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Trends in streamflow, evapotranspiration, and groundwater storage across the Amazon Basin linked to changing precipitation and land cover

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ABSTRACT

Study region: The study region is the Amazon River Basin, which controls globally important water and energy fluxes.
Study focus: In the face of a changing climate and landscape, it is critical that we understand how, where, and why surface water resources are changing. Specifically, we must consider holistic changes to the water cycle to understand how water resources are affected by climate change and landscape alterations. In this study, we investigate changes to all major components of the water balance across the entire Amazon Basin. We seek to understand: 1) how changes to land cover and precipitation affect streamflow, 2) how these factors affect evapotranspiration and groundwater storage water balance components, and 3) how changes to the water balance partitioning may in turn alter streamflows.
New hydrological insights: We find significant changes to streamflow of ±9.5 mm/yr on average across the Amazon Basin. Streamflow alterations show a spatially variable pattern, with increasing discharge in the northern and western portions of the basin, and decreasing discharge in the southern and eastern basin. We also observe significant changes in evapotranspiration of ±29 mm/yr and groundwater storage increases of 7.1 mm/yr. Together, these results indicate that studies of streamflow change in the Amazon should consider changes to the whole water budget, including understudied aspects of groundwater storage across the Basin.

1. Introduction

Changes in climate and land cover, including infrastructure development, have been shown to alter the quality and availability of freshwater resources around the world at multiple scales (Vörösmarty et al., 2000; Pekel et al., 2016). Rivers are a critical component of many human and natural systems, and river discharge patterns are changing globally (Hyndman et al., 2017; Hyndman, 2014). The Amazon River and its associated rainforest is one of the world's largest and most important freshwater ecosystems; water fluxes to the ocean and atmosphere from this system affect the global water cycle (Coe et al., 2016). River discharge is determined by the balance

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among precipitation, surface and groundwater storage, and evapotranspiration (ET). To understand how Amazon River discharge is changing, we must understand each component that governs the water balance.

Previous work has investigated changes in streamflow dynamics across the Amazon Basin, with some studies finding opposing trends across regions (e.g., Espinoza Villar et al., 2009a; Gloor et al., 2013; Hayhoe et al., 2011; Dias et al., 2015; Timpe and Kaplan, 2017; Levy et al., 2018, and Richey et al., 1989). Analysis of historical streamflow patterns at the confluence of the Amazon River and Rio Negro at Manaus by Richey et al. (1989), showed no significant change in long-term discharge between 1903 and 1985. The discharge record analyzed in the study, however, predates a significant amount of the Amazon Basin deforestation, and much of the observable changes in climate. Analysis of more recent discharge records have shown significant changes in Amazonian streamflows. For example, Gloor et al. (2013) showed increases in streamflow and a shift toward more severe flows on the Amazon's main stem at Obidos from 1990−2010. They attributed this change to observed increases in precipitation, which were attributed to increased sea surface temperatures and delivery of water vapor to the basin. Espinoza Villar et al. (2009a) investigated the regional (sub-basin scale) changes in streamflow in the Amazon Basin, focusing primarily on the Andean region. They demonstrated increased streamflow in the northwestern basin, and decreased streamflow in the western and southern basin, with these observed changes attributed to changing precipitation. Patterns of streamflow change also vary in different locations and elevations across the basin. Molina-Carpio et al. (2017) observed decreasing baseflows in lowland tributaries of the Madeira River, although such changes in baseflow were not observed in the Andean tributaries of the Madeira. They also demonstrated that the Andean region is influenced by changes in Pacific Ocean sea surface temperatures (SST's), while the lowland tributaries are affected by alterations to changes in the North Atlantic Ocean SST's.

The Amazon River Basin water balance is primarily driven by precipitation, but is also affected by complex interactions between land cover, land use, soils, temperature, humidity, precipitation, and other landscape characteristics (Espinoza Villar et al., 2009a; Coe et al., 2016, 2017; Maeda et al., 2017). There are also significant feedbacks from changes in such landscape characteristics. For example, deforestation decreases evapotranspiration and increases land surface temperature and streamflow (Costa et al., 2003; Dias et al., 2015; Coe et al., 2017). Interactions between these systems are especially complex in the Amazon, where the rainforest plays an important role in regulating regional and global climate and hydrologic cycles. There, intense evapotranspiration in excess of 1000 mm/yr provides considerable atmospheric moisture, much of which is recycled within the system, affecting precipitation and streamflow across the basin (Salati et al., 1979; Maeda et al., 2017).

Regional-scale modeling efforts coupled with satellite and ground-based data have examined streamflow, precipitation, evapotranspiration and groundwater storage to assess the changing water balance in the Amazon Basin. Costa and Foley (1999) expanded the study of changing Amazon hydrology to investigate changes in evapotranspiration and atmospheric water vapor transport between 1979 and 1996. Their work demonstrated a significant decrease in water vapor transport both into and out of the Amazon basin, which was compensated by an increase in precipitation recycling within the basin. While they observed no significant change in runoff, the authors did note that future deforestation or climate change may disrupt evapotranspiration and precipitation recycling, altering the other water balance components. Costa et al. (2003) and Coe et al. (2011) showed that deforestation, by decreasing evapotranspiration, has contributed to an about 20 % increase in the discharge of the Tocantins/Araguaia River system in southeastern Amazon. Panday et al. (2015) quantified the opposing effects of deforestation (+6%) and climate change (-14 %) on streamflow, which led to an overall modest reduction in streamflow in the Xingu Basin. This demonstrated how the streamflow effects of deforestation can be masked by those of climate change in the opposite direction. These confounding responses are due to the complex interactions between land cover, precipitation and streamflow. While decreased ET from deforestation can directly increase streamflows, it can also decrease rainfall, indirectly decreasing streamflow (Stickler et al., 2013). Levy et al. (2018) analyzed observed streamflow, land cover and climate data using advanced statistical modeling approaches to isolate the effects of change in individual components on observed streamflow in the southern Amazon and Tocantins Basins. They found that climate changes have reduced the deforestation driven changes in streamflows by 42 %. Smaller site-scale studies in the Upper Xingu basin have demonstrated through observational data (Hayhoe et al., 2011) and models (Dias et al., 2015) that conversion to soy agriculture decreased ET and increased catchment outflow. These studies estimated the contribution of baseflow to river discharge but did not quantify changes in groundwater storage.

Large, basin-scale modeling efforts have also been undertaken in the Amazon region to study hydrologic function and understand changing hydrologic conditions. Work by Miguez-Macho and Fan (2012a, 2012b) investigated the role of groundwater in the Amazon hydrologic cycle, showing groundwater to be an important component in regulating both streamflows and evapotranspiration rates in the Amazon. The contribution of groundwater to total water storage has also been investigated. Work by De Paiva et al. (2013) modeled the hydrologic and hydrodynamic conditions of the Amazon Basin using the MGB-IPH model to investigate which hydrologic processes control total water storage (TWS) change in the Amazon. Their results demonstrate that surface water accounts for 56 % of total water storage change, while soil water accounts for 27 % and groundwater 8 %. Conversely, a similar study by Pokhrel et al., 2013 using the LEAF-Hydro-Flood (LHF) model found that ground and soil water account for 71 % of TWS change, while flood waters accounted for 24 % and rivers 5 %. The difference in the estimated contribution of ground and soil waters between these two studies is likely due to the explicit simulation of deep groundwater in LHF. This disagreement between the two simulation methods highlights the need to consider groundwater in studies of Amazon hydrology. While the importance of groundwater in the Amazon Basin has been considered in these studies, the long term effects of land cover and climate change on groundwater storage is less well understood. Guimberteau et al., 2017 used an ensemble of land surface models at the Amazon Basin scale to investigate the confounding effects of changing precipitation and land cover on streamflow in the region. They modeled changes in streamflow and ET using a range of deforestation scenarios. Their results corroborate those of Panday et al. (2015) indicating that deforestation offsets the climate change driven impacts on ET and streamflow.

