Inundation patterns in the Pantanal wetland of South America determined from passive microwave remote sensing

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With 10 figures and 1 table in the text

Abstract: Seasonal inundation determines the structure and function of tropical floodplain ecosystems, and therefore information on the spatial and temporal variability of inundation is fundamental to understand and manage these ecosystems. This study uses the 37-GHz polarization difference observed by the Scanning Multichannel Microwave Radiometer (SMMR: Nimbus-7 satellite) to reveal inundation patterns in the Pantanal, a vast savanna floodplain located largely in Brazil. We calculated inundation area separately for 10 subregions using mixing models that account for the major landscape units with distinctive microwave emission characteristics. Maximum inundation occurred as early as February in the northern subregions and as late as June in the south, reflecting the delayed drainage of the region. As much as 131,000 km² was inundated annually during the 9 years of SMMR observations (1979–87). Monthly estimates of the total area inundated in the region varied from 11,000–110,000 km², averaging 53,000 km². We reconstructed regional inundation patterns over the past 95 years from the correlation between the Paraguay River stage and total inundation area during the SMMR period. Both the maximum and minimum inundation area showed large interannual variability.

Introduction

Information on inundation patterns is required for understanding the hydrology, biogeochemistry and ecology of the extensive floodplains of tropical re-

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gions (Richey et al. 1991, Bartlett & Harriss 1993, Junk 1993). Such information is also essential to assess the viability and environmental impacts of proposed development projects that entail the regulation of floodplain rivers (e.g., Sutcliffe & Parks 1987, Bucher et al. 1993). River stage records have historically provided the best available information on inundation patterns in floodplains, but for many tropical regions stage records are often incomplete and limited in spatial coverage, and may not represent flooding conditions in areas distant from the main river channels. Remote sensing now offers the opportunity for synoptic observation of inundation patterns. However, the application of optical remote sensing systems to observe inundation dynamics in wetlands has been hampered by persistent cloud cover and dense vegetation canopies overlying the water (Melack et al. 1994). In contrast to optical systems, passive microwave remote sensing from satellites can detect inundation when clouds and vegetation are present and can thus provide a multi-year record of inundation area in large wetlands (Giddings & Choudhury 1989, Choudhury 1991, Sipper et al. 1994).

In this study, we present data on seasonal and interannual variation in inundation area in the Pantanal, one of the world's largest tropical wetlands. These data are derived from passive microwave emission measured at 37 GHz by a satellite-borne sensor, the Scanning Multichannel Microwave Radiometer (SMMR). Our methods are based on the approach described by Sipper et al. (1994), who determined fractional inundation area for a reach of the central Amazon floodplain by using mixing models to account for the major landscape units with distinctive microwave emission characteristics. The passive microwave observations provide an unprecedented view of inundation dynamics in large, remote wetlands such as the Pantanal.

Study area

The Pantanal is a vast savanna wetland in tropical South America, occupying an area of 137,000 km$^2$ (approximately 450 by 300 km) in the upper Paraguay River basin (Fig. 1). Most of the region is in Brazil, with smaller areas to the west in Bolivia and Paraguay. A mosaic of alluvial fans of Pleistocene origin fills the Pantanal depression (Klammer 1982), where elevation ranges from 85–150 m and the land slopes gently toward the Paraguay River. The upland drainage basin surrounding the Pantanal occupies 359,000 km$^2$ and consists of elevated plateaus and low mountains to the north and east (250–1200 m elevation) and flat plains to the west. Human population density is very low within the Pantanal (<2/km$^2$: Brazil 1982), where the main economic activity is cattle ranching.
The climate of the Pantanal is tropical with a marked wet season (BraZIL 1979). Annual rainfall is generally 1000–1700 mm across the region, with most rain falling between November and March (Fig. 2). Rainfall is highest in some parts of the surrounding uplands, particularly in the north, and lowest in the floodplain areas of the southwest Pantanal. The hydrology of the main river systems remains unregulated. Flooding in the region is distinctly seasonal, although the flooding period tends to be delayed after the rains due to slow passage of floodwaters through the Pantanal (BraZIL 1979). Many areas are flooded by riverine overflow and are thus true floodplains, while other areas normally flood with local rainfall, although their geomorphological origin may be alluvial (HAMILTON et al., in press). The water in most floodplain areas tends to flow slowly in a characteristic direction, at least during high water. Water depth is usually <6 m outside of the river channels and is most commonly <2.5 m on the floodplains (HAMILTON et al. 1995).

