04

Nível da *água*

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As águas superficiais são recursos-chave para todas as comunidades que vivem ao longo do rio Amazonas. No entanto, o monitoramento do nível da água (NA) e da vazão nos rios da bacia Amazônica é um desafio. Enquanto o ciclo hidrológico da bacia vem sendo pressionado pelas atividades humanas, o monitoramento *in situ* diminuiu globalmente nas últimas décadas (Vörösmarty et al., 2000). Isto ameaça nossa capacidade de compreender os impactos das mudanças ambientais e climáticas nos rios amazônicos. Embora, até esta data, nenhuma missão de satélite tenha sido lançada especificamente para monitorar as águas continentais, as observações do NA derivadas de radares altimétricos a bordo dos satélites lançados nas últimas décadas se mostraram complementares às séries históricas de medições (Fekete et al., 2012) e aprimoram o monitoramento dos rios amazônicos (Calmant e Seyler, 2006; Silva et al., 2014).

A bacia Amazônica tornou-se um laboratório ideal para estudos pioneiros que demonstraram a capacidade de estimar informações precisas de NA em locais específicos (cruzamento entre os cursos de água e as trajetórias teóricas dos satélites) graças a tratamentos específicos dos ecos de radar. Os primeiros estudos sobre NA na Amazônia utilizaram observações do Seasat (*Sea Satellite* da NASA), lançado em 1978, para estimar a declividade da linha d'água e sua variação temporal no curso principal do rio Amazonas (Guzkowska et al., 1990).

A configuração da órbita dos satélites com radares altimétricos define as interseções entre as faixas do satélite na Terra e o rio, as chamadas estações virtuais (VSs, na sigla em inglês), onde o NA pode ser estimado. Em uma determinada VS, o NA é estimado por meio de inversão do tempo de propagação do sinal de ida e volta que fornece o alcance. Várias correções de incertezas, devido ao atraso na propagação causada pela atmosfera e a dinâmica da superfície terrestre, por exemplo, devem ser aplicadas para estimar o NA. Stammer e Cazenave (2017) apresentaram uma extensa discussão sobre a estimativa do NA a partir de altimetria por satélite e dos erros associados. Desde os primeiros satélites, a precisão da órbita, que depende da densidade da atmosfera e da resolução do campo gravitacional, melhorou e agora está em torno de um centímetro (comparado aos 60 centímetros do Seasat). No entanto, o cálculo correto do *range* continua sendo um desafio, pois é necessário rastrear (a bordo) ou rastrear novamente (no solo) a forma de onda altimétrica (Frappart et al., 2006; Zhang et al., 2010) usando algoritmos que se adequem melhor à distribuição altamente variável da energia recebida pelo radar, que varia fortemente em função dos diferentes tipos de superfícies no campo de visão do satélite (Calmant et al., 2016).

Desde os primeiros estudos com dados Seasat, hoje já temos mais de 30 anos de monitoramento de águas interiores usando altimetria por satélite. Depois do Seasat, surgiu o *GEodetic and Oceanographic SAtellite* (GEOSAT), que foi usado por Koblinsky et al. (1993) para estimar séries temporais do NA sobre a Amazônia com incertezas variando de 0,19 a 1,09 m em relação aos dados *in situ*. O Satélite Europeu de Sensoriamento Remoto (ERS-1, na sigla em inglês; lançado em 1991) iniciou uma longa família de satélites que seguiram a mesma órbita de repetição de 35 dias (ERS-1, ERS-2, ENVISAT -Satélite Ambiental e SARAL -Satélite com ARgos e ALtika), cobrindo o período de 1991 a 2016. Um grande avanço foi feito pelo projeto *Observations des Surfaces Continentales par Altimetrie Radar* (OSCAR), que avaliou o rastreamento específico ICE-2 de ecos de radar para calotas de gelo (Legresy et al., 2005) - um novo processamento (*retracking*) baseado no ajuste da borda de frente (*leading edge*) e da inclinação da borda de fuga (*trailing edge slope*) das formas de onda do radar a uma função Brown - para ERS-1, ERS-2 e ENVISAT, e promoveu sua entrega nos Registros de Dados Geofísicos (arquivos de dados contendo as medidas do altímetro ao longo da faixa e as correções que são necessárias para ser aplicadas à faixa a fim de recuperar o NA).

