

Supplementary Material: Blind Universal Bayesian Image Denoising with Gaussian Noise Level Learning

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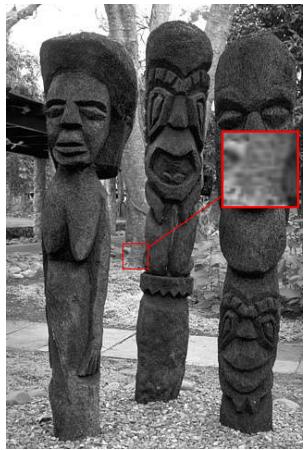
1 Additional Results

We present supplementary image denoising results, for test noise levels 25 and 75, of our Blind Universal Image Fusion Denoiser (BUIFD), and the corresponding results of BM3D [1] (both blind and non-blind), and DnCNN [5] on the first 15 images of BSD68 and CBSD68 [3, 4] where the sets are ordered alphabetically based on image names. Color denoising results are obtained with the color versions CBUIFD, CBM3D [2] and CDnCNN [5]. For the neural networks DnCNN and BUIFD, we show results for the models trained up to noise level 55, and up to noise level 75, called respectively DnCNN₅₅, BUIFD₅₅ and DnCNN₇₅, BUIFD₇₅. We highlight in red the best denoising PSNR for each of the two training noise level ranges.

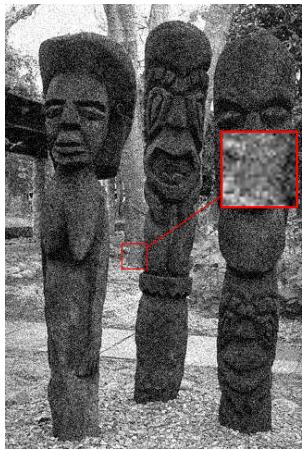
In general, BM3D tends to smooth the results too much but obtains good PSNR relative to DnCNN, which on the contrary tries to favor high frequency content. Our BUIFD outperforms BM3D (even non-blind BM3D) in terms of PSNR while also preserving high frequency content. Note that our model trained only up to noise level 55 sometimes outperforms even the DnCNN trained up to noise level 75, *on denoising test noise level 75*, for instance with the images in Fig. 3 (+0.85dB), Fig. 9 (+0.74dB) and Fig. 11 (+0.68dB). This shows again the generalization strength of our fusion denoising approach on real images.

References

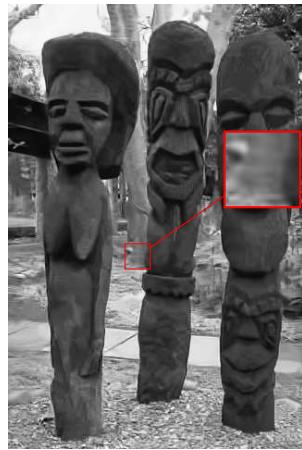
- [1] K. Dabov, A. Foi, V. Katkovnik, and K. Egiazarian. Image denoising by sparse 3-D transform-domain collaborative filtering. *IEEE TIP*, 16(8):2080–2095, 2007.
- [2] K. Dabov, A. Foi, V. Katkovnik, and K. O. Egiazarian. Color image denoising via sparse 3D collaborative filtering with grouping constraint in luminance-chrominance space. In *ICIP*, pages 313–316, 2007.
- [3] D. Martin, C. Fowlkes, D. Tal, and J. Malik. A database of human segmented natural images and its application to evaluating segmentation algorithms and measuring ecological statistics. In *ICCV*, pages 416–423, 2001.
- [4] S. Roth and M. J. Black. Fields of experts. *International Journal of Computer Vision*, 82(2):205, 2009.
- [5] K. Zhang, W. Zuo, Y. Chen, D. Meng, and L. Zhang. Beyond a Gaussian denoiser: Residual learning of deep CNN for image denoising. *IEEE TIP*, 26(7):3142–3155, 2017.



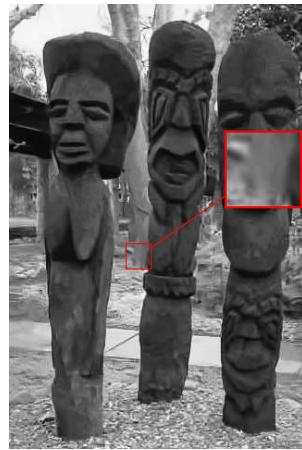
(a) Original



(b) Noisy (level 25)



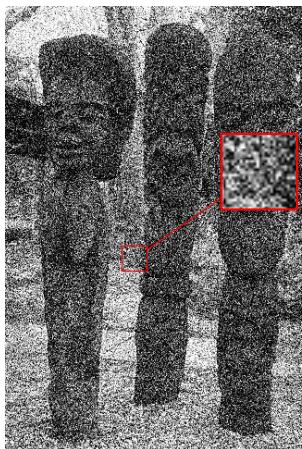
(c) BM3D (blind) 25.17dB



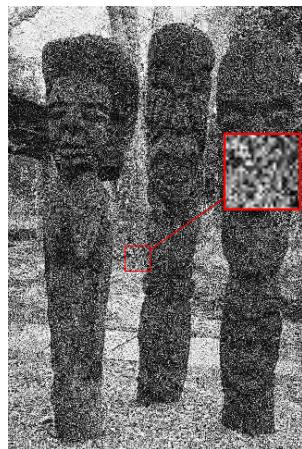
(d) BM3D (non-blind) 25.16dB

(e) DnCNN₅₅ 25.43dB(f) BUIFD₅₅ 25.68dB(g) DnCNN₇₅ 25.55dB(h) BUIFD₇₅ 25.69dB

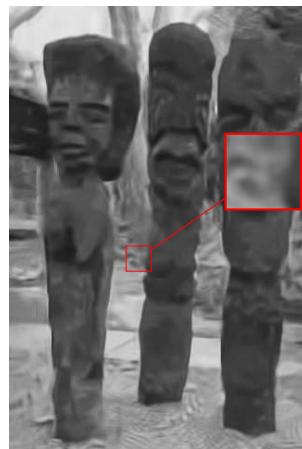
(i) Original



(j) Noisy (level 75)



(k) BM3D (blind) 13.62dB



(l) BM3D (non-blind) 20.31dB

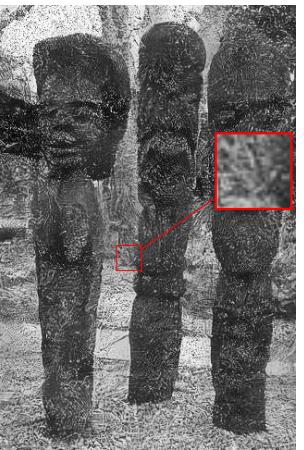
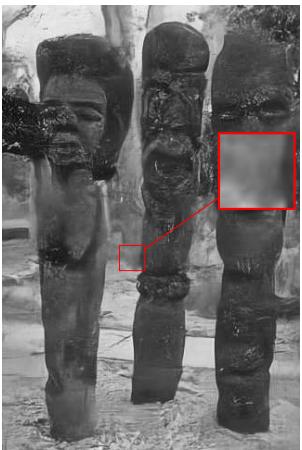
(m) DnCNN₅₅ 17.49dB(n) BUIFD₅₅ 19.56dB(o) DnCNN₇₅ 19.84dB(p) BUIFD₇₅ 20.47dB

Figure 1: Grayscale image ID 0 from the (ordered) BSD68, tested with all methods on noise levels 25 and 75.



(a) Original



(b) Noisy (level 25)



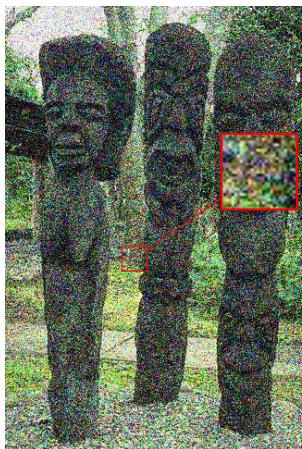
(c) CBM3D (blind) 24.11dB



(d) CBM3D (non-blind) 27.49dB

(e) CDnCNN₅₅ 27.89dB(f) CBUIFD₅₅ 27.96dB(g) CDnCNN₇₅ 27.91dB(h) CBUIFD₇₅ 27.99dB

(i) Original



(j) Noisy (level 75)



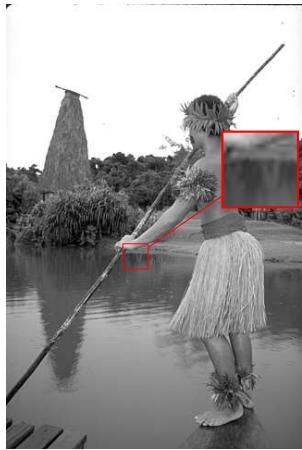
(k) CBM3D (blind) 20.94dB



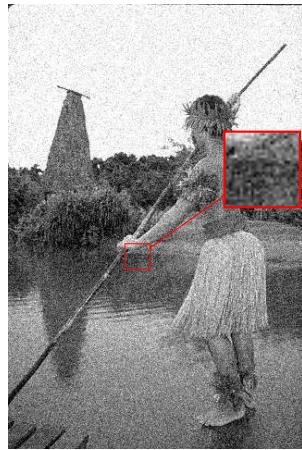
(l) CBM3D (non-blind) 20.90dB

(m) CDnCNN₅₅ 21.62dB(n) CBUIFD₅₅ 21.69dB(o) CDnCNN₇₅ 21.62dB(p) CBUIFD₇₅ 21.65dB

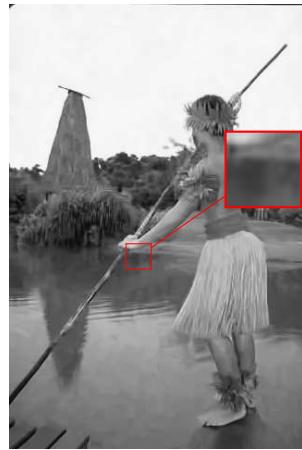
Figure 2: Color image ID 0 from the (ordered) CBSD68, tested with all methods on noise levels 25 and 75.



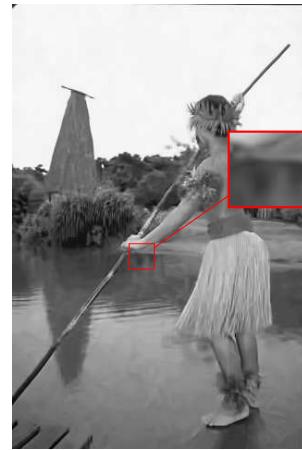
(a) Original



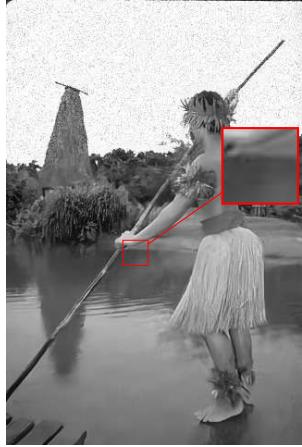
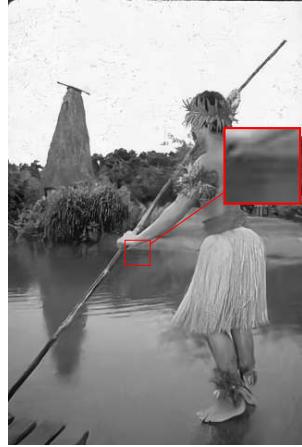
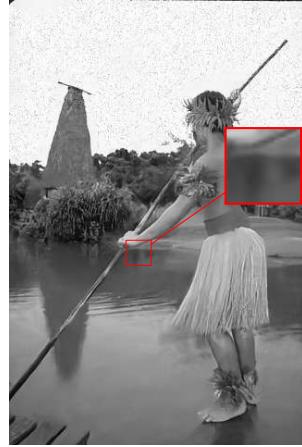
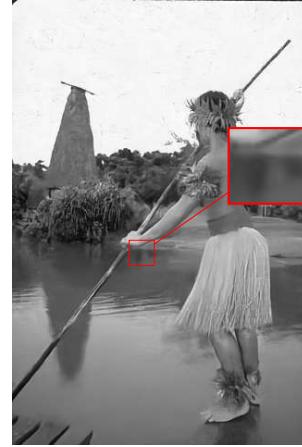
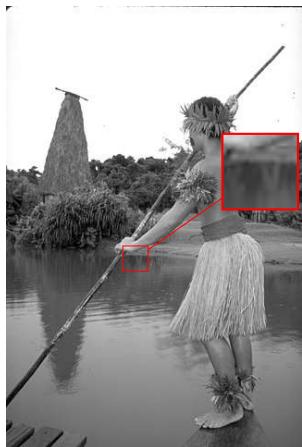
(b) Noisy (level 25)