Changes to streamflow patterns are also predicted to continue under projected changes to global climate and precipitation patterns.

Sorribas et al. (2016) used the same MGB-IPH model to investigate changes in streamflow under the IPCC's Fifth Assessment Report (CMIP5) projected climate changes. They found significant alteration to streamflow and inundation extent from the Andean rivers to the lower Amazon River.

Changing streamflows driven by climate and landscape alterations also threaten other resources, such as energy development. Stickler et al. (2013) used land surface and climate models to demonstrate that when the land-atmosphere interactions of deforestation are considered, predicted energy generation at the Belo Monte hydropower dam on the Xingu River will be drastically reduced. By including the effects of deforestation on precipitation recycling, they found that projected deforestation of 40 % of the Xingu basin would lower Belo Monte's energy generation capacity to 60 % of the power industry's projections. This failure to consider the effects of changing water resources on energy production is widespread within Brazil. In the Tapajos Basin, with accounts for almost 50 % of the planned potential hydropower development, climate and land cover change could result in decreased energy generation (up to -7.4 %) and increased interannual variability in power generation capacity (up to 69 %) (Arias et al., 2020).

The studies outlined above have generally focused on changes in streamflow and precipitation driven by changes in land cover, climate, and sea surface temperature (Gloor et al., 2013; Espinoza Villar et al., 2009a). Few studies have investigated changes in the other major water balance comports of evapotranspiration and groundwater storage. While changes in evapotranspiration have been included in some investigations of changing water resources, alterations to the groundwater system have been the most understudied. Studies that have considered these factors used models and data at large watershed or catchment scales. In particular, Panday et al. (2015), using GRACE data and the IBIS land surface model, showed that changes in the groundwater storage associated with drought events significantly impacts interannual discharge variability in the 510,000 km^2 Xingu River basin. Niu et al. (2017), using a process-based hydrological model, found that surface runoff variations in an upland Amazon catchment were largely controlled by interannual precipitation variability, evapotranspiration variability had less impact. There is a need to further study the integrated changes in water resources through all major components of the water balance across the full Amazon Basin, and to consider a broad range of factors affecting these changes. This need is driven by the rapid alteration to the landscape across the Amazon Basin (including deforestation and hydropower development). To better protect the water resources of the Amazon Basin in the face of such landscape

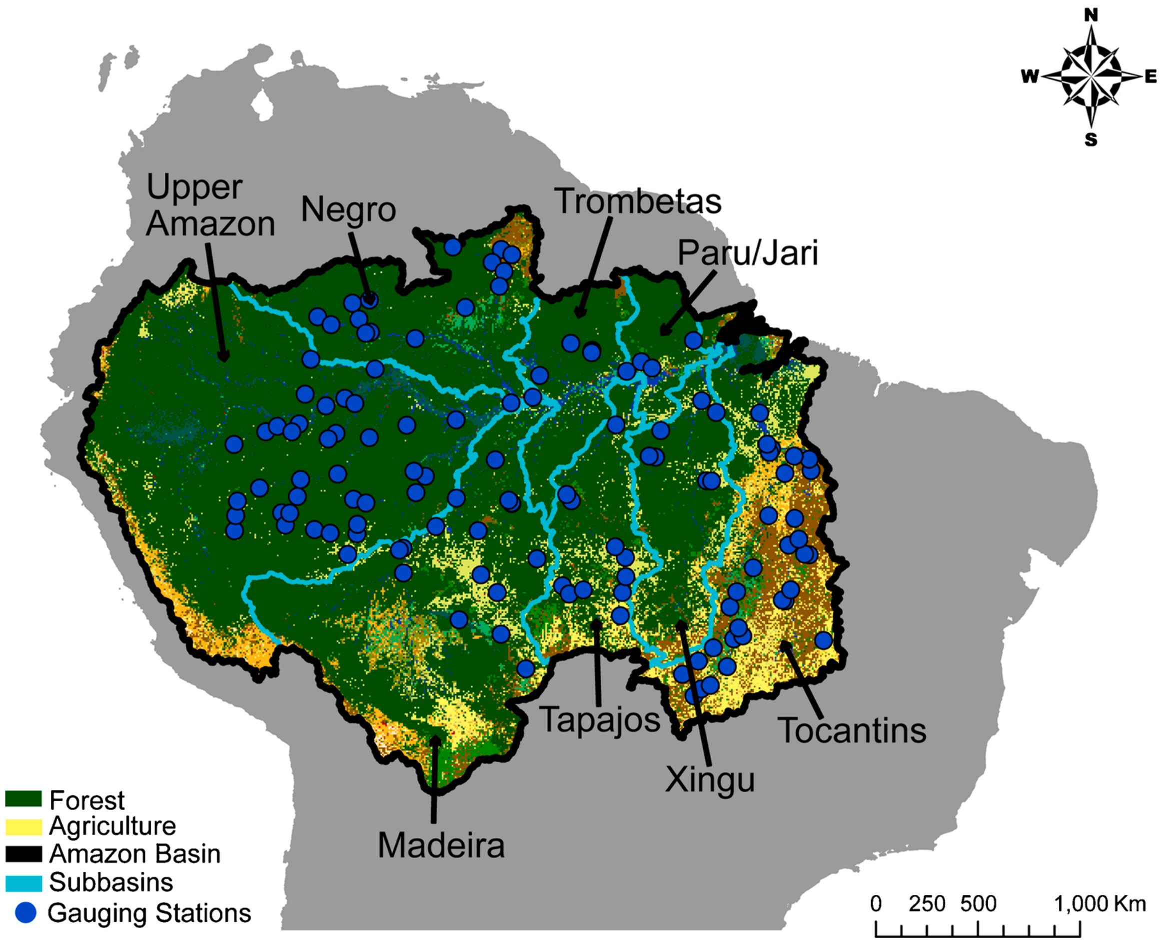

Fig. 1. Locations of the stream gauging stations and the major sub-basins of the Amazon, on top of 2015 remotely sensed land cover estimates from the European Space Agency (ESA, 2017).

changes along with a changing climate, a more holistic understanding of how the landscape responds to such alteration is needed. This includes considering changes to the groundwater storage and evapotranspiration components of the water balance. Because streamflow is physically linked to the rest of the water balance, any change in the amount of precipitation routed to groundwater storage or evapotranspiration is likely to affect streamflows.

Here, we seek to identify how and where streamflow characteristics change across the entire Amazon Basin in relation to changes in precipitation, land cover, groundwater storage, and evapotranspiration across scales, using a data-driven approach. We hypothesize that changes to the climate and landscape have altered all major components of the water balance, and that this shift of water balance partitioning affects streamflows. We first analyze over 35 years of streamflow data across the entire Brazilian Amazon and the neighboring Tocantins/Araguaia Basin, and quantify changes in the magnitude and timing of discharge at seasonal and annual scales. These discharge data are from a set of 126 gauged river basins ranging in drainage area from 12,396 km^2 to 4,668,984 km^2, with an average of 243,810 km^2. We explore changes in streamflow patterns, which manifest as changes in the magnitude, timing, and number of events based on summary streamflow metrics (e.g., minimum and maximum flows). We expect that the magnitude and direction of these changes will vary across the basin, as has been demonstrated at coarser (Amazon Basin and large sub-basin) scales (Gloor et al., 2013). We then investigate changes in the other major components of the water balance by quantifying catchment-scale precipitation, groundwater storage, and evapotranspiration across the Basin. To fully investigate changes in the storage and ET components, as well as their relationship to discharge dynamics, we calculate the residual water budget within each streamflow basin and identify trends in these two components. We then compare our calculated residual water budget to independent, remotely sensed quantifications of groundwater storage and ET. While the data record for these products are not as long as those for our discharge and precipitation data, they provide valuable insights into recent changes to groundwater and ET, and aid in our interpretation of the residual water budget. We then discuss how changes in precipitation and land cover may be controlling the observed changes in streamflow, ET and groundwater storage. This research furthers our understanding of how the water balance in the Amazon Basin is changing and highlights the important and understudied role of changes in groundwater storage and ET across the basin.

