre, E. B. Rastetter, J. Grace, M. G. P. Pereira, Seasonal variation in net carbon exchange and evapotranspiration in a Brazilian rain forest: a modelling analysis. Plant Cell and Environment 21, 953-968 (1998); published online EpubOct (10.1046/j.1365-3040.1998.00339.x).

***Interactive comment on* "Land–atmosphere interactions in the tropics" *by* Pierre Gentine et al.**

Anonymous Referee #3

Review: Land-Atmosphere interactions in the tropics, by Gentine et al.

As a review paper, there are not really any new findings here, but rather a summary of previous work. The paper does a fine job of this, and I believe it will be a valuable resource for others. I recommend acceptance with minor revisions.

Response: we thank the reviewer for the positive feedback

That being said, I do have some comments.

Lines 202-203: When I looked at the WECANN papers I did not see proof that seasonal cycles were reproduced. I see r-squared values in the tables, but not evidence showing seasonal cycles (also: I think the sentence should have 'variability' added at the end). I'm not sure I'm convinced that WECANN is better than other models in the tropics (really, Brazil. Do we have enough tower data in Africa or the Maritime Continent to really make an assessment?). Is there a way to establish this?

Response: we now add some caveats during the discussion to further emphasize that WECANN might have issues. However we point out that the retrieval better captured variability (mostly through the use of SIF than most other products).

This brings up something else: By using the words 'wet tropics', the implication is that tropical forests do not experience any water stress. I don't agree with this. There are a couple of papers [da Rocha et al., 2009, Costa et al., 2010] that discuss the variation in 'environmental control' (light limitation) and 'biotic control' (water limitation across precipitation and vegetation gradients in Brazil. Yes, the cerrado (savanna) is generally water-limited, and the wettest forest is light-limited, but the transition is not binary, nor is it limited to the cerradao (transition forest). I think a discussion of light- and water-limitation across gradients, and our uncertainty about the relative importance of each is an important part of tropical land-atmosphere interaction that is missing from this manuscript. George Vourlitis and coauthors have done some good work in the cerradao that should be described (I'm not going to list them all here). Baker et al. (2013) put forth a conceptual description of this gradient in a modeling study. Whether describing Brazil, the forest-to-desert transitions in Africa (both north and south), or the ecotone in Australia, there is important ecophysiological information in these transitions (and their response to changing climate) that is ignored here.

Response: we completely agree with the reviewer and indeed we see this as a continuum – we now have tried to clarify the text throughout.

On a potentially related note, I'm curious if the European Centre Amazon conversion papers need to be mentioned (Cox, Huntingford, Jones, et al.). I understand a review paper is not the same thing as a history paper, but these HADGCM papers got a lot of attention, and actually initiated quite a bit of investigation. The fact that there has been somewhat of a retreat from the initial findings means that these papers are no longer the 'state of the science', but they were seminal, along with the Saleska 2003 paper (in my opinion) in the initiation of some pretty important lines of investigation.

Response: those are good suggestions – we now have added those references which indeed are important.

Figures:

The figures don't flow smoothly with the text, in that the sequence of figures doesn't match when they are referenced. I was jumping back and forth in the figures as they were mentioned in the text, and I think a little rearranging would make the readability better.
Response: we have now corrected the ordering of the figures
Labels are too small in Figure 3, and are very difficult to read.
Response: those have been corrected and increased
Figures 5-10. The deformation of continents makes these plots hard to interpret. I would prefer to see the horizontal scale of the 4 seasonal plots stretched to match the longitude panel on the bottom of the plot. It would make the plots a little bigger, but readability would be improved. Also, the reader would be able to look directly up from the bottom panel and see the spatial variability in the latitudinal averages.
Response: we have now modified those plots as they were too stretched
Figure 16 seems to be thrown in, without much explanation in the text. I'm not sure I understand what is going on here, please clarify.
Response: we have clarified both the figure and caption as well as better described when it is referenced.
Miscellaneous comments:
Lines 74-75: Could include Friedlingstein (2006) and ?? here as citations.
Response: indeed this has been added
Lines 84-85: is it worth mentioning previous land-atm coupling papers, like Koster et al. (2004), or Dirmeyer (2011)?
Response: yes this was a big omission – those are added now
Lines 130-133: Cumbersome sentence, maybe some typos. Please reword.
Response: we have reformulated this to –
AMMA built upon previous field work in the region [*e.g. HAPEX-Sahel*, *Gourtorbe et al. 1993*]. This experiment advanced understanding of mesoscale convective systems and their initiation, as well as the role of surface processes
Line 169: If you say 15 S, you probably don't need the minus sign.
Response: corrected
Line 277: Looks like a laTex citation typo.
Response: corrected

Line 287: Grabowski (1999) could be cited too.
Response: this has been added
Line 289: 'models'
Response: this has been corrected
Line 324: I think the citation '[*Anber et al., 2015a*]' should be 'Anber et al. [2015a]', since the author name is part of the sentence. This looks like a place where \citep is used instead of \citet in the creation of the manuscript. There are a lot of instances of this in the manuscript, especially from line 587 on.
Response: those have been corrected throughout
Lines 398-400: 'Tropically-averaged EF does not evolve much...' With time? With space?
Response: we meant temporally, which is now added.
Lines 400-402: incomplete sentence.
Response: this has been corrected
Line 406: 'through' not 'though'

Response: corrected
Line 428: The text is talking about vertical gradients of light and water availability, yet refers to figure 3, which shows temperature response to ENSO. This recalls the earlier comment about figures and how they are referred to in the text.
Response: indeed, it was supposed to be figure 11, which has now been corrected.
Line 430: delete 'because'
Response: this sentence has been corrected to: However, water is typically not limiting for low-canopy species, as relative humidity is high and VPD is low, leading to low stress on understory conductance
Line 476: knownknows
Response: this has been corrected
Line 539: delete 'though,'
Response: this has been removed
Lines 549-550: I'm not sure I agree. Mesoscale-Induced clouds may be *initiated* preferentially in clearings and deforested regions, but they don't necessarily *stay* there. When I look at the GOES-16 images over Amazonia, I see clouds moving, not standing still. Do you have evidence that demonstrates that, integrated over time, the cleared/deforested regions are effected by clouds more than non-deforested regions? This may require some clarification.
Response: we have replaced this by saying that shallow clouds are triggered more. Yet, the life cycle of shallow clouds is very short (~30 minutes – i.e. PBL time scale) so that they cannot be advected very far, unlike mesoscale systems as we better calrify now.
Lines 567-569: confusing sentence, please reword.
Response: this has been reformulated
Lines 574-577: You might want to cite Fu and Li (2006) here as well.
Response: this has been added
Line 585: 'increased'
Line 625: 'lightning'
Lines 617-620: cumbersome sentences, some rewording would be helpful.
Line 703: inconsistent reference style.
Line 790: 'dry-to-wet'
Lines 815, 832: inconsistent reference style.
Line 893: 'through'
Response: these have been corrected

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Land-atmosphere interactions in the tropics – a review

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ABSTRACT

The continental tropics play a leading role in the terrestrial energy, water, and carbon cycles. Land-atmosphere interactions are integral in the regulation of these fluxes across multiple spatial and temporal scales over tropical continents. We review here some of the important characteristics of tropical continental climates and how land-atmosphere interactions regulate them. Along with a wide range of climates, the tropics manifest a diverse array of land-atmosphere interactions. Broadly speaking, in tropical rainforest climates, light and energy are typically more limiting than precipitation and water supply for photosynthesis and evapotranspiration, whereas in savanna and semi-arid climates, water is the critical regulator of surface fluxes and land-atmosphere interactions. We discuss the impact of the land surface, how it affects shallow and deep clouds and how these clouds in turn can feed back to the surface by modulating surface radiation and precipitation. Some results from recent research suggest that shallow clouds may be especially critical to land-atmosphere interactions. On the other hand, the impact of land surface conditions on deep convection appears to occur over larger, non-local, scales and may be a more relevant land-atmosphere feedback mechanism in transitional dry to wet regions and climate regimes.

1 Introduction

The Tropics play a substantial role in regulating the global hydrologic and carbon cycles. Tropical rainforests are one of the main terrestrial carbon sinks [*Nakicenovic*, 2000; *Friedlingstein et al.*, 2006] but their projected responses to a warming climate remain unclear because of uncertainties associated with the representation of abiotic and biotic processes in models as well as confounding factors such as deforestation and changes in land use and land cover [*Wang et al.*, 2009; *Davidson et al.*, 2012; *Fu et al.*, 2013; *Saatchi et al.*, 2013; *Hilker et al.*, 2014; *Boisier et al.*, 2015; *Doughty et al.*, 2015; *Gatti et al.*, 2015; *Knox et al.*, 2015; *Saleska et al.*, 2016]. The ecosystems of tropical monsoonal and seasonal wet-dry climates are also important contributors to the global carbon cycle, especially with respect to the interannual variability of the tropical terrestrial carbon sink [*Poulter et al.*, 2014; *Jung et al.*, 2017; *Green et al.*, 2019].

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Some regions of the tropics have been further identified as hotspots in which land-atmosphere interactions modify the climate [*Dirmeyer et al.*, 2011; *Koster et al.*, 2011; *Green et al.*, 2017] either locally, i.e. at horizontal scales on the order of a few boundary layer heights, regionally, at scales up to a few hundreds of kilometers, or at larger scales, over several of thousands of kilometers, through coupling between the surface and the overlying atmosphere [*Lintner and Neelin*, 2009]. These interactions may in turn dramatically affect the future state of rainforests [*Cox et al.*, 2004].

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While tropical land-atmosphere interactions are often examined through the lens of coupling between land surface states (e.g., soil moisture) and rainfall, other aspects of the coupling are also important. For example, even under nonprecipitating conditions, surface radiation, temperature and vapor pressure deficit (VPD) may be altered [*Lawton et al.*, 2001; *Pielke et al.*, 2016; *Green et al.*, 2017] through coupling with clouds, aerosols and shallow (non-precipitating) convection [*Avissar and Nobre*, 2002; *Medvigy et al.*, 2011; *Seneviratne*, 2013; *Cook et al.*, 2014; *Guillod et al.*, 2015; *Krakauer et al.*, 2016; *Martin et al.*, 2016; *Green et al.*, 2017; *Khanna et al.*, 2017; *Martin et al.*, 2017; *Thiery et al.*, 2017; *Vogel et al.*, 2017]. In addition, tropical forests can exhibit important variations in canopy photosynthetic capacity with new leaves [*Lopez et al.*, 2016; *Saleska et al.*, 2003, 2016]. These variations can further feed back onto the atmosphere on seasonal time scales [*Green et al.*, 2017]. It is clear that the tropical energy, water, and carbon cycles cannot be understood in isolation; rather, the interactions among these cycles are essential. For example, knowledge of such interactions must be taken into account to ascertain whether the terrestrial tropics will act as a future carbon sink or source [*Zhang et al.*, 2015; *Swann et al.*, 2015].

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The two-way interactions that occur between the land surface and overlying atmosphere represent one of the more uncertain aspects of the terrestrial climate system, particularly in the Tropics [*Betts and Silva Dias*, 2010]. While the land surface is widely recognized as integral to the occurrence of important tropical climate phenomena such as monsoons [*Zeng and Neelin*, 1999; *Zeng et al.*, 1999], isolating and quantifying its precise role remains elusive. Indeed, such efforts have frequently been hampered by the paucity of

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observational data, not to mention the complex and multiple pathways through which land-atmosphere interactions can take place.

Several notable field campaigns have been conducted in the tropics with the purpose of advancing knowledge of land-atmosphere interactions. One of the most well-known campaigns was the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) [*Avissar et al.*, 2002; *Keller et al.*, 2004], which aimed at refining our understanding of climatological, hydrological, biogeochemical and ecological processes of the Amazon and their linkages, in addition to the anthropogenic impacts (e.g., land-use land cover changes and deforestation) on these. Among many other topics, LBA generated fundamental insights on the structure of the tropical atmosphere, processes generating precipitation, and the seasonal variability of surface turbulent fluxes in tropical rainforests [*Avissar and Nobre*, 2002; *Betts et al.*, 2002; *Laurent et al.*, 2002; *Machado and Laurent*, 2002; *Acevedo et al.*, 2004; *Khairoutdinov and Randall*, 2006; *Fitzjarrald*, 2007; *Juárez et al.*, 2007; *Restrepo-Coupe et al.*, 2013]. One thrust of LBA research sought to isolate the effect of deforestation on precipitation, both in a local context as well as remotely via teleconnections [*Avissar et al.,* 2002; *Werth and Avissar*, 2002]. Such research has pointed to deforestation decreasing precipitation, albeit with uncertain magnitude and dependence on the spatial scales involved. Even now, two decades after the inception of LBA, the relationship between tropical deforestation and precipitation remains uncertain, despite progress with respect to key processes such as vegetation access to deep water in the dry season [*Oliveira et al.* 2005], and modulation of energy availability for photosynthesis via cloud cover [*Betts and Dias*, 2010].

