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# EMPIRICAL HYDROLOGIC PREDICTIONS FOR SOUTHWESTERN POLAND AND THEIR RELATION TO ENSO TELECONNECTIONS

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**ABSTRACT.** Recent investigations confirm meaningful but weak teleconnections between the El Niño/Southern Oscillation (ENSO) and hydrology in some European regions. In particular, this finding holds for Polish riverflows in winter and early spring as inferred from integrating numerous geodetic, geophysical and hydrologic time series. The purpose of this study is to examine whether such remote teleconnections may have an influence on hydrologic forecasting. The daily discharge time series from southwestern (SW) Poland spanning the time interval from 1971 to 2006 are examined. A few winter and spring peak flows are considered and the issue of their predictability using empirical forecasting is addressed. Following satisfactory prediction performance reported elsewhere, the multivariate autoregressive method is used and its modification based on the finite impulse response filtering is proposed. The initial phases of peak flows are rather acceptably forecasted but the accuracy of predictions in the vicinity of local maxima of the hydrographs is poorer. It has been hypothesized that ENSO signal slightly influences the predictability of winter and early spring floods in SW Poland. The predictions of flood wave maxima are the most accurate for floods preceded by normal states, less accurate for peak flows after La Niña episodes and highly inaccurate for peak flows preceded by El Niño events. Such a finding can be interpreted in terms of intermittency. Before peak flows preceded by El Niño there are temporarily persistent low flows followed by a consecutive melting leading to a considerable intermittency and hence to difficulties in forecasting. Before peak flows preceded by La Niña episodes there exist ENSO-related positive temperature and precipitation anomalies in SW Poland causing lower, but still considerable, intermittency and thus better, but not entirely correct, predictability of hydrologic time series.

**Keywords:** El Niño, hydrology, time series, forecasting, Poland.

## 1. INTRODUCTION

Forecasting in hydrology still remains to be an ongoing challenge. There are numerous methods which aim at predicting different hydrologic variables. Due to possible practi-

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cal applications, the particular emphasis is put on the flood prediction problem. There are a lot of methods which aim to forecast riverflows. According to Beven (2001), these techniques are based on physically-based and empirical rainfall-runoff models. Although model selection plays a key role in predicting performance in hydrology, there are also some additional, often minor, factors that may amend forecasting accuracy. Among them, there are influences of remote climatic teleconnections on site-specific riverflows and hence on their predictions.

The most intriguing climatic teleconnections are driven by the El Niño/Southern Oscillation (ENSO) which can transfer its signal from the equatorial Pacific to remote regions located thousands of kilometres away. ENSO-climate and ENSO-hydrology teleconnections have been extensively studied, both globally (e.g. Ropelewski and Halpert, 1987; Kiladis and Diaz, 1989; Dettinger and Diaz, 2000; Dettinger et al., 2000; Chiew and McMahon, 2002) and locally (e.g. Price et al., 1998; Pongrácz et al., 2003). In particular, a few authors have considered such links for Europe. The comprehensive geophysical insight into ENSO-climate teleconnections in Europe has been provided in 1990's by Fraedrich (1990; 1994) and Fraedrich and Müller (1992). These extensive analyses have shown that such links exist in winters after the occurrence of warm and cold ENSO episodes and are driven by shifts of the North Atlantic cyclone tracks. There have also been the attempts to investigate ENSO-hydrology teleconnections for some European regions (Rimbu et al., 2004; Karabörk and Kahya, 2009; Niedzielski, 2010a). In the context of Polish hydrology, this body of knowledge has been expanded by Niedzielski (2010a) who provided a detailed examination of such associations for southwestern (SW) Poland by integrating numerous geodetic and geophysical ENSO indices (e.g. length of day, axial component of atmospheric angular momentum, Niño 3.4 index, Southern Oscillation Index) with discharge time series. Accordingly, it has been found that ENSO may belong to a few factors controlling winter or early spring snow-melt floods in SW Poland. However, such an impact has been reported to be meaningful, but rather minor.

The time series methods have been widely used in hydrology (Ledolter, 1978; Vogel and Shallcross, 1996; Toth et al., 2000; Porporato and Ridolfi, 2001; Laio et al., 2003; Elek and Márkus, 2004; Özcelik and Baykan, 2009). These techniques have also been employed in hydrologic studies focusing on SW Poland, particularly extensively after the devastating flood in 1997 which began a broad discussion on the extreme behaviour of the Odra River (Dubicki et al., 1999). For instance, Van Gelder et al. (1999) have studied the annual maximum riverflow data from the Odra River basin and fitted several probability distributions to these time series. Strupczewski et al. (2001) have examined the annual maximum riverflow data from major Polish rivers and found trends in their mean values and variances. More recently, Sen and Niedzielski (2010) have examined numerous statistical characteristics of riverflow in SW Poland with a particular emphasis put on quantitative regulation assessment, streamflow-topography associations and probabilistic flood frequency analysis. In particular, the multivariate autoregressive (MAR) models have been shown as tools for short-term riverflow prediction in SW Poland (Niedzielski and Czystołowski, 2005; Niedzielski, 2007; Niedzielski, 2010b).

The existing hydrologic forecasting techniques for SW Poland do not utilise ENSO-hydrology teleconnections. Knowing that such teleconnections may belong to many factors controlling winter or early spring peak flows in SW Poland, there is a need to verify the hypothesis that such teleconnections influence not only the hydrologic signal but also the accuracy of riverflow predictions. This paper presents an initial analysis based on a simple comparison between prediction accuracies calculated during winter and spring peak flows preceded by normal ENSO states as well as by warm and cold ENSO episodes.

## 2. METHODS

The multivariate daily discharge time series is denoted as $\mathbf{x}(t)$ and is of length $n$. In this study, $\mathbf{x}(t)$ is composed of 15 univariate data sets $x_i(t)$ representing temporal discharge variation between November 1971 and October 2006 at a site $i$, $i = 1, \ldots, 15$.