2. Methods

2.1. Site description

The Amazon River Basin (Fig. 1) spans ~6.3 million km^2 from the Andes Mountains in the west to the Atlantic Ocean in the east, accounting for ~17 % of the world's total freshwater discharge and hosting a majority of the Amazon rainforest. In total, about half of the world's remaining tropical forest lies within the Amazon Basin (Gloor et al., 2013). The Amazon Rainforest ecosystem encompasses ~5.4 million km^2, providing 15 % of global terrestrial photosynthesis, ~10 % of global species diversity, and storing ~150 Pg of carbon (Malhi et al., 2008; Lewinsohn and Pardo, 1994). Annual average rainfall is between ~1000 and ~3000 mm across most of the basin, with peak values of ~4000 mm in the northwestern basin, and minimum values of ~100 mm in the Andes along the southwestern rim of the basin (Haghtalab et al., 2020; Maeda et al., 2017). The timing of rainfall also varies from early arrival in the southwestern basin (December to February) and later arrival in the northern basin (March to May). The far north and northwestern regions of the basin remain wet throughout most months of the year (Espinoza Villar et al., 2009b). The rainforest also provides a massive water flux to the atmosphere, with annual average ET ranging from ~1000 to ~1500 mm/yr (Maeda et al., 2017). The water flux between the Amazon and the atmosphere is so large that the ecosystem partially regulates its own climate through precipitation recycling. As such the Amazon region affects atmospheric circulation and energy fluxes on the global scale (Gloor et al., 2013; Coe et al., 2016; Costa and Foley, 2000).

2.2. Data

Here, we used five major data sources to quantify changes in streamflow, precipitation, land cover, groundwater storage, and evapotranspiration. We used daily discharge data from stream gauging stations operated by Agência Nacional de Águas (ANA), Brazil's National Water Agency. The length of record for stations varies, but discharge data are generally available from the 1980′s to 2014. These streamflow stations are only within the Brazilian Amazon, as we did not have access to streamflow data for any Amazon streamflow stations in Bolivia, Columbia, Ecuador and Peru, or more recent data from Brazil. Streamflow records are affected by all hydrologic processes upstream of the sampling point, so these data are affected by changing climate and land cover conditions outside the Brazilian Amazon. As such, we compare changing streamflow at these stations to climate and land cover change data across the entire Amazon Basin. We obtained precipitation data from the Climate Hazards group InfraRed Precipitation with Stations (CHIRPS) gridded daily precipitation product, with 0.05 degree resolution from 1981-present (Funk et al., 2014). Haghtalab et al. (2020) validated this data against the ANA climate stations, and found that the CHIRPS data was more accurate than the Tropical Rainfall Measuring Mission (TRMM) product across our study region. For our land cover data, we used the European Space Agency (ESA) Climate Change Initiative (CCI) Land Cover Climate Research Data, which is available annually from 1992 to 2014 with 300 m resolution (ESA, 2009). We derived groundwater storage changes over the study area from Gravity Recovery and Climate Experiment (GRACE) monthly Land Mass Grids from 2002 to 2014 with ~1 degree resolution (Swenson, 2012; Landerer and Swenson, 2012; Swenson and Wahr, 2006). To quantify evapotranspiration, we used the Moderate Resolution Imaging Spectroradiometer (MODIS) MOD16A2 gridded 8-day net evapotranspiration product available from 2000 to 2018 with 500 m resolution (Running and Mu, 2015; Mu et al., 2007).

Before data processing and analysis, we formatted and quality-checked the discharge data using Python. Data for each station were cleaned to remove non-numeric, missing, or duplicate values. We then filtered the data by station to retain only years with greater than 95 % of values present, and only stations with at least 10 years of available data. We further restricted this data to remove stations with drainage basins smaller than 12,321 km^2, which is the approximate spatial resolution of our coarsest gridded dataset, the GRACE total water storage estimates. This resulted in a data set with 126 stations where the discharge records passed the quality assurance steps. Remotely sensed data were spatially and temporally resampled over the gauge basins as described below.

2.3. Analysis

For our analysis, we defined the water year as extending from December 1 to November 30 of the following year. This allowed us to capture a full hydrograph cycle starting and ending at relatively low-flows for most stations in each annual period. We defined the wet and dry seasons as December 1 to April 30 and May 1 to November 30, respectively, which provided a uniform seasonal definition across the basin based on previously established research in this region. Espinoza Villar et al. (2009a) state that the wet season is December, January, and February in the south and March, April, and May in the north, although peak precipitation may fall outside these bounds in the far northwestern parts of the Amazon Basin. Our use of December through April is thus logical for the scale of our analyses. A different definition of the wet and dry seasons could alter results of seasonal metrics at some stations, however this should not significantly alter long-term trends in annual streamflow indices. All data sets with monthly or finer resolution were assigned a time index identifying both the water year and a wet season/dry season flag.

To understand how and where hydrology is changing within the study region, we developed a set of hydrologic indices to quantify changes in volumetric and temporal components of the hydrograph (Table S1). The indices generally correspond to characteristics in the magnitude, timing, and patterns of hydrograph events. Specifically, they describe average, high and low flows, flood and low flow occurrence, hydrologic reversals, and rates of water mass gain and loss in each subbasin. These indices were selected as they summarize the major components of the hydrograph, including important hydrologic conditions such as flood and baseflow. We quantified these indices at monthly, seasonal, and annual timescales. In addition to describing the hydrograph, each defined streamflow index is also relevant to both ecological and ecosystem responses. For example, the timing, number, and magnitude of high flow events can alter habitat for fish species, affecting their spawning, migratory cycles, and abundance (e.g., Tomasella et al., 2013; Castello et al., 2015, 2019, Timpe and Kaplan, 2017). While a detailed discussion of the ecological impacts is beyond the scope of this study, the results of change in these indices may be useful to ecological investigations in this region (Melack and Coe, 2020). To facilitate comparison with gauge basin-averaged driver variables (precipitation and land cover), the selected indices were computed using basin yield (BY), calculated as $BY = D/A$, where D is discharge and A is the basin area. We quantified all of the indices using statistical tools available in Python or in the NumPy (Oliphant, 2006), SciPy (Virtanen et al., 2020) and StatsModels (Seabold and Perktold, 2010) packages.

Discharge data are available at many stations prior to 1980, however we chose to limit the temporal scope of our analysis based on the number of stations available in each year, and the availability of precipitation data. Many of the discharge records before 1980 were incomplete, as assessed by our quality control process described above.

To link spatially-distributed drivers (i.e., land cover, precipitation, evapotranspiration, and groundwater storage) to gauged discharge, we delineated watersheds upstream of each river gauging station. For this, we generated D8 flow direction (Greenlee, 1987) and resultant flow accumulation rasters from the HydroSHEDS 3-arc second conditioned DEM (Lehner et al., 2006) using the ArcMap 10.2 Spatial Analyst Toolbox. Gauge stations were located according to their latitude/longitude coordinates and then snapped to the raster cell with the highest flow accumulation within 1500 m. The location of each gauge station was checked manually, with 56 stations moved to overlie the appropriate cell (identified from the flow accumulation raster). Once proper placement of the gauge stations was confirmed, watersheds were generated from the flow direction raster using the watershed delineation routine within ArcMap.

