

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 processes (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 $\lambda \cdot P$ that is shown, not P .

[Response: indeed this is a good point: we now say: in units of energy \(\$\text{W/m}^2\$, by multiplying it by the latent heat of vaporization\)](#)

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 essentially 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 paper. 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. Spracklen 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 modeling, 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 suggestions 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 thinking 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 unknown 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 capability 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" - necessary?

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 intercepted 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 Geophysical Research-Atmospheres 103, 31593-31612 (1998); published online EpubDec 27 (10.1029/98jd02647).

Harris P. P., C. Huntingford, P. M. Cox, J. H. C. Gash, Y. Malhi, Effect of soil moisture on canopy conductance of Amazonian rainforest. Agricultural and Forest Meteorology 122, 215-227 (2004); published online EpubApr 20 (10.1016/j.agrformet.2003.09.006).

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 cerrado (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 cerrado 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 clarify 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

References

Baker et al., 2013: Surface ecophysiological behavior across vegetation and moisture gradients in tropical south America. *Agricultural and Forest Meteorology*, 182- 182, 177-188, <http://dx.doi.org/10.1016/j.agrformet.2012.11.015>

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1 **Land-atmosphere interactions in the tropics – a review**

Style Definition: Heading 2

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3 Pierre Gentine

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13 Benjamin R. Lintner

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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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115 Some regions of the tropics have been further identified as hotspots in which land-
 116 atmosphere interactions modify the climate [*Dirmeyer et al., 2011; Koster et al., 2011;*
 117 *Green et al., 2017*] either locally, i.e. at horizontal scales on the order of a few boundary
 118 layer heights, regionally, at scales up to a few hundreds of kilometers, or at larger scales,
 119 over several of thousands of kilometers, through coupling between the surface and the
 120 overlying atmosphere [*Lintner and Neelin, 2009*]. These interactions may in turn
 121 dramatically affect the future state of rainforests [*Cox et al., 2004*].
 122

123 While tropical land-atmosphere interactions are often examined through the lens of
 124 coupling between land surface states (e.g., soil moisture) and rainfall, other aspects of the
 125 coupling are also important. For example, even under nonprecipitating conditions, surface
 126 radiation, temperature and vapor pressure deficit (VPD) may be altered [*Lawton et al.,*
 127 *2001; Pielke et al., 2016; Green et al., 2017*] through coupling with clouds, aerosols and
 128 shallow (non-precipitating) convection [*Avissar and Nobre, 2002; Medvigy et al., 2011;*
 129 *Seneviratne, 2013; Cook et al., 2014; Guillod et al., 2015; Krakauer et al., 2016; Martin et*
 130 *al., 2016; Green et al., 2017; Khanna et al., 2017; Martin et al., 2017; Thiery et al., 2017;*
 131 *Vogel et al., 2017*]. In addition, tropical forests can exhibit important variations in canopy
 132 photosynthetic capacity with new leaves [*Lopez et al., 2016; Saleska et al., 2003, 2016*].
 133 These variations can further feed back onto the atmosphere on seasonal time scales [*Green*
 134 *et al., 2017*]. It is clear that the tropical energy, water, and carbon cycles cannot be
 135 understood in isolation; rather, the interactions among these cycles are essential. For
 136 example, knowledge of such interactions must be taken into account to ascertain whether
 137 the terrestrial tropics will act as a future carbon sink or source [*Zhang et al., 2015; Swann*
 138 *et al., 2015*].

139
 140 The two-way interactions that occur between the land surface and overlying atmosphere
 141 represent one of the more uncertain aspects of the terrestrial climate system, particularly in
 142 the Tropics [*Betts and Silva Dias, 2010*]. While the land surface is widely recognized as
 143 integral to the occurrence of important tropical climate phenomena such as monsoons
 144 [*Zeng and Neelin, 1999; Zeng et al., 1999*], isolating and quantifying its precise role
 145 remains elusive. Indeed, such efforts have frequently been hampered by the paucity of

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

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

178
179 Another field campaign, the African Monsoon Multidisciplinary Analysis (AMMA)
180 campaign, focused on the West African monsoon system, especially the Sahel transition
181 zone [Redelsperger et al., 2006; Boone et al., 2009b]. Building on previous field work in
182 the region [e.g. HAPEX-Sahel, Goutorbe et al. 1993], AMMA generated fundamental
183 understanding of mesoscale convective systems and surface processes [Lebel et al., 2009;
184 Taylor et al., 2009; Boone et al., 2009a; Lohou et al., 2010; Couvreux et al., 2011a; 2011b].
185 More recently, the 2014-2015 Green Ocean Amazon (GO-Amazon) campaign [Martin et

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al., 2016] sought to quantify the impact of atmospheric composition and aerosols under clean and polluted conditions on cloud formation and radiation over the Amazon basin, as well as on shallow to deep convection development [Anber et al., 2015a; Tang et al., 2016; Giangrande et al., 2017].

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.

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

249
250 *An important point is that shallow convection is frequently generated by thermals rooted*
251 *in the boundary layer and is thus ultimately related to surface sensible (H) and latent heat*
252 *(LE) flux and their partitioning [Gentine et al., 2013a; 2013b; de Arellano et al., 2014;*
253 *Tawfik et al., 2014, 2015a,b]. Within the Amazon, shallow convection and associated*
254 *clouds frequently occur over the vegetated surface, while over cooler and more humid river*
255 *basins, shallow clouds are virtually absent [Gentine et al., 2013a; Rieck et al., 2014; 2015;*
256 *see also Figure 1]. In addition, shallow convection is strongly influenced by the diurnal*
257 *cycle of surface radiation and surface turbulent heat fluxes [Gentine et al., 2013a; 2013b;*
258 *de Arellano et al., 2014].*

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259
260 *On the other hand, we use the term deep convection in association with deep, precipitating*
261 *clouds. Deep convection may be triggered by a suite of thermodynamic or dynamic*
262 *processes, including: boundary layer thermals [D'Andrea et al., 2014; Guillod et al., 2014;*
263 *Rochetin et al., 2014a; 2014b; Anber et al., 2015a], radiative destabilization [Anber et al.,*
264 *2015b], cold pools (cold density currents due to rain evaporation that cools the air within*
265 *precipitating downdrafts) [Engerer et al., 2008; Del Genio and Wu, 2010; Böing et al.,*
266 *2012; Feng et al., 2015; Torri et al., 2015; Gentine et al., 2016; Heever, 2016; Drager and*
267 *van den Heever, 2017] forced vertical motions such as via mesoscale and large-scale*
268 *circulations [Werth and Avissar, 2002; Roy et al., 2003] or propagating tropical wave*
269 *activity [Kuang, 2008; 2010]. As such, deep convection may be viewed as less dependent*
270 *on the surface state compared to shallow convection.*

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272 *Over the central Amazon a large fraction of wet season precipitation occurs during the*
273 *nighttime (Figure 2). Moreover, during the daytime in both the dry and the wet seasons,*
274 *the diurnal cycle reflects not only locally surface-triggered deep convection*
275 *[Khairoutdinov and Randall, 2006; Ghate and Kollias, 2016] but also propagating*

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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; Couvreur 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 provide indirect 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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 <#>What (where) are the Tropics?¶
 <#>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 $\sim 23\frac{1}{2}^{\circ}$ N and $\sim 23\frac{1}{2}^{\circ}$ 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 $\sim 35^{\circ}$. 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.

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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 CO₂ 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.

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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

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, R_n , 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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734 compensation, the wettest parts of the Amazon exhibit weak ET seasonality. On the other
 735 hand, most land-surface models exaggerate water stress in the Amazon [Powell *et al.*,
 736 2013], and typically exhibit much lower rates of ET and GPP in the dry season, and simulate
 737 opposite seasonality of net ecosystem exchange, compared to observations [de Gonçalves
 738 *et al.*, 2013; Alemohammad *et al.*, 2016; 2017]. This exaggerated water stress results from
 739 incorrect access to deep soil water, whether due to limited groundwater representation
 740 [Maxwell and Condon, 2016], because of the functional relationship of the water stress
 741 representation which does not obey physical constraints (such as flow down potential
 742 gradients as in plant hydraulics models) [Kennedy *et al.*, 2019] or simply because their
 743 assumed rooting depth is too shallow [Fan *et al.*, 2017].

