Modelling the effects of climate change and sea level rise on the evolution of incised coastal gullies

Final Summary Report

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1. Introduction

This report provides a summary of the key findings of a three year study assessing the impacts of climate change (in terms of temperature, rainfall, and coastal wave regimes) and sea level rise on the evolution of a series of incised coastal gullies (‘Chines’) found in the soft cliff environment of the SW Isle of Wight, UK. Soft cliffs are poorly resistant to the forces of erosion operating upon them. Their highly active nature provides ideal habitats for many rare and endangered invertebrates. Along the SW Isle of Wight, the Chines which intersect the coastline provide a valuable extension of this important habitat. This coastline is a significant national resource, in that it comprises 16% of the total UK soft cliff coastline. The significance of this area is recognised in its designation as an SSSI, SAC and as a Heritage Coast. Given the importance of this coastline, the Chines, and the perceived threats posed by future (~100 year) anthropogenic climate change, the opportunity to investigate the response of the Chines to the pressures of a changing climate is very timely. The research conducted is the doctoral research of Christopher Hackney and was undertaken within Geography and Environment at the University of Southampton. Prof. Stephen Darby and Dr. Julian Leyland supervised the work. Financial support was provided by the Environment Agency and the Hampshire and Isle of Wight Wildlife Trust.

This report first presents a conceptual model of our understanding of Chine response to environmental change, before summarising the main findings of the research, with a specific focus on making projections of the physical status of the Chines in 2100. This report then concludes with a discussion of some of the main implications of these findings for the sustainable management of the Chines.

2. Synthesis of Key Findings

As discussed above, the Chines provide a valuable extension of the soft cliff environment along the SW Isle of Wight coastline. The value of this additional habitat can be seen as a function of the extent of the Chines. Accordingly, a focus on the extent of these features under scenarios of future climate change will allow an assessment as to potential future changes in habitat provision. To make these projections, it is necessary to understand the forces which operate on the Chines and drive their development. Prior research funded by the Environment Agency, and subsequently published in peer-reviewed academic literature (Leyland and Darby 2008; Leyland and Darby 2009), has shown that these features are driven by the balance between knickpoint erosion and cliff retreat. Therefore an extension in Chine extent will occur when knickpoint erosion outpaces cliff retreat, whilst a reduction in Chine extent will occur if cliff retreat outpaces knickpoint erosion. In order to make qualitative projections of the processes described above, modelling tools capable of representing the response of these drivers to changes in climate are needed.

2.1. Developing suitable modelling tools

The first substantive part of the research involved the development of a simple model of soft cliff erosion. Based on the premise that the accumulated excess energy (AEE) of a combined sea level and significant wave height time series (H_T) is the key hydraulic driver of coastal erosion, the new model was calibrated over the period 2001 – 2011 using high resolution (annual and bi-annual) shoreline data and contiguous H_T data. The AEE model may be expressed as

$$E = \int_{t=0}^{t} [f((\Omega(t) - \Omega_c) + c)]\, dt \qquad (1)$$

where E is erosion (m), Ω is the energy of a given the H_T (J/m^3), Ω_c is the threshold H_T (J/m^3) required to initiate erosion, c is a calibration coefficient and t is time. The average energy of a wave per unit surface area, Ω, is;

$$\Omega = \frac{1}{8}\rho g H_T^2 \tag{2}$$

Where ρ is the density of sea-water (~1020 kg/m^3) and g is the gravitational potential energy of the wave (9.81 m/s^2).

The AEE statistical model (Eq. 1) developed in the research was shown to produce significant ($p < 0.05$) relationships for the south west Isle of Wight coastline (figure 1) explaining 75% of the variation in observed rates of retreat. This suggests that the AEE parameter developed in the research is the dominant control on coastal retreat, and that the AEE model can replicate observed rates of erosion.