To understand how the spatial and temporal pattern of precipitation and land cover compare to those of the water balance components in our gauge basins, we quantified changes in land cover and precipitation within each basin. The area and relative proportion of each land cover class were calculated for each basin in all available years. We combined all of the ESA land cover classes for different natural vegetative types into summary land cover classes of “natural vegetation” and different agricultural classes as “agriculture”. The “natural vegetation” summary class includes all naturally occurring terrestrial land cover types of the Rainforest and Cerrado Biomes. Both contain significant tree cover, and are the dominant biomes in the deforested regions of the Amazon Basin. We then developed time series of forest and agriculture proportions in each basin. To quantify daily gridded precipitation data, we first spatially averaged over each gauge basin then temporally resampled to summarize mean-annual and total-annual precipitation

We applied the Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975) to detect significant changes in our time-series records for discharge and the associated driver variables, implemented through a Python script (Schramm, 2016). We interpreted the results of this test using the z-score metric, where the sign indicates the direction and magnitude in the trend. The Mann-Kendall test was applied to annually averaged discharge, precipitation, and land cover change data, as well as annual summaries of the discharge indices. In the Results section below, we report results for gauges and basins that were shown to have significant change using a p-value threshold of 0.1.

For basins with a significant trend as identified by the MK test, we used the Theil-Sen slope estimator (Theil, 1950; Sen, 1968) to calculate the slope of change. This method, which computes the median slopes of lines fit though pairs of points in the dataset, is much less sensitive to outliers than simple linear regression methods (Lavagnini et al., 2011). It has been used to identify trend magnitudes in hydrology and climate data records, and is often used with the MK test (Li et al., 2014). As with the Mann-Kendall test, the Theil-Sen Slope was applied to annual summaries of all data for which a trend was calculated. The Theil-Sen regression was implemented thought the SciPy-stats package in Python (Oliphant, 2006).

To understand changes in observed discharge in the context of the complete hydrologic cycle, we calculated the water balance for all data availabe in each gauge basin from 1983−2014. The standard water balance is shown in Equation 1, where the change in total basin storage (ΔS, mm/yr), is calculated by subtracting annual total basin yield (BY, mm/yr), and annual evapotranspiration (ET, mm/yr) from annual precipitation (P, mm/yr).

$$\Delta S = P - ET - BY \tag{1}$$

Because we do not have evapotranspiration data for the entire period of the precipitation data, we calculated the water balance residual (WBR). We define the WBR as the difference between basin-averaged annual precipitation (P, mm/yr) and annual total basin yield (BY, mm/yr) for each gauge, which equals the sum of the basin-averaged annual evapotranspiration (ET, mm/yr) and change in total basin storage (ΔS, mm/yr), as shown in Equation 2.

$$WBR = \Delta S + ET = P - BY \tag{2}$$

To reduce the effects of outliers, we computed a three-year moving average of our calculated WBR value. We assessed linear trends in this annual rolling-average metric over the entire record length, and over shorter periods for comparison to other products as discussed below.

We used the GRACE Tellus Monthly Mass Grids to separate the ET and soil water storage values lumped within the WBR. While the GRACE data do not cover our full discharge period, they can help constrain changes to the individual components of the WBR from 2001 to 2014. We spatially averaged the GRACE data over each gauge basin using Google Earth Engine (Gorelick et al., 2017) to create time series data. These data are reported in units of Liquid Water Equivalent (LWE), which is the mass anomaly recorded by GRACE reported in terms of water depth. LWE values represent the monthly total water storage (TWS) on the landscape relative to the 2004–2010 average. We calculated the mean of the three monthly TWS products (calculated independently by NASA JPL, University of Texas Center for Space Research, and GFZ Potsdam) to use for further analyses. We then computed two annual quantities from monthly TWS: 1) annual (water year) average total water storage, and 2) annual change in storage (ΔS, originally cm/yr) for each basin by subtracting the LWE value in December of the next water year from the December value at the beginning of the current water year. Taking the difference in TWS values at the end of the dry season (December of the water year, November of the calendar year) minimized the effect of surface water on the signal, as this is the most hydrologically stable time of year. As such, the change between December TWS values is assumed to be due to changes in groundwater storage. We used data from 2003 to 2014 and interpolated the monthly mass values to fill in missing December values for 2011. An example of the time series data and trends for total water storage, groundwater storage, and delta S are shown in Figure S1 for selected basins. We then computed WBR-estimated ET for each basin as shown in Eq. (3).

$$ET = WBR - \Delta S \tag{3}$$

To estimate changes in groundwater storage, we also analyzed the linear trends in the December TWS values. As with our analysis of ΔS, we used the December TWS values in this analysis to minimize the effect of surface water changes on the signal. To further validate this approach, we quantified trends in the December streamflow values over the same period, as an indication of changes to the end of dry season surface water storage.

To constrain our estimated changes in ET, we compared our ET estimates with the MODIS Evapotranspiration 8-Day gridded product. We prepared the MODIS grids for comparison with our estimated ET value by spatial and temporal resampling in Python. First, we spatially-averaged the MODIS ET composites over each gauge basin. To minimize the effect of missing pixel values, we then calculated the monthly average MODIS ET value for each basin. Because ET values are relatively stable day to day in this region, monthly averages provide a robust estimate of ET variation across the year. Here we do not assess the seasonality of missing composites or pixels, which might impart biases into our calculated average MODIS ET values. Analysis of the seasonality of missing MODIS data, or its overall accuracy, is beyond the scope of this study, but should be investigated in subsequent research. We then used monthly ET values to create annual averages of ET for each basin. Finally, we compared trends and average values of these annual ET estimates to our WBR-estimated ET calculations. Both the GRACE TWS data and MODIS ET data streams have much shorter records than precipitation and discharge in our region and as such, the length of record for the WBR estimated ET records were considerably shorter (see Figure S2). A graphical representation of our workflow for this study is presented in Figure S3.

Due to different temporal spans of the data sources used in this analysis, we were not able to independently quantify each water balance component for our full record from the early 1980′s to 2014 for which precipitation and discharge records are available. Instead, we quantify the remotely sensed land cover, ET and groundwater storage estimates for their available records of: 1992–2014 for ESA land cover, 2002–2014 for GRACE total water storage and 2006–2014 for MODIS ET. We then use these data sources to contextualize our results, and validate our numerical water balance estimates of ET. A summary of the length of record for each dataset is presented in Figure S2. Additionally, the long term average of basin yield, CHIRPS precipitation, MODIS ET, and GRACE TWS are shown in Supplemental Figures S4 and S5.

3. Results

All of the hydrologic indices of the magnitude and timing of hydrograph events showed significant changes between 1980 and 2014 across most of the Amazon Basin. Here, we focus on five indices to describe changes in streamflow across the available data record: 1)

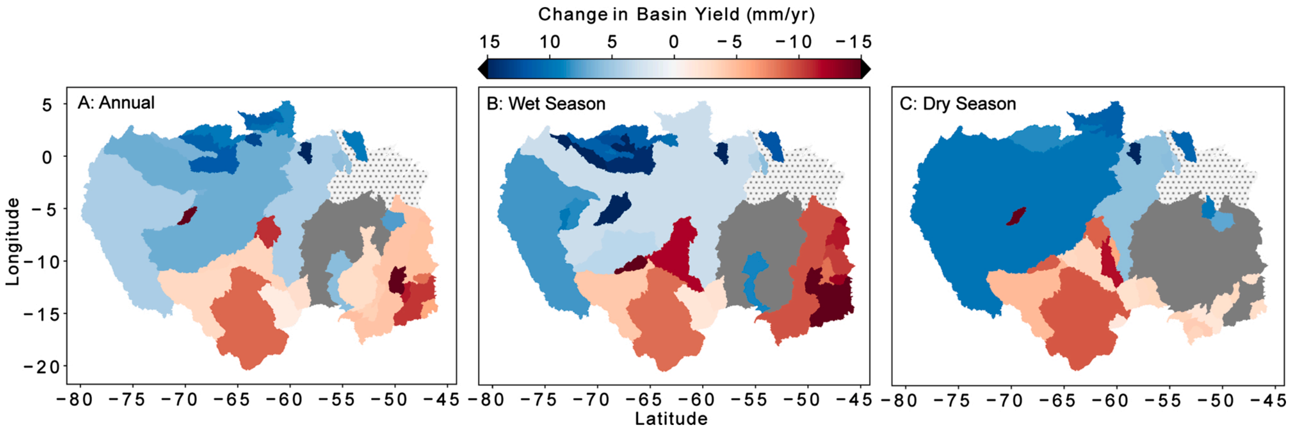

Fig. 2. Slope of change in water- year basin yield (mm/yr) for: A) annual, B) wet season, and C) dry season periods between 1980 and 2014. The basins are drawn in descending size (largest first) to ensure all basins with significant changes are shown. Changes in average daily streamflow exist at both annual and seasonal intervals, with spatially distinct trends of decreased streamflow in the south and east, and increased streamflow in the north and west. Catchment areas in solid grey have no significant trend at the $p = 0.1$ level, while the stipple patterned areas fall outside of gauged catchments.

annual average, 2) wet and 3) dry season averages (Fig. 2), as well as 4) 10th and 5) 90th percentile discharge (Fig. 3). These indices have a similar spatial pattern in trend direction, with the northern and western basin showing increasing discharge, and the southern and eastern basin showing decreasing discharge. Some of the smaller gauge basins show greater trend magnitudes or opposite trends as their surrounding larger regions, indicating heterogeneous hydrologic trends across the basin.