Following Niedzielski (2007), each component $y_i(t)$ of the residual time series $\mathbf{y}(t)$ is computed using the lag-1 differencing operator defined as $y_i(t) = \nabla x_i(t) = x_i(t) - x_i(t-1)$. The aim of such a time series transformation is to obtain the stationary data. The sample autocorrelation function (ACF) is given by $\hat{\rho}(k) = \hat{\gamma}(k)/\hat{\gamma}(0)$ and thus is expressed in terms of the sample autocovariance function $\hat{\gamma}(k)$ and variance $\hat{\gamma}(0)$. On the other hand, the cross-correlation function (CCF) is defined as $\hat{\rho}_{ab}(k) = \hat{\gamma}_{ab}(k)/\sqrt{\hat{\gamma}_a(0)\hat{\gamma}_b(0)}$ and hence is expressed by means of the sample cross-covariance function $\hat{\gamma}_{ab}(k)$ for two univariate time series $a(t)$ and $b(t)$ and their variances $\hat{\gamma}_a(0), \hat{\gamma}_b(0)$, respectively. Both ACF and CCF are used to access if the signal can be modelled with autoregressive processes.

A zero-mean MAR process of order $p$ is given by

$$\mathbf{y}(t) = \mathbf{A}(1)\mathbf{y}(t-1) + \ldots + \mathbf{A}(p)\mathbf{y}(t-p) + \mathbf{e}, \tag{1}$$

where $\mathbf{y}(t)$ is a random vector at a fixed time $t$ defined above, $\mathbf{A}(j)$, $j = 1, \ldots, p$, are coefficient matrices, $\mathbf{e}$ is a multivariate white noise vector with a covariance matrix $\mathbf{C}$. An order $p$ is estimated using the Schwarz Bayesian Criterion (Schwarz, 1978) whereas autoregressive coefficient matrices $\mathbf{A}(1), \ldots, \mathbf{A}(p)$ are determined by the stepwise least-squares procedure for MAR models (Neumaier and Schneider, 2001).

The prediction of $\mathbf{x}(t)$ for $k$ days in the future is computed in the indirect way, i.e. first, $k$-day prediction of $\mathbf{y}(t)$ is determined and attached to $\mathbf{y}(t)$ time series; second, the inverse differencing procedure is applied to the combined time series.

In order to determine $k$-day prediction of $\mathbf{y}(t)$, first, 1-day prediction $\mathbf{Py}(s)$, from day no. $(s-1)$ to $s$-th day, is determined using past values of the stochastic process by the following equation

$$\mathbf{Py}(s) = \mathbf{A}(1)\mathbf{y}(s-1) + \ldots + \mathbf{A}(p)\mathbf{y}(s-p), \tag{2}$$

where $\mathbf{Py}(s) = [Py_1(s), \ldots, Py_m(s)]^T$; $Py_i(s)$ is the prediction of the residual univariate time series $y_i(t)$ determined at a fixed day $(s-1)$; $i = 1 \ldots, m$; $\mathbf{A}(j)$, $j = 1 \ldots, p$, are the above-mentioned autoregressive coefficient matrices. Second, the predicted $\mathbf{Py}(s)$ vector is attached to the multivariate time series $\underline{\mathbf{y}}(s-1) = [\mathbf{y}(1), \ldots, \mathbf{y}(s-1)]$ and hence the new multivariate time series $\underline{\tilde{\mathbf{y}}}(s) = [\mathbf{y}(1), \ldots, \mathbf{y}(s-1), \mathbf{Py}(s)]$ is constructed. Third, 1-day prediction of $\underline{\tilde{\mathbf{y}}}(t)$ time series is determined using equation (2). This procedure can be repeated $k$-times to obtain $k$-day prediction of $\mathbf{y}(t)$. The prediction accuracy is assessed by a qualitative comparison between the predicted and observed data.

The finite impulse response (FIR) filter based on past and present discharge values has been used to determine the smoothed discharge time series $\hat{\mathbf{x}}(t)$. The following FIR filter can be applied to each discharge time series $x_i(t)$, $i = 1, \ldots, m$:

$$\hat{x}_i(t) = \sum_{l=1}^{L} g_l x_i(t-l+1), \tag{3}$$

where $g_l$, $l = 1, \ldots, L$, are filter coefficients; $L$ is a number of filter coefficients. Both $\mathbf{x}(t)$ and $\hat{\mathbf{x}}(t)$ are concurrently predicted by the MAR technique. The application of the two time series should help to assess if the smoothed riverflow data can be predicted more accurately than the raw discharge time series.

## 3. DATA

The database processed in this study covers the period from November 1971 to October 2006 and includes 15 daily discharge time series from the upper and middle parts of the Odra River basin (SW Poland). The data have been obtained from Hydrological Yearbooks of Surface Waters in Poland 1972-1982 and the Geoserver supported by Polish Ministry of Science and Higher Education (project no. PBZ-KBN-086/P04/2003).


**Fig. 1.** Map showing the study area and the distribution of gauges

The Odra River drains a large area located mainly in western Poland. The headwaters of this river are situated in the Sudetes Mountains in the Czech Republic territory. However, only a tiny section of the river belongs to the Czech Republic. The elevations of the Sudetes Mountains reach 1602 m a.s.l. The mountains are aligned in respect to the NW-SE setting. The rivers draining the Sudetes Mountains transport their waters northward towards the Odra River. High precipitation in the mountains, especially in summer (June-September), introduces a local flood risk and increases water transport towards the Odra River. Similarly, melting of snow in winter/spring increases river discharges, both in the mountains and in the lowland. On the other hand, the majority of right tributaries of the Odra River drain the lowland and hence do not significantly contribute to the occurrence of peak flows.

The following left tributaries of the Odra River are examined: Nysa Klodzka, Olawa, Sleza, Bystrzyca and Kaczawa. The considered right tributaries are: Olza, Klodnica and Mala Panew. The spatial distribution of gauges with their names is presented in Fig. 1. The examined part of the basin is relatively large, i.e. 29605 km$^2$. Additionally, the FIR filter given by equation (3), assuming that the only two filter coefficients are equal to 0.5, has been applied to determine the smoothed 15-variate time series. The filter modifies a time series so that its extreme amplitudes become smaller.

