A HYDROMETEOROLOGICAL FORECAST SYSTEM FOR THE METROPOLITAN AREA OF SÃO PAULO

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1. INTRODUCTION

The Metropolitan Area of São Paulo (MASP) is one of the largest urban environments of the planet with a population of over 18 million people. It is located within the Alto Tietê River basin (Fig. 1). Flash floods in the summer (Pereira e Barros, 1998) and heavy pollution in the winter (Braga et al., 1999) are a common place. There are hundreds of flood prone areas within the MASP. Recent studies of convective events have shown higher rainfall accumulations and higher probabilities of heavy precipitation over the MASP (Fig 2).

These events were related to the local circulation generated by the MASP heat island and the sea breeze circulation (Pereira, 1999). Heavier rainfall events also tend to produce higher density lighting flashes that can damage the electrical power supply. Additionally, strong wind gusts, shear turbulence caused by heavy precipitation also affect two major airports within the MASP.

Since the MASP is expanding due to the population growth, extreme weather conditions shall cause worse impacts. Therefore, good nowcasting and short range forecasting procedures can effectively mitigate human and material losses in the MASP.

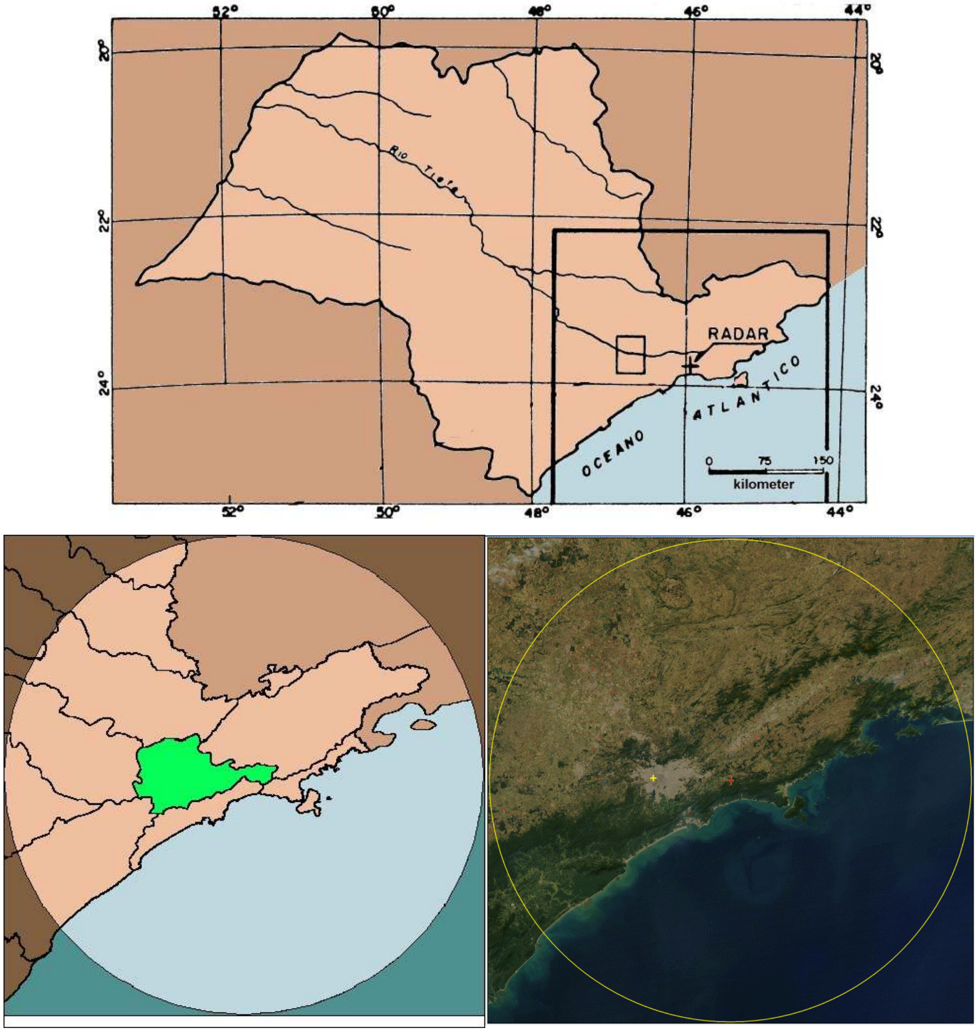

Fig. 1: Map of the Sate of São Paulo, Brazil (top) showing the São Paulo Weather Radar (SPWR) surveillance area (square), the location of the Limão basin (small rectangle), geographic coordinates and main drainage systems. The bottom maps show the Alto Tietê Basin in green and other basins in the SPWR umbrella (left) and a visible image from ACQUA satellite of the same area.

