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“Climate Change Impacts and Adaptation for Coastal Transport Infrastructure in Caribbean SIDS”

Sea Level Rise, SIDS and Transport Infrastructure: Lessons From Real Examples of Coastal Subsidence

By

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Sea Level Rise, SIDS and Transport Infrastructure: Lessons From Real Examples of Coastal Subsidence

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The University of Tokyo (Japan)

Summary

- Adaptation to Sea Level Rise
  - Small Islands:
    - Case Study in Philippines
  - Cities:
    - Case Study of Jakarta
  - Ports:
    - Case Study of Jakarta
    - Case Study of Tohoku
- Breakwaters and Climate Change
- Port Downtime
- Cost of Adapting in Tokyo

Sea Level Rise Adaptation: Learning from >0.5m “rise” in the Philippines (possibly up to 1.0m)

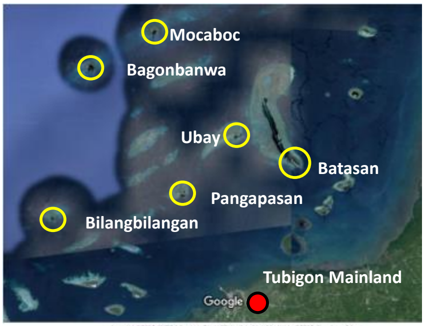
(Think of my presentation as a Time Machine into the Future!)

This work is reported in Jamero et al., 2016, 2017

Jamero, L., Esteban., M. and Onuki, M. (2017) *“Small island communities in the Philippines prefer local measures to relocation in response to sea-level rise”,* Nature Climate Change (accepted)

Jamero, L**., Esteban., M.** and Onuki, M. (2016) *“Potential In-Situ Adaptation Strategies for Climate-Related Sea-Level Rise: Insights from a Small Island in The Philippines Experiencing Earthquake-Induced Land Subsidence”,* J-SustaiN 4 (2) pp 44-53.

Coral Islands off Bohol, Philippines (Jamero et al., 2016, 2017)

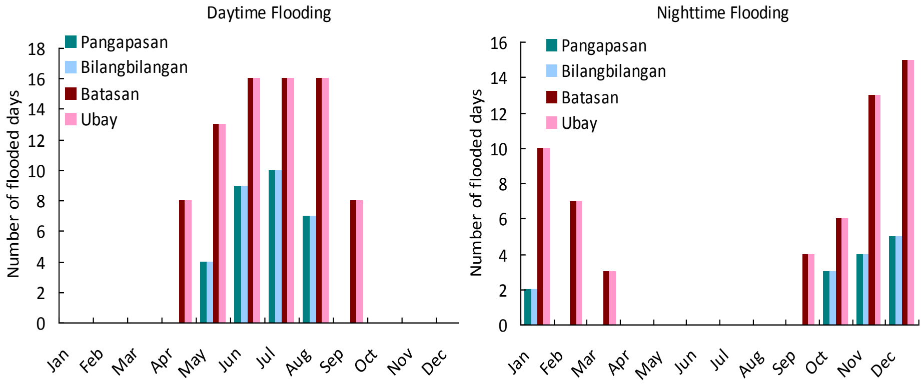


Imagery ©2015 CNES / Astrium, DigitalGlobe, Landsat, Map data ©2015 Google 2 km

Consequences of >0.5 subsidence due to the 2013 Earthquake

Island	Highest elevation (m)	Area (m^2)	Cross-section (m)	Built environment	Flooding situation	Severity
Batasan	**2.28**	**58,296**	**47.4**	From the start, ground raised using coral stones; houses built up to the sea	- **Before earthquake: Flooded during strong typhoons** - **After earthquake: Completely flooded during spring tides (e.g. 1 hour daily floods for 1 week around new and full moon)**	**2**
Ubay	**2.15**	**14,638**	**84.8**			**1**
Pangapasan	1.91	20,694	71.1			**3**
Bilangbilangan	1.99	16,668	100.3	Ground not raised; Has beach, with some areas lined with seawall; houses built well within grounds		**4**
Mocaboc	2.06	29,674	118.1		- Before and after earthquake: Houses near waterline occasionally flooded during very high tides (i.e. +2.0m) and typhoons. No perceived changes in flood levels before and after earthquake	**5**
Bagonbanwa	2.5	60,839	187.4		- Before and after earthquake: Not flooded	**6**

Flooding Severity

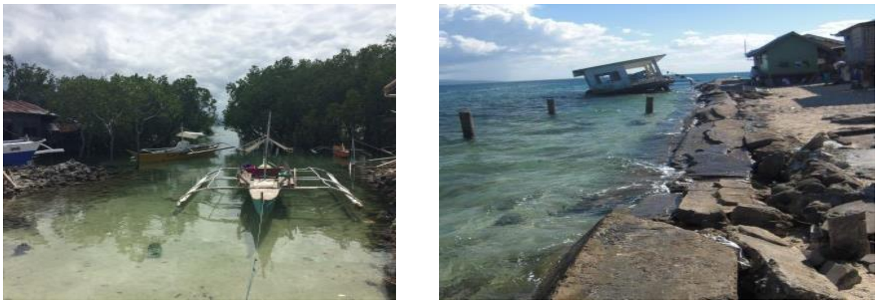


By 2100 global mean sea level will rise by 0.28m-0.98m, or higher, as numerous presenters have explained

(IPCC 5AR, 2013)

Current situation (Ubay Island, typical water levels) Coping?

Adaptation: Bio-adaptation vs Engineering

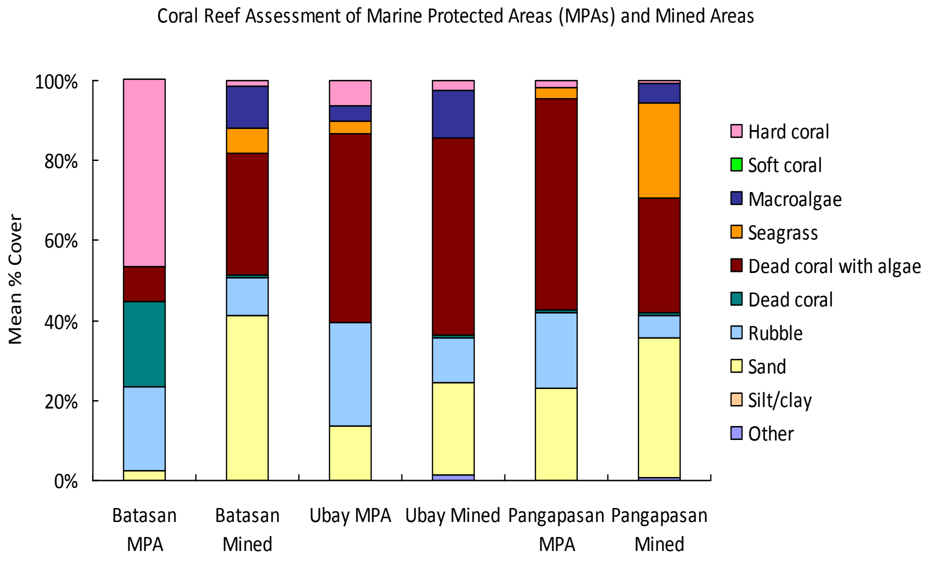


Islands with mangroves are facing far less problems that those that have attempted to build seawalls

However, not so easy to plant mangroves!