There occurred many peak flows along the Odra River between November 1971 and October 2006, however for the purpose of the analysis seven major winter and spring peak flows have been chosen. The selection criterion has been based based on the 99% discharge quantile attained at Malczyce site (580 m$^3$/s) and at Scinawa site (670 m$^3$/s). According to Niedzielski (2010a), winter or early spring peak flows in Poland can be somehow (rather weakly) controlled by ENSO. The selected peak flow events, the corresponding maximum discharges and information on the preceding ENSO conditions are listed in Tab. 1.

**Tab. 1**. Winter and spring peak flows in the middle reach of the Odra River between November 1971 and October 2006 selected by the 99% quantile discharge threshold attained at both Malczyce and Scinawa sites

| Date of peak flow | Max. discharge at Malczyce site [m$^3$/s] | Max. discharge at Scinawa site [m$^3$/s] | ENSO episode a few months before peak flow |
|---|---|---|---|
| January 1975 | 604 | 708 | Weak La Niña |
| February/March 1977 | 710 | 795 | Weak El Niño |
| March 1979 | 840 | 869 | Normal state |
| February 1987 | 850 | 919 | Moderate El Niño |
| May 1996 | 622 | 714 | Weak La Niña |
| March 2005 | 653 | 702 | Weak El Niño |
| March/April 2006 | 1210 | 1190 | Normal state |

## 4. WINTER AND SPRING PEAK FLOW FORECASTING VS. ENSO

It can be inferred from Figs. 2-8 that data pre-processing using the FIR filter can improve the accuracy of the MAR-based empirical predictions. This is probably due to smoothing which removes insignificant irregularities and emphasizes the flood wave signal. Indeed, a few last data points have always the greatest influence on the MAR model and the corresponding prediction. Thus, small departures from riverflow increase during a flood may amend the model and lead to predictions that deviate form short-term tendencies.

In order to address the issue of ENSO impact on riverflow empirical forecasting for SW Poland, it is convenient to classify the aforementioned peak flows in accordance with ENSO episodes acting before their occurrence (Tab. 1).

Neither March 1979 event nor March/April 2006 peak flow were preceded by ENSO activity. In the first instance, the hydrograph has been successfully predicted, both in the first flood phase and in the vicinity of the riverflow maximum (Fig. 4). In the case of March/April 2006 event, the prediction accuracy has also been kept at the acceptable level. In the first phase of the peak flow, the predictions are rather accurate or slightly overestimated (Fig. 8). The maximum is poorly predicted but data processing with the FIR filter may significantly improve the accuracy around the maximum value.

There are two peak flows under study, i.e. in January 1975 and in May 1996, which were preceded by La Niña events. In the first instance, the predictions derived over the initial flood phase have been found to be moderately accurate. However, the maximum of the flood wave has been poorly forecasted. Such a performance has been improved using the FIR filter pre-processing (Fig. 2). A Slightly different result holds for the peak flow in May 1996. The predictions are accurate in the first phase and are also quite acceptable for the flood wave maximum (Fig. 6). This is probably because May goes beyond the period of ENSO teleconnections for Europe (Fraedrich and Müller, 1992).

El Niño episodes preceded peak flows in SW Poland in February/March 1977, February 1987 and March 2005. In the first case, hydrologic predictions have been relatively accurate for the first phase of the peak flow (fast incline in the discharge values) and have been found non-acceptable in the vicinity of the local maximum. The FIR-based pre-processing have offered better predictions, however – even in the smoothed case – the maximum of the flood wave has not been accurately forecasted (Fig. 3). The similar finding holds for February 1987. Indeed, the maxima are rather poorly predicted whereas the forecasts determined for the first phase of the peak flow coincide with the observational data (Fig. 5). The worst prediction performance amongst peak flows preceded by El Niño episodes has been reported for March 2005. Only a few 3-days forecasts fit the observational data during the first phase of the peak flow. The majority of individual 3-days predictions have been found to be inaccurate, specifically around local flood wave maxima (Fig. 7).

Although the above-mentioned analysis is entirely qualitative and rather subjective, it offers an initial assessment on how prediction techniques are vulnerable to the minor ENSO signal in SW Poland detected earlier by Niedzielski (2010a). It can be inferred from the aforementioned analysis that the best prediction performance is found for peak flows which are not preceded by ENSO episodes. Worse, but still acceptable especially in the first phase of a flood, are forecasts calculated for peak flows preceded by La Niña events. Finally, the worst predictions amongst those considered in this paper have been determined for peak flows preceded by El Niño episodes.

It is thus likely that the minor ENSO signal in the hydrologic data from SW Poland may slightly influence their forecasting accuracy. However, this finding can be treated as a hypothesis because only a few winter and early spring peak flows have been considered. In addition, it should be noted that qualitative evaluation given in the present paper leaves a lot be desired and hence further quantitative investigations are needed in the future.

