A rainforest-initiated wet season over the southern Amazon

Jonathon S. Wright*, Rong Fu, John Worden, Sudip Chakrabority, Nicholas Clinton, Max Reuter, Camille Risi, Ying Sun & Lei Yin

*Center for Earth System Science, Tsinghua University
jswright@tsinghua.edu.cn

April 13, 2017
Introduction
The southern Amazon
Monsoon onset
Stable water isotopes

The dry-to-wet transition
Rainfall, sunlight, and the energy budget
The rainforest moisture source
The shallow convection moisture pump

Context
Summary
Reconciling previous understanding
Implications for model development priorities
The Amazon basin

- 15% of terrestrial photosynthesis
- 25% of terrestrial biospecies

The southern Amazon

- A transitional zone from tropical rainforest to subtropical savanna
- 30–40% of the Amazon
- Hydroclimate is marginal for sustaining rainforests
- Recent rapid land use changes
The Amazon basin

- 15% of terrestrial photosynthesis
- 25% of terrestrial biospecies

The southern Amazon

- A transitional zone from tropical rainforest to subtropical savanna
- 30–40% of the Amazon
- Hydroclimate is marginal for sustaining rainforests
- Recent rapid land use changes

Rainforests in this region are particularly vulnerable to climate change.
Repeated severe droughts

▶ 2005: a 100-year drought in the southwestern Amazon

▶ 2010: more widespread, with severe drought over virtually all of the southern Amazon

▶ 2014–2015: described as the worst drought in 80 years in southeastern Brazil

▶ the rainforest has been unable to recover between droughts: an extended “megadrought”?

▶ models warn of the potential for an abrupt transition to savanna

Fig. 1. (A and B) Satellite-derived standardized anomalies for dry-season rainfall for the two most extensive droughts of the 21st century in Amazonia. (C and D) The difference in the 12-month (October to September) MCWD from the decadal mean (excluding 2005 and 2010), a measure of drought intensity that correlates with tree mortality. (A) and (C) show the 2005 drought; (B) and (D) show the 2010 drought.

from Lewis et al., 2011
Dry season length

- rainforest vitality depends critically on dry season length
- dry season length has increased in recent decades
- this increase is mainly attributable to delays in dry season end / wet season onset

**Fig. 1.** (A) Annual time series of the DSL (red line) and DSE (blue line) dates derived from the $P_M$ daily rainfall data over the southern Amazonian domain show a decrease of DSL due to a delay of DSE. The unit is pentad (5 d). On the left axis, the 55th pentad corresponds to September 2–7 of the calendar date and the 70th pentad corresponds to December 10–15. (B) Time series of austral spring seasonal rainfall over southern Amazonia derived from the $P_M$ and GPCP datasets show decrease of rainfall consistent with the delay of DSE shown in (A). The linear trend is determined by a least-square fitting. Trends are significant at $P < 5\%$ based on Santer et al. (24).
Dry season length

- rainforest vitality depends critically on dry season length
- dry season length has increased in recent decades
- this increase is mainly attributable to delays in dry season end / wet season onset

**What controls wet season onset?**

---

Fig. 1. (A) Annual time series of the DSL (red line) and DSE (blue line) dates derived from the $P_M$ daily rainfall data over the southern Amazonian domain show a decrease of DSL due to a delay of DSE. The unit is pentad (5 d). On the left axis, the 55th pentad corresponds to September 2–7 of the calendar date and the 70th pentad corresponds to December 10–15. (B) Time series of austral spring seasonal rainfall over southern Amazonia derived from the $P_M$ and GPCP datasets show decrease of rainfall consistent with the delay of DSE shown in (A). The linear trend is determined by a least-square fitting. Trends are significant at $P < 5\%$ based on Santer et al. (24).
Canonical wet season onset