But, generally it seems to be the way to go…

Long-term sustainability of adaptation strategies: importance of sediment budgets



Adaptation strategies (Batasan Island)

-Rising floors (using coral stones or rubbish)

-Building seawalls (using coral stones)

-Houses on stilts

-Learning to live with flooding

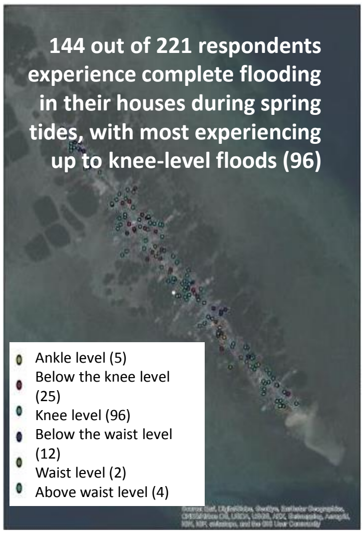
Adaptation strategies: Effectiveness

		Flood height	**Hard Measures**			
			Stilted House		Raised Floor	
Flooding Severity	Island	Median (cm)	Median (cm)	Households Not Flooded	Median (cm)	Households Not Flooded
Low	**Pangapasan**	20.5	87	100%	29	73%
	Bilangbilangan	24.5	79	100%	27.5	67%
Medium	**Batasan**	36	100	100%	44	22%
	Ubay	43	120.5	100%	67.25	46%

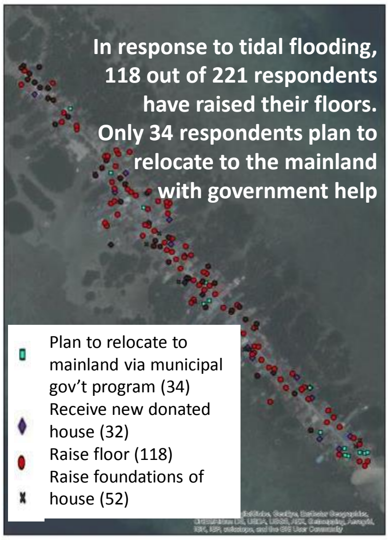
✓ **STILTED HOUSES** *have great allowances for flooding, and even for high waves during typhoon and monsoon seasons. However, they also need to be properly engineered against strong winds*

Jamero, L., Esteban., M. and Onuki, M. (2017) *"Small island communities in the Philippines prefer local measures to relocation in response to sea-level rise",* Nature Climate Change (accepted)

Willingness to Relocate



144 out of 221 respondents experience complete flooding in their houses during spring tides, with most experiencing up to knee-level floods (96)



In response to tidal flooding, 118 out of 221 respondents have raised their floors. Only 34 respondents plan to relocate to the mainland with government help

Jamero, L., **Esteban., M.** and Onuki, M. (2016) *"Potential In-Situ Adaptation Strategies for Climate-Related Sea-Level Rise: Insights from a Small Island in The Philippines Experiencing Earthquake-Induced Land Subsidence",* J-SustaiN 4 (2) pp 44-53.

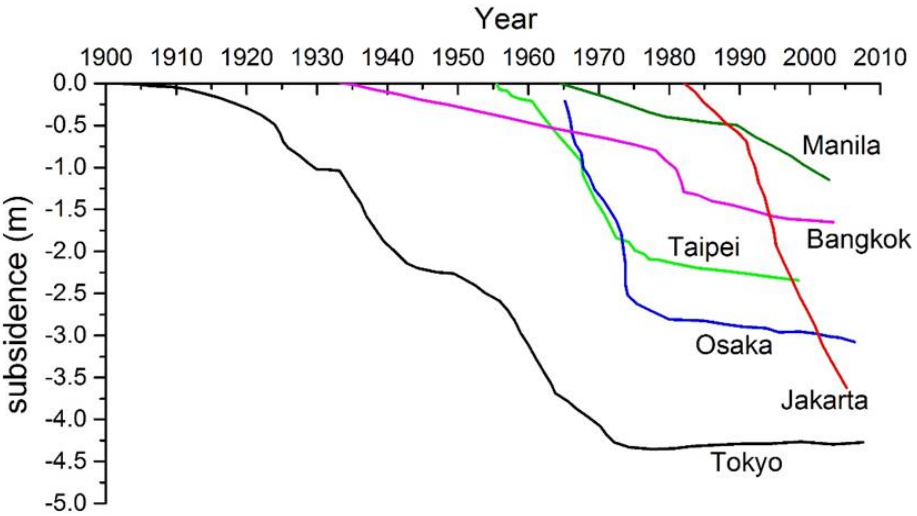
Sea Level Rise Adaptation: Learning from >5.0m “rise” in Jakarta

This work is reported by Takagi et al., 2016, 2017

Takagi, H., Fujii, D., Mikami, T. and Esteban, M. (2016) *“Mangrove Forest against Dyke-break induced Tsunami in Rapidly Subsiding Coasts”*, Natural Hazards and Earth System Science, 16, 1629-1638.

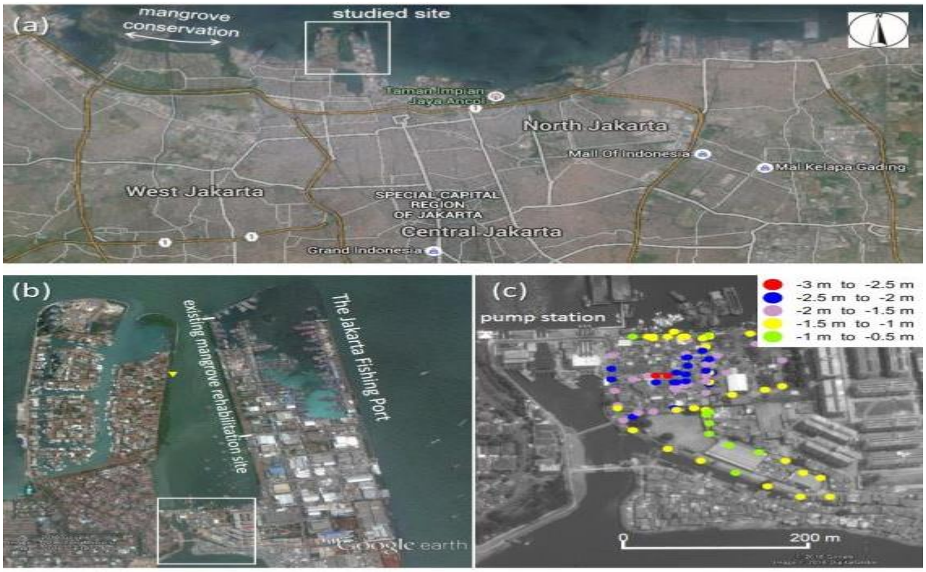
Takagi, HJ., Fujii, D., Esteban, M., Yi, X. (2017) *“Effectiveness and Limitation of Coastal Dykes in Jakarta: the Need for Prioritising Actions against Land Subsidence”.* Sustainability 9, 619