Another field campaign, the African Monsoon Multidisciplinary Analysis (AMMA) campaign, focused on the West African monsoon system, especially the Sahel transition zone [*Redelsperger et al.*, 2006; *Boone et al.*, 2009b]. Building on previous field work in the region [*e.g. HAPEX-Sahel*, *Gourtorbe et al. 1993*], AMMA generated fundamental understanding of mesoscale convective systems and surface processes [*Lebel et al.*, 2009; *Taylor et al.*, 2009; *Boone et al.*, 2009a; *Lohou et al.*, 2010; *Couvreux et al.*, 2011a; 2011b]. More recently, the 2014-2015 Green Ocean Amazon (GO-Amazon) campaign [*Martin et*

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The remainder of this review article is organized as follows. In sections 2-4, we introduce some fundamental considerations of the climate system components necessary for understanding tropical land-atmosphere interactions, including convection, clouds, and rainfall (Section 2), surface turbulent fluxes (Section 3), and vegetation and ecosystem processes (Section 4). We then synthesize prior work on tropical land-atmosphere interactions from both local and non-local perspectives (Section 5). We close this review (Section 6) by highlighting what we view as the outstanding issues, challenges, and knowledge gaps for tropical land-atmosphere interactions. For example, we argue that shallow cloud feedback and its impact on radiation has received too little attention compared to precipitation feedback, in rainforests especially.

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2 Convection, clouds, and rainfall in the Tropics

The net radiative heating of the atmosphere in the global tropics—arising from the top-of-the-atmosphere imbalance of net incoming solar (shortwave) radiation exceeding outgoing terrestrial (longwave) radiation—leads to one of the defining hallmarks of the tropics, namely very high rain rates. This is not to say, of course, that rainfall in the tropics is high everywhere or at all times, as climates within the tropics can be both wet and dry. Indeed, many of earth's desert regions are found on the margins of the tropics, and apart from deserts, parts of the tropics may experience very dry conditions seasonally. In this review, we will exclude consideration of deserts and focus on the humid tropics.

2.1 Shallow vs. deep convection

The distinction between shallow and deep convection remains imprecise, as these have been regarded as both fundamentally distinct or as a continuum, in both observations and model convection parameterizations [*Khairoutdinov and Randall*, 2006; *Bretherton and Park*, 2009; *Park and Bretherton*, 2009; *Rio et al.*, 2009; *Wu et al.*, 2009; *Del Genio and*

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Wu, 2010; *Hohenegger and Bretherton*, 2011; *Böing et al.*, 2012; *D'Andrea et al.*, 2014; *Rochetin et al.*, 2014b]. We will loosely refer to shallow convection as convection confined below the freezing level (typically less than 3km deep) and comprising non-precipitating clouds small characteristic motion scales (typically less than a km in the horizontal).

An important point is that shallow convection is frequently generated by thermals rooted in the boundary layer and is thus ultimately related to surface sensible (H) and latent heat (LE) flux and their partitioning [*Gentine et al.*, 2013a; 2013b; *de Arellano et al.*, 2014; *Tawfik et al.*, 2014, 2015a,b]. Within the Amazon, shallow convection and associated clouds frequently occur over the vegetated surface, while over cooler and more humid river basins, shallow clouds are virtually absent [*Gentine et al.*, 2013a; *Rieck et al.*, 2014; 2015; see also Figure 1]. In addition, shallow convection is strongly influenced by the diurnal cycle of surface radiation and surface turbulent heat fluxes [*Gentine et al.*, 2013a; 2013b; *de Arellano et al.*, 2014].

On the other hand, we use the term deep convection in association with deep, precipitating clouds. Deep convection may be triggered by a suite of thermodynamic or dynamic processes, including: boundary layer thermals [*D'Andrea et al.*, 2014; *Guillod et al.*, 2014; *Rochetin et al.*, 2014a; 2014b; *Anber et al.*, 2015a], radiative destabilization [*Anber et al.*, 2015b], cold pools (cold density currents due to rain evaporation that cools the air within precipitating downdrafts) [*Engerer et al.*, 2008; *Del Genio and Wu*, 2010; *Böing et al.*, 2012; *Feng et al.*, 2015; *Torri et al.*, 2015; *Gentine et al.*, 2016; *Heever*, 2016; *Drager and van den Heever*, 2017] forced vertical motions such as via mesoscale and large-scale circulations [*Werth and Avissar*, 2002; *Roy et al.*, 2003] or propagating tropical wave activity [*Kuang*, 2008; 2010]. As such, deep convection may be viewed as less dependent on the surface state compared to shallow convection.

Over the central Amazon a large fraction of wet season precipitation occurs during the nighttime (Figure 2). Moreover, during the daytime in both the dry and the wet seasons, the diurnal cycle reflects not only locally surface-triggered deep convection [*Khairoutdinov and Randall*, 2006; *Ghate and Kollias*, 2016] but also propagating mesoscale convective systems and squall lines throughout the Amazon basin *[Greco et al.*, 1990; *Ghate and Kollias*, 2016; *Rickenbach et al.*, 2002]. However, during the dry season, precipitation occurs more frequently with the "popcorn type" deep convection that is more locally triggered and thus directly related to the state of the land surface [*Ghate and Kollias*, 2016] (see an example here https://youtu.be/c2-iquZziPU). While shallow convection does not produce much rainfall, it exerts significant influence on deep convection through its control on surface radiative fluxes and on transport of moisture into the lower troposphere. More discussion will be given in Section 4.2.

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2.2 Considerations for modeling tropical clouds, convection, and rainfall

Current generation climate models struggle to represent both shallow and deep convection over continents and their transitions [*Guichard et al.*, 2004; *Bechtold et al.*, 2013; *Yin et al.*, 2013; *D'Andrea et al.*, 2014; *Couvreux et al.*, 2015], especially in the tropics, as they exhibit substantial errors in the phasing and intensity of both the diurnal and seasonal cycles of convection [*Bechtold et al.*, 2013], as well as biases in the climatological distribution of rainfall over land. For example, over the Amazon, many climate models underestimate surface precipitation, evapotranspiration, and specific humidity [*Yin et al.*, 2013], with the dry bias in moisture extending upwards into the lower free troposphere [*Lintner et al.*, 2017]. Such biases may reflect deficiencies or errors in how convection is represented in models [*Yano and Plant*, 2012; *Stevens and Bony*, 2013; *Bechtold et al.*, 2014]. Indeed, in current generation climate models, cloud processes occur at scales smaller than resolved grid-scale prognostic variables and therefore need to be parameterized, i.e. represented as a function of the resolved-scale variables. This is important as it means that climate models do not explicitly represent the small-scale convective physics of the climate system. Evaluation of model performance for the Central Amazon can be found in Adams et al. [2013, 2015, 2017].

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Cloud resolving models (CRMs) that include explicit convection at scales of ~1km alleviate many of the biases evident in coarser-scale, parameterized convection climate models, especially in terms of the diurnal cycle of convection or the sign and magnitude of the feedbacks between deep convection and surface evaporative fraction [*Grabowski* 1999, *Taylor et al.*, 2013; *Anber et al.*, 2015a]. Nonetheless, due to convective wave coupling in the Tropics, a simple prescription of lateral boundary conditions in small-domain CRMs may be problematic, as the convective scales ultimately interact with and are coupled to planetary scales. With a sufficiently large domain and fine enough resolution, coupling between the convective scales and planetary scales may be explicitly resolved, but simulations of this nature are likely to be computationally too expensive for many applications. However, techniques exist to represent the effect of large-scale dynamics on the convective scales, which, when combined with cloud resolving simulations, yield powerful tools for understanding land-atmosphere interactions in the tropics, as we elaborate further below.

3 Surface turbulent fluxes in the Tropics

A major component of land-atmosphere interactions considered is related to surface turbulent fluxes and associated momentum, energy, water and trace gases exchanges between the land surface and atmosphere [*Goulden et al.*, 2004; *Fisher et al.*, 2009; *Restrepo-Coupe et al.*, 2013]. Surface turbulent flux measurements are usually obtained from eddy-covariance methods, typically located above the canopy [*Baldocchi et al.*, 2001]. Observing turbulent fluxes is challenging in tropical environments given logistics, cost, maintenance, and harsh environmental factors such as intense rainfall, high wind, and relative humidity, which impact sensors [*Campos et al.*, 2009; *Da Rocha et al.*, 2009; *Restrepo-Coupe et al.*, 2013; *Zahn et al.*, 2016; *Chor et al.*, 2017; *Gerken et al.*, 2017]. In light of these challenges, it is perhaps not surprising that even the best estimates of surface turbulent fluxes manifest large uncertainties [*Mueller et al.*, 2011].

Apart from site level measurements, which are limited to a small number of locations around the tropics, remote sensing observations can provideindirect information about surface turbulent fluxes and other relevant quantities over tropical land regions. Remote sensing observations are useful for generalizing and comparing fluxes across the tropics, even if they are not as direct as site level measurements. Yet, there are considerable uncertainties in remote sensing and reanalysis estimates of rainfall [*Washington et al.*,

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<#>There exist multiple definitions of the Tropics. On the one hand, the Tropics can be defined spatially as the area between the Tropics of Cancer and Capricorn, located at ~23½° N and ~23½° S, respectively. On the other hand, it is sometimes useful to define the Tropics in terms of underlying climate or physical characteristics. One such physically-motivated definition of the Tropics is the region over which mean top-of-the-atmosphere solar incoming radiation exceeds outgoing radiation (reflected shortwave and outgoing longwave), which occurs equatorward of ~35°. Another definition is the region near the equator where the Coriolis effect is small and planetary scale equatorial wave dynamics are dominant, which strongly affects the dynamics, as we elaborate below [*Sobel et al.*, 2001; *Sobel and Bretherton*, 2003; *Lintner and Chiang*, 2005; *Raymond and Zeng*, 2005]. ¶
<#>Over land, the Tropics are often defined biogeographically, as in the traditional Köppen climate classification scheme [*Köppen*, 1884]: tropical regions are divided into three main groups—tropical rainforest, tropical monsoon, and tropical wet and dry (or savanna)—all of which are characterized by annual mean temperatures exceeding 18°C but which differ in terms of precipitation amount and seasonality. ¶
<#>The latitudes between the Tropics of Cancer and Capricorn encompass some regions of large-scale subsidence and limited rainfall, including drylands and deserts, which we largely neglect here, even though land-atmosphere coupling processes within these regions is clearly of interest. Thus, throughout this manuscript, we define the Tropics as the latitudinal band between -15° S and 15° N, as it captures most of the wet regions of the ... [3]

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2013; *Levy et al.*, 2017], radiation [*Jimenez et al.*, 2011], and surface turbulent fluxes [*Jung et al.*, 2009; *Alemohammad et al.*, 2016] and especially in terms of upscaling point observations to larger areas as those measurements are fundamentally indirect.

While direct, satellite-based retrievals of carbon (e.g., gross primary production (GPP)) and water fluxes would be most suitable for the study of tropical land-atmosphere interactions, such retrievals are beyond current remote sensing capabilities. However, some recent work demonstrates that existing satellite observations, especially Solar-Induced Fluorescence (SIF), may be leveraged to remotely assess surface turbulent fluxes in the tropics. In contrast to the normalized difference vegetation index (NDVI) or many other vegetation indices which are indirect byproducts of photosynthesis [*Morton et al.*, 2014], SIF (at the leaf scale) is directly related to the ecosystem-scale photosynthesis rate, providing important information on the impact of stressors on photosynthesis and is available from existing remote sensing platforms [*Frankenberg et al.*, 2011; *Joiner et al.*, 2011; *Frankenberg et al.*, 2012; *Joiner et al.*, 2013; *Frankenberg et al.*, 2014; *Guanter et al.*, 2014; *Lee et al.*, 2015; *Duveiller and Cescatti*, 2016; *Liu et al.*, 2017; *Thum et al.*, 2017; *Alexander et al.*, 2017]. SIF is thus an important indicator of the rates of photosynthesis and transpiration through stomatal (small pores at the leaf surface) regulation [*Alemohammad et al.*, 2017; *Pagán et al.*, 2019]. Indeed, during photosynthesis plants take up CO_2 from the atmosphere while releasing water to the atmosphere through stomata. We note that recent developments in observations of SIF seem to indicate that the major fraction of the SIF signal might be related to chlorophyll photosynthetically active radiation and that changes in SIF yield (equivalent to light use efficiency) may account for only a small fraction of the observed SIF signal [*Du et al.*, 2017]. This is still an open topic to better understand what is actually observed by SIF remote sensing.

Alemohammad et al. [2016] applied a machine learning algorithm based on remotely-sensed SIF, called WECANN (Water Energy and Carbon Artificial Neural Network) to derive surface turbulent fluxes. WECANN reproduces exhibits reasonable interannual variability and its seasonality is constrained by the use of SIF [*Alemohammad et al.*, 2016], yet like any other products it is not a direct observation of the fluxes, which are only

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available at sparse tower observations. WECANN performs well compared to eddy-covariance observations and has less uncertainty compared to many other retrievals (see [*Alemohammad et al.*, 2017]).