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

752
 753 Turning to the Maritime Continent, rainfall is intense throughout the year and seasonality
 754 is modest, with a short peak in November to January (Figure 3). Much of the seasonal cycle
 755 is attributable to monsoon circulations, which are strongly influenced by topography and
 756 the land- and ocean-surface thermal contrast [Chang 2005]. The topography and the
 757 distribution of island land masses leads to strong local variability (Figure 4e) and
 758 pronounced diurnal cycles in convection are evident [Nitta, 1987; Hamada *et al.*, 2008].
 759 Additionally, the Madden Julian Oscillation, an important mode of climate variability in
 760 the tropical Indo-Pacific with a lifecycle of 30-90 days, strongly impacts rainfall on
 761 intraseasonal timescales [Hidayat and Kizu, 2009]. Convective activity in the region also
 762 regulates the East Asian Monsoon [Huang and Sun, 1992]. The region is also influenced
 763 by topographic effects and land-sea breeze interactions, which may impart considerable
 764 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).

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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].

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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 throughout 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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833 more seasonal variation. The surface moist static energy flux, $H+LE$, shows some slight
 834 variations in SON and JJA but otherwise remains relatively steady across longitudes
 835 because of the compensation between the increased H and reduced ET , in the dry season.
 836 In the dry to wet transition, SON, moist static energy flux exhibits an interesting peak at
 837 about -60 longitude (Figure 9) through the combined increase in radiation, due to reduced
 838 cloudiness, inducing higher sensible heat flux and maintained high ET rates.

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839
 840 Over tropical Africa, the precipitation is highest in JJAS during the wet phase of the West
 841 African Monsoon, with a secondary maximum in DJF corresponding to the Southern
 842 African Monsoon (Figure 4). Similarly the latitudinal-averaged GPP and ET increase
 843 during the West African Monsoon (Figure 5, Figure 6), accompanied by a strong decrease
 844 in sensible heat flux (Figure 7). In DJF the southern African Monsoon displays increased
 845 water flux (Figure 6) and photosynthesis tracking the increased rainfall (Figure 4). The
 846 Congo rainforest clearly exhibits two brief rainy seasons (Figure 3, Figure 8), with peaks
 847 in March-April-May and September-October-November (Figure 3) and displays
 848 substantial water stress and strong reduction in EF to values below 0.6 during the dry
 849 season (Figure 8).

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851 4 Vegetation and ecosystem processes in the Tropics

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

860
 861 One outstanding challenge in simulating tropical land regions is determining why most
 862 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].

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5 Tropical land-atmosphere interactions: Local and nonlocal perspectives

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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

1011 between convective and large-scales. We will revisit the seasonality of tropical climate
1012 through the lens of these local and nonlocal perspectives of land-atmosphere interactions.

1014 5.1 Quantifying land-atmosphere interactions

1015 [Green et al., 2017] recently developed a method to define the feedback between the
1016 biosphere and atmosphere using multivariate conditional Granger causality (based on
1017 lagged autoregressive vectors). We here use a similar framework using ET from WECANN
1018 and precipitation from GPCP as well as photosynthetically active radiation from CERES
1019 (Figure 12).

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1021 Most of the feedback between surface ET and precipitation occurs in the climatically
1022 transitional and/or monsoonal regions, such as the savanna region of Northeastern Brazil
1023 and the monsoonal regions over South Asia, the Sahel, Southern Africa, and Northern
1024 Australia. In Brazil, these results are consistent with spatial transition inherent in the
1025 convective margins concept introduced by Lintner and Neelin (2007; see also Figure 13)
1026 and the impact of soil moisture and evapotranspiration on setting the location of the
1027 transition between the dry and wet regions. The Sahelian and Southern African Monsoon
1028 are also located in regions between very dry (deserts) and humid regions, where surface
1029 feedback may be crucial for the penetration of the Monsoonal flow inland [Lintner and
1030 Neelin, 2009; Lintner et al., 2015]. Indeed, the biosphere in this region modulates the local
1031 climate state: multiple equilibrium states, corresponding to different ecosystem initial
1032 conditions, may exist under the same external (e.g., top of the atmosphere solar) forcing
1033 [Wang et al., 2000]. The effect of vegetation on land-atmosphere coupling manifests itself
1034 at multiple timescales. At short timescales after precipitation, evaporation is accelerated
1035 with intercepted water in the canopy. However, at longer timescales vegetation acts to
1036 delay and prolong evaporation of water stored in the root zone. The magnitude and
1037 timescale of these sources of water recycling vary depending on ecosystem structure,
1038 including rooting depth and canopy structure, which may co-evolve with atmospheric
1039 conditions at the interannual timescale [Nicholson, 2000]. This represents a clear pathway
1040 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.

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<#>We suggest that that the most

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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1082 season, especially in the morning [Anber *et al.*, 2015a; Giangrande *et al.*, 2017], which in
 1083 turn leads to strong reduction in GPP and ET. These clouds are also tightly connected to
 1084 surface processes and especially the surface energy partitioning. Indeed, nighttime fog,
 1085 which often persists into the early daylight hours, This fog is due to nighttime longwave
 1086 cooling in very humid boundary layers, due for instance to evening rain in the wet season,
 1087 [Anber *et al.*, 2015a]. Shallow clouds are themselves directly forced by surface-generated
 1088 thermals, i.e. boundary layer processes, and they are modified by the sensible and latent
 1089 heat flux magnitude [de Arellano *et al.*, 2014, 2019]. Shallow convection and low-cloud
 1090 cover are also tightly connected to ecosystem seasonality, and to the diurnal cycle [Anber
 1091 *et al.*, 2015a; Tang *et al.*, 2016; Giangrande *et al.*, 2017].

1092
 1093 Historically, the study of land-atmosphere interactions in the Tropics, and tropical
 1094 rainforests in particular, has emphasized effects of heterogeneity, especially due to
 1095 deforestation, on the generation of deep convection through mesoscale circulations (see
 1096 [Lawrence and Vandecar, 2015] for a complete review, as well as [Avissar and Pielke,
 1097 1989; Pielke and Avissar, 1990; Pielke *et al.*, 1991; Dalu *et al.*, 1996; Avissar and Schmidt,
 1098 1998; Taylor *et al.*, 2007; 2009; 2011; Rieck *et al.*, 2015; Khanna *et al.*, 2017]). The
 1099 hypothesis behind this is that deforestation reduces EF and surface roughness [Khanna *et al.*, 2017].
 1100 The associated increased buoyancy flux over the deforested areas, mostly
 1101 reflecting a shift toward increased sensible heating, induces mesoscale circulations. These
 1102 circulations enhance cloudiness through local buoyancy fluxes, turbulent kinetic energy
 1103 generation, and low-level moisture advection from adjacent forested areas, thus providing
 1104 all the key ingredients for moist convection generation [Rieck *et al.*, 2014; 2015]. It seems
 1105 unlikely however that momentum roughness plays a major role in this high radiation
 1106 environment [Park *et al.*, 2017], where circulations are mostly buoyancy-driven. Instead,
 1107 the heat and moisture roughness lengths [Park *et al.*, 2017] as well as leaf area index and
 1108 stomatal conductance, which scales the magnitude of the evapotranspiration flux, are the
 1109 main players, in addition to changes in soil moisture availability, for the circulation. The
 1110 impact of the deforestation on surface fluxes and local circulation can change from
 1111 buoyancy-driven to surface roughness driven as the spatial scale of the deforestation
 1112 increases [Khanna *et al.* 2017].

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1123
1124 Induced mesoscale circulations and associated deep convection are clearly observable with
1125 remote sensing observations [Khanna *et al.*, 2017] and are more important in the dry season
1126 [Khanna *et al.*, 2017], when convection is more locally, and regionally, triggered [Anber
1127 *et al.*, 2015a; Ghate and Kollias, 2016]. Once precipitation occurs, cold pools, i.e., density
1128 currents induced by ice melt and evaporating rain in downdrafts, dominate the surface-
1129 induced mesoscale circulation [Rieck *et al.*, 2015], and reduce the surface heterogeneity
1130 signal. In the wet season, the relative contribution of local forcing to the total rainfall is
1131 small as the bulk of the precipitation is due to mesoscale convective systems or larger-scale
1132 systems propagating throughout the basin, less tightly connected to surface and boundary
1133 layer processes [Ghate and Kollias, 2016].