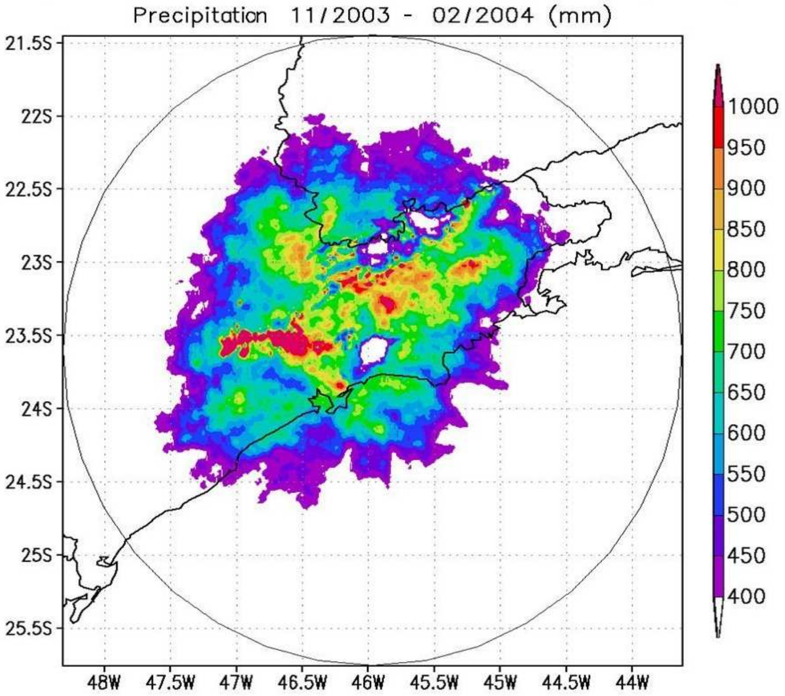

Fig. 2: Total rainfall accumulation between 1 Nov 2003 and 28 Feb 2004 estimated within a 240-km radius of the SPWR. The SPWR is located at the center of the square. Color scale indicates rainfall in mm. Latitudes and Longitudes indicated.

Most significant rainfall events are associated with squall lines (spring), fronts (winter) and thermal convection (summer) or a combination of them, especially during the warmer months (Pereira Filho et al., 1991). Surface data indicate that 75% of all rainfall events were associated with the incoming sea breeze in mid afternoon. Dew point temperatures above 20 ^{o}C have higher probability of heavy precipitation. For instance, the 12 January 2000 event depicted in Fig. 3 caused floods in the Limão basin (780 km^2) with a peak stream flow of 573 m^3 s^{-1}.

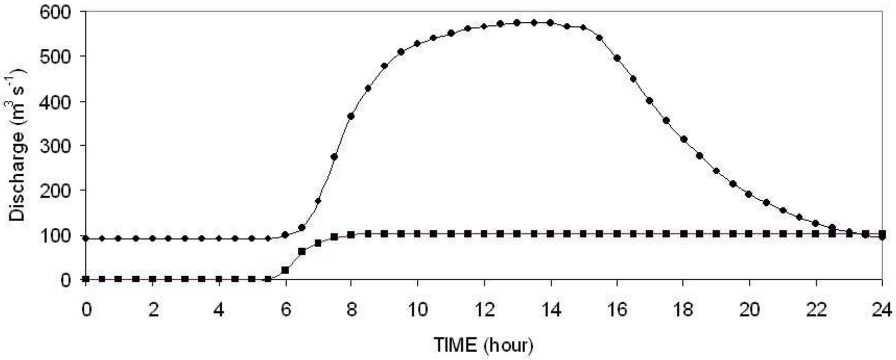

Fig. 3: Time evolution of discharge at the Limão stream gage (located at the intersection between the left side of small rectangle and the Alto Tietê River in Fig. 1) starting at 1200 LT on 12 January 2000. Bottom curve corresponds to rainfall accumulations (mm) measured by a rain gage near the center of the storm (Fig. 4).

Isolated showers were located around the MASP in mid afternoon, while heavy precipitation was over the MASP after 1700 LT (Fig. 4). Vertical mass and heat fluxes were stronger in the MASP due to the diurnal heating, the urban area and pollution and moisture from the sea breeze.

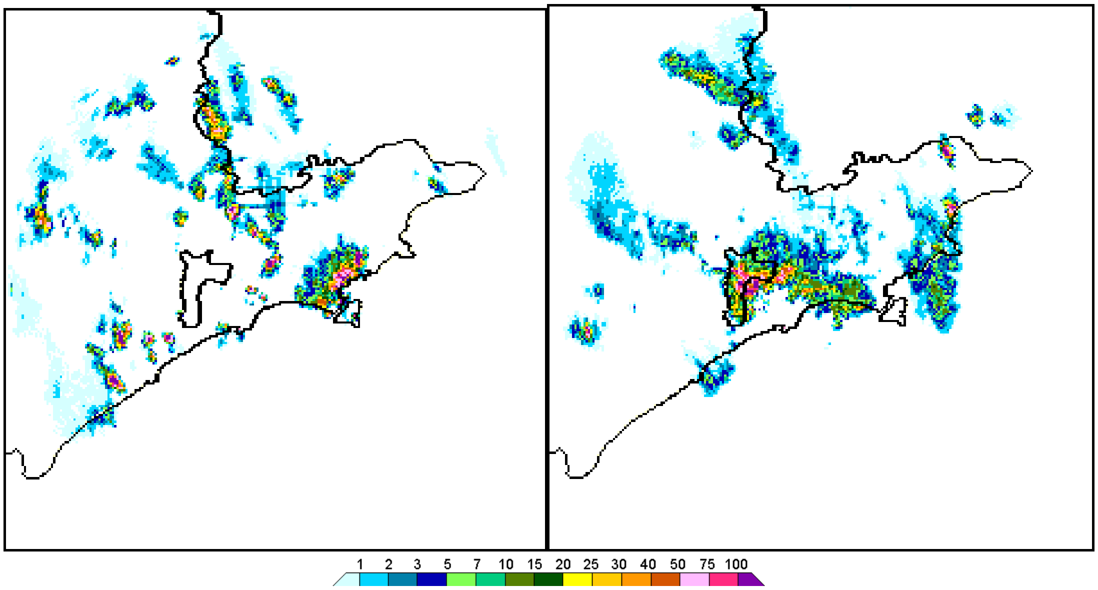

Fig. 4: Spatial distribution of rainfall rates (mm h^{-1}) on 12 January 2000 at 15:03 LT (left) and 17:03 LT (right) within a 240-km radius from the SPWR.