Reason: Groundwater Extraction (currently ~0.2m* subsidence/year) (Takagi et al., 2016)



**No, this is not a typo, it really is 20cm per year!*

Study site: Coastal Jakarta (-0.5 to -3m below sea level)



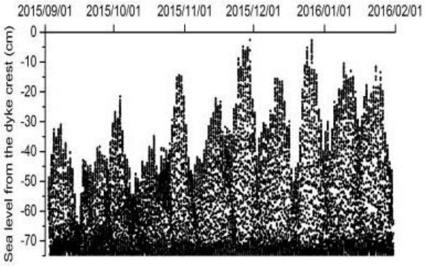
Adaptation (coping?): Building of Sea Dykes

2007 Flooding and Raising of Dyke

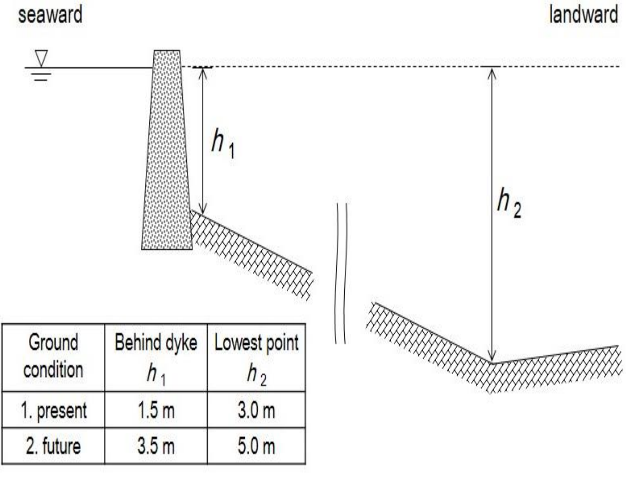
Pluit District suffered extensive inundation during a high tide on November 26, 2007

The thin dyke protecting the settlement was raised by about a meter after the 2007 event by the local government

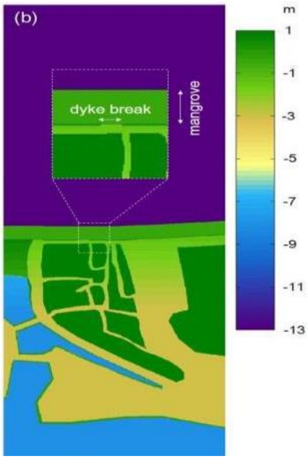
However, sea levels almost reach the top of the dyke on a monthly basis (dike is being raised almost on a yearly basis…)



Future Scenarios (2025, with 20cm SLR/year)

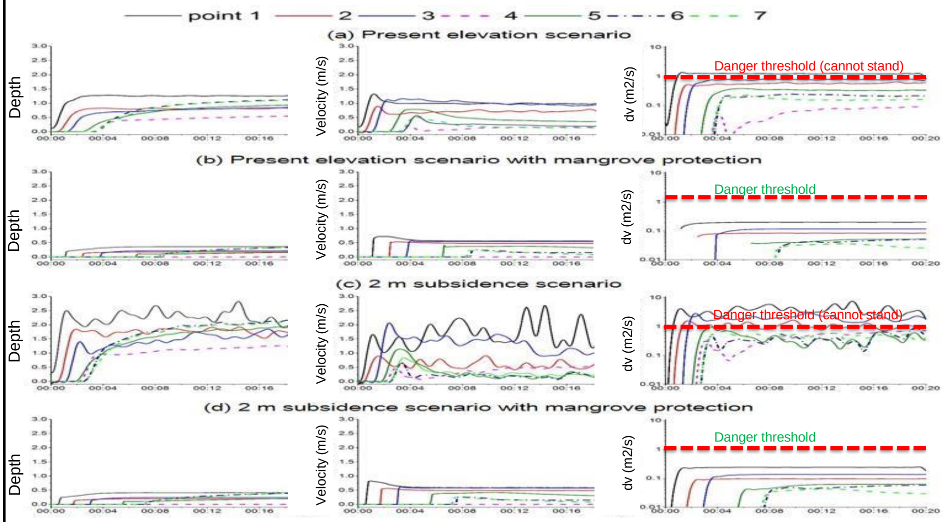


Ground condition	Behind dyke h_1	Lowest point h_2
1. present	1.5 m	3.0 m
2. future	3.5 m	5.0 m



Takagi, H., Fujii, D., Mikami, T. and Esteban, M. (2016) *"Mangrove Forest against Dyke-break induced Tsunami in Rapidly Subsiding Coasts"*, Natural Hazards and Earth System Science, 16, 1629-1638.

Dyke-Break Induced Tsunami (2m inundation within 2-3 minutes, Takagi et al., 2017)



Takagi, HJ., Fujii, D., Esteban, M., Yi, X. (2017) *"Effectiveness and Limitation of Coastal Dykes in Jakarta: the Need for Prioritising Actions against Land Subsidence".* Sustainability 9, 619

Adaptation Counter-Measures

Pluit has one of the main pumps for Jakarta (needed to pump the water out of the city, as it no longer flows out!)

Dykes are being built around all waterways, which anyway are below MWL.