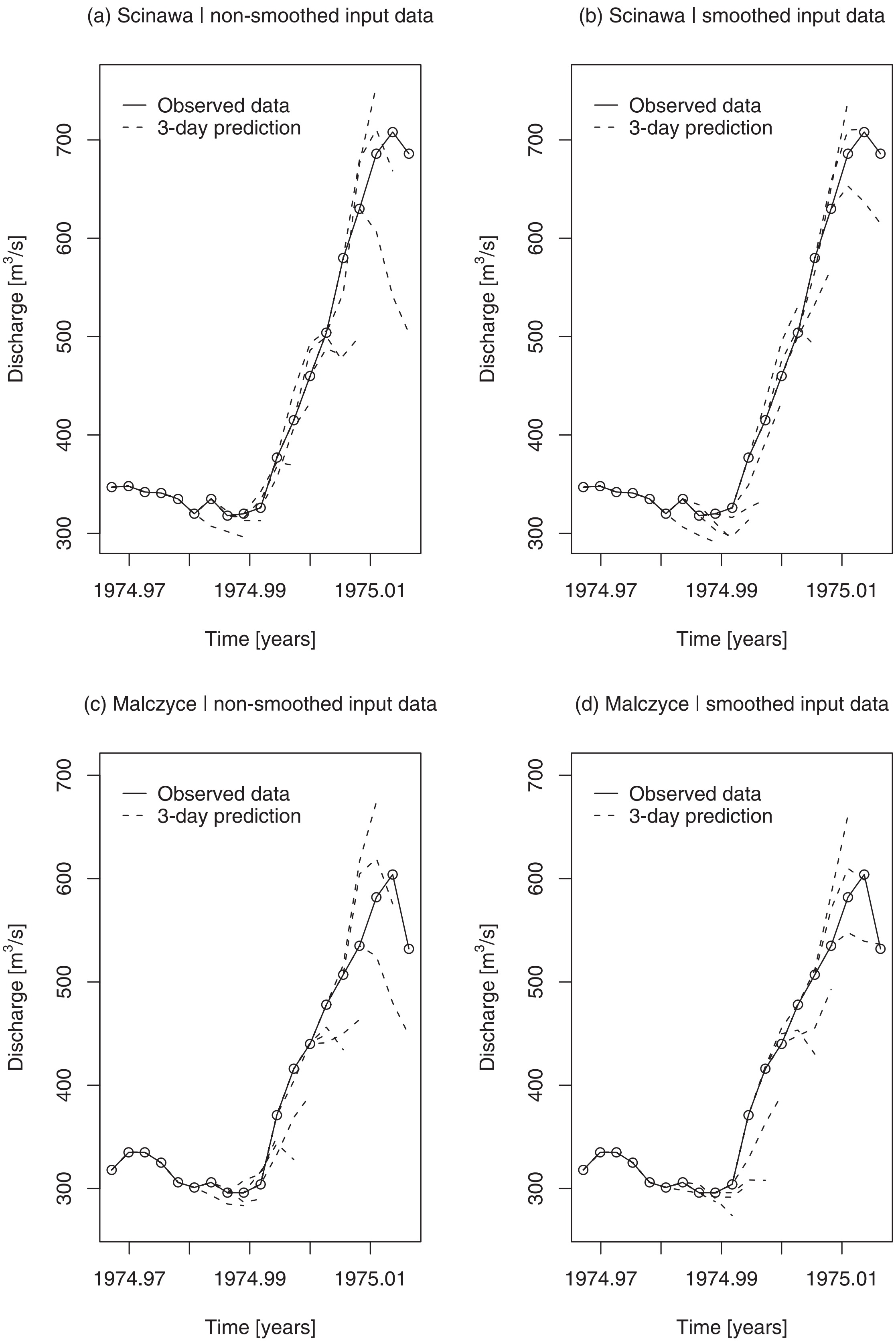


**Fig. 2**. Comparison between the observed discharge and its 3-day predictions based on the MAR technique (January 1975); (a) Scinawa, non-filtered data, (b) Scinawa, filtered data, (c) Malczyce, non-filtered data; (d) Malczyce, filtered data

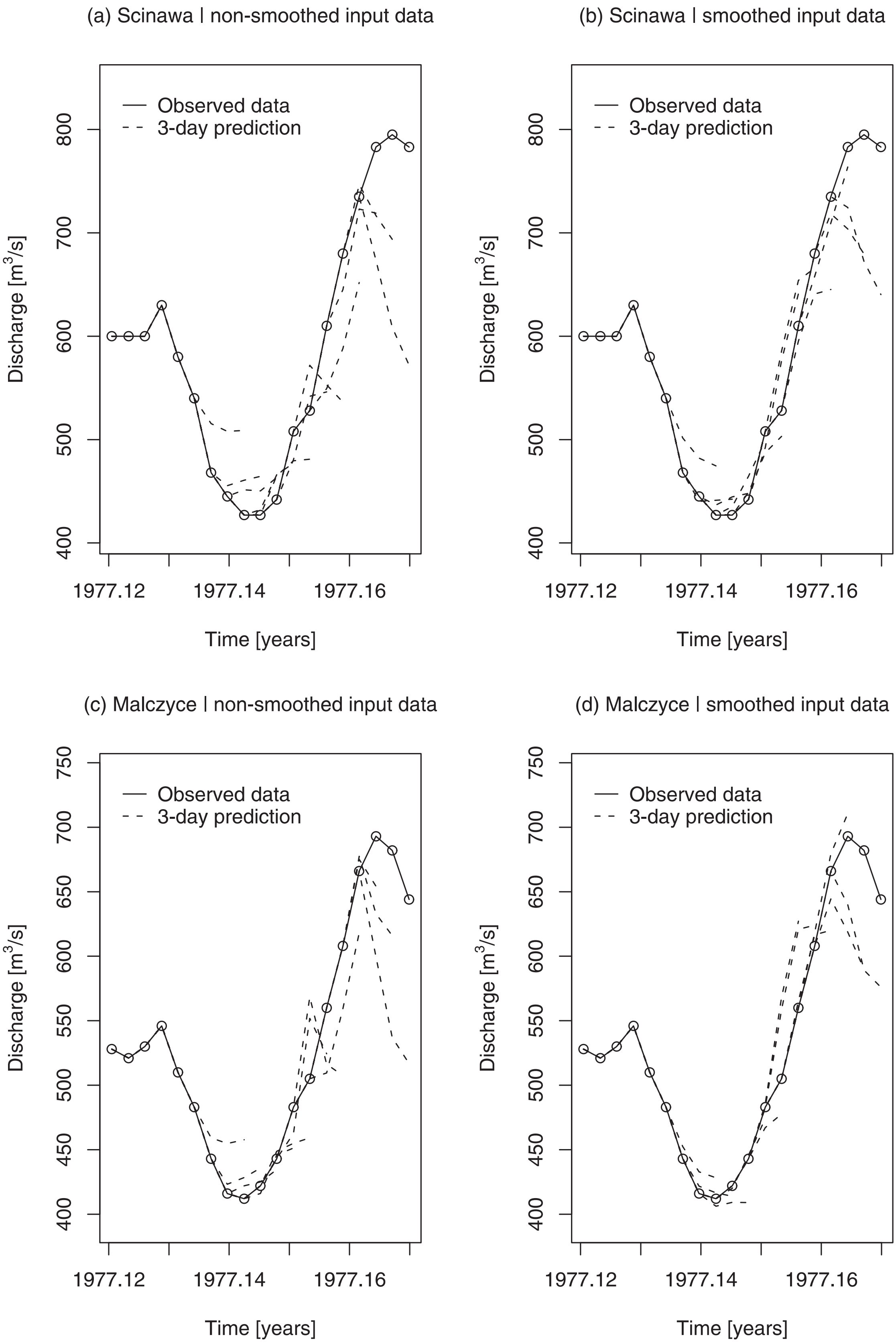


**Fig. 3**. Comparison between the observed discharge and its 3-day predictions based on the MAR technique (February/March 1977); (a) Scinawa, non-filtered data, (b) Scinawa, filtered data, (c) Malczyce, non-filtered data; (d) Malczyce, filtered data