The Paraguay River runs from north to south along the western side of the Pantanal, collecting water from the various tributaries and non-channelized floodplain flow paths (Fig. 1). The slope of the Paraguay River in the Pantanal is 2.5 cm/km (BraZIL 1979). Seasonal variation in the discharge of the Paraguay River is strongly damped by the storage of water on adjacent floodplains, and in the southern Pantanal the flood wave is delayed by up to 4–5 months after the peak rainfall (Fig. 2). The mean annual discharge of the Paraguay River is 1260 m³/s at Corumbá, where the river carries 80% of the total outflow from the region, and interannual variation in discharge is large (BraZIL 1979). Water levels of the tributaries are controlled by the Paraguay River near their confluences because of the gentle elevational gradients. The peak dis-

charge of these tributaries tends to occur earlier than that of the Paraguay River, and the later rise of the Paraguay impounds the lower courses of the tributaries, decreasing their current and sometimes even reversing their flow temporarily (HAMILTON et al., in press).

Savanna and mixtures of grassland with semideciduous forest are the most common vegetation types, although gallery forest occurs along rivers (PRANCE & SCHALLER 1982, RATTER et al. 1988, PRADO et al. 1992, JUNK 1993). Trees and shrubs are often present but usually have sparse canopies in areas subject to inundation, allowing herbaceous plants to coexist in the understory. Extensive stands of trees dominated by a single species are common. The most important of these species include the Cambará (Vochysia spp.), which often grows in dense patches throughout the region, and the Carandá palm (Cope-ncia australis) and Paratudo (Tabebuia cariaba), which commonly occur as more open stands in the southern Pantanal. Human impact on vegetation in the Pantanal has occurred mainly through the introduction of cattle and the use of fire during the last 200 years, which have influenced the nature and distribution of vegetation (PRANCE & SCHALLER 1982, WILCOX 1992).

Aquatic or semi-aquatic vascular plants occur almost everywhere surface water persists for more than a few weeks, and floating and rooted emergent forms often cover much of the water surface (PRANCE & SCHALLER 1982, POTT et al. 1989). Floating emergent plants such as Eichhornia azuerae, E. crassipes, Scirpus cubensis, and Salvinia spp. tend to dominate in more deeply flooded environments. Rooted emergent species with more vertical, erect stems colonize areas of shallower water, and sometimes develop extensive stands of one or a few species, including Cyperus giganteus, Thalia geniculata, Typha domingensis, Pontederia cordata var. lanciafolia, Ipomoea sp., Polygonum spp., Oryza sp., and Paspalum spp.

## Passive microwave sensor systems and data

Passive microwave sensors measure the very faint natural emission of microwave energy from the Earth’s surface and atmosphere. Their coarse spatial resolution compared to optical remote sensing systems results because the sensors must integrate the emission over a large area to yield a measurable signal (LILLESAND & KIEFER 1994). Measurements are expressed as brightness temperatures (in Kelvins), and are obtained at several frequencies and at both vertical and horizontal polarizations. The difference between vertically and horizontally polarized brightness temperatures observed by satellite at the 37 GHz frequency (hereafter referred to as $\Delta T_{b0}$) provides a sensitive indicator of the presence of surface water, particularly where water occurs against a background of vegetated land surfaces (GIDDINGS & CHODHURY 1989, CHOD-
HURY 1991). The spatial resolution of the SMMR sensor is approximately 27 km at 37 GHz (Fu et al. 1988), and the processed global data sets are gridded into cells of 0.25° latitude by longitude. The theoretical basis for interpretation of 37 GHz emission has been reviewed by Choudhury (1989).

A continuous record of vertically and horizontally polarized 37 GHz observations from satellites is available for the present, at intervals of weekly or better. From December 1978 to August 1987, these data were collected by the SMMR instrument operated on board the Nimbus-7 satellite (Gloersen et al. 1984, Fu et al. 1988). Similar observations are available from the Special Sensor Microwave/Imager (SSMI) instruments, which began operation in July 1987 and continue operation now as part of the Defense Meteorological Satellite Program (Hollinger et al. 1990).