Changes in annual, wet, and dry season basin yields are on average ±9.5 mm/yr, but range up to ±30 mm/yr. (Fig. 2). The strongest trends of increasing flows in the north and decreasing flows in the south and east are intensified during the wet season (72 basins with significant trends), especially in the northern Rio Negro and southeastern Tocantins basins (see location in Fig. 1). Here, intensification (or intensified) refers to an increase in the absolute magnitude of the trend or value for a given streamflow index. Trends in dry season streamflow are similar to trends in annual averages in both number of stations with significant change (79 for annual average, 81 for dry season) and magnitude of changes. The 90th percentile of flow (Fig. 3A) had trends across 69 stations similar to those in annual streamflow, however for this index the dichotomy between north and south is intensified. Changes in peak discharge and flood pulses, represented by the 90th percentile of flow, range from -60 to +100 mm/yr. In contrast, the 10th percentile flow (Fig. 3B, indicator of baseflow) had a different spatial pattern of change than those of annual discharge or peak flows across 107 stations. Baseflow, which we calculated as the 10th percentile of discharge, values are decreasing across most of the southern, eastern and western portions of the basin. The only areas experiencing increasing baseflow are in the far northern basin and select regions in the Tocantins. The magnitude of change in baseflow is also much smaller, as might be expected given their lower absolute magnitude, with a general range of ±10 mm/yr, however increases as high as +40 mm/yr were observed in the upper Rio Negro river basin.

In addition to changes in streamflow volume, other hydrologic characteristics are changing across the Amazon Basin, including: the number of high/low flow events (Figure S6), the rates of water entering and leaving the basin (Figure S8), and the amplitude and period of the hydrograph (Figure S10). As with metrics of streamflow volume, changes in the number and timing of events are also spatially variable. For example, the northern and western basins are experiencing an increase in the number of flood events, while the southern and southeastern basin are experiencing fewer flood events annually. Together, these metrics indicated intensification of the hydrologic cycle across the northern basin, with an increase in the number of flood events (Figure S6A), the rate of water gain and loss from the basin (Figure S8), and the amplitude and period of the annual hydrograph (Figure S9). Conversely, the annual hydrograph of the southern and eastern basin has dampened, with decreases in the number of flood events, a shorter hydrograph period, and a smaller hydrograph amplitude. The timing of hydrologic events is also changing; most notably a shift to later minimum flows in the western basin and earlier center of mass of flows in the northern and southern basin.

There have been significant increases in annual precipitation over most of the central and western basin (Fig. 4). Areas of significant decrease in annual precipitation occurred in a small number of watersheds in the southern basin. Wet season precipitation shows a wider extent of increased precipitation across the basin (Fig. 4B). Dry season precipitation shows much fewer areas of significant change, with increasing amounts in the western basin, and decreasing amounts in the upper Madeira Basin (Fig. 4C).

Most of the forest loss in the basin from 1992 to 2015 occurred in the southern region, also known as the "Arc-of-Deforestation", which encompasses the upper Xingu, Tapajos and Madeira Basins (Fig. 5, S11 and S12). At the basin scale, the amount of forest lost is directly proportional to the increase of agricultural land in the same basin. The Tocantins basin had already experienced significant clearing of the natural Cerrado vegetation and conversion to agriculture prior to the start of our land cover record in 1992. Typical forest loss rates in the central and southern portions of the Amazon range from 0.5 to 1.5 % of the basin area per year. Much of the western and northern Basin has experienced relatively little deforestation since 1992.

Analysis of the water balance residual for each gauge basin (Equation 1) shows significant changes in the sum of evapotranspiration and groundwater storage across the region (Fig. 6C). Previously discussed trends in precipitation (Fig. 6A) and basin yield (Fig. 6B) are

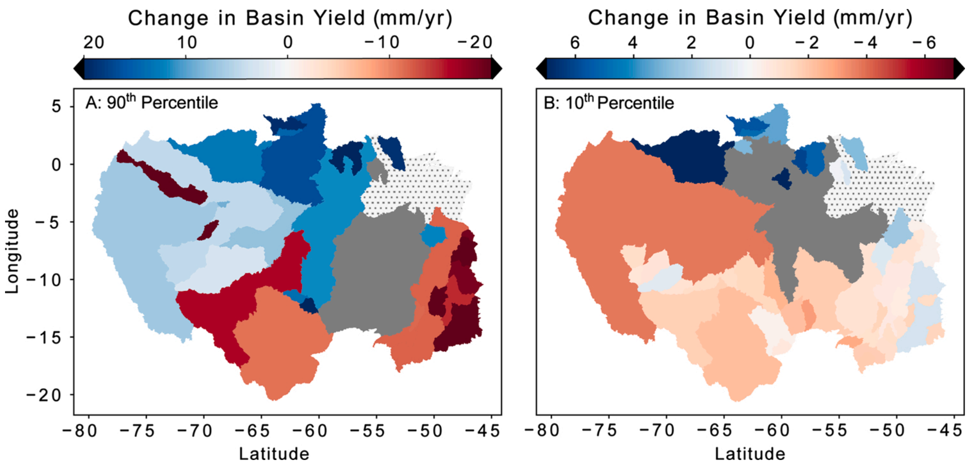

Fig. 3. Slope of change in 90th (A) and 90th (B) percentile discharge for between 1980 and 2014. Similar to the average discharge trends, both metrics show spatial variance in magnitude and trend direction. 10th percentile discharge is decreasing over most portions of the basin, though at a slower rate than change in annual averages. 90th percentile discharge shows similar patterns to the averages, but with larger magnitudes of change. Areas in solid grey represent no significant trend, while the patterned grey areas have no data.

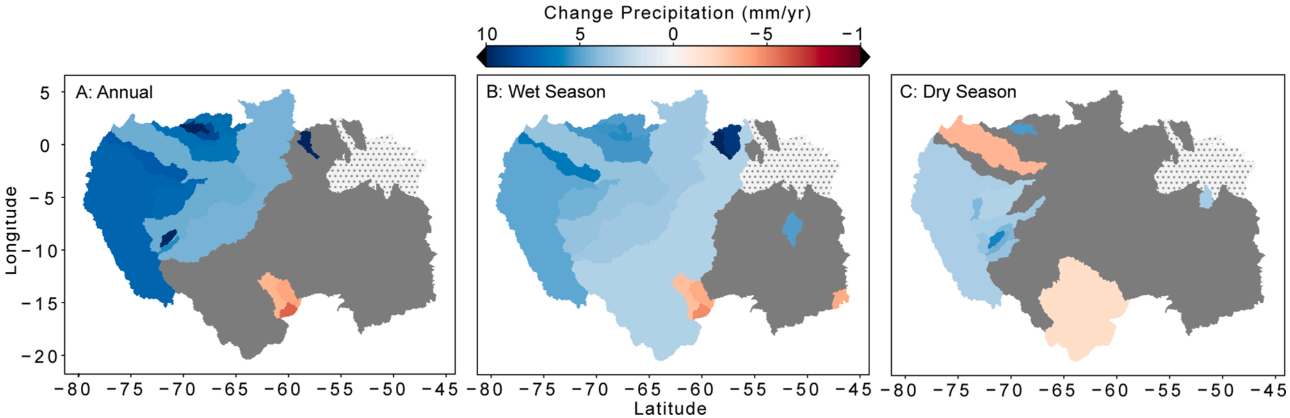

Fig. 4. Slope of change (mm/yr) in cumulative precipitation over the Amazon for A) annual, B) wet season and C) dry season between 1983 and 2014. Patterns are generally similar in the annual and wet season trends, with increasing precipitation in the northern and western portions of the basin, and isolated areas of the southern basin experiencing decreased precipitation. Areas in solid grey have no significant trend, while the patterned grey areas have no data.

