THE UNIVERSITY OF MELBOURNE

Estimating Global Extreme Sea Levels and the Resulting Impacts for the 21st Century

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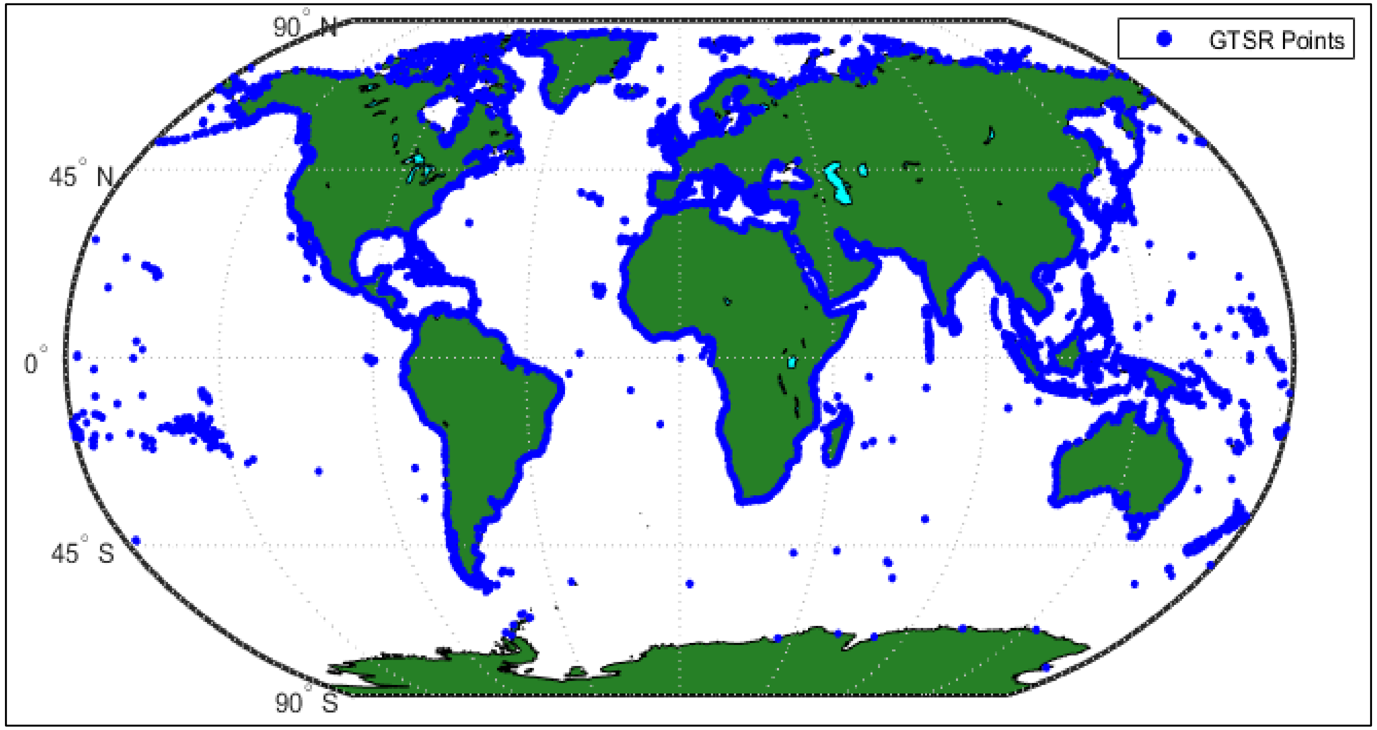
INTRODUCTION
Motivation

- More than 600 million people reside in the low-lying coastal areas (below 10 m from the mean sea level) globally
- Generating approximately US$1 trillion of global wealth
- It is estimated as 0.8–1.1 million people per year are flooded
- Climate Change and Sea level rise will further increase the resulting effects
- Extreme sea levels are of great concern
- There are increasing number of studies on global analysis regarding extreme sea levels

INTRODUCTION
DIVA Database and GTSR dataset

- A sufficient **temporal** and **spatial resolution** for global assessments
- To date, many regional and global extreme sea level studies undertaken based on **Dynamic Interactive Vulnerability Assessment (DIVA)** database for coastal locations
- **Global Tide and Surge Reanalysis (GTSR)** dataset developed by Muis et al. (2016) based on the DIVA input database



GTSR Dataset Locations (we used 9866 points)

METHODOLOGY
Historical Sea Levels

A linear addition of the contributors for mean sea level calculation, we create a 36 years (1979-2014) reanalysis time series with 10 min resolution:

Historical Sea Level = Tide* + Storm Surge + Wave Setup

$$\text{Historical Sea Level} = \underbrace{\text{Tide*}}_{\text{FES2014}} + \underbrace{\text{Storm Surge}}_{\text{GTSM}} + \underbrace{\text{Wave Setup}}_{\text{from ERA-Interim and GOW2}}$$

For 9,866 DIVA locations

We validate the resulting Historical Sea Levels against **GESLA-2** tide gauge dataset among **681 TG locations**

METHODOLOGY
Dataset and Model Descriptions

Tide Model:

Previously in GTSR used FES2012

Here, we adopted the updated version

FES2014:

Better gridding

Improved data assimilation by adding tide gauges in addition to Satellite Altimeter Data

Surge Model:

GTSR surge levels

(modelled previously with Delft3D FM)

6h temporal

0.75° x 0.75° spatial

Time Period:

1979-2014

Wave Setup:

Two SWH datasets:

ERA-I

GOW2

Wave setup is determined with **two methods** among 3 representative bed slopes of

m=1/15

m=1/30

m=1/100

METHODOLOGY
Extreme Value Analyses

- Annual Maxima
  - Generalized Extreme Value (GEV)
  - Gumbel (GUM)
- Peaks over Threshold (P-O-T)
  - Generalized Pareto (GPD)
    - 98.0 – 99.5 Percentiles (0.5 step)
  - Exponential (EXP)
    - 98.0 – 99.5 Percentiles (0.5 step)

