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Brief communication: Seasonal prediction of salinity intrusion in the Mekong Delta

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Abstract. The Mekong Delta is the most important food production area in Vietnam. Salinity intrusion during the dry season poses a serious threat to agricultural production and local livelihoods. A seasonal forecast of salinity intrusion is required in order to mitigate the negative effects. This communication present a simple statistical seasonal forecast model able to predict the salinity intrusion up to 9 months ahead with high skill. The model can thus be used as a basis for timely adaptation and mitigation planning, which is urgently needed for the imminent severe salinity intrusion expected in spring 2020.

1 Problem setting

The Mekong Delta is the most important food production area in Vietnam, responsible for about 50% of the rice production of Vietnam alone. As a low lying coastal area in a monsoonal climate with distinct wet and dry season it is naturally prone to salt water intrusion into the river and channel network during the dry low flow season. Sea level rise and climate change aggravate this problem causing increasing and more frequent droughts and consequent salinity intrusion during the dry season (Smajgl et al., 2015). While the current agricultural production system and peoples livelihood developed over historical periods and thus adapted to normal intensity of salinity intrusion, these changes pose a serious threat to the agricultural production and livelihood of the population. A drastic example of the immense negative effects of a strong salinity intrusion is the dry season 2015/2016. This unprecedented high salinity intrusion caused widespread crop losses throughout the delta. 9 of the 13 provinces in the Mekong Delta were affected by severs salinity intrusion, all provinces were affected by water shortages (Nguyen, 2017). Approximately 400,000 ha of cropland were subject to saline irrigation water, of which 238,276 ha were paddy rice fields. The salinity intrusion also affected 6,575 ha of vegetables, 29,277 ha of fruit trees and 79,000 ha of aquaculture, mainly brackish water shrimp. Figure 1 provides an overview of the land use in the Mekong Delta, as observed and classified in 2010 by satellite remote sensing. It illustrates roughly the main affected cropping types in the coastal areas of the delta. The overall economic damage amounted to 5,500 billion VND, equivalent to about 236 million US$. Furthermore the Vietnamese National Steering Center for Natural Disaster Prevention and Control reported that 194,000 households lacked freshwater for domestic use in the Mekong Delta (VDMA, 2016).

The main damaging effect is the lack of fresh water required for irrigation of rice paddies, but also of fruit orchards and vegetable farming. Because of this lack the crops die either by lack of water or by the adverse effects of high salt concentration in the irrigation water. Therefor salinity intrusion in the Mekong Delta can also be termed as agricultural drought and is a serious hazard for large parts of the population, for which agriculture is still the basis of íts livelihood. An important factor for the large damages were the lack of appropriate mitigation plans, and a timely early warning of the serious salinity intrusion in order to prepare and adapt the agricultural practices for damage reduction. Forecasts of salinity intrusion in the Mekong Delta is provided by the Southern Regional Hydro-Meteorological Center SRHMC. Those forecasts are based on a complex chain of hydrological models, thus requiring a large amount of input data and computational demand. Those forecast require flow and rainfall data until the end of October, thus enabling lead times of 4-6 weeks to the planting of the winter crops only. This lead time is, however, too short to plan and adapt the cropping system well ahead of the drought event. Forecasts with lead times of several months are required to change the cropping system and prepare the crop during the dry (December to April) season.

A drought such as in 2016 is expected to occur more often in future, as rainfall anomalies deficiencies occurring with El Nino events are expected to occur more frequently (Azad and Rajeevan, 2016). Additionally sea levels around the Mekong Delta continue to rise (Smajgl et al., 2015), thus causing increasing backwater effects restricting the discharge during the dry season and consequently promote salinity intrusion. The 2016 event was a wake-up call for the society and officials in Vietnam, as it proved that large structural problems in drought management and mitigation exist.

In order to support disaster management this study aims at the development of a reliable and simple salinity intrusion forecast system enabling lead times of several months, and thus a better adaptation to salinity intrusion and agricultural droughts in the Mekong Delta.