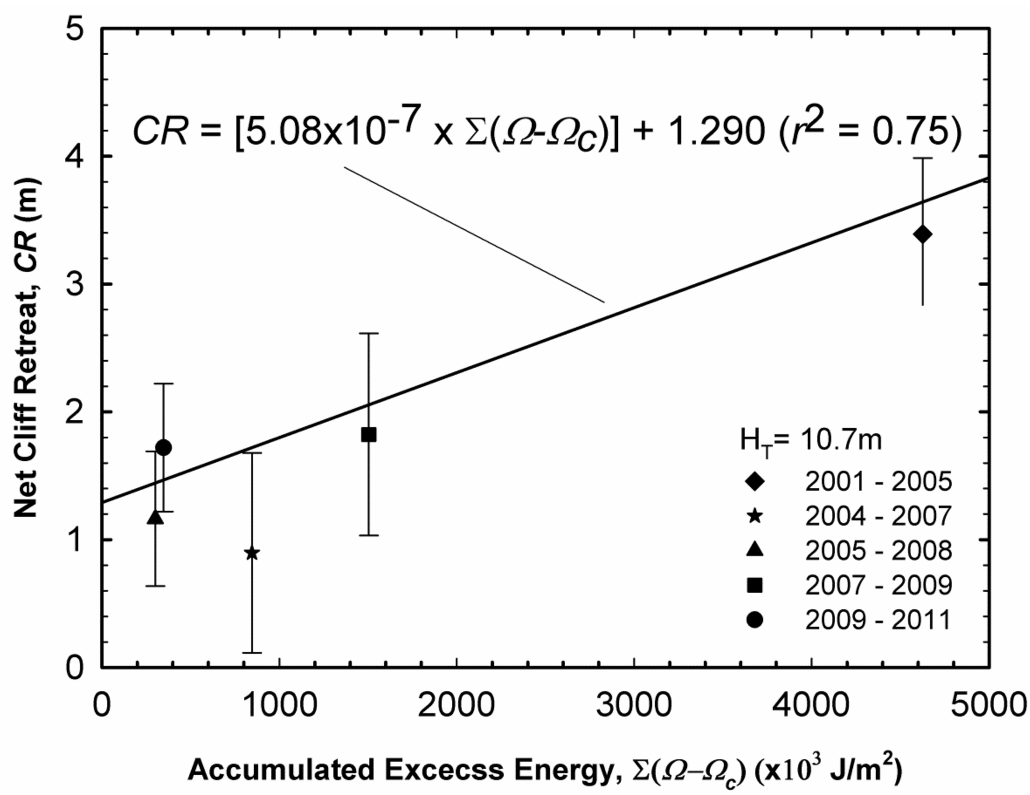

Figure 1: Relationship between accumulated excess energy and amount of coastal erosion. The regression is a Thiel-Sen nonparametric regression which is more robust for samples when $n < 30$ (Theil, 1950; Sen, 1968; Wilcox, 1998).

The AEE model presented in Eq. 1 was then coupled to a Landscape Evolution Model (LEM), CHILD (Tucker 2001a,b). Previously, the suite of LEMs available to the modelling community have failed to incorporate any representation of coastal processes, therefore the coupling of the AEE model to CHILD is an important (novel and significant) contribution of the research to the broader scientific community. The coupled model was termed Marine-Terrestrial CHILD (MT-CHILD). MT-CHILD was validated against the historic development of Shepherds Chine, which is known from historical sources (Fitton, 1836; White, 1921) to have developed wholly since 1810. Metrics describing the geomorphology of the model output at the end of the modelling period (2009) were compared with measurements taken from Shepherds Chine in 2009. These metrics included width/depth ratio at the gully mouth, gully mouth elevation (m), gully area (km^2) and mean bank angle at the gully mouth (°). A normalised amalgamation of these metrics was used to compare model outputs to observed values. The Root Mean Square Error (RMSE) of the best fit model was 1.59, suggesting that when optimally parameterised, MT-CHILD is able to adequately replicate observed process interactions over the timeframes (100 – 200 years) in question. In short, the modelling tools developed in the research are capable of replicating the behaviour of real-world coastal gully systems and may, therefore, be applied with confidence when assessing the impacts of future climate change on coastal gully systems.