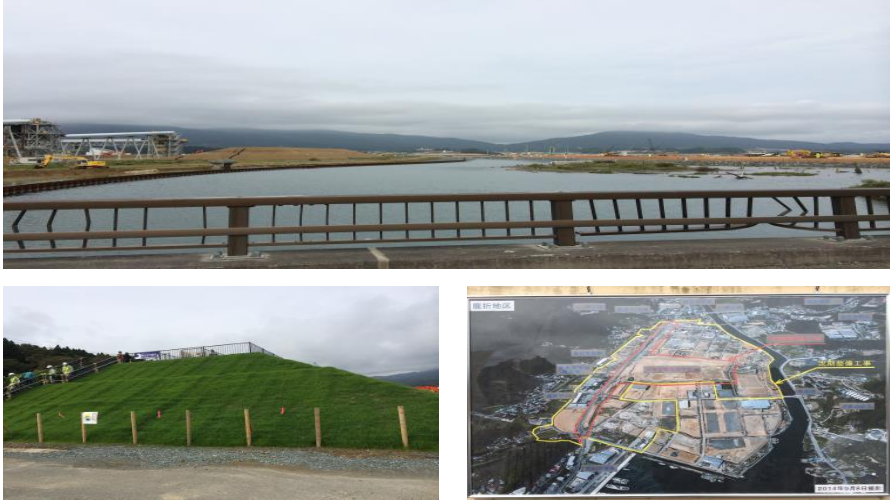
Esteban, M., Takagi, H., Mikami, T., Aprilia, A., Fujii, D., Kurobe, S. and Utama, N. A. (2017) *"Awareness of coastal Floods in Impoverished Subsiding Coastal Communities in Jakarta: Tsunamis, Typhoon Storm Surges and Dyke-Induced Tsunamis"*, International Journal of Disaster Risk Reduction 23, 70-79

Problems for Ports (I)

Problems for Ports (II)

Tohoku and Land Subsidence
(0.5 to 1m subsidence)

Adaptation on a pharaonic scale? (Tsunami Layer 2 Measures)



Esteban, M., Onuki, M., Ikeda, I and Akiyama, T. (2015) *"Reconstruction Following the 2011 Tohoku Earthquake Tsunami: Case Study of Otsuchi Town in Iwate Prefecture, Japan"* in Handbook of Coastal Disaster Mitigation for Engineers and Planners. Esteban, M., Takagi, H. and Shibayama, T. (eds.). Butterworth-Heinemann (Elsevier), Oxford, UK

Shallow Breakwaters and Climate Change

Current Philosophy Behind Breakwater Construction

Traditional breakwater design assumes that:

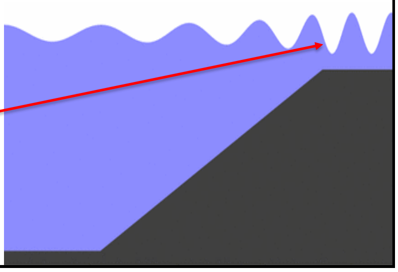
- **Sea level does not change**
- **Future weather patterns will be the same as historical weather (i.e. by studying past weather we can obtain future return periods for a given design wave height)**

It appears that both of these assumptions might be incorrect in the future

- Increase in tropical cyclone intensity (i.e. hurricanes)
- Sea level rise (as discussed yesterday in detail)

Can Breakwaters in the Future be Designed in the Same Way?

- **Currently we use the significant wave height (H_s) as the main design parameter.**
- **However to obtain the design H_s we use historical data**
- **But in the future the weather will change!!!**
- **As they approach the coastline waves will deform, increasing in height until they break**

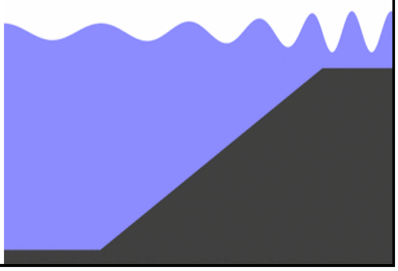


Design According to Limiting Breaker Height (H_b)

- **Many breakwaters in the world are in shallow water (small fishery ports, typically protected just by rock armour)**
- **Limiting Breaker Height (H_b) gives us the maximum wave that is possible at a structure for a given water depth (i.e. H_b will take the place of H_s)**
- **Goda (1985)**

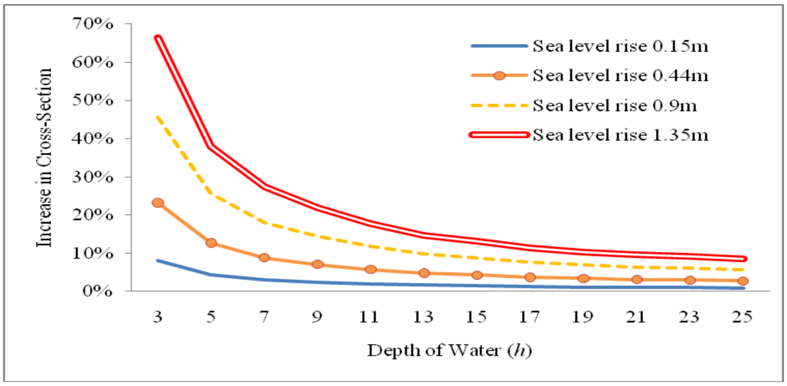
$$H_b = 0.17 L_0 \left\{1 - exp\left[-1.5 \frac{\pi h}{L_0}\left(1 + 15 tan^{4/3} \alpha\right)\right]\right\}$$

in which *h* is the water depth at the breakwater,
L_0 is the deep water wave length, α is the slope of sea



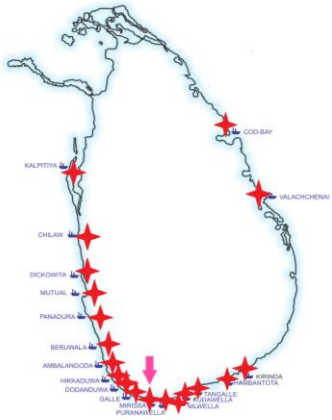
Average Total Increase in Cross-Sectional Area

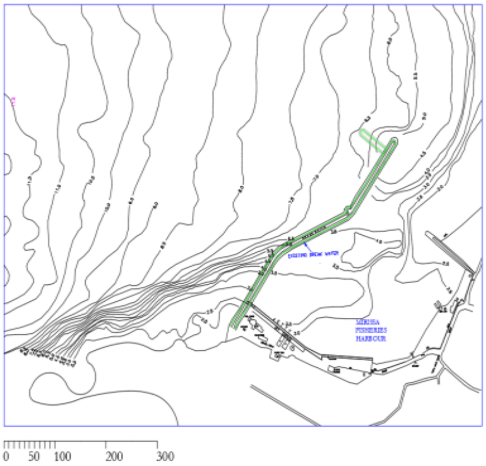
- **As sea level increases, so will stronger waves be able to arrive at the breakwater**
- **Many breakwaters in the world are in shallow water (small fishery ports, typically protected just by rock armour)**



Mirissa Port. Sri Lanka

- **A small fishing port in relatively shallow water**





Images from: google maps

Cyclone: shallow water prevents wave damage

Year	Classification
1906	Cyclonic Storm
1907	Severe Cyclonic Storm
1908	Cyclonic Storm
1912	Cyclonic Storm
1913	Cyclonic Storm
1919	Cyclonic Storm
1922	Severe Cyclonic Storm
1925	Cyclonic Storm
1931	Severe Cyclonic Storm
1964	Severe Cyclonic Storm
1966	Cyclonic Storm
1967	Cyclonic Storm
1978	Severe Cyclonic Storm
1980	Cyclonic Storm
1992	Severe Cyclonic Storm
2000	Severe Cyclonic Storm