- springtime increases in sunlight over the continent reverse the land–ocean temperature gradient
- enhanced sensible heating warms the air over the land, creating instability and upward motion
- upward motion drives convergence, pulling moist air from the ocean to the land, where it ascends in deep moist convection
- latent heating associated with deep moist convection reinforces convergence and sustained rainfall
- example: the Tibetan Plateau “sensible heat-driven air pump” (SHAP), in which sensible heating of the middle troposphere by the plateau initiates convergence, mechanical and thermal uplift of moist air cause deep convection and latent heating, and latent heating drives further convergence

see also Wu et al., 2012
Wet season onset over the southern Amazon

- no reversal of the land–ocean temperature gradient — another mechanism creates the instability
- one hypothesis: enhanced springtime (late dry season) transpiration by the rainforest moistens the low-level troposphere
- northward incursions of cold fronts lift moist low-level air and cause increases in deep convection
- convective heating drives large-scale moisture transport from the tropical Atlantic
- the mechanism by which deep convective heating drives convergence is called the “deep convection moisture pump” (DCMP)

See also Li & Fu, 2004; 2006
Is wet season onset driven by the rainforest?

- this hypothesis is based mainly on models, with few observational constraints

- satellite observations indicating late dry season “green-up” (e.g., Myneni et al., 2007) support the hypothesis, but these observations remain controversial (e.g., Morton et al., 2014)

- regardless of whether green-up occurs, it remains unclear whether rainforest transpiration can moisten the free atmosphere above the boundary layer (which it must to activate the DCMP)

- some studies suggest that dry season Bowen ratio is a key predictor of onset timing (Fu et al., 1999); others implicate large-scale climate modes such as ENSO and AMO (Marengo et al., 2011)

- these distinctions are critical for understanding and projecting climate in this region:
  1. if onset is driven by sensible heating then deforestation could accelerate onset; if onset is driven by rainforest transpiration then deforestation will delay onset
  2. if dry season Bowen ratio determines the timing of onset then the trend toward more droughts may be irreversible; if large-scale climate modes dominate then it may just be interdecadal variability
Is wet season onset driven by the rainforest?

- this hypothesis is based mainly on models, with few observational constraints
- satellite observations indicating late dry season “green-up” (e.g., Myneni et al., 2007) support the hypothesis, but these observations remain controversial (e.g., Morton et al., 2014)
- regardless of whether green-up occurs, it remains unclear whether rainforest transpiration can moisten the free atmosphere above the boundary layer (which it must to activate the DCMP)
- some studies suggest that dry season Bowen ratio is a key predictor of onset timing (Fu et al., 1999); others implicate large-scale climate modes such as ENSO and AMO (Marengo et al., 2011)
- these distinctions are critical for understanding and projecting climate in this region:
  1. if onset is driven by sensible heating then deforestation could accelerate onset; if onset is driven by rainforest transpiration then deforestation will delay onset
  2. if dry season Bowen ratio determines the timing of onset then the trend toward more droughts may be irreversible; if large-scale climate modes dominate then it may just be interdecadal variability

- our goal: constrain the role of rainforest transpiration in initiating wet season onset
- our approach: analyze satellite data from multiple platforms, including isotopes in water vapor
Stable water isotopes

- useful tracers of the sources and histories of air masses
- the most common isotopes include H$_2^{16}$O, HDO, and H$_2^{18}$O
- fractionation: during phase transitions, heavier isotopes preferentially condense and lighter isotopes preferentially evaporate
- the ratio of heavy isotopes in a water sample is generally expressed relative to a standard ratio:

$$\delta = \left( \frac{R}{R_{\text{std}}} - 1 \right)$$

where $R = N_i/N$ is the ratio of isotopic molecules to water molecules in the sample and the standard is often Vienna standard mean ocean water (VSMOW)
Stable water isotopes

- isotopic fractionation depends on the interface, the temperature, and various kinetic effects
- because of fractionation, both evaporation from the ocean surface and subsequent condensation events reduce the ratio of heavy isotopes in vapor relative to its source (ocean water)
- effectively zero fractionation occurs during transpiration at steady state, so that transpired moisture retains the isotopic composition of its source (soil water)
- we examine the evolution of $\delta D$ in water vapor in the boundary layer (ABL; below 825 hPa) and free troposphere (FT; 750–350 hPa) using Tropospheric Emission Spectrometer (TES) satellite observations
Isotopes in southern Amazon precipitation