Winds were from the NW with gusts of 5 m s^{-1} from early in the morning until 1700 LT when they shifted to the SW with the inflow of the see breeze. It increased T_d above 21 ^{o}C and was followed by rain (Fig. 5). This convective system yielded 17.5 million cubic meters of water in a couple of hours causing flash floods. Fortunately, it was predicted with at least one hour in advanced, based on surface data and the SWPR.

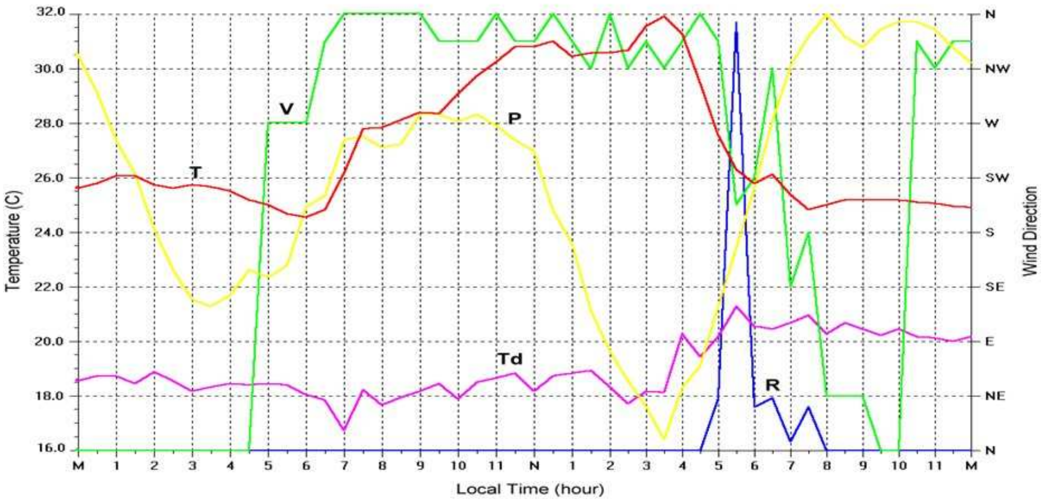

Fig. 5: Time evolution of temperature (T), pressure (P), dew point temperature (Td), Rainfall accumulation (R), and wind direction (V) measured at USP on 12 January 2000. Pressure and half-hour rainfall accumulation scales (not shown) vary from 923.0 to 927.0 hPa and from 0 to 10 mm, respectively.

Heavy precipitation events are also associated to high lightning activity. The electric discharges have an average current of 64 kA and 37 kA for negative and positive polarization, respectively (Gin et al., 1999). The number of cloud-to-ground and cloud-to-cloud lightning flashes within a 50-km radius over the MASP (Fig. 6) were measured during summer and compared to radar-derived variables.

The number of flashes was highly correlated to the vertical liquid water (VIL) and cloud echo tops. Fig. 6 shows the electric activity associated with a super cell thunderstorm that passed by the lighting sensor surveillance area and developed within the lightning device surveillance area in 6 January 1998. Cloud echo top altitudes at 18 dBZ exceeded 14 km.