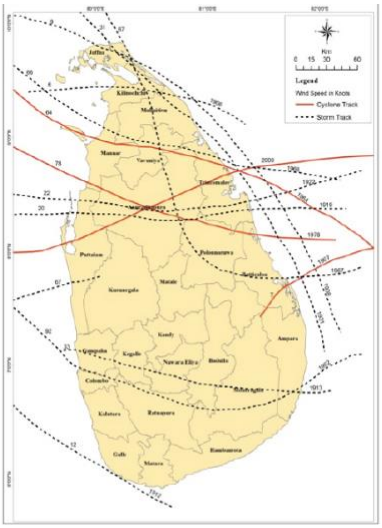


Image from: Dmc.gov.lk: Hazard profiles of Sri Lanka, Chapter 8. Tracks of past cyclones and storms

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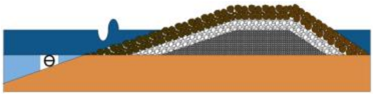
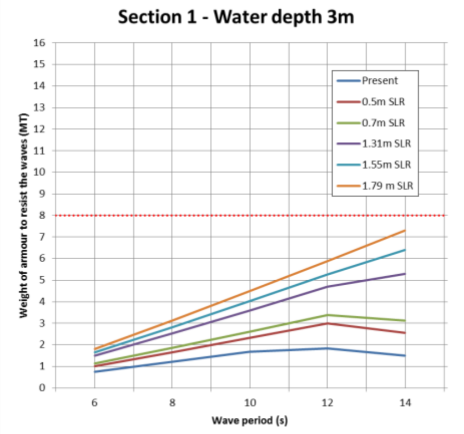
Bathymetry is very important

- **Cross section 1**
  - **Water depth - 3m, Front slope – 1^0**



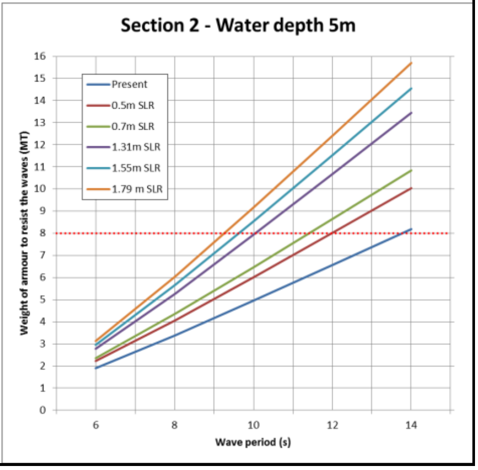
Images from: google maps



The slope of the sea in front of the breakwater is critical!

- Cross section 2
  - Water depth - 5m, Front slope – 3^0

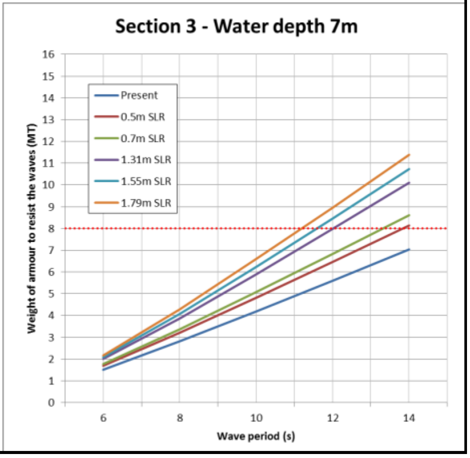
Images from: google maps



How will bathymetry change in the future?

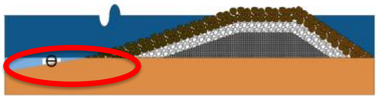
- Cross section 3
  - Water depth - 7m, Front slope – 0.5^0

Images from: google maps



Food for thought: current research

- **By now various researchers are talking about the problems with armour units**
- **SLR will lead to greater waves and stronger longshore movement of sand**



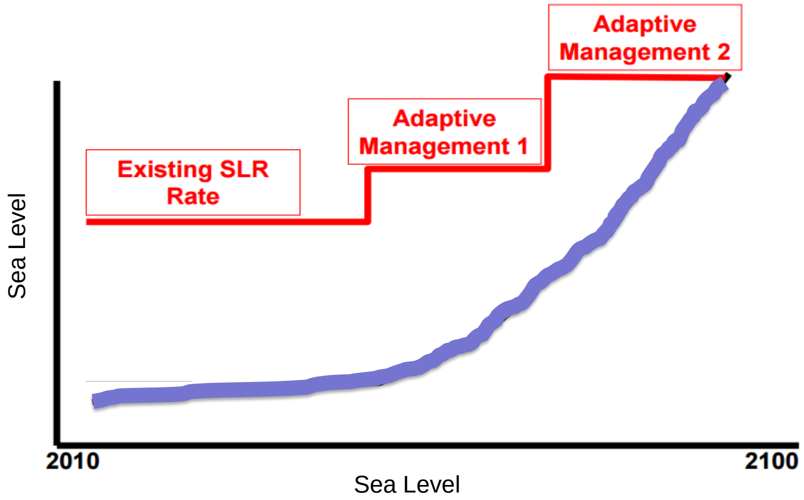
Images from: google maps

- **Problems:**
  - **Toe armour/scour apron requirements are likely to increase!**
  - **More longshore movement means more dredging!**
  - **More dynamic planet: humans don’t like things that move!**

Considerations

- Need to move from a classical engineering design approach to an **adaptive management approach**
- Port installations have **long design lives** (>30 years?) and typically remain in service long after the end of their lives
- In many cases it **does not make financial sense** to build with conditions of 50 or 100 years later in mind
- However, engineers should think about those, and design **structures that can easily be upgraded** (note also the idea of “no regrets” strategies)

Adaptive Management and SLR (Headland, 2011)



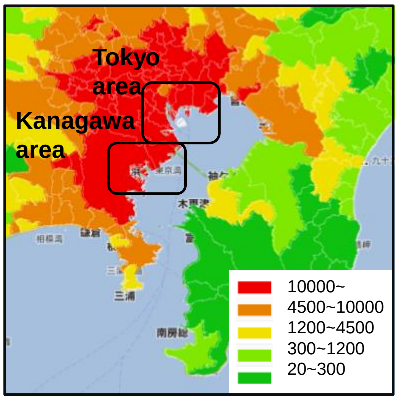
Headland, J.R., 2011. Coastal structures and sea level rise: an optimized adaptive management approach.In: Proc. of Coastal Structures Conference, Yokohama, 6th-8th, September 2011.