O novo processamento dos ecos de radar foi analisado por Frappart et al. (2016, 2006) e J. S. Da Silva et al. (2010) para mais de 70 VSs do ERS-2 e ENVISAT para rios de diferentes larguras (de dezenas de metros a quilômetros). Eles relataram que a seleção adequada dos dados considerados representativos do corpo hídrico é tão importante quanto a escolha do algoritmo de processamento (*retracking*). Os dados da órbita de repetição de 10 dias do Topex/Poseidon (T/P) e Jason-2/3 também foram avaliados na bacia Amazônica. Seyler et al. (2013) destacaram o ganho do Jason-2 (variando de 2008 a 2016 em sua órbita nominal) em comparação ao T/P (do final de 1992 a 2005), com uma incerteza em torno de 0,35 m, possivelmente devido à melhor capacidade do sensor de discriminar a planície de inundação circundante do rio.

Todas essas missões operam em modo de baixa resolução, ou seja, a cobertura da terra é grande (alguns quilômetros, dependendo da banda de operação do radar) e os ecos que retornam para a antena são influenciados pelo ambiente. O modo SAR, ativo nos satélites Sentinel-3, permite uma redução das contribuições ao redor, cortando a área circular iluminada pelo eco de radar em um determinado momento (Raney, 1998). Esta redução proporciona uma resolução espacial muito melhor ao longo do traço (*track*), porém não resolve algumas questões como as medidas de inclinação transversal (Bercher et al., 2013). A adição de uma segunda antena, como no Cryosat-2, permite que o modo Interferométrico SAR corrija essas medições transversais, permitindo assim uma melhoria na precisão das séries temporais de NA. Entretanto, o uso do Croysat-2 não é comum para o monitoramento do NA dos rios, já que sua órbita se desloca em torno de 30 km a oeste a cada 28,9 dias, 7 km a leste a cada 89 dias e retorna ao mesmo lugar a cada 369 dias. De fato, a maioria dos estudos sobre o uso de altimetria por satélite na bacia Amazônica tem se concentrado em órbitas repetitivas, embora alguns estudos tenham explorado o uso de missões à deriva ou com repetitividade longa encontrando boa precisão para monitoramento do NA (por exemplo, Bogning et al., 2018). Até hoje, as principais aplicações de missões à deriva ou com repetitividade longa consistem em limitar ou calibrar modelos hidrodinâmicos, porém nenhum estudo focou ainda na bacia Amazônica. Tais missões, em vez de fornecer uma observação do NA em uma base de 10 dias ou quase mensalmente, com uma grande distância entre traços no Equador (entre 60 km e 100 km), fornecem uma distribuição espacial muito mais densa, mas com observações menos frequentes. O uso de dados de altimetria a laser do ICESat (*Ice, Cloud, and land Elevation Satellite*) foi investigado por Hall et al. (2012). Eles concluíram que esta missão pode ser uma valiosa fonte de dados para o monitoramento de rios da Amazônia, com precisões de algumas dezenas de centímetros quando comparadas aos dados *in situ*. A missão ICESat foi continuada pelo ICESat-2, lançado em 2018. Estudos realizados por Bercher et al. (2013) e Jiang et al. (2017) concluíram que a missão SAR CryoSat-2 oferece novas oportunidades para monitorar os rios estreitos na bacia Amazônica e deve ajudar a conectar as missões de altimetria presentes e futuras.

A técnica de interferometria diferencial com dados SAR permite obter informações sobre mudanças nos deslocamentos de superfície, tais como mudanças topográficas. Medições em escala de centímetros das mudanças do NA em toda a área alagada na planície de inundação usando SAR interferométrico foram obtidas sobre as planícies de inundação da Amazônia pela primeira vez (Alsdorf et al., 2001a, 2001b, 2000). Esta estimativa é possível devido às interações do pulso de radar com a superfície da água e os troncos da vegetação alagada, causando um caminho de salto duplo (*double-bounce path*) (Alsdorf et al., 2000; Hess et al., 1995). Lee et al. (2020) e Mohammadimanesh et al. (2018) revisaram os métodos e limitações da técnica para aplicações em áreas úmidas.