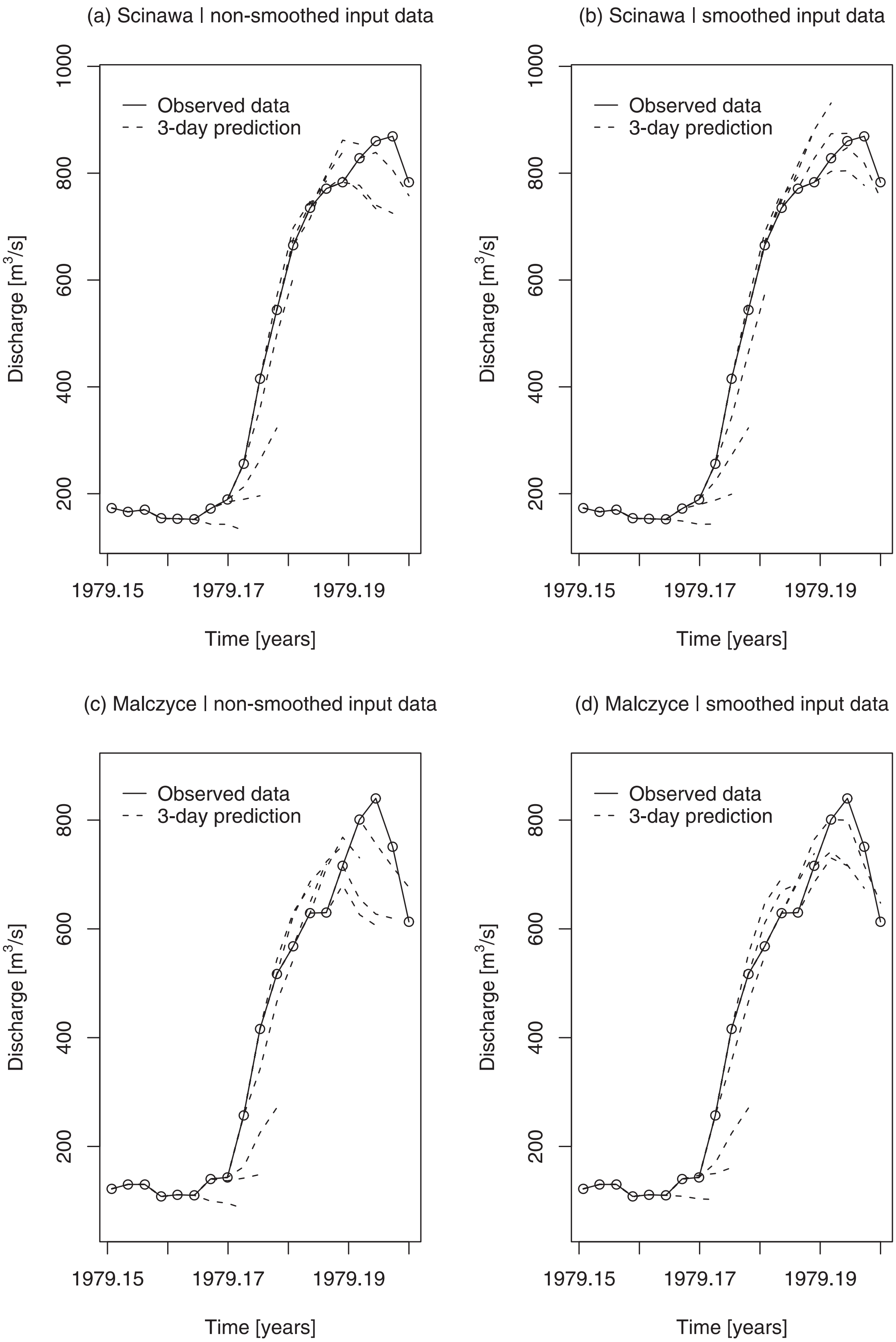


**Fig. 4**. Comparison between the observed discharge and its 3-day predictions based on the MAR technique (March 1979); (a) Scinawa, non-filtered data, (b) Scinawa, filtered data, (c) Malczyce, non-filtered data; (d) Malczyce, filtered data