As a result we find the $ESL_{historical}$ (ESLs derived from historical data)

METHODOLOGY
Relative Sea Level Rise

- ❖Regional Relative Sea Level Rise scenarios from IPCC AR5 is added (RCP 4.5 and RCP 8.5) for the future ESL calculations
- ❖For each DIVA location we applied

$$ESL_{future} = ESL_{historical} + RSLR$$

Note: average global RSLR across all the DIVA points is 0.21-0.71 m for RCP4.5 and 0.34-0.99 m for RCP8.5 by 2100

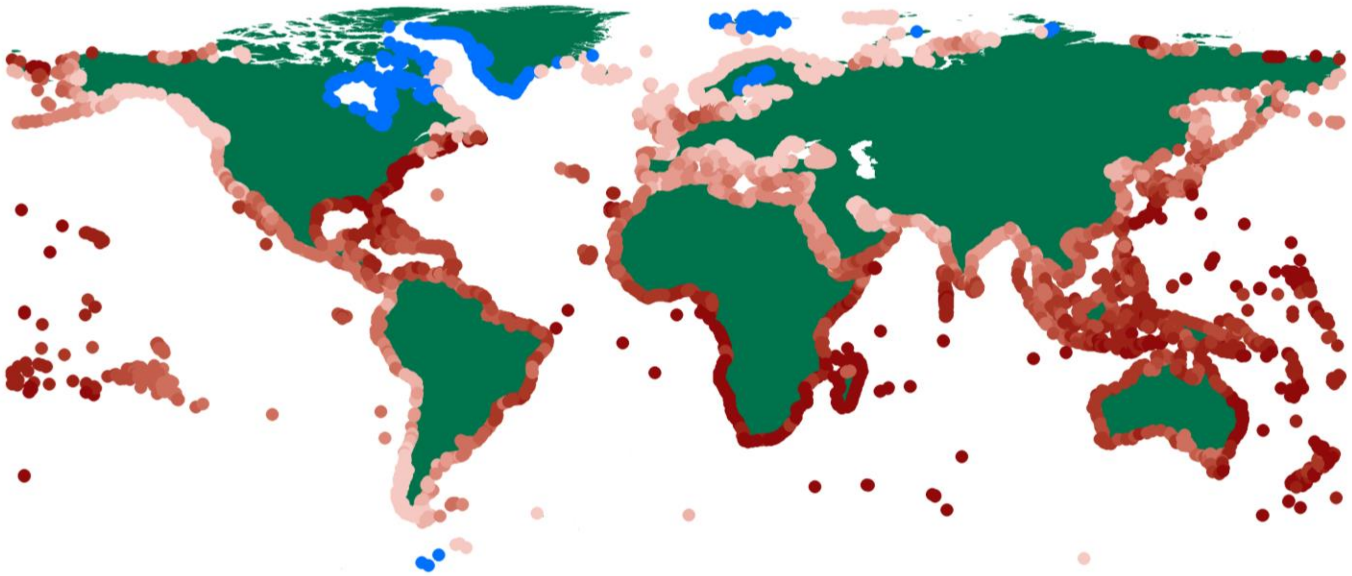


Fig. Regional RSLR at DIVA points for RCP 8.5 in 2100 (blue colour shows negative SLR and red colour shows (0-1m)

METHODOLOGY
Global Inundations

- Inundation Extents are determined for the **present** conditions and for **2050** and **2100** with **RCP 4.5 – RCP 8.5**.
- Firstly, Shuttle Radar Topography Mission (SRTM) is considered
- Problematic due to vertical resolution (1m)
- **Multi-Error-Removed Improved-Terrain DEM (MERIT DEM)** with **1 km** resolution (global scale assessment)
- MERIT DEM is based on SRTM with enhanced vertical resolution
- **Bathtub** approach (connection to coastline)
- Analysed with ArcGIS
- Assumed no coastal protection
- ESLs are originally referenced to mean sea level
- To be consistent with the topographic vertical datum, the GTSR extremes are corrected with **Mean Dynamic Ocean Topography (MDOT)** to determine inundation (Muis et al, 2017)

METHODOLOGY
Societal and Economic Impacts

- Depending on the flooding extents, exposed populations and assets are determined
- Global Population data: Gridded Population of the World (GPW), v4, **30 arc-sec** resolution (~1 km at equator)
- Asset exposure is determined by the approach proposed by Hallegatte et al (2013):

$$\mathbf{A=2.8*P*G}$$

where

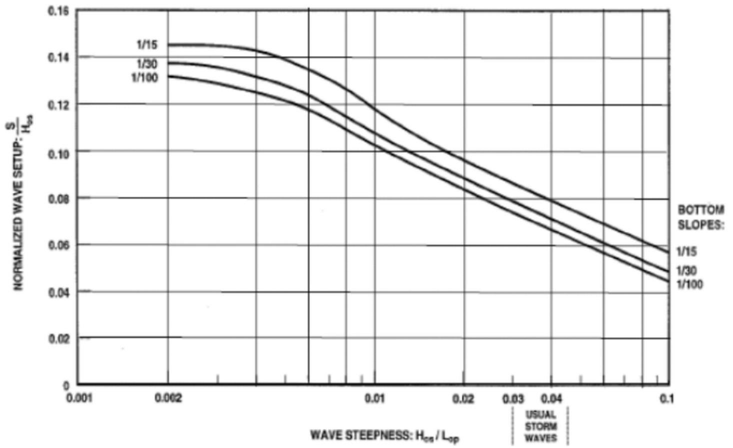
P= population count & **G=** Gross Domestic Product (GDP)

- GDP data: Global gridded GDP data of Kummu et al (2018) with **30 arc sec** resolution (~1 km at equator)

RESULTS
Historical Time Series and Validation

- Wave Setup : ERA-Interim and GOW2 with 1/15, 1/30 and 1/100 bed slopes
- **GOW2 waves** are preferred here as it has higher temporal and spatial resolutions (especially near coastlines)
- A representative bed slope is preferred here as **1/30** to account for the global bed slopes
- Two wave setup formulae:

