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Sensitivity analysis of the dynamic CO_2 storage capacity estimate for the Bunter Sandstone of the UK Southern North Sea

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Abstract

Carbon capture and storage (CCS) in subsurface reservoirs has been identified as a potentially cost-effective way to reduce CO_2 emissions to the atmosphere. Global emissions reductions on the gigatonne scale using CCS will require regional or basin-scale deployment of CO_2 storage in saline aquifers. Thus the evaluation of both the dynamic and ultimate CO_2 storage capacity of formations is important for policy makers to determine the viability of CCS as a pillar of the greenhouse gas mitigation strategy in a particular region. We use a reservoir simulation model representing the large-scale Bunter Sandstone in the UK Southern North Sea to evaluate the dynamics and sensitivities of regional CO_2 plume transport and storage. At the basin-scale, we predict hydrogeological changes in the storage reservoir in response to multiple regional carbon sequestration development scenarios. We test the sensitivity of injection capacity to a range of target CO_2 injection rates and fluctuations in CO_2 supply. Model sensitivities varying the target injection rates indicate that in the absence of pressure management up to 3.7 Gt of CO_2 can be stored in the Bunter region over 50 years given the pressure constraints set to avoid fracturing the formation. Long-term (approx. 1000 years), our results show that up to 16 Gt of CO_2 can be stored in the Bunter region without pressure management. With pressure management, the estimate rises to 32 Gt. However, consideration must be given to the additional operational and economic requirements of pressure management using brine production.

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Keywords: CO_2 storage; sensitivity analysis; storage capacity

1. Introduction

The capture of carbon dioxide from large stationary sources (e.g., coal-fired plants and natural gas processing) and injection into deep geological formations for long-term storage, is a viable technology to mitigate carbon emissions while allowing continued large-scale use of fossil fuels (Bandilla et al., 2015; Celia et al., 2015). CCS

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technology can have a significant impact on the carbon problem only if it is undertaken on a massive scale by storing large volumes of CO_2 underground (Celia et al., 2015).

Large-scale deployment of CCS will benefit greatly from dynamic modelling of the CO_2 plume injection and migration in the subsurface. Dynamic modelling can be used to estimate the dynamic and ultimate CO_2 storage capacity (i.e. maximum time-constrained and pressure-constrained amount of CO_2 that can be injected and securely stored in a geological storage formation) (e.g., Linderberg et al., 2009). Accurate estimates of the CO_2 storage capacity must not only account for the pore space available to CO_2 storage but also the pore fluid pressure rise induced by the displacement of in situ pore fluids (e.g., Bradshaw et al., 2007; Birkholzer and Zhou, 2009). This is in stark contrast to static storage capacity estimates that only consider the fraction of the pore space available for CO_2 storage and give little consideration to the pressure buildup limitations (e.g., Halland et al., 2011; Bachu, 2015)

Dynamic models for CO_2 storage are, therefore, critical to our understanding of the storage system and enable us to analyze and optimize storage capacity. Dynamic models have been used to evaluate CO_2 storage at several current and proposed industrial storage sites. For example, 3D multiphase flow models have been used predict injectivity, storage capacity and the nature and extent of the CO_2 plume migration in the Utsira Sandstone at the Sleipner injection site, located in the Norwegian sector of the North Sea (e.g., Zweigel et al., 2000; Nilsen et al., 2011). Studies evaluating the feasibility of proposed large-scale CO_2 storage in the Mount Simon Sandstone of the Illinois Basin used dynamic models to determine storage capacity and evaluate pressure buildup and plume migration (e.g., Birkholzer and Zhou, 2009; Zhou et al., 2010; Person et al., 2010). At the In Salah site in Algeria, dynamic modelling was used to design CO_2 injection, predict plume migration and determine fluid flow impacts associated with geological heterogeneity (Ringrose et al., 2009; Morris et al., 2011).

The aim of this paper is to evaluate the sensitivity of regional CO_2 plume transport and storage using a reservoir simulation model of the large-scale Bunter Sandstone Formation in the United Kingdom sector of the Southern North Sea. We predict hydrogeological changes in response to multiple carbon sequestration development scenarios. We test the sensitivity of injection capacity to a range of target CO_2 injection rates. In addition to geology, the model is constrained by local bottom-hole-pressure limits and site spacing. Large-scale pressure buildup limitations and the impact of brine production on storage capacity are also evaluated.