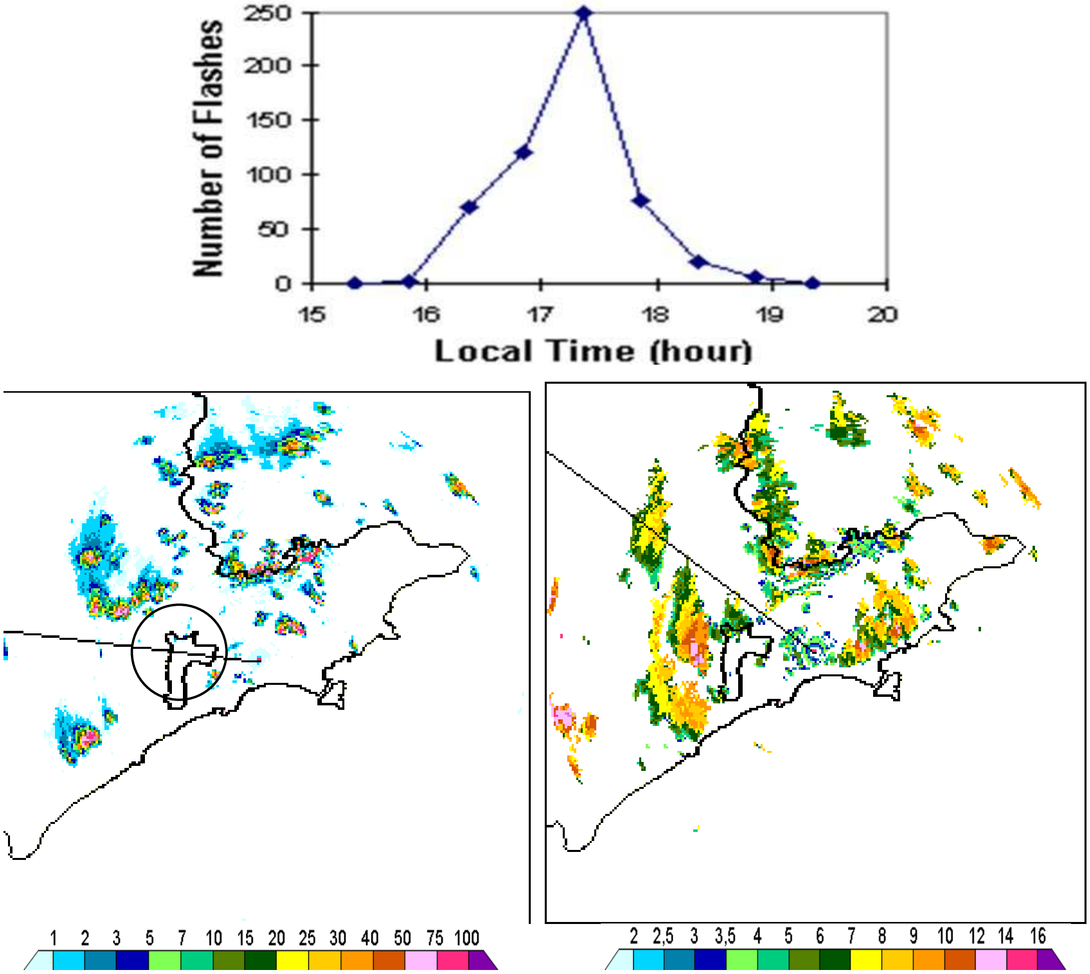

Fig. 6: Convective activity on 6 January 1998. Top graphic shows the time evolution of the number of lightning flashes. Bottom maps shows the spatial distribution of rainfall rates (left) and echo top altitude (right) at 1515 LT and 1620 LT, respectively. Circle in the map indicates the lightning detection area within a 50-km radius. São Paulo State and City borderlines are indicated. Rainfall rate scale (mm) and echo top altitude (km) are also indicated.

Thus, the MASP is at higher risks of severe weather and flooding. A Center for Emergency Management (CGE) was established in 1999 by São Paulo City Hall to operate 24 hours daily, 7 days a week during spring and summer seasons. Its forecast system (Pereira Filho and Barros, 1998) is based on an irregularly-spaced and sparse network of automatic rain gages (Braga Junior, 1989) and conventional radar (Pereira Filho et al., 1991). More recently, the State Government is investing in new observing platforms with higher spatial and temporal resolution measurements as well as in new methods to diagnose and to predict severe weather, as shown next.

2. METHODOLOGY

The hydrometeorological forecast system (HFS) described in this manuscript is based on a similar system developed for Oklahoma, USA (Pereira Filho, 1996). It is both a technological and scientific effort to integrate several hydrological and meteorological researches carried out over the past twenty years. The Integrated Hydrometeorological System for the State of São Paulo Program (SIHESP) established by the State Government of São Paulo made it possible to build a state of the art HFS for the MASP that may be applied to other parts of the state and the country.

The HFS for the MASP is being developed to: 1-Quantify precipitation with high spatial and temporal resolution; 2-Nowcasting rainfall amounts up to three hours in advance; 3-Forecast rainfall amounts up to twelve hours in advance; 4-Predict discharge and stage level of the main tributaries of the Alto Tietê River; 5-Demonstrate the operational use of the HFS; and 6-Mitigate disasters due to hazardous weather.

The HFS will allow more accurate high spatial and temporal resolution measurements of winds, temperature, humidity, pressure, solar and terrestrial radiation, precipitation, cloudiness, among other hydrological variables such as stream flow, water level and soil moisture. Fig. 7 shows a schematic of the HFS that is being implemented in four main modules described below. Each module is going to be built around new observing platforms and numerical modeling.