SPM (1984) and **Stockdon et al** (2006)



$$<\eta> = 0.35\beta_f \left(H_0 L_0\right)^{1/2}$$

Wave Setup **Bed slope**

RESULTS
Historical Time Series and Validation

Among 681 GESLA-2 TG locations

❖**Root Mean Square Error (RMSE)**

T+S	**0.197 m**
T+S+WS	**0.204 m**

Not surprising, WS has impacts during storm events

RMSE is less than 0.2 m at 75% and 0.5 m 93% of locations

❖**Percentile Bias** (to better observe the effects of WS):

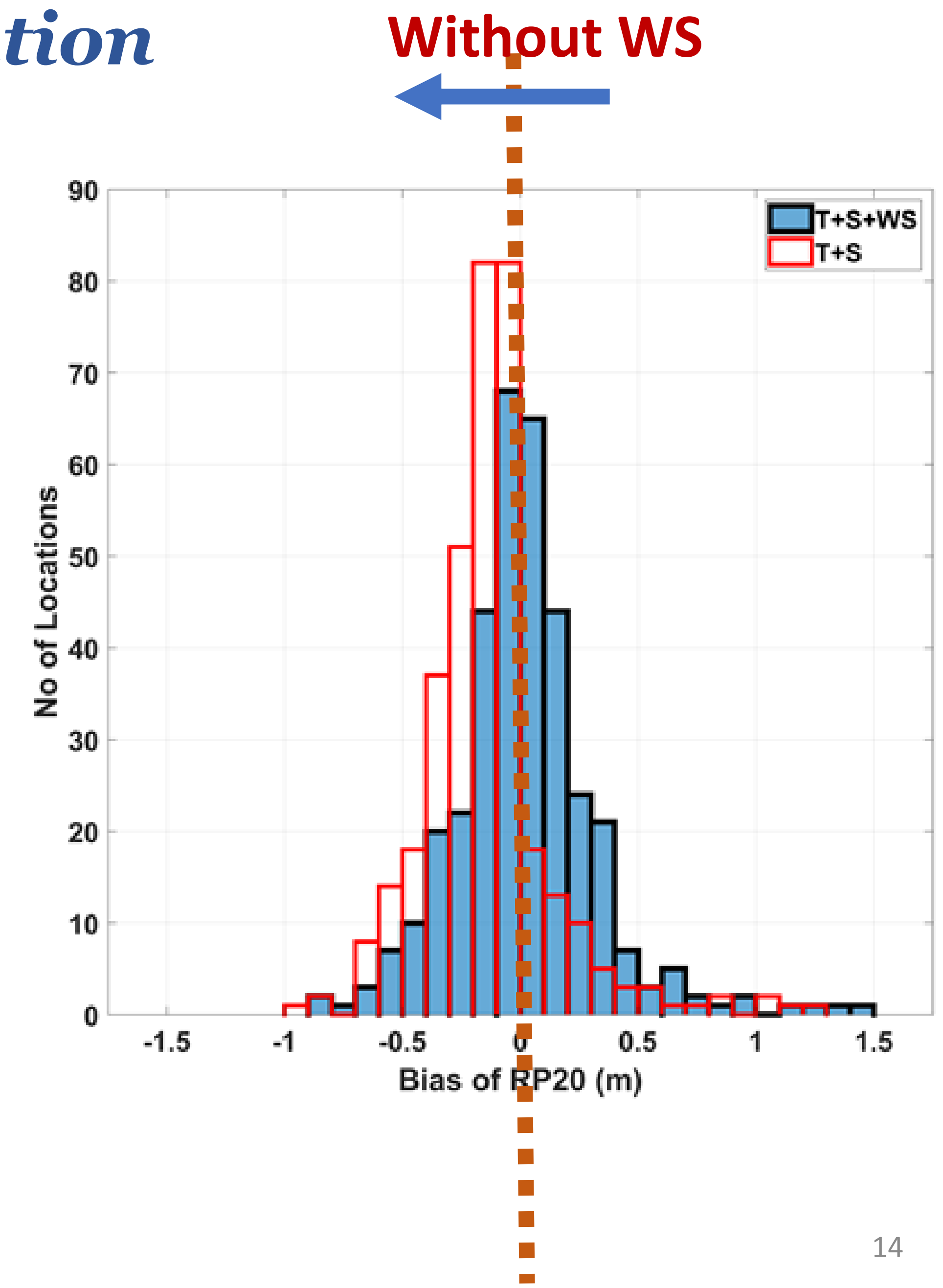
Bias reduced by 60% at the 99th percentiles of timeseries among TG locations, indicating better agreement with WS especially during extremes

RESULTS
Extreme Value Estimates and Validation

- EVA method can make significant impacts on the ESL results.
- The optimal representation of EVA method is determined as

BEST : GPD98 (33% of TG locations, 34% of DIVA locations)

- 20 year return period ESLs are validated against TG location that have at least 20 year timeseries data between 1979-2014