(c) BM3D (blind) 28.19dB



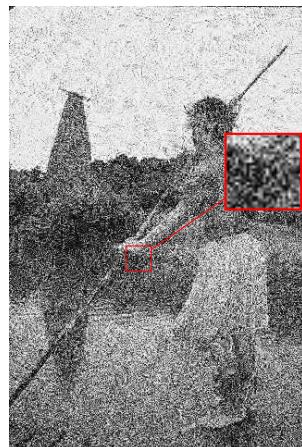
(d) BM3D (non-blind) 28.24dB

(e) DnCNN₅₅ 26.57dB(f) BUIFD₅₅ 28.41dB(g) DnCNN₇₅ 27.18dB(h) BUIFD₇₅ 28.58dB

(i) Original



(j) Noisy (level 75)



(k) BM3D (blind) 13.77dB



(l) BM3D (non-blind) 21.60dB

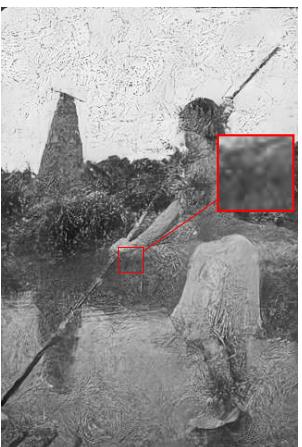
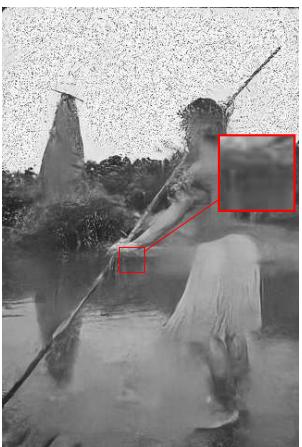
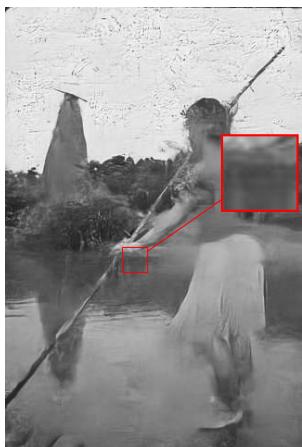
(m) DnCNN₅₅ 16.63dB(n) BUIFD₅₅ 19.97dB(o) DnCNN₇₅ 19.12dB(p) BUIFD₇₅ 21.30dB

Figure 3: Grayscale image ID 1 from the (ordered) BSD68, tested with all methods on noise levels 25 and 75.



(a) Original



(b) Noisy (level 25)



(c) CBM3D (blind) 27.36dB



(d) CBM3D (non-blind) 29.39dB



(e) CDnCNN₅₅ 29.95dB



(f) CBUIFD₅₅ 29.89dB



(g) CDnCNN₇₅ 29.87dB



(h) CBUIFD₇₅ 29.96dB



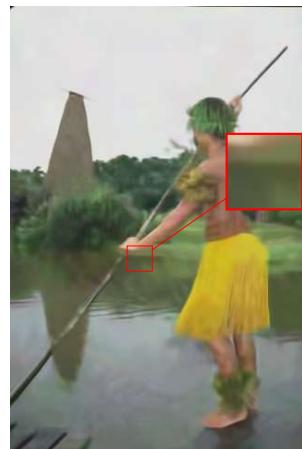
(i) Original



(j) Noisy (level 75)



(k) CBM3D (blind) 20.78dB



(l) CBM3D (non-blind) 21.42dB



(m) CDnCNN₅₅ 21.83dB



(n) CBUIFD₅₅ 21.91dB

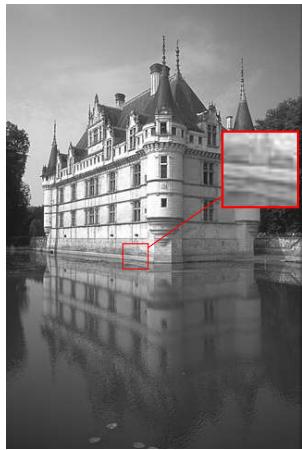


(o) CDnCNN₇₅ 21.84dB

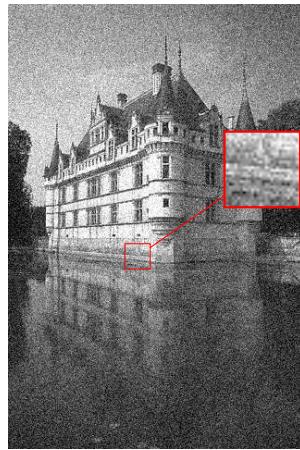


(p) CBUIFD₇₅ 21.87dB

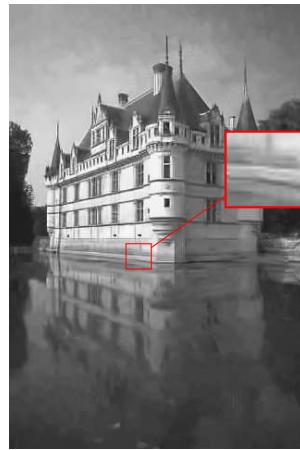
Figure 4: Color image ID 1 from the (ordered) CBSD68, tested with all methods on noise levels 25 and 75.



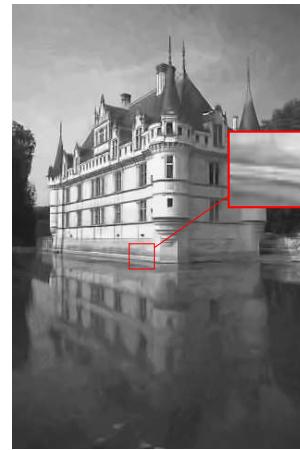
(a) Original



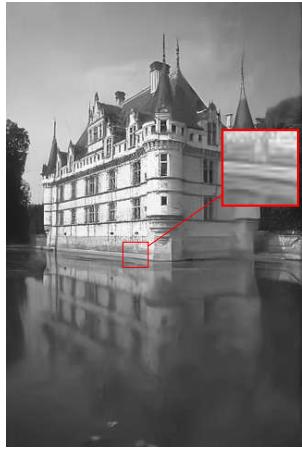
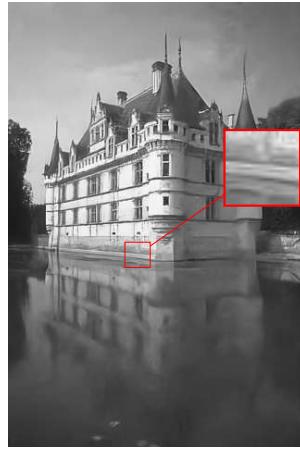
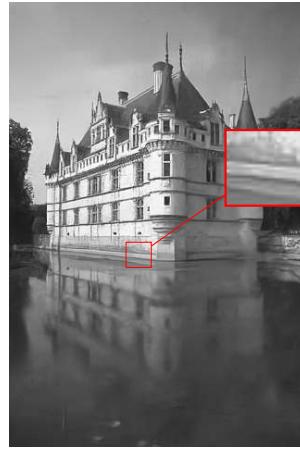
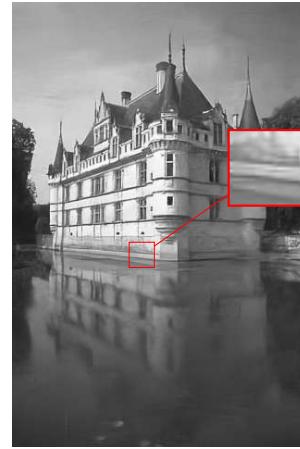
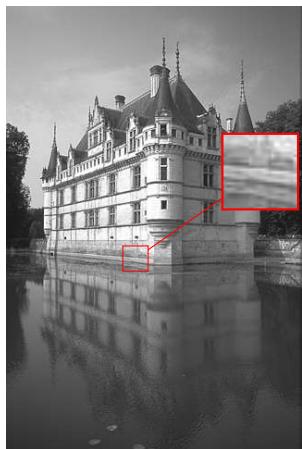
(b) Noisy (level 25)



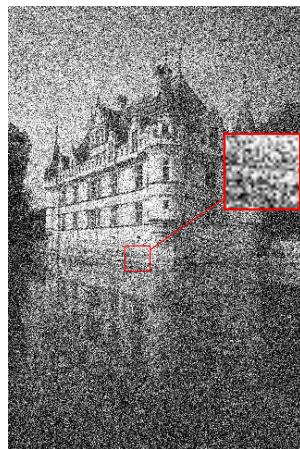
(c) BM3D (blind) 29.42dB



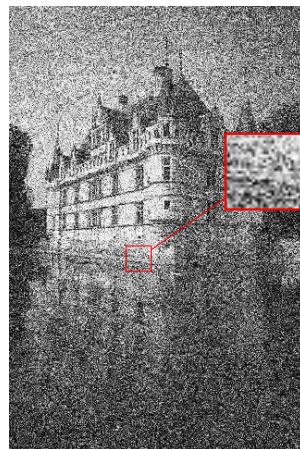
(d) BM3D (non-blind) 29.37dB

(e) DnCNN₅₅ 29.77dB(f) BUIFD₅₅ 29.87dB(g) DnCNN₇₅ 29.91dB(h) BUIFD₇₅ 29.90dB

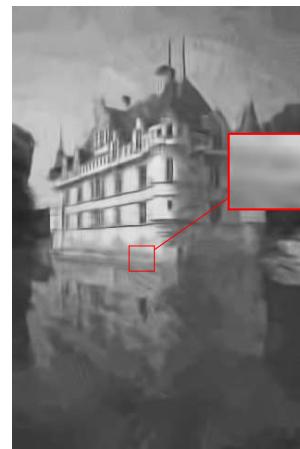
(i) Original



(j) Noisy (level 75)



(k) BM3D (blind) 13.31dB



(l) BM3D (non-blind) 23.37dB

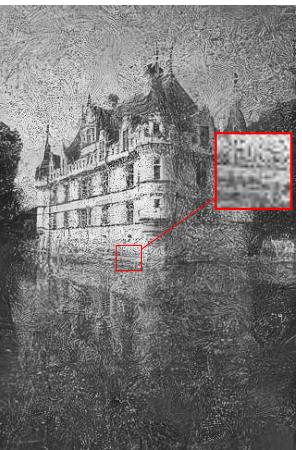
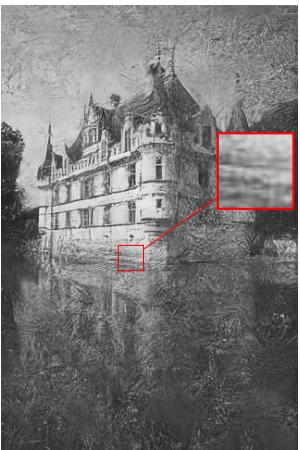
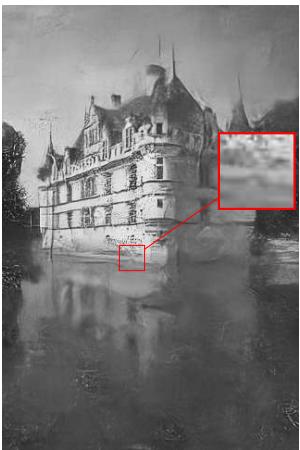
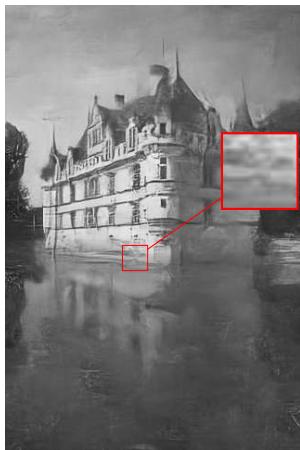
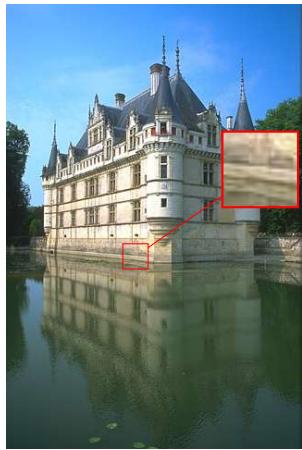
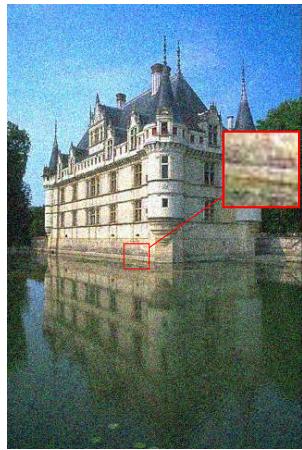
(m) DnCNN₅₅ 18.66dB(n) BUIFD₅₅ 21.70dB(o) DnCNN₇₅ 23.18dB(p) BUIFD₇₅ 23.67dB

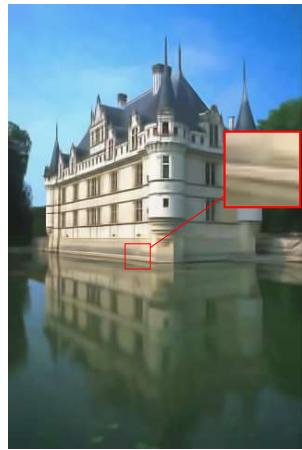
Figure 5: Grayscale image ID 2 from the (ordered) BSD68, tested with all methods on noise levels 25 and 75.