2.2. Modelling future climate change

In order to provide scenarios of future climate change that mapped on to the temporal (daily and sub-daily) and spatial ($< 10\ km^2$) scales required for this research, downscaling of Global Climate Model (GCM) outputs was necessary. The Statisitical DownScaling Model (SDSM) of Wilby et al. (2002) was used to provide high temporal and spatial resolution downscaled time series of precipitation, sea level and wave heights. SDSM is a hybrid regression – weather generator downscaling tool which uses large scale atmospheric predictors (e.g. atmospheric turbulence and pressure parameters) to condition local-scale weather generator parameters (Wilby & Dawson 2007). Careful calibration of SDSM for each climate parameter (precipitation, sea level and wave height) was conducted using observed records and NCEP-NCAR re-analysis data (Kalnay et al. 1996) for a baseline period (1961 – 1990 for precipitation and sea level, and 1993 – 2011 for wave height[1]). The NCEP-NCAR variables which best described the variation in observed climate records were selected and used to develop statistical models which were then applied to a series of GCM outputs.

It has long been recognised that the uncertainties associated with producing scenarios of future climate change are considerable (Christensen & Christensen 2007; Fowler et al. 2007). In an attempt to account for the inherent uncertainties in climate modelling, ensembles of climate scenarios were generated using multiple GCM outputs and emissions scenarios. To cover the range of possible emissions scenarios developed in the IPCC SRES report (Nakicenovic et al. 2000), the high-end A2 emissions scenario and lower-end B2 emissions scenario were selected. In an attempt to account for the uncertainties associated with differing GCM representations of the global climate system, two GCMs (the HadCM3 model (Gordon et al. 2000; Pope et al. 2000) and the CGCM2 model (Flato and Boer 2001)) were forced with the A2 and B2 emissions scenarios. By generating 100-member ensembles of scenarios for each GCM-emissions scenario combination, the range of uncertainty associated with producing these scenarios of future climate change was accounted for.

The resulting downscaled future climate change projections suggest that, by 2100 and when compared to the baseline scenarios, the south west Isle of Wight may be expected to experience:

- An increase in *mean* precipitation that, depending on the GCM and emissions scenario, varies between 0.058 mm/yr, an increase of 3% (HadCM3 GCM, A2 emissions scenario) and 0.008 mm/yr, an increase of <1% (CGCM2 GCM forced with the B2 emissions scenario). Increases in *extreme* (precipitation events greater than the 95th percentile value in the observed record, equivalent to 11.7 mm) precipitation rates were projected in all four ensembles.
- Increases in *mean* sea level of between 0.21 m (7%) (CGCM2 GCM forced with the B2 emissions scenario) and 0.73 m (26%) (HadCM3 GCM, A2

[1] The difference in baseline period for the wave height parameter reflects the availability of long term records of wave height. For the south west Isle of Wight, wave data was only available for the period 1993 – 2011.

emissions scenario) are projected. Furthermore, *extreme* sea levels (defined as sea-level values greater than 3.09 m) are projected to become more common, with the number of days exceeded in a year rising by 1 day per year.

- Decreases in *mean* wave heights of between 0.001 m to 0.002 m (<1% decrease in both cases), depending upon the GCM and emissions scenario. However, all four ensembles project that the occurrence of *extreme* wave heights (defined as wave heights greater than 4.3m) is likely to increase by 2100, with the number of days per year *extreme* wave height values were exceeded increasing by 0.5 to 1.

In order to account for the uncertainties within climate downscaling, the climate projections derived from the SDSM downscaling were refined to ease their use within MT-CHILD. In order to account for the uncertainties inherent in the climate modelling, Monte Carlo analysis was conducted on each ensemble to constrain the uncertainty of the ensemble to within 5% of the ensemble mean. This process resulted in approximately 18000 scenarios of future climate change for use in the geomorphological model. A further ~4000 scenarios were developed from the NCEP/NCAR reanalysis data to represent a baseline scenario, resulting in a total of ~22000 model runs. Such an approach means that the model results were constrained within the uncertainty associated with the development of the climate scenarios. The significance of employing a Monte Carlo approach in this work is that it enables the probabilities of different future projections of Chine response to be determined. Details of these projections are now discussed.