- $\delta D$ in transpiration fluxes should approximately match $\delta D$ in precipitation
- precipitation $\delta D$ measured sporadically from 1965–1990 at two regional sites
- precipitation-weighted mean $\delta D$ at Porto Velho $\sim -38\%$, at Manaus $\sim -26\%$
Composite analysis

- the dry and wet season are clearly distinguishable; dry season rain rates are 70–90% less
- reanalysis estimates of evapotranspiration (ET) are almost constant year-round
- reanalysis estimates of moisture flux convergence (MFC) vary substantially

![Composite analysis graph](image-url)

- Data from TRMM, ERA-Interim, and CERES
- Dry season and wet season clearly distinguishable
- Evapotranspiration (ET) almost constant year-round
- Moisture flux convergence (MFC) varies substantially
Composite analysis

- covers six wet season transitions: 2005–06 to 2010–11
- filtered using fast Fourier transforms to remove variability at time scales shorter than 25 days

![Composite analysis diagram](image-url)

- Water fluxes [mm d$^{-1}$]: Precipitation, Evapotranspiration, Moisture flux convergence
- Surface insolation [W m$^{-2}$]
- Pentad relative to wet season onset
- 6 pentads (30 days) before onset
- Wet season onset
- Data from TRMM, ERA-Interim, and CERES
Wet season onset is defined as the first pentad with mean daily rainfall...

1. ...larger than the climatological mean daily rainfall
2. ...smaller than the climatological mean for five of the eight preceding pentads
3. ...larger than the climatological mean for five of the eight following pentads
The transition season

- Li and Fu (2004) found that the transition begins around pentad –18; our data support this
- We therefore focus on the evolution of the atmosphere, land surface, and vegetation from pentad –24 to pentad +6 (150 days)

The dry-to-wet season transition

data from TRMM, ERA-Interim and CERES
The transition season

▶ precipitation increases from its dry season minimum starting around 60–70 days before onset
▶ ERA-Interim ET and MFC increase in tandem, also from about 60–70 days before onset
▶ dry season ET provides water both for local dry season rainfall and for export out of the region
How realistic is the ERA-Interim reanalysis?

- systematically overestimates dry season precipitation relative to TRMM
- timing of initial rainfall increase matches TRMM, but ERA-Interim “onset” is two weeks early
- this accelerated dry-to-wet transition seems to be a common characteristic in many models
How realistic is the ERA-Interim reanalysis?

- ERA-Interim surface fluxes also show biases relative to CERES SYN1Deg
- may underestimate solar radiation at the surface during the early dry season
- may overestimate solar radiation at the surface during the late dry season
Surface radiation fluxes

- Atmospheric aerosols sharply attenuate solar radiation during the late dry season (the burning season)
- These aerosol effects are not included in the reanalysis, which uses annual mean climatologies for various aerosol types
- Aerosol effects are small during the early dry season – biases during this period are likely due to differences in estimated cloud radiative effect
- Errors in the surface radiation budget could propagate into the physics of the transition in unpredictable ways
- For this and other reasons, reanalyses cannot be used to definitively identify the processes involved in onset
Sensible and latent heat fluxes: reanalysis estimates

- latent heat flux (ET) begins to increase around pentad –14 to –12 (60–70 days before onset)
- sensible heat flux increases through the dry season and peaks around pentad –9 (45 days before onset)
Sensible and latent heat fluxes: observational context

- changes in surface air temperature approximately match changes in reanalysis sensible heating
- daytime total column water vapor increases before nighttime total column water vapor
- increase in daytime total column water vapor leads reanalysis estimates of ET (and MFC)
Is there a late dry season increase in rainforest ET?
Carbon dioxide and vegetation greenness

- Column mean carbon dioxide decreases sharply from \(~90\) days before onset.
- These decreases occur as fire emissions grow, potentially implicating enhanced vegetation uptake.
- Enhanced vegetation index (EVI) indicates a rainforest green-up from about \(60\) days before onset.