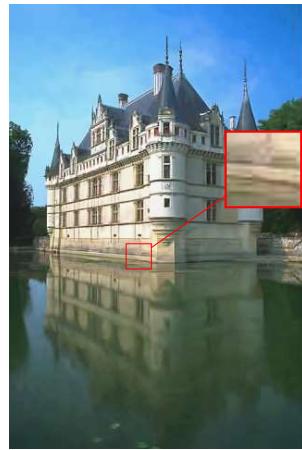
(a) Original



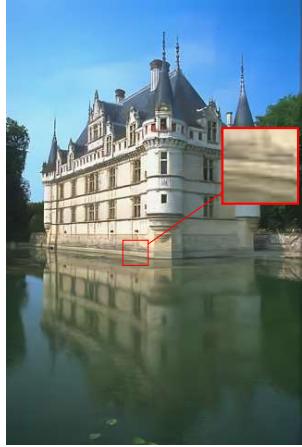
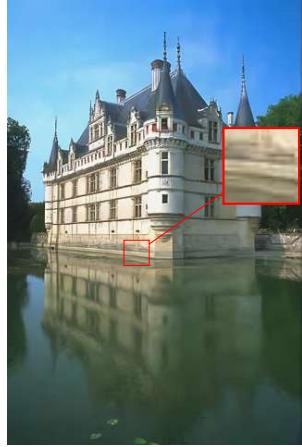
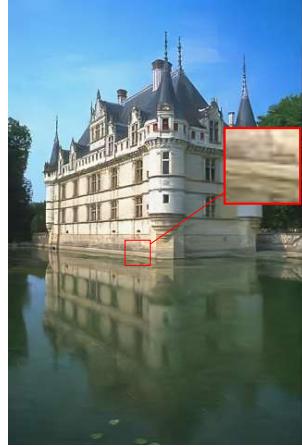
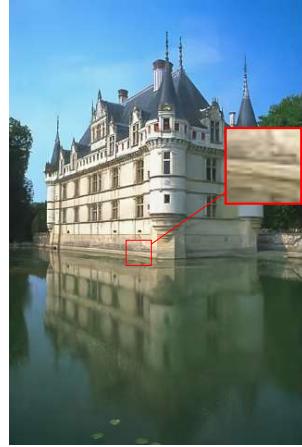
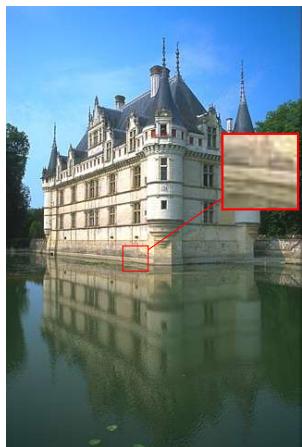
(b) Noisy (level 25)



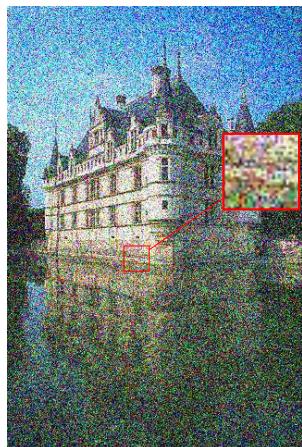
(c) CBM3D (blind) 28.40dB



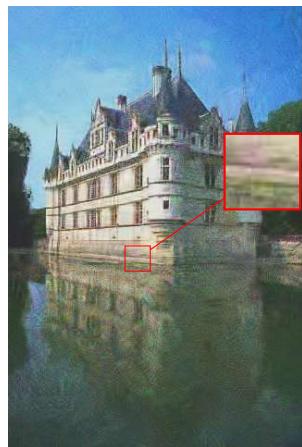
(d) CBM3D (non-blind) 30.97dB

(e) CDnCNN₅₅ 31.39dB(f) CBUIFD₅₅ 31.46dB(g) CDnCNN₇₅ 31.23dB(h) CBUIFD₇₅ 31.44dB

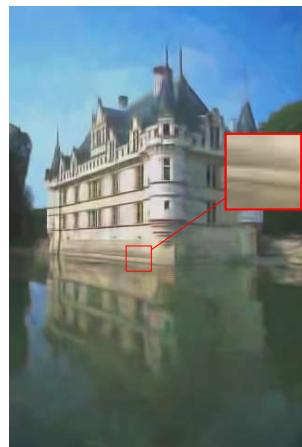
(i) Original



(j) Noisy (level 75)



(k) CBM3D (blind) 22.54dB



(l) CBM3D (non-blind) 23.23dB

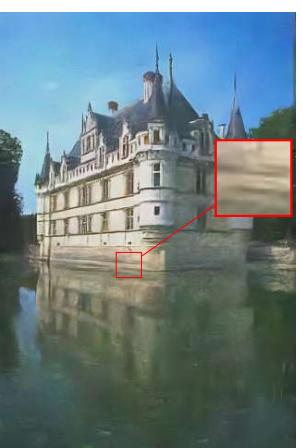
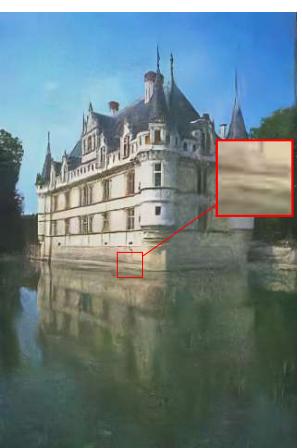
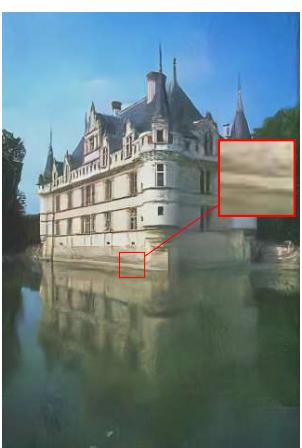
(m) CDnCNN₅₅ 23.81dB(n) CBUIFD₅₅ 23.82dB(o) CDnCNN₇₅ 23.78dB(p) CBUIFD₇₅ 23.88dB

Figure 6: Color image ID 2 from the (ordered) CBSD68, tested with all methods on noise levels 25 and 75.

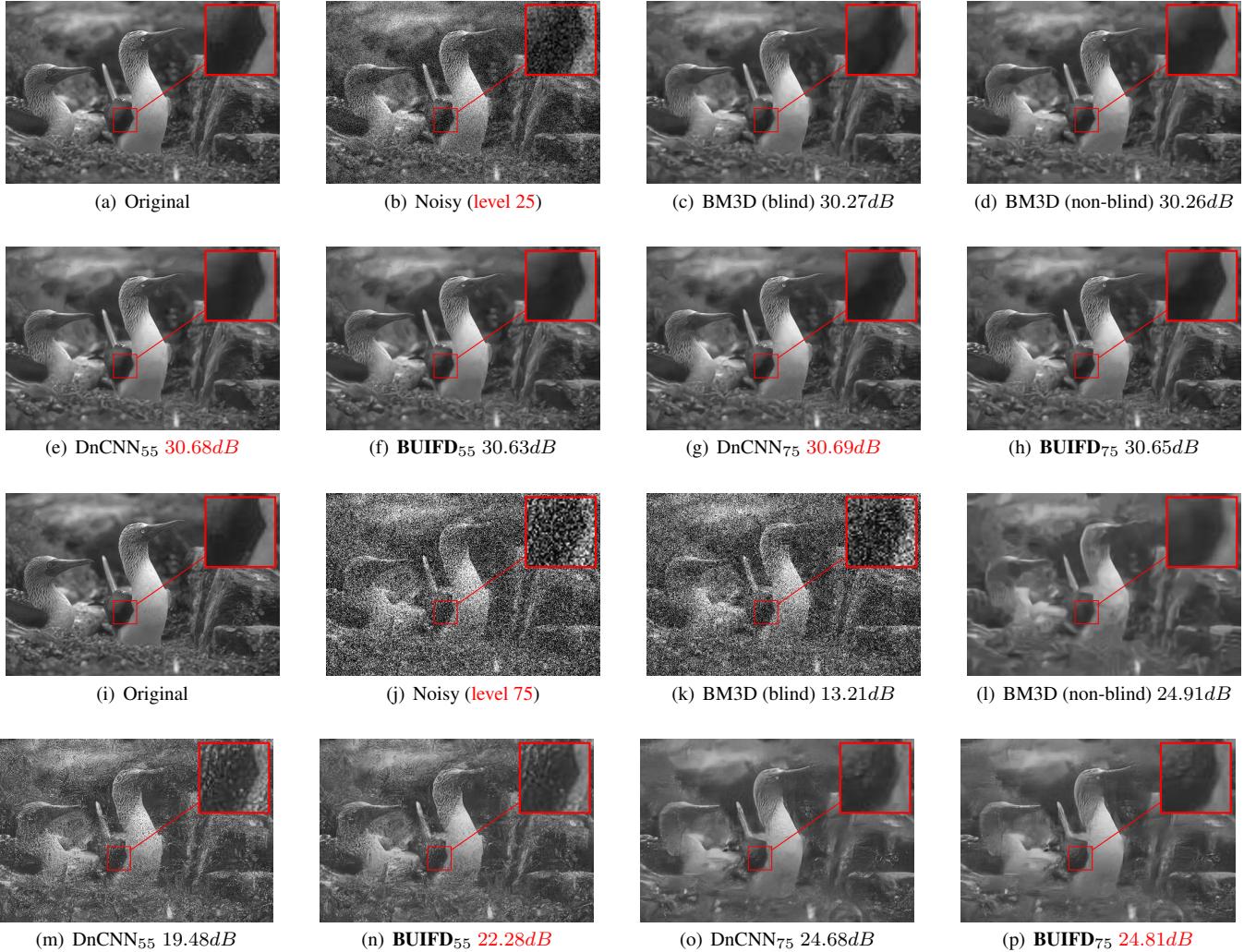


Figure 7: Grayscale image ID 3 from the (ordered) BSD68, tested with all methods on noise levels 25 and 75.



Figure 8: Color image ID 3 from the (ordered) CBSD68, tested with all methods on noise levels 25 and 75.

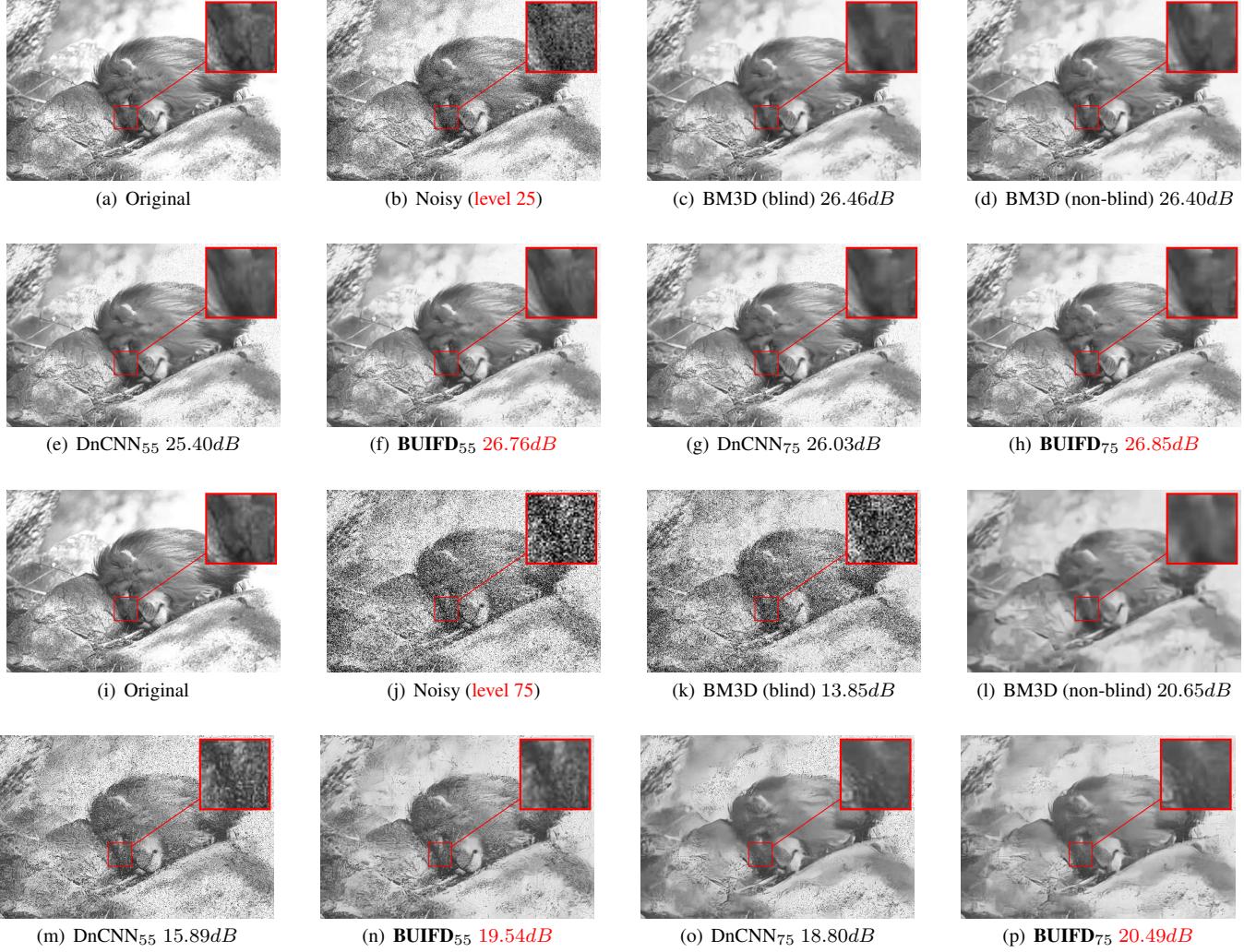


Figure 9: Grayscale image ID 4 from the (ordered) BSD68, tested with all methods on noise levels 25 and 75.