2.3. The response of incised coastal gullies to climate change

The use of the probabilistic approach adopted in this research requires a large number of model runs (~22000), it allows for *likely* ranges of changes (changes with a probability of occurrence greater than 66%; Mastrandrea et al. 2010) to be identified; facilitating easier communication of the implications of the model predictions. In the following section we first discuss the impacts of future climate change on (i) future rates of coastal erosion, and (ii) future changes in the extent of the Chines (i.e. changes of overall Chine habitat), so that it can be understood how the constituent processes contribute to net changes in Chine resource (the differences in (i) and (ii) representing future changes in the rate of headwards erosion of the Chines, in accordance with the conceptual model defined at the beginning of section 2).

Results show complex responses to climate forcing, with CGCM2 inputs, forced with the A2 emissions scenario, displaying a modal value which depicts an extension of the gully system of 13.73 m. Conversely, HadCM3 runs (forced with A2 emissions scenarios) display modal values depicting a loss of gully extent of 54.36 m (figure 3). Although modal values provide an idea of the most probable values of change, it is arguably of great benefit to understand the possible changes in *extreme* change in gully extent, changes which will have tangible effects on habitat provision and ecosystem stability. Results show that the likelihood of *extreme* rates of coastal erosion (defined as rates of erosion exceeding 1.38 ma^{-1})[2] is predicted to change by between -2% and +22% by the year 2100, relative to baseline scenarios, dependent upon emissions scenario and GCM (figure 2). By combining projections of coastal erosion with those of headward retreat, changes in overall gully extent could also be predicted (figure 3). However, all scenarios depict a future where the likelihood of extreme loss of gully extent (defined as losses greater than 15 m)[3], and thus habitat provision, is greater. HadCM3 runs predict that extreme losses will become 61% and 42% more likely, relative to baseline scenarios, whilst CGCM2 outputs predict extreme losses will become 12% and 18% more likely, under the A2 and B2 emissions scenarios, respectively.

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[2] The value of 1.38 ma^{-1} represents the 95th percentile value of change in gully extent as projected by the baseline climate scenarios. As such it represents a value of extreme loss of gully extent under current climatic conditions.

[3] All extreme values are defined as the 95th percentile value of the baseline scenario outputs.

