



**Fig. 11.** Expectation for response values versus time. The pressure value for initial time step in (c) goes up to 670 bar.

variables, i.e., from the interaction of uncertain parameters. If we add all indices that contain a given variable  $\theta_i$ , the sum is called the total Sobol index:

$$S_{Ti} = S_i + \sum_{j \neq i} S_{ij} + \sum_{j \neq i} \sum_{k \neq i} S_{ijk} + \dots \quad (11)$$

The total Sobol index is a sensitivity measure to rank parameters according to their influence on the model results. When this index is close to zero, the corresponding parameter has a negligible role in the variation of the system response. In that case, the uncertainty in that parameter does not introduce a considerable uncertainty in the response, and the parameter could be omitted from further analyses.

In practice, we evaluate the Sobol indices analytically from the expansion coefficients of the aPC as described by Oladyshkin et al. (2012).

#### 4.2. Sensitivity analysis

We calculate the total Sobol indices for the geological CO<sub>2</sub> storage problem that is described earlier. The results are based on an aPC expansion of order two that is obtained by fifteen detailed simulations. The choice of order two is supported by the results of Oladyshkin et al. (2011), where the authors found in a similar CO<sub>2</sub> storage problem that second order may be the cheapest non-linear expansion, but still sufficiently accurate for this type of purpose. Recently, Oladyshkin et al. (2012) provided the results of a numerical convergence analysis for aPC-based Sobol analysis. They report that increasing the expansion order beyond 2 introduces only small changes to the sensitivity values for their considered system, and

does not change the ranking of the analyzed parameters anymore. A study similar to the current study without aPC needed one hundred and sixty runs to perform a sensitivity analysis with a different method (Ashraf et al., 2010b). The pattern of sensitivity reported here is similar to what is produced in that study, but at dramatically reduced costs.

#### 4.3. Results

The flow behavior in the domain is influenced by the type and intensity of different heterogeneities. This influence can be traced in the CO<sub>2</sub> pressure and saturation distributions over time. During injection, viscous forces imposed by the injector dominate the force balance. Viscous forces act in the form of spatial pressure gradients in all directions. After 30 years, the injection stops, and gravity starts playing the major role in the flow dynamics, acting in the vertical direction (Ashraf et al., 2010a,b).

Barriers and aggradation angle have different impacts on the flow during each flow regime, i.e., injection or after injection. Low fault transmissibility hinders the flow and keeps the pressure in compartments. Geometry distortion in the geological layers because of the faulting processes plays a considerable role in the splitting of CO<sub>2</sub> plumes within the domain. Water flux from lateral boundaries due to the regional groundwater effect enhances the spread of CO<sub>2</sub> and leads the mass of CO<sub>2</sub> toward the other open boundaries.

Fig. 8 shows the sensitivity of different responses to the uncertain parameters. Total Sobol indices are plotted at specific times. End of simulation refers to the year 100, i.e., 70 years after injection stops. This time duration is long enough for the flow to