Given the paucity of flux towers and associated surface flux measurements across the tropics, we use WECANN to calculate surface flux climatologies across the continental tropics. WECANN has been validated against available flux tower data and outperforms other products in terms of reproducing both the seasonality and interannual variability [*Alemohammad et al.*, 2017]. While remote sensing retrievals are not perfect and cannot be considered the truth, they do provide spatially extensive data coverage, including regions with sparse (or no) site-level measurements (e.g., Congo). In what follows, we present climatologies of evapotranspiration (ET) and gross primary production (GPP) and compare these against precipitation (based on GPCP 1DD v1.2 [*Huffman et al.*, 2001]) and net radiation (based on CERES SYN [*Kato et al.*, 2013]) in order to understand the typical seasonal cycles of those energy, water, and carbon fluxes across the continental tropics.

We first focus on the main tropical rainforests and the northeastern savanna (Cerrado) region of Brazil (Figure 3). In the wetter part of the Amazon, net radiation, Rn, peaks in the dry season (August to November) (Figure 3) when precipitation (Figure 4) and cloud cover—especially shallow cloud cover, including fog—are reduced, [*Anber et al.*, 2015a]. As a result of reduced dry season cloud cover, incident surface solar radiation increases, and both GPP (Figure 5) and ET (Figure 6) increase in the dry season (Figure 3). As discussed further in the next section, the forest in the climatologically wetter Amazon is primarily light limited, while water stress there is moderate in the dry season. The seasonal cycle is more pronounced for GPP than for ET (Figure 3): canopy photosynthetic regeneration [*Lopez et al.*, 2016; *Saleska et al.*, 2003, 2006, 2016] is an important factor affecting the seasonal cycle of GPP in rainforests potentially increasing the maximum rate of GPP in the dry season. In addition, canopy evaporation (of intercepted rain) comprises a large fraction of total ET in the wet season [*Scott et al.*, 1997; *Oleson et al.*, 2008; *Miralles et al.*, 2010; *Sutanto et al.*, 2012; *van Dijk et al.*, 2015; *Andreasen et al.*, 2016] and partly compensates for reduced transpiration in the wet season. In fact, because of this

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In contrast to the everwet western and central Amazon, over the Cerrado region of Northeastern Brazil, the seasonal cycles of Rn, precipitation, GPP and ET are much more pronounced, with a marked dry season (Figure 3). The seasonal cycle of GPP tracks precipitation, and water stress, exhibiting a strong increase during the wet season. Similarly, ET increases sharply in the wet season and then decreases more slowly than precipitation in the dry region (Figure 3). Conversely, net radiation increases sharply during the dry season. This region clearly exhibits a strong water stress response.

Turning to the Maritime Continent, rainfall is intense throughout the year and seasonality is modest, with a short peak in November to January (Figure 3). Much of the seasonal cycle is attributable to monsoon circulations, which are strongly influenced by topography and the land- and ocean-surface thermal contrast [Chang 2005]. The topography and the distribution of island land masses leads to strong local variability (Figure 4e) and pronounced diurnal cycles in convection are evident [*Nitta*, 1987; *Hamada et al.*, 2008]. Additionally, the Madden Julian Oscillation, an important mode of climate variability in the tropical Indo-Pacific with a lifecycle of 30-90 days, strongly impacts rainfall on intraseasonal timescales [*Hidayat and Kizu*, 2009]. Convective activity in the region also regulates the East Asian Monsoon [*Huang and Sun*, 1992]. The region is also influenced by topographic effects and land-see breeze interactions, which may impart considerable regional heterogeneity. Given the relatively constant regional-averaged precipitation with

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regular convection occurring over course of the annual cycle, ET and GPP remain near steady throughout the entire year in this mostly light limited environment (Figure 3).

The Congo basin exhibits two rainy seasons (Figure 3), with peaks in March-April-May and September-October-November, related to seasonal changes in moisture convergence associated with the African Easterly jet and Intertropical Convergence Zone (ITCZ) over the Atlantic [*Washington et al.*, 2013]. Throughout the year, monthly-mean precipitation is much less than that observed over the Amazon or Indonesia. The seasonality of GPP and, to a lesser extent, ET tracks that of precipitation, with substantial decreases during the June to August dry season and even more pronounced reduction during the December to February period. This seasonality in GPP and ET (Figure 3) suggests that the Congo basin should exhibit substantially more water stress during dry seasons compared to the Amazon or Indonesian rainforests [Guan et al. 2015].

Integrated over the entire tropical latitudinal band, precipitation is highest in DJF and MAM when the wet season extends over most of the Amazon and adjacent savanna regions (Figure 4). This seasonal cycle of tropical-mean precipitation largely determines the seasonal cycle of GPP. GPP peaks during the wet season in South America, as GPP is highest in the savanna regions while GPP over the rainforest exhibits less seasonal variations (Figure 6). The seasonal pattern of ET resembles GPP (Figure 6). Indeed, the seasonality in ET reflects the combined influences of 1) the seasonality of water availability in drier, water-limited regions, 2) the seasonality of surface radiation in the wetter, more energy-limited portion of the Amazon, and 3) changes in photosynthetic capacity thoughout the year. The seasonal cycle of sensible heat flux (Figure 7) largely follows water stress, especially in the rainforest where radiation remains high throughout the year, with an increase during the dry season. Water stress is further apparent in the evaporative fraction, EF, the ratio of latent heat flux to the sum of latent and sensible heat fluxes (Figure 8). Tropically-averaged EF does not evolve much over the year; the modest seasonality may be understood in terms of variation of the latitudinal peak in radiation and compensation of decreased canopy interception by transpiration (because of increased net surface radiation) in the dry season. However, in transitional and dry regions, EF exhibits much

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more seasonal variation. The surface moist static energy flux, H+LE, shows some slight variations in SON and JJA but otherwise remains relatively steady across longitudes because of the compensation between the increased H and reduced ET in the dry season. In the dry to wet transition, SON, moist static energy flux exhibits an interesting peak at about -60 longitude (Figure 9) through the combined increase in radiation, due to reduced cloudiness, inducing higher sensible heat flux and maintained high ET rates.

Over tropical Africa, the precipitation is highest in JJAS during the wet phase of the West African Monsoon, with a secondary maximum in DJF corresponding to the Southern African Monsoon (Figure 4). Similarly the latitudinal-averaged GPP and ET increase during the West African Monsoon (Figure 5, Figure 6), accompanied by a strong decrease in sensible heat flux (Figure 7). In DJF the southern African Monsoon displays increased water flux (Figure 6) and photosynthesis tracking the increased rainfall (Figure 4). The Congo rainforest clearly exhibits two brief rainy seasons (Figure 3, Figure 8), with peaks in March-April-May and September-October-November (Figure 3) and displays substantial water stress and strong reduction in EF to values below 0.6 during the dry season (Figure 8).

4 Vegetation and ecosystem processes in the Tropics

We cannot understand tropical land-atmosphere interactions, not to mention the basic features of terrestrial tropical climate, without consideration of vegetation and ecosystem processes. Indeed, over land, what is viewed as the Tropics has traditionally been defined with vegetation and ecosystems implicitly considered, as in the Köppen climate classification scheme [Köppen, 1884]. Under this scheme, the terrestrial Tropics is divided into three main *groups*—tropical rainforest, tropical monsoon, and tropical wet and dry (or savanna)—all of which are characterized by annual mean temperatures exceeding 18°C but which differ in terms of precipitation amount and seasonality.

One outstanding challenge in simulating tropical land regions is determining why most contemporary land-surface models incorrectly represent the wettest rainforest GPP and ET

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rates, their seasonal cycles, and how they relate to water stress? In the wettest tropical forests, such as the western portion of the Amazon or Indonesia, energy and light limit the rates of ET and GPP. It is thus reasonable to conclude that soil moisture and water stress should have minor effects in such regions, and consequently, that precipitation variability should not matter much. In fact, there exist sharp vertical gradients in the canopy (as well as at the surface of the soil in the dry season) in terms of light and water availability, along with nutrient allocation, as well (Figure 10). Understory species receive only a small amount of mostly diffuse light. However, water is typically not limiting for low-canopy species, as relative humidity is high and VPD is low, leading to low stress on understory conductance [*Leuning*, 1995; *Leuning et al.*, 1995; *Wang and Leuning*, 1998; *Medlyn et al.*, 2011; 2012; *Heroult et al.*, 2013].

On the other hand, tall canopy species receive a large amount of radiation, especially in the dry season, causing sunlit leaf warming and higher leaf VPD (e.g., Penman-Monteith equation) that lead to heat and water stress [*Jardine et al.*, 2014]. Leaf and xylem water status are regulated by the relative demand of sap from transpiration, which depends on leaf VPD. It also depends on sap supply to the leaves, the rate of which is controlled by the xylem conductivity and which is high for tall tropical rainforest trees [*Liu et al.*, 2019]. This conductivity is reduced by cavitation in the xylem (formulation of air bubbles blocking the ascent of sap flow from the roots to the leaves) [*Martinez-Vilalta et al.*, 2014; *Martinez-Vilalta and Garcia-Forner*, 2016]. To avoid leaf desiccation and xylem cavitation stomatal closure is usually observed during peak daytime sunlight hours in rainforest top canopy species [*Brodribb*, 2003; *Pons and Welschen*, 2003; *Zhang et al.*, 2013]. This limits the risk of leaf desiccation or xylem cavitation (Figure 11), in those usually efficient xylems. This type of behavior with strong stomatal regulation appears to be typical in the tropical rainforests [*Fisher et al.*, 2006; *Konings and Gentine*, 2016], even though this appears to contradict results from isotopic measurements showing that stomata remain relatively open [*Ometto et al.*, 2006]. On seasonal time scales, this is modulated by the change in photosynthetic capacity of the canopy due to leaf flush and canopy regeneration [*Saleska et al.*, 2003, 2006]. More work is needed to understand stomatal and

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canopy regulation of tropical rainforests in response to stressors, especially given the importance of rainforests in the global carbon cycle.

In tall canopy species the flow in the xylem from the roots may be limited as the xylem hydraulic conductivity is inversely proportional to height, though this is partially compensated by a more efficient xylem (higher specific conductivity) [*Liu et al.*, 2019]. However, higher evaporative demand in the dry season and/or under anomalously dry conditions can only be partially be mitigated by the more efficient xylem and by the plant internal storage; stomatal shutdown may therefore be inevitable to avoid desiccation and xylem cavitation (Figure 11) [Dawson, 1993; *Phillips et al.*, 1997; 2004; *Lee et al.*, 2005; *Oliveira et al.*, 2005; *Phillips et al.*, 2008; *Scholz et al.*, 2011; *Zeppel et al.*, 2014; *Konings and Gentine*, 2016]. In summary, water stress in tropical rainforest canopy species may not primarily be due to soil water stress but rather to atmospheric demand or a combination of soil moisture stress and atmospheric demand. The reduction of leaf and xylem water potentials increase stress in the soil-plant continuum. Radiation, temperature and VPD are therefore essential to understand tropical wet forests dryness response.

Land-surface and ecosystem models, apart from a few exceptions [*Xu et al.*, 2016; *Kennedy et al.*, *2019*], do not represent plant hydraulics and typically only rely on an empirical reduction of stomatal and ecosystem conductance, and therefore transpiration and GPP, as functions of root-averaged soil moisture or water potential (e.g., [*Noilhan and Planton*, 1989; *Sellers et al.*, 1996a; 1996b; *Ek*, 2003; *Boulet et al.*, 2007; *Gentine et al.*, 2007; *Ngo-Duc et al.*, 2007; *Stoeckli et al.*, 2008; *Balsamo et al.*, 2009; *Boone et al.*, 2009a; *Bonan et al.*, 2011; *Lawrence et al.*, 2011; *Niu et al.*, 2011; *Bonan et al.*, 2012; *Canal et al.*, 2014; *Han et al.*, 2014; *Naudts et al.*, 2014; *De Kauwe et al.*, 2015; *Chaney et al.*, 2016; *Chen et al.*, 2016; *Haverd et al.*, 2016 among others). The root profile averaging of soil moisture or water potential to define water stress exaggerates the impact of surface drying, as in reality deeper roots may still effectively transport water to the plant xylem even if surface roots experience dry conditions and therefore can maintain overall high rates of GPP and transpiration.

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The inclusion of plant hydraulics in tall canopy species leads to strong differentiation between leaf (and upper xylem) and soil water potential (Figure 11) during midday, especially in the dry season. Indeed, leaf and xylem water potentials substantially drop because of the large transpiration rates through the stomata and because the xylem cannot be instantaneously refilled due to the large flow drag in the elongated xylem. As a result, plant hydraulics induce a shutdown of stomata during the day reducing the transpiration rate near peak solar hours, also known as "midday depression," [*Malhi et al.*, 1998; *Williams et al.*, 1998; *Harris et al.*, 2004] in order to reduce desiccation of the leaf and xylem. In addition, plant hydraulics also induces a natural hydraulic redistribution of water in the root profile reducing dryness in the upper profile in the dry season [*Lee et al.*, 2005; *Oliveira et al.*, 2005; *Domec et al.*, 2010; *Prieto and Ryel*, 2014; *Kennedy et al.*, *2019*], using deep root moisture rather than surface soil moisture when needed, as the water flows down gradient of water potentials. This is fundamentally different from typical parameterizations using average water stress of the root water profile, which are oversensitive to surface water stress, in typical parameterizations. Both of those effects lead to reduced sensitivity to water stress and help maintain higher rates of transpiration throughout the entire dry season, whereas typical land surface models overestimate water stress in the dry season [*de Gonçalves et al.*, 2013; *Alemohammad et al.*, 2016; 2017].