In this study, we use the SMMR observations for 1979–87, which are drawn from the global data set of the 37 GHz $\Delta T_{o-b}$ that was originally studied by Choudhury (1989 and 1991). Global SMMR observations are available for approximately 6-day intervals, and are compiled separately for day and night (local equator crossings at noon and midnight). After calculation of $\Delta T_{o-b}$ for each grid cell from the daytime brightness temperatures, the observations were ranked within each month and the second lowest value (usually out of 4) was selected, thereby yielding one $\Delta T_{o-b}$ value per month. The screening served to eliminate outlying values that might have resulted from atmospheric scattering by heavy rainfall, or from temporary pooling of water on the land surface after heavy rainfall.

Methods

Fractional inundation area was calculated for each 0.25° × 0.25° grid cell from the monthly 37 GHz $\Delta T_{o-b}$. The algorithms for calculation of fractional inundation area are linear mixing models that incorporate the $\Delta T$ values of the major landscape units within a grid cell (Sippel et al. 1994):

$$\Delta T_{o-b} = f_w(\Delta T_w) + f_d(\Delta T_d) + f_f(\Delta T_f)$$

$$1 = f_w + f_d + f_f$$

where $\Delta T_{o-b}$ is the $\Delta T$ observed by the radiometer, $f_w$, $f_d$, and $f_f$ are the fractional areas of open water (rivers and lakes), non-flooded land, and seasonally flooded land, respectively, and $\Delta T_w$, $\Delta T_d$ and $\Delta T_f$ are the $\Delta T$ values for open water, non-flooded land, and seasonally flooded land.

We used a $\Delta T_w$ value of 60 K, which is the approximate value expected for a smooth water surface (Choudhury 1989). SMMR and aircraft measurements of the $\Delta T$ over calm seas support this assumption (Hollinger et al. 1990, Gloersen et al. 1992). Non-flooded, vegetated land surfaces typically range in $\Delta T$ from 4–7 K (Justice et al. 1989). We used a $\Delta T_d$ value of 4.2 K, which was determined by averaging all dates for 16 grid cells of uplands just west of the Pantanal which are not subject to extensive seasonal flooding (i.e., 1.0; N = 1664 observations). The $\Delta T_{o-b}$ falls to about 4 K over many floodplain areas within the Pantanal that dry completely at low water, indicating that non-flooded floodplain resembles nearby savanna uplands in its radiometric characteristics. In contrast to $\Delta T_w$ and $\Delta T_d$, the $\Delta T_f$ value is expected to vary among wetland types because of the variable density and structure of emergent vegetation that covers seasonally flooded land. We therefore determined the $\Delta T_f$ value empirically for different subregions of the Pantanal, as described below.

The $\Delta T$ values of open water, non-flooded land, and flooded land are used together with a measurement of $f_w$ from maps or Landsat Thematic Mapper images to calculate $f_f$, the fractional inundation area. Simultaneous solution of equations (1) and (2) yields the following equation for $f_f$:

$$f_f = \frac{\Delta T_{o-b} - f_w(\Delta T_w) - f_d(\Delta T_d) + f_w(\Delta T_f)}{\Delta T_f - \Delta T_d}$$

Inundation area includes the open-water area of lakes and river channels, and is thus calculated as the sum of $f_w$ and $f_f$ times the total grid cell area.

For the purposes of data analysis and presentation, we divided the Pantanal into 10 subregions based on predominant differences in hydrology and geomorphology (Fig. 1). The principal sources used to delineate subregion boundaries were the 1:1,000,000 geomorphology and vegetation maps produced by the RADAMBRA'S project from Side-Looking Airborne Radar imagery and ground studies (Brazil, 1982). We also consulted Landsat TM images from several dates, topographic maps, and Adamoli (1982). In most cases the subregions reflect areas influenced by flooding from a particular river system.