2. Introduction

The Triassic Bunter Sandstone Formation of the Southern North Sea is considered to have sufficient storage capacity, injectivity and structural competence to ensure that CO_2 storage is successful (Holloway et al., 2006). The Bunter Sandstone Formation is overlain by the predominantly red mudstones of the Triassic Haisborough Group, which act as a seal or caprock, and underlain by the evaporites of the Zechstein Group strata. Due to post-depositional late Triassic to tertiary movement of the underlying evaporites, the Bunter formation has been folded into domes (Bentham et al., 2013). Detailed description of the hydrogeology of the Bunter Sandstone Formation can be found elsewhere (e.g., Chadwick et al., 2009; Heinemann et al., 2012; Williams et al., 2014).

A regional-scale simulation model was developed for the Bunter Sandstone by the British Geological Survey (Noy et al., 2012; Williams et al., 2014), to predict hydrogeological changes in response to multiple carbon sequestration scenarios. The model (Fig. 1) has dimensions of 143 km x 125 km x 1.8 km and is represented with 285 x 250 x 25 grid cells. Lateral and vertical variations in grain size, lithology and degree of cementation, result in heterogeneous reservoir property distributions in the modelled area.

At the reservoir grid-block scale, the porosity varies from 2% to 35%, while, the permeability varies between 0.4 mD and 1050 mD indicating good reservoir quality for CO_2 injection and plume migration. The lateral and underlying boundaries of the model are impermeable, while, a 500 m thick sealing caprock overlies the reservoir. Impermeable (or closed) lateral boundaries represent a conservative estimate of CO_2 storage and pressure buildup. The Bunter formation appears to crop out to the sea bed in a 7.68 km^2 area close to the southern boundary of the modelled region (see blue circle in figure 1b). Injection of CO_2 into the Bunter Sandstone is evaluated using CO_2-brine multiphase flow simulation in computer modelling group's simulator IMEX.

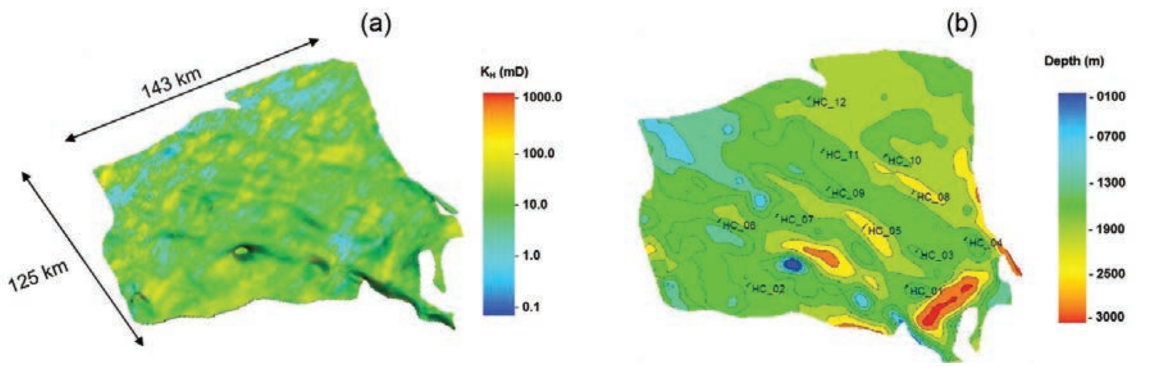

Fig. 1: (a) Three-dimensional model representation of the Bunter Sandstone Formation, and (b) and topographical depth contours of the Bunter region indicating a seabed outcrop (blue circle) and 12 injection sites.

3. Results and Discussion

We evaluate the efficiency of geological CO_2 storage by analyzing the footprint of the CO_2 plume and the pressure buildup at multiple observation points. Figure 2 shows a distribution of CO_2 saturation at the top layer of the model after 50 years injection (Fig. 2a) and an additional 50 years monitoring (Fig. 2b).

The results indicate that the CO_2 plumes remain relatively localized at the injection locations but migrate upwards due to buoyancy. Upward migration is enhanced by the absence of geological barriers to vertical flow within the storage formation (e.g., thin shale layers). After injection, the CO_2 plume continues to spread on the top layer as buoyancy transports CO_2 from the lower layers and the pressure perturbations spread throughout the basin (Fig. 2b).

3.1. Varying injection rates

Model results showing the short-term response of the bunter region to variations in the target annual injection rate per site are presented in figure 3a. Note that CO_2 injection is limited to 50 years after which only the pressure buildup is monitored. Over the 50 year period, modelling indicates that the bunter region can accommodate between 0.6 Gt and 3.7 Gt as the target rate increases from 1 MT/year-site to 10 MT/year-site. Ten MT/year-site corresponds to the maximum target injection rate that can be accommodated by the formation due to the local site pressure constraints set to avoid fracturing the formation.