Figure 10: Color image ID 4 from the (ordered) CBSD68, tested with all methods on noise levels 25 and 75.

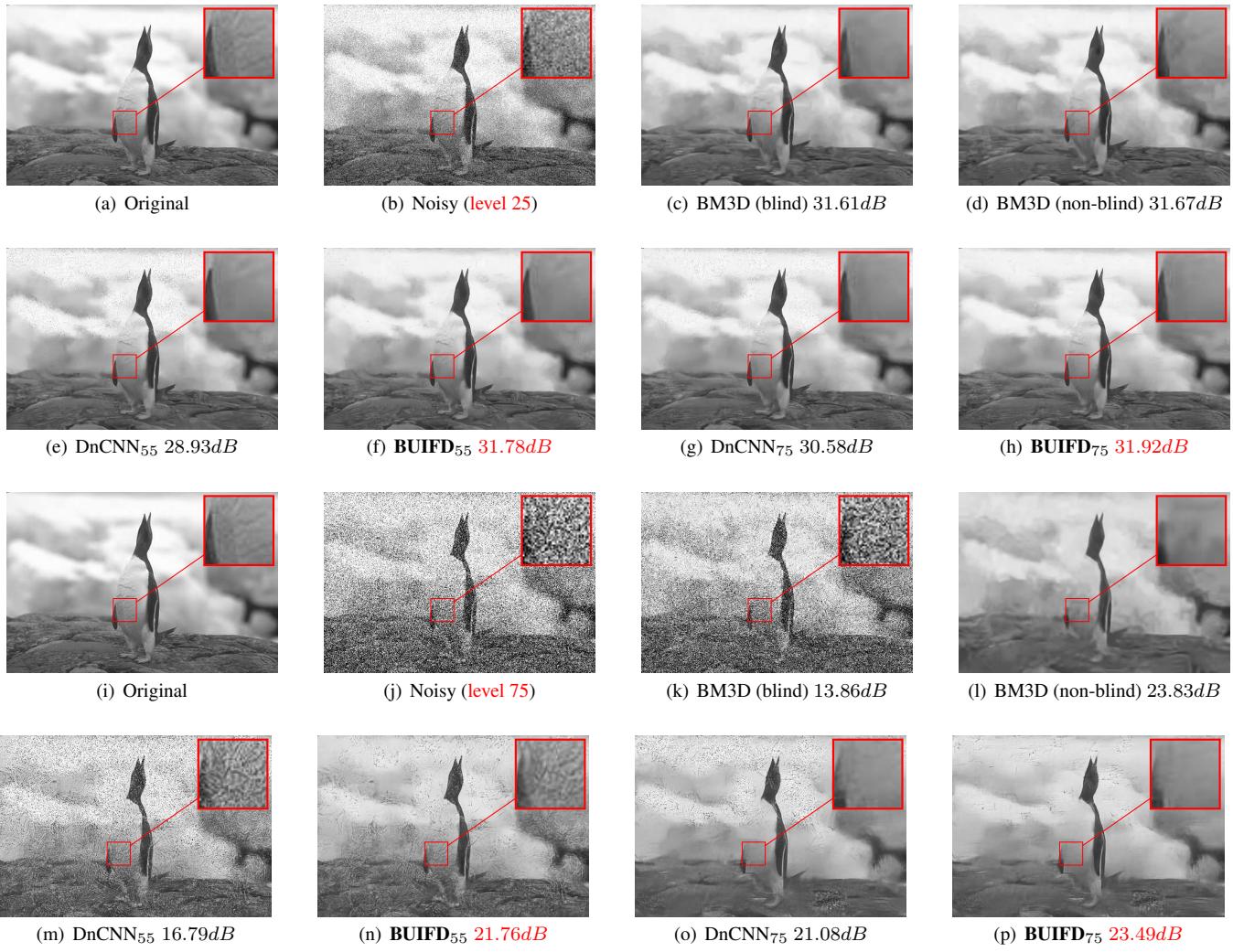


Figure 11: Grayscale image ID 5 from the (ordered) BSD68, tested with all methods on noise levels 25 and 75.

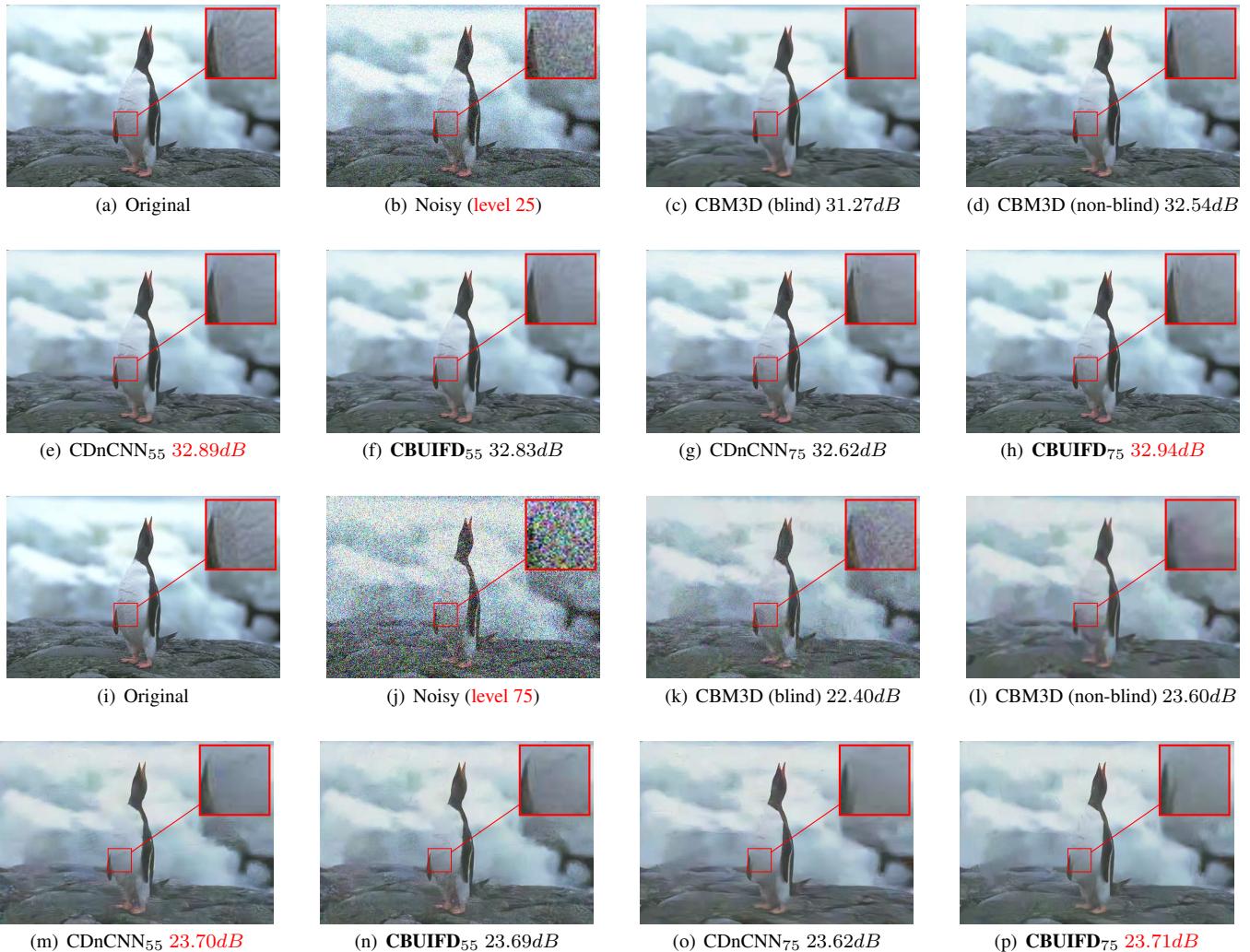


Figure 12: Color image ID 5 from the (ordered) CBSD68, tested with all methods on noise levels 25 and 75.

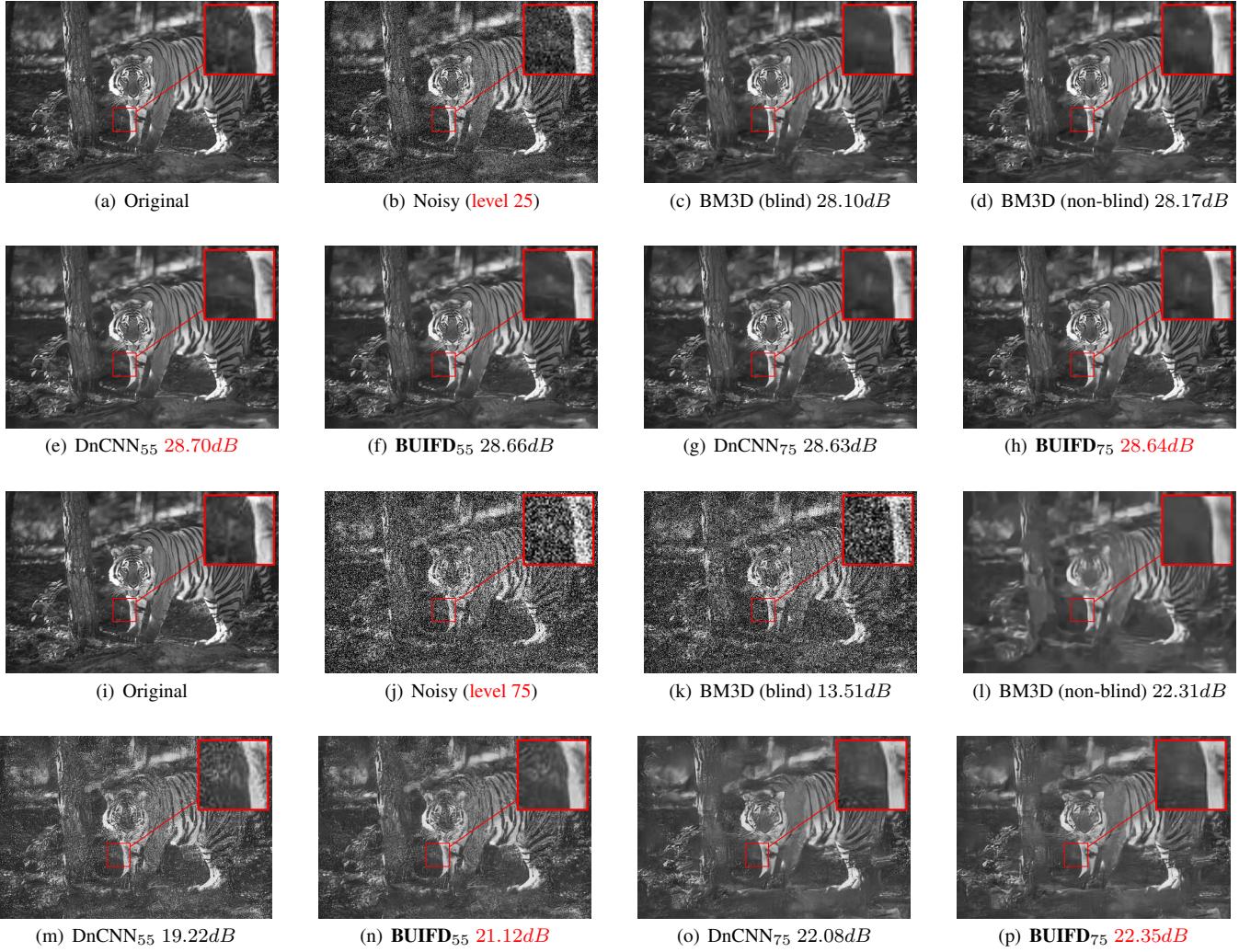


Figure 13: Grayscale image ID 6 from the (ordered) BSD68, tested with all methods on noise levels 25 and 75.