Test cells were identified within each subregion for the determination of $\Delta T_f$. Test cells are representative of the subregion, are almost entirely subject to inundation, and are surrounded by similar landscapes. We found a total of 53 test cells that met these criteria, representing 28% of the total area of the Pantanal. They were carefully selected based on maps, Landsat TM imagery, and our field experience in the region. We measured the area of open water (lakes and rivers) within each test cell using topographic maps of either 1:250,000 (Brazil) or 1:50,000 scale (Bolivia and Paraguay). A few cells contained significant upland areas that is subject to inundation, which we also measured from maps. Assuming that the remaining area within the test cell flooded completely during the highest flood years, we used the above equations and the mean of the maximum $\Delta T_{o-b}$ of the four highest flood years to estimate the $\Delta T_f$ of the test cells. For a test cell in the high Pantanal subregion, which is composed of thousands of small lakes and narrow strips of non-inundable forest (locally called cordilheiras), the forested upland areas were measured from a 1:100,000 topographic map and open water was measured from a low-water Landsat TM image (22 Sep 1991).

The $\Delta T_f$ values of the test cells were then averaged for each subregion and used in calculations for the remaining cells in the subregion. Two of the subregions (Tiquari Fan and Aquidauana/Negro) showed east-west gradients in $\Delta T_f$ and therefore instead of using the overall mean $\Delta T_f$, only the $\Delta T_f$ values of the closest test cells were averaged to determine the appropriate $\Delta T_f$ for a cell. For cells that spanned more than one subre-
gion, a weighted mean $\Delta T_f$ was calculated, based on the mean $\Delta T_f$ values and fractional areas of each subregion within the cell.

Open water areas for the remaining cells were measured from maps, as for the test cells. Field observations and Landsat TM imagery confirmed that the maps depicted the approximate low-water boundaries of lakes and rivers; seasonally flooded land bordering permanent water bodies tends to be occupied by emergent vegetation, so open-water/floodplain boundaries tend not to change greatly as the water level rises and falls. The particularly small lakes of the Nhecolândia subregion are not accurately depicted on the maps, but are readily visible on Landsat TM images. However, they are too numerous to measure individually across the entire subregion. Therefore, we measured lake area only for the test cell (which contained 964 lakes). Lake area for the remaining cells of Nhecolândia was then determined from the mean low-water $\Delta T_{obs}$ after finding that the mixing models predicted low-water lake area for the test cell if $f_j$ is assumed to be negligible during the dryest periods (measured test-cell $f_w = 0.099$, predicted $f_w = 0.092$).

Results and discussion

Effects of atmospheric variability and rainfall

We have found that the seasonal variation in the 37 GHz $\Delta T_{obs}$ over the large wetlands of lowland South America is driven by changes in the area inundated rather than by atmospheric variability and local rainfall. Fig. 3 illustrates the effect of inundation on $\Delta T$ by comparing the $\Delta T_{obs}$ over the floodplain of the Paraguay River north of Corumbá with that over nearby upland grid cells. The mean seasonal patterns of rainfall and river stage in this area are plotted in Fig. 2, showing that the peak in riverine flooding occurs about 4 months later than peak rainfall. The floodplain at this site is flooded by the river rather than by local rainfall, as indicated by the correspondence between river stage and the $\Delta T_{obs}$. The adjacent upland, which is not subject to seasonal inundation, shows relatively little seasonal variation in $\Delta T_{obs}$ (Fig. 3). If atmospheric variability or rainfall events produced the seasonal cycle of $\Delta T_{obs}$ for the Paraguay River floodplain, then the nearby upland area would show more variability, and the close relationship of the floodplain $\Delta T_{obs}$ with river level would not be observed. Similar comparisons yield the same conclusions for the central Amazon floodplain near Manaus (Sippel et al. 1994).

The concern has recently been raised that seasonal atmospheric variability can significantly modulate the observed seasonal changes in the 37 GHz $\Delta T_{obs}$, and that correction for this variability might be necessary for studies of seasonal variation in emission from the land surface (Kerr & Njoku 1993). The importance of atmospheric variability in seasonal tropical climates has been postulated based on modeling the effects of seasonal changes in temperature, atmospheric water vapor, and cloud optical thickness on radiative transfer through the atmosphere, using the Sahel region of Africa as an example (Choudhury et al. 1992, Kerr & Njoku 1993). For studies of South American wetlands, correction of the $\Delta T_{obs}$ for the effects of atmospheric variability would not be worthwhile because it would require meteorological data that can only be crudely estimated, and it would introduce new uncertainties into the data set. The above comparison between the $\Delta T_{obs}$ over floodplain and upland areas strongly suggests that any effects of seasonal atmospheric variability are not large enough to obscure the effects of seasonal changes in inundation area. Our empirical determination of $\Delta T_f$ for each subregion during maximum flooding would help to account for the typical atmospheric conditions during the flood season.