5 Tropical land-atmosphere interactions: Local and nonlocal perspectives

Having reviewed some of the important components of tropical land-atmosphere interactions, we now turn to the coupling of these components. Often, land-atmosphere interactions are framed in terms of a one dimensional column, comprising a "point" of interest, although a point here may be understood not only as a site (such as an eddy covariance flux tower) but also as spatial averages of varying scales. While this local, column view is certainly instructive, we suggest that it is also necessary to consider land-atmosphere interactions through an interplay with remote influences, i.e., a nonlocal perspective. This may be especially true in the tropics, given the strong coupling that exists

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between convective and large-scales. We will revisit the seasonality of tropical climate through the lens of these local and nonlocal perspectives of land-atmosphere interactions.

5.1 Quantifying land-atmosphere interactions

[*Green et al.*, 2017] recently developed a method to define the feedback between the biosphere and atmosphere using multivariate conditional Granger causality (based on lagged autoregressive vectors). We here use a similar framework using ET from WECANN and precipitation from GPCP as well as photosynthetically active radiation from CERES (Figure 12).

Most of the feedback between surface ET and precipitation occurs in the climatically transitional and/or monsoonal regions, such as the savanna region of Northeastern Brazil and the monsoonal regions over South Asia, the Sahel, Southern Africa, and Northern Australia. In Brazil, these results are consistent with spatial transition inherent in the convective margins concept introduced by Lintner and Neelin (2007; see also Figure 13) and the impact of soil moisture and evapotranspiration on setting the location of the transition between the dry and wet regions. The Sahelian and Southern African Monsoon are also located in regions between very dry (deserts) and humid regions, where surface feedback may be crucial for the penetration of the Monsoonal flow inland [*Lintner and Neelin*, 2009; *Lintner et al.*, 2015]. Indeed, the biosphere in this region modulates the local climate state: multiple equilibrium states, corresponding to different ecosystem initial conditions, may exist under the same external (e.g., top of the atmosphere solar) forcing [*Wang et al.*, 2000]. The effect of vegetation on land-atmosphere coupling manifests itself at multiple timescales. At short timescales after precipitation, evaporation is accelerated with intercepted water in the canopy. However, at longer timescales vegetation acts to delay and prolong evaporation of water stored in the root zone. The magnitude and timescale of these sources of water recycling vary depending on ecosystem structure, including rooting depth and canopy structure, which may co-evolve with atmospheric conditions at the interannual timescale [*Nicholson*, 2000]. This represents a clear pathway for two-way feedbacks between the land surface and precipitation.

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We further emphasize that those feedbacks (Figure 12) are likely to also be influenced by non-local conditions, with regional and large-scale changes in ocean to land flow and the in-land distance of penetration influencing local coupling. We note that climate models seem to exhibit soil moisture (and therefore evapotranspiration)- precipitation feedbacks in similar tropical regions, when averaged across models, even though individual model response varies [*Koster et al.*, 2011; *Seneviratne*, 2013] (one degree pixel and monthly time scales). We emphasize that the PAR radiation product is very uncertain in the tropics [*Jimenez et al.*, 2011] as it ultimately relies on a model to obtain surface incoming radiation, which might explain the reduced biosphere-precipitation feedback strength in the wet tropics compared to other regions. It is also likely that the bulk of the radiative feedbacks are taking place at smaller times scales such as the ones observed with MODIS (Figure 15). This shallow cloud cover is relatively steady spatially and in time, especially in the dry season.

5.2 A local view of tropical land-atmosphere interactions

A critical aspect of land-atmosphere interactions in tropical rainforests is related to shallow clouds and fog rather than deep convective clouds. Clearly, much of the focus of tropical land-atmosphere interactions has been on feedbacks involving precipitating deep convection, and the impact of surface heterogeneity on convective rainfall. On the other hand, the coupling of the land surface to radiation has been relatively understudied. Shallow clouds lead to reduced productivity and transpiration [*Anber et al.*, 2015a], yet the latter depends on cloud thickness as cumulus clouds (shallow convection) generate more diffuse light and may consequently boost photosynthesis when they are not too thick [*Pedruzo-Bagazgoitia et al., 2017*], Figure 14. Fog on the other hand, strongly diminishes the amount of incident light for ecosystems. Fog [*Anber et al.*, 2015a] and shallow clouds [*Giangrande et al.*, 2017] appear to be two of the primary differences between the dry and the wet season (in addition to the preferential occurrence of nighttime mesoscale convective systems in the rainy season, which are not directly relevant for land-atmosphere interactions associated with daytime processes). Low-level cloudiness largely affects the surface incoming radiation by reducing shortwave surface incoming radiation in the wet

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season, especially in the morning [*Anber et al.*, 2015a; *Giangrande et al.*, 2017], which in turn leads to strong reduction in GPP and ET. These clouds are also tightly connected to surface processes and especially the surface energy partitioning. Indeed, nighttime fog, which often persists into the early daylight hours. This fog is due to nighttime longwave cooling in very humid boundary layers, due for instance to evening rain in the wet season [*Anber et al.*, 2015a]. Shallow clouds are themselves directly forced by surface-generated thermals, i.e. boundary layer processes, and they are modified by the sensible and latent heat flux magnitude [*de Arellano et al.*, 2014, 2019]. Shallow convection and low-cloud cover are also tightly connected to ecosystem seasonality and to the diurnal cycle [*Anber et al.*, 2015a; *Tang et al.*, 2016; *Giangrande et al.*, 2017].

Historically, the study of land-atmosphere interactions in the Tropics, and tropical rainforests in particular, has emphasized effects of heterogeneity, especially due to deforestation, on the generation of deep convection through mesoscale circulations (see [*Lawrence and Vandecar*, 2015] for a complete review, as well as [*Avissar and Pielke*, 1989; *Pielke and Avissar*, 1990; *Pielke et al.*, 1991; *Dalu et al.*, 1996; *Avissar and Schmidt*, 1998; *Taylor et al.*, 2007; 2009; 2011; *Rieck et al.*, 2015; *Khanna et al.*, 2017]). The hypothesis behind this is that deforestation reduces EF and surface roughness [*Khanna et al.*, 2017]. The associated increased buoyancy flux over the deforested areas, mostly reflecting a shift toward increased sensible heating, induces mesoscale circulations. These circulations enhance cloudiness through local buoyancy fluxes, turbulent kinetic energy generation, and low-level moisture advection from adjacent forested areas, thus providing all the key ingredients for moist convection generation [*Rieck et al.*, 2014; 2015]. It seems unlikely however that momentum roughness plays a major role in this high radiation environment [*Park et al.*, 2017], where circulations are mostly buoyancy-driven. Instead, the heat and moisture roughness lengths [*Park et al.*, 2017] as well as leaf area index and stomatal conductance, which scales the magnitude of the evapotranspiration flux, are the main players, in addition to changes in soil moisture availability, for the circulation. The impact of the deforestation on surface fluxes and local circulation can change from buoyancy-driven to surface roughness driven as the spatial scale of the deforestation increases [Khanna et al 2017].

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Induced mesoscale circulations and associated deep convection are clearly observable with remote sensing observations [*Khanna et al.*, 2017] and are more important in the dry season [*Khanna et al.*, 2017], when convection is more locally, and regionally, triggered [*Anber et al.*, 2015a; *Ghate and Kollias*, 2016]. Once precipitation occurs, cold pools, i.e., density currents induced by ice melt and evaporating rain in downdrafts, dominate the surface-induced mesoscale circulation [*Rieck et al.*, 2015], and reduce the surface heterogeneity signal. In the wet season, the relative contribution of local forcing to the total rainfall is small as the bulk of the precipitation is due to mesoscale convective systems or larger-scale systems propagating throughout the basin, less tightly connected to surface and boundary layer processes [*Ghate and Kollias*, 2016].

Even during the dry season, a large fraction of the Amazon and of Indonesia only experience minimal water stress (Figure 8 and Figure 7) so that increased radiation generates higher rates of photosynthesis (Figure 5) and ET (Figure 6) [*Anber et al.*, 2015a]. Indeed, higher transpiration in the dry season (due to the higher demand which is not entirely compensated by the slight water stress) can compensate the effect of reduced rain reevaporation intercepted by the canopy. As a result the feedback loop between precipitation and ET is weakened and the impact of the dry season on ET (and hence clouds) is strongest (Figure 14). In addition, the feedback of shallower clouds and surface radiation may be more important, Figure 14, than the feedback of deeper clouds and precipitation, as those shallow clouds are preferentially triggered over drier surfaces. Because shallow clouds have a small life cycle (typically less than 30 minutes) compared to deep convective and mesoscale systems, they are more directly connected to the underlying surface conditions and interact more with the local conditions.

Fewer studies have studied changes in shallow clouds [*Wang et al.*, 2000; *Lawton et al.*, 2001; *Chagnon et al.*, 2004; *Ray et al.*, 2006; *Wang et al.*, 2009; *Pielke et al.*, 2011; *Rieck et al.*, 2014; *Anber et al.*, 2015a], even though the impact of changes in the surface energy partitioning and heterogeneity on low-level clouds is clear and spatially systematic (Figure 15). Given the importance of cloud cover on shortwave radiation and their importance for

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the differentiation between the dry and wet seasons over wet tropical rainforests we believe that this low-cloud feedback might be quite critical for rainforest ecosystem functioning. Indeed it was pointed out by [*Morton et al.*, 2014; *Anber et al.*, 2015a; *Morton and Cook*, 2016] that light changes between the dry and wet season due to changes in cloud cover were one of the primary reasons for changes in the seasonality of surface fluxes, in addition to leaf flush out [*Lopes et al.*, 2016; *Saleska et al.*, 2016]. At sub-daily scales, the shading due to low clouds reduces surface temperature and ecosystem respiration [*Mahecha et al.*, 2010; *Peterhansel and Maurino*, 2011; *Thornley*, 2011; *Hadden and Grelle*, 2016; *Ballantyne et al.*, 2017]. This reduction depends strongly on the cloud cycling and thickness. As a result, cloud-induced reductions in respiration can cancel reductions in photosynthesis, such that the net effect of cloud shading on net ecosystem exchange is unclear. *Horn et al.* [2015] showed that by explicitly calculating the surface coupling leads to a change in the length scales of clouds, and a reduction of the cloud life time. As a result, and although the cloud cover remains almost the same there are larger populations of smaller shallow cumuli. This responses to vegetation influence also the moisture transport and the cloud characteristics [*Sikma et al*, 2019].

In addition to regulating radiative energy balance at the surface, [*Wright et al.*, 2017] have shown that shallow convection transports moisture, provided by plants' transpiration, from the atmospheric boundary layer to the lower troposphere during the late dry season and early dry to wet transition seasons (July-September) [*Fu and Li*, 2004]. This mechanism, referred to as the "shallow convective moisture pump", plays an important role in priming the atmosphere for increasing deep convection (e.g., [*Schiro et al.*, 2016; *Zhuang et al.*, 2017]), and wet season onset over the Amazon [*Wright et al.*, 2017].

The results discussed until now omitted the relation between physical processes and the atmospheric composition, and more specifically the role of chemical reactions and aerosols. Over rainforests, the pristine and undisturbed conditions of the atmospheric boundary layer described in the seminal study by [*Garstang and Fitzjarrald*, 1999] are currently undergoing rapid changes due to atmospheric composition modifications. Their direct impact on the radiative and microphysical properties are due to biomass burning and

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enhancement of concentrations of secondary organic aerosol precursors. Biomass burning in Amazonia leads to increased aerosol optical depth and to abnormal distributions of the heating rate profile. Analyzing systematic experiments performed by large-eddy simulations, *Feingold et al.*, [2005] studied the processes that lead to the suppression of clouds. Firstly, at the surface there are clear indications that the latent and sensible heat flux are reduced, yielding convective boundary layers characterized by less turbulent intensity and by delays in the morning transition [*Barbaro and Vilà-Guerau de Arellano*, 2014]. Both aspects tend to reduce cloud formations. Secondly, [*Barbaro and Vilà-Guerau de Arellano*, 2014] indicated that the vertical location of the smoke layer is crucial in determining the dynamics of the boundary layer which can delay the onset of shallow cumulus. In turn, and ass. As described by [*Feingold et al.*, 2005], smoke confined in the well-mixed sub-cloud layer might positively benefit the cloud formation since it distributes the heat uniformly that contributes to enhance convection. On the other hand, smoke layers located within the cloud layer tend to stabilize the cloud layer and therefore decrease the possibility of cloud formation. These results are very much dependent on the aerosol optical properties defined by their heating, scattering and hygroscopic properties. As a first indicative figure, the mentioned LES study and observations by [*Koren et al.*, 2004] stressed that smoke layers with an aerosol optical depth larger than 0.5 might already lead to cloud suppression by 50%. *Yu et al*. [2008] have shown observationally that the influence of aerosols on shallow clouds varies with meteorological conditions. When the ambient atmosphere is drier (relative humidity ≤60%), cloud burning effect (evaporation of cloud droplets) due to increased absorption of solar radiation by aerosols outweighs the increase of cloud droplets due to aerosol-cloud microphysical effect. The reduced shallow clouds can further enhance the surface dryness. In contrast, when the ambient atmosphere is relatively humid (relative humidity ≥60%), the aerosol-cloud microphysical effect outweighs the cloud burning effect, leading to an increase of shallow clouds and relative humidity near surface. In so doing, aerosols can amplify the original moisture anomalies near the surface. Aerosols have also shown to increase the lifetime of mesoscale convection over Congo and Amazon, due to the delay of the precipitation that enhances ice formation and increased lifetime of the mature and decay phase of deep convection [*Chakraborty et al.*, 2016].