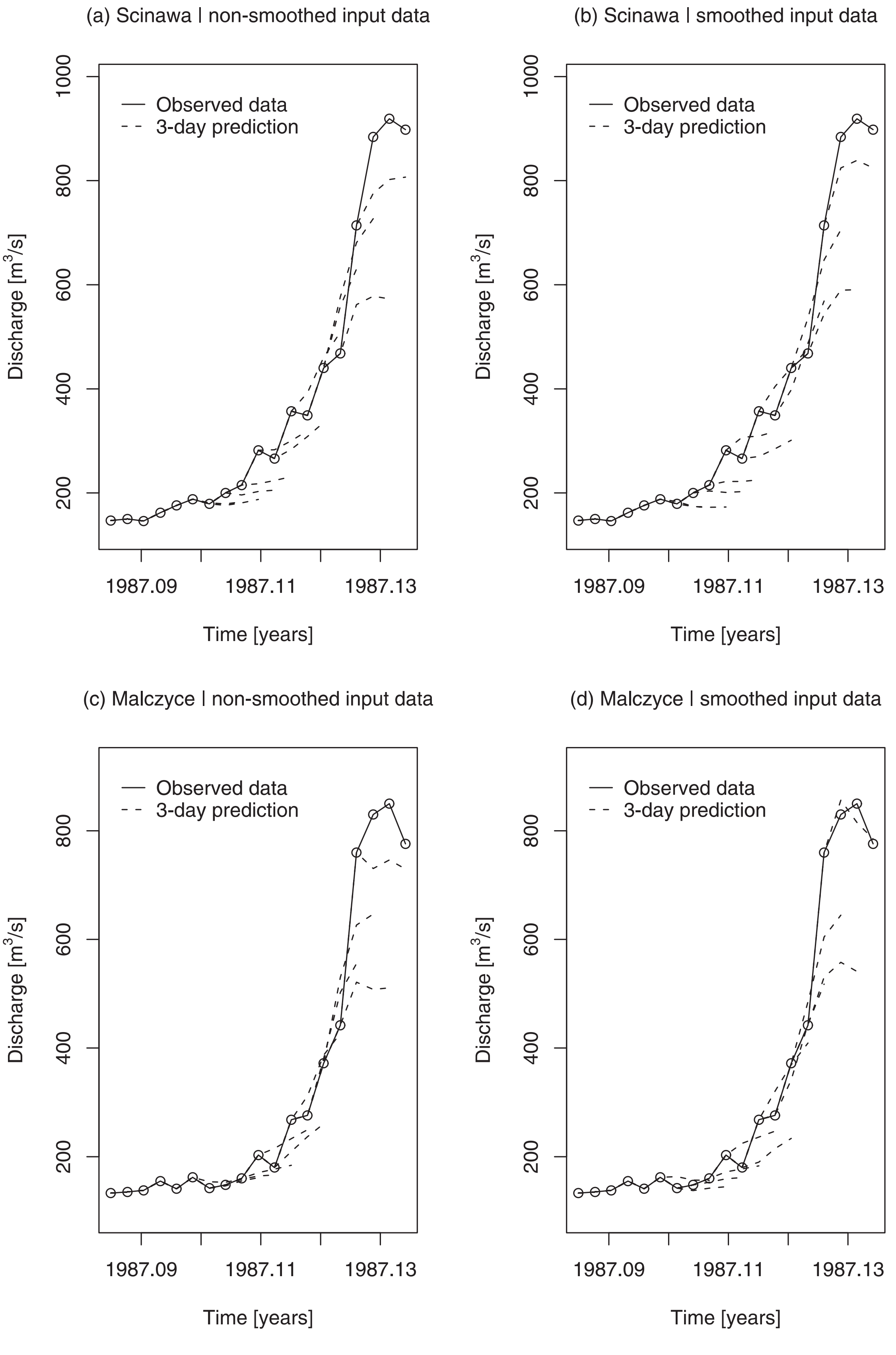


**Fig. 5**. Comparison between the observed discharge and its 3-day predictions based on the MAR technique (February 1987); (a) Scinawa, non-filtered data, (b) Scinawa, filtered data, (c) Malczyce, non-filtered data; (d) Malczyce, filtered data