Até o momento, as informações sobre o NA estão disponíveis como dados brutos

TABELA 3
Conjuntos de dados de séries temporais do nível da água superficial sobre os corpos hídricos de água.

NOME	FONTE	LINK DA WEB	REFERÊNCIA	ALVO	PRAZO DE ENTREGA*
G-REALM	USDA NASA	*https://ipad.fas.usda.gov/cropexplorer/global_reservoir/Default.aspx#SatellteRadarAltimetry*	Birkett et al. (2017)	Lagos e reservatórios	NTC
River & Lake	Universidade De Montfort	*http://altimetry.esa.int/riverlake/shared/main.html*	Berry et al. (2005)	Rios, lagos e reservatórios	SCT (descontinuado)
Base de dados DAHITI	German Geodetic Research Institute	*https://dahiti.dgfi.tum.de/en/*	Schwatke et al. (2015)	Rios, lagos, reservatórios e áreas úmidas	NTC e reanálise
Produto GRRATS	Universidade Estadual de Ohio	*https://podaac.jpl.nasa.gov/dataset/PRESWOT_HYDRO_GRRATS_L2_VIRTUAL_STATION_HEIGHTS_V2*	Coss et al. (2020)	Rios	Somente reanálise
Hidrosat	ORE-HYBAM e ANA	*http://hidrosat.ana.gov.br/*	Carvalho et al. (2015)	Rios	NTC
Hydroweb	IRD/LEGOS, CNES (Agência Espacial Francesa) e Universidade do Estado de Amazonas	*http://hydroweb.theia-land.fr/*	Crétaux et al. (2011); J. S. Da Silva et al. (2010)	Rios, lagos e reservatórios	STC e reanálise

STC: *Slow-Time Critical* - entregue no máximo após três dias; NTC: *Non-Time Critical* - normalmente entregue dentro de um mês.
*Tempo que leva para o dado ser disponibilizado nos sites.

e como dados processados, sendo que alguns grupos ou instituições fornecem as séries temporais já processadas (ver **Tabela 3**). Cada conjunto de dados fornece o NA em corpos de água selecionados, em todo o mundo ou em regiões específicas, e têm objetivos diferentes em termos de operacionalidade. Os procedimentos de processamento e filtragem variam entre cada grupo, e as séries temporais das mesmas estações virtuais podem variar de um grupo para outro.

A **Figura 5** fornece a localização de todas as estações virtuais na bacia Amazônica da base de dado Hydroweb. A **Figura 5a** é uma representação da amplitude mediana do NA em cada estação virtual. A amplitude do NA medida pelos satélites é menor nas cabeceiras (0-3 m) e rios de médio porte (3-6 m) em relação ao trecho principal do rio Solimões-Amazonas e seus afluentes (9 - 12 m). Os maiores valores são encontrados para o rio Purus (> 15 m), afluente da margem direita. As **Figura 5b** e **c** fornecem, respectivamente, o mês em que tipicamente ocorrem os níveis altos e baixos, indicando a influência do regime das chuvas nas partes norte e sul da bacia e o deslocamento gradual devido ao tempo de propagação das cheias ao longo dos rios e planícies de inundação (~ 1- 3 meses). As **Figura 5d** e e fornecem séries temporais de NA de múltiplas missões, que variam de 2002 até o presente com ENVISAT e Sentinel3-B e de 2008 a 2020 com Jason-2 e Jason-3, respectivamente. Elas mostram o forte sinal sazonal da cheia gradual dos rios amazônicos e a variabilidade interanual dos níveis máximo e mínimo.