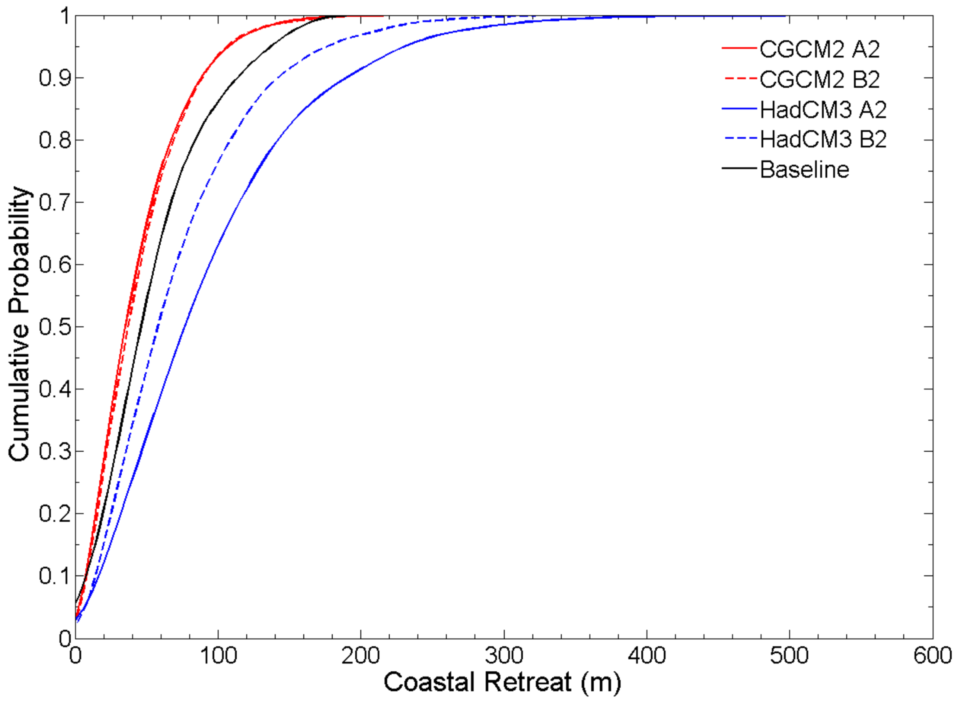

Figure 2: Cumulative probability density functions of MT-CHILD model outputs of coastal erosion (m). Different GCM and baseline scenarios are shown in different colours; HadCM3= blue, CGCM2 = red, Baseline = black. A2 emissions scenario is depicted by solid line and the B2 emissions scenario is depicted by dashed lines.

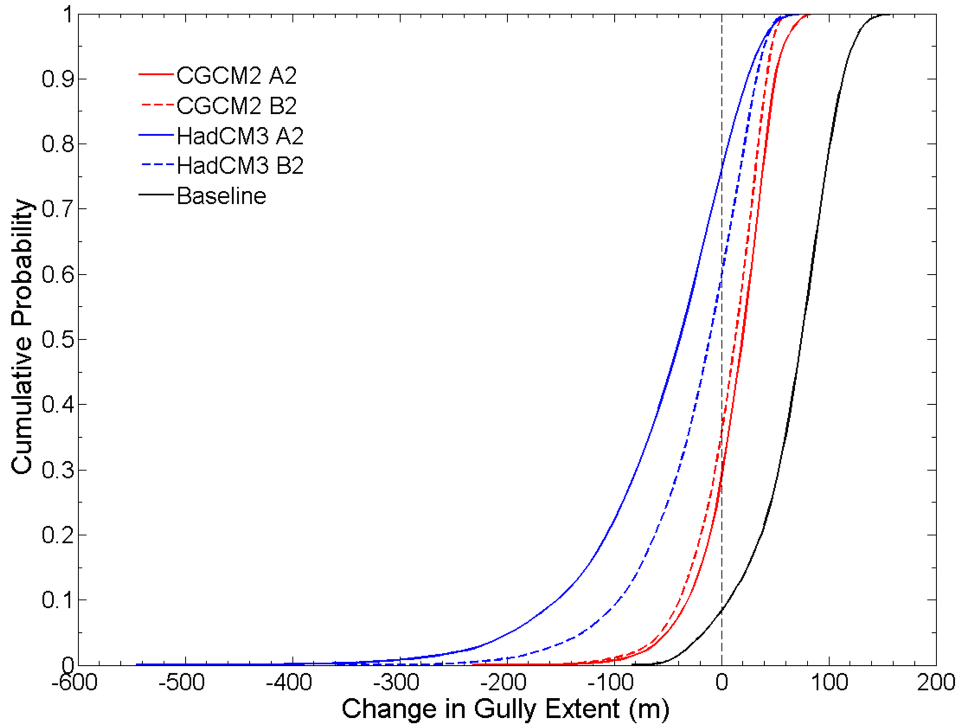

Figure 3: Cumulative Probability Density Functions of MT-CHILD model outputs for change in gully extent (m). The different GCMs and baseline scenario are shown in different colours; HadCM3 = blue, CGCM2 = red, Baseline = black. A2 emissions scenarios are depicted by solid lines and the B2 emission scenarios are depicted by dashed lines. The dashed black line at x = 0 represents no change in gully extent, where coastal retreat and headwards erosion are equal over the 100 year period.

3. Implications for the management of the Chine landscape

The results presented above refer specifically to Grange Chine, as this catchment was the focus of the modelling work (due to it being the largest Chine catchment (~12 km^2), making it the most resilient to changes in climate). Projections suggest that there is a 1% chance that rates of coastal erosion will exceed 3.20 ma^1. In this case, it is likely that the whole of Grange Chine coast-ward of the A3055 would be eroded, with complete loss of the habitats it supports (figure 4). In the case of Grange Chine, the likelihood of this occurring is low (1%), however in other gully systems along the south west Isle of Wight coast, such occurrences may be more likely to happen as they may be less able to maintain rates of headwards erosion due to their smaller drainage areas (table 1).