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1134
1135 Even during the dry season, a large fraction of the Amazon and of Indonesia only
1136 experience minimal water stress (Figure 8 and Figure 7) so that increased radiation
1137 generates higher rates of photosynthesis (Figure 5) and ET (Figure 6) [Anber *et al.*, 2015a].
1138 Indeed, higher transpiration in the dry season (due to the higher demand which is not
1139 entirely compensated by the slight water stress) can compensate the effect of reduced rain
1140 reevaporation intercepted by the canopy. As a result the feedback loop between
1141 precipitation and ET is weakened and the impact of the dry season on ET (and hence
1142 clouds) is strongest (Figure 14). In addition, the feedback of shallower clouds and surface
1143 radiation may be more important, Figure 14, than the feedback of deeper clouds and
1144 precipitation, as those shallow clouds are preferentially triggered over drier surfaces.
1145 Because shallow clouds have a small life cycle (typically less than 30 minutes) compared
1146 to deep convective and mesoscale systems, they are more directly connected to the
1147 underlying surface conditions and interact more with the local conditions.

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1148
1149 Fewer studies have studied changes in shallow clouds [Wang *et al.*, 2000; Lawton *et al.*,
1150 2001; Chagnon *et al.*, 2004; Ray *et al.*, 2006; Wang *et al.*, 2009; Pielke *et al.*, 2011; Rieck
1151 *et al.*, 2014; Anber *et al.*, 2015a], even though the impact of changes in the surface energy
1152 partitioning and heterogeneity on low-level clouds is clear and spatially systematic (Figure
1153 15). Given the importance of cloud cover on shortwave radiation and their importance for

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1161 the differentiation between the dry and wet seasons over wet tropical rainforests we believe
 1162 that this low-cloud feedback might be quite critical for rainforest ecosystem functioning.
 1163 Indeed it was pointed out by [Morton *et al.*, 2014; Anber *et al.*, 2015a; Morton and Cook,
 1164 2016] that light changes between the dry and wet season due to changes in cloud cover
 1165 were one of the primary reasons for changes in the seasonality of surface fluxes, in addition
 1166 to leaf flush out [Lopes *et al.*, 2016; Saleska *et al.*, 2016]. At sub-daily scales, the shading
 1167 due to low clouds reduces surface temperature and ecosystem respiration [Mahecha *et al.*,
 1168 2010; Peterhansel and Maurino, 2011; Thornley, 2011; Hadden and Grelle, 2016;
 1169 Ballantyne *et al.*, 2017]. This reduction depends strongly on the cloud cycling and
 1170 thickness. As a result, cloud-induced reductions in respiration can cancel reductions in
 1171 photosynthesis, such that the net effect of cloud shading on net ecosystem exchange is
 1172 unclear. Horn *et al.* [2015] showed that by explicitly calculating the surface coupling leads
 1173 to a change in the length scales of clouds, and a reduction of the cloud life time. As a result,
 1174 and although the cloud cover remains almost the same there are larger populations of
 1175 smaller shallow cumuli. This responses to vegetation influence also the moisture transport
 1176 and the cloud characteristics [Sikma *et al.*, 2019].

1177
 1178 In addition to regulating radiative energy balance at the surface, [Wright *et al.*, 2017] have
 1179 shown that shallow convection transports moisture, provided by plants' transpiration, from
 1180 the atmospheric boundary layer to the lower troposphere during the late dry season and
 1181 early dry to wet transition seasons (July-September) [Fu and Li, 2004]. This mechanism,
 1182 referred to as the "shallow convective moisture pump", plays an important role in priming
 1183 the atmosphere for increasing deep convection (e.g., [Schiro *et al.*, 2016; Zhuang *et al.*,
 1184 2017]), and wet season onset over the Amazon [Wright *et al.*, 2017].

1185
 1186 The results discussed until now omitted the relation between physical processes and the
 1187 atmospheric composition, and more specifically the role of chemical reactions and
 1188 aerosols. Over rainforests, the pristine and undisturbed conditions of the atmospheric
 1189 boundary layer described in the seminal study by [Garstang and Fitzjarrald, 1999] are
 1190 currently undergoing rapid changes due to atmospheric composition modifications. Their
 1191 direct impact on the radiative and microphysical properties are due to biomass burning and

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1205 enhancement of concentrations of secondary organic aerosol precursors. Biomass burning
 1206 in Amazonia leads to **increased** aerosol optical depth and to abnormal distributions of the
 1207 heating rate profile. Analyzing systematic experiments performed by large-eddy
 1208 simulations, *Feingold et al.*, [2005] studied the processes that lead to the suppression of
 1209 clouds. Firstly, at the surface there **are** clear indications that the latent and sensible heat
 1210 flux are reduced, yielding convective boundary layers characterized by less turbulent
 1211 intensity and by delays in the morning transition [*Barbaro and Vilà-Guerau de Arellano*,
 1212 2014]. Both aspects tend to reduce cloud formations. Secondly, [*Barbaro and Vilà-Guerau*
 1213 *de Arellano*, 2014] indicated that the vertical location of the smoke layer is crucial in
 1214 determining **the dynamics of the boundary layer which can delay the onset of shallow**
 1215 **cumulus. In turn, and ass.** As described by [*Feingold et al.*, 2005], smoke confined in the
 1216 well-mixed sub-cloud layer might positively benefit the cloud formation since it distributes
 1217 the heat uniformly that contributes to enhance convection. On the other hand, smoke layers
 1218 located within the cloud layer tend to stabilize the cloud layer and therefore decrease the
 1219 possibility of cloud formation. These results are very much dependent on the aerosol
 1220 optical properties defined by their heating, scattering and hygroscopic properties. As a first
 1221 indicative figure, the mentioned LES study and observations by [*Koren et al.*, 2004]
 1222 stressed that smoke layers with an aerosol optical depth larger than 0.5 might already lead
 1223 to cloud suppression by 50%. *Yu et al.*, [2008] have shown observationally that the
 1224 influence of aerosols on shallow clouds varies with meteorological conditions. When the
 1225 ambient atmosphere is drier (relative humidity $\leq 60\%$), cloud burning effect (evaporation
 1226 of cloud droplets) due to increased absorption of solar radiation by aerosols **outweighs** the
 1227 increase of cloud droplets due to aerosol-cloud microphysical effect. The reduced shallow
 1228 clouds can further enhance the surface dryness. In contrast, when the ambient atmosphere
 1229 is relatively humid (relative humidity $\geq 60\%$), the aerosol-cloud microphysical effect
 1230 **outweighs** the cloud burning effect, leading to an increase of shallow clouds and relative
 1231 humidity near surface. In so doing, aerosols can amplify the original moisture anomalies
 1232 near the surface. Aerosols have also shown to increase **the lifetime** of mesoscale convection
 1233 over Congo and Amazon, due to **the** delay of the precipitation that enhances ice formation
 1234 and **increased** lifetime of the mature and decay phase of deep convection [*Chakraborty et*
 1235 *al.*, 2016].