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These modifications are not only related to the direct emission of aerosol, but also to changes in the gas phase chemistry that act as a precursor for the formation of secondary organic aerosol. *Andreae et al.*, [2002] showed large differences in NO_x and ozone (O_3) mixing ratio throughout the Amazon from rather pristine conditions with NO_x and ozone levels below 0.1 ppb and 20 ppb, to values above 0.1 ppb and maximum levels of O_3 near 50 ppb near Manaus. Recent field experiments within the Green Ocean Amazon campaign (GoAmazon) [*Fuentes et al*, 2016; *Martin et al.*, 2016] corroborate these levels as well as the high levels of the bio-organic compounds, in particular isoprene and monoterpene. Closely related, these changes are accentuated by anthropogenic emissions, from Manaus. The unique distribution of aerosols in Amazonia might explain observed differences in deep convection, in particular lightning frequency, between Amazonia, the Maritime continent and the Congo basin [Williams et al. 2004]. To represent these chemistry changes and their effect on convection adequately, the dynamics that drive processes such as the entrainment of pollutants from the free troposphere need to be taken into account [Vila-Guerau de Arellano et al., 2011]. As a result of this interaction between radiation, the land surface, dynamics and chemical processes, the frequency of the clear convective vs. shallow cloudy conditions may be modified in the future. Current efforts in monitoring them and improving the parameterizations of convection are under way [Dias et al., 2014]. These efforts should include also in an integrated manner the combined role of dynamics and chemistry to quantify relevant processes. Two of them are relevant and difficult to be represented in large-scale models. First, the role of canopy in controlling the emission and deposition of the aerosol precursors on tropical rain forest [*Freire et al.*, 2017]. Second ventilation of pollutants from the sub-cloud layer into the cloud layer, i.e. mass flux parameterizations, under representative Amazon conditions [*Ouwersloot et al.*, 2013].

In addition to affecting cloud microphysics, biomass burning in the tropics significantly affects the global carbon budget. For example, in September and October of 2015 fires in the Maritime continent released more terrestrial carbon (11.3 Tg C) than the anthropogenic emissions of the EU (8.9 Tg C) [*Huijnen et al.*, 2016]. The extent of forest fires in this region is tied to El Niño-induced drought conditions, and antecedent sea surface

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temperature (SST) patterns are closely related to burned area at the global scale, particularly in hotspots concentrated in the tropics [*Chen et al., 2016*]. Aerosol emissions and biomass burning exert a strong control on land-atmosphere coupling of the carbon and water cycles, and the consequences of this coupling is observable globally.

5.3 Nonlocal view of tropical land-atmosphere interactions

5.3.1 Moisture tracking and source attribution

A fundamental consideration in the study of the hydrologic cycle over tropical continents is where the moisture for precipitation ultimately derives. In fact, many of the seminal studies of tropical land region water cycle in the 1980s and 1990s focused on the concept of recycling, i.e., the contribution of evapotranspiration over a region of interest to precipitation in that region [*Salathi et al.* 1983, *Brubaker et al.* 1993; *Eltahir and Bras*, 1994; *Trenberth* 1999]. While these early studies typically estimated recycling used bulk formulas derived under simplifying assumptions, more sophisticated approaches for estimating recycling have emerged [*van der Ent et al* 2010, including comprehensive moisture tracking operating on subdaily inputs on models and reanalysis, e.g., the Dynamic Reycling Model [*Dominguez et al.* 2006], the Water Accounting Model (van der Ent et al. 2010), and Lagrangian approaches using parcel dispersion models such as Flexpart [*Gimeno et al.* 2012]. Contemporary estimates of recycling ratios for the Amazon Basin range from 25%-35% [*Zemp et al.* 2014].

These more sophisticated approaches have also enabled identification and quantification of upstream sources of moisture that lead to downstream rainfall over tropical land regions [*Dirmeyer et al.*, 2007; *Drumond et al.*, 2014; *Hoyos et al.*, 2018; *Stohl and James*, 2005]. For example, by combining a Lagrangian back trajectory approach with rainfall and leaf area index data, [*Spracklen et al.*, 2012] quantified the linkage between downstream rainfall amount and upstream air mass exposure to vegetation (Figure 17). Over more than half of the tropical land surface, Spracklen et al. estimate a twofold increase in downstream rainfall for those air masses passing over extensive vegetation compared those passing over little upstream vegetation. Based on these estimates and extrapolating current Amazonian deforestation trends into the future, these authors project wet and dry season rainfall

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Thus far, we have largely viewed land-atmosphere coupling through the lens of local conditions, but how should we modify this

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$\frac{dq}{dt} = S(q)$ (3)
where $S(q)$ is the sum of sources and sinks of specific humidity. In the absence of sources and sinks, (3) implies that the specific humidity of a parcel of air is conserved following the atmospheric flow. In what follows, we consider a vertically-integrated form of (3) such that:
$\langle\frac{\partial q}{\partial t}\rangle = E - P - \langle \mathbf{v_H} \cdot \nabla q\rangle - \langle \omega \frac{\partial q}{\partial p}\rangle$ (4)
Here E and P represent, respectively, the surface evapotranspiration source and the precipitation sink of water vapor, while $\langle ... \rangle$ represents a mass-weighted ... [18]

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decreases of 12 and 21%, respectively, by the year 2050. In some regions, such attributions underscore the importance of upstream land regions as moisture sources: for example, [*Drumond et al.*, 2014] used the FLEXPART model forced with ERA-Interim reanalysis to estimate $E - P$ along trajectories passing over the La Plata Basin in subtropical South America to establish that much of the moisture entering this region derives from the Amazon Basin to the north and west.

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Other analyses using air mass histories have demonstrated

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5.3.2 Large-scale coupling, idealized modeling

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Seasonality and seasonal transitions¶

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Some studies have attempted to frame tropical land-atmosphere interactions in larger-scale, and implicitly non-local, way [*Zeng and Neelin* 1999, *Lintner et al.* 2013; *Berg et al.* 2017; *Langenbrunner et al.* 2019]. For example, Lintner et al. [2013] developed an idealized prototype for diagnosing large-scale land-atmosphere coupling constructed from coupling the vertically-integrated temperature and moisture equations to a simple bucket soil moisture model. From this model, they derived analytic sensitivity of precipitation to soil moisture spatial variation along a transect to various process parameters related to convection and radiation, such as the timescale for convective adjustment and the strength of cloud-radiative feedback. *Schäfli et al.*, [2012] developed a conceptually similar model from which an analytic expression for the ratio of evapotranspired moisture integrated along flow path to precipitation (or recycling ratio) was obtained (Figure 16). Such idealized model frameworks, which consider tropical land-atmosphere interactions by coupling both water and energy cycles, can be helpful in interpreting and diagnosing linkages between local and non-local feedbacks.

5.4 Land-atmosphere interactions and their impact on tropical seasonality

One of the outstanding issues in the study of tropical land region climates involves controls on precipitation seasonality, particularly its regional variability. Generally, the seasonality follows the variation in maximum solar heating, but other factors, such as ocean thermal inertia, topography, dynamics and circulation, and moisture transport, as well as the state of the land surface, can exert considerable influence on the timing and amplitude of tropical land region seasonal evolution. Over the Amazon basin, seasonality exhibits marked

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variation in both latitude and longitude: for example, at 5S, the dry-to-wet transition proceeds from the central Amazon eastward toward the Atlantic coast [*Liebmann and Marengo*, 2001]. It is also worth noting a pervasive tendency for the dry-to-wet season transition to occur much more rapidly than the wet-to-dry transition, as evident in tropical monsoon systems including South Asia, West Africa, and South America.

Analyzing multiple observational and reanalysis products, [*Fu and Li*, 2004] identified a strong influence of surface turbulent fluxes on the dry-to-wet transition and its interannual variability over the Amazon. In particular, their results link earlier wet season onset to wetter conditions in the antecedent dry season: the higher latent fluxes at the end of a wetter dry season encourage weaker convective inhibition (CIN) and enhance CAPE, both of which are more favorable to wet season rainfall occurrence. However, these authors also underscore the participation of the large-scale circulation and its role in establishing a background environment (e.g., moisture convergence) to support wet season rainfall. Incursion of cold fronts into the southern Amazon may act as triggers for rapid initiation of wet season onset once the local thermodynamics become favorable [*Li et al.*, 2006].

Recent research suggests that the land-atmosphere coupling is integral to the earlier occurrence of determining earlier occurrence of wet season onset over western and southern Amazonia, relative to that of eastern Amazonia. Both in situ and satellite ecological observations have consistently shown that rainforests increase their photosynthesis, and thus evapotranspiration (ET), during late dry season across Amazonia (e.g., [*Huete et al.*, 2006; *Lopes et al.*, 2016; *Munger et al.*, 2016; *Wehr et al.*, 2016]). The wet season onset over the Southern Hemisphere portion of western Amazonia occurs during September to October, about two to three months before the Atlantic ITCZ [*Fu et al.*, 2016]. Using several satellite measurements, including the isotopic signature of deuterium in atmospheric water vapor (HDO) and SIF, Wright et al. [2017] have shown that increasing late dry season ET is the primary source of increasing water vapor in the lower troposphere that initiates the increase of deep convection and rainfall over southern Amazonia. In particular, the increase of water vapor with enriched HDO in the boundary layer and free troposphere follows the increase of photosynthesis during late dry season

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prior to wet season onset. During this period, the water vapor HDO is too high to be explained by transport from Atlantic Ocean, and is consistent with that from plant transpiration. Such a moistening of the atmosphere starts in western southern Amazonia, the part of Amazonia that is most remote from the Atlantic Ocean with high biomass. It then progresses towards eastern southern Amazonia. Thus, during the late dry season this appears to contribute to the timing and spatial variation of the initial moistening of the atmosphere, that ultimately lead to wet season onset over southern Amazonia.

Wet season onset over southern Amazonia has been increasingly delayed since the late 1970s [*Marengo et al.*, 2011; *Fu et al.*, 2013]. In addition to the influence of global circulation change, such a change has been attributed to land use. For example, [*Butt et al.*, 2011] have compared long-term rainfall data between deforested and forested areas over part of the southern Amazonia. They observed a significant delay in wet season onset over the deforested areas, consistent with that implied by Wright et al. [2017]. In addition, [*Zhang et al.*, 2008; 2009] have shown that biomass burning aerosols, which peak in late dry season, can also weaken and delay dry to wet season transition by stabilizing the atmosphere, reducing clouds and rainfall.

6 Discussion – conclusions

In this review paper, we have discussed some of the important aspects of land-atmosphere interactions pertaining to the tropics. While our review is by no means exhaustive, it illustrates some of the key processes in the coupled tropical land-atmosphere system acting across multiple spatial and temporal scales, especially in rainforest ecosystems.

We have argued that feedbacks between the land surface and precipitation in the tropics are possibly non-local in nature (for instance due to the weak temperature gradient) and may mostly impact moisture advection from the ocean and the position of deep convection onset. Local rainfall feedback associated with mesoscale heterogeneities appear to be rather small in magnitude, at least compared to the annual-mean rainfall, and not sufficiently spatially systematic to truly affect ecosystem functioning.

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Moreover, we contend that land surface-cloud feedbacks, especially those involving shallow clouds and fog, are critical in terms of regulating light (direct and diffuse), temperature, and water vapor deficit over tropical forest, but such feedbacks have received relatively less attention. Remote sensing platforms provide useful information for quantifying such feedbacks, but these need to be complemented by ground measurements. Eddy-covariance measurements may prove difficult to use, as mesoscale circulations alter the homogeneity assumption of eddy-covariance methods.

We have also discussed errors and biases in the representation of tropical continental climates in current generation climate and Earth system models. Multi-model assessments of soil moisture-precipitation feedback strength in ensembles of earth system models such as [*Koster et al.*, 2004] manifest strong land-precipitation feedbacks in similar transitional regions as the ones observed [*Green et al*., 2017], which seems to be mostly related to modification of the moisture advection penetration distance from the ocean rather than to local feedbacks. These feedbacks appear to be of relatively minor importance in the core of tropical rainforests but are more critical for more marginal rainfall regions (savanna). These regions are of critical importance for the terrestrial global carbon cycle, providing the main terrestrial sink, but might be severely impacted by climate change and droughts in particular [*Laan Luijkx et al.*, 2015]. Whether the interannual variability in surface CO_2 flux in those regions is a zero-sum game with wet years compensating dry years still is an open question especially in the context of rising CO_2 concentration.

