Adaptation to Future Sea Level Rise and an Increase in Typhoon Intensity: The Challenges Facing Tokyo

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The Intergovernmental Panel on Climate Change (IPCC) has highlighted through its various reports not only that sea level rise (SLR) is taking place, but that it is accelerating and will likely continue to do so through the course of the 20th century. Much literature has highlighted how this could have grave consequences for coastal communities and infrastructure (Esteban et al., 2016, Takagi et al., 2011). This poses a particularly important problem for the case of Tokyo, given how the land subsidence that took place in the early and mid 20th century has resulted in large parts of the city being under mean water level. Adaptation to this land subsidence was sequential, and started with the construction of small concrete walls and other retention structures, which was followed by the localized elevation of some roads, houses and neighbourhoods. Eventually, pumping stations were built in order to drain water, which can no longer flow out by gravity, and this was then followed by the construction of stronger dykes and other water control structures. Currently, the Tokyo super-levee project is elevating entire districts to place them on top of greatly enhanced levees, the width of which is much longer than their height.

Throughout the 21st century Tokyo will have to continue to adapt not only to rising water levels, but also to the potential for typhoons to intensify as a consequence of warmer sea surface temperatures. Figure 1 shows the present and future probability distribution of typhoon intensity at Tokyo Bay according to Yasuda et al. (2010), and how a storm with the same return period as the 1917 typhoon could be expected to have a central pressure of 933.9 hPa by 2100, increasing the expected generated storm surge by 0.2 – 0.5 m, compared to the 1917 historical event. It is important to note that, while the city is generally considered to be well-protected against tsunamis, the effects of SLR will also gradually increase the risk of these events around the Bay (Nagai et al., 2019). If more onerous sea-level-rise scenarios are considered, such as the 1.9 m given by Vermeer and Rahmstorf (2009), this would require even higher sea defence to be built to counteract the expected increase in typhoon intensity, costing in excess of 370 bn yen (see Fig. 2, Hoshino et al., 2016). In this case, the likely increase in storm surge would be small compared to the effect of sea level rise, but would warrant even more dramatic adaptation measures to be taken, which could even include a (very costly and probably environmentally controversial) storm surge barrier across the entrance of Tokyo Bay (Fig. 2 right see Esteban et al., 2015). This would behave in a similar way to something like the Thames Barrier, but on a far more massive scale.

It is important to note that considering more onerous scenarios also means that action would have to be taken earlier, and require for planning of such defences to start within the next decade or two. The cost of inaction, however, would be even more significant, and potentially in excess of 100 trillion yen (see Fig. 2, around 20 % of the current GDP of Japan), assuming no inflation or economic growth between now and the year 2100.

The lessons learnt by Tokyo in how to adapt to the relative increase in sea water levels (brought about by land subsidence) and how to adapt to future SLR holds very important lessons for the rest of the planet, which could learn much from the successes and challenges the city faces.

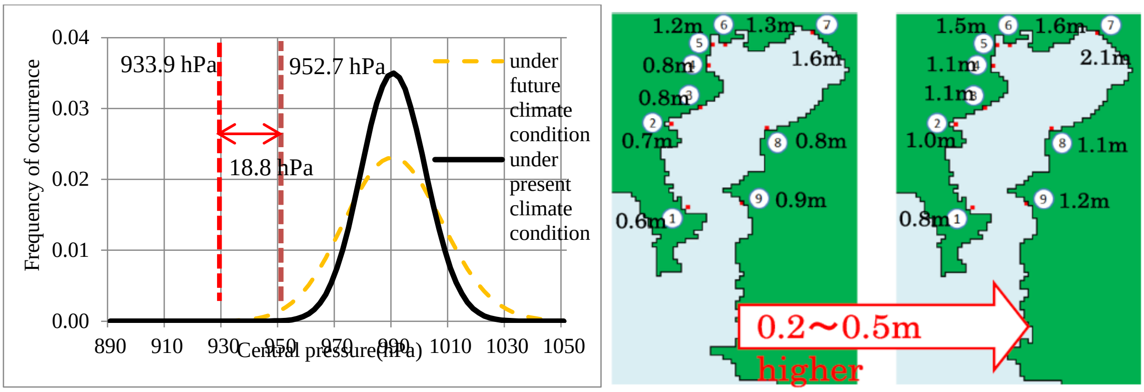

Figure 1. Left. Present and future probability distribution of typhoon intensity at Tokyo Bay according to Yasuda et al. (2010). The central pressure of a storm similar to that in 1917, and another with the same return period by the year 2100 are also shown. Right. Expected average storm surge height of a typhoon with a central pressure of 952.7 hPa (current climate) or 933.9 hPa (year 2100).

