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Tracking water level changes of the Amazon Basin with space-borne remote sensing and integration with large scale hydrodynamic modelling: A review

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ABSTRACT

With the improvement of remote sensing systems, in particular active sensors, our ability to make regular observations of the Amazon Basin has greatly increased. Water levels and other related features such as discharge, floodplain–river connectivity, and flood extent are now being monitored using space-borne sensors, thereby complimenting *in situ* gauging networks. This review concludes that the main advances remote sensing has had on our knowledge of hydrology includes the ability observe the seasonal cycles of the Amazon River across the entire basin, including the movement of the flood wave downstream. Flood extent can now be mapped, including the direction of floodplain flow, thanks to the extensive coverage provided by various active remote sensing systems. Our knowledge of the relationship between water levels in the main channel and the floodplain has been reassessed. It is now known that floodplain levels are related to the distance of the location from the main channel. The addition of new and future satellites, such as ICESat-1 and -2, GRACE and SWOT, will guarantee the continuation of research in this field and the continued advancement of knowledge and understanding of the Amazon Basin.

1. Introduction

Being able to track changes in the water level of remote rivers such as the River Amazon is invaluable for many areas of research. With recent advances in remote sensing systems, monitoring catchments from space has been greatly improved, and these data can be used to complement data from *in situ* gauging networks. The development of active remote sensing systems, such as Synthetic Aperture Radar (SAR) and radar altimetry, means that regular data can be collected without the problems associated with passive, visible and infrared sensors, such as cloud cover effects. Many studies have been carried out using active remote sensing systems in the Amazon Basin (e.g. Alsdorf et al., 2007a; Frappart et al., 2005; Jung and Alsdorf, 2010) and research continues to be undertaken in this area.

This review will firstly discuss the importance of the Amazon as a study area; its hydrology, climate and global impacts. Research that has been carried out to date in this location using active remote sensing systems and the Gravity Recovery And Climate Experiment (GRACE) will be discussed in Section 3, in particular studies monitoring water levels. The final section, before concluding, will investigate studies which have used these active remote sensing data to improve or be integrated with hydrodynamic models of the Amazon.

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2. The River Amazon

The Amazon River is the largest river in the world in terms of discharge, with an average flux to the Atlantic Ocean of 200,000 m^3/s (Richey et al., 1989). A detailed description of this massive river and why it is of interest is given here. Then, a brief explanation of the available *in situ* data in this area will follow, showing the difficulties associated with carrying out research without the use of remote sensing. The review will then go on to discuss current research being carried out in the Amazon using state-of-the-art active remote sensing systems.

2.1. Hydrological processes

The water discharged by the Amazon equates to approximately 20% of the total runoff discharged into the world's oceans (Richey et al., 1989). The Amazon's two largest tributaries, the Negro and the Madeira, are also the fifth and sixth largest rivers by discharge (Meade et al., 1991). The Amazon River, known locally as the Solimões in Brazil until its confluence with the Rio Negro, has a catchment of approximately 6 million km^2 (Richey et al., 1989), with headwaters across the Andes in three countries; Columbia, Peru and Brazil (Mertes et al., 1996). The area lies within the tropics; the Amazon River itself is situated only a few degrees south of the equator. The Inter-Tropical Convergence Zone (ITCZ) moves north and south across the Amazon Basin throughout the year (Mertes, 1997). These changes in the ITCZ's position and the basin's size causes the degree of rainfall to vary greatly from 2000 mm/yr to 7000 mm/yr (Richey et al., 1989), which causes the Amazon's annual mono-modal flood wave discussed below. Orographic effects also add to the heterogeneous nature of precipitation in the Amazon Basin (Bourgoin et al., 2007). The river system of the Amazon is unique primarily due to its size; in many places the Amazon River and its tributaries are often 1 km wide, but can be more than 6 km in places (Filizola et al., 2009).

The floodplain is an important component in the Amazon's water mass balance and it is estimated by Alsdorf et al. (2010) that 5% of the water discharged from the Amazon has been through the floodplain. This estimate has been calculated using mass changes observed by the GRACE mission, and is considerably less than previously estimated, e.g. 30% by Richey et al. (1989). The Amazon and Purus rivers have wide expansive floodplains to either side of the main channels due to the low relief of the surrounding areas (Alsdorf et al., 2005). The floodplain is surrounded by areas that do not flood, named terra firme. The low lying floodplain areas are inundated at high water; however, there are often permanent lakes and channels across the floodplain (Alsdorf et al., 2005). However, this is not a universal pattern and the Amazon floodplain shows considerable complexity. For example, the Negro differs in that, near its confluence with the Amazon, it does not have a floodplain around the main channel. The river, over a 15 km stretch, is surrounded by terra firme; however, the channel is wide and made up of many small channels and lakes which act in a similar way to a floodplain (Alsdorf et al., 2005). Water in the floodplain is derived locally from groundwater, hyporheic water, tributary water and precipitation or from across the region in the form of overbank flow (Mertes, 1997).