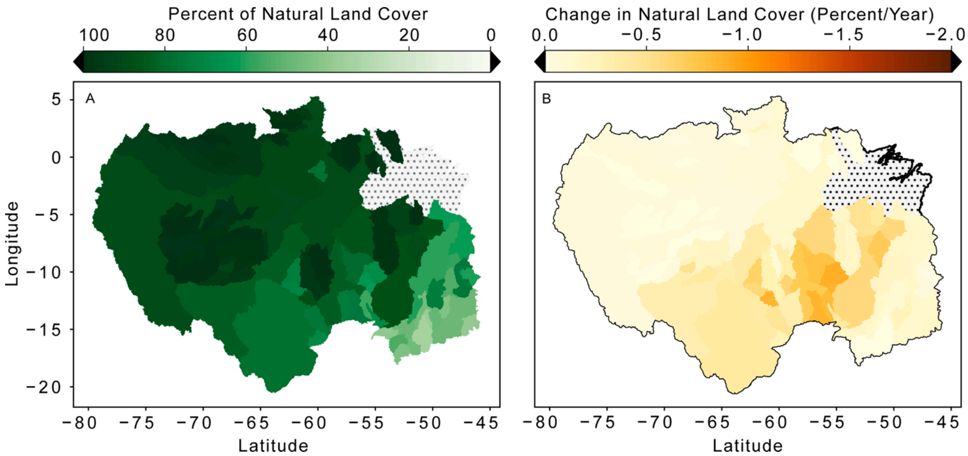

Fig. 5. A) Proportion of natural vegetation in each gauge basin at the start of the ESA Land Cover record (1992). (B) The slope of change in natural vegetation between 1992 and 2015 shows the greatest loss in the Xingu, Tapajos and Madeira basins, south of the Amazon River. For comparison, proportion agricultural cover in 1992, and trends in agriculture proportion are shown in Figure S11. Areas in patterned grey lie outside of stream gauge catchments used in this study.

mapped for the corresponding period from 1983 to 2014 (limited by precipitation data availability). Trends in the three-year moving average of this residual showed increases in the water balance residual over much of central and western portions of the region at the large gauge basin scale. Smaller basins throughout the region, and most of the Tapajos basin showed decreases in the water balance residual. The Tocantins showed a split pattern with increases in the WBR in the north and east, and decreases in the southwest portion of the basin. Most basins have changes between ±10 mm/yr, but they range from -20 to +39 mm/yr. No significant trend was detected for the Xingu basin or the northwestern Tocantins.

Trends in the December TWS values from GRACE (Fig. 7A) indicate significantly increased groundwater storage in the Xingu, Tapajos, and upper Madeira basins in the south, as well as in the upper Trombetas basin in the north. Average increases in groundwater storage across these basins were +7.1 mm/yr, with a maximum increase of 10.5 mm/yr; no significant decreases in groundwater storage were observed. During this same period (2002–2014), the end of dry season discharge, shown in Supplemental Figure 14, has not significantly changed in the Xingu, Madeira or Trombetas river basins. We do not have sufficient data to assess change in the Tapajos basin over this period, however analysis for the full discharge record show end of dry season discharge increases in the Trombetas, and decreases in the Tapajos basin. The GRACE gravity anomaly data also showed significant increases in annual total water storage over most of the Amazon Basin, but decreasing TWS in the Tocantins (Figure S12). The highest rates of TWS increase are observed in basins along the main stem of the Amazon River, and in the northern Trombetas Basin.

Basins with significant changes in estimated ET (Equation 3) are shown in Fig. 7B. The results of this analysis show increasing ET in the western and south-central Amazon, and decreasing ET in the far northern region of the Basin. The trends in ET are strong relative to the other water balance components, with increases of 30 or more mm/yr and decreases of a similar magnitude.

Analysis of the MODIS ET data (available from 2006 to 2014) shows changes in annual average ET (Figure S13) with slopes from ±20 mm/yr. Specifically, the western and northern basins are showing decreases in ET, while portions of the upper Madeira and

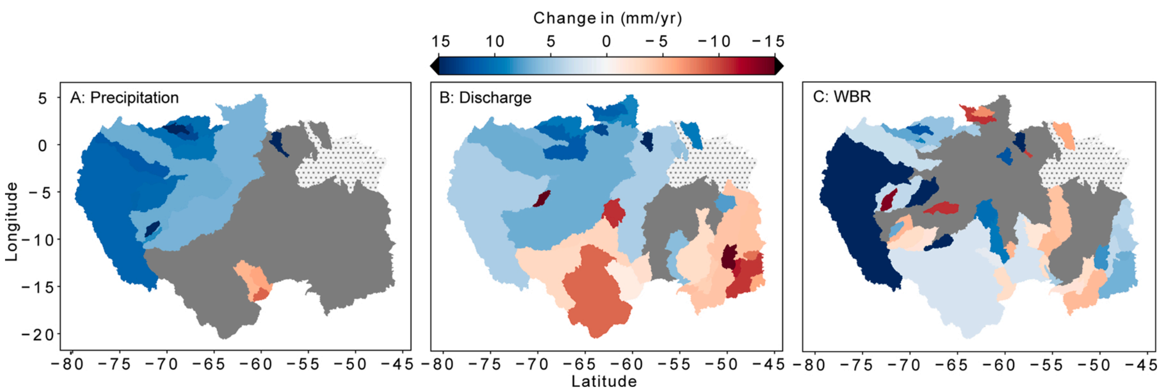

Fig. 6. Slope of change in water year basin-average: A) precipitation, B) basin yield, and C) water balance residual (Equation 2) calculated from discharge and precipitation databetween 1983 – 2014. There are significant changes in the sum of ET and ΔS, representing shift in water partitioning within the landscape over this period. Areas in solid grey have no significant trend, while the patterned grey areas have no data.

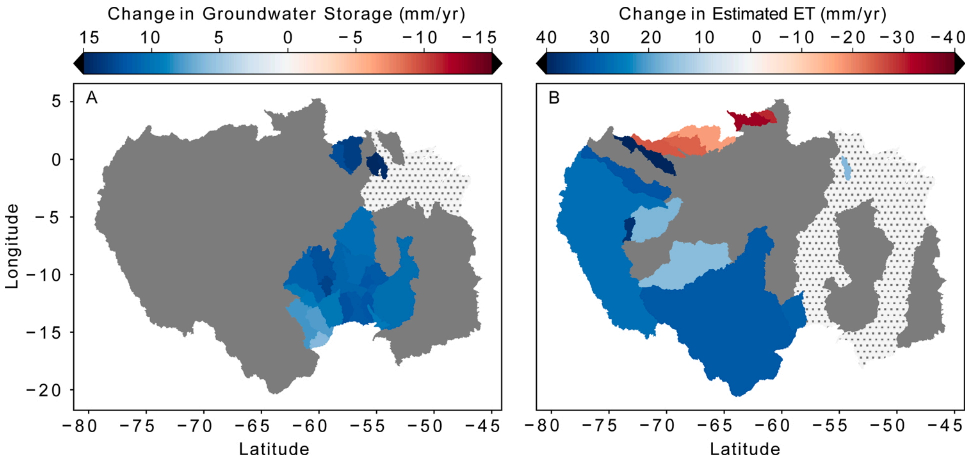

Fig. 7. A) Changes in GRACE derived groundwater storage values, assessed as the trend in December TWS values between 2002 and 2014. Groundwater storage is shown to be increasing in the areas affected by deforestation and significant increases in precipitation. The GRACE-derived ΔS data were also used to estimate ET from the WBR. B) Trends in the resulting estimated ET between 2002 and 2014 show increasing ET in the south and west, and decreasing ET in the north. Areas in solid grey have no significant trend, while the patterned grey areas have no data.