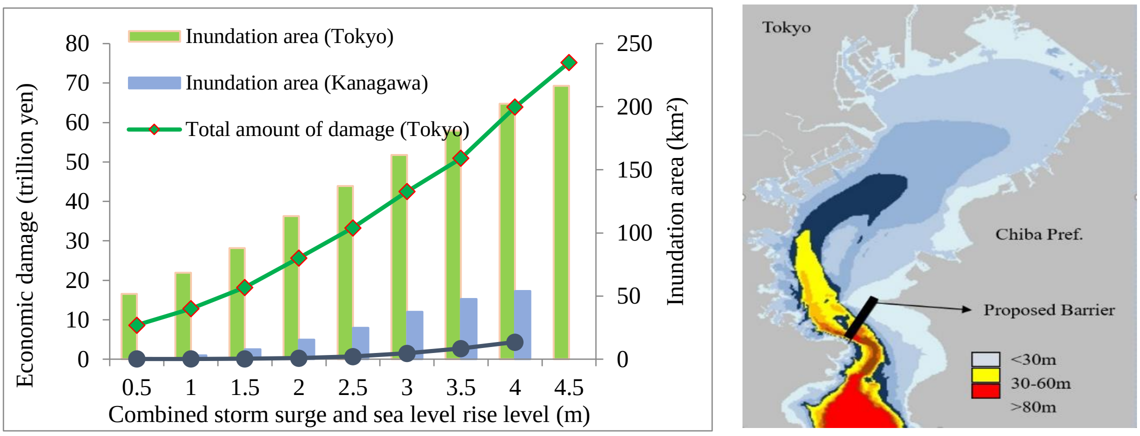

Figure 2. Left. Total economic damage in Tokyo and Kanagawa for different inundation levels. Right. Proposed location of storm surge barrier by Esteban et al. (2015), together with bathymetry of Tokyo Bay.

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将来の海面上昇と台風強度の増加への適応： 東京に直面する課題

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気候変動に関する政府間パネル（IPCC）は、海面上昇が進行中であり、20 世紀を通じて加速し、その傾向が続く可能性が高いことを、様々な報告書を通じて強調してきました。多くの文献が、これが沿岸コミュニティやインフラに深刻な影響を与える可能性があることを指摘しています（Esteban et al., 2016、Takagi et al., 2011）。変動は、東京の場合には特に重要な問題を提起します。なぜなら、20 世紀初頭から中盤にかけての地盤沈下の結果、江東デルタの多くの部分が平均水準面以下になってしまったからです。この地盤沈下への適応は段階的に行われ、まず小規模な高潮防潮コンクリート壁やその他の保水構造物の建設から始まり、その後、一部の道路、家屋、および地区の高度化が行われました。やがて、水を排水するためのポンプステーションが建設されました。これにより、重力による排水が不可能になったため、より強力な堤防やその他の水制御構造物の建設が行われました。現在、東京スーパー堤防計画では、地区全体を大幅に高めた堤防の上に配置することで、地区全体の地盤を高める作業が行われています。この堤防の幅は高さよりもはるかに長いです。

21 世紀を通じて、東京は海面上昇だけでなく、温暖化による海面温度の上昇の結果として台風が強度を増す可能性にも適応し続けなければなりません。Yasuda ら（2010）によると、図 1 は東京湾での台風強度の現在と将来の確率分布を示しており、1917 年の台風と同じ回帰期間を持つ台風が 2100 年までに中心気圧が 933.9 hPa となり、1917 年の歴史的なイベントと比較して予想される高潮が 0.2 – 0.5 m 増加する可能性があることを示しています。一般的に都市は津波から十分に保護されていると考えられていますが、海面上昇の影響により、湾内でのこのような沿岸災害のリスクが徐々に増加するでしょう。より厳しい海面上昇シナリオが考慮される場合、例えば Vermeer と Rahmstorf（2009）による 1.9 m のシナリオでは、予想される台風強度の増加に対抗するためにより高い防潮堤が建設される必要があり、そのコストは 3700 億円を超える可能性があります（図 2、Hoshino et al.、2016 参照）。この場合、高潮の増大は海面上昇の影響に比べて小さいかもしれませんが、効果が重なり合い、さらに劇的な適応策が必要になります。対策には、東京湾の入り口に（非常に高額でおそらく環境的にも議論のある）防潮水門を建設することさえ含まれる可能性があります（図 2 右参照 Esteban et al.、2015）。これは、英国のテムズバリアのようなものと似た働きをしますが、はるかに巨大なスケールで行われます。