When lower target rates are employed, lower buildup of pressure is encountered around the injection sites because a limited volume of CO_2 is mobilized through the formation pore space per unit area (Fig. 3b and 3c). Similarly, higher target rates lead to higher buildup in local pressures around injection sites due to the high volume of CO_2 being mobilized through the same pore space (porosity) and pore throat connections (permeability). Hence, the pressure buildup at near-field observation point 1 rises to a maximum between 1.4 MPa and 6.7 MPa corresponding to an increase in target rate from 1 MT/year-site to 10 MT/year-site, respectively (Fig. 3b). Similarly, the pressure buildup at far-field observation point 5 rises to a maximum between 0.9 MPa and 4.3 MPa corresponding to an increase in target rate from 1 MT/year-site to 10 MT/year-site, respectively (Fig. 3c).

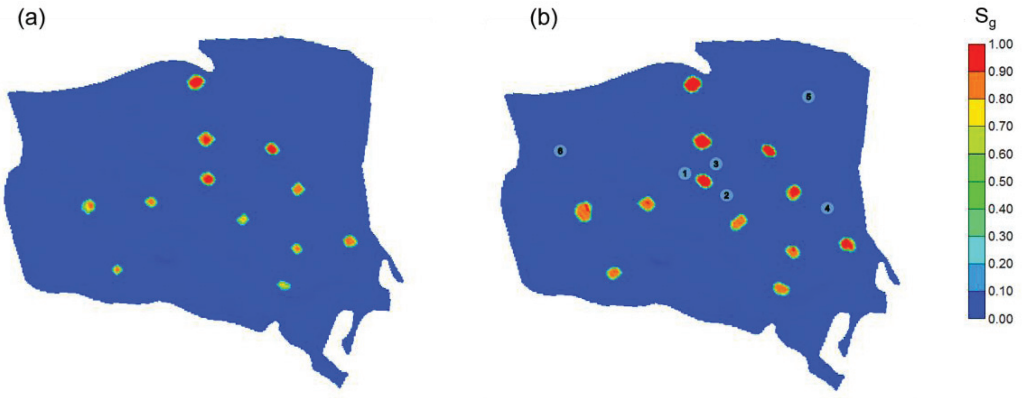

Fig. 2: (a) Distribution of CO_2 saturation at the top layer of the Bunter region after 50 years of injection, and (b) an additional 50 years of monitoring. CO_2 is continuously injected at 12 sites for 50 years at a rate of 2MT/year-site. Light blue circles and numbers indicate the location of pressure observation points in the model.

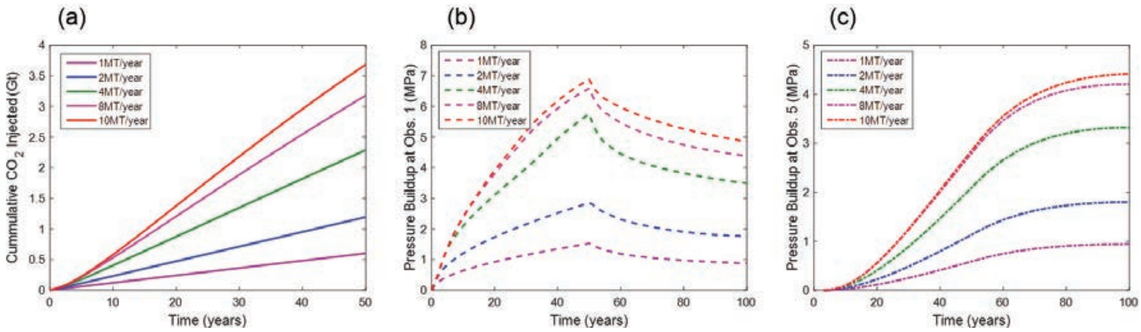

Fig. 3: Profiles of gas saturation and pressure buildup associated with varying injection rates. (a) Total CO_2 injected when target rate for each site varies between 1 MT/year-site and 10 MT/year-site, (b) the corresponding pressure build up at observation point 1, and (c) the corresponding pressure buildup at observation point 5.

3.2. Dynamic storage capacity during long-term CO_2 injection

To determine the ultimate storage capacity for the Bunter region, all subsequent simulations use a maximum target rate of 10 MT/year-site which is only constrained by the BHP limits set to avoid fracturing the formation. Similarly, all flow simulations are extended to 1000 years. Given that the flow characteristics of the Bunter seabed outcrop (see Fig. 1) during long-term CO_2 injection are uncertain we test scenarios with and without brine flow through the seabed outcrop. Brine flow can potentially relieve pressure buildup in the basin.