2 Hydrology, data and method

The climate and hydrology of the Mekong Delta and Mekong basin are dominated by the monsoonal climate, separating the hydrological year into distinct rainy/high flow and dry/low flow seasons, whereas the hydrological regime lags the climate regime depending on the location in the basin. In the Mekong Delta this lag is most noticeable due to the time required for transforming rainfall in the about 800,000 km^2 large basin into runoff formation and discharge concentration in the basin and routing to the delta. The lag time in the delta between onset and end of rainy and flood season can be up to 2 months. This lag time opens the possibility of a hydrological forecast, i.e. flow magnitude, by anteceding discharge in general. In fact, anteceding discharge is still the main predictor for the flow forecast published by the Mekong River Commission MRC (Shahzad and Plate, 2014). Moreover, the dry season discharge in the Mekong Delta crucially depends on the runoff generated in the Mekong basin, which is in turn depending on the amount of rainfall in the basin during the monsoon period, i.e. depending on the monsoon intensity (Delgado et al., 2012). The SE-Asian monsoon intensity is itself determined by the periodically changing sea surface temperatures in the western central Pacific Ocean (West Pacific Warm Pool), associated with the El Nino Southern Oscillation ENSO. Of particular importance for the monsoon strength is the situation of ENSO in winter and spring prior to the monsoon season, when the general circulation and moisture fluxes for the monsoon season are initiated (Ju and Slingo, 1995). Therefor the following general causal chain for dry season discharge and thus salinity intrusion in the Mekong Delta can be formulated: ENSO determines the intensity of the SE-Asian monsoon, the monsoon intensity determines the rainfall amount over the Mekong basin, the rainfall amount determines the flood season discharge, the flood season discharge is itself indicative for the following dry season discharge, and the dry season discharge determines the salinity intrusion into the delta.

This general causal chain forms the basis for the simple salinity intrusion forecast model presented in this study. First, an early forecast will be attempted utilizing ENSO indexes as predictor. Secondly, an additional forecast will be tested using flood season and early dry season discharge as predictor. Monthly ENSO indexes were collected from the Asia-Pacific Research Centre in Hawaii (http://apdrc.soest.hawaii.edu/projects/monsoon/daily-data.html#montar). Furthermore monthly discharge data were collected from SRHMC for the gauging station Tan Chau in the Vietnamese part of the Mekong Delta, situated at the Mekong (Tien in Vietnam) branch of the Mekong in the Delta (Figure 1). The salinity intrusion in the Delta is measured by the hydro-meteorological services during the dry season at several non-permanent gauging location in the Mekong Delta usually at 2 hour intervals. The measurements are, however, not continuous, but typically performed for several days in a row, with some days without measurements in between. The longest time series of these measurements was available for gauge Son Doc in Ben Tre province in the estuary of the Mekong (Tien) river branch (Figure 1). The salinity measurements covered the time span 1996 – 2016. In order to derive a meaningful predictand of salinity intrusion, the mean salinity of February and March was calculated from the available salinity measurements. This aggregation time period was chosen, because it coincides with the vegetative stage of irrigated paddy grown during the dry season, which is the most sensitive phase of paddy rice to high salinity levels (Kotera et al., 2014).

The envisaged seasonal forecast of salinity intrusion does not aim at forecasting the exact mean salinity intrusion of this period, but rather at forecasting the probability of critical levels of salinity intrusion are likely to be exceeded. For paddy rice a salinity of the irrigation water exceeding 4 g/l is seen as too high for the plants to survive during the vegetative stage. Therefore a mean salinity of 4 g/l during February and March (FebMar) is adopted as critical salinity level for the forecast model. The mean salinity threshold during this period means that this threshold will be exceeded at 46% of the time considering the negative exponential distribution of the data. In addition to the critical salinity level a threshold of 3 g/l mean FebMar salinity is used as predictand. This threshold is exceeded at 56% of the time in February and March and serves as a warning threshold, indicating a strong salinity intrusion with chances of salinity also exceeding 4 g/l at times.

The forecast model is then based on a logistic regression (LR), i.e. a linear statistical model. The logistic regression is selected because categories (exceedance of the salinity thresholds or not) are forecasted by continuous variables. For this kind of regression the logistic regression is the appropriate tool. LR is very flexible, as it is not limited to normally

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distributed predictors, as e.g. the Linear Discriminant Analysis. Regression models are tested using either ENSO indexes or antecedent streamflow indexes as predictors. The ENSO indexes tested were monthly ENSO1, ENSO3, ENSO4, and ENSO34 indexes starting in April before the dry season, i.e. with a lead time of up to 9 months before the start of the forecasted FebMar time period. For the streamflow predictors the monthly discharges at Tan Chau were transformed into Standardized Streamflow Indexes (SSI). This is similar to transforming precipitation into Standardized Precipitation Indexes (SPI), as typically done in drought studies and drought definitions. SSI has been applied e.g. for predicting streamflow in Southern Africa (Seibert et al., 2017), and has the advantage that a drought condition can be directly recognized by the SSI value, and that the prediction models can be easier transferred and compared to other gauging station with different streamflow magnitudes. SSI was derived for different aggregating time spans ranging from 1 month (SSI1) to 6 months (SSI6), each starting in June prior to the dry season, i.e. with a maximum of 7 months lead time.