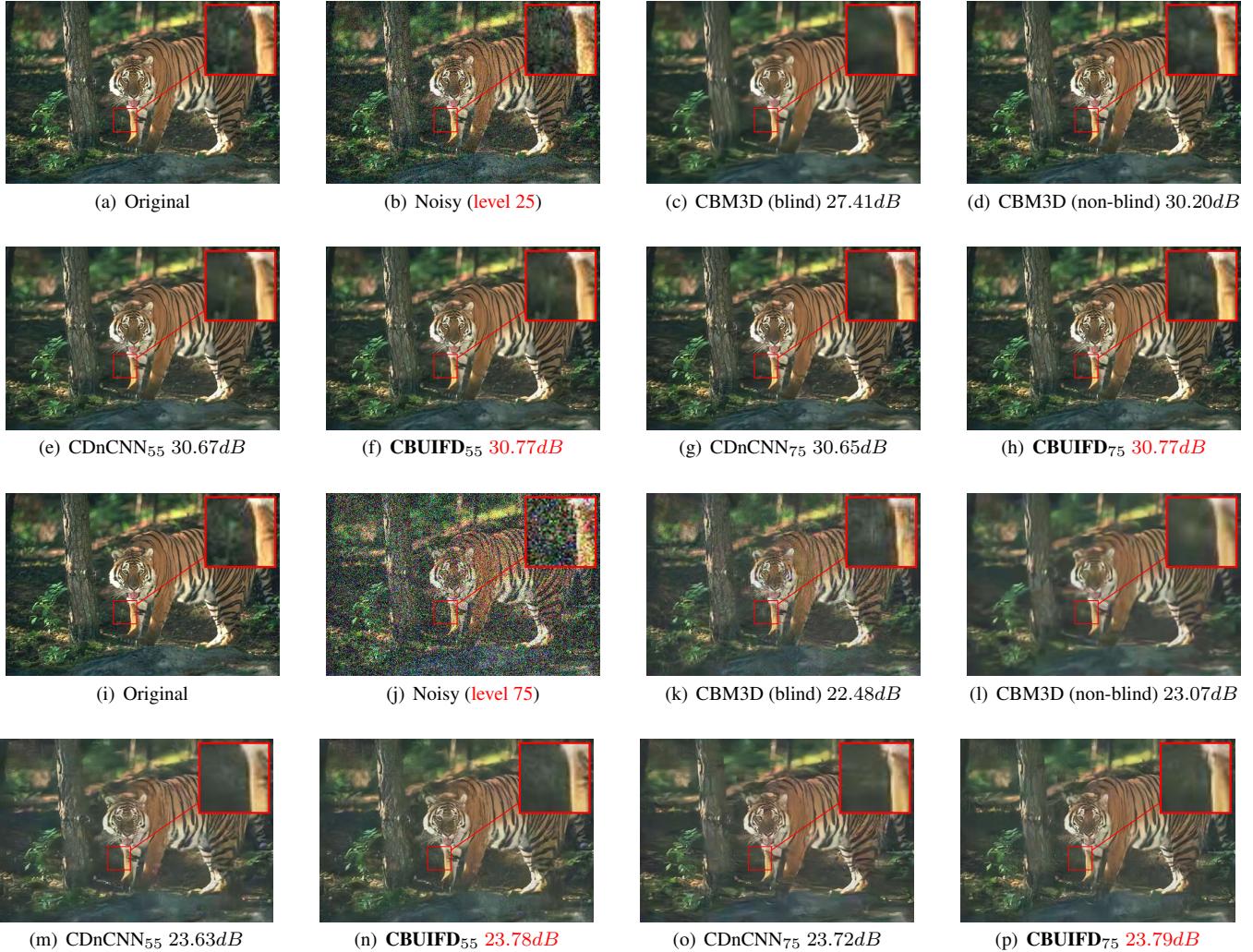
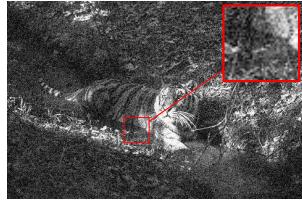


Figure 14: Color image ID 6 from the (ordered) CBSD68, tested with all methods on noise levels 25 and 75.



(a) Original



(b) Noisy (level 25)



(c) BM3D (blind) 25.60dB



(d) BM3D (non-blind) 25.56dB



(e) DnCNN₅₅ 26.19dB



(f) BUIFD₅₅ 26.17dB



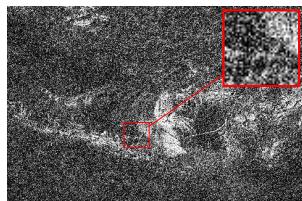
(g) DnCNN₇₅ 26.22dB



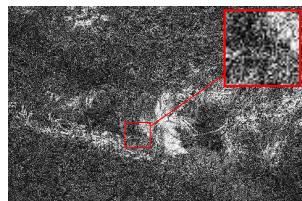
(h) BUIFD₇₅ 26.22dB



(i) Original



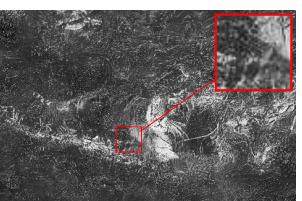
(j) Noisy (level 75)



(k) BM3D (blind) 13.66dB



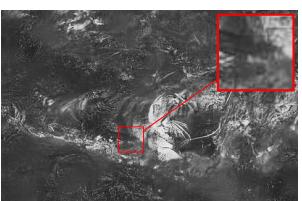
(l) BM3D (non-blind) 20.20dB



(m) DnCNN₅₅ 18.39dB



(n) BUIFD₅₅ 19.92dB



(o) DnCNN₇₅ 20.40dB



(p) BUIFD₇₅ 20.67dB

Figure 15: Grayscale image ID 7 from the (ordered) BSD68, tested with all methods on noise levels 25 and 75.

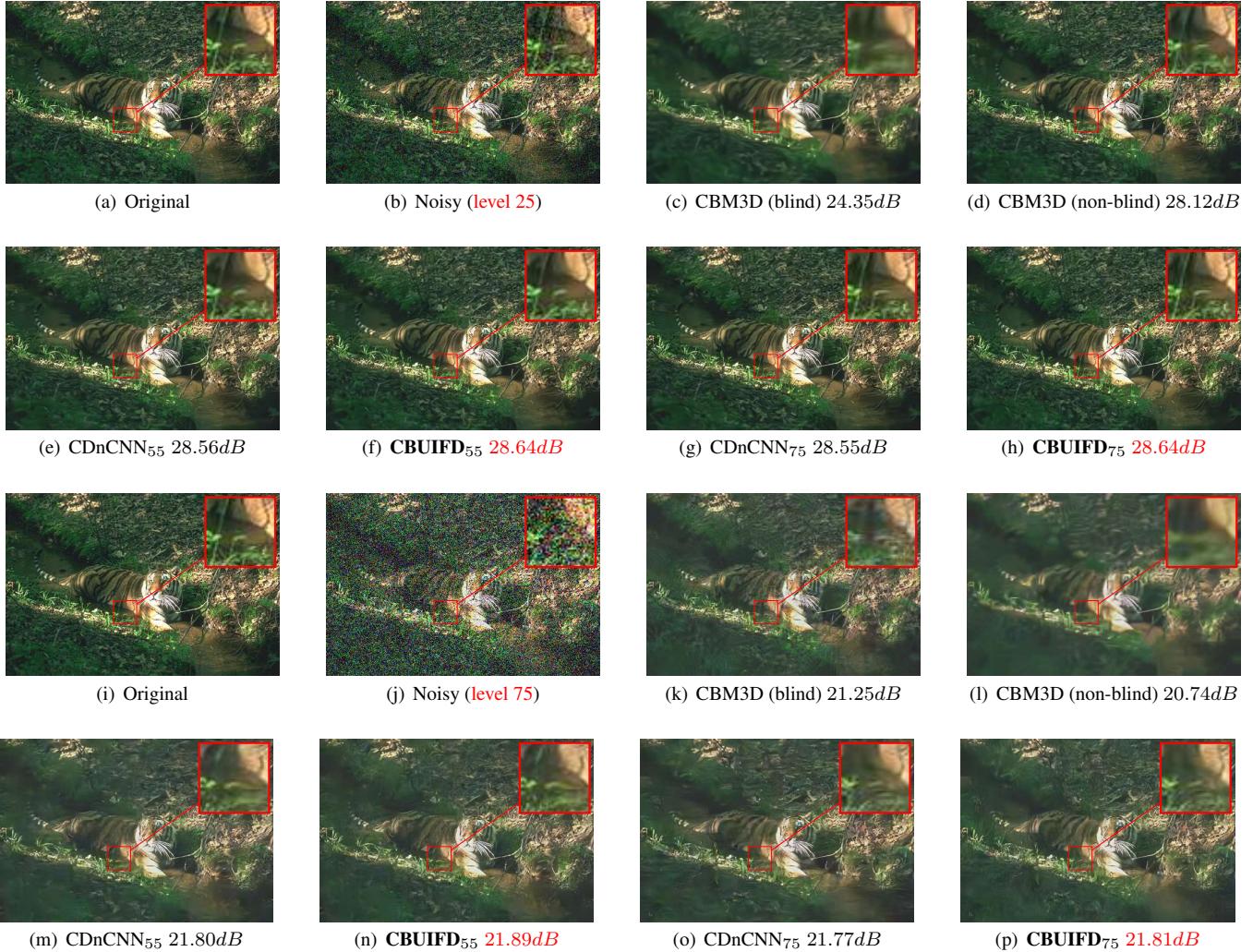


Figure 16: Color image ID 7 from the (ordered) CBSD68, tested with all methods on noise levels 25 and 75.

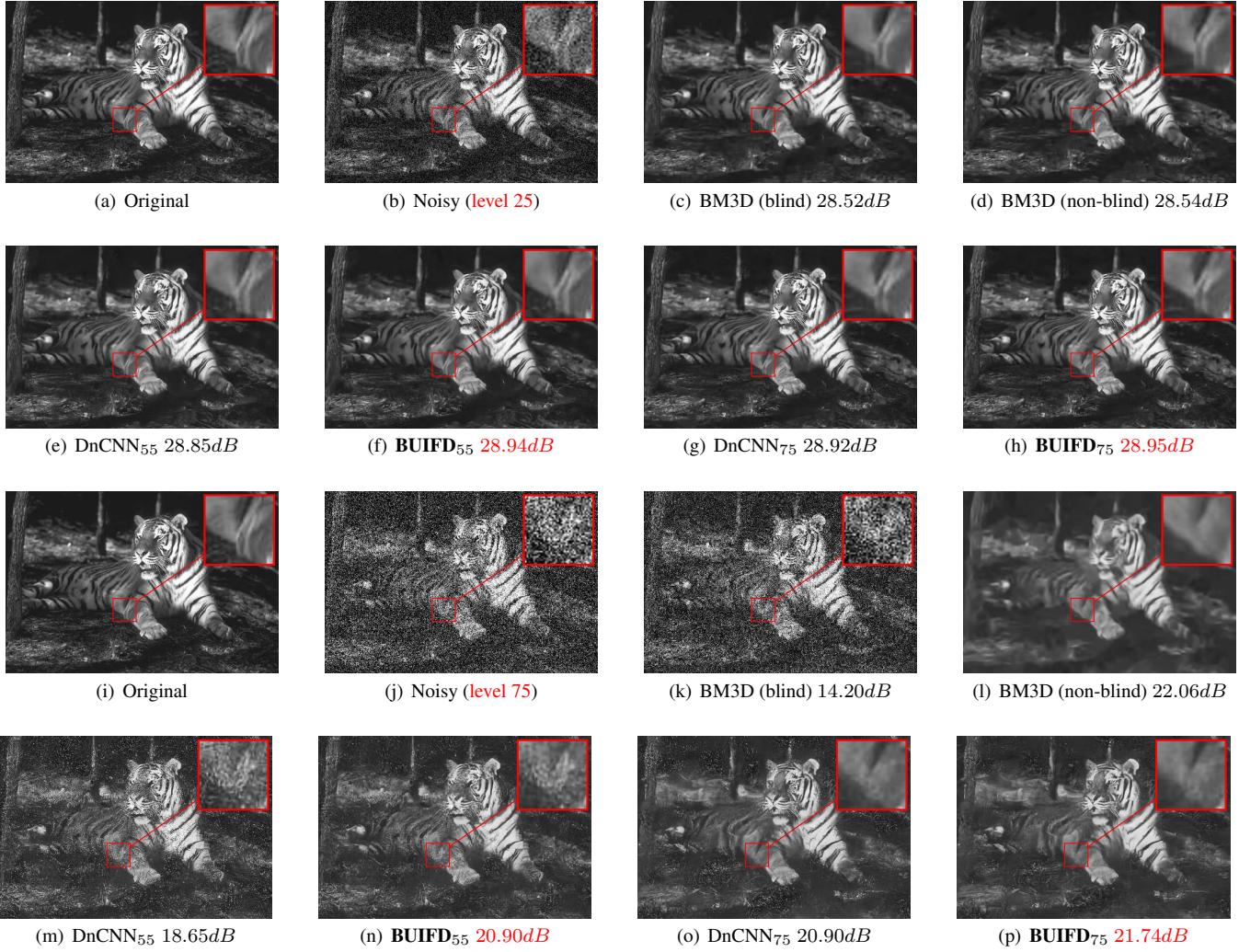


Figure 17: Grayscale image ID 8 from the (ordered) BSD68, tested with all methods on noise levels 25 and 75.