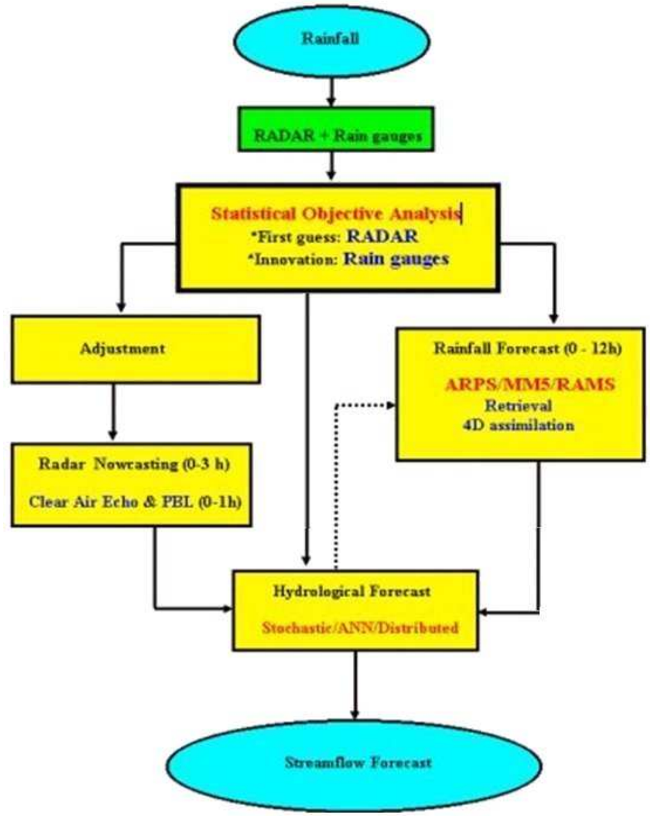

Fig.7: Schematic of the HFS for the Alto Tietê Basin adapted from Pereira Filho (1996). Rainfall measurements from the Mesonetwork of automatic weather stations and two Doppler weathers radars will be integrated through an objective analysis scheme. The analyzed rainfall accumulation field will be used to adjust radar rainfall estimates for nowcasting by extrapolation. Additionally, clear air radar echoes as well as surface measurements of temperature, wind, pressure, moisture and solar radiation from the MASP Micronetwork of automatic surface stations will be used to detect convergence and other local features that generate convective systems. On the other hand, the analyzed rainfall will be assimilated into a high resolution mesoscale model initialized with a regional scale model together with all available data sets from the wind profiler, soundings, satellite, lighting, and the automatic weather stations. Model rainfall forecasts will be input to hydrological models to forecast stream flood within the Alto Tietê basin.

2.1 *Objective Analysis*

This module will integrate rain gage, radar, and satellite measurements and estimates of rainfall rates and accumulations. A statistical objective analysis scheme (SOAS) will be used to reduce observation errors. The SOAS has been successfully applied to analyze rainfall accumulations between 30 minutes and 2 hours in mid latitudes (Pereira and Crawford, 1999). All necessary statistics will be obtained from the SIHESP measured variables. These variables will be interpolated to grid points to initiate the mesoscale model and assimilated continuously through a 4D scheme (Stauffer et al., 1991).

Data quality is an essential part of this module. Significant mesoscale fluctuations can be lost if sensor calibration is not performed systematically (Brock et al., 1995). Thus, data quality assurance procedures will be developed. Each measured variable will be check against lower and upper limits, temporal tendencies and spatial coherence to identify possible errors. A calibration laboratory will be established to ensure each sensor factory calibration. The procedures above as well as others such as data transmission, storage and dissemination will be based on a state-of-the-at system (Fiebrich, and Crawford, 2001).

2.2 *Nowcasting*

This module will anticipate severe weather conditions during the raining season. This technique is based on weather radar and surface and altitude measurements to diagnose pre-storm environment conditions linked to convergence lines, convergence zones, boundary-relative steering flows and cumulus cloud development. Once thunderstorms develop, radar rainfall rates and wind measurements will be used in very short-term rainfall prediction. Rainfall rates will be adjusted based on the objective analysis scheme module described in Pereira Filho et al. (1999). Three-dimensional wind fields will be obtained from radar radial winds and a retrieval scheme (Pereira Filho and Calvetti, 2003). The goal is to develop a nowcasting module similar to the one by Wilson et al. (2001).

2.3 *Mesoscale Modeling*

The Advanced Regional Prediction Systems or the ARPS (Xue et al., 1995) will be used to forecast the weather up to 24 hours in advance. This model can be run in massive parallel processing and is truly scalable (Haas et al. 2000), allowing a significant reduction in processing time by adding more processors. The ARPS comes with an analysis system capable of assimilating diverse data sets with variable spatial and temporal resolution (Droegemeier et al., 1996). The model will use boundary and initial conditions form regional models (ETA, AVN or other) and all available data sets from the SIHESP.

The model will run with 3-km horizontal resolution or higher. Research is also being developed to couple mass and energy flux between the atmosphere and the surface through biosphere-atmosphere schemes (Betts et al., 1993; Bouttier et al., 1993) and urban boundary schemes (Masson, 2000) since the MASP is a major boundary feature in the domain. Additionally, alternative cumulus schemes will be investigated in the light of the dynamic, thermodynamic, and microphysical properties of clouds in the region that will be obtained by radar, disdrometer and aircraft measurements.

2.4 *Hydrologic modeling*

The hydrologic modeling will include lumped, distributed, stochastic and artificial neural network (ANN) models for different basins and purposes, though greater emphasis will be given to distributed models that can be used to couple the atmosphere over the Alto Tietê Basin (Fig. 7). The Topography Based Hydrological Model - TOPMODEL (Mine and Clarke, 1996) will be used. This model is built on two basic assumptions: the saturated zone is modeled by successive uniform conditions and the hydraulic gradient of the saturated zone is obtained by the slope of the terrain. Thus, good topographic mapping is required. Further details can be found in Mine and Clark (1996).

Rain gages measurements, radar and satellite estimates are the basic input variables to the TOPOMODEL. Calibration will be made against measures stream flow data. The Alto Tietê has a good network of stream gages. Surveys are planned to obtain new river and creek cross sections for hydrodynamic modeling of river stage (Lobo et al. 1999).

2.5 *Innovative Technology*

The HFS project incorporates all measuring systems made available by SIHESP. State-of-the-art technology will be employed in the observing platforms of the University of São Paulo such as mobile dual Doppler X-band weather radar (DDXBR), a Micronetwork of automatic weather stations (Fig. 9) and a calibration lab. The calibration lab will also give support to a Mesonetwork to be deployed in the State of São Paulo. The central computer and the lab will be installed at the Department of Atmospheric Sciences of the University of São Paulo since it is also an important tool in undergraduate and graduate courses. Fig. 8 shows a location for the DDXBR over higher elevations. The radar system will be used to measure shallow rainfall systems on top of the coastal mountain range that tend to cause land slights.