The core of rainforests seems to be more affected by radiation feedbacks at relatively small spatial scales (~1km), which can be dramatically influenced by land cover and land use change. Projected rates of future deforestation are poorly constrained, especially regionally, though in recent years, the Congo and Indonesia have experienced increasing deforestation while the deforestation rate in the Amazon has dropped.

Acknowledgments. PG acknowledges new investigator grant NNX14AI36G, DOE Early Career grant DE-SC0014203, NSF CAREER and GoAmazon DE-SC0011094. BRL

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Deleted: Earth system models tend to predict very diverse responses to global warming leading to broad spread in the capacity of rainforests to continue to act as net carbon sinks [*Swann et al.*, 2015] in the future. Indeed, in the Amazon in particular, the models' response varies from becoming much drier to more humid. El Niño events are sometimes thought as a proxy of global warming in the tropics [*Pradipta et al.*, 2016] as they warm the free-troposphere. Nonetheless for continents the change in the Walker circulation associated with El Niño may strongly differ from the change associated with a more uniform sea surface temperature warming in future climate. In particular, mature El Niño events are associated with strong subsidence over Indonesia, increased ascent off the coast of Peru but reduced precipitation over the Amazon basin and a relatively neutral response over the Congo basin. With SST warming across the tropics, the Maritime continent will most likely become wetter [*Byrne and O'Gorman*, 2015; *Wills et al.*, 2016]. The fate of the Amazon basin is less clear, as the climate in the region will be impacted by a combination of free tropospheric warming stabilizing the atmosphere to deep convection while warming of the Atlantic enhances the low-level MSE of inflow into the basin. Additionally, warming-induced changes to large-scale circulation such as the intensity or orientation of low-level Atlantic trade winds could impact Amazonian precipitation change. Knowledge of the Congo basin remains limited but it appears that the basin will become dryer under the combined effect of increased temperature and reduced precipitation [*Greve et al.*, 2014]. One important question involves how the effect of rising [CO_2] modifies surface energy flux partitioning though changes in stomatal physiology and modify the regional climate though land-atmosphere interactions [*Lemordant*, 2016].

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Table 1. The surface friction velocity, subcloud layer height (where the minimum of virtual potential temperature flux occurs), ratio of subcloud layer height and Obukhov length, ratio of surface friction velocity and Deardorff convective velocity scale, and the total number of identified clouds for 12 time instants in each case.

Case	S3	S2	S1	CTL	R1	R2	R3
u_* u_* [m s^{-1}]	0.07	0.14	0.21	0.28	0.35	0.42	0.56
z_i [m]	590	590	590	590	590	610	630
z_i / L	392.1	49.0	14.5	6.1	3.1	1.9	0.8
u_*/ w_* u_*/ w_*	0.10	0.20	0.30	0.40	0.50	0.60	0.79
N_{cloud}	2248	2229	2283	2302	2250	2703	2776

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Figure 12: Land-atmosphere feedback strength (change in the variance due to the feedback) between Precipitation and ET (top) and Photosynthetically Active Radiation (PAR) (bottom) based on recent metric developed by Green et al. [2017] using a multivariate Granger causality approach.

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Figure 15: MODIS visible image of the Northwestern Amazon as the basin transition into the wet season. In the dry season surface heterogeneity whether due to rivers, forest-deforested patches or land-ocean contrast are very clear. In the wet season those sharp gradients disappear as cloud cover mostly dominated by deep convection starts organizing at scales independent from the surface heterogeneity.

Figure 16: Continental recycling ratio, ρ, and recycling length scale, λ, normalized by length scale, L, along the inflow direction x for atmospheric moisture either increasing or decreasing along the inflow path in the idealized model of Schäfli et al. (2012). ρ represents how much of the rainfall is derived from terrestrial evapotranspiration, while λ represents the length scale over which evapotranspired water is removed from the atmosphere via precipitation. Generally ρ increases for larger distances into the continental interior, meaning recycling increases in importance, while λ decreases. From Figure 8 of Schäfli et al. (2012).

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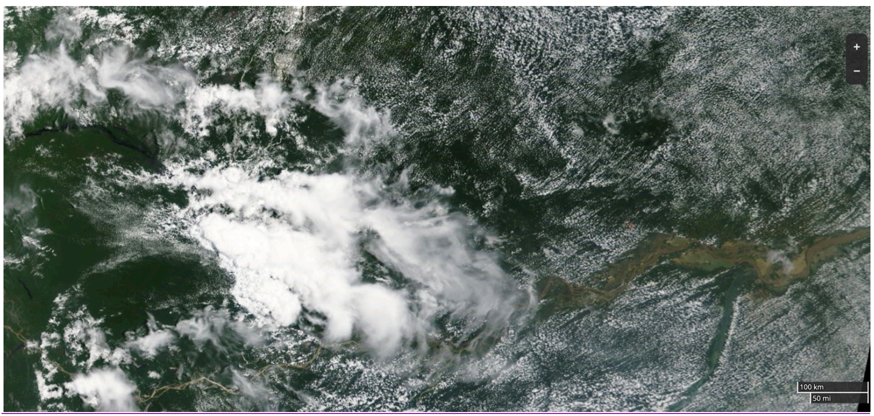
Figure 17: 10 day-back trajectory analysis over several regions of the continental tropics, along with LAI, mean TRMM estimated rainfall, and GLDAS ET estimates.

Figures



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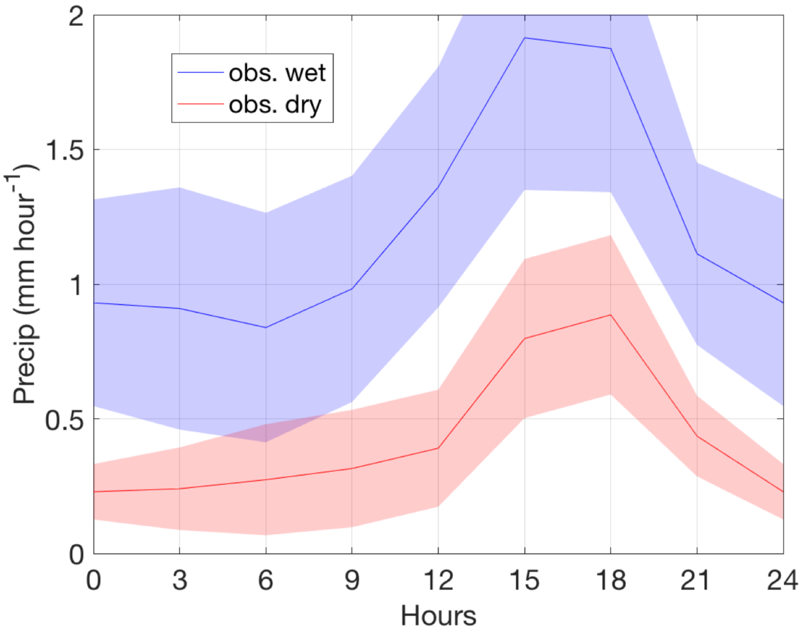

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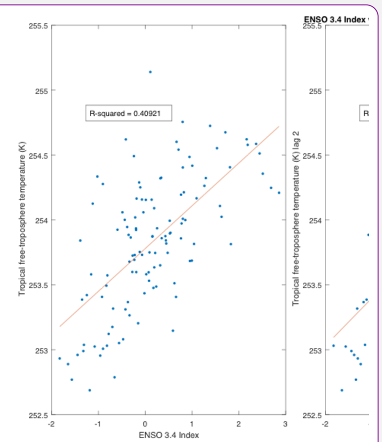

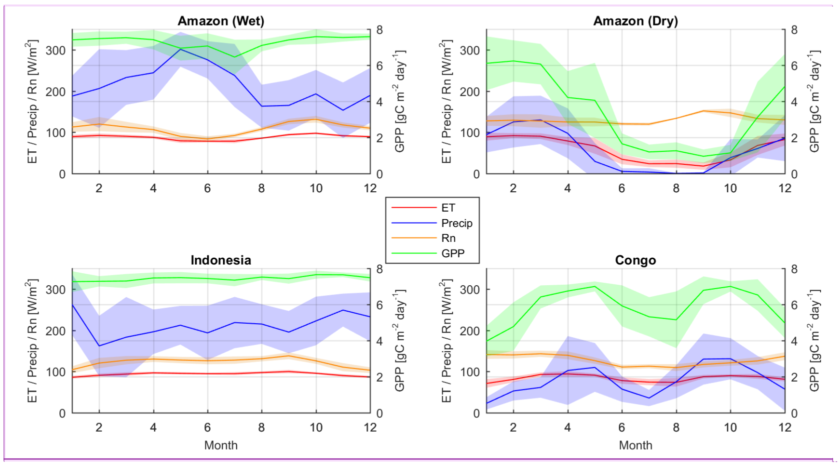

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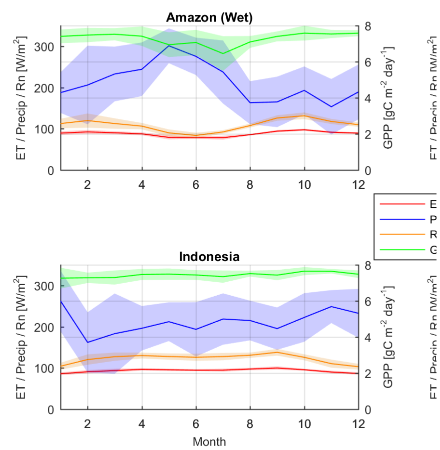

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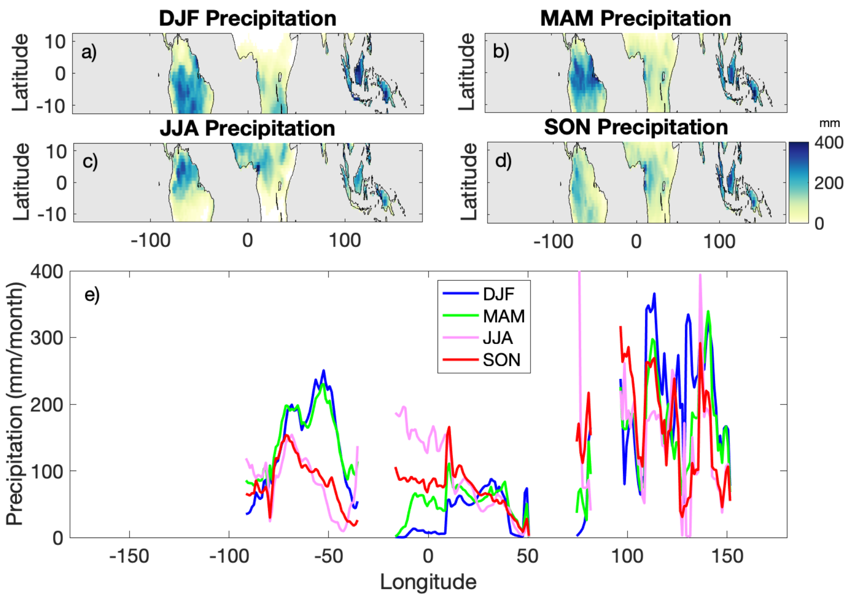

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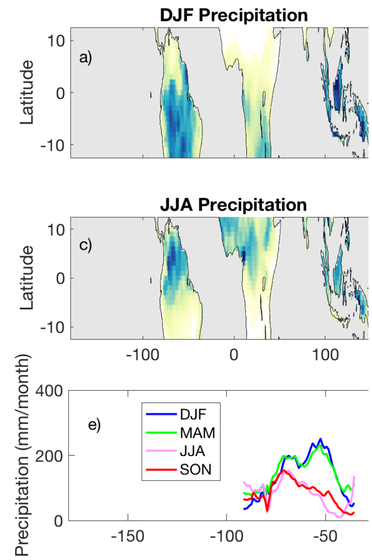