Devido à sua cobertura espacial relativamente densa (ver **Figura 5**), a altimetria por satélite tem sido utilizada para derivar os perfis altimétricos dos rios em toda a bacia. Esses perfis, calculados para águas baixas e altas do rio Negro a partir de VSs T/P (Frappart et al., 2005) e VSs ENVISAT (Leon et al., 2006), indicaram uma declividade mais baixa para o rio Negro ao longo de mais de 500 km (de sua foz até o curso de água) do que para o rio Solimões (confirmado por Callède et al., 2013). Tal diferença explica o forte efeito de remanso que ocorre na seção inferior do rio Negro e altera a época de pico e de vazões baixas. Outros efeitos de remanso, principalmente no trecho principal no rio Amazonas e em seus tributários, ficam evidentes nos perfis do rio a partir da altimetria por satélite. As observações de altimetria por satélite, embora escassas no tempo, agora fornecem uma rede densa o suficiente para monitorar eventos extremos, como os ocorridos em 2005 e 2010 na Amazônia (Frappart et al., 2012; Silva et al., 2012).

Uma aplicação direta desses perfis é a obtenção das variações espaço-temporais da declividade da superfície da água. Enquanto os estudos anteriores focaram nas variações espaciais do gradiente da superfície da água, uma primeira tentativa de estimar as variações temporais da declividade do trecho principal do Amazonas foi realizada por Birkett et al. (2002) usando VSs da missão T/P. Eles revelaram