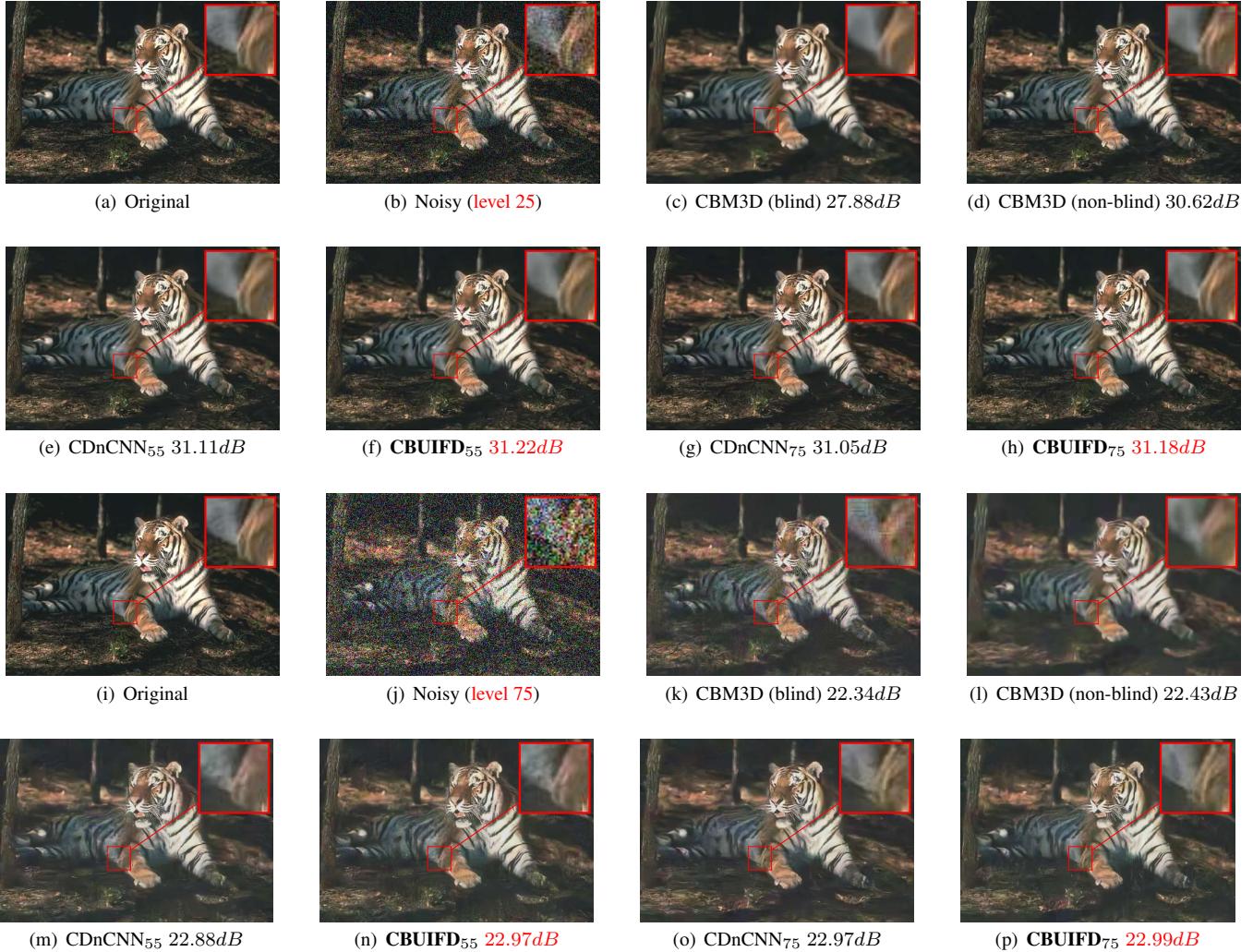


Figure 18: Color image ID 8 from the (ordered) CBSD68, tested with all methods on noise levels 25 and 75.



(a) Original



(b) Noisy (level 25)



(c) BM3D (blind) 29.12dB



(d) BM3D (non-blind) 29.15dB



(e) DnCNN₅₅ 29.76dB



(f) BUIFD₅₅ 29.74dB



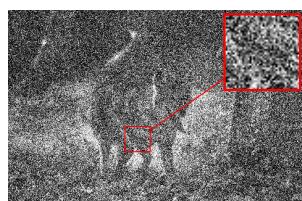
(g) DnCNN₇₅ 29.71dB



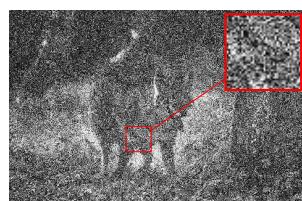
(h) BUIFD₇₅ 29.68dB



(i) Original



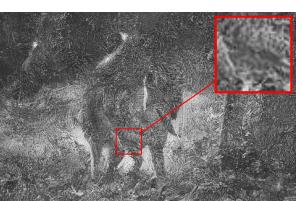
(j) Noisy (level 75)



(k) BM3D (blind) 13.07dB



(l) BM3D (non-blind) 24.57dB



(m) DnCNN₅₅ 19.34dB



(n) BUIFD₅₅ 22.04dB



(o) DnCNN₇₅ 24.41dB



(p) BUIFD₇₅ 24.48dB

Figure 19: Grayscale image ID 9 from the (ordered) BSD68, tested with all methods on noise levels 25 and 75.

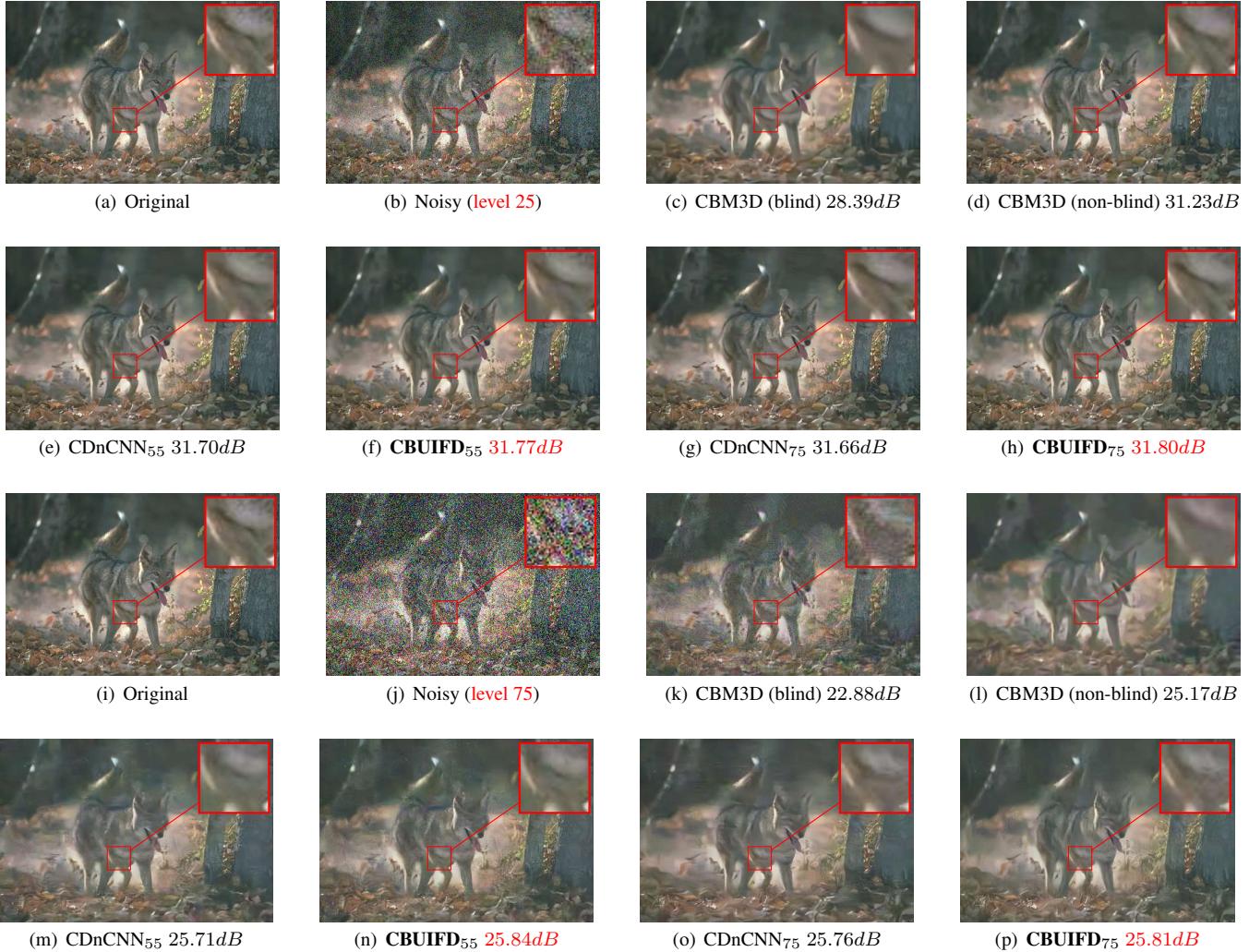
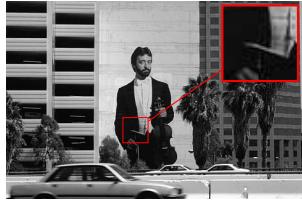
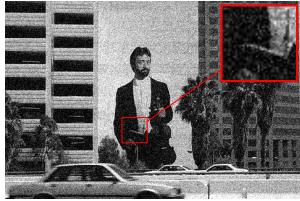


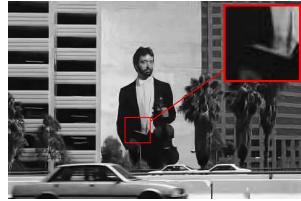
Figure 20: Color image ID 9 from the (ordered) CBSD68, tested with all methods on noise levels 25 and 75.



(a) Original



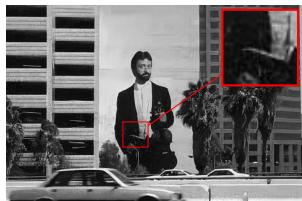
(b) Noisy (level 25)



(c) BM3D (blind) 28.21dB



(d) BM3D (non-blind) 28.17dB



(e) DnCNN₅₅ 28.08dB



(f) BUIFD₅₅ 28.42dB



(g) DnCNN₇₅ 28.16dB



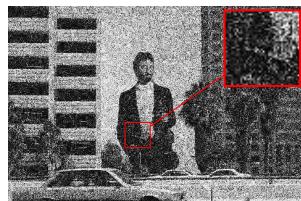
(h) BUIFD₇₅ 28.46dB



(i) Original



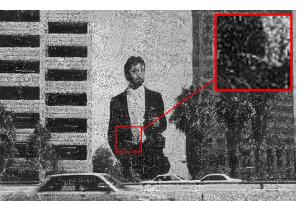
(j) Noisy (level 75)



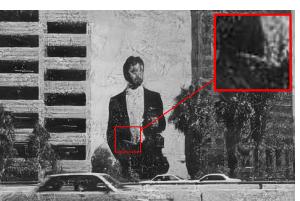
(k) BM3D (blind) 13.86dB



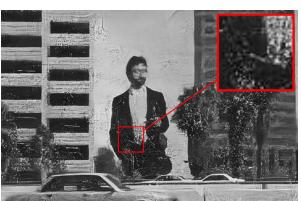
(l) BM3D (non-blind) 21.10dB



(m) DnCNN₅₅ 17.42dB



(n) BUIFD₅₅ 20.17dB



(o) DnCNN₇₅ 20.19dB



(p) BUIFD₇₅ 21.19dB

Figure 21: Grayscale image ID 10 from the (ordered) BSD68, tested with all methods on noise levels 25 and 75.



Figure 22: Color image ID 10 from the (ordered) CBSD68, tested with all methods on noise levels 25 and 75.