Heavy rainfall events can have contrasting effects on the 37 GHz $\Delta T_{obs}$: liquid hydrometeors in precipitating clouds have a depolarizing effect, reducing the $\Delta T_{obs}$, while temporary saturation of soils and pooling of water after a heavy rain could increase $\Delta T_{obs}$ (Heymsfield & Fulton 1992). The cloud effects during heavy rains may have been minimized in the monthly data set that we used because of the screening procedure, which would eliminate outliers in a particular month. The lack of strong episodic changes in $\Delta T_{obs}$ over upland areas suggests that heavy rainfall events have little effect on the monthly data.
Saturation of soils by rainfall would persist for longer periods, but Heymsfield & Fulton (1992) have shown that the degree of soil saturation has little effect on $\Delta T_{obs}$ over vegetated (grassland) areas. The available evidence suggests that for inundation to significantly increase the $\Delta T_{obs}$ over vegetated areas, enough water must accumulate above the soil surface to begin to submerge the vegetation that otherwise effectively attenuates the emission from underlying soil.

Algorithm parameters and sensitivity

As noted above, calculation of inundation area from equation (3) requires knowledge of $\Delta T_f$, the $\Delta T$ of inundated areas with emergent vegetation, which we determined empirically for each of the 10 subregions. The results for a total of 53 test cells are summarized in Table 1. Considerable variation in $\Delta T_f$ was found among subregions, possibly reflecting variation in the degree of coverage of the water surface with vegetation canopies. However, it is difficult to relate these $\Delta T_f$ values to differences in the vegetation or inundation depth among subregions because of the lack of quantitative information on these characteristics at the landscape scale.

East to west gradients of increasing $\Delta T_f$ were observed in the test cells of the Taquari Fan and Aquidauana/Negro subregions, where inundation depth tends to be greatest toward the west. The highest mean $\Delta T_f$ value (51 K) was observed in the Nabileque subregion, where Landsat images indicate that during inundation emergent vegetation is sparser than elsewhere. Several grid

<table>
<thead>
<tr>
<th>Subregion</th>
<th>Total area* (km²)</th>
<th>Fraction as open water ($f_o$)</th>
<th>$\Delta T_f$ (K)</th>
<th>Mean (K)</th>
<th>Range (K)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corixo Grande</td>
<td>11,479</td>
<td>0.021</td>
<td>41.5</td>
<td>37–47</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Cuiahi</td>
<td>14,406</td>
<td>0.015</td>
<td>20.0</td>
<td>19–21</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>São Lourenço/Piquiri</td>
<td>15,996</td>
<td>0.006</td>
<td>17.3</td>
<td>15–20</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Paraguacity River</td>
<td>16,258</td>
<td>0.089</td>
<td>32.9</td>
<td>25–39</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Taquari Fan</td>
<td>39,344</td>
<td>0.006</td>
<td>gradient</td>
<td>18–32</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Taquari River</td>
<td>2,927</td>
<td>0.007</td>
<td>42.9</td>
<td>39–47</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Nhecolândia</td>
<td>8,623</td>
<td>0.062</td>
<td>33.0</td>
<td></td>
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<td>1</td>
</tr>
<tr>
<td>Miranda</td>
<td>5,035</td>
<td>0.007</td>
<td>18.0</td>
<td></td>
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<tr>
<td>Aquidauana/Negro</td>
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<td>gradient</td>
<td>16–24</td>
<td>3</td>
<td></td>
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<tr>
<td>Nabileque</td>
<td>13,662</td>
<td>0.015</td>
<td>31.0</td>
<td>25–58</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>

*The total area is the area of the subregion in Fig. 1, and may not all be subject to inundation.

Error in the calculated inundation area can arise from the five different input terms in equation (3). Propagation of the component errors to estimate the error in $f_o$ is not possible because the variances are indeterminate for some of the components. However, we can perform a sensitivity analysis individually for each component to demonstrate the effects of possible biases in our estimates of the $\Delta T$ values for open water, non-flooded land, and seasonally flooded land, and in our measurement of open-water area ($f_o$).