より厳しいシナリオを考慮することは、より早期に行動を起こす必要があり、そのような防災計画を立案するには今後 10 年から 20 年以内に開始する必要があります。無行動の場合のコストはさらに重大であり、2100 年までのインフレーションや経済成

長を考慮しない場合、被災額は日本の現在の GDP の約 20%に相当する 1 兆円を超える可能性があります（図 2 参照）。

東京が地盤沈下によってもたらされた相対的な海水位の上昇および将来の海面上昇に適応する方法の検討から得た教訓は、多くの都市が直面する成功と課題からも学ぶことができるため、地球上の他の地域にとっても非常に重要です。

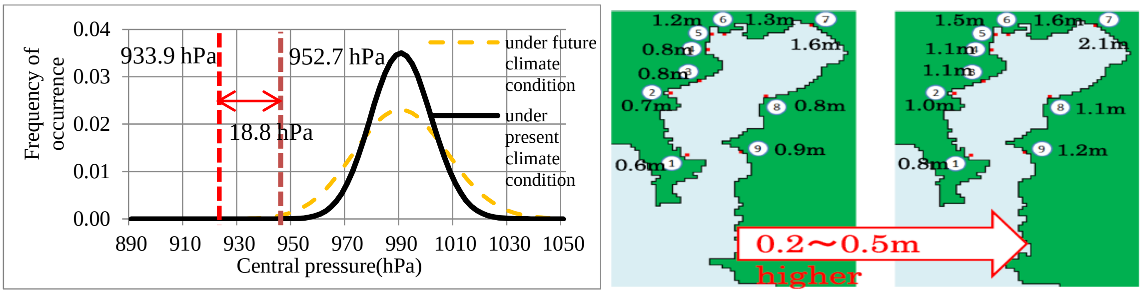

図 1. 左図：Yasuda ら（2010）によると、東京湾での台風強度の現在と将来の確率分布。1917 年と同様の台風、および 2100 年までに同じ回帰期間を持つ別の台風の中心気圧も示されています。右図：中心気圧が 952.7 hPa（現在の気候）または 933.9 hPa（2100 年）の台風により予想される平均高潮の高さ。

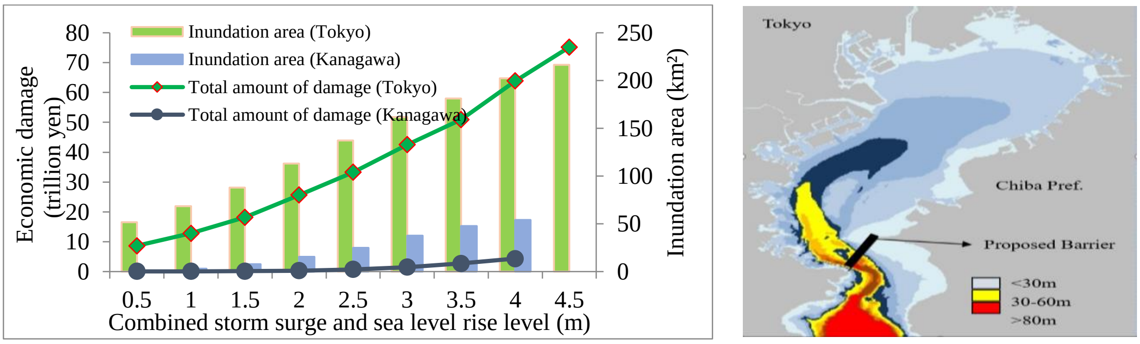

図 2. 左図：東京と神奈川の異なる浸水レベルに対する総経済被害。右図：Esteban ら（2015）による防潮水門の提案された位置と東京湾の水深情報。

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