The Amazon floodplain contains permanent lakes, such as Lake Calado studied by Lesack and Melack (1995). This is one of the only floodplain lakes out of the many thousands in the basin that has been extensively studied and is therefore worth considering in more detail. In particular, although the lake area that is permanently flooded is only 2 km^2 at times of high water, Lake Calado greatly increases in size and connects with two other floodplain lakes during this time. In other locations the floodplain area is so large that it consists of numerous interconnected lakes and channels, some of which are permanent and connected to the main channel (Bourgoin et al., 2007). Lago Grande de Curuai, a floodplain area of flooded forests, termed várzea, has at least 30 floodplain lakes and various channels which connect it to the main river (Bourgoin et al., 2007). It is separated from the main channel by banks covered with young forests and is contained to the south by terra firme. The Bonnet et al. (2008) study of Lago Grande de Curuai investigated the sources and residence time of water in the floodplain using *in situ* measurements of water levels, discharge, rainfall and evaporation, however because of the spatial complexity of the Amazon system it is difficult to scale up these insights to the whole basin.

The hydrographs of large river systems in tropical areas, such as the Amazon River, often have one clear annual flood peak, a result of the seasonal changes in precipitation, however, other systems, such as the Congo, have a smaller secondary flood peak (Birkett, 1998). The Amazonian flood wave is a mono-modal flood pulse which, after investigation by Trigg et al. (2009), has been found to be subcritical and diffusive. Studies into kinetic and diffusive waves show that rivers with low gradients, such as the Amazon, are expected to have a diffusive nature, with the peak inflow exceeding the outflow, producing a time lag in the hydrograph (Kazezyilmaz-Alhan and Medina, 2007). Due to the size of the Amazon Basin it can be more than one month after the major rainy season before the water levels peak at Manaus in the central Amazon, downstream of the Negro and Solimões confluence (Junk et al., 1989). The Amazon's large drainage basin introduces another unusual factor; the northern and southern tributary flood peaks do not coincide (Richey et al., 1989). This is due to the movements of the ITCZ causing the wet and dry seasons to be at different times in the northern and southern parts of the basin (Richey et al., 1989). In fact, there is a three month lag between flood peaks due to the different precipitation patterns. The total area of floodplain that the flood pulse inundates has been estimated to be 140,000 to 500,000 km^2 (Seyler et al., 2009). This large ranging estimate represents seasonal variations, but also that we cannot fully monitor this hydrologic system using only *in situ* measurements (Seyler et al., 2009). This annual hydrological process is of great importance in terms of biogeochemistry, geomorphology and sediment transport (Mertes, 1994), as well as in sustaining the biota present within the floodplain (Junk et al., 1989).

2.2. Past research on Amazon hydrology

Due to the interesting nature of the Amazon River and its floodplain many studies have been carried out to investigate its hydrology. River stage and flood extent are characteristics of large river basins that have often been measured *in situ* in the past and are of great importance to understand and predict flood patterns. River stage, or water level, is commonly recorded at gauging stations that often provide discharge data as well. Although the Negro River's stage has been recorded at Manaus since 1902, the majority of stage data sets began to be available at various locations within the basin from the 1970s (Meade et al., 1991). Filizola et al. (2009) documented that in the Brazilian Amazon there are hydrological records from the early 20th century, with specific discharge measurement schemes carried out in the 1970s, 1980s and still continuing today. The need to gauge these river systems is related to the importance of understanding the hydrological and biogeochemical processes occurring (Richey et al., 1989). Rivers also play an important part in the global carbon cycle, transporting carbon to the oceans (Richey et al., 2002). However, research on the Amazon using only *in situ* data clearly shows that there are factors limiting how well research on this scale can be said to represent the Amazon River as a whole.

The width of rivers in the Amazon Basin means that in complex and highly variable systems such as the Amazon, gauge measurements only represent a one-dimensional point within the channel, thus neglecting variations in flow across the floodplain (Alsdorf et al., 2007b). However, this is not the main problem with gauges in the Amazon. The major issue is that the data available for use in scientific studies are limited by the scale of the basin and as a result the hydrometric network is of relatively low density (Alsdorf et al., 2007b) with point measurements limited to a few accessible locations. In the area surrounding Manaus, Brazil there are 10 gauges, compared to 700 in an area of the same size around Washington DC (Alsdorf et al., 2007b). Hence, the Amazon River gauges are comparatively few and far between, with measurements being taken up to 200 km apart on the main stem (Wilson et al., 2007). The River Negro, the fifth largest in the world by discharge, is nearly completely ungauged (Alsdorf et al., 2007b). Also, despite the high level of connectivity between floodplain and main channel, there are no gauges at all within the floodplain (Wilson et al., 2007) and only one floodplain lake out of many thousands has had direct water balance measurements taken (Bonnet et al., 2008). The Amazon floodplain is complex in terms of water height and inundation extent (Wilson et al., 2007), with complex hydraulic processes being locally confined and acting diffusively over the whole floodplain (Alsdorf et al., 2007a). Therefore, extensive gauging networks are required to provide a basic understanding of the processes occurring. However, gauging systems on rivers are becoming less common, particularly outside of industrialised or urban areas (Alsdorf and Lettenmaier, 2003). One main reason for