For the overall region, the sensitivity analysis shows that the calculated inundation area varied by an average of only 1% when $\Delta T_w$ was varied by $\pm$ 5 K, and by an average of only 4% when $f_o$ was varied by $\pm$ 30%. This insensitivity is explained by the low fractional area of open water in the region (overall $f_o$ = 0.02: Table 1). In contrast, varying the $\Delta T_{sf}$ by $\pm$ 1 K and the $\Delta T_f$ by $\pm$ 15% produced greater changes in the calculated inundation area, with the largest absolute effects at low and high $\Delta T_{obs}$, respectively. The magnitude of these effects is shown for a typical annual cycle of $\Delta T_{obs}$ in Fig. 4. The effect of error in $\Delta T_{obs}$ was evaluated by taking the standard deviation of the 1664 observations over upland areas (1.0 K; see 5.1 above) as an estimate of the overall precision (Fig. 4). This may overestimate random instrument error because it incorporates any temporal variability in emission from the upland areas, although similar variability has been observed over stable regions of the Antarctic ice sheet (Gloersen et al. 1992). The sensitivity analyses indicate that the calculation of inundation area in the Pantanal is most sensitive to possible error in the satellite observations and to possible bias in our empirical estimates of $\Delta T_{sf}$ and $\Delta T_f$. In other wetlands with a greater proportion of open water, $f_o$ and $\Delta T_w$ would become more important.

The geolocation error of the SMMR data analyzed in this study is likely to be about 12 km (Choudhury et al. 1992). Grid cells should therefore be aggregated for data analysis whenever possible to reduce the relative uncertainty in location, and the possible effects of nearby surface features must be consid-
show different radiometric characteristics, such as uplands, open water, or neighboring subregions.

The algorithms that we have used in this study could also be applied to the 37 GHz \( \Delta T_{\text{obs}} \) recorded since 1987 by the SSM/I sensors, but the empirically determined SMMR AT values are not directly applicable. There are several changes in the design of the SSM/I instrument and in data processing that affect the absolute values of \( \Delta T_{\text{obs}} \) (SPENCER et al. 1989, HOLLINGER et al. 1990, CHAUDHURY et al. 1992, CHAUDHURY 1993). The comparability of SMMR and SSM/I data sets remains under study.

**Subregional inundation patterns**

Time series for the entire period of the SMMR observations illustrate differences among subregions in the seasonal and interannual variability of inundation area (Fig. 5). The upper limit of the ordinate in each panel is the approximate total area of the subregion. The heights of the peaks show that simultaneous inundation of entire subregions generally does not occur, and that all of the subregions reach a fractional inundation area of at least 50% for several months in most years. The seasonal cycle of inundation is generally more regular in the northern subregions, which have unimodal flooding patterns with gradual changes. The Miranda and Aquidauana/Negro subregions show more short-term variability, and in some years these subregions lack a distinct seasonal peak of inundation. The Nabileque subregion generally shows gradual changes in inundation area, but is highly variable in the extent of flooding among years.

Differences among subregions are also apparent in the fraction of the total area that remains inundated during the driest parts of the year. Permanent open-water area is included in the total inundation area, and is thus a baseline area to which the seasonally variable area of inundated land is added. Open water is a significant fraction (>2%) of the total area in only two subregions (Table 1): the Paraguay River subregion (\( f_a = 0.089 \)), where the five largest lakes marked in Fig. 1 comprise much of the total open water, and the Neocolândia subregion (\( f_a = 0.062 \)), which has thousands of small lakes and ponds. In all subregions a significant area of flooded land (in addition to the open-water areas) usually persisted through the dry season, although the amount varied substantially among years. For example, in the Nabileque subregion at least 1000 km\(^2\) of inundated floodplain persisted through the dry seasons from 1979–85, but low flooding in 1986 was followed by more severe desiccation by the end of that year, when only a few hundred km\(^2\) remained inundated.

Differences in the timing of the inundation peaks among subregions are readily visible by comparing the monthly means from the SMMR time series (Fig. 6). The monthly minima and maxima are plotted together with the means.
Fig. 5. Monthly estimates of inundation area for each subregion of the Pantanal, derived from the 1979–87 SMMR observations. Subregion abbreviations are defined in Fig. 1.