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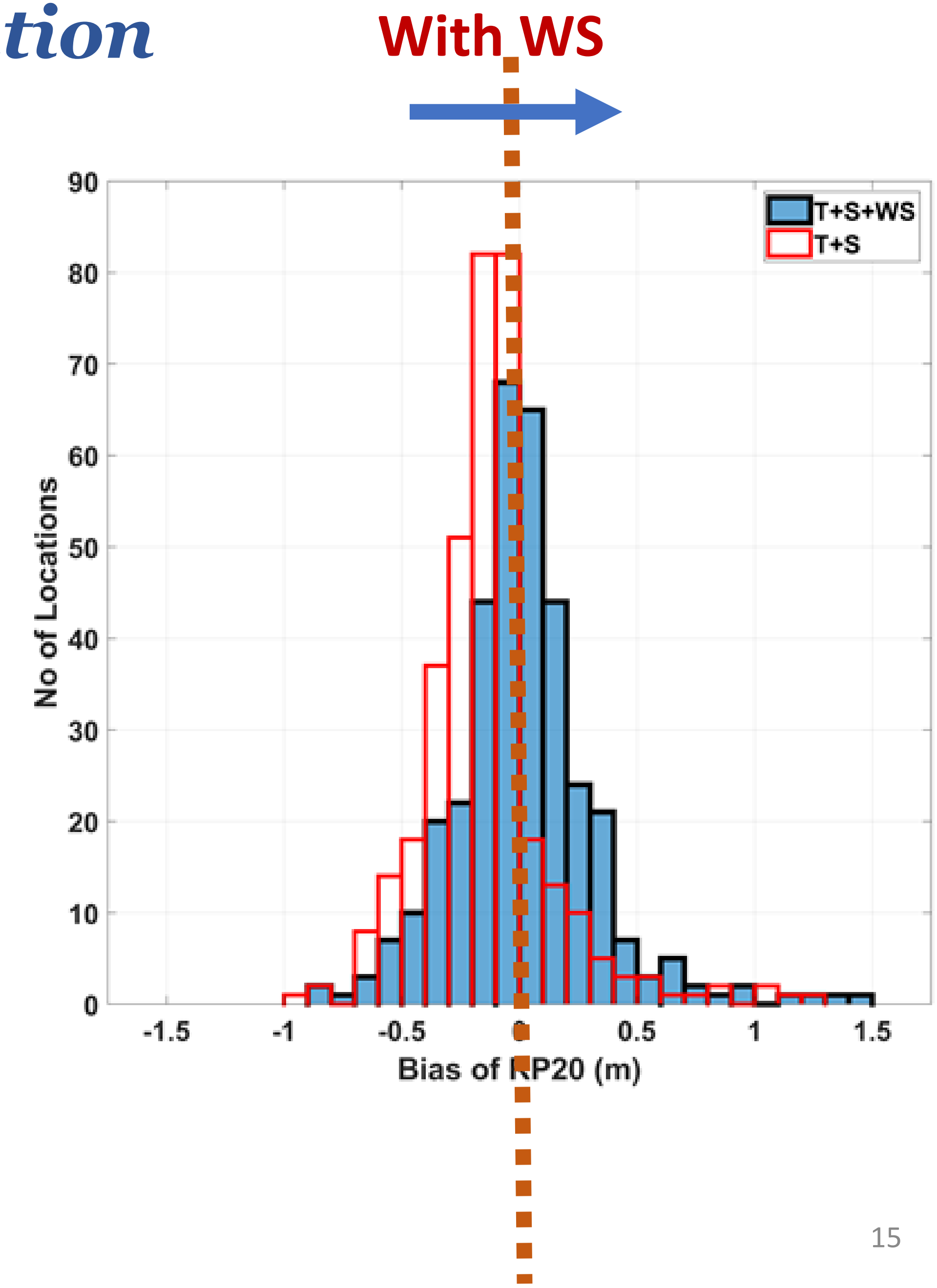
