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Armazenamento *total* de água e armazenamento de *águas subterrâneas*

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A distribuição da massa de água na Terra é uma informação necessária para entender o sistema climático e suas variações temporais em escalas de tempo mensais a multidecadal. Sobre a terra, ela corresponde à troca contínua de massas de água na superfície (isto é, rios, lagos, áreas úmidas, cobertura de neve e geleiras de montanha) e na subsuperfície (água no solo e águas subterrâneas) com a atmosfera e o oceano por intermédio das chuvas, evapotranspiração e diversas formas de escoamento superficial e subsuperficial. O armazenamento total de água é a soma da água contida nos diferentes estoques hidrológicos. A importância das águas superficiais na bacia Amazônica foi apresentada no capítulo 5. O armazenamento de águas subterrâneas também desempenha um papel importante na hidrologia da Amazônia e exerce uma grande influência na variabilidade climática e nos ecossistemas da floresta tropical (Pokhrel et al., 2013). Os fortes efeitos de memória do sistema de águas subterrâneas da Amazônia propagaram anomalias climáticas sobre a região por vários anos (Frappart et al., 2019; Miguez-Macho e Fan, 2012; Pfeffer et al., 2014).

A missão GRACE, em operação de março de 2002 a junho de 2017, e a missão *GRACE Follow-On*, em órbita desde maio de 2018, têm permitido o monitoramento das mudanças espaço-temporais do armazenamento de água terrestre (*Terrestrial Water Storage*, TWS; Tapley et al., 2004). A anomalia temporal do TWS é proveniente das observações do satélite GRACE, que medem as variações pequenas no campo gravitacional da Terra (Tapley et al., 2004). As observações do GRACE da anomalia do armazenamento de água terrestre (TWS *Anomaly* - TWSA), apesar de sua resolução espacial grosseira de ~200-300 km, têm sido amplamente utilizadas para analisar o impacto da variabilidade climática e das mudanças globais na distribuição das massas de água sobre o solo (Tapley et al., 2019), e dos estoques de água subterrânea em combinação com observações externas (Frappart e Ramillien, 2018).

Considerando toda a bacia Amazônica, a estimativa da amplitude anual do TWS derivada do GRACE varia de 300 a 450 mm (**Figura 9**; Chen et al., 2009; Crowley et al., 2008; Frappart et al., 2013b; Xavier et al., 2010). Essa faixa corresponde ao dobro da amplitude anual do armazenamento de água superficial de toda a bacia (Frappart et al., 2012; Ndehedehe e Ferreira, 2020), o que significa que a amplitude anual das variações de armazenamento subsuperficial (umidade do solo e água subterrânea) também representa metade da amplitude anual do TWS. Grandes variações desse valor foram observadas entre as principais sub-bacias amazônicas, dependendo da extensão de planícies de inundação (Frappart et al., 2019, 2011;

Papa et al., 2013). A chuva e a TWSA baseada no GRACE foram consideradas altamente correlacionadas na Amazônia e suas principais sub-bacias (período de 2003-2010), mesmo em escalas de tempo interanuais, com os coeficientes de correlação de Pearson geralmente superiores a 0,7 (exceto nas bacias localizadas nos Andes), e defasagem de tempo variando de zero a três meses (Frappart et al., 2013a; Ndehedehe e Ferreira, 2020). Resultados semelhantes foram obtidos entre a TWSA e vazões dos rios ao longo dos mesmos períodos (Frappart et al., 2013a). Observou-se também uma boa concordância entre o TWS e a extensão de águas superficiais obtida por satélite (GIEMS), as chuvas e vazões ao longo de vários períodos (Papa et al., 2008; Prigent et al., 2012, 2007; Tourian et al., 2018). Esses estudos revelaram a complexidade do transporte de água entre as diferentes sub-bacias da Amazônia com a presença de histerese na relação entre extensão de água superficial e a TWSA.