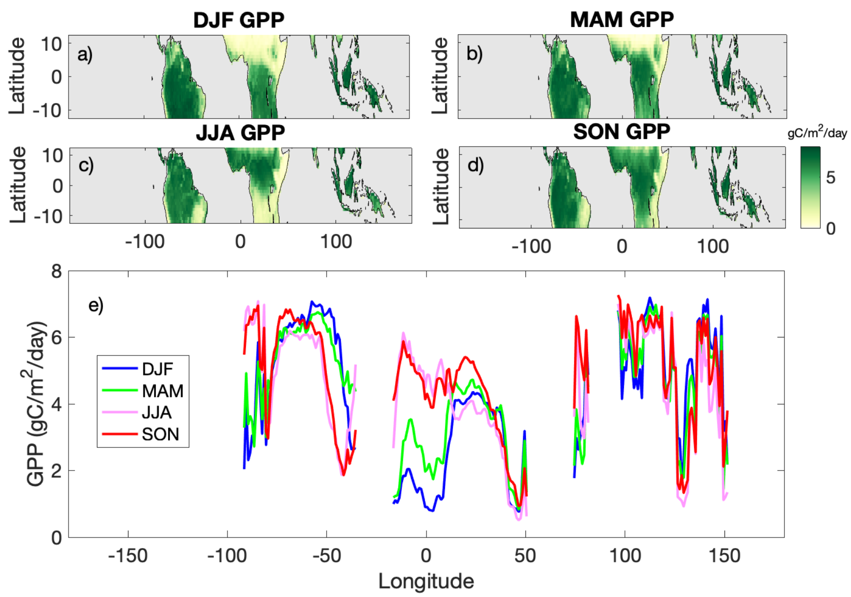

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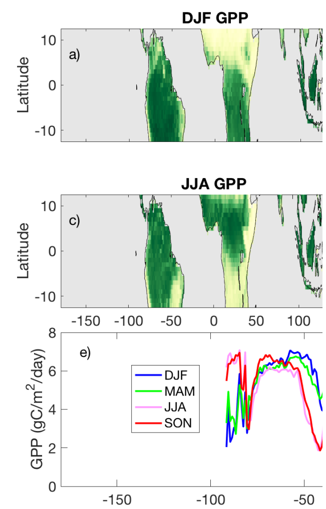

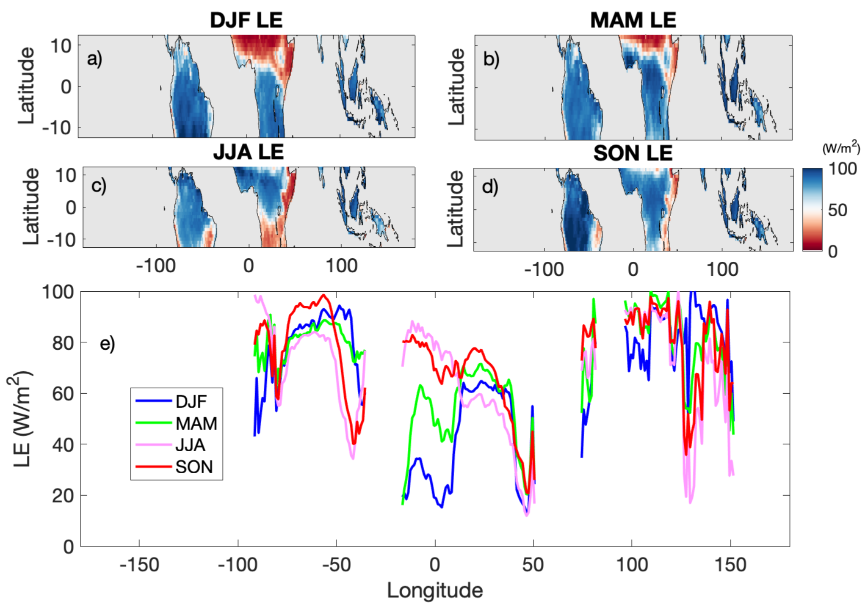

Figure 6: same as Figure 4 for latent heat flux LE

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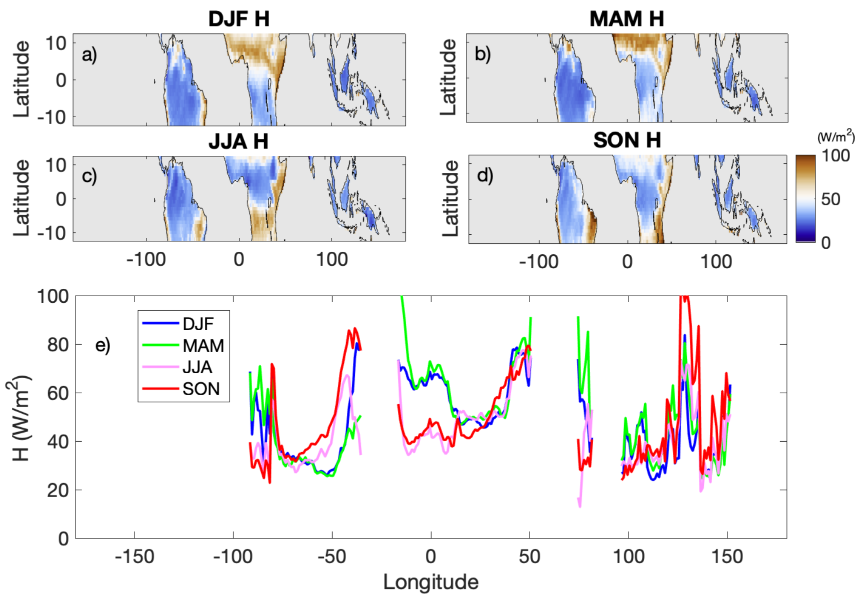

Figure 7: same as Figure 4 for sensible heat flux H

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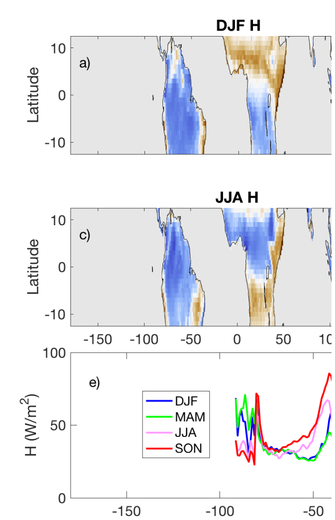

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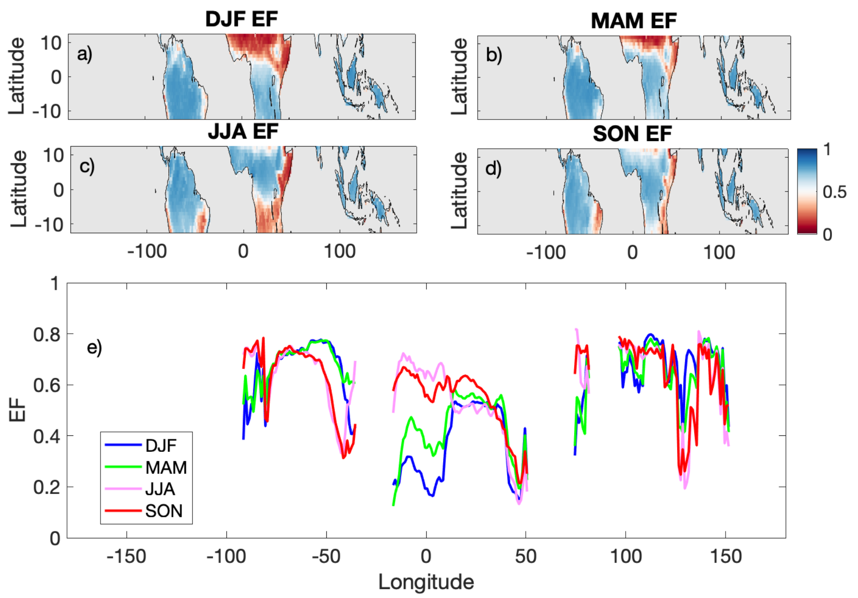

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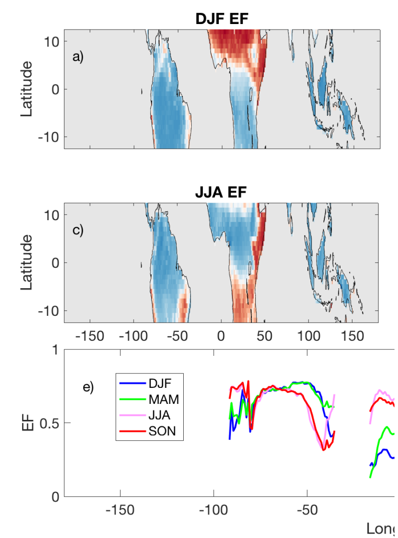

Figure 9: same as Figure 5

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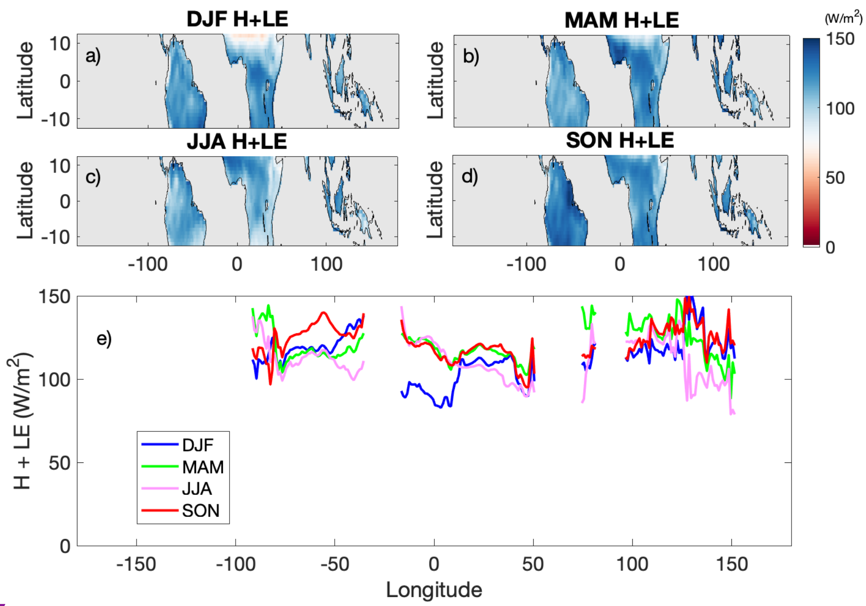
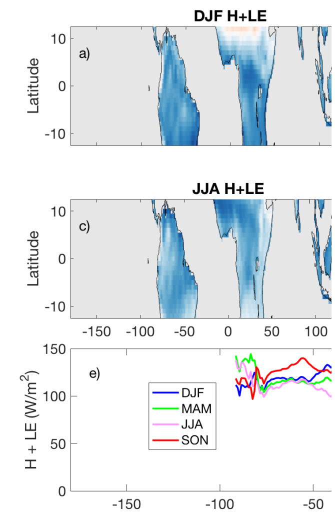


Figure 9: same as Figure 4 for sea-level surface moist static energy flux, the sum of sensible heat flux H and latent heat flux



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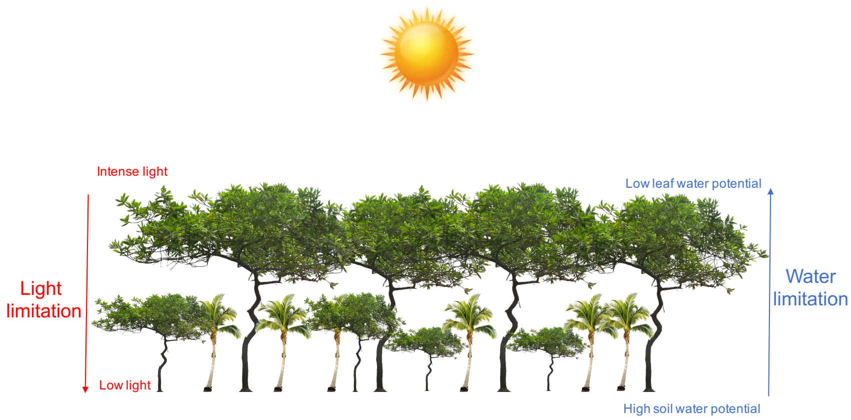

Figure 10: Schematic showing the vertical structure of light and water limitations in a tropical forest.

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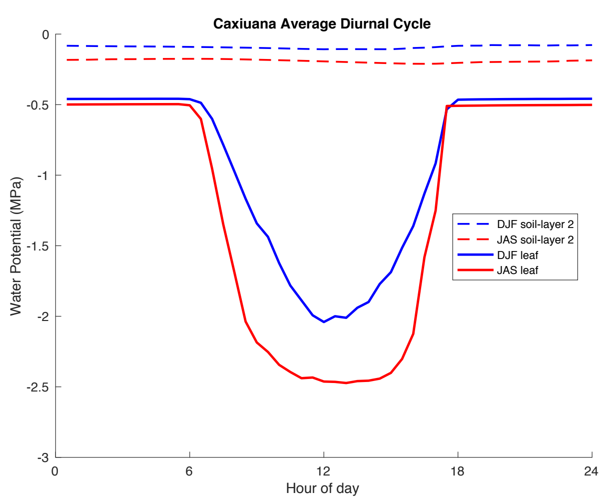


Figure 11: Climatology of the diurnal cycle of leaf water potential and top soil water potential in the dry and wet seasons in Caxiuana, Brazil simulated by the Community Land Model (CLM) with plant hydraulics.