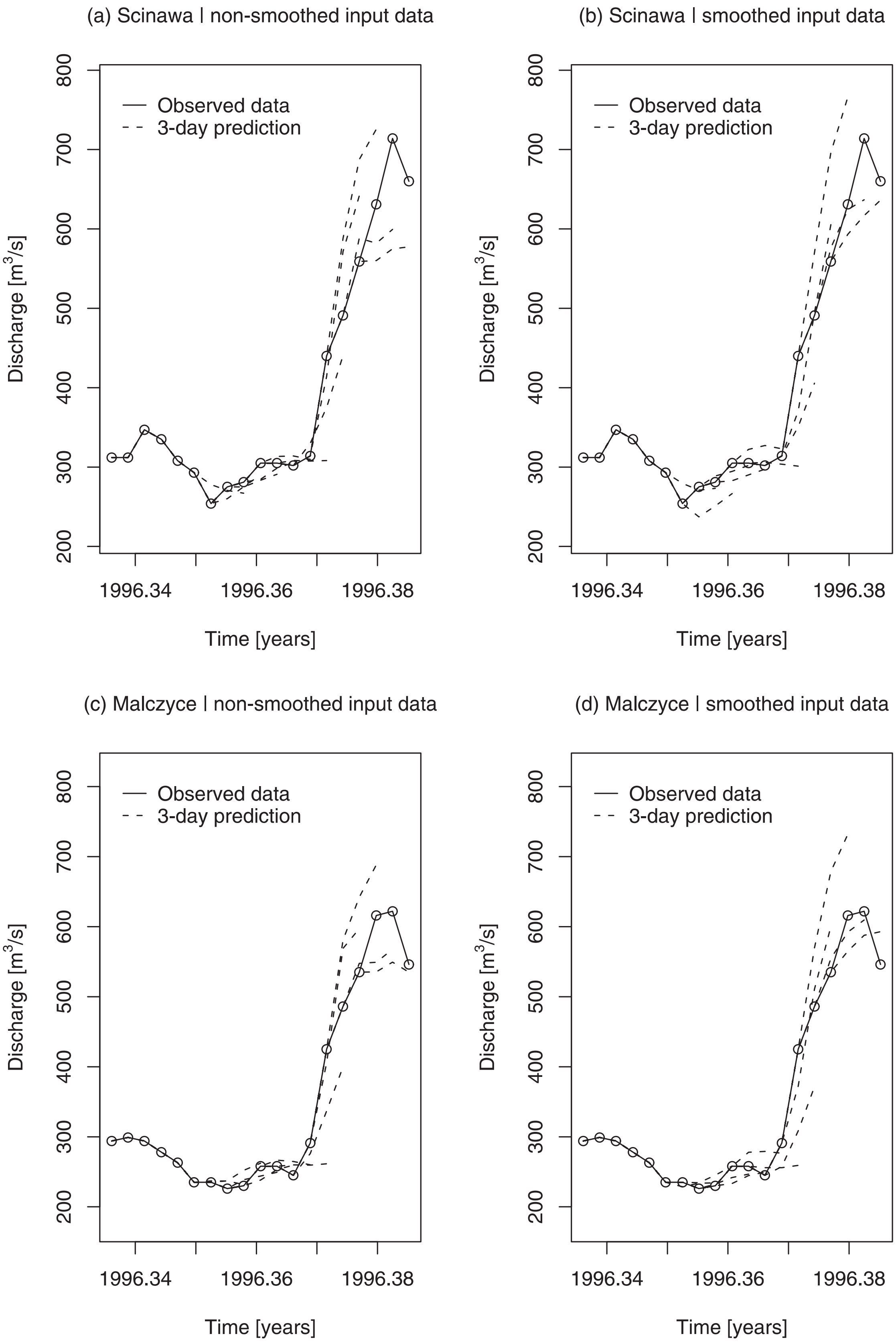


**Fig. 6**. Comparison between the observed discharge and its 3-day predictions based on the MAR technique (May 1996); (a) Scinawa, non-filtered data, (b) Scinawa, filtered data, (c) Malczyce, non-filtered data; (d) Malczyce, filtered data

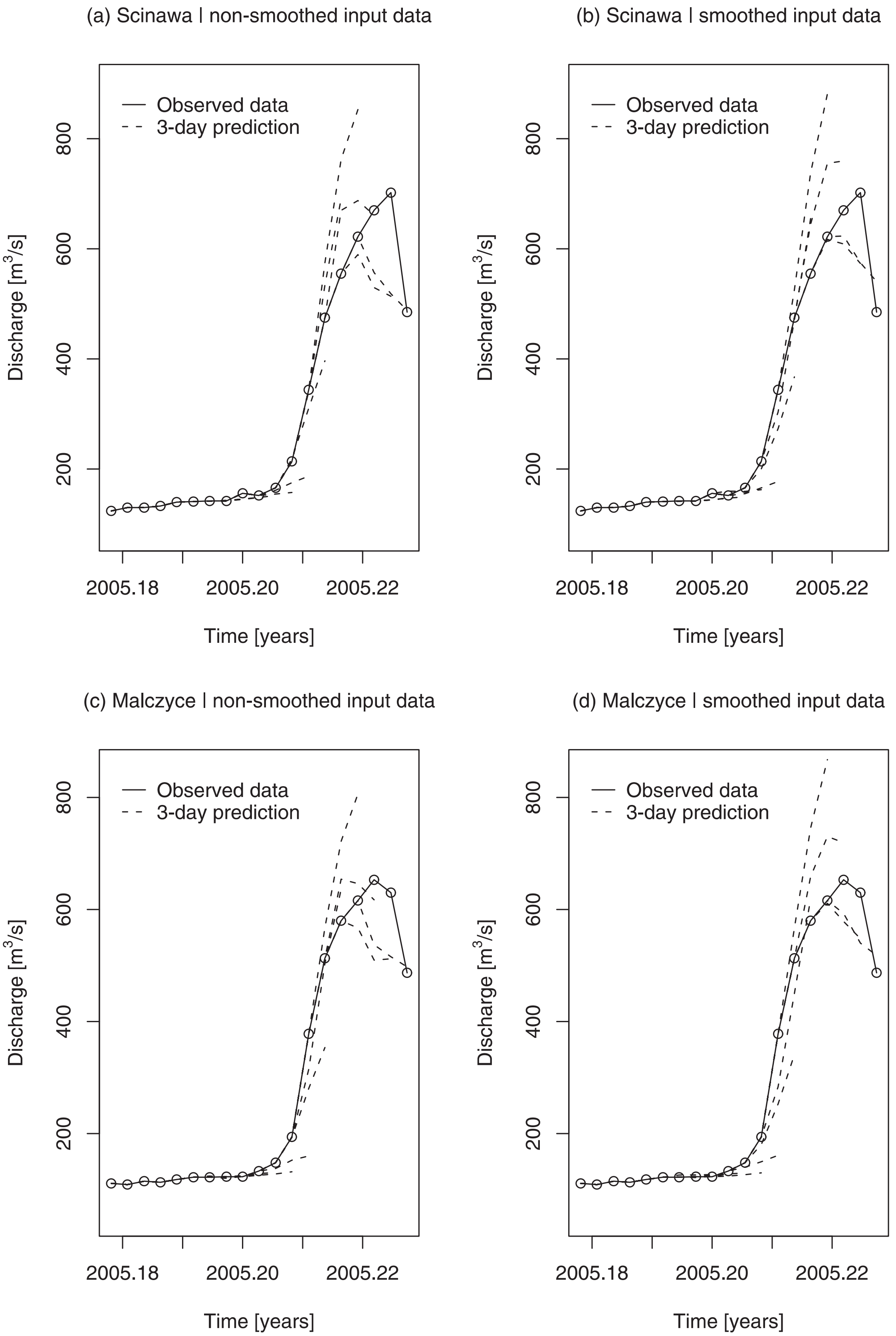


**Fig. 7**. Comparison between the observed discharge and its 3-day predictions based on the MAR technique (March 2005); (a) Scinawa, non-filtered data, (b) Scinawa, filtered data, (c) Malczyce, non-filtered data; (d) Malczyce, filtered data