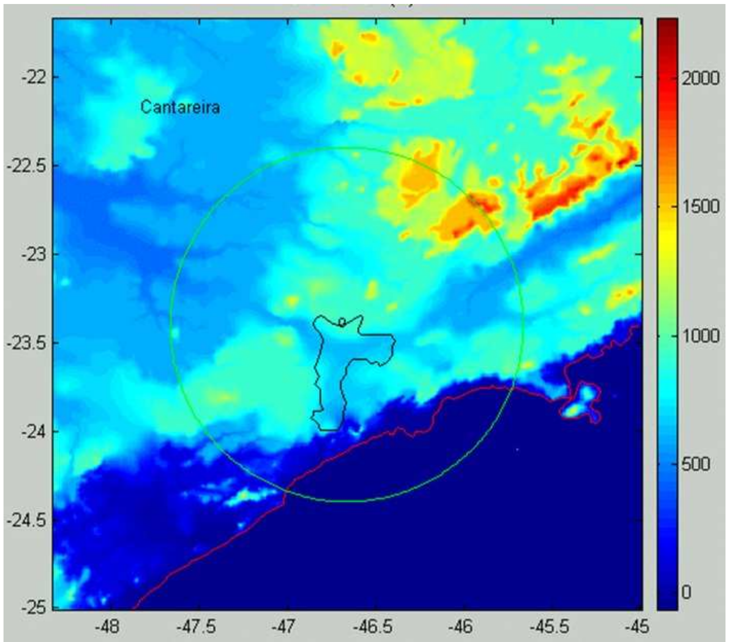

Fig. 8: Map of the topography on the East area of the State of São Paulo, Brazil. A possible site for the DDXBR is indicated by the yellow circumference. Color scale indicates altitude (m).

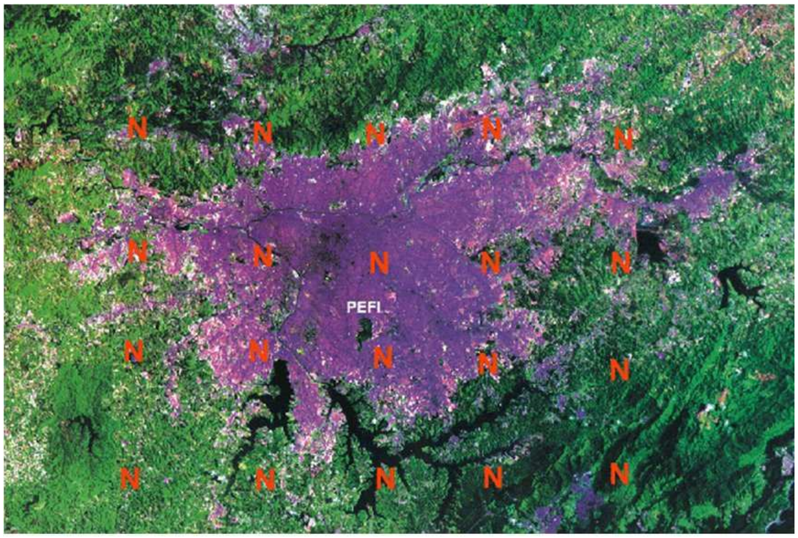

Fig. 9: LANDSAT view of the MASP (purple) with added sites for the twenty automatic weather stations indicated by the letter "N". Reservoirs, sections of the Alto Tietê River and the Ipiranga Springs and State Park (PEFI) can be seen.

3. RESULTS

Procedures, schemes and models to be used in the HFS have been developed. Some are presented in this section to illustrate results; namely, the statistical objective analysis scheme (SOAS), the mesoscale and hydrological model.

3.1 *Objective Analysis*

The SOAS merges satellite, radar and gauge 24-hour rainfall accumulation within the surveillance area of the SPWR (Pereira Filho, 2004). Fig. 10 shows the spatial distribution of errors given the network of rain gauge and the statistics of the background error correlation obtained from radar and satellite daily rainfall accumulations. Clearly, data void areas to the West have higher errors. They can be reduced by a more regular and denser network of rain gauges.

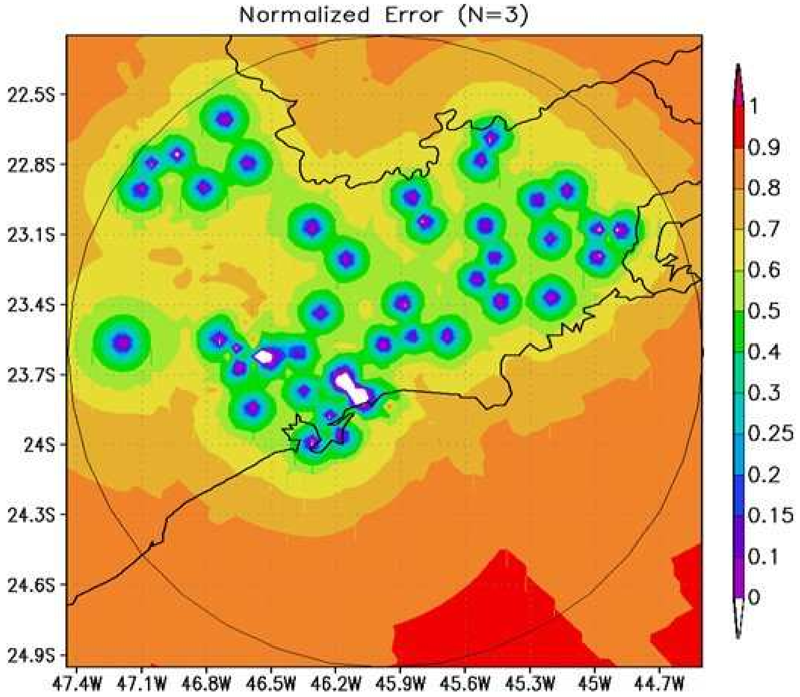

Fig. 10: The normalized expected analysis error variance field of radar and satellite-derived rainfall analysis integrated to the network of rain gauges for three station analyses. Center of circles indicate the location of rain gauges in the network. Latitudes and Longitudes are indicated.