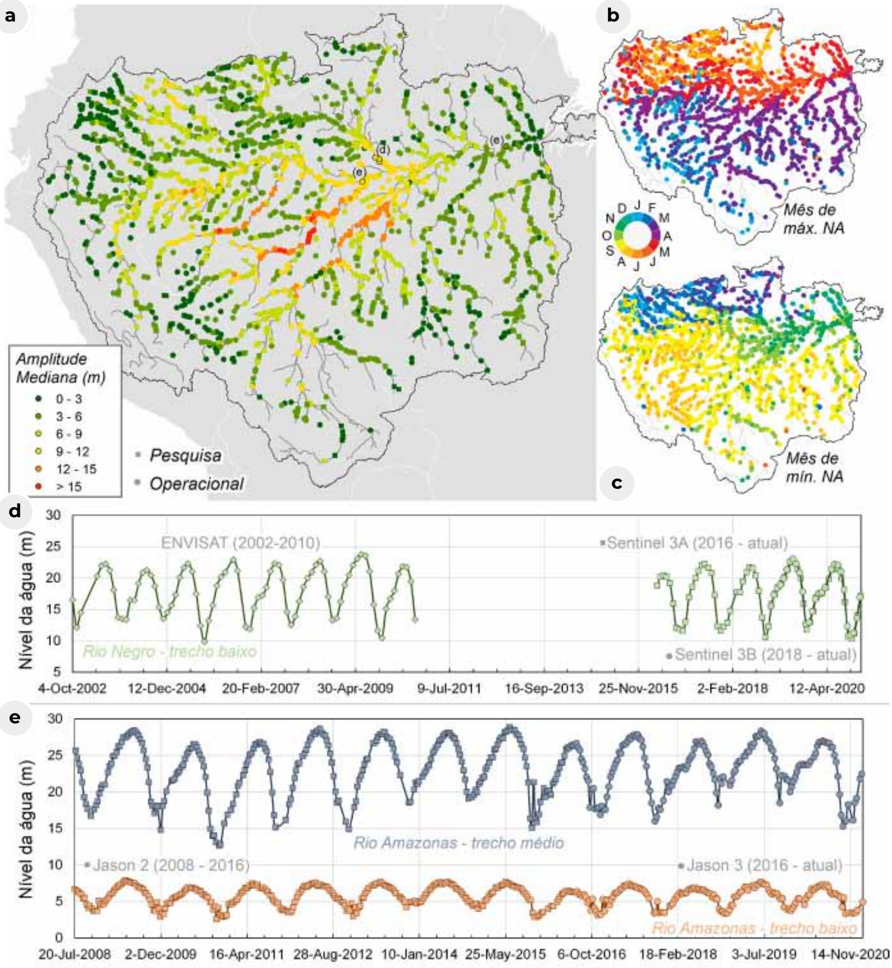

Figura 5: a) Localização das estações virtuais disponíveis gratuitamente no portal Theia-hydroweb (*http://hydroweb.theia-land.fr/*) e amplitude mediana da série temporal. Os pontos se referem as VSs operacionais (missões atuais em operação e atualizados em tempo quase real) e os quadrados são VSs de pesquisa (identificados como reanálise na tabela 3). As VSs estão destacadas por círculos pretos em (d) e (e); b) mês de máximo NA para a média da série temporal mensal em cada VS; c) mês de mínimo NA para a média da série temporal mensal; d) séries temporais compostas das VSs próximas umas das outras no trecho baixo do rio Negro, VSs NEGRO_KM1444, NEGRO_KM1420 e NEGRO_KM1404, e) séries temporais nos trechos médio e baixo do Amazonas compostas pela observação do Jason-2 e Jason-3 na VS AMAZONAS_KM1534 e AMAZONAS_KM0397, respectivamente.

mudanças no sinal da taxa de variação da declividade que foram explicadas pelo fato de o rio não alcançar o equilíbrio. Embora as declividades de Birkett et al. (2002) tenham se comparado bem com a declividade derivada do Modelo Digital de Elevação (MDE) da missão *Shuttle Radar Topography Mission* (SRTM) - um instantâneo de perfis e declividades em fevereiro de 2000 (LeFavour e Alsdorf, 2005) - e com dados de instrumentos in situ (Calmant et al., 2013), essas quebras na taxa de variação de declividade não foram encontradas em perfis extraídos de bases de dados altimétricos mais recentes e completas (Calmant et al., 2016). Paris et al. (2016) estimaram duas séries temporais diferentes de declividades a partir da altimetria por satélite no trecho baixo do rio Negro: a primeira foi calculada usando uma interpolação diária das séries temporais de NA a montante e a jusante, fornecendo uma série temporal de declividades diárias, e a segunda foi calculada usando a climatologia média das VSs a montante e a jusante. Embora a curva-chave (relação entre NA e vazão do rio) tenha melhorado se considerarmos a variação da declividade com o tempo, utilizando ambos os métodos, foi a média mensal que forneceu o melhor resultado, ilustrando a dificuldade de inferir declividades a partir de observações incertas não obtidas diariamente.

Acoplando a altimetria por satélite e um modelo hidrológico e hidráulico por meio de curvas-chave, Paris et al. (2016) estimaram mapas da profundidade do rio ao longo da bacia Amazônica usando dados das missões ENVISAT e Jason-2. Esses mapas foram então utilizados por Garambois et al. (2017) em um trecho do rio Xingu para parametrizar um modelo hidráulico. Em casos em que a faixa terrestre do satélite corta várias vezes o mesmo curso do rio, é possível realizar uma análise mais refinada de NA. Isto ocorre em rios sinuosos que fluem de norte a sul (ou o contrário) como o rio Xingu, um tributário da margem direita do rio Amazonas (**Figura 2**). Dadas estas condições, os autores verificaram que a presença de um obstáculo no leito do rio produz alterações temporais no NA a partir de altimetria orbital. Brêda et al. (2019) propuseram um novo método de assimilação de dados altimétricos, desde a inserção direta até um filtro Kalman de base hidráulica, para melhorar as estimativas batimétricas do rio Madeira. Eles concluíram que a altimetria por satélite pode ser usada para limitar melhor as estimativas de NA e de inundação. Uma análise de NA da missão ENVISAT revelou a passagem de água do rio Negro para o rio Solimões através de suas planícies de inundação interligadas em períodos de cheia (Silva et al., 2012).