Data from SCIAMACHY, MODIS and GFED.
Alternative vegetation metrics

- solar-induced chlorophyll fluorescence is more sensitive to photosynthesis than EVI
- SIF slightly leads EVI, but both indicate that rainforest vegetation activity increases at around the same time as rainfall (from about pentad –12)
Isotopic composition in the boundary layer

- $\delta D$ in the southern Amazon ABL increases from $\sim 90$ days before onset, as CO$_2$ decreases
- this increase is not due to cross-correlations with free-tropospheric $\delta D$, and is significantly different from $\delta D$ over the nearby tropical Atlantic

![Graph showing isotopic composition in the boundary layer]
Isotopic composition in the boundary layer

Differences between ABL δD over the southern Amazon and tropical Atlantic are likely underestimated:
Isotopic composition in the boundary layer

- the increase in ABL $\delta D$ over the southern Amazon is consistent with an increase in transpiration, but could also be caused by the deepening of the ABL
- timing discrepancies mean we can only constrain the transpiration increase to a $\sim 30$-day window
Multiple lines of evidence for a late dry season increase in rainforest ET...

Can enhanced ET account for regional-scale increases in free tropospheric moisture?
Isotopic composition in the free troposphere

- $\delta D$ in the free troposphere also increases through the late dry season, peaking 2–3 weeks before onset
- this increase could be due to either upward mixing of ET or large-scale transport of moist air
The vertical distribution of cloud cover

- whereas middle and high cloud cover increase from about pentad –12, low cloud cover increases from about pentad –18
- suggests an increase in forest cumulus, which often form over the Amazon (Heiblum et al., 2014)

Data from MODIS via CERES SYN1Deg
Relative humidity and atmospheric heating

- vertical redistribution of RH consistent with mixing across ABL top (and surface heating)
- strong heating at 700 hPa and below during the early transition season (shallow convection)
- heating shifts to the upper troposphere during the late transition season (deep convection)
Relative humidity and atmospheric heating

- vertical redistribution of RH consistent with mixing across ABL top (and surface heating)
- strong heating at 700 hPa and below during the early transition season (shallow convection)
- heating shifts to the upper troposphere during the late transition season (deep convection)
Relative humidity and atmospheric heating

- vertical redistribution of RH consistent with mixing across ABL top (and surface heating)
- strong heating at 700 hPa and below during the early transition season (shallow convection)
- heating shifts to the upper troposphere during the late transition season (deep convection)
Equivalent potential temperature

- depends on $T$, $q$ and saturation deficit (RH)
- decreases with height indicate conditional instability
- increases with height indicate stable layers that cap or inhibit convection
- SCMP deepens the conditionally unstable layer (shifts the minimum upward) and flattens the inversion (largest increases in lower–middle troposphere), preconditioning the atmosphere for deep convection
- DCMP shifts the heating to the upper troposphere, establishing large-scale moisture convergence
Relative humidity and atmospheric heating

- vertical redistribution of RH consistent with mixing across ABL top (and surface heating)
- strong heating at 700 hPa and below during the early transition season (shallow convection)
- heating shifts to the upper troposphere during the late transition season (deep convection)
Transition from shallow to deep convection

- Radiosonde data show that area mean results are consistent with individual cases.
- Humidity profiles are moist in the LT and dry above, similar to area mean before pentad –6.
- Deep convection requires deeper layer of high RH, similar to area mean after pentad –6.

Data from GO Amazon 2014.
Convective instability

- increases in convective available potential energy (CAPE) and decreases in convective inhibition energy (CINE) from pentad -18 confirm the development of a favorable convective environment
- this favorable environment initially only develops in the daytime, when the boundary layer deepens
Where does the moisture come from?