A análise dos padrões espaço-temporais das mudanças do TWS forneceu novas informações sobre o impacto dos eventos climáticos extremos (secas e inundações excepcionais que ocorreram em 2005, 2010, 2012-2015 e 2009, 2012, respectivamente) no armazenamento de água terrestre em toda a bacia Amazônica ou em suas principais sub-bacias (Chen et al., 2010, 2009; Espinoza et al., 2013; Ferreira et al., 2018; Frappart et al., 2013a). Exemplos de mapas de diferença na TWSA entre um determinado mês e sua média climatológica são apresentados na **Figura 9a-b** para maio de 2009 e outubro de 2010, respectivamente. Esses meses foram escolhidos por corresponderem ao extremo desses eventos climáticos (secas de 2005, 2010 e 2015, e inundação de 2009). Essa informação é complementar ao que pode ser obtido por meio de dados de chuva, níveis de água e vazões *in situ*. Por exemplo, os padrões da TWSA mínima durante as secas de 2005 e 2010 na bacia foram coincidentes com as áreas com grande atividade de fogo (Aragão et al., 2008; Zeng et al., 2008) e de considerável mortalidade de árvores (Phillips et al., 2009) como relatado em Frappart et al. (2013a). A TWSA também ajudou, em conjunto com a modelagem hidrológica, a caracterizar as recentes secas extremas ocorridas na Amazônia, ressaltando a importância das interações entre os armazenamentos de subsuperfície e de água superficial para mitigar o déficit nos reservatórios superficiais (Chaudhari et al., 2019).

Uma abordagem direta para estimar anomalias de armazenamento de águas subterrâneas (GWSA) é remover a contribuição dos diferentes compartimentos hidrológicos da TWSA, baseada no GRACE, da seguinte forma:

$$\Delta GW = \Delta TWS - \Delta SW - \Delta SM - \Delta CW - \Delta SWE \quad (1)$$

Onde Δ representa a anomalia do armazenamento de água nos diferentes compartimentos hidrológicos, SW é o armazenamento de água superficial, SM é a umidade do solo ou água contida na zona da raiz, CW é a água contida no dossel, e SWE é o equivalente à água da neve. Esse último termo foi negligenciado