This research has shown that by the end of the 21st Century, rates of coastal erosion along the south west Isle of Wight are *likely* (probability >66%) to remain comparable to current observed rates (0.43 ma^{-1} under HadCM3 A2 runs). However, the model projections also indicate that the likelihood of extreme rates of coastal erosion (defined as rates >1.38 ma^{-1}) is projected to increase from 5% to 21% (under HadCM3 runs forced with the A2 emissions scenario). If such extreme values of coastal erosion were experienced in the future, not only would the availability of habitat provision be under threat (table 1), infrastructure such as the A3055 (Military Road) would also be effected (figure 4). Coastal retreat in excess of 138 m would require re-location of the Military Road in many locations (particularly in the northern areas; figure 5a and b). In other locations along the coastline, coastal erosion may approach but not threaten the current position of the Military Road. As such figure 5 may provide a useful tool in ensure the key transport links along the south west coast are maintained given the increased threat of extreme rates of coastal erosion under climate change.

Results also suggest that gully extent, a metric describing the provision of available habitat, may undergo large changes in the future. For example, the research undertaken here has identified a 10% chance that gully extent may be reduced by 195 m by the year 2100 (under HadCM3 runs forced with A2 emissions scenarios). Such a loss would considerably reduce the amount of valuable habitat that is available along