The forecast models were tested with all predictors, and the best performing ENSO and SSI predictors were manually selected according to the Receiver Operator Characteristic (ROC) score, the Akaike Information Criteria (AIC), the Cragg and Uhlers Pseudo-R^2, which is defined for categorical variables analogously to the normal R^2 for continuous variables, and the accuracy (rate of correct forecasts). In order to test the robustness of the linear models a Leave-one-Out Cross validation (LOOCV) was also performed, as in Apel et al. (2018) for forecasting seasonal streamflow in Central Asia.

3 Results and discussion

The performance testing of the ENSO predictors identified the ENSO34 index as best performing ENSO index. The best forecast could be obtained with the April index, i.e. with a lead time of 9 month. Figure 2 (top) illustrates the performance of the forecast model. Using only the ENSO34 index of April a ROC score of 0.98 and 0.8 and an accuracy of 95% and 71% could be achieved for the 3 g/l and 4 g/l thresholds, respectively. Also the pseudo-R2's with 0.89 and 0.4 are very high considering the usually lower values of pseudo-R^2 compared to normal R^2 values. This is extraordinary high for a seasonal forecast with such a long lead time. The LOOCV resulted in similar high performances, thus indicating the robustness of the statistical model. The logistic regression curves in the top-right insets show that the 3 g/l threshold can be very well discriminated by the ENSO34 index. The steep slopes of the probabilities changing from drought classification to non-drought classification illustrate this. For the 4 g/l threshold the slopes are more gentle indicating a less pronounced discrimination, which is expressed by the lower performance values. The bottom insets in the figure panels show the observed drought events with reported high salinity intrusion and the forecasts of the model, including the LOOCV forecasts. It can be seen that only 1 out of 21 dry seasons would have been misclassified as drought for the 3 g/l threshold. For the 4 g/l threshold 6 out of 21 events would have been wrongly predicted. In this context it has to be noted that the probability threshold for classifying a forecast as droughts was set to 0.5. Using different probability thresholds for drought classification has been tested and resulted in different classification errors, but the number of wrong classifications and thus the performance values remained the same.

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The forecast performance with ENSO is decreasing with decreasing lead times, as shown in Figure 3 by decreasing ROC scores and increasing AIC values. This finding is in line with the causal chain explained above, where ENSO is preceding the monsoon development. During the monsoon period ENSO changes already to a different state, but having less impact on the monsoon intensity (Ju and Slingo, 1995), thus the value of ENSO as predictor for the salinity intrusion is decreasing.
An opposite behaviour is observed for the SSI predictors (Figure 3). These show in general an increasing performance with decreasing lead time. This behaviour also reflects the hydrological system of the Mekong, where the streamflow at the late flood (October-November) and early dry (December) season are an aggregated measure of the total monsoonal rainfall amount over the Mekong basin, which is more reliable compared to streamflow during the early and high flood season. The SSI3 predictor, i.e. an aggregated index of three months of discharge, performs best, but only slightly better than SSI4 and SSI6 (not shown). The best forecasts were obtained for November and December, i.e. with 1 – 2 month lead time. Interestingly the SSI forecasts were in general better for the 4 g/l threshold than for the 3 g/l threshold (Figure 3), which is also opposite to the forecasts with ENSO. The 4 g/l threshold exceedance can be forecasted with a ROC score of 0.85 and an accuracy of 85% with SSI3 in December and November (Figure 2, bottom panel). Only 3 out of 21 events were wrongly classified for this salinity threshold. This means that the early salinity intrusion forecast by ENSO for the critical salinity threshold of 4 g/l can be further improved with SSI forecasts a few months prior to the dry season, which is important for the actual implementation of disaster mitigation plans.