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1251
 1252 These modifications are not only related to the direct emission of aerosol, but also to
 1253 changes in the gas phase chemistry that act as a precursor for the formation of secondary
 1254 organic aerosol. *Andreae et al.*, [2002] ~~showed large~~ differences in NO_x and ozone (O₃)
 1255 mixing ratio ~~throughout the Amazon from~~ rather pristine conditions with NO_x and ozone
 1256 levels below 0.1 ppb and 20 ppb, to values above 0.1 ppb and maximum levels of O₃ near
 1257 50 ppb ~~near Manaus~~. Recent field experiments within the Green Ocean Amazon campaign
 1258 (GoAmazon) [*Fuentes et al.*, 2016; *Martin et al.*, 2016] corroborate these levels as well
 1259 as the high levels of the bio-organic compounds, in particular isoprene and monoterpene.
 1260 Closely related, these changes are accentuated by anthropogenic emissions, ~~from~~ Manaus.
 1261 The unique distribution of aerosols in Amazonia might explain observed differences in
 1262 deep convection, in particular ~~lightning~~ frequency, between Amazonia, the Maritime
 1263 continent and the Congo basin [*Williams et al.* 2004]. To represent these chemistry changes
 1264 and their effect on convection adequately, the ~~dynamics~~ that drive processes such as the
 1265 entrainment of pollutants from the free troposphere need to be taken into account [*Vila-*
 1266 *Guerau de Arellano et al.*, 2011]. As a result of this interaction between radiation, the land
 1267 surface, dynamics and chemical processes, the ~~frequency of the clear convective vs.~~
 1268 shallow cloudy ~~conditions~~ may be modified in the future. Current efforts in monitoring
 1269 them and improving the parameterizations of convection are under way [*Dias et al.*, 2014].
 1270 These efforts should include also in an integrated manner the combined role of dynamics
 1271 and chemistry to quantify relevant processes ~~Two of them are relevant and difficult to be~~
 1272 ~~represented in large-scale models. First, the role of canopy in controlling the emission and~~
 1273 ~~deposition of the aerosol precursors on tropical rain forest~~ [*Freire et al.*, 2017]. ~~Second~~
 1274 ventilation of pollutants from the sub-cloud layer into the cloud layer, i.e. mass flux
 1275 parameterizations, under representative Amazon conditions [*Ouwensloot et al.*, 2013].
 1276
 1277 In addition to affecting cloud microphysics, biomass burning in the tropics significantly
 1278 affects the global carbon budget. For example, in September and October of 2015 fires in
 1279 the Maritime continent released more terrestrial carbon (11.3 Tg C) than the anthropogenic
 1280 emissions of the EU (8.9 Tg C) [*Huijnen et al.*, 2016]. The extent of forest fires in this
 1281 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 Recycling 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

Deleted: in light of remote influences (see WTG discussion) or coupling between local and larger-scale conditions? Here we illustrate some aspects of how land-atmosphere coupling in the Tropics is impacted by the larger-scale. ¶

Deleted: Consider the Lagrangian tendency equation for conservation of atmospheric water vapor, expressed in terms of specific humidity q : ¶

$$\frac{dq}{dt} = S(q) \rightarrow (3) \quad \text{¶}$$

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: ¶

$$\left\langle \frac{\partial q}{\partial t} \right\rangle = E - P - \langle \mathbf{v}_H \cdot \nabla q \rangle - \left\langle \omega \frac{\partial q}{\partial p} \right\rangle \rightarrow (4) \quad \text{¶}$$

Here E and P represent, respectively, the surface evapotranspiration source and the precipitation sink of water vapor, while $\langle \dots \rangle$ represents a mass-weighted [18]

Deleted: by coupling both water and energy cycles, [19]

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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.

5.3.2 Large-scale coupling, idealized modeling

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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Other analyses using air mass histories have demonstrated

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1563 variation in both latitude and longitude: for example, at 5S, the dry-to-~~wet~~ transition
 1564 proceeds from the central Amazon eastward toward the Atlantic coast [*Liebmann and*
 1565 *Marengo*, 2001]. It is also worth noting a pervasive tendency for the dry-to-wet season
 1566 transition to occur much more rapidly than the wet-to-dry transition, as evident in tropical
 1567 monsoon systems including South Asia, West Africa, and South America.

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1568
 1569 Analyzing multiple observational and reanalysis products, [*Fu and Li*, 2004] identified a
 1570 strong influence of surface turbulent fluxes on the dry-to-wet transition and its interannual
 1571 variability over the Amazon. In particular, their results link earlier wet season onset to
 1572 wetter conditions in the antecedent dry season: the higher latent fluxes at the end of a
 1573 wetter dry season encourage weaker convective inhibition (CIN) ~~and enhance~~ CAPE, both
 1574 of which are more favorable to wet season rainfall occurrence. However, these authors also
 1575 underscore the participation of the large-scale circulation and its role in establishing a
 1576 background environment (e.g., moisture convergence) to support wet season rainfall.
 1577 Incursion of cold fronts into the southern Amazon may act as triggers for rapid initiation
 1578 of wet season onset once the local thermodynamics become favorable [*Li et al.*, 2006].

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1579
 1580 Recent ~~research suggests~~ that the land-atmosphere coupling ~~is integral to the earlier~~
 1581 ~~occurrence of determining earlier occurrence of~~ wet season onset over western and
 1582 southern Amazonia, relative to that of eastern Amazonia. Both in situ and satellite
 1583 ecological observations have consistently shown that rainforests increase their
 1584 photosynthesis, ~~and~~ thus evapotranspiration (ET), during late dry season across Amazonia
 1585 (e.g., [*Huete et al.*, 2006; *Lopes et al.*, 2016; *Munger et al.*, 2016; *Wehr et al.*, 2016]). The
 1586 wet season onset over the ~~Southern Hemisphere portion of~~ western Amazonia occurs
 1587 during September to October, about two to three months before the Atlantic ITCZ [*Fu et*
 1588 *al.*, 2016]. Using several satellite measurements, including the isotopic signature of
 1589 deuterium ~~in~~ atmospheric water vapor (HDO) and SIF, Wright et al. [2017] have shown
 1590 that ~~increasing~~ late dry season ET is the primary source of increasing water vapor in the
 1591 lower troposphere that initiates the increase of deep convection and rainfall over southern
 1592 Amazonia. In particular, the increase of water vapor with enriched HDO in the boundary
 1593 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.

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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.

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6 Discussion – conclusions

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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.

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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.

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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 Luijckx et al., 2015]. Whether the interannual variability in surface CO₂ 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 CO₂ concentration.

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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 [CO₂] 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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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.

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1728 Foundation.
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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
$u_* \text{ [m s}^{-1}\text{]}$	0.07	0.14	0.21	0.28	0.35	0.42	0.56
$z_i \text{ [m]}$	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_*	0.10	0.20	0.30	0.40	0.50	0.60	0.79
N_{cloud}	2248	2229	2283	2302	2250	2703	2776

List of Figures

Figure 1: Snapshot of cloud cover over the Amazon basin on 2018, Sept 25 (courtesy NASA Earth Observatory, MODIS visible bands). Small clouds are shallow convective clouds, highlighting surface Bowen ratio changes between the river and the forest. On the left, the deep convective cells do not follow the surface heterogeneity (and is much larger in scale). Not the cold pool bow effect on the bottom left corner, with no clouds within the cold pools and clouds on the edge of the cold pool.

Figure 2: Diurnal cycle in local hour of dry (red) and wet (blue) season observations of precipitation at K34, near Manaus, along with their standard deviation averaged across years 2010-2014.

Figure 3: Seasonal variations in Evapotranspiration (ET) from WECANN, Precipitation (Precip) based on GPCP in units of energy (W/m², by multiplying it by the latent heat of vaporization). Net Radiation (Rn) from CERES and Gross Primary Production (GPP) based on WECANN informed by Solar-Induced Fluorescence (SIF) over the wet part of the Amazon (top left), the Savanna region of Brazil (top right), over Indonesia (bottom left) and over the Congo basin (bottom right).

Figure 4: Seasonality of Precipitation based on GPCP in the tropics in December-January-February (a), March-April-May (b), June-July-August (c), and September-October-November (SON) and its latitudinal average (e).

Figure 5: same as Figure 4 but for Gross Primary Production (GPP)

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

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

Figure 8: same as Figure 4 for evaporative fraction (EF), the ratio of LE to H+LE.

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

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

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.