Figure 4 shows the distribution of CO_2 plumes at 12 sites after gas injection for 50 years, 200 years and 1000 years with brine flow through the seabed outcrop (4a, b, c) and without brine flow through the seabed outcrop (4c, d, e), respectively. The corresponding reservoir pressure distribution with and without brine flow indicates reduced pressure when brine flow is considered (Fig. 5a, b, c and Fig. 5d, e, f). Consequently, the dynamic CO_2 storage capacity rises to 32 Gt when brine flow considered compared to 16 Gt when brine flow is not considered (Fig. 6a, b and c).

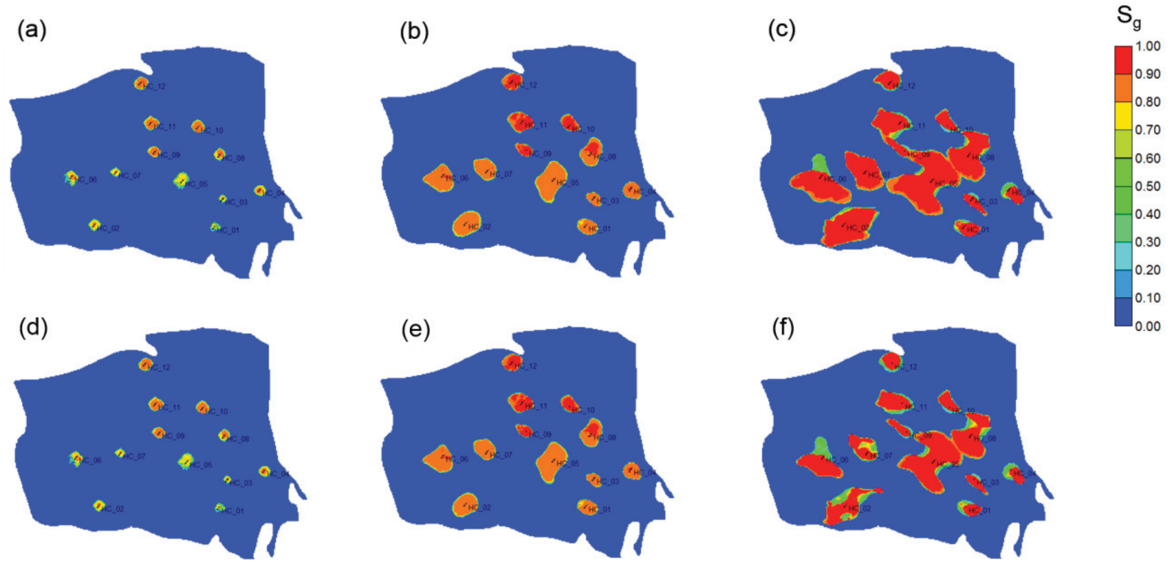

Figure 4: Distribution of gas saturation after 50 year (a, d), 200 year (b, e) and 1000 year (c, f) CO_2 injection into the Bunter region. Brine displacement through the seabed outcrop is implemented in a – c, while, brine flow is not permitted in d – f to simulate a fully pressure constrained dynamic CO_2 storage system.