Adaptation around Tokyo Bay (Intensified Storm Surges and SLR

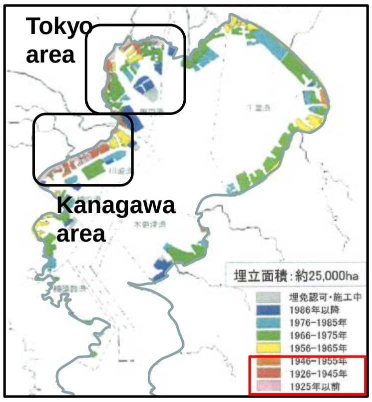
Hoshino, S., Esteban, M., Mikami, T., Takagi, H. and Shibayama, T. (2016) *"Estimation of Increase in Storm Surge Damage Due to Climate Change and Sea Level Rise in the Greater Tokyo Area"*, Natural Hazards, Vol. 80 (1), pp. 539-565.

Areas at Risk in Tokyo bay

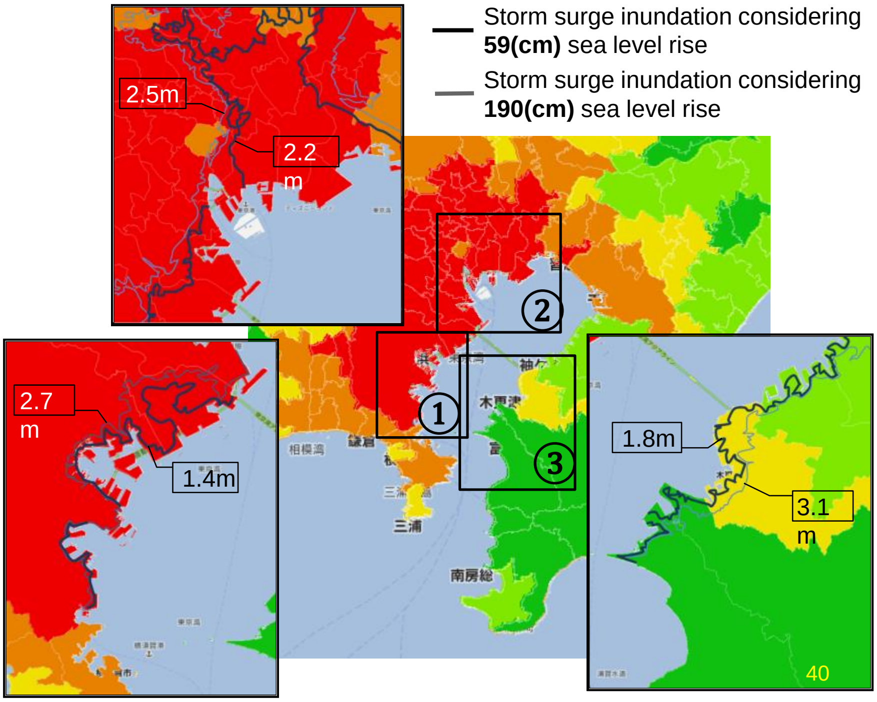
Population / 1km²



Reclaimed lands according to year of construction

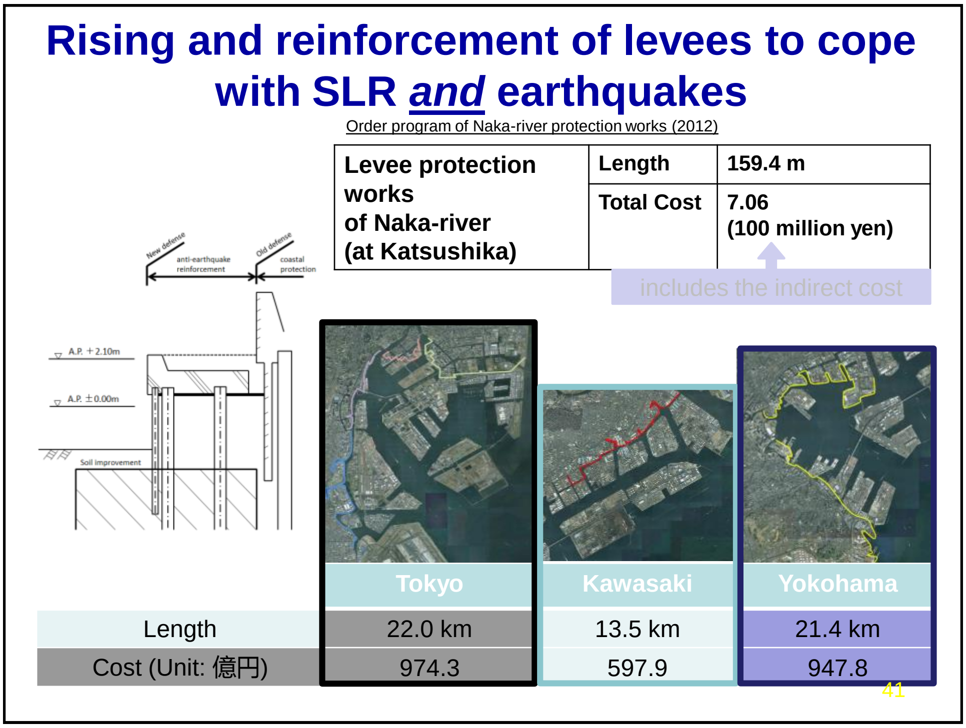


Hoshino, S., Esteban, M., Mikami, T., Takagi, H. and Shibayama, T. (2016) *"Estimation of Increase in Storm Surge Damage Due to Climate Change and Sea Level Rise in the Greater Tokyo Area"*, Natural Hazards, Vol. 80 (1), pp. 539-565.