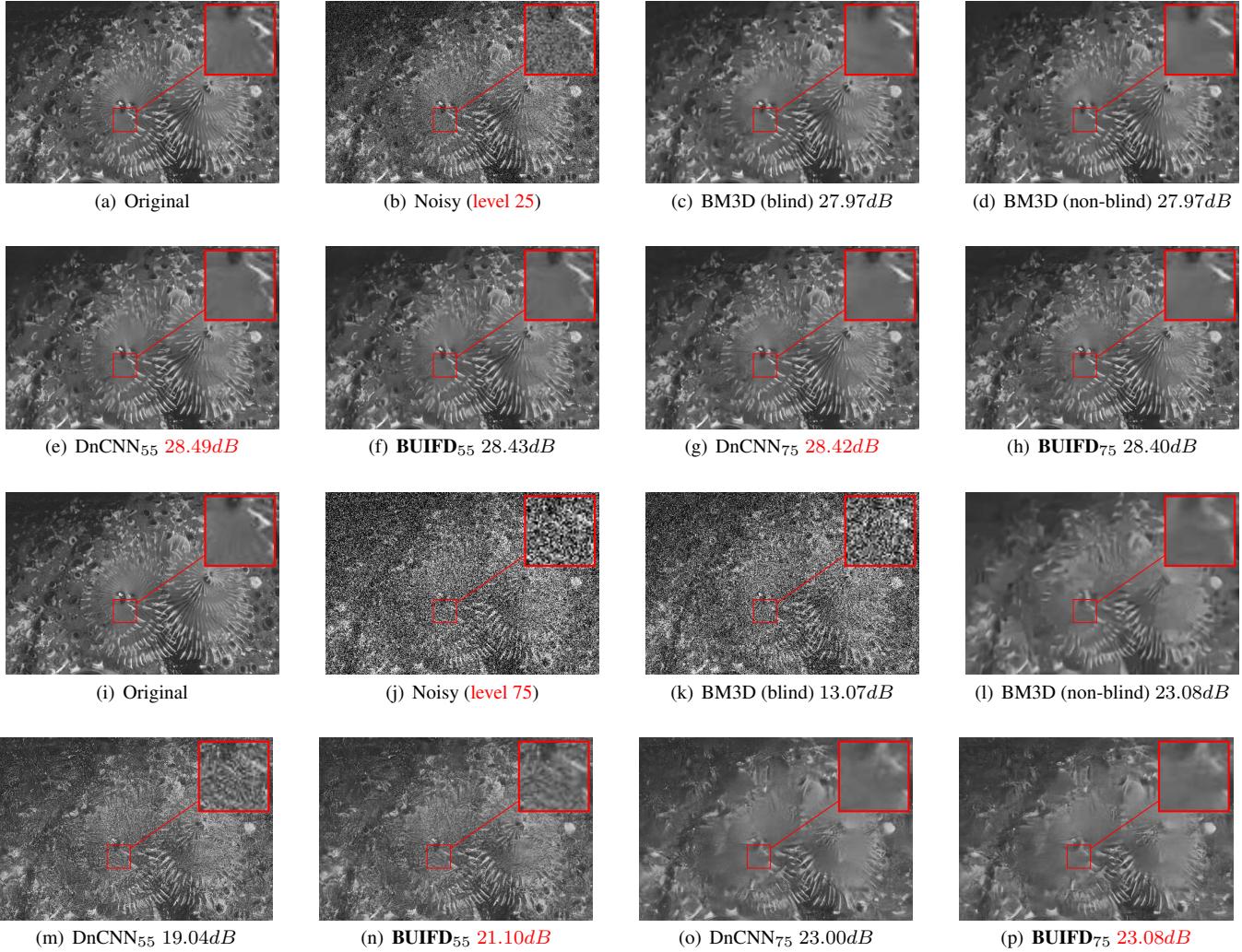


Figure 23: Grayscale image ID 11 from the (ordered) BSD68, tested with all methods on noise levels 25 and 75.

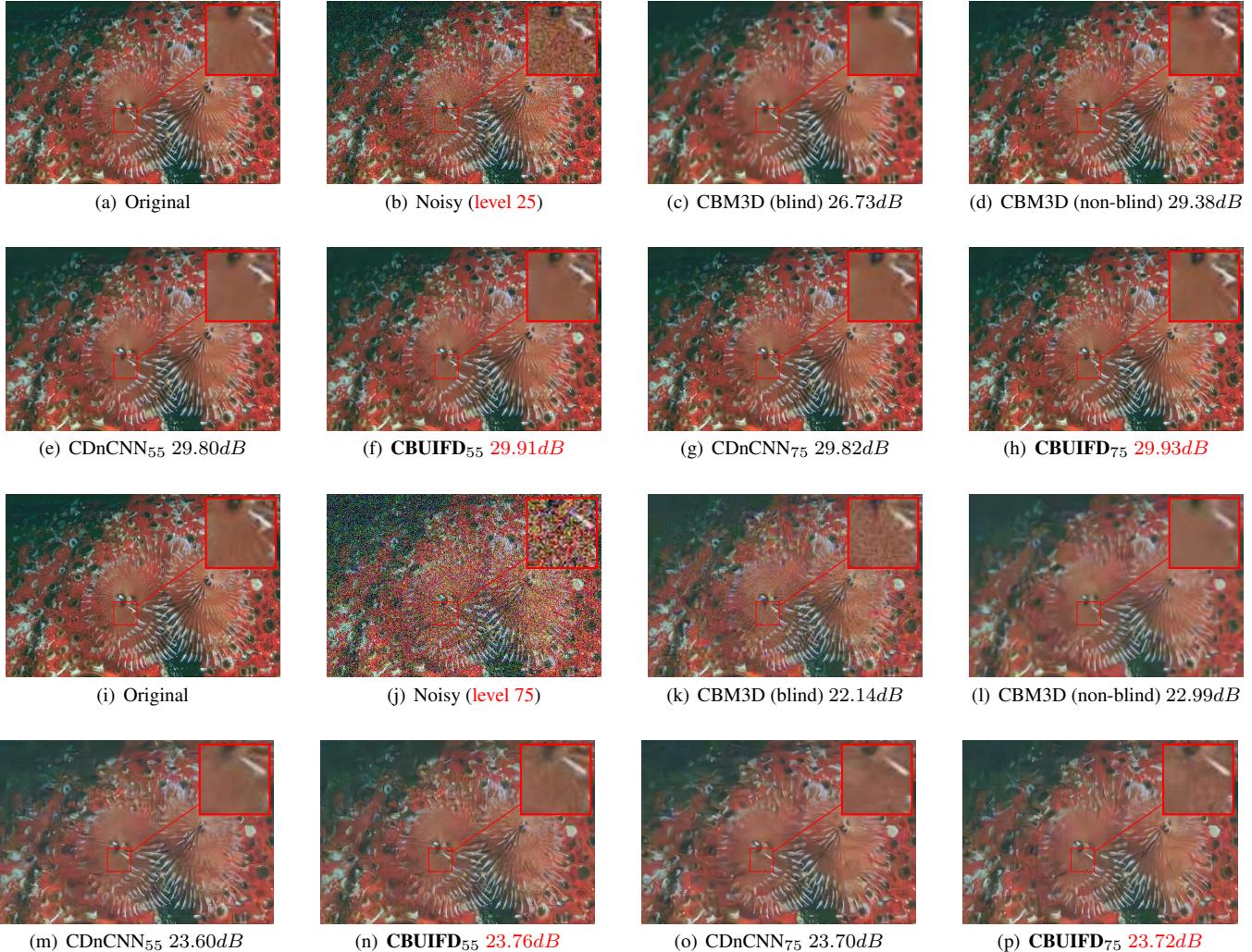


Figure 24: Color image ID 11 from the (ordered) CBSD68, tested with all methods on noise levels 25 and 75.

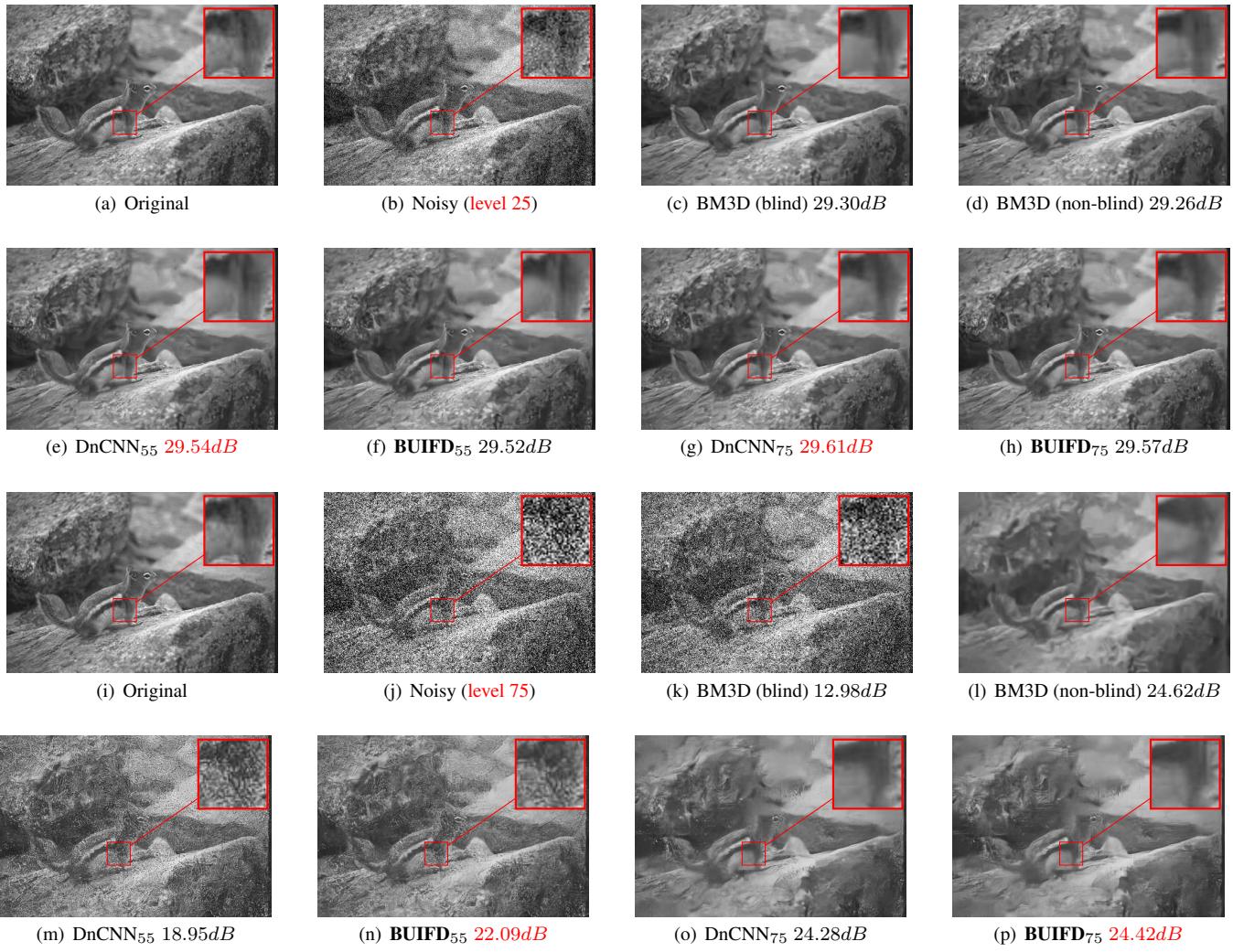


Figure 25: Grayscale image ID 12 from the (ordered) BSD68, tested with all methods on noise levels 25 and 75.