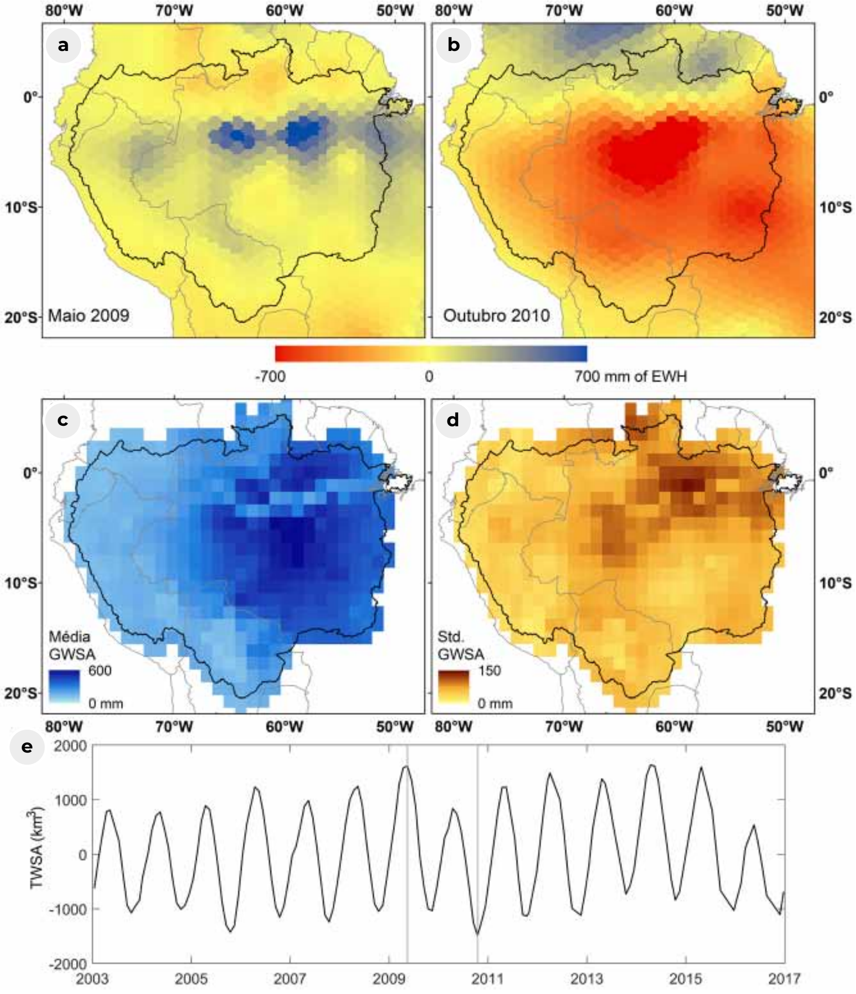

Figura 9: Mapas da TWSA durante dois eventos extremos: (a) a inundação em maio de 2009, e (b) a seca em outubro de 2010. Mudanças anuais médias na anomalia de armazenamento de águas subterrâneas (*Groundwater Storage Anomaly* – GWSA) (c) e desvio padrão associado (d) ao longo de 2003-2010 (adaptado de Frappart et al., 2019). (e) Série temporal de TWSA baseado no GRACE (km3) sobre a bacia Amazônica entre 2003-2016. As linhas verticais mostram os meses de valores máximos (maio de 2009) e mínimo (outubro de 2010).

nos estudos realizados na bacia Amazônica, pois não havia informações confiáveis sobre esse tipo armazenamento de água. Na maioria dos casos, a água proveniente dos outros compartimentos (SW e SM) é fornecida por saídas de modelo e/ou por medições *in situ*. Para a Amazônia, é necessário levar em conta, com precisão, o componente SW, pois ele representa cerca de metade da TWSA (Frappart et al., 2019, 2012). Utilizando informações externas de modelos hidrológicos para SW, SM e CW, as anomalias de armazenamento de águas subterrâneas (GWSA) foram estimadas ao longo de 2003-2015, revelando uma forte ligação entre propriedades geológicas e armazenamento de GW: a maior capacidade de armazenamento de águas subterrâneas no Brasil foi encontrada em regiões com maior permeabilidade das camadas rochosas (por exemplo, os aquíferos Guarani e Alter do Chão; Hu et al., 2017). Mas, nesses casos, o armazenamento de SW limitou-se ao armazenamento dos rios, negligenciando o armazenamento nas extensas planícies de inundação da bacia Amazônica. Para levar em conta, adequadamente, a contribuição dos componentes de SW, foram desenvolvidas metodologias para estimar as variações de armazenamento de SW a partir de observações de SR (Frappart et al., 2012, 2008; Ndehedehe e Ferreira, 2020). As anomalias de armazenamento de SW foram obtidas pela combinação da extensão de águas superficiais (geralmente do GIEMS, ver capítulo 5) e da série temporal baseada em altimetria dos níveis de água (ver capítulo 4) sobre rios e planícies de inundação. Frappart et al. (2012) estimaram as variações mensais do armazenamento de SW na escala da bacia durante a seca de 2005 e constataram que a quantidade de água armazenada no rio e nas planícies de inundação da Amazônia, durante este evento extremo, foi 130 km^3 (70%) a menos que sua média de 2003-2007, representando quase metade da anomalia do TWS mínimo, conforme estimado por meio das observações do GRACE.

Usando essas informações externas sobre as variações de armazenamento de SW, juntamente com as estimativas de armazenamento de SM de modelos hidrológicos, as anomalias de armazenamento de GW foram estimadas pela primeira vez ao longo de 2003-2004 na Bacia do rio Negro, um dos maiores afluentes da bacia Amazônica (Frappart et al., 2011). O padrão espacial da amplitude anual das anomalias de GW adequa-se bem aos mapas hidrogeológicos regionais e a amplitude é consistente com as observações do nível da água em poços locais e séries temporais baseadas em altimetria de níveis de água em duas áreas úmidas adjacentes onde o nível da água subterrânea atinge a superfície durante todo o ciclo hidrológico (Frappart et al., 2011).

Essa abordagem foi então estendida para toda a bacia Amazônica ao longo de 2003-2010, usando cerca de 1000 estações virtuais de altimetria ENVISAT RA-2 de nível da água (Frappart et al., 2019). O armazenamento de SW em toda a bacia teve uma amplitude anual variando entre 900 e 1300 km^3 (Frappart et al., 2012). As estimativas da GW adequaram-se bem às observações de águas subterrâneas *in situ* e aos mapas de águas baixas da tabela GW (Frappart et al., 2008). Em escala de bacia, os resultados têm padrões espaciais realistas quando comparados aos mapas hidrogeológicos do Brasil (por exemplo, mapas de porosidade, limites de aquíferos, recarga de GW). Estima-se que a amplitude sazonal de GW contribua entre 20 a 35% da amplitude TWS proveniente de observações do GRACE na bacia Amazônica (Frappart et al., 2019). O impacto da seca extrema de 2005 no armazenamento de GW também foi por vários anos (Frappart et al., 2019).