— Storm surge inundation considering **59(cm)** sea level rise

— Storm surge inundation considering **190(cm)** sea level rise



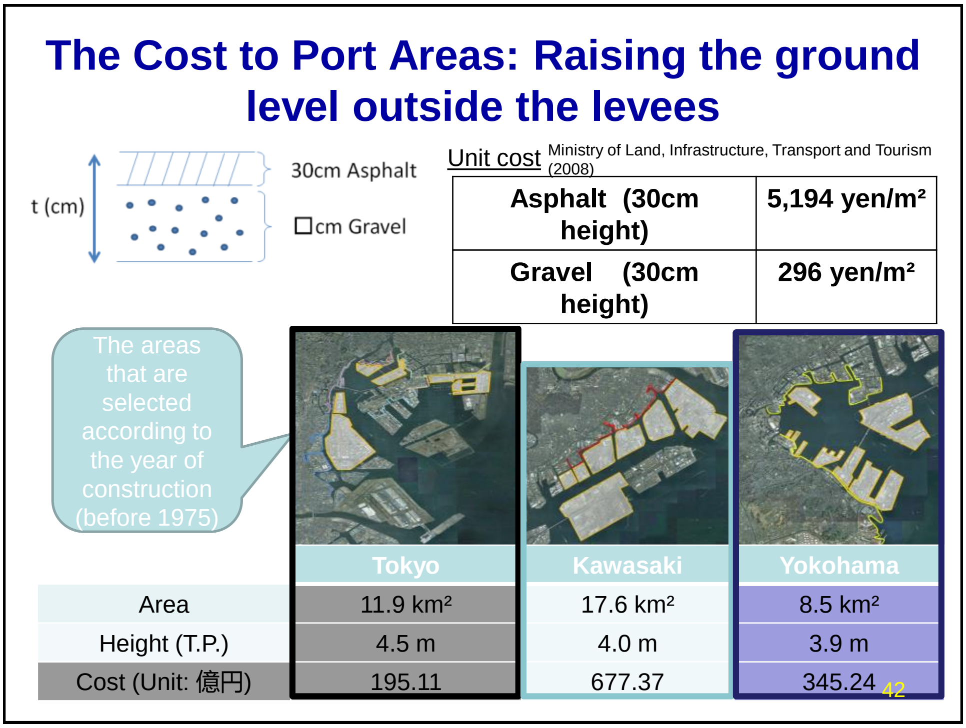
Rising and reinforcement of levees to cope with SLR *and* earthquakes

Order program of Naka-river protection works (2012)

Levee protection works of Naka-river (at Katsushika)	**Length**	**159.4 m**
	Total Cost	**7.06 (100 million yen)**

includes the indirect cost

	Tokyo	Kawasaki	Yokohama
Length	22.0 km	13.5 km	21.4 km
Cost (Unit: 億円)	974.3	597.9	947.8



The Cost to Port Areas: Raising the ground level outside the levees

Unit cost Ministry of Land, Infrastructure, Transport and Tourism (2008)

Asphalt (30cm height)	**5,194 yen/m²**
Gravel (30cm height)	**296 yen/m²**

The areas that are selected according to the year of construction (before 1975)

	Tokyo	Kawasaki	Yokohama
Area	11.9 km²	17.6 km²	8.5 km²
Height (T.P.)	4.5 m	4.0 m	3.9 m
Cost (Unit: 億円)	195.11	677.37	345.24

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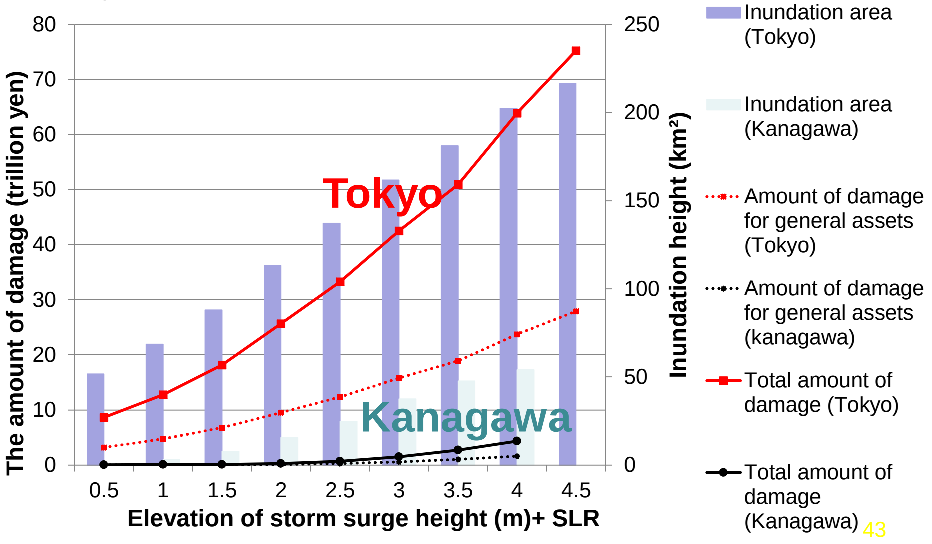
Global Leadership Initiative

Inundation area and economic damage

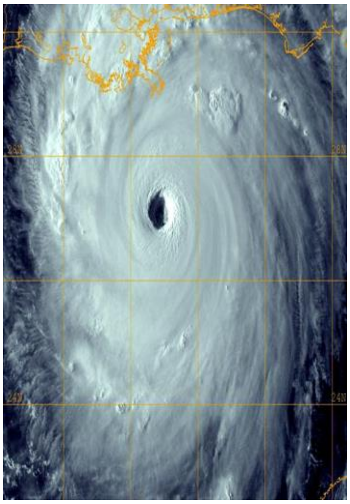


Port Downtime

Esteban, M., Webersik, C., Shibayama, T. (2009) "*Methodology for the Estimation of the Increase in Time Loss Due to Future Increase in Tropical Cyclone Intensity in Japan*", Journal of Climatic Change, Volume 102 (3) pp. 555-578,

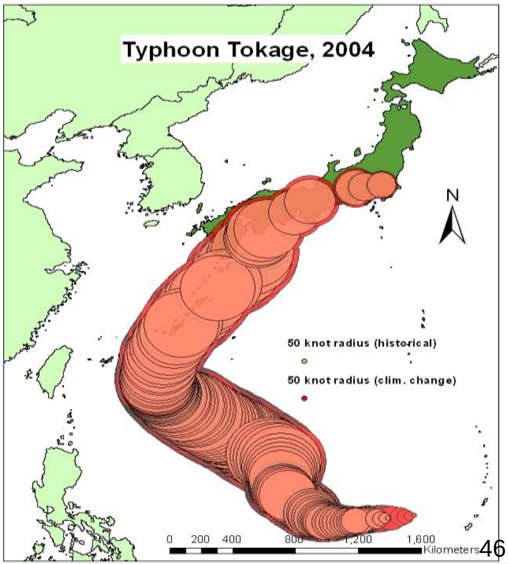
Port Downtime

- **Ports have to close when wind speed is too high, as it interferes with crane operations, etc**
- **Assumed that knots port operation will stop when wind speed is over 30 knots**
- **Disclaimer: Many problems with this and other assumptions, it might be possible to work a bit longer, there is also the issue of preparations for typhoon, etc.**



Increase in Port Downtime (I)

- **If typhoons get stronger, they also get bigger**
- **Carried out a Monte Carlo simulation of how many hours a port is likely to stay closed due to winds higher than 30 knots**