A capacidade de observar a conectividade entre canal e planície de inundação por meio de altimetria foi investigada por Park (2020). Ao observar mudanças sazonais no NA em rios e planícies de inundação adjacentes, eles separaram o papel dos fluxos canalizados e do escoamento difuso por sobre as margens (*overbank flow*), que contribuem para o armazenamento da água de superfície e suavizam a topografia induzida pela canalização. A planície de inundação localizada entre os rios Madre-de-Dios, Beni, Guaporé e Mamoré, na bacia do alto rio Madeira, foi caracterizada usando dados ENVISAT e SARAL (Ovando et al., 2018). As diferenças de nível da água entre as regiões frequentemente alagadas, sem conexão direta com os Andes, e as regiões sujeitas a eventos esporádicos, embora com grandes cheias, foram destacadas. Recentemente, Fleischmann et al. (2020) produziram séries temporais de NA nas complexas áreas úmidas interfluviais do rio Negro a partir dos dados do Sentinel3-A. Pela primeira vez, eles relataram variações do nível da água inferiores a 1 m nessas áreas complexas. Seus resultados mostram que a altimetria por satélite pode ajudar a entender o comportamento hidráulico de áreas complexas pouco exploradas e ajudar a validar modelos hidrológicos e hidráulicos.

Alsdorf et al. (2000, 2005, 2007) aplicaram pela primeira vez o SAR interferométrico (InSAR, na sigla em inglês) nas planícies de inundação da Amazônia central e mostraram que nelas os fluxos de água são dinâmicos no espaço e no tempo, mudando de direção ao longo do pulso de inundação anual. Antes da cheia, as vazões são controladas pela topografia local e o NA na planície de inundação não é equivalente ao nível do rio (Alsdorf et al., 2007). Ao assumir que a superfície da água na planície de inundação é equivalente à do canal principal, as estimativas de armazenamento de água derivadas da propagação de cheias podem ser superestimadas, como mostrou Alsdorf (2003). H. C. Jung et al. (2010) compararam as mudanças temporais nas águas das planícies de inundação nas bacias da Amazônia e do Congo. Enquanto o rio Amazonas está conectado por muitos canais às planícies de inundação e tem padrões de fluxo complexos, os rios do Congo (e especialmente o *Cuvette Centrale*) têm conexões esparsas com áreas interfluviais e padrões de fluxo que não são bem definidos e com fronteiras difusas. Os padrões de variações da superfície da água nas planícies de inundação localizadas nos rios Tapajós e Solimões foram analisados por Wang et al. (2011) e Cao et al. (2018), respectivamente. As missões SAR mais recentes permitiram o monitoramento de corpos de água menores.

A altimetria por satélite pode ser usada para derivar variáveis hidrológicas usualmente não medidas, por meio da avaliação direta ou combinação com outros produtos de SR. Pfeffer et al. (2014) conseguiram inferir as diferentes trocas entre as águas superficiais e subterrâneas a partir de 491 VSs ENVISAT localizados em toda a bacia Amazônica. A estimativas de desvios do nível de base das águas subterrâneas atingiram até 5 m. Frappart et al. (2012) fizeram um uso conjunto de altimetria por satélite e extensão de inundação para gerar variações do armazenamento de águas continentais superficiais (ver capítulo 8). Estas duas variáveis foram usadas em Frappart et al. (2019) para estimar a variabilidade espaço-temporal do armazenamento de água subterrânea na bacia Amazônica. Campos et al. (2001) e Silva et al. (2019) encontraram marcas de eventos climáticos globais como ENSO e variações da temperatura da superfície do mar nas séries temporais de NA do T/P e do Jason-2, respectivamente. Como as estimativas de NA são agora entregues em tempo quase real, as curvas-chave que relacionam NA com vazão e profundidade têm sido o foco de vários estudos (ver detalhes no capítulo 10). Essas curvas-chave foram calculadas usando altímetros locais (Zakharova et al., 2006) ou resultados de modelos (Getirana et al., 2012; Leon et al., 2006). Ao restringir os parâmetros da curva-chave em limites realistas do coeficiente de rugosidade de Manning, Paris et al. (2016) mostraram que as vazões previstas da altimetria por satélite são comparáveis àquelas medidas in situ. A série temporal original de NA ou sua conversão em vazão oferece uma ferramenta independente para validar modelos hidrológicos (Paris et al., 2016) e seus dados de entrada de chuva (Silva et al., 2014).