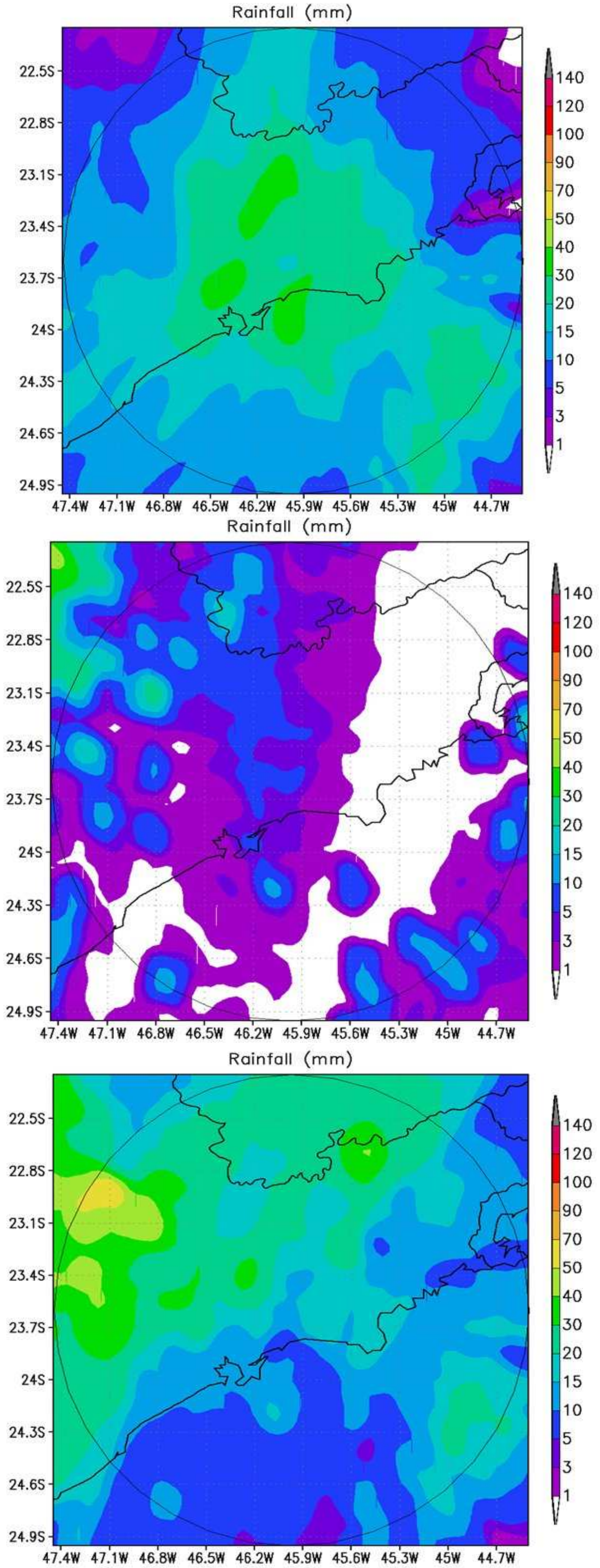

Fig. 11: Daily rainfall accumulations fields for raw radar (top) and raw satellite (middle) estimates, merged radar and satellite analysis with three rain gauge analysis (bottom) on 14 JAN 2002. Color scale indicates accumulations in *mm*.

The SOAS is applied to integrate raw radar (and raw satellite) derived rainfall estimates to rain gauge. Both radar and satellite analyzed fields together with respective raw fields are then used to estimate the analysis error and the final merged analysis field (Pereira Filho, 2004). Fig. 11 shows both raw rainfall field estimates and the final merged field.

3.5 *Mesoscale Modeling*

An example of simulation of convection for a day with very strong thermodynamic forcing is shown in Fig. 12. A convergence line, caused by the local sea breeze, is apparent. This boundary layer feature tends to interact with the MASP heat island and reinforce the lifting to produce rigorous updrafts and thunderstorms. This rainfall event caused significant flooding parallel the cost over the MASP, as shown in the rainfall field estimated with the SPWR (Fig. 12).