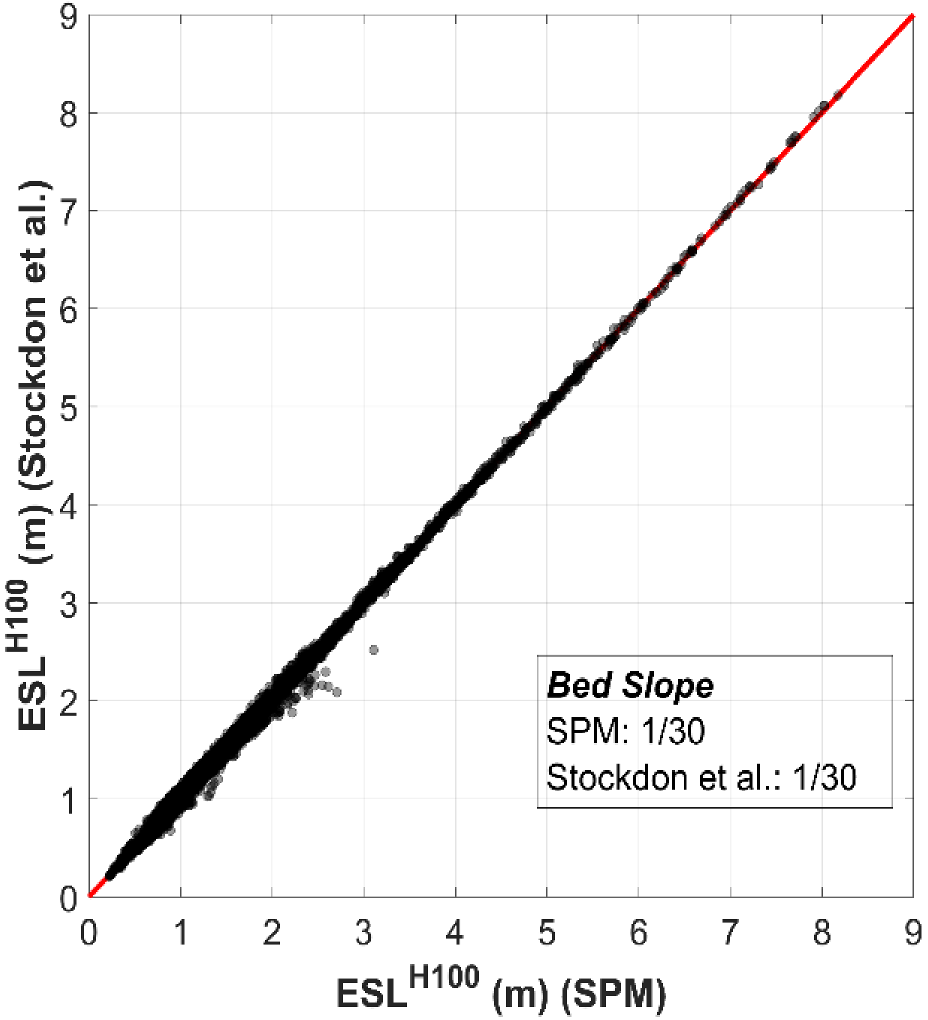
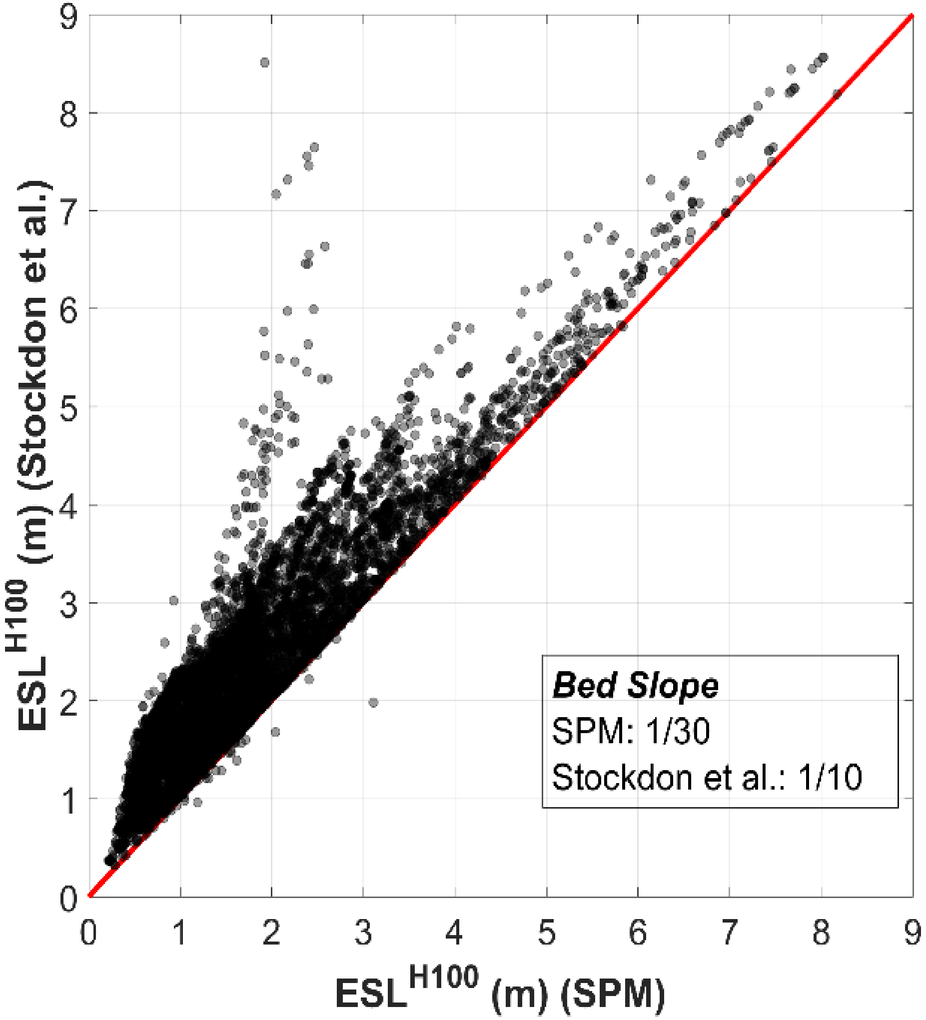
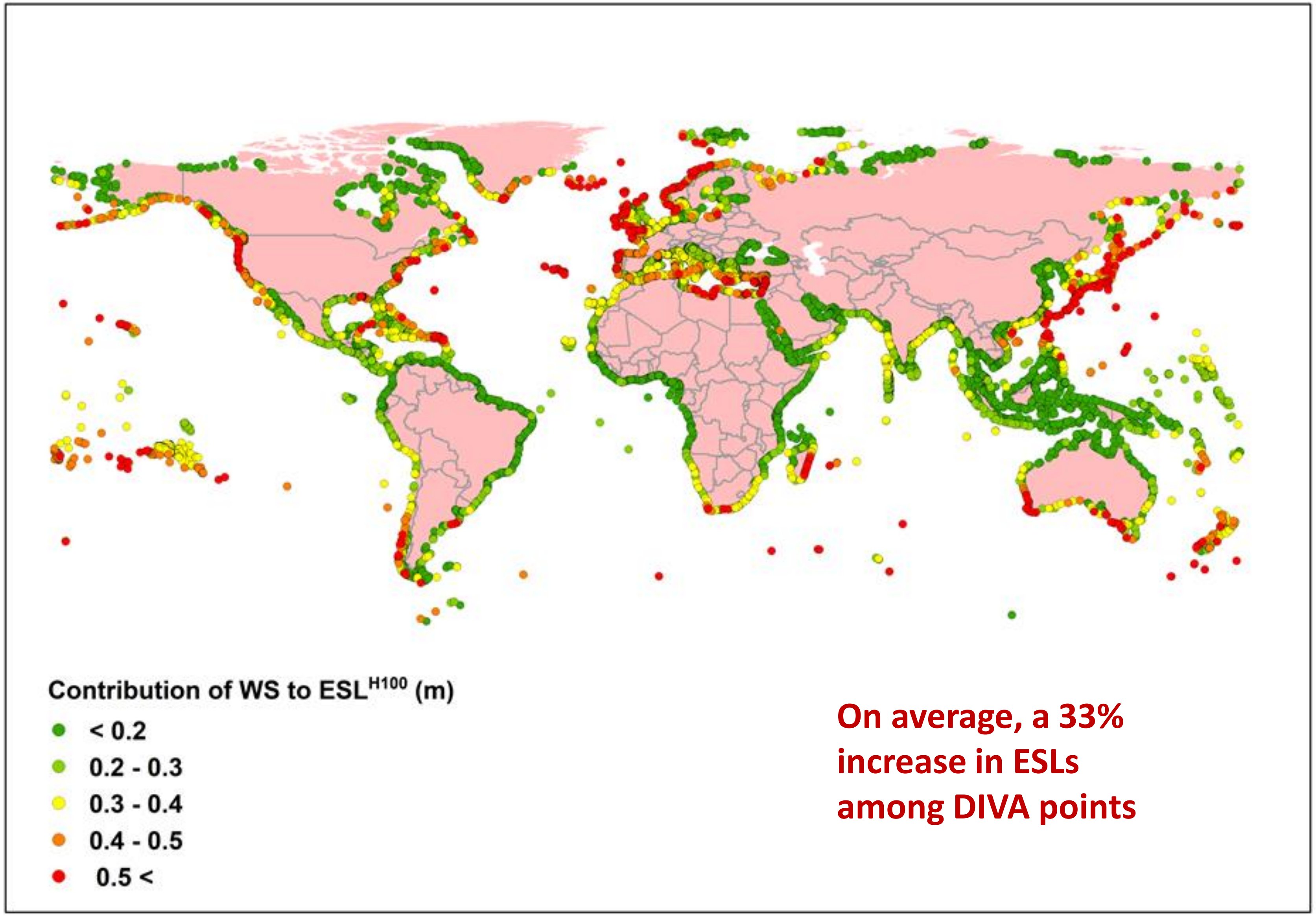