Fig. 6. Annual cycle of inundation area for each subregion of the Pantanal, derived from the 9-year time series in Fig. 5. Mean, maximum and minimum areas for each month are depicted. Subregion abbreviations are defined in Fig. 1.
to provide an indication of the interannual variability. Peak rainfall tends to occur from November–March in most of the region, as in the example in Fig. 3 (Brasil 1979). The monthly means in Fig. 6 show that inundation tends to peak from 2–6 months after the peak rainfall. There is a general progression of the flood wave along regional hydrologic flow paths, with the earliest flooding in northern and eastern parts of the Pantanal, followed by delayed flooding in the Paraguay River and Nabileque subregions, which receive water draining from the aforementioned areas. Nabileque provides the most dramatic example of delayed flooding, with maximum inundation corresponding with the beginning of the local dry season, 4–6 months after the peak rainfall.

The range between the minimum and maximum inundation in a particular month shows that in most subregions inundation area is particularly variable during the initial flooding and at maximum inundation, and is much less variable as the flood waters recede (Fig. 6). This reflects the variable timing and magnitude of the rainfall that produces the flooding. The ranges show that seasonal flooding patterns are particularly variable in the subregions of the southern Pantanal. Inundation of floodplains in the southern Pantanal that are contiguous with the floodplain of the Paraguay River, such as those of the Taquari River and Miranda subregions, may be variable in timing in part because inundation is controlled not only by over spill of the tributary rivers at high discharges, but also by impeded drainage due to the later impoundment by the delayed flood wave of the Paraguay River (Silva & Kux 1992). In addition, the greater variability of flooding in the southernmost subregions (Miranda, Aquidauana/Negro, and Nabileque) reflects the less marked seasonality of rainfall in the uplands to the southeast (Serra da Bodoquena), where winter rains are more common (Brasil 1979).

**Regional inundation patterns**

Summation of the monthly observations of inundation area in each of the ten subregions yields a time series of inundation area for the entire Pantanal (Fig. 7). The upper limit of the ordinate reflects the total area (137,000 km²). The area inundated at a particular time oscillated between approximately 11,000 and 110,000 km². There is no apparent relationship between the minimum and maximum inundation areas in the given seasonal cycle; the maximum inundation area in a particular year cannot be predicted from the previous minimum area, nor can the minimum area be predicted from the previous maximum area. The seasonal pattern of regional inundation is depicted by the monthly means (Fig. 8), which peak in March and April.

The total wetland area in the Pantanal is considerably greater than the peaks in Fig. 7 because of differences in the timing of inundation across the region. The total area subject to inundation in at least one month over the course of the year is graphed in Fig. 9, which provides a measure of the extent of seasonal wetlands in the region. These data show that 90–95% of the 137,000 km² area delineated in Fig. 1 was subject to inundation in 4 of the 9 years. In the driest year of the series (1986), two-thirds of the total area was still subject to inundation at some month during the annual cycle.

**Extension of the inundation record**

The 9-year series of SMMR data analyzed in this study provides an indication of the recent interannual variability in inundation dynamics in the Pantanal, but more dramatic fluctuations in rainfall and inundation are known to occur in the region. A longer record of inundation dynamics can be reconstructed by relating inundation area to river stage. The longest record of river stage in the
region is available for the Paraguay River at Ladário (near Corumbá), which began in 1900 (UNESCO 1973). The Paraguay River stage is appropriate for prediction of inundation area because of its central location in the Pantanal, and because the Paraguay River discharge reflects drainage from floodplains throughout the region.

A plot of the total inundation area (data in Fig. 7) against mean monthly stage at Ladário (data in Fig. 3) for the 9 years of SMMR observations reveals a strong clockwise hysteresis and is not well approximated by a single linear or curvilinear model (Pearson product-moment correlation coefficient \( r = 0.66 \)). Examination of a cross-correlation function plot for the two time series revealed that changes in river level tend to lag behind changes in inundation area by 1–2 months, which makes sense because the stage was measured at a point downstream from much of the inundable area. Correlation improved by introducing a lag of either 1 or 2 months in the stage data, but the best correlation was obtained between inundation area and the mean Paraguay River stage 1 and 2 months later (Pearson \( r = 0.95 \)). Linear regression produced the following equation (\( P \leq 0.001, N = 102 \)):

\[
\hat{y} = 18,520 \bar{X}_{t+1, t+2} - 17,309
\]  

(4)

to predict inundation area in month \( t \) (\( \hat{Y} \), in km\(^2\)) from the mean stage of the following two months (\( \bar{X}_{t+1, t+2} \), in m). The standard error of the estimate is 7943 km\(^2\). This model reproduces the salient features of seasonal and interannual fluctuations in inundation area, as depicted in Fig. 7, which compares the model predictions to the SMMR inundation area observations.