Conclusions and outlook

The proposed simple linear seasonal forecasting model of salinity intrusion in the Mekong Delta based on ENSO and SSI predictors proved to be a useful tool for an early warning of salinity intrusion during the dry, low flow season in the Mekong delta. The exceedance and non-exceedance of critical and high levels of salinity at the Son Doc gauging station could be forecasted with high probabilities. Combining the ENSO and SSI forecast models results in a forecasting system that could deliver an early warning as early as 9 months prior to the period of the dry season most critical for paddy rice, but also for other crops and fruit orchards. The early forecasts with ENSO in April before the actual flood and the following dry season could serve as an early warning of a likely high salinity intrusion. The later forecasts based on SSI would then provide more reliable forecasts of a severe salinity intrusion that would cause high damages and negative impacts of the livelihood of the population in the coastal provinces of the Mekong Delta, if no mitigation action are initiated in time. Based on the long lead times of the forecasts appropriate mitigation measures can be planned already during the flood season, i.e. well ahead of the dry season, and then activated if the early forecasts are confirmed by the late forecasts based on SSI, i.e. actual observed discharges. Therefore the proposed forecasting model could be used as a data based support for disaster mitigation planning.
Due to its simplicity the model can easily be transferred to other gauging stations in the Mekong Delta thus providing a larger picture on a larger data base, if sufficient data is available. The studied gauge Son Doc can be seen representative for the general salinity intrusion in the Mekong Delta, but forecasts of a larger number of stations would increase the data based

evidence of an imminent severe salinity intrusion affecting the whole delta. Moreover, the model should also be easily transferable to other coastal areas draining larger basins in a monsoonal climate, which face similar hazards by dry season salinity intrusion.

Timely mitigation planning is particularly advisable for the coming dry season 2019/2020, because of the very strong El Nino event recorded in spring 2019. The ENSO34 index value in April 2019 is 28.45, which is just slightly lower than in April 2015 (28.52) prior to the record breaking salinity intrusion in the following dry season 2015/2016. Based on ENSO34 April value the proposed forecast model predicts the exceedance of the 3 g/l and 4 g/l thresholds to 100% and 88.8% respectively for the dry season 2019/2020. The proposed model provides a data based support for the rumours in the media[1] and among authorities in Vietnam, fearing a severe salinity intrusion in the presence of El Nino and the already observed exceptional low flows in the upper part of the Lower Mekong basin. The model forecasts could thus support a decision of the Vietnamese government to plan in time for disaster mitigation in order to avoid severe damages and negative impacts as occurred in 2015/2016, when no preventive and mitigating actions were taken. This could include negotiations with the riparian countries to adapt the operation schedule of reservoirs in the Mekong basin to maintain sufficient flow during the dry season for mitigation of the impacts of the expected very low dry season flow in 2020, as well as sharing the operation information to downstream countries for mitigation planning.

Data availability. Data are available upon request **from** the corresponding author (heiko.apel@gfz-potsdam.de).

Author contributions. HA developed the method and wrote the original draft of the paper. All authors contributed to the preparation of this paper.

Competing interests. The authors declare that they have no conflict of interest.

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References

Apel, H., Abdykerimova, Z., Agalhanova, M., Baimaganbetov, A., Gavrilenko, N., Gerlitz, L., Kalashnikova, O., Unger-Shayesteh, K., Vorogushyn, S., and Gafurov, A.: Statistical forecast of seasonal discharge in Central Asia using observational records: development of a generic linear modelling tool for operational water resource management, Hydrol. Earth Syst. Sci., 22, 2225-2254, 10.5194/hess-22-2225-2018, 2018.

[1] https://www.nationalgeographic.com/environment/2019/07/mekong-river-lowest-levels-100-years-food-shortages/
https://vietnamnet.vn/en/sci-tech-environmennt/mekong-delta-forecast-to-have-small-floods-this-year-555838.html

Azad, S., and Rajeevan, M.: Possible shift in the ENSO-Indian monsoon rainfall relationship under future global warming, Scientific Reports, 6, 20145, 10.1038/srep20145, 2016.

Delgado, J. M., Merz, B., and Apel, H.: A climate-flood link for the lower Mekong River, Hydrol. Earth Syst. Sci., 16, 1533-1541, 10.5194/hess-16-1533-2012, 2012.

Ju, J., and Slingo, J.: The Asian summer monsoon and ENSO, Quarterly Journal of the Royal Meteorological Society, 121, 1133-1168, 10.1002/qj.49712152509, 1995.