RESULTS
Extreme Value Estimates and Validation -SPM vs Stockdon



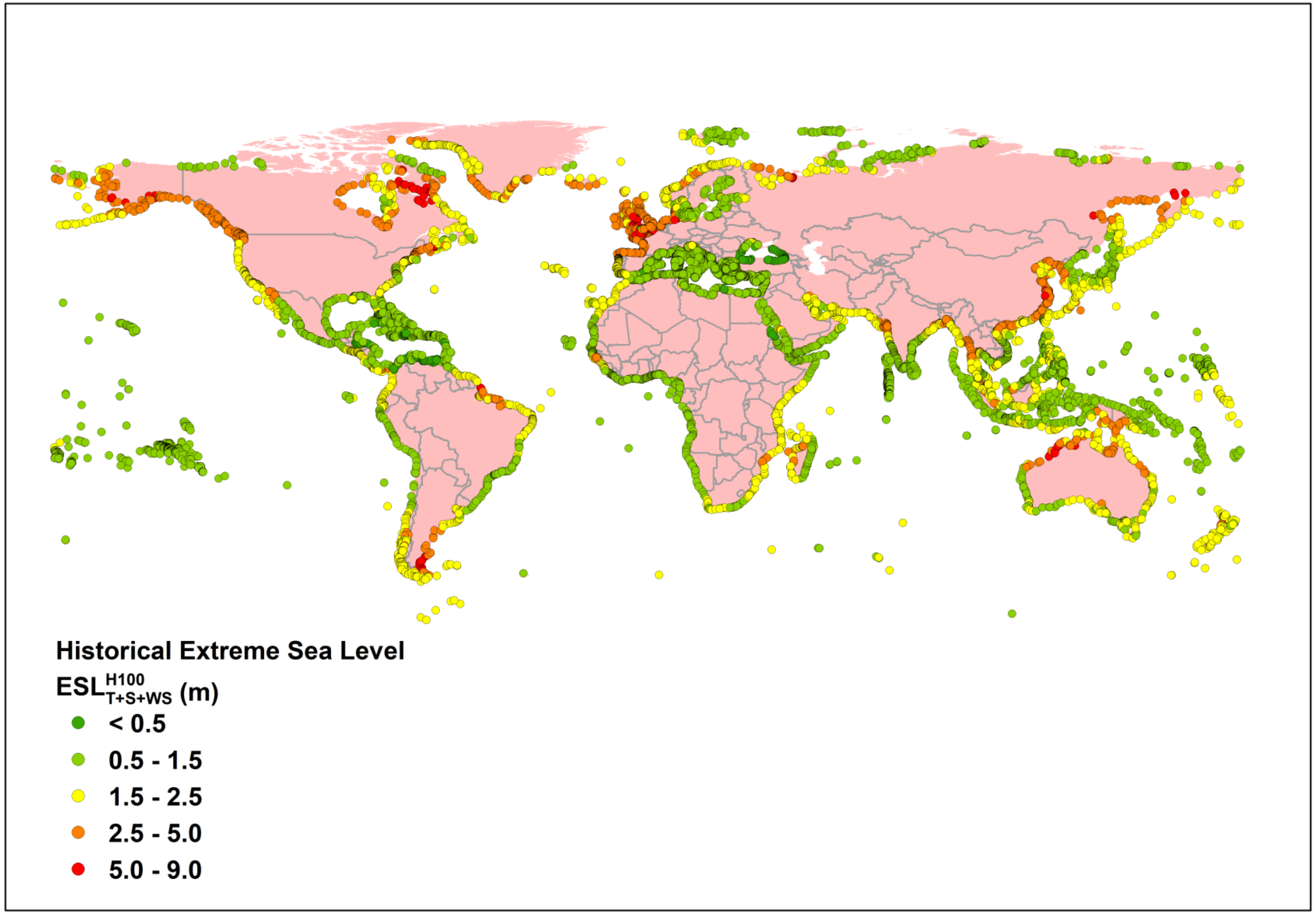


RESULTS
WS contribution on ESL (RP100)