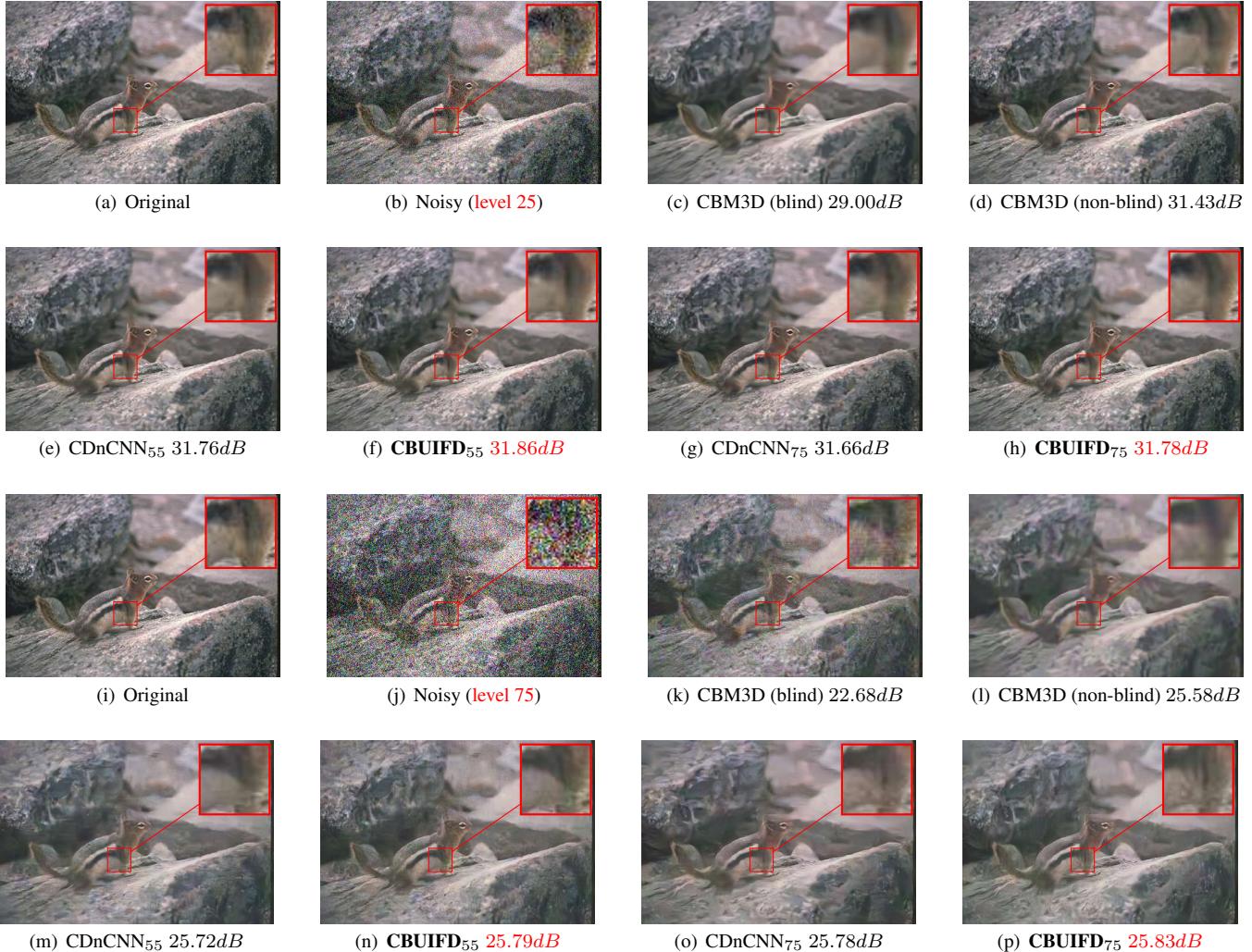


Figure 26: Color image ID 12 from the (ordered) CBSD68, tested with all methods on noise levels 25 and 75.

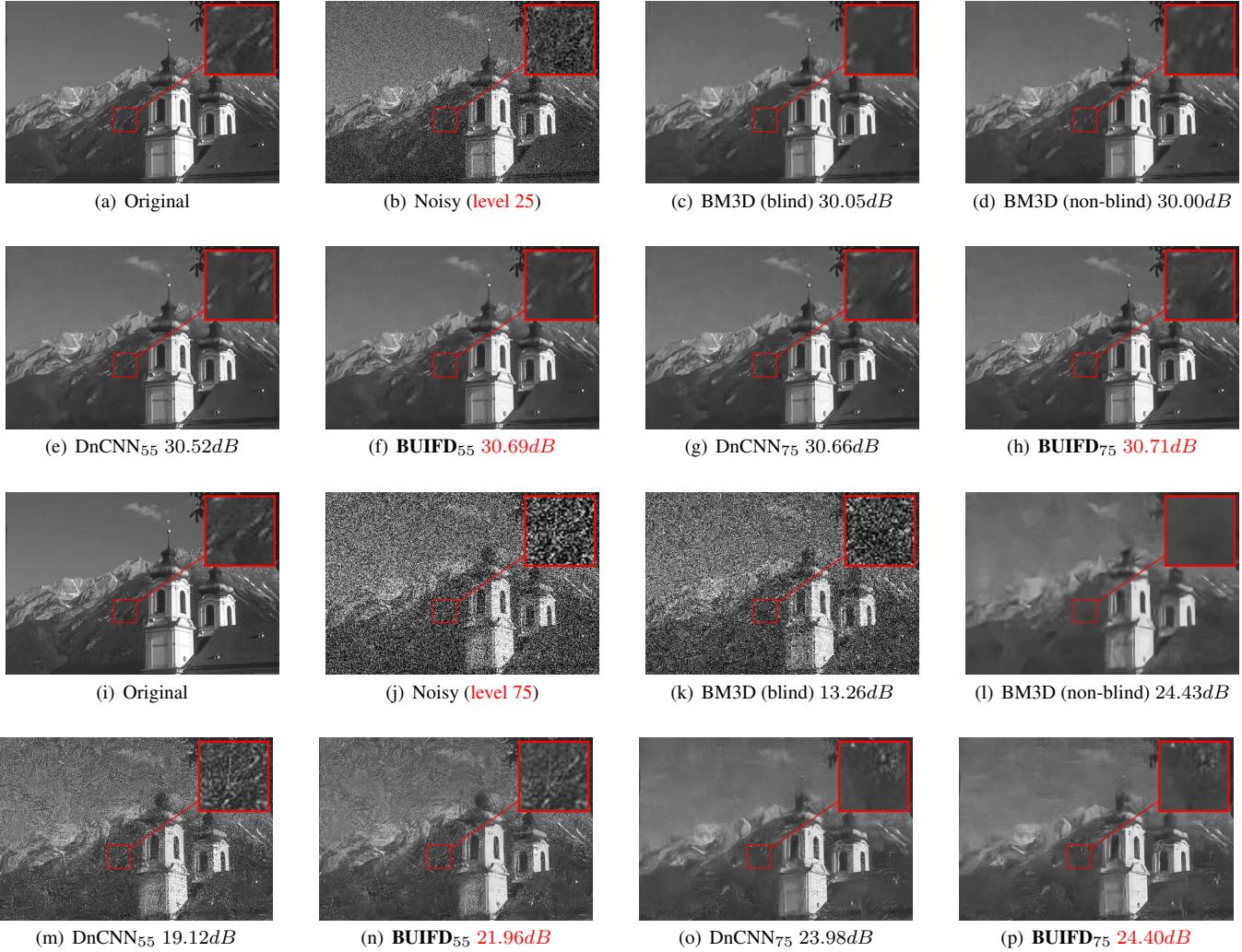
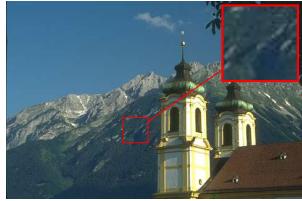
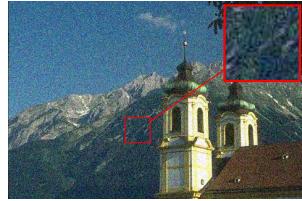


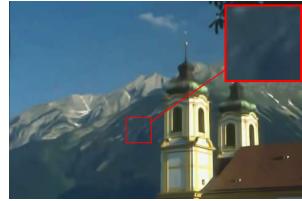
Figure 27: Grayscale image ID 13 from the (ordered) BSD68, tested with all methods on noise levels 25 and 75.



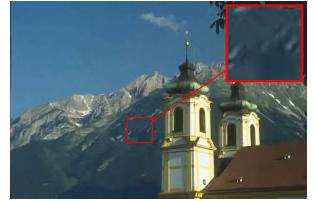
(a) Original



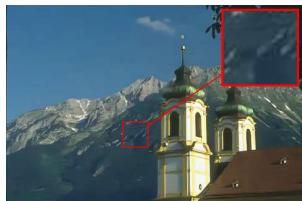
(b) Noisy (level 25)



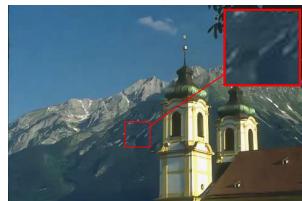
(c) CBM3D (blind) 29.09dB



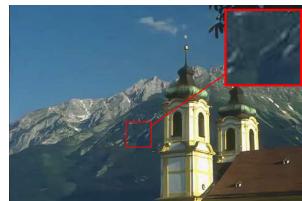
(d) CBM3D (non-blind) 31.78dB



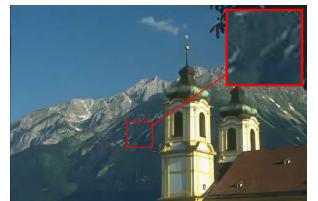
(e) CDnCNN₅₅ 32.56dB



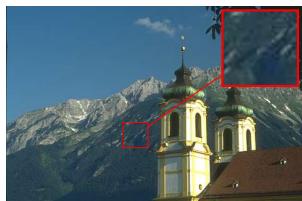
(f) CBUIFD₅₅ 32.64dB



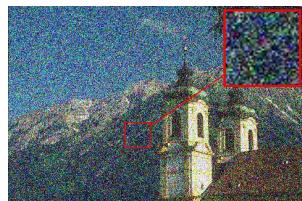
(g) CDnCNN₇₅ 32.45dB



(h) CBUIFD₇₅ 32.69dB



(i) Original



(j) Noisy (level 75)



(l) CBM3D (non-blind) 24.63dB



(m) CDnCNN₅₅ 25.31dB



(n) CBUIFD₅₅ 25.38dB

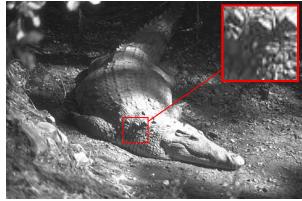


(o) CDnCNN₇₅ 25.16dB

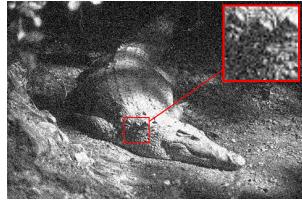


(p) CBUIFD₇₅ 25.33dB

Figure 28: Color image ID 13 from the (ordered) CBSD68, tested with all methods on noise levels 25 and 75.



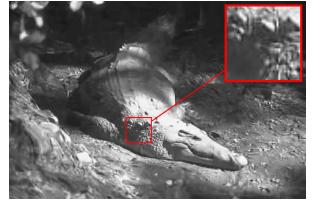
(a) Original



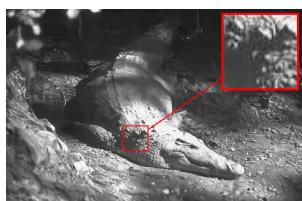
(b) Noisy (level 25)



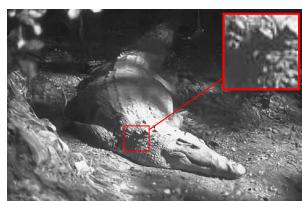
(c) BM3D (blind) 26.64dB



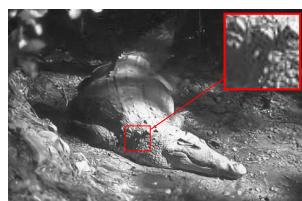
(d) BM3D (non-blind) 26.58dB



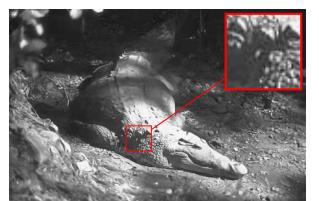
(e) DnCNN₅₅ 27.03dB



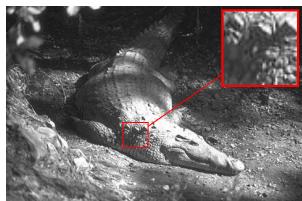
(f) BUIFD₅₅ 27.17dB



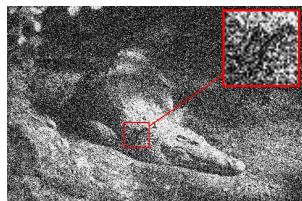
(g) DnCNN₇₅ 27.06dB



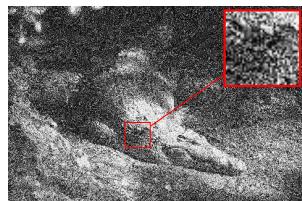
(h) BUIFD₇₅ 27.17dB



(i) Original



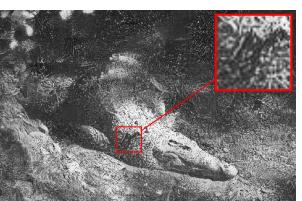
(j) Noisy (level 75)



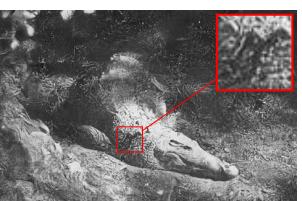
(k) BM3D (blind) 13.63dB



(l) BM3D (non-blind) 21.34dB



(m) DnCNN₅₅ 18.19dB



(n) BUIFD₅₅ 20.35dB



(o) DnCNN₇₅ 20.81dB



(p) BUIFD₇₅ 21.34dB

Figure 29: Grayscale image ID 14 from the (ordered) BSD68, tested with all methods on noise levels 25 and 75.



Figure 30: Color image ID 14 from the (ordered) CBSD68, tested with all methods on noise levels 25 and 75.