Com sua tecnologia inovadora baseada em *swath altimetry* (altimetria de bandas largas, em livre tradução do inglês), cobertura quase global e observação conjunta de NA, largura e declividade da linha da água, a missão SWOT, a ser lançada em 2022, permitirá uma observação sem precedentes de NA em toda a rede fluvial e nos principais lagos e planícies de inundação. Como salientado por Biancamaria et al. (2016), a observação do NA usando o SWOT permitirá um melhor monitoramento das águas transfronteiriças e das planícies de inundação na Amazônia. Dedicada a fazer amostragem de todos os rios com largura superior a 100 m e lagos maiores que 250 x 250 m, a missão permitirá uma consequente redução de incertezas de modelos hidrológicos e hidrodinâmicos globais e regionais, através de técnicas como assimilação de dados (Emery et al., 2020; Wongchuig et al., 2020). A estimativa da vazão obtida via altimetria por satélite se beneficiará dos dados SWOT, tanto pela cobertura global quanto pela observação de declividade, permitindo uma melhor correção de modelos hidráulicos (Wilson et al., 2015).

Graças a mais de vinte anos de estudos, as bases de dados de observação da Terra por satélite, especialmente as de altimetria por satélite, têm se revelado como uma ferramenta sem precedentes para monitorar bacias hidrográficas continentais e suas secas e enchentes (Lopez et al., 2020). As atuais missões de altimetria por satélite inauguraram a era do monitoramento operacional em larga escala a partir do espaço, e isto será de importância fundamental nas próximas décadas na grande bacia hidrográfica transfronteiriça tropical que é a bacia Amazônica. Com quase duas mil estações virtuais distribuídas por toda a bacia e disponíveis gratuitamente, e potencialmente centenas mais no futuro próximo, a altimetria por satélite pode complementar, de maneira promissora, a rede tradicional de campo (*in situ*), cuja localização geralmente depende da proximidade de uma cidade ou comunidade. Entretanto, monitorar operacionalmente águas não abertas, como as planícies de inundação cobertas por vegetação permanentemente ou sazonalmente alagadas, continua sendo um desafio. Na verdade, poucos lagos e reservatórios são monitorados por altimetria rotineiramente na bacia, e este número poderia ser maior (Crétaux et al., 2011; Crétaux e Birkett, 2006). As próximas missões se beneficiarão de pesquisas anteriores para melhorar a precisão das séries temporais de NA e promover seu uso para monitorar mais fenômenos locais, tais como os intercâmbios entre planícies de inundação e canais. Embora limitados devido à disponibilidade de dados apropriados, os conjuntos de dados InSAR ajudam a caracterizar a conectividade e a dinâmica das planícies de inundação e rios. A cobertura global da próxima missão SWOT aumentará muito nossa compreensão do ciclo global da água e deverá permitir uma melhor quantificação dos vieses entre missões passadas e atuais, ajudando a transformar os arquivos de altimetria por satélite em um conjunto de dados climáticos único e a compreender os impactos das mudanças climáticas e das atividades humanas na bacia. Tal tarefa será beneficiada pelo projeto em andamento VASHYB (*Validation of Altimetric Satellites for HYdrology in Brazil*, *https://swot.jpl.nasa.gov/documents/1054/*), que visa a validar observações SAR e InSAR. A missão SWOT irá aumentar drasticamente nossa capacidade de modelar a bacia Amazônica e as variações de seu ciclo da água, graças à nova capacidade de monitorar variáveis hidrológicas (altura, declividade e vazão associada) de centenas de rios de 100 m de largura (Biancamaria et al., 2016). A precisão centimétrica do NA e declividade (Desai, 2018) devem trazer novas percepções sobre os fluxos de água na Amazônia. Como a principal limitação para um uso mais amplo da altimetria por satélite continua sendo sua amostragem temporal relativamente baixa, missões futuras, como a missão SMASH (*SMall Altimetry Satellites for Hydrology*, Blumstein et al., 2019), lançada junto com a constelação atual, devem ajudar a resolver esta questão.

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