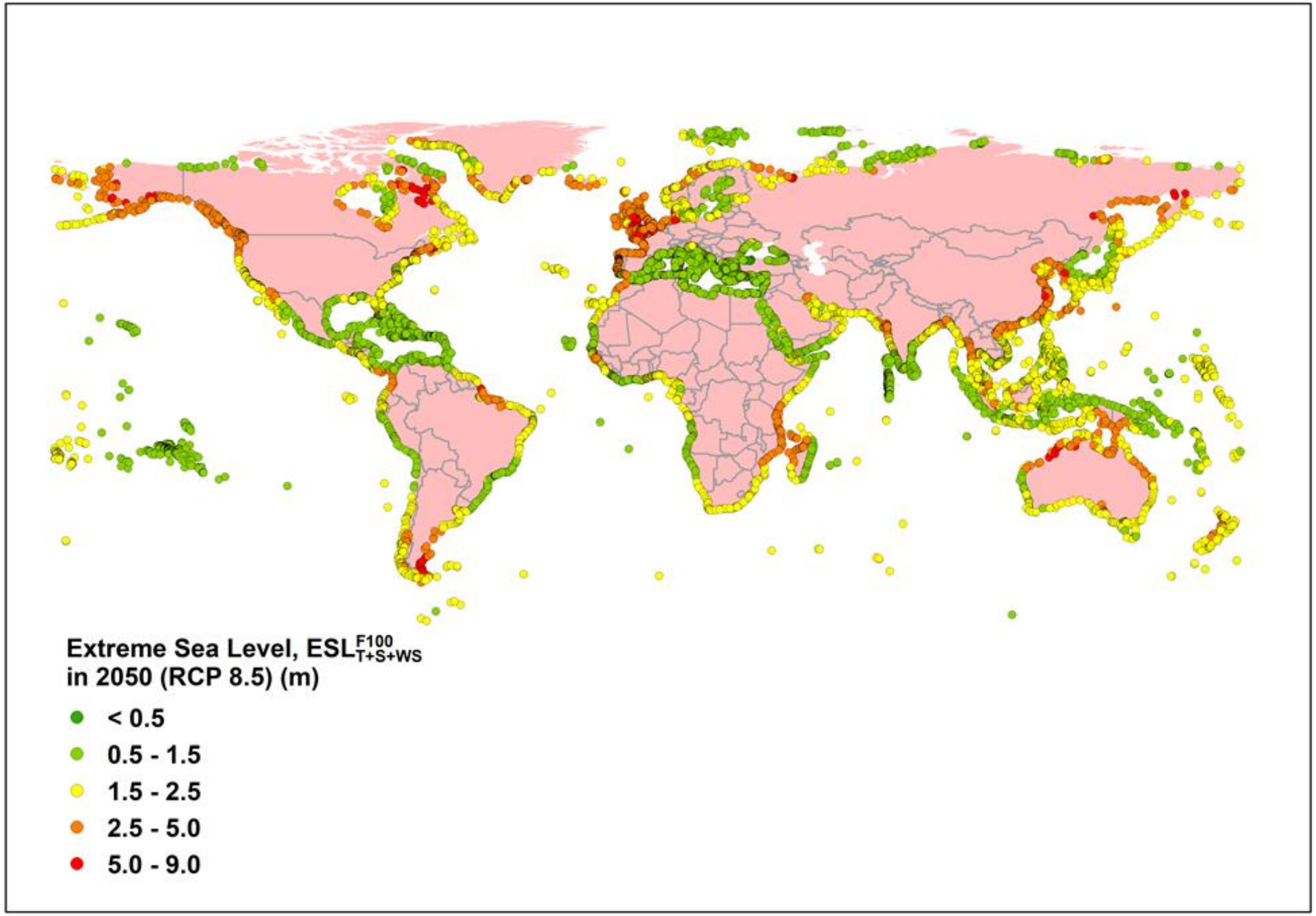


On average, a 33% increase in ESLs among DIVA points

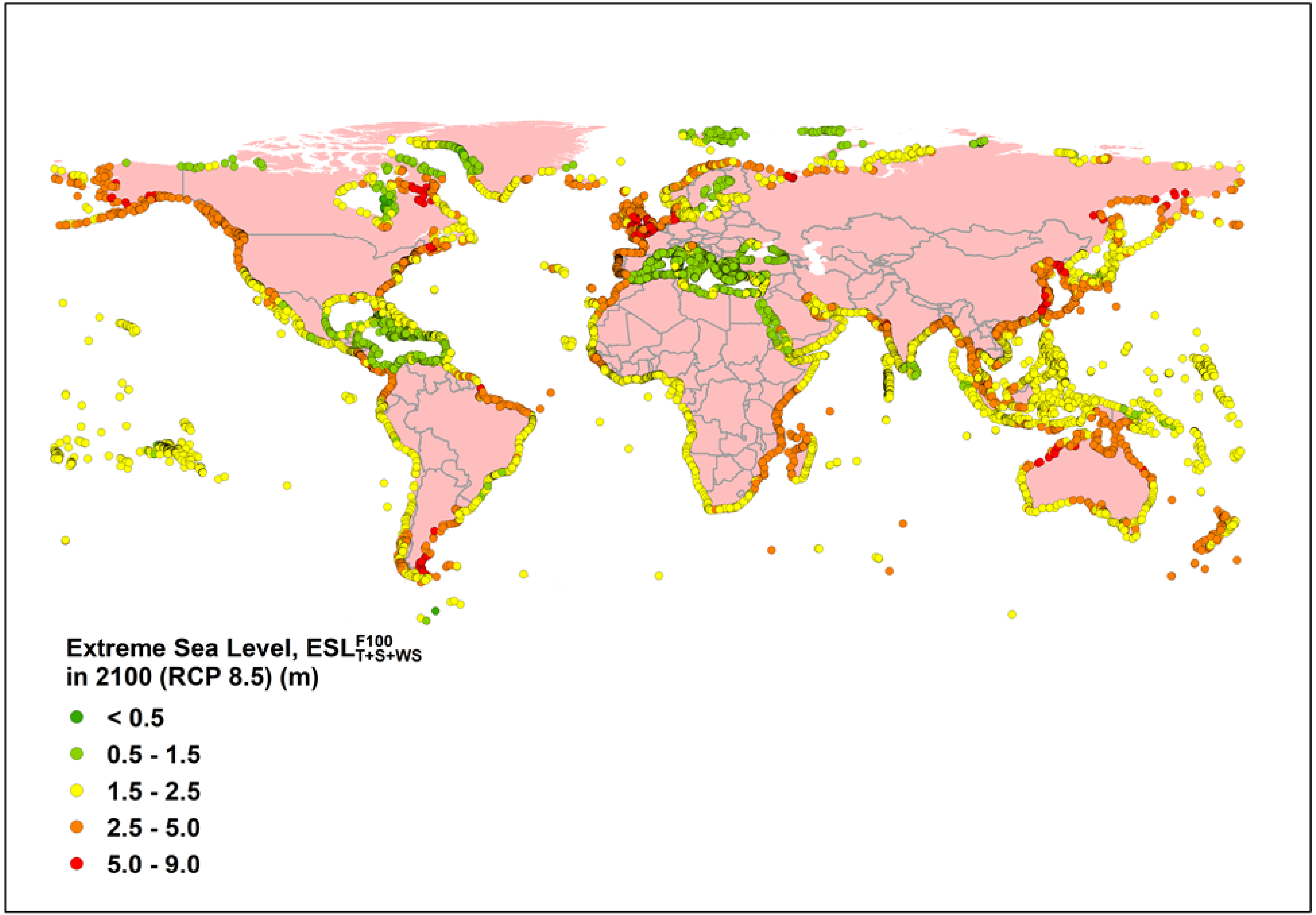
RESULTS
Historical *ESL RP100 (i.e. at present)*