Tocantins show increases in ET. Trends in our estimated ET (Fig. 7B) over this period are similar to those in the MODIS ET data (Figure S13) for the far southern (Madeira) and northern portions of the basin, but contrast markedly in the Andean western part of the Basin. In addition, the significant increases in ET in the Tocantins shown in the MODIS data are not observed in our estimated ET. The magnitude of the significant trends in both datasets were similar. In addition to quantifying trends in both datasets, we also compared the values for annual average ET between the two datasets (Fig. 8C).

4. Discussion

Within the water balance, streamflow is the most accurately measured quantity and commonly has the longest record (Figure S2). Streamflow is an integrator of landscape water dynamics because it is affected by changes in all parts of the water balance. As such, changes in streamflow provide an important record of changes in water resources in basins like the Amazon. A number of previous studies demonstrate significant streamflow changes in specific regions, or over restricted time spans, and have generally focused on one driving factor to help explain these changes (Costa et al., 2003; Espinoza Villar et al., 2009a, Gloor et al., 2013, Coe et al., 2011; Hayhoe et al., 2011; Timpe and Kaplan, 2017 and Levy et al., 2018). Our results demonstrate long-term changes in streamflow across the entire Amazon Basin at multiple scales that are affected by complex interactions between climate and landscape factors. In addition to changing streamflow patterns, our research also demonstrates a significant and spatially variable change in precipitation patterns across the Amazon Basin. Haghtalab et al. (2020), analyzed changing precipitation patterns, including changes to the number of dry days and extreme events across the Amazon Basin. Their work showed a similar spatially explicit pattern of change in precipitation,

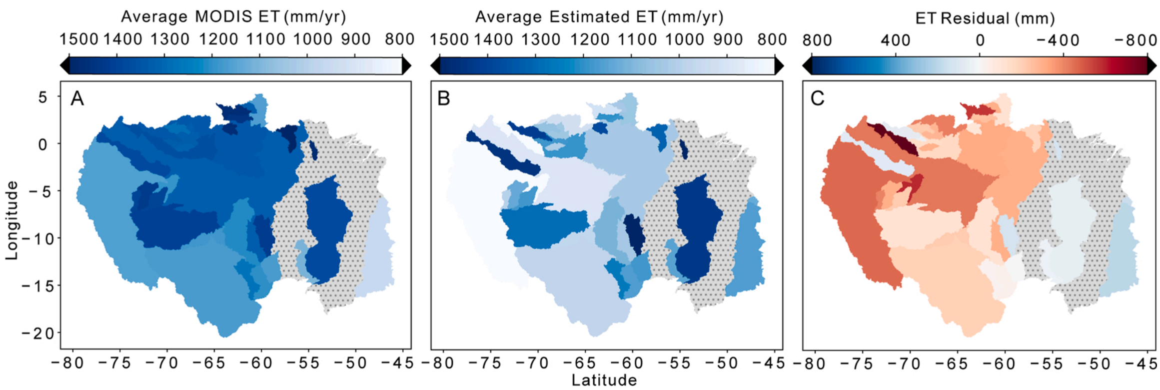

Fig. 8. Annual average ET from: A) MODIS ET estimates (2006-2014) and B) estimated ET values corrected with GRACE data (2002-2014). Estimated ET values are higher in the Tocantins and lower in the western basin than those from the MODIS estimates. The residual of the two ET quantifications (C) shows that over most of the basin the WBR calculation provides lower ET estimates than MODIS. Areas in solid grey have no significant trend, while the patterned grey areas have no data. MODIS ET data are only quantified in basins for which we have sufficient data to estimate ET.

with increasing rainfall in the northern basin, and decreasing rainfall in the southern basin.

In addition to changes in land cover and climate, the development of physical infrastructure such as hydroelectric dams can alter hydrologic dynamics. Hydropower is an important energy source across the Amazon Basin (Moran et al., 2018), with approximately 277 new hydroelectric dams in the early stages of planning and development across the basin (Castello and Macedo, 2016). Previous work has demonstrated that hydropower infrastructure can affect the timing and magnitude of hydrologic events such as dampening the annual flood pulse (Timpe and Kaplan, 2017). While we do not explicitly quantify the effects of hydropower dams, they are unlikely to affect long-term annual average flows. Isolating the effects of dams is difficult as records of discharge both before and after installation are limited across the Amazon, and such changes are overprinted by climate and land cover induced hydrologic alterations.

Furthermore, our results indicate that changes in streamflow are also spatially variable, with increasing flows in the western and northern basin, and decreasing flows in the southern and eastern basin, as shown in Fig. 2. These results support those of Espinoza et al. (2009a,b), which show a similar pattern of spatial variation in both precipitation and streamflow across the Amazon Basin. Work by Duffy et al. (2015) and Sorribas et al. (2016) indicates that this pattern of change in precipitation and discharge will continue with changing climate. The Duffy et al. (2015) analysis of the outputs of 35 climate models in the Coupled Model Intercomparison Project (CMIP), as summarized in the Intergovernmental Panel on Climate Change 5th Assessment Report (IPCC AR5), indicates that decreased rainfall and more frequent drought will likely occur in the southern and eastern Amazon, while increased rainfall will likely occur in the north and west in the coming century. Hydrologic model discharge estimates from 2070 to 2099 by Sorribas et al. (2016), driven by the IPCC's Fifth Assessment Report CMIP5 indicate that the predicted changes in climate will continue to cause decreased streamflow in the eastern basin, and increased flows in the western basin.

In addition to changes in streamflows, we also observe significant changes in water balance residual (WBR, Equation 2) shown in Fig. 6, which indicates that evapotranspiration and groundwater storage are also changing significantly across the Basin. This conclusion is supported by a first-principles understanding of the water balance. All of the precipitation reaching the land surface must be routed to streamflow, surface water bodies, subsurface storage, or evapotranspiration. Given the relatively limited surface water storage in the basin, any discrepancy in water mass between precipitation and discharge must either be stored in the subsurface or returned to the atmosphere via ET. Together, changes in streamflow data and the calculated WBR indicate that alterations to the landscape have likely affected all major components of the water balance in the Amazon Basin. Furthermore, processes exerting control on ET and groundwater storage including changes in climate, land cover, sea surface temperature and precipitation patterns have changed significantly since the 1980's (Malhi et al., 2008; Haghtalab et al., 2020; Espinoza Villar et al., 2009a).

The observation that all parts of the water balance, including understudied groundwater storage processes (Gleeson et al., 2019) are changing, is further supported by our analysis of MODIS ET estimates and GRACE mass anomaly data. These independent quantifications of ET and groundwater storage show significant change in both parameters across the Basin. It is important to note that there are increasing trends in groundwater storage (Fig. 7A) in areas of deforestation (Fig. 5B, specifically in the Xingu, Madeira and Tapajos basins) and significant precipitation increases (Fig. 4, in the northern Trombetas basin). A comparison of GRACE data to the LEAF-HydroFlood model indicated that changes in TWS in the southeastern Amazon are dominated by subsurface groundwater storage (Pokhrel et al., 2013), which supports our results indicating groundwater storage increased in the Madeira and Tapajos basins. The Trombetas basin also shows some of the highest increases in groundwater storage, while the Xingu, Tapajos, and Madeira show lower rates of storage increase. This further indicates that the processes driving groundwater storage increase are likely associated with precipitation increase in the northern basin, and deforestation in the southern basin. Our approach to estimating change in groundwater storage is further supported by the analysis of changing streamflow at the end of the dry season (December of the water year) shown in Figure S14. Changes in streamflow are representative of those in surface water storage. If changes in the end of dry season total water storage values were a result of changing surface water storage, we would expect to observe increasing streamflows. However, we observe no increases in end of wet season streamflows in the Xingu, Madeira or Trombetas basins between 2002–2014. This further indicated that changes in end of dry season total water storage in these regions are a result of increased groundwater storage. While we do not have a sufficient discharge record to assess trends in end of dry season discharge for the Tapajos basin during the GRACE record (2002–2014), trends calculated over the full discharge record show no significant increase in December discharge in the Tocantins.