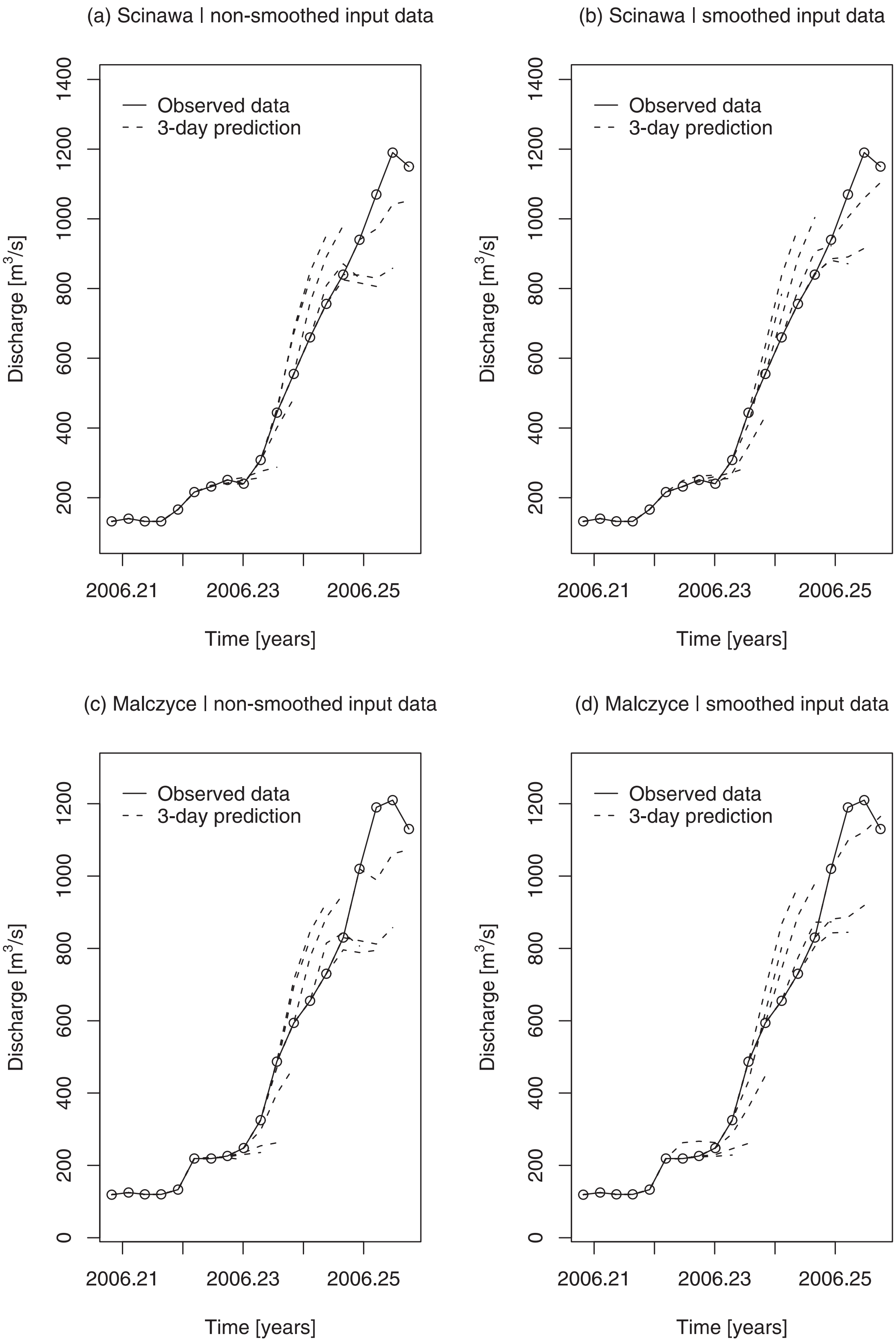


**Fig. 8**. Comparison between the observed discharge and its 3-day predictions based on the MAR technique (March/April 2006); (a) Scinawa, non-filtered data, (b) Scinawa, filtered data, (c) Malczyce, non-filtered data; (d) Malczyce, filtered data

In the light of the process-based interpretation given by Niedzielski (2010a) and based on the influential work by Fraedrich and Müller (1992) a few conclusions can be made. Winter or early spring peak flows in SW Poland after El Niño occurrence may be partially driven by a prolonged and increased snow retention (ENSO-related) and a subsequent melting of snow (probably due to non-ENSO reasons). This may lead to the intermittency in the sense that a prolonged snow retention determines temporarily persistent low flows which can be abruptly changed into peak flows at the beginning of a thawing period. Such a burst of activity is highly irregular and may cause problems in forecasting discharge data. Following Niedzielski (2010a), peak flows in SW Poland, which occur after La Niña, may be partially controlled by positive temperature and precipitation anomalies leading to their contribution to riverflow. If major regional hydrometorological controlling factors are superimposed on such ENSO-related conditions, a burst of activity is probably less abrupt, which still generates uncertainty, but also makes hydrologic predictions less noisy than those calculated after El Niño episodes. This may explain the worst prediction performance for peak flows after warm ENSO events and better, but still mediocre, performance for peak flows preceded by cold ENSO episodes.

## 5. CONCLUSIONS

The MAR technique has been applied to predict winter and spring peak flows in the Odra River basin in SW Poland. Two input data sets have been considered, i.e. the observed daily discharge data and the same data smoothed using the FIR filter. The MAR model applied to the non-filtered data allows one to compute accurate discharge predictions at the very beginning phase of winter and spring peak flows. The predictions of maximum discharges during winter and spring peak flows are less accurate, or inaccurate at all, which may be probably linked to ENSO occurrence. Such an inaccuracy can be partially removed using the MAR technique with the FIR-processed input discharge time series, however a level of improvement is hypothesized to be somehow related to ENSO episodes preceding hydrologic events in SW Poland.

It has been hypothesized that ENSO signal may slightly influence the predictability of winter and early spring peak flows in SW Poland. A few experiments accounting for peak flows preceded by normal states as well as La Niña and El Niño conditions have been carried out. The predictive performance of the aforementioned empirical method in these three ENSO-related states has been qualitatively assessed. In the light of the exercise, short-term hydrologic forecasts seem to be the most accurate for floods preceded by normal states, less accurate for peak flows after La Niña events and rather inaccurate for floods preceded by El Niño episodes. This has been explained by the notion of intermittency. Its values may be considerable in the latter instance because of temporarily persistent low flows due to ENSO followed by a subsequent melting due to different hydrometeorological processes. Lower, but still considerable, intermittency can be associated with cases when La Niña events precede peak flows. This, on the other hand, is due to ENSO-related positive temperature and precipitation anomalies in SW Poland during winter which lead to less abrupt changes in discharge time series. Such irregularities make forecasting complex.

It is worth mentioning that the present exercise provides only qualitative assessment of potential ENSO impact on hydrologic predictability. Only several peak flows have been consider and thus there is need for more comprehensive study in this field.

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