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Deleted: Figure 3: Response of tropically-averaged free tropospheric temperature between 700mb and 200mb to El Niño Southern Oscillation (choosing the ENSO 3.4 index)

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Figures

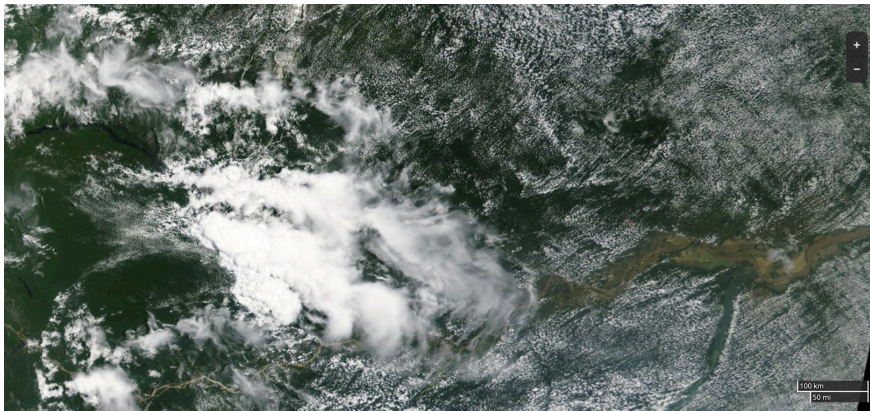


Figure 1: Snapshot of cloud cover over the Amazon basin on 2018, Sept 25 (courtesy NASA Earth Observatory, MODIS visible bands). Small clouds are shallow convective clouds, highlighting surface Bowen ratio changes between the river and the forest. On the left, the deep convective cells do not follow the surface heterogeneity (and is much larger in scale). Not the cold pool bow effect on the bottom left corner, with no clouds within the cold pools and clouds on the edge of the cold pool.

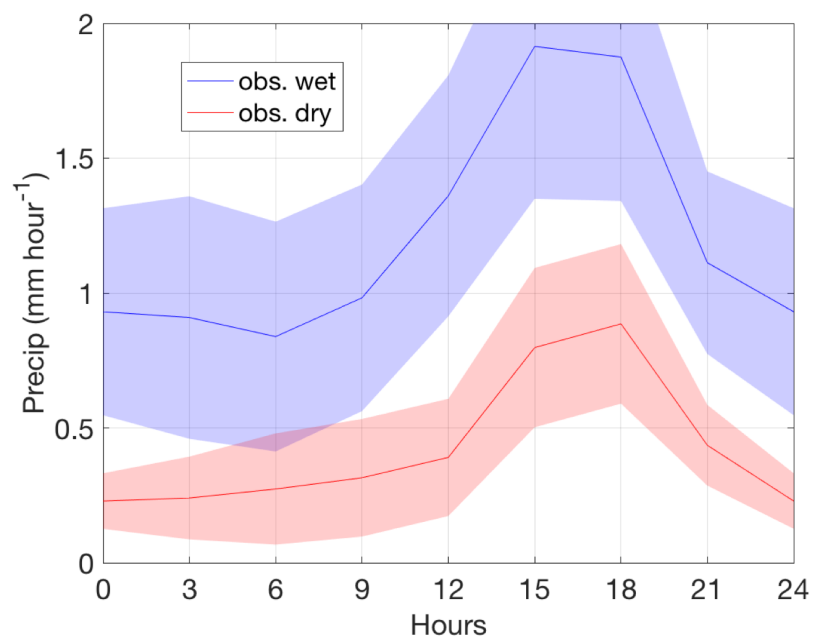
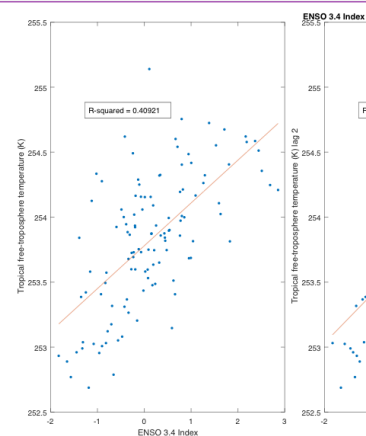


Figure 2: Diurnal cycle in local hour of dry (red) and wet (blue) season observations of precipitation at K34, near Manaus, along with their standard deviation averaged across years 2010-2014.

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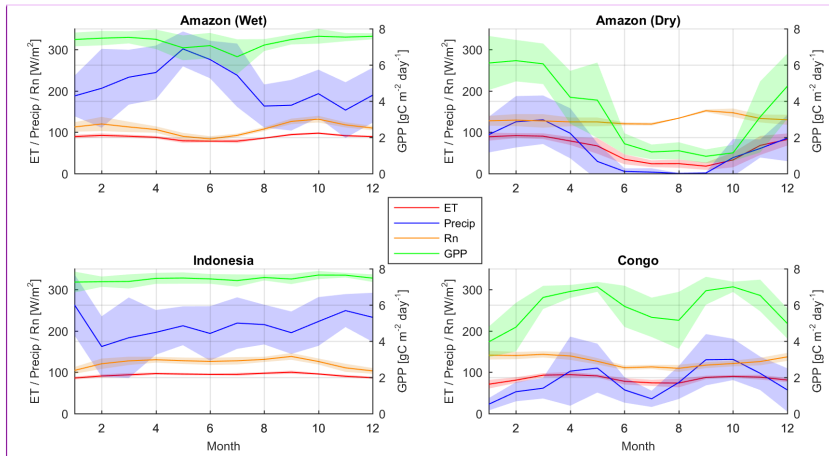


Figure 3: Seasonal variations in Evapotranspiration (ET) from WECANN, Precipitation (Precip) based on GPCP, in units of energy (W/m^2 , by multiplying it by the latent heat of vaporization), Net Radiation (Rn) from CERES and Gross Primary Production (GPP) based on WECANN informed by Solar-Induced Fluorescence (SIF) over the wet part of the Amazon (top left), the Savanna region of Brazil (top right), over Indonesia (bottom left) and over the Congo basin (bottom right).

Commented [PG1]: Correct Amazon Wet/dry by Amazon (rainforest) / Amazon (Savanna)

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Deleted: Response of tropically-averaged free tropospheric temperature between 700mb and 200mb to El Niño Southern Oscillation (choosing the ENSO 3.4 index) with either no lag (left) or 2-month lag (middle) or 4-month lag (right)