- Rainforest ET and ocean evaporation have very different isotopic signatures, but both may be enriched in deuterium relative to water vapor in the dry season free troposphere (depending on transport conditions).

- Regressions of $\delta D$ against specific humidity distinguish these sources more clearly:
  - If moistening of the free troposphere is dominated by upward mixing of ET, then the highest humidities will be more enriched in deuterium (larger positive slopes).
  - If moistening is dominated by transport from oceanic sources, then the highest humidities will be relatively depleted in deuterium (smaller or negative slopes).
Comparison with theoretical estimates

- isotopic ratios during the late dry season are consistent with theoretical expectations based on transpiration as the primary moisture source
- both dry adiabatic and convective mixing appear to play a role in delivering transpired moisture to the free troposphere
- isotopic ratios during the early wet season are consistent with a mixture of sources, with large-scale transport of moisture from the tropical ocean a key contributor
- linear regressions of $q$ against $\delta D$ track the evolution of moisture sources
Evolution of regression slopes

- slopes are positive through the peak of the dry season, and increase between pentad –18 and pentad –12 (when other metrics indicate growing shallow convective activity)
- slopes begin to decrease from pentad –12, consistent with a greater role for large-scale transport
Evolution of regression slopes

- slopes are positive through the peak of the dry season, and increase between pentad –18 and pentad –12 (when other metrics indicate growing shallow convective activity)
- slopes begin to decrease from pentad –12, consistent with a greater role for large-scale transport

![Graph showing the evolution of regression slopes with pentads relative to wet season onset.](image-url)
Regressions are strong and significant for most of the late dry season...

![Graph showing correlation coefficient and two-sided p-value over pentads relative to wet season onset.](a) Correlation coefficient ranges from 0 to 1, with significant values indicated above the dashed line. (b) Two-sided p-value ranges from 0 to 1, with values below the dashed line indicating statistical significance.
Positive slopes are not spurious artefacts of diurnal or interannual variability...

Data from TES
...nor are they artifacts of land cover or aerosol optical depth
The amount effect

- the regression slopes begin to decrease much earlier than FT $\delta$D
- this difference highlights the different impacts of the amount effect (in which repeated precipitation events leave vapor progressively more depleted in heavy isotopes) and an increase in the relative role of large-scale transport (in which the most humid air becomes more depleted in heavy isotopes)
- the amount effect becomes more prevalent as sustained deep convection sets in (decrease in FT $\delta$D)
Changes in the spatial gradients of $q$ and $\delta D$:
early in the transition, $q$ and $\delta D$ both peak in the heavily forested northwest...
Changes in the spatial gradients of $q$ and $\delta D$:

...moist, isotopically enriched air then spreads across the region...

Early transition (pentads −12 to −6)

[Diagram showing specific humidity and $\delta D$ distributions with arrows indicating wind direction and contour lines for specific humidity and $\delta D$.]
Changes in the spatial gradients of $q$ and $\delta D$:

...moist, isotopically enriched air then spreads across the region...

Late transition (pentad −6 to onset)
Changes in the spatial gradients of $q$ and $\delta D$:
...and the spatial gradient of $\delta D$ reverses in the early wet season

Early wet season (onset to pentad +18)
Summary

▶ strong, comprehensive evidence that rainforest ET during the late dry season initiates the dry-to-wet transition (rather than a canonical monsoon onset mechanism)

▶ rainforest transpiration can and does account for regional-scale increases in free tropospheric moisture during the initial stages of the transition

▶ transpiration first activates a shallow convection moisture pump (SCMP) that preconditions the atmosphere for deep convection, rather than directly activating the DCMP as previously thought

▶ indications that moderate pollution from biomass burning can increase the efficiency of the SCMP and promote wet season onset, while heavy pollution reduces the efficiency of the SCMP and could delay wet season onset