Because the ability to estimate water balance fluxes remotely across large areas is a recent advance due to satellite data, the record lengths for the remotely sensed groundwater storage and ET datasets are relativity short. As such, validation of our WBR calculation across its whole streamflow record is not possible. Observed changes in the GRACE groundwater storage and MOIDS ET data are of similar magnitude to those of the WBR and estimated ET. However, our ET estimates are consistently lower than those derived from MODIS data in the central and western portions of the basin. While the absolute values of ET are different in the two products, both estimates show similar patterns of increased ET in the southern basin, and decreased ET in the northern basin. One notable exception is in the western Andean region of the Amazon which shows opposite trends in the two analysis. This is likely caused by discrepancies in the CHIRPS rainfall over the Andes as discussed below. Although we cannot disentangle either groundwater storage or ET from the WBR over its full record length, this calculation suggests that changing climate and land cover have resulted in long-term changes in groundwater storage and/or ET in the Amazon Basin.

Site- and regional-scale studies of water dynamics in the Amazon also support our conclusion of changing water balance dynamics. Transitions from forest to pasture or cropland results in shallow rooted land cover, which cannot access deep soil moisture or groundwater (Coe et al., 2016; von Randow et al., 2004), and thus decreasing ET and affect groundwater storage in the system (Neill et al., 2013). For example, research in the upper Xingu and Tocantins Basins shows that deforestation can increase both runoff to stream channels and soil moisture, and decrease ET (Coe et al., 2011; Hayhoe et al., 2011; Neill et al., 2013; Silvério et al., 2015, Arantes et al., 2016; Spera et al., 2016; Coe et al., 2017). However, extensive deforestation can result in reduced precipitation recycling, leading to decreased streamflows (Stickler et al., 2013). As agriculture continues to expand in conjunction with changing climate patterns, Brazilian agricultural systems may shift from being rainfed to the use of irrigation, as evidenced by changes already occurring in the Tocantins region. A recent paper by Latrubesse et al. (2019) suggests that expansion of both agriculture and the use of irrigation could result in decreasing water storage and streamflows across the Tocantins. Hydrologic modeling investigations have suggested groundwater plays an import role in the hydrology of the Amazon Basin. Miguez-Macho and Fan (2012a) used the LEAF-Hydro-Flood model to investigate the importance of groundwater in streamflow and surface hydrology across the Amazon. Their results indicate that groundwater buffers surface water resources during the dry season and drought conditions. These results also indicate that groundwater has varying contribution to streamflow, exerting the most control in headwater catchments. Further work by Miguez-Macho and Fan (2012b) indicates that groundwater can also affect ET capacity in the Amazon. The presence of groundwater below about 10 m depth can increase root water uptake, allowing for continued evapotranspiration across the dry season and drought periods.

There are uncertainties in the data sets used to quantify changes in the water balance. For example, the ET product is affected by cloud cover and land surface classifications, and the CHIRPS precipitation data product may underestimate rainfall in the western Amazon basin in a similar manner as has been shown for the Climatic Research Unit (CRU) data (Coe et al., 2009). This likely causes an underestimate of the water balance residual in this region, which may explain some of the discrepancy between our estimated ET and the MODIS data product. Second, MODIS ET underestimates ET from 2000 to 2005 in the Pantanal wetland of Brazil and Xingu (Penatti et al., 2015; Silvério et al., 2015), and a similar bias was observed for the Amazon Basin in this study. We thus restricted our MODIS data analysis to 2006–2014. While data availability for MODIS is limited in time, it does provide a robust estimation of ET across the entire Amazon. Previous estimates of ET have relied on mathematical estimation (from incoming solar radiation or precipitation and rainfall data) or the use of global climate models. At the basin scale, our water balance derived ET estimates are lower than those from MODIS. This indicates that either: 1) our methods underestimate ET due to discrepancies in one of the other water balance components (such as underestimation of precipitation by CHRIPS), or 2) the MODIS ET data overestimates ET in the region. Further research would be necessary to investigate the cause of this mismatch. Specifically, more direct measurements of ET across the Amazon are needed to compare with both statistical and remote sensing derived ET estimates. Direct measurements of ET exist from field campaigns such as the Large-Scale Biosphere Atmosphere (LBA), but have limited spatial coverage (Werth and Avissar, 2004). To better understand both natural variations in ET and its responses to climate and land cover changes, we will need to expand our quantifications of ET across the basin. These methods have been used to demonstrate the seasonality of ET (Maeda et al., 2017) and the change in ET due to deforestation Silvério et al. (2015) but have not been used to assess long term trends in ET across the Amazon Basin. In addition, limited understanding of certain physical process dynamics in the Amazon also limits our analysis. For example, widespread measurements of depth to water or aquifer properties are not currently available in the Amazon. As such, we do not have good constraints on the extent of storage change in these systems. These processes affect the degree to which land cover and total storage change affect streamflow in a given region.

5. Conclusions

The combined data records for discharge, precipitation, evapotranspiration and groundwater storage suggest spatially-variable changes in all components of the water balance across the Amazon Basin. Alterations to the water balance include average changes of $\pm$9.5 mm/yr to discharge, $\pm$7.7 mm/yr to precipitation, $\pm$29 mm/yr to ET and $+$7.1 mm/yr to groundwater storage. These observed changes are occurring in a spatially heterogeneous pattern, with the northern and western basins showing different hydrologic responses than the southern and eastern basins. Previous research has attributed changing streamflows to: 1) altered precipitation driven by natural climate variability and long-term climate changes, 2) increased runoff and deceased ET due to land cover change, 3) reduced precipitation due to reduced ET and water vapor recycling in deforested regions. Our results support these previous findings, and show that changing climate and land cover alter the major components of the water balance. Furthermore, we suggest that that streamflows are also altered by changes to the water balance partitioning, specifically due to altered groundwater storage in response to deforestation.

While our work demonstrates significant changes to the Amazon Basin's water balance, we do not currently have enough data to separate changes in groundwater storage and ET over the full discharge record. Such an analysis would require a model based investigation of alterations to the region's water balance. Using process-based landscape hydrology and groundwater models would provide better understanding of the complex water cycle dynamics across the Amazon Basin. Such models could be used to explicitly simulate the historic effects of deforestation on groundwater storage and ET rates, and project changes in the Amazon water balance in response to climate change scenarios though the end of this century. In particular, it will be important to explicitly model the role of changing groundwater storage in the basin's hydrology, including how this storage is affected by landscape changes. Developing an understanding of this complex system through both field and modeling investigations is critical to better project the state of surface water resources within the Amazon in the face of changes to both the climate and landscape.

Changes in climate, land cover and the hydrologic cycle are likely to continue in the Amazon as population growth and increased resource demand continues. The resulting alterations to streamflow, precipitation, groundwater storage and ET can affect hydropower production, agricultural yield, fisheries, nutrient cycling and carbon sequestration. Better understanding how the water balance changes in response to an altered climate and landscape will be important to preserve the water, food, energy and ecologic resources of the Amazon Basin.

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Writing – review & editing: D.W. Hyndman, A.D. Kendall, M.T. Coe, B.P. Heerspink

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ejrh.2020.100755.

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