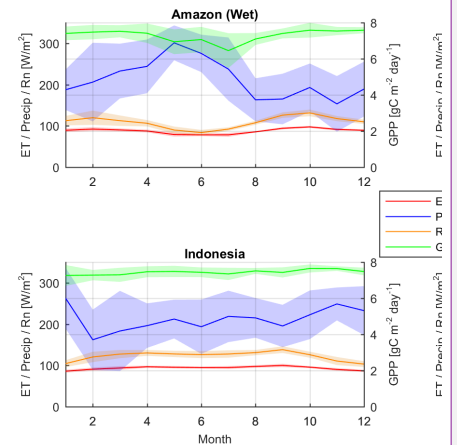


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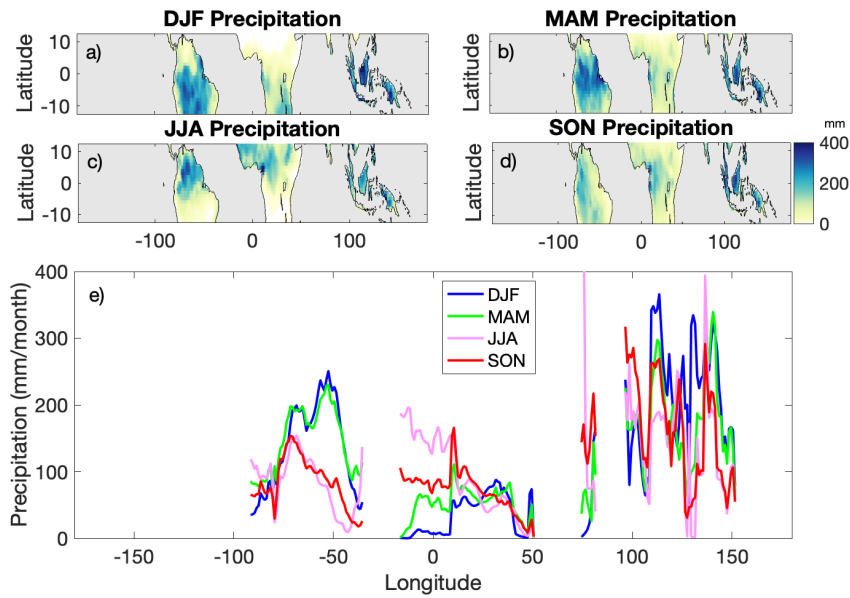
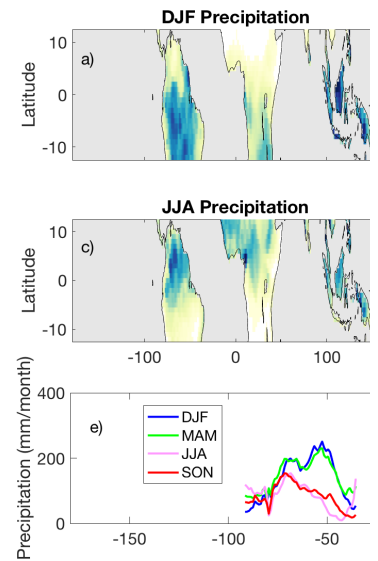
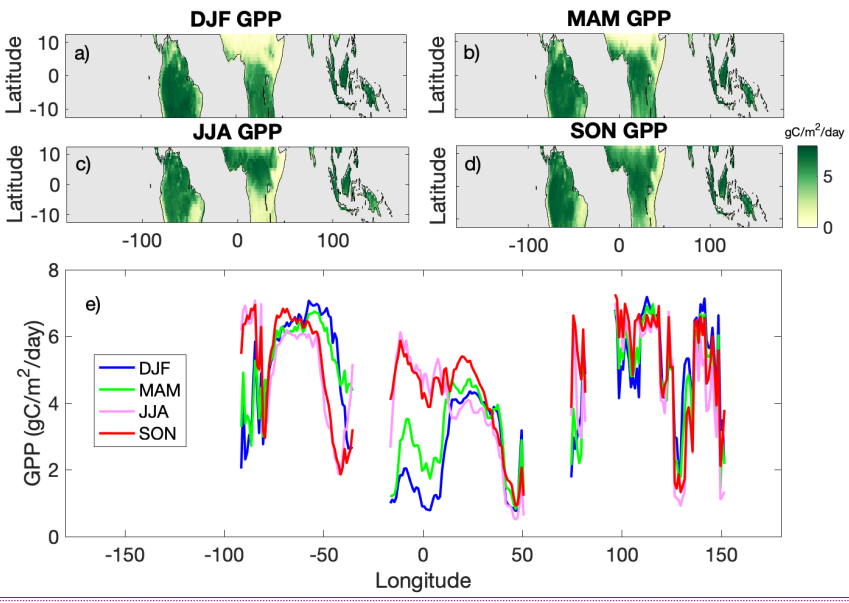


Figure 4: Seasonality of Precipitation based on GPCP in the tropics in December-January-February (a), March-April-May (b), June-July-August (c), and September-October-November (SON) and its latitudinal average (e).



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2893 Figure 5: same as Figure 4 but for Gross Primary Production (GPP)

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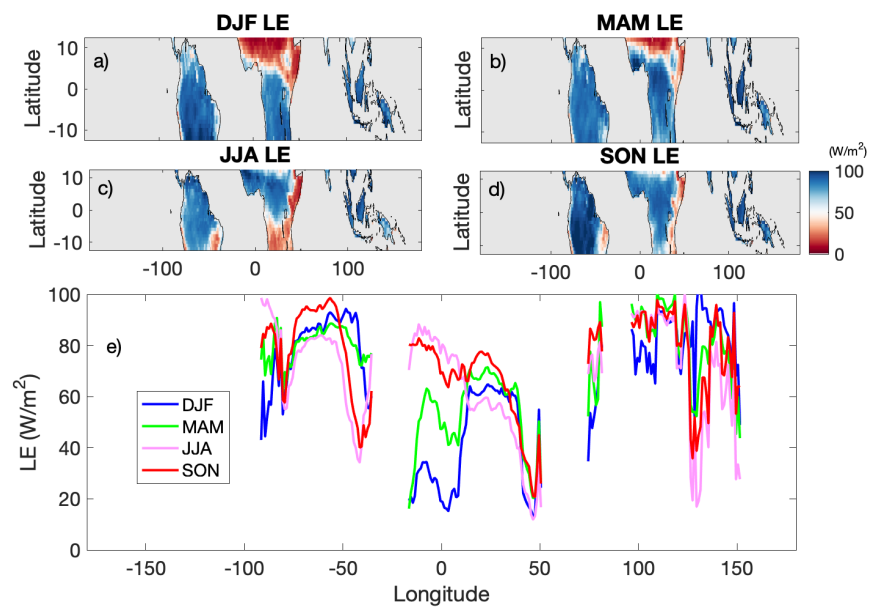


Figure 6: same as Figure 4 for Latent heat flux LE

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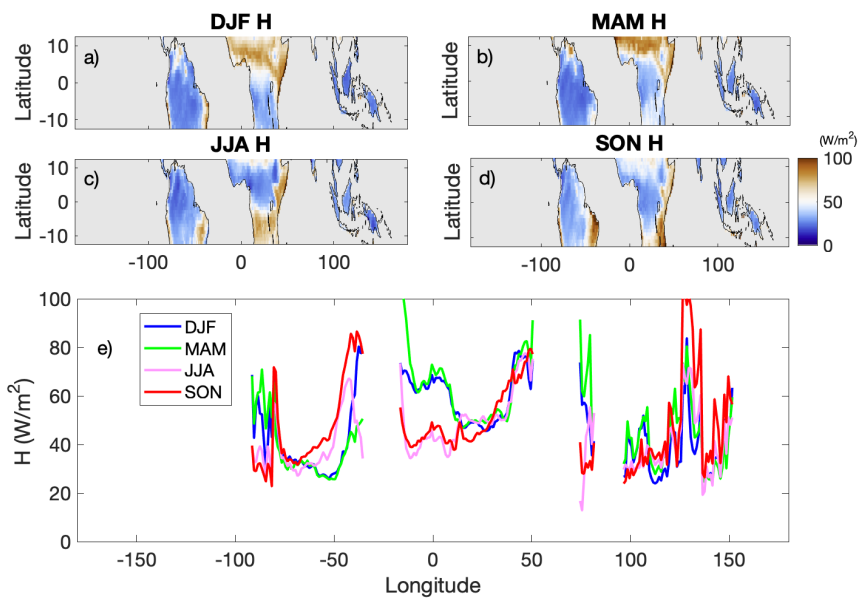
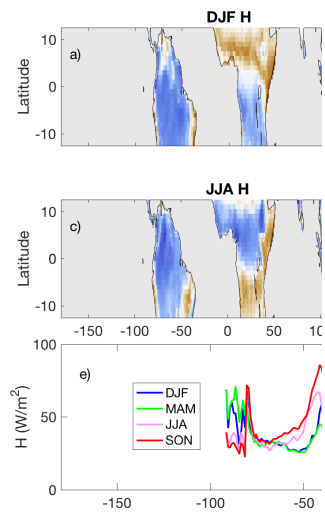


Figure 7: same as Figure 4 for sensible heat flux H .



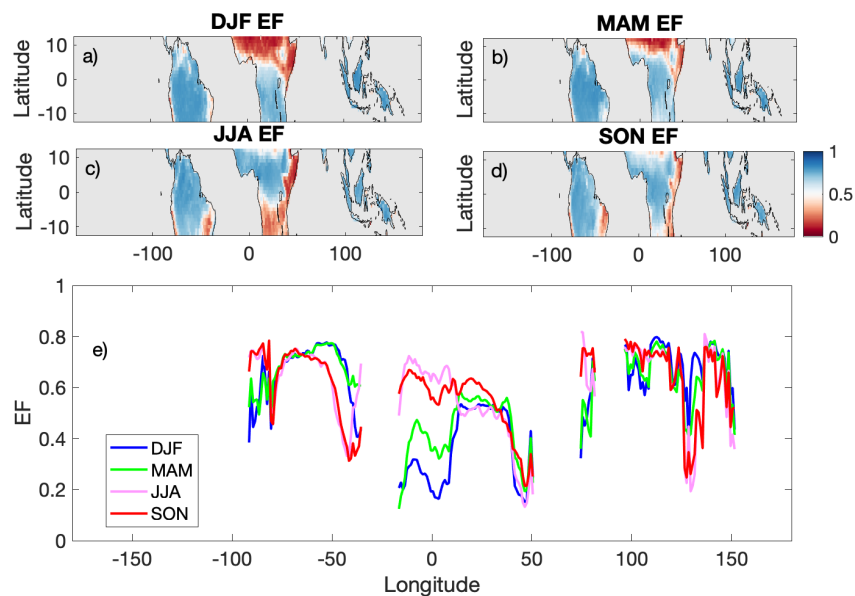


Figure 8: same as Figure 4 for evaporative fraction (EF), the ratio of LE to H+LE.