Kotera, A., Nguyen, K. D., Sakamoto, T., Iizumi, T., and Yokozawa, M.: A modeling approach for assessing rice cropping cycle affected by flooding, salinity intrusion, and monsoon rains in the Mekong Delta, Vietnam, Paddy Water Environ, 12, 343-354, 10.1007/s10333-013-0386-y, 2014.

Leinenkugel, P., Kuenzer, C., Oppelt, N., and Dech, S.: Characterisation of land surface phenology and land cover based on moderate resolution satellite data in cloud prone areas - A novel product for the Mekong Basin, Remote Sensing of Environment, 136, 180-198, 10.1016/j.rse.2013.05.004, 2013.

Nguyen, N. A.: Historic drought and salinity intrusion in the Mekong Delta in 2016: Lessons learned and response solutions, Vietnam Journal of Science, Technology and Engineering - Environmental Sciences, 59, 4, 2017.

Seibert, M., Merz, B., and Apel, H.: Seasonal forecasting of hydrological drought in the Limpopo Basin: a comparison of statistical methods, Hydrol. Earth Syst. Sci., 21, 1611-1629, 10.5194/hess-21-1611-2017, 2017.

Shahzad, K. M., and Plate, E. J.: Flood forecasting for River Mekong with data-based models, Water Resources Research, 50, 7115-7133, 10.1002/2013WR015072, 2014.

Smajgl, A., Toan, T. Q., Nhan, D. K., Ward, J., Trung, N. H., Tri, L. Q., Tri, V. P. D., and Vu, P. T.: Responding to rising sea levels in the Mekong Delta, Nature Clim. Change, 5, 167-174, 10.1038/nclimate2469, 2015.

VDMA: Report on Drought, Salinization and Response Options, Vietnam Disaster Management Authority (VDMA) - National Steering Center for Natural Disaster Prevention and Control, 2016, http://dmc.gov.vn/Uploads/Thong%20tin%20Thien%20tai%20-%20Disaster%20Information/2016/03.2016/Han%20han/Bai%20trinh%20bay%20bao%20cao%20han%20han_EN.pdf.

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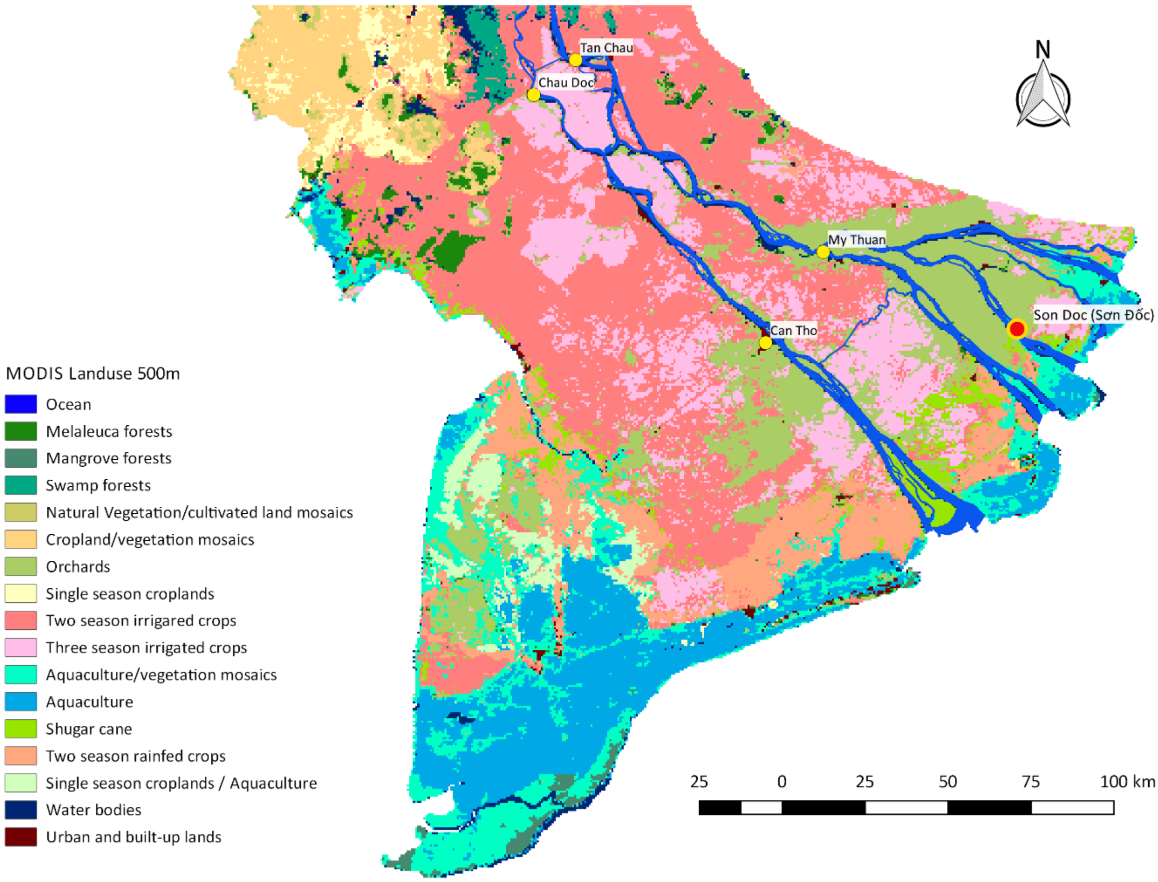