A altimetria por radar foi usada para estimar mapas de águas baixas da tabela de GW na parte central da bacia Amazônica (Frappart et al., 2008). Devido à conexão entre a superfície e as águas subterrâneas durante o período de águas baixas nas planícies de inundação da Amazônia central (54°-70° W, 0°-5°S), níveis anuais de águas baixas de 593 estações virtuais de altimetria foram interpolados para gerar mapas anuais do nível de base das águas subterrâneas (*Groundwater Base Level*, GWBL) entre 2003 e 2009. Os resultados mostram que o GWBL é regido pela topografia superficial e que vários anos foram necessários para que o GWBL se recuperasse da seca extrema de 2005 (Pfeffer et al., 2014).

O recente lançamento do GRACE *Follow-On* oferece a oportunidade de estender o monitoramento das alterações do TWS e do GWS após 2018. Apesar da falta de dados entre outubro de 2017 (fim da operação do GRACE) e maio de 2018 (lançamento do GRACE *Follow-On*), duas décadas de TWSA estarão disponíveis em breve, permitindo a análise do impacto de eventos climáticos de vários anos, como o ENSO em armazenamento de água terrestres e subterrânea. As principais desvantagens desses dados são suas baixas resoluções espacial (200-300 km) e temporal (1 mês), que não são suficientes para estudar a dinâmica de eventos hidrológicos rápidos. Para superar esses obstáculos, os sensores a bordo do GRACE *Follow-On* são versões avançadas dos sensores que estavam presentes no GRACE, além de um novo interferômetro a laser (LRI), que mede a distância de satélite para satélite em paralelo com o instrumento de radar de banda K. Espera-se que o LRI seja 26 vezes mais preciso que o radar de banda K a bordo do GRACE (Tapley et al., 2019). Essa melhor acurácia provavelmente aperfeiçoará a qualidade e a resolução espacial da estimativa da TWSA. Novas abordagens baseadas no uso do filtro Kalman foram desenvolvidas para aumentar a resolução temporal da TWSA para quase diária, sem degradar a resolução espacial (Ramillien et al., 2020, 2015).

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HIDROLOGIA da AMAZÔNIA VISTA do ESPAÇO

AVANÇOS CIENTÍFICOS E DESAFIOS FUTUROS

ORGANIZADORES
ALICE Fassoni-Andrade — **AYAN** Fleischmann — **FABRICE** Papa
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Dados Internacionais de Catalogação na Publicação (CIP)
(Câmara Brasileira do Livro, SP, Brasil)

Hidrologia da Amazônia vista do espaço [livro eletrônico] : avanços científicos e desafios futuros / organizadores Alice Fassoni-Andrade... [et al.] ; [coordenação] Alice César Fassoni-Andrade ; tradução Hilcéa Ferreira. -- Porto Alegre, RS : ABRHidro, 2023.
PDF

Vários autores.
Outros organizadores: Ayan Fleischmann, Fabrice Papa, Rodrigo Paiva, Sly Wongchuig, John Melack.
Título original: Amazon hydrology from space : scientific advances and future challenges.
Bibliografia.
ISBN 978-85-88686-48-9

1. Amazônia 2. Amazônia - Aspectos ambientais 3. Hidrologia 4. Sensoriamento remoto I. Fassoni-Andrade, Alice. II. Fleischmann, Ayan. III. Papa, Fabrice. IV. Paiva, Rodrigo. V. Wongchuig, Sly. VI. Melack, John.

23-170901 CDD-574.52642

Índices para catálogo sistemático:

1. Hidrologia florestal : Planejamento : Ecologia 574.52642

Tábata Alves da Silva - Bibliotecária - CRB-8/9253

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Fotos das páginas 8, 9, 16 e 17: Thiago Laranjeira.

Coordenação: Alice César Fassoni-Andrade.

Tradução: Hilcéa Ferreira.

Revisão: Alice César Fassoni-Andrade, Ayan Santos Fleischmann, Evlyn Novo, Sly Wongchuig, John Melack, Adriana Aparecida Moreira, Adrien Paris, Claudio Barbosa, Daniel Andrade Maciel, Gabriel Medeiros Abrahão, Jefferson Ferreira-Ferreira, Leonardo Laipelt, Marcos Heil Costa.

Projeto gráfico, capa e diagramação: Rebeca Medeiros de Andrade Eugênio - BRAVA DESIGN.