Fig. 9. Total area of the Pantanal that was subject to inundation in at least one month during the calendar year.

Fig. 10. Reconstruction of a 95-year time series of inundation area in the Pantanal, based on the observed correlation between inundation area and the stage of the Paraguay River at Ladário, near Corumbá. The inundation area was estimated at monthly intervals from mean monthly stage using equation (4) (stage data are from UNESCO 1973 and the Brazilian Navy at Ladário). The dashed line marks the overall mean of inundation area for 1900–94 (34,190 km\(^2\)).

Equation (4) was employed to reconstruct the fluctuations in inundation area in the Pantanal since 1900 (Fig. 10). The range in stage during this time period was similar to that observed during the 1979–87 period from which the
model was derived, except for occasional very low stages during dry periods. We lack SMMR observations of inundation area at stages <1.3 m, so for these dates we used a fixed value of 6770 km², which is the area predicted by (4) for a stage of 1.3 m.

The reconstructed record of inundation area in Fig. 10 reveals that in the past, interannual variability in inundation has been much larger than observed in the 9 years of SMMR observations. The overall mean of inundation area for 1900–94 is 34,190 km², and is depicted by the horizontal dashed line in Fig. 10. Relatively regular cycles of inundation and desiccation occurred throughout the period from 1974–93. Prior to 1974 there was a 10-year period of relatively dry conditions with little inundation. From 1900–64, interannual variability was large but multi-year cycles of wetter or drier conditions are less evident. As in the 9-year SMMR time series, prediction of the extent of inundation in a given year from the inundation of the previous year appears difficult.

Applications of the inundation observations

The inundation observations derived from the SMMR data are valuable for understanding the floodplain ecosystem because inundation is one of the key physical factors that control the biogeochemical cycles and ecological dynamics of the floodplain environment (Richey et al. 1991, Junk 1993). For example, emission from natural wetlands is a major source of atmospheric methane, a greenhouse gas that plays important roles in the regulation of climate (Loreto & Berner 1988). Significant emission occurs only during inundation, when anaerobic environments produce methane. Estimates of methane emission from tropical wetlands are important to our understanding of the global methane cycle, but they currently suffer from a lack of information on the extent and timing of inundation (Bartlett & Harris 1993). The SMMR inundation observations could be combined with knowledge of the seasonal variation in emission rates from inundated land to improve estimates of the total emission of methane from floodplain environments.

The inundation observations provide insight into the seasonal and interannual fluctuations in habitat for economically important fishes as well as for wildlife that is affected by inundation. Variability in fish yields among years might be related to differences in inundation during the life history of the fishes (Welcomme 1985). Several endangered or threatened species of mammals and birds remain relatively abundant in the Pantanal (Mittermeier et al. 1990), including the jaguar (Panthera onca), which seeks dry refuges during inundation, and the giant otter (Pteronura brasiliensis), which depends on inundated areas for food and protection. Improved information on inundation might help in the conservation of these species because their populations are likely to be regulated by occasional extreme floods or droughts.

Information on inundation is equally important for management of floodplains, and for minimizing the impact of flooding on human activities. Data on annual variation of natural flooding could prove valuable in present attempts to evaluate the environmental impact of a proposed river navigation project known as the Hidrovia, which would entail modifications of the Paraguay River channel throughout the Pantanal, with poorly understood implications for floodplain inundation (Ponce 1995). Improved prediction of inundation some months in advance would help to reduce the socioeconomic impacts of the natural variability. For example, the very dry period of 1964–73 corresponded with expansion of cattle ranching within the Pantanal, and the unforeseen return of high floods in 1974 resulted in large losses of cattle that could not be moved to higher ground before the floods arrived (Wilcox 1992). Prediction might be improved through consideration of the spatial and temporal variation in inundation area, which might be a better indicator of the progress of the flood wave than river level, which is monitored only along the major rivers.

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