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Figure 1: Land use map of the Mekong Delta in 2010 derived at 500m resolution from MODIS images (Source: Catch-Mekong Knowledge Hub, https://catchmekong.eoc.dlr.de/Elvis/, provided by the German Aerospace Center DLR, (Leinenkugel et al., 2013))

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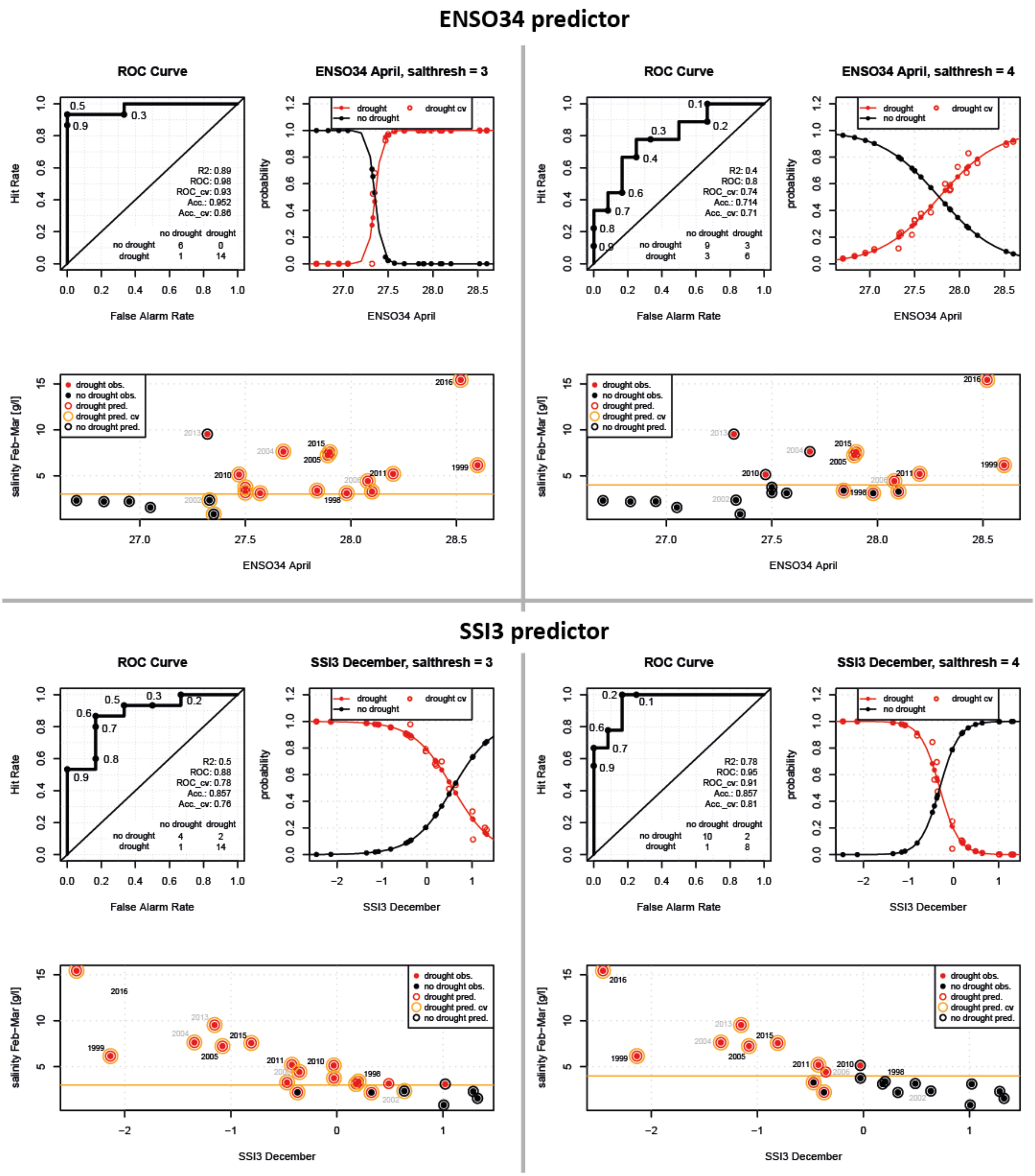
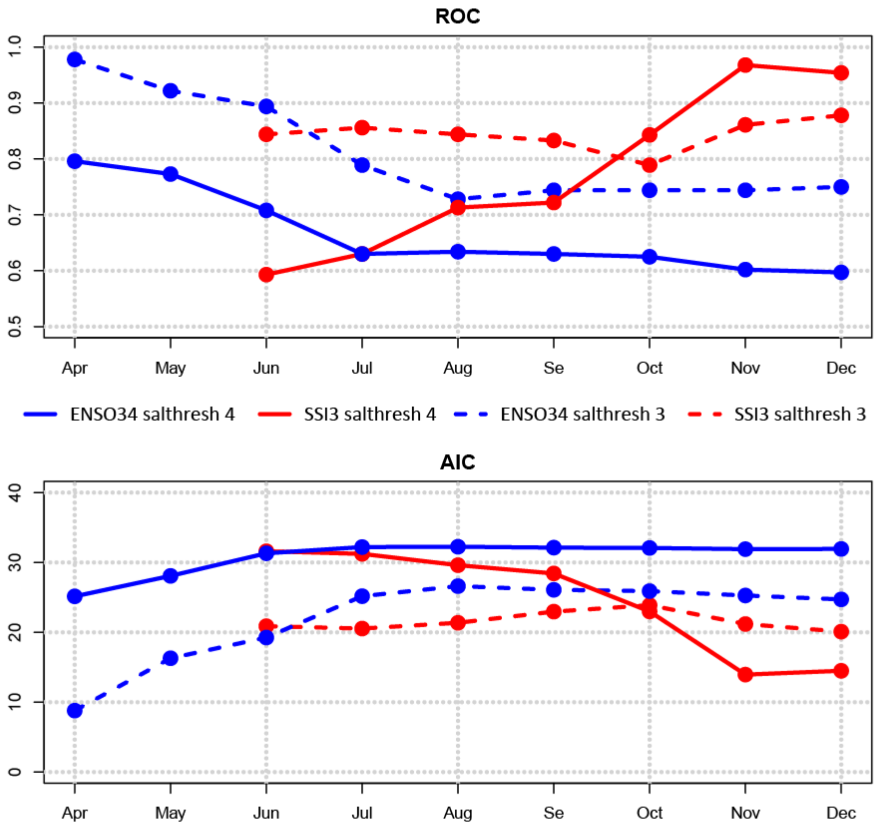


Figure 2: Best prediction models using ENSO34 index (top row) and SSI3 (bottom row) as predictors for forecasting exceedance of the 3 g/l (left) and 4 g/l (right) salinity threshold ("salthresh"). The top-left insets show the ROC curves with the following performance criteria: R2 = Cragg & Uhlers pseudo-R^2, ROC = ROC score, ROC_cv = ROC score of the LOOCV, Acc = accuracy (fraction correct predictions), Acc_cv = accuracy of the LOOCV. Top-right insets show the logistic regression results with the probabilities of exceedance and non-exceedance of the salinity thresholds in dependence of the predictor. The bottom insets show the observed mean February-March salinity levels at Son doc and the predictions in terms of exceedance of the salinity thresholds.



230 **Figure 3: Performance of logistic model with ENSO34 and SSI3 predictors at different lead time in terms of ROC and AIC. The months of the x-axis denote a forecast at the end of the indicated month prior to the dry season. For the mean February-March predictand a forecast in December means 1 month lead time for the predictand season, in April a lead time of 9 months.**