▶ results are ambiguous about whether the late dry season intensification of rainforest photosynthesis and transpiration coincides with the activation of the SCMP (as indicated by CO$_2$ and ABL $\delta^D$) or closer to the increase in rainfall (as indicated by EVI and SIF), but they unambiguously show that the SCMP depends on the ability of the rainforest to maintain high transpiration rates during the dry season
How these results fit into the big picture

- provide observational evidence that explains the observed relationship between dry season ET and wet season onset (Fu & Li, 2004)
- establish a framework for understanding why early wet season demise so often leads to enhanced fire activity and late onset of the subsequent wet season (Chen et al., 2013)
- bolster the hypothesis that decreases in regional transpiration due to deforestation or CO$_2$ fertilization could delay wet season onset (Fu et al., 2013)
- the strong sensitivity of shallow convection to land cover in this region (Heiblum et al., 2014) and the pivotal role of the SCMP imply that the dry-to-wet transition may be more sensitive to land use and vegetation changes than previously thought
- help to clarify how dry season biomass burning can influence wet season onset
- suggest an alternative mechanistic explanation for the recent uptick in severe drought occurrence and why models are unable to capture it (in addition to hypotheses based on the interdecadal variability of large-scale climate modes as proposed by Marengo et al., 2011)
- highlight the climatic importance of rainforest conservation
The transition in ERA-Interim

- overestimates dry season precipitation
- onset is accelerated relative to observations
- evolution of model-derived moisture fluxes lags observed evolution of total column water vapor
- evolution of total and low cloud cover is substantially different from observed — the increase in shallow convection is too weak and too deep
The transition in LMDZ

- onset (calculated independently for LMDZ) is accelerated and generally late
- evapotranspiration almost completely disappears during the late dry season, implying serious problems in representing soil–vegetation–atmosphere system
- period of moisture flux divergence is short and early
- these problems are still present if LMDZ is nudged toward reanalysis winds or coupled to the sophisticated land surface model ORCHIDEE

![Graph showing LMDZ precipitation and surface air temperature](image-url)

Data from TRMM, ERA-Interim, and LMDZ.
The transition in LMDZ

▶ onset (calculated independently for LMDZ) is accelerated and generally late
▶ evapotranspiration almost completely disappears during the late dry season, implying serious problems in representing soil–vegetation–atmosphere system
▶ period of moisture flux divergence is short and early
▶ these problems are still present if LMDZ is nudged toward reanalysis winds or coupled to the sophisticated land surface model ORCHIDEE
Introduction

The dry-to-wet transition

Context

Summary

Reconciling previous understanding

Implications for model development priorities

Trends in CMIP5

▶ models do not reproduce observed trends in wet season onset date
▶ natural variability or its role in onset underestimated?
▶ inability to adequately model coupling between the rainforest and atmosphere and/or shallow convective processes?
▶ confidence in model projections of future climate in this region is very low

Fig. 4. Distributions of the nonoverlapped 27-y trends of the DSE generated by the natural variability simulations (blue), historical simulations (red), and projections of future changes under the RCP8.5 scenario (green), respectively, suggest that the modeled DSE changes, including the projected future change, are significantly weaker than that which are observed during 1979–2005. The top 5% of the modeled trend samples are marked by blue, red, and green vertical dashed lines for the natural variability, historical simulations, and RCP8.5 scenario, respectively. The observed 27-y trend and confidence interval with uncertainties of $P < 5\%$ are marked by the black circle and horizontal bar in the upper right corner and are derived from the $P_M$ daily rainfall data following method of Santer et al. (24).
Model development priorities

- many models remain unable to realistically represent rainforest transpiration and shallow convection, due in part to a lack of observational constraints
- poor representation of these processes causes biases in regional water and energy budgets
- these biases can result in misdiagnosis of the mechanisms that control wet season onset and contribute to large discrepancies in climate change projections in this region
- model developers who want to achieve more credible projections of future climate change (and simulations of current climate) in this region should focus on the representations of shallow convection (and the overall convective spectrum) and soil–rainforest–atmosphere interactions
- additional stable water isotope observations could provide valuable constraints for model evaluation and development in these areas