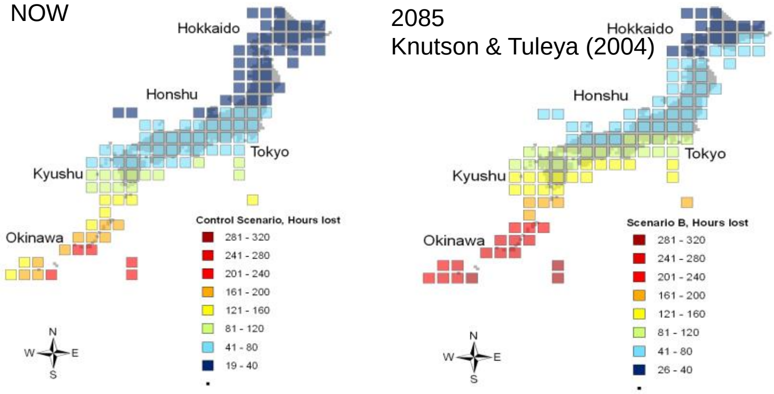


Increase in Port Downtime (II)

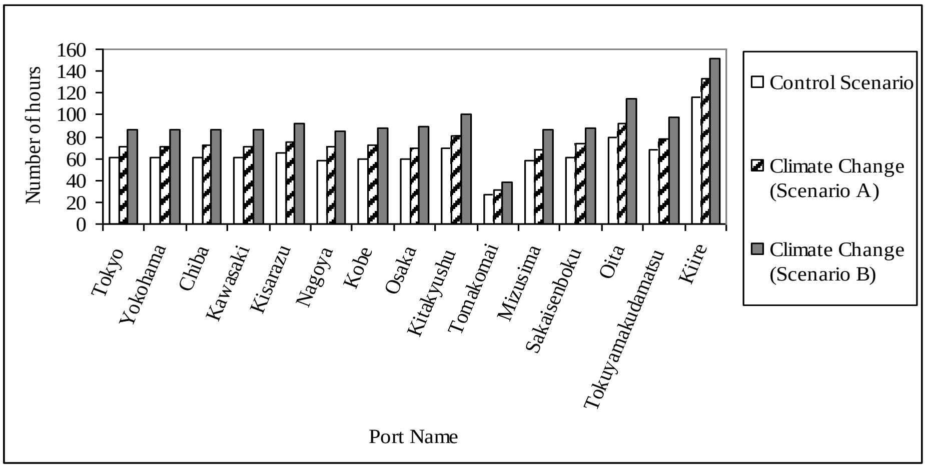
- **All Japan will be affected by 30 knot winds for longer periods in 2085**

NOW

2085
Knutson & Tuleya (2004)

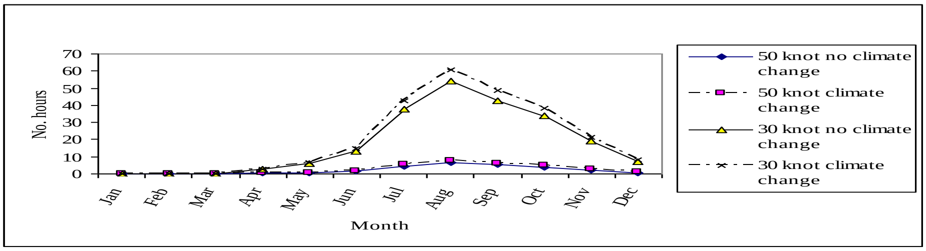


Increase in Port Downtime (III)

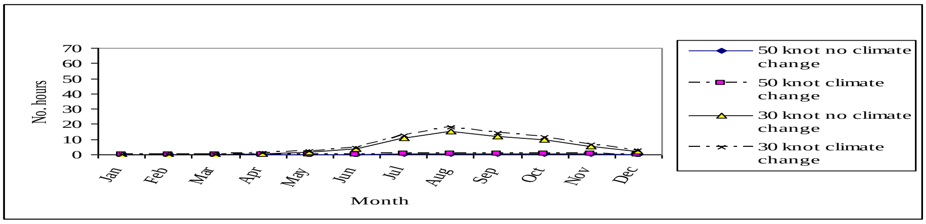


Expected hours that selected Japanese ports are affected by 30 knot winds for the control and climate change scenarios.

Increase in Port Downtime (IV)



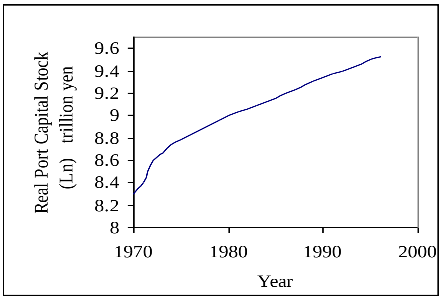
Expected hours that the **Port of Naha** will be affected by various winds for the control and climate change events for each month of the year.



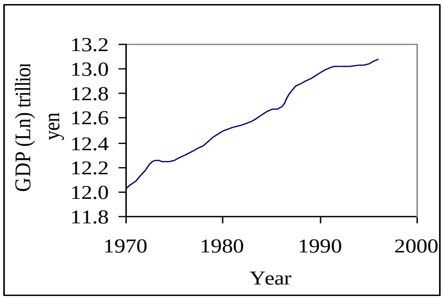
Expected hours that the **Port of Yokohama** will be affected by various winds for the control and climate change events for each month of the year.

Relation between GDP and RPCS

- **Direct correlation between the natural logarithm of the Real Port Capital Stock (*RPCS*) and the growth in Japanese GDP (Kawakami and Doi 2004).**



Growth in *RPCS* in Japan, 1990 Prices in trillion yen (Ln)



Growth in GDP in Japan, 1990 Prices in trillion yen (Ln)

Extra required *RPCS* due to climate change (I)

- If port downtime increases, then port capacities must also be higher to deal with the bottlenecks created by this
- Using the relationships in the previous slide calculated what would be the extra investment needed
- i.e. ports will need to be bigger in the future to deal with increased uncertainty

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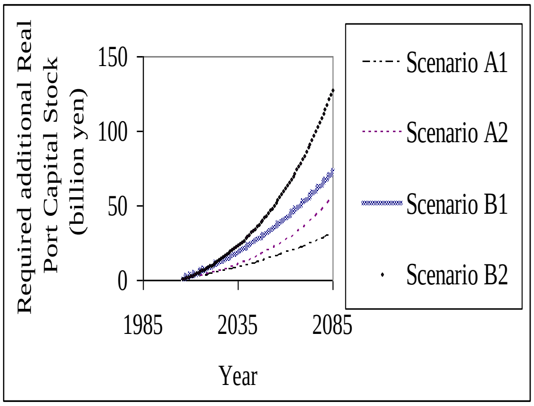
Extra required *RPCS* due to climate change (II)

- 4 Scenarios, depending on rate of economic growth (1 or 2%) and the relationship between maximum wind speed and typhoon area
- 30.6 and 127.9 billion additional Yen required to be invested by the year 2085



- Failure to spend this money could reduce GDP by between 1.5 and 3.4% by 2085.

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There is more but no time…

Thanks for listening!