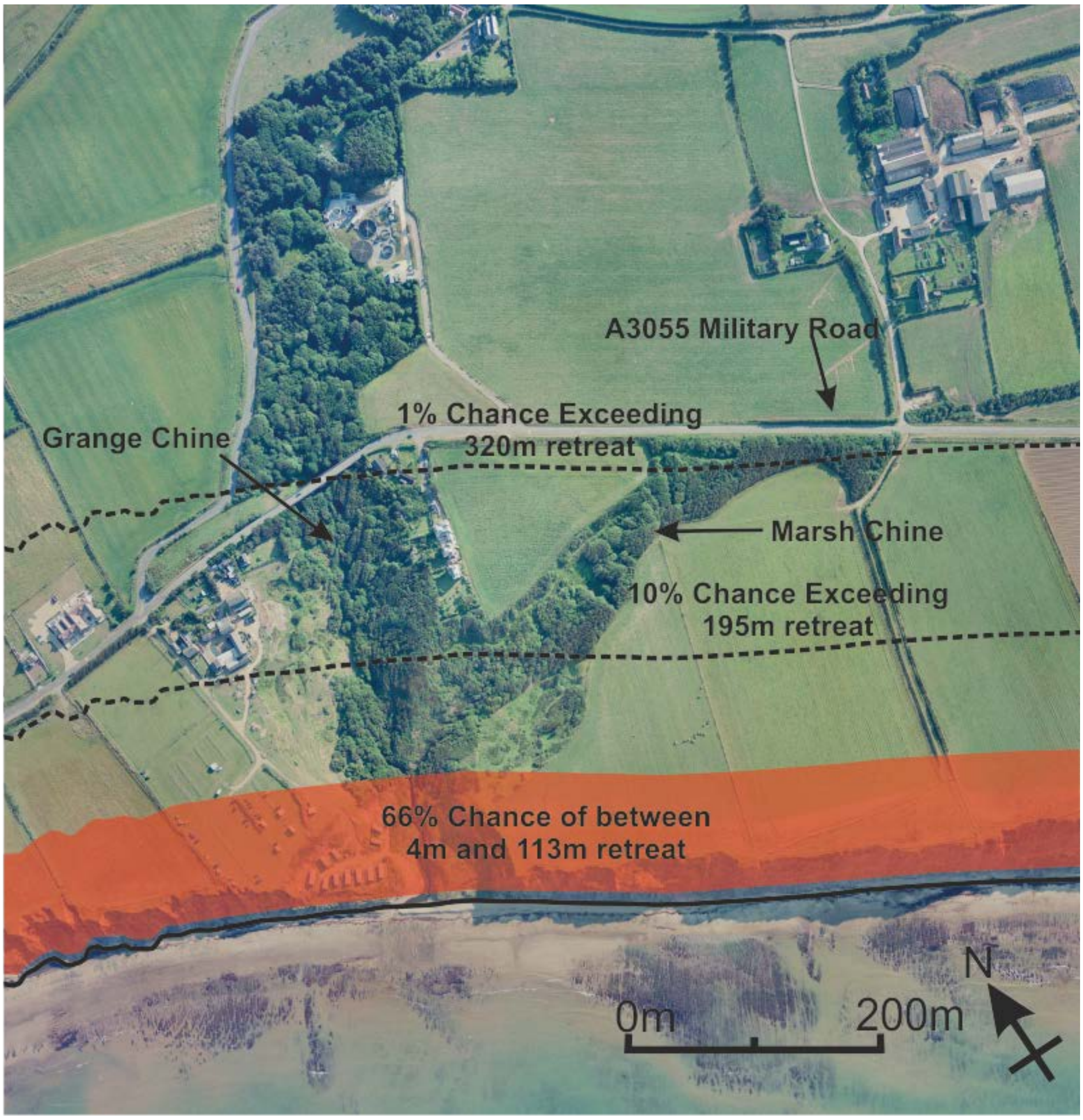

Figure 4: Projections and likelihood of amounts of coastal retreat as projected by HadCM3 A2 inputs, the more extreme input scenario. The red shaded area represents the likely range of coastal erosion, containing 66% of projections. The solid black line represents current (2011) cliff toe position. The dashed black lines represent cliff positions at 2100 at different likelihood bands. Aerial photo courtesy of the Channel Coastal Observatory.

this coastline. In order to ensure that this habitat is maintained, it is important that headwards erosion is permitted to continue unobstructed. Accordingly stream discharges, in particular during high flow events, need to be maintained to ensure geomorphologically effective flows are sustained. This may be achieved through careful monitoring of stream flows and the careful management of abstraction licenses. Likewise, any remedial work carried out on, or any full scale redirection of the Military Road must ensure that any culverts and diversions installed permit the continued inland erosion of knickpoints. It may be that detailed analysis of the effects

	Modal	*Likely Range*		*Extreme*
		Lower Bound	*Upper Bound*	
Compton	✓	✓	✗	✗
Shippards	✓	✓	✗	✗
Churchill	✓	✓	✗	✗
Brook	✓	✓	✓	✓
Chilton	✓	✓	✓	✓
Grange/Marsh	✓	✓	✓	✓
Barnes	✗	✗	✗	✗
Cowleaze	✓	✓	✓	✗
Shepherds	✓	✓	✓	✓
Whale	✓	✓	✓	✗
Ladder	✗	✓	✗	✗
Walpen	✗	✓	✗	✗

Table 1: Projections of whether a currently observed Chine feature will be present under the differing projections of shoreline positions shown in figure 5. Modal = 43.28 m, Likely Range Lower Bound = 4.19 m, Likely Range Upper Bound = 113.92 m, Extreme = 195 m. Values relate to HadCM3 GCM outputs forced with the A2 emissions scenario.

of such installations is needed to ensure they do not inhibit the inland retreat of the Chines.

This research has also highlighted that the timings of future changes in gully trajectories is uncertain. It may be that major changes in gully extent do not occur until after 2050, if this is the case then there may be time to plan effective and efficient strategies to best manage this landscape. However, it may be that changes are experienced relatively quickly in which case the timescales available to implement strategies may be limited. It has been identified that changes in gully extent are demonstrably linked to changes in extreme wave height. If larger extreme wave heights are experienced, greater losses in gully extent occur. Therefore, to aid the management of the Chine landscape, and in order to develop informed policy and management strategies, it may be necessary to closely monitor changes in extreme wave height in the English Channel so as to better understand the likely response of these systems to observed changes.