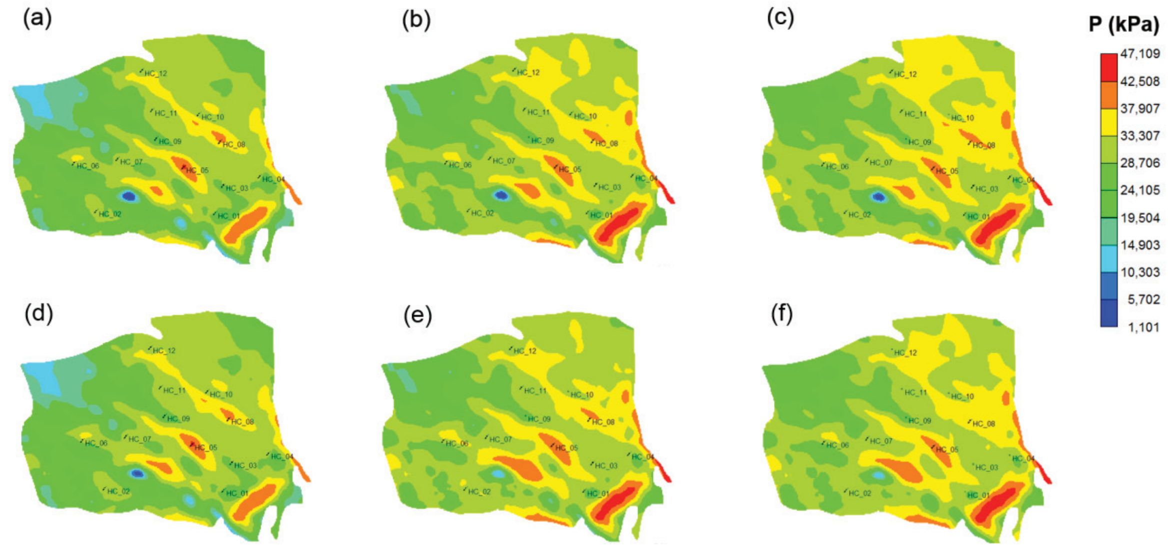

Figure 5: Distribution of reservoir pressure after 50 year (a, d), 200 year (b, e) and 1000 year (c, f) CO_2 injection into the Bunter region. Brine displacement through the seabed outcrop is implemented in a – c, while, brine flow is not permitted in d – f to simulate a fully pressure constrained dynamic CO_2 storage system.

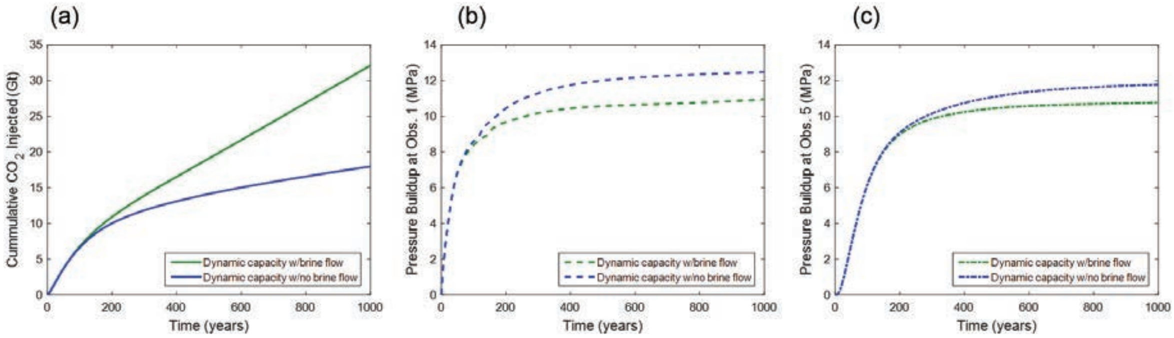

Figure 6: Profiles of gas saturation (a) and Pressure buildup (b, c) after long-term CO_2 injection into the Bunter formation. Higher dynamic CO_2 storage capacity when brine flow through the seabed outcrop is accounted for.

4. Conclusions

We show that by increasing the target rate for CO_2 injection, significantly large amounts of CO_2 can be stored in the Bunter region. Because CO_2 injection leads to local and regional pressurisation within the storage formation, the maximum target injection rate is determined by pressure limits set to avoid fracturing the formation. Pressure buildup monitored at near-field observation points indicate a rapid rise in pressure during injection which declines rapidly at the end of injection. Conversely, the pressure buildup at far-field observation points increases gradually during injection and continues to rise slowly at the end of injection before steadying at a constant value.

The results highlight the importance of carefully managing the pressure buildup in areas close to the injection centers to prevent geomechanical failures in the storage formation. Pressure management can be achieved by specifying a maximum site pressure during injection to ensure that the near-wellbore pressures do not exceed a predefined limit. However, if the pressure buildup specifications limit the efficiency of CO_2 storage, other pressure management strategies may be considered such as active or passive brine production (e.g., Buscheck et al., 2012; Dempsey et al., 2012).

In this paper, we evaluate the sensitivity of regional CO_2 plume transport and storage using a simulation model of the large-scale Bunter Sandstone in the UK Southern North Sea. We find that CO_2 plume behaviour is controlled by buoyancy and the depth of injection sites. Model sensitivities varying the target injection rates indicate that up to 3.7 Gt of CO_2 can be stored in the Bunter region over 50 years given the pressure constraints. Long-term (approx. 1000 years), we estimate that up to 16 Gt of CO_2 can be stored in the Bunter region if there is no brine flow through the seabed outcrop. If the seabed outcrop provides a conduit for brine flow, the estimate rises to 32 Gt.

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