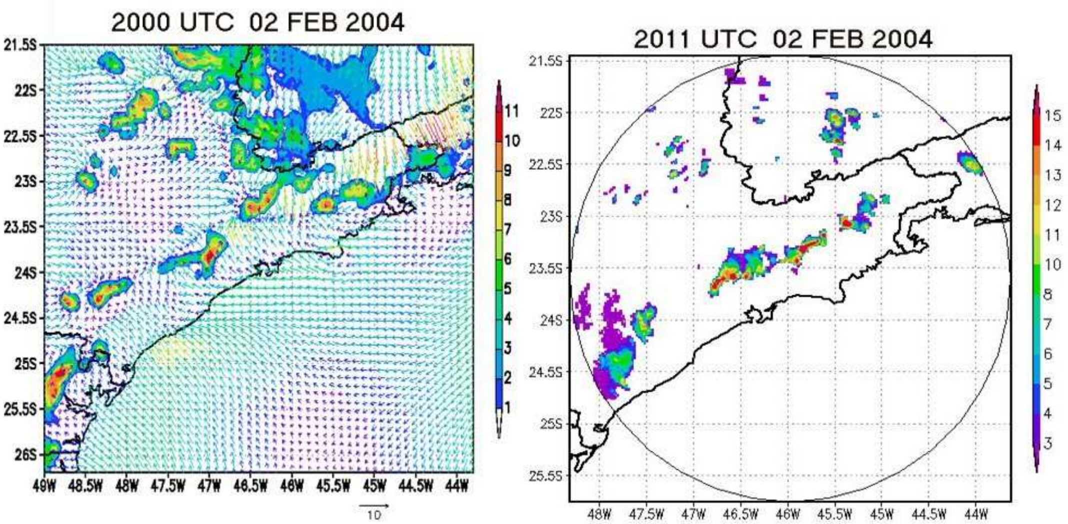

Fig.12: Rainfall (mm) and surface wind (m s^{-1}) fields simulated with the ARPS model (top) and SPWR derived rainfall on 2 February 2004. Latitudes, Longitudes and respective times (UTC) indicated.

3.2 *Hydrologic Modeling*

The Tamanduateí watershed is an important tributary of the Alto Tietê River and is within the MASP (Fig. 13). This densely urbanized watershed has a drainage area of 310 km^2 with an estimated time of concentration of 4 hours. More than 80% of its area is impermeable, especially upstream from the outlet. Its channel has a regular concrete cross-section to drain a maximum peak flow of 485 m^3 s^{-1}. Fig. 13 shows observed and modeled stage levels with an ANN model (Pereira Filho and Santos, 2005). The model was trained with radar-derived rainfall accumulations.

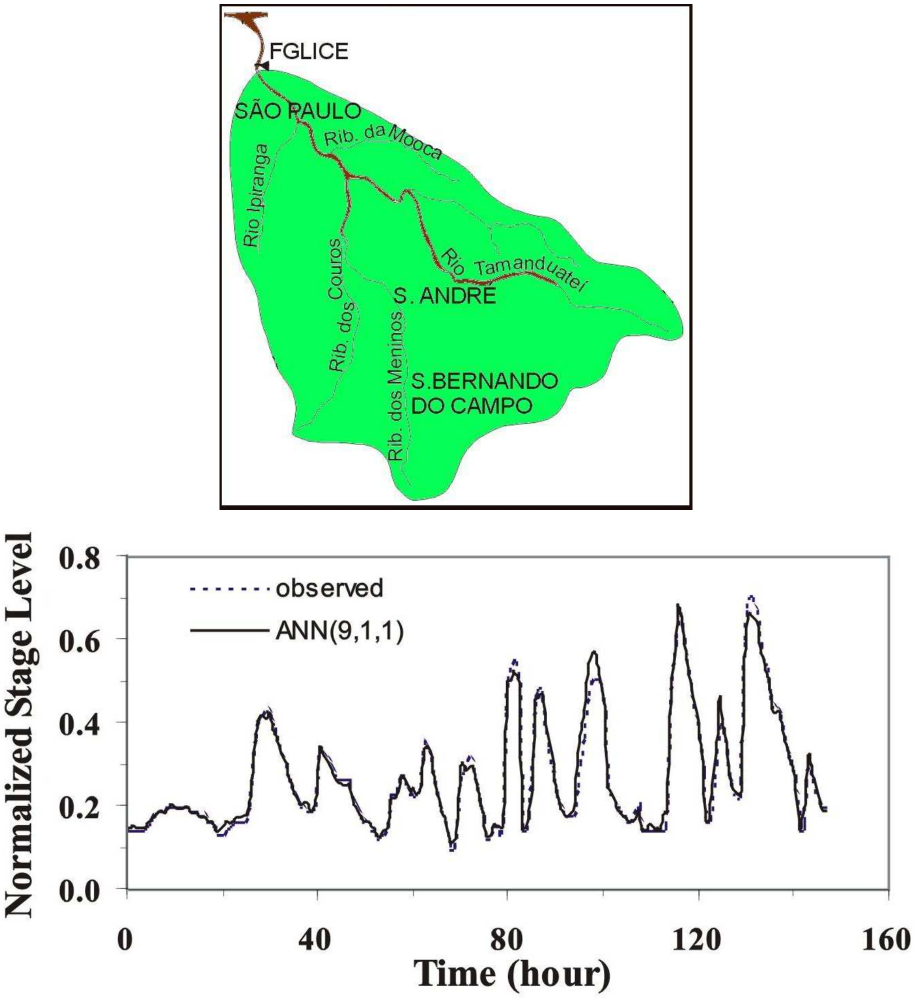

Fig. 13: Map of the Tamanduateí Watershed in São Paulo State (top) and observed and simulated normalized stage level with an Artificial Neural Network (ANN) model (bottom). Watershed box corresponds to the lower part of the one in Fig. 1. The outlet is indicated (FGLICE).

4. CONCLUDING REMARKS

The HFS will also allow a better physical understanding of the local and mesoscale circulation features such as the sea breeze, low level convergence, and topographic effects. Also, the analysis of triggering mechanisms of convection such as gravity waves, thermally induced instability, gust fronts, convergence lines and others. It will lead to better rainfall analysis, forecast of rainfall and stream flow and basin water budgets. It is expected to demonstrate the gain in leading time and accuracy of the forecast in an operational environment.

5. ACKNOWLEDGEMENTS

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