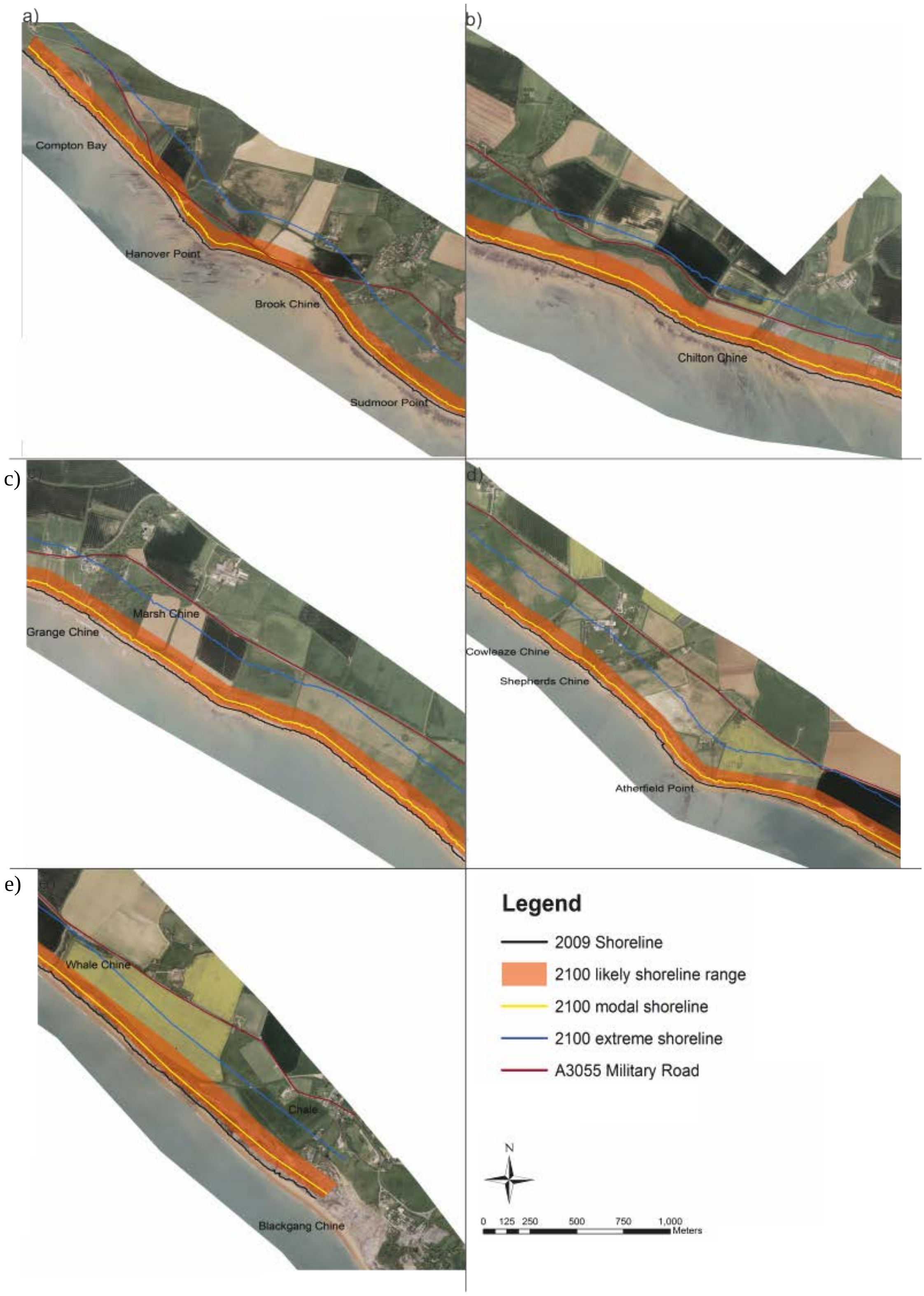

Figure 5: Map showing shoreline positions as projected by HadCM3 A2 outputs. The 2011 shoreline position is shown in black. The range covered by the *likely* projections of 2100 shorelines (4.19 m to 113.92 m) is shown by the orange band. The 2100 modal shoreline position (43.28 m) is shown in yellow, and the 2100 extreme shoreline position (195 m) is shown in blue. The A3055 Military Road is also shown in grey. Key gully features are labelled. KMZ files of these shoreline positions are available to download from http://chrishackney.wordpress.com/downloads

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