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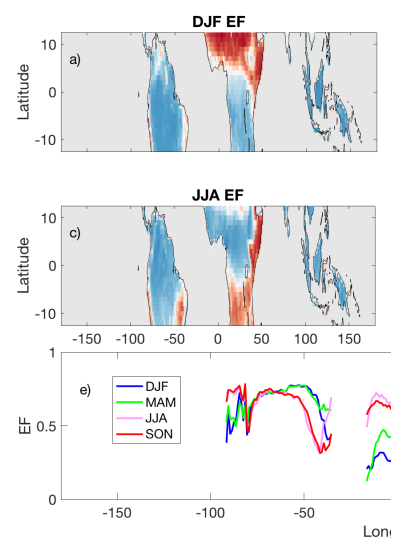


Figure 9: same as Figure 5

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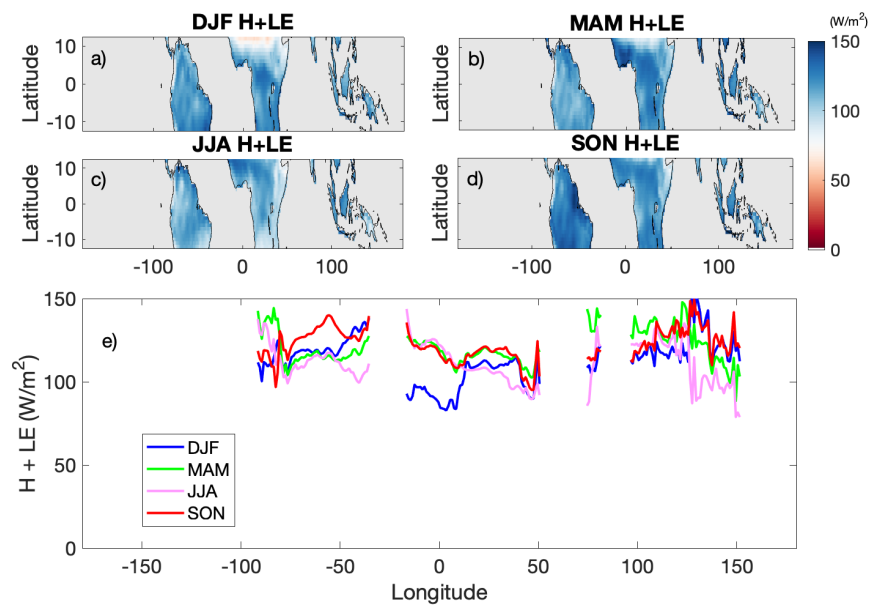
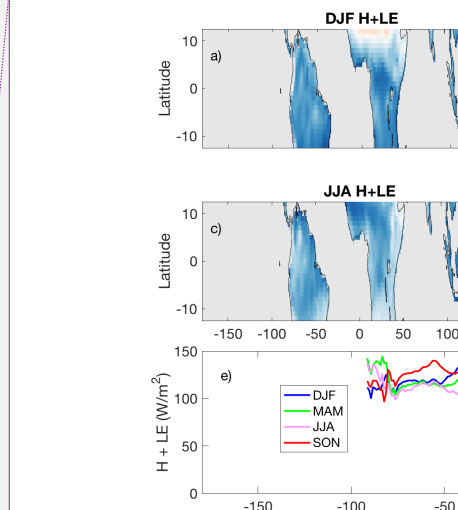


Figure 9: same as Figure 4 for sea-level surface moist static energy flux, the sum of sensible heat flux H and latent heat flux



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

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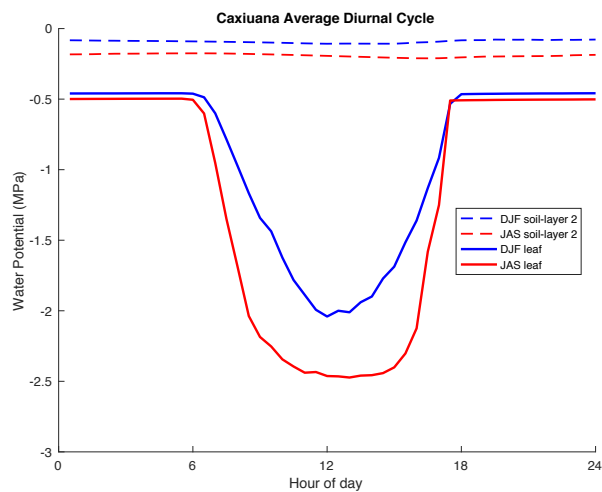


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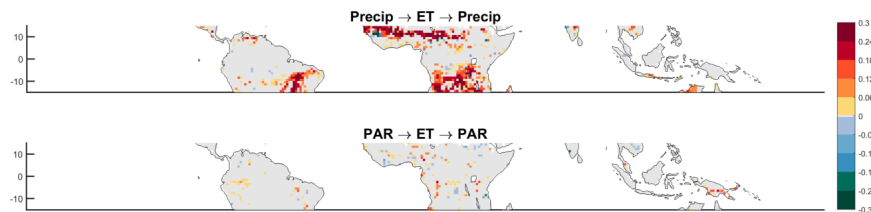
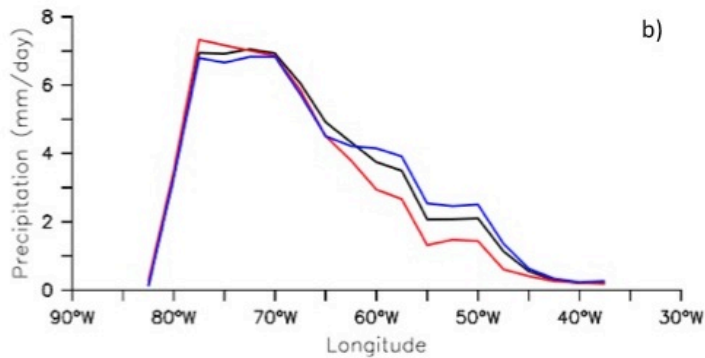
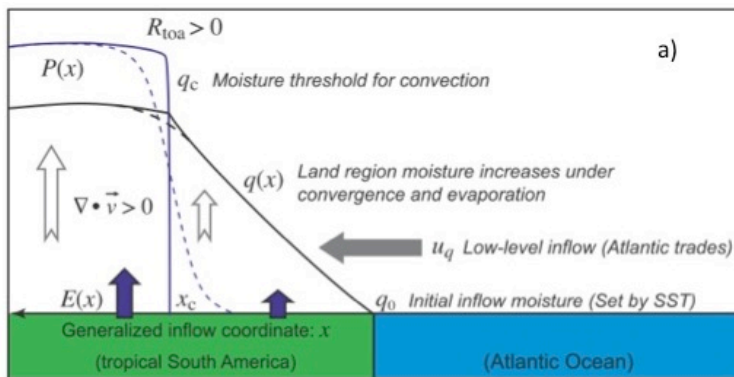
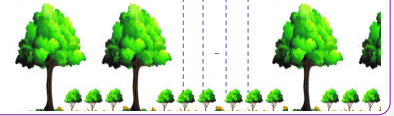


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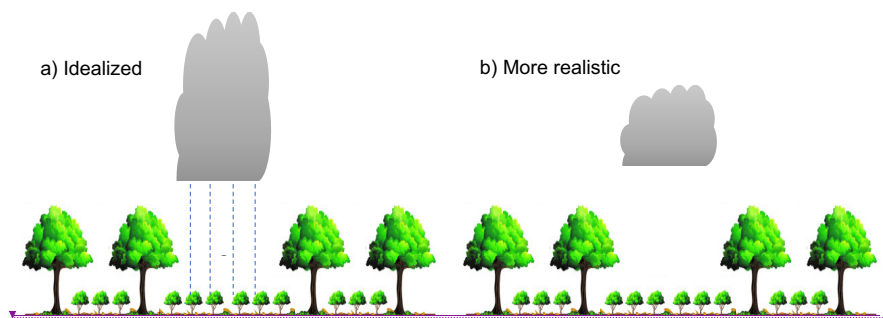


