computational issues in such studies (e.g., Class et al., 2009), and the modeling procedure is accompanied by a huge extent of geological uncertainties (e.g., Walton et al., 2004; Brennan et al., 2010; Wilson et al., 2003; Hansson and Bryngelsson, 2009).

In an approach to quantify the impact of geological hetero-geneity on model predictions of multiphase flow in geological formations, a large number of shallow marine depositional real-izations have been generated and used in the sensitivity analysis of the impact of geological uncertainties on production forecasting (SAIGUP) (see Howell et al., 2008; Manzocchi et al., 2008; Matthews et al., 2008). There, the impact of variable geological parameters has been quantified for oil recovery in different field development sce-narios. The main general conclusion of that study is that realistic features of geological uncertainty in modeling (other than typical hydrological parameters) can lead to considerable uncertainties in prediction. Ashraf et al. (2010a,b) used a number of SAIGUP real-izations to study the impact of geological heterogeneity on the injection and early migration of CO_2 in a shallow-marine aquifer with a complex, heterogeneous geological structure. That study transferred the significance of some of the geological structural features to the case of CO_2 injection.

In practice, modeling complicated physical phenomena in the subsurface requires stochastic approaches. Uncertainty can exist in different levels, from the formulation of dependency rules in the model to uncertainty about appropriate values for the model input parameters. Uncertainty coming from any source in the mod-eling procedure propagates through the model to the predicted responses. Ranking the important model parameters based on their influence on the model responses can support a better understand-ing of the system, and it can result in a better design of subsequent studies on the stochastic nature of the process. Hence, identifying and evaluating the sensitivities and uncertainties of model param-eters and their impact on prediction uncertainties and projected risks is a significant task. Sensitivity analysis is known to be the right approach to identify the significance of uncertainty sources within the modeling process (Oladyshkin and Nowak, 2012) and to improve the understanding of model behavior (Sobol, 2001). For example, the European Commission and the United States Envi-ronment Protection Agency recommend using sensitivity analysis in the context of extended compact assessment for policy making (Commission, 2002).

Uncertainty sources within the CO_2 storage problem can be classified in different types as geological, physical and operational uncertainties. This work is devoted to geological uncertainties. However the same procedure can be applied to extend the work for other types as well. Here, we use a set of SAIGUP realizations to perform a sensitivity analysis and to assess the risks caused by uncertainties in a choice of parameters that govern the geological structure of the featured shallow-marine deposit.

The goal of this study is to test and demonstrate the applicabil-ity of a recent set of methods to a realistic scenario. We choose a stochastic response surface method to project the model response to parameter changes onto high-dimensional polynomials via the arbitrary polynomial chaos expansion (aPC) (Oladyshkin and Nowak, 2012; Oladyshkin et al., 2011). Highly similar ideas to the aPC have also been proposed in other scientific areas (Witteveen et al., 2007; Witteveen and Bijl, 2006; Ghanem and Doostan, 2006; Soize and Ghanem, 2004). As we review in Section 2, the involved orthogonal polynomial basis can be constructed for arbitrary prob-ability distributions of the uncertain parameters. This data-driven approach provides fast convergence (Oladyshkin and Nowak, 2012) in comparison to the classical polynomial chaos expansion (e.g., Wiener, 1938; Ghanem and Spanos, 1991; Le Maître and Knio, 2010). Moreover, it avoids the subjectivity of data treatment that would arise when being forced to fall back onto a limited num-ber of theoretical distributions that can be tolerated with previous

generalized versions of polynomial chaos expansions (Wan and Karniadakis, 2007; Xiu and Karniadakis, 2002). The reduced model represented by the response surface is significantly faster than the original complex one, and thus provides a promising starting point for global sensitivity analysis, uncertainty quantification, and prob-abilistic risk assessment.

In the current paper, we use global sensitivity analysis rather than a local one, because local analysis fails to cover the non- linear variation of model responses over the entire range of probabil-ity distributions of the input parameters. A practical approach in global sensitivity analysis is to work with the impact of uncertain parameters on prediction variances, because this shows a good suc-cess in nonlinear problems (Reuter and Liebscher, 2008). In the current study, we use Sobol indices (Sobol, 2001) for sensitivity analysis, which are indeed working with variances. The fact that the aPC based response surface is based on orthonormal polyno-mials with exploitable known properties (Oladyshkin et al., 2012) substantially simplifies this analysis.

Finally, we perform risk analysis by applying a Monte-Carlo pro-cedure to the response surface. The approximating polynomial is fast enough to be used for a large number of Monte-Carlo realiza-tions. This makes it possible to cover the entire range of variations in the model input described by the assigned probability distri-butions, and thus provides accurate estimates for the risk in the system. We conclude with a discussion of the results.

The global sensitivity analysis and uncertainty quantification studies for CO_2 storage existing in the literature are concerned with classic hydrological uncertain parameters like porosity, pore vol-ume and permeability as global constants (see for example Brennan et al., 2010; Kovscek and Wang, 2005; Oladyshkin et al., 2011). To the best of our knowledge, the current study is the first one that implements the proposed mathematical analysis tools on realistic geological structural parameters at reservoir scale. The parameters we consider are the level of barriers presence, aggradation angle, fault transmissibility, and regional groundwater effects. The con-sidered features are the structural and depositional features that dictate the distribution of hydrological parameters such as perme-ability and porosity, both in terms of value and spatial distribution. These are among the most uncertain geological parameters identi-fied with the SAIGUP study (except the regional groundwater effect, which is specific to this study).

2. Response surface via arbitrary polynomial chaos expansion

Working with uncertain parameters in complex, non-linear and dynamic systems puts a high demand on stochastic tools to analyze the system and to propagate uncertainties through the system. Con-ceptually straightforward numerical Monte-Carlo (MC) techniques are computationally demanding since the statistical accuracy of their predictions depends on the number of realizations used. The Monte-Carlo estimation error (measured as standard deviation) for output statistics typically decreases only with the square root of the number of realizations used. Using a stochastic response surface is a promising approach in this respect.

Obviously, a response surface can be constructed in different ways, e.g. it can be constructed directly on a dense Cartesian grid of input parameters at extremely high computational efforts. In the current paper, we apply an alternative methodology which demands only a minimum number of model evaluations to con-struct the response surface. This approach is based on the theory of polynomial chaos expansion (PCE) introduced in Wiener (1938). Generally, all PCE techniques can be viewed as an efficient approx-imation to full-blown stochastic modeling (e.g., exhaustive MC). The basic idea is to represent the response of a model to changes in