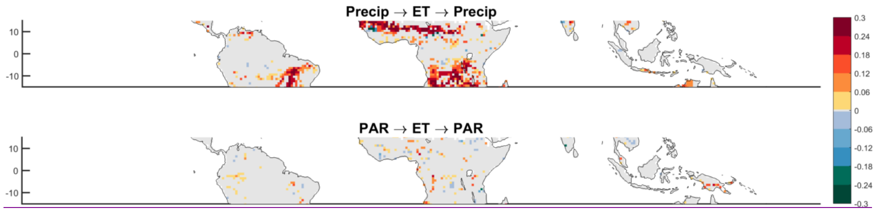
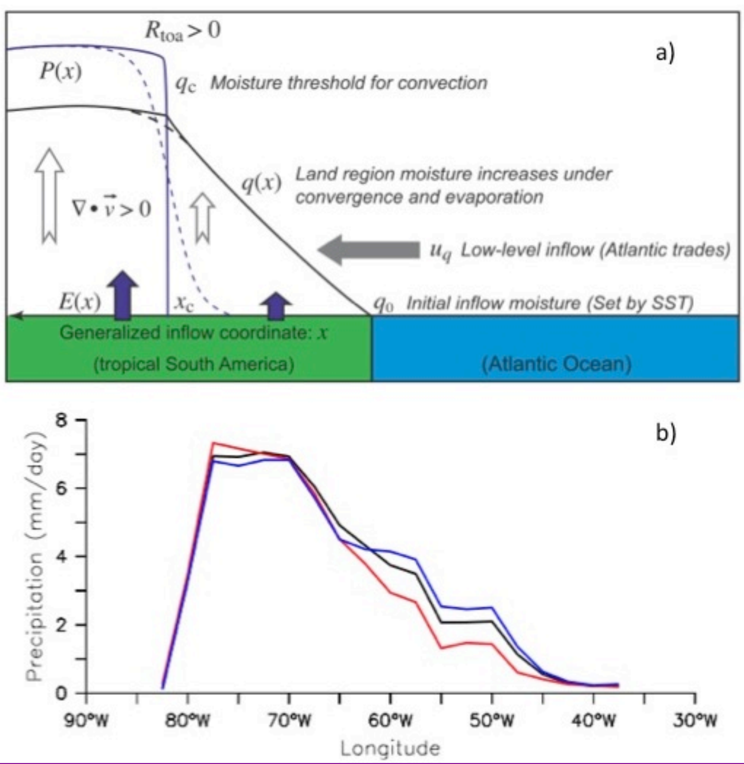


Figure 12: Land-atmosphere feedback strength (change in the variance due to the feedback) between Precipitation and ET (top) and Photosynthetically Active Radiation (PAR) (bottom) based on recent metric developed by Green et al. [2017] using a multivariate Granger causality approach.



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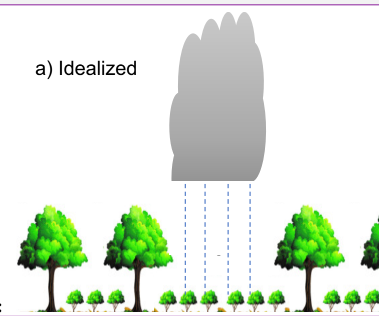

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Figure 13: (a) Schematic of the key elements of the convective margins framework as applied along an inflow path across northeastern South America. The solid blue and black lines are precipitation and vertically-integrated moisture for steady-state conditions, while the dashed blue and black lines correspond to precipitation and vertically-integrated moisture "smeared out" in the presence of time-varying, transient behavior. Adapted from Figure 2 of Lintner and Neelin (2009). (b) Rainfall longitudinal transects from the Climate Anomaly Monitoring System (CAMS) raingauge-derived precipitation data for September-October-November for the period 1950-2000 for El Niño (red), La Niña (blue), and all (black) years, averaged over 3.75°S-1.75°S. From Figure 4b of Lintner and Neelin (2007).

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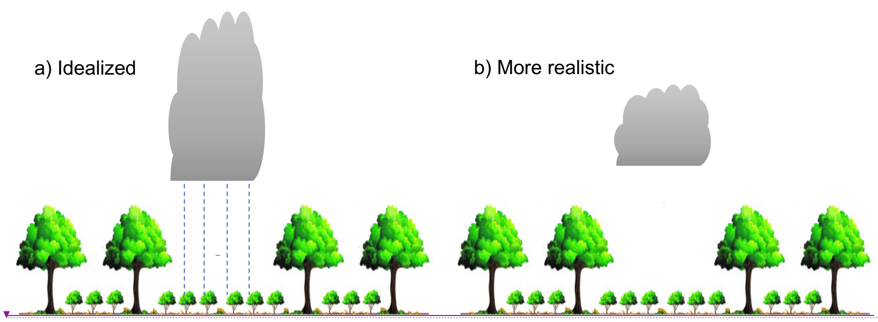

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Figure 14: Mesoscale heterogeneity impact on cloud generation in the dry season. a) Typical perspective regarding the impact of deforestation and clearings generating deep convective clouds and b) more realistic impact, in terms of mostly a modification of shallow convection cloud cover, impacting radiation more than precipitation.

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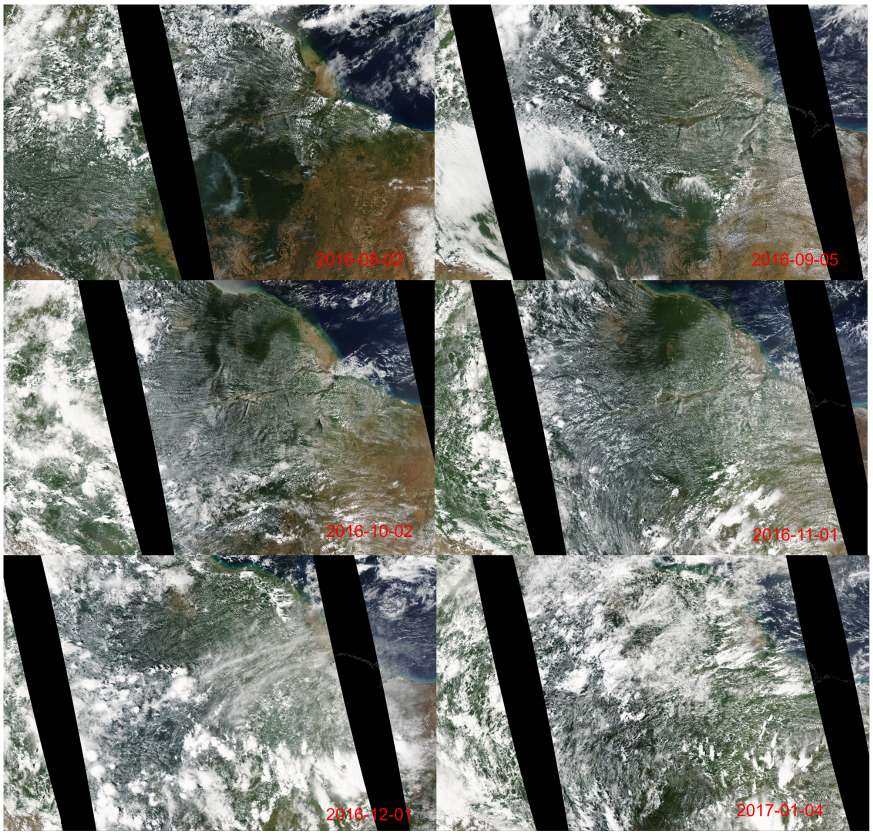
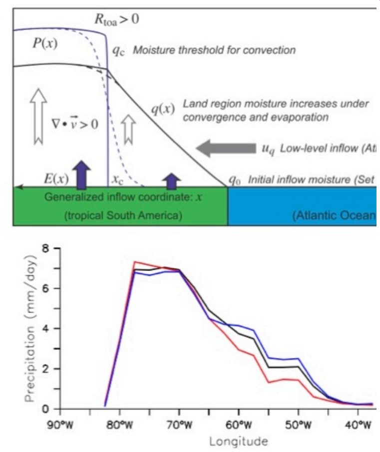


Figure 15: MODIS visible image of the Northwestern Amazon as the basin transition into the wet season. In the dry season surface heterogeneity whether due to rivers, forest-deforested patches or land-ocean contrast are very clear. In the wet season those sharp gradients disappear as cloud cover mostly dominated by deep convection starts organizing at scales independent from the surface heterogeneity.



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Moved up [22]: Adapted from Figure 2 of Lintner and Neelin (2009). (b) Rainfall longitudinal transects from the Climate Anomaly Monitoring System (CAMS) raingauge-derived precipitation data for September-October-November for the period 1950-2000 for El Niño (red), La Niña (blue), and all (black) years, averaged over 3.75°S-1.75°S. From Figure 4b of Lintner and Neelin (2007).¶
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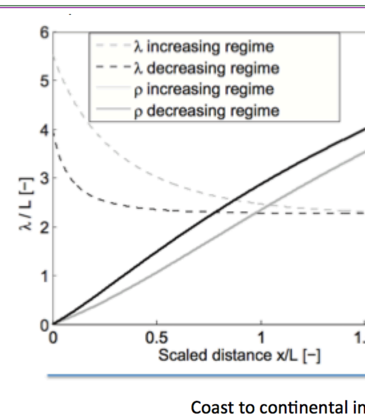

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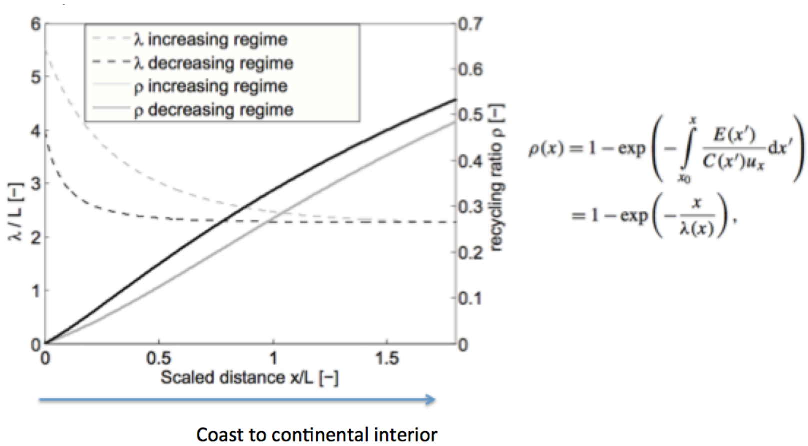

Figure 16: Continental recycling ratio, ρ, and recycling length scale, λ, normalized by length scale, L, along the inflow direction x for atmospheric moisture either increasing or decreasing along the inflow path in the idealized model of Schäfli et al. (2012). ρ represents how much of the rainfall is derived from terrestrial evapotranspiration, while λ represents the length scale over which evapotranspired water is removed from the atmosphere via precipitation. Generally ρ increases for larger distances into the continental interior, meaning recycling increases in importance, while λ decreases. From Figure 8 of Schäfli et al. (2012).

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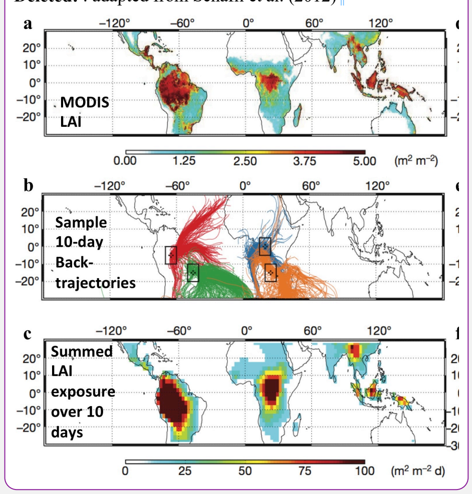

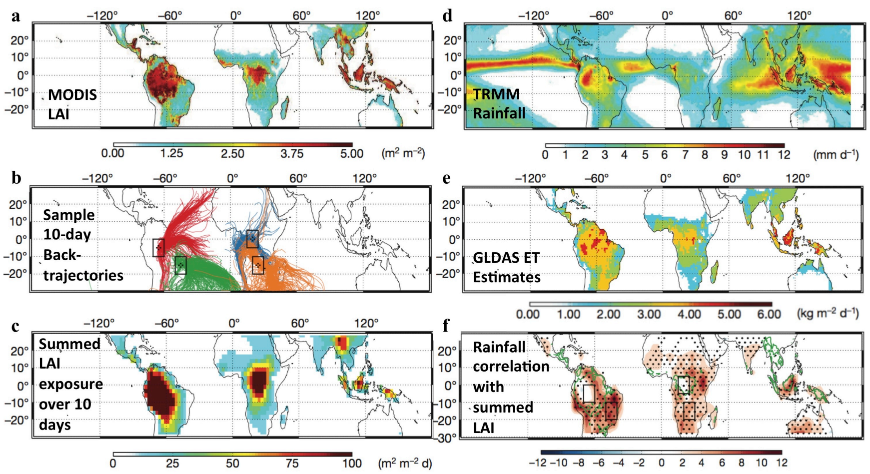

Figure 17: 10 day-back trajectory analysis over several regions of the continental tropics, along with LAI, mean TRMM estimated rainfall, and GLDAS ET estimates.

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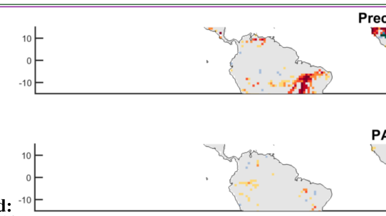

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