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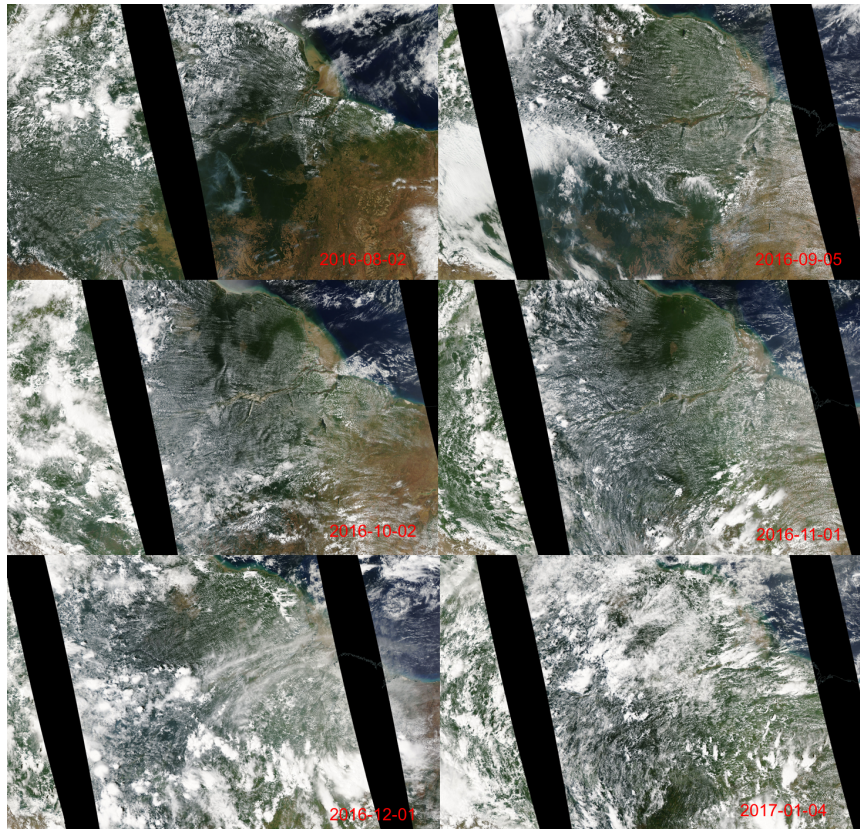
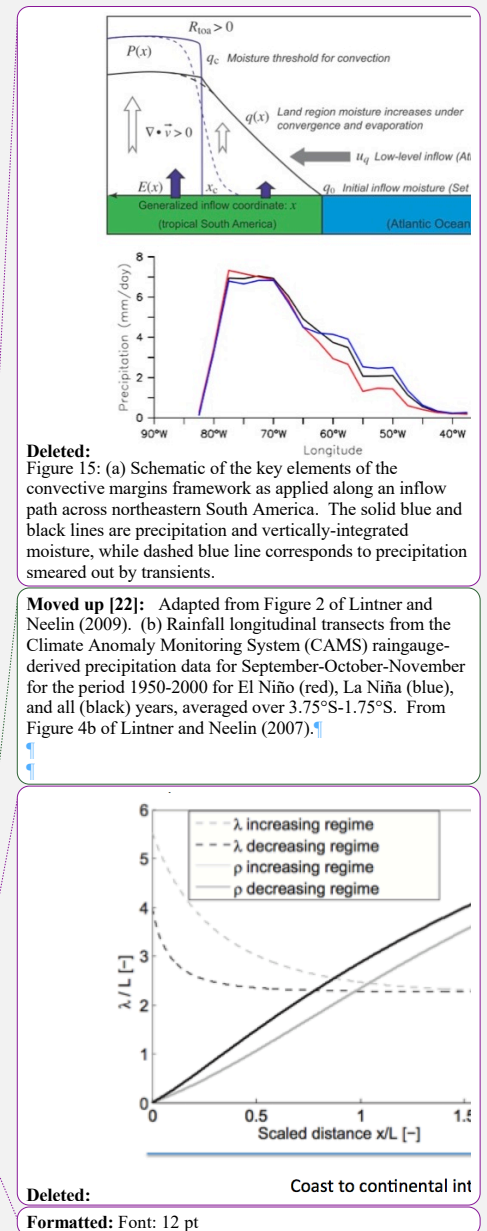


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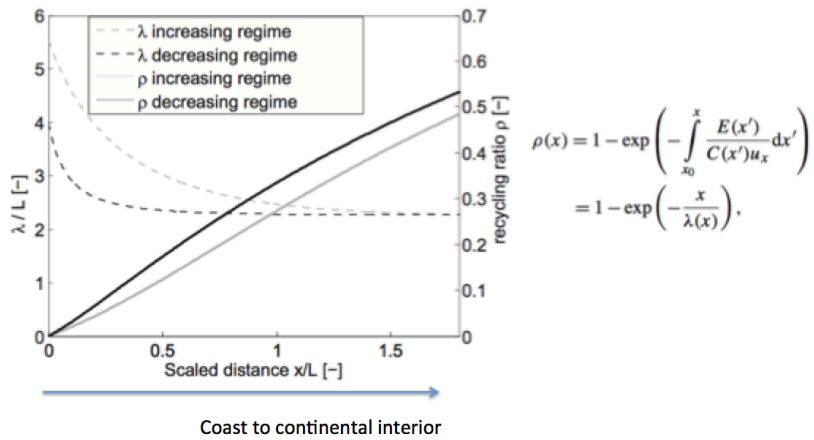
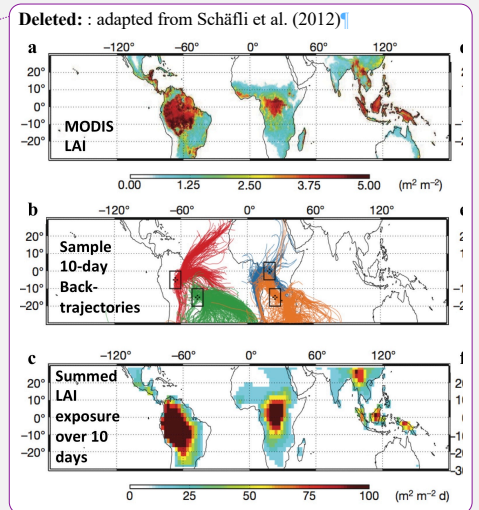


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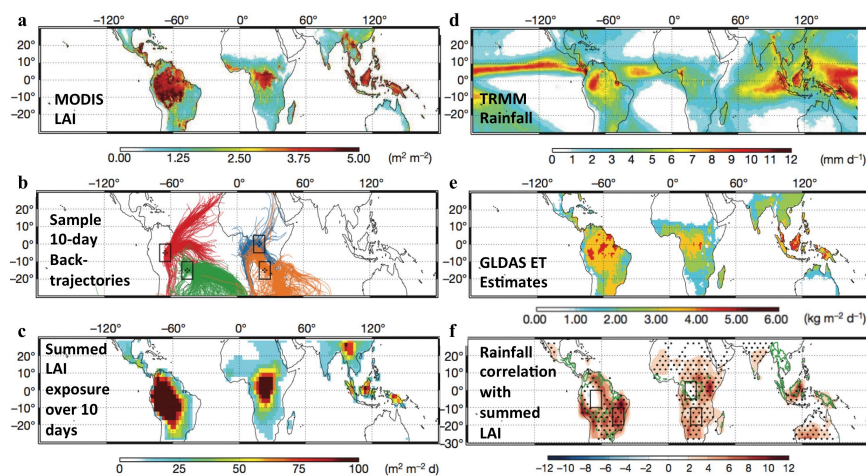


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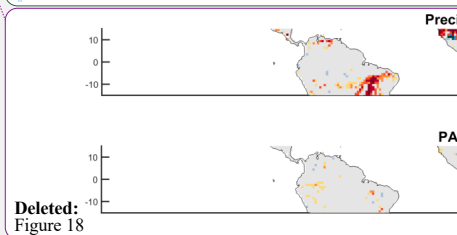
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