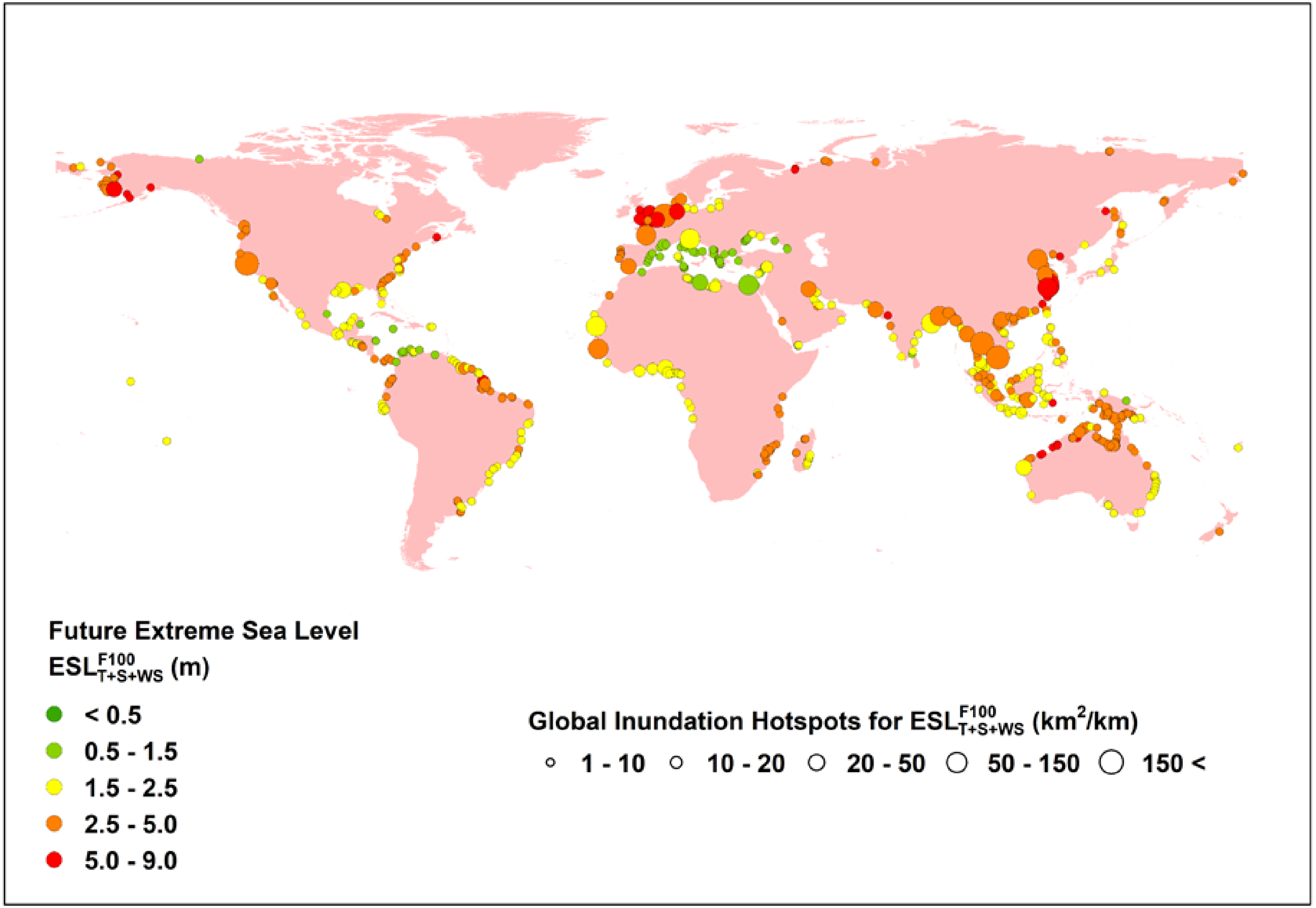
RESULTS
Future *ESL RP100 at 2050*



RESULTS
Future *ESL RP100 at 2100*



RESULTS
Global Coastal Hotspots



RESULTS
Inundation Extents with Uncertainties

RCP4.5	ESL_{lower} (10^3 km^2)	ESL_{mean} (10^3 km^2)	ESL_{upper} (10^3 km^2)	Uncertainty span
$RSLR_{lower}$ (10^3 km^2)	604	647	697	-6.5% to 7.8%
$RSLR_{mean}$ (10^3 km^2)	699	737	789	-5.2% to 7.0%
$RSLR_{upper}$ (10^3 km^2)	797	837	894	-4.8% to 6.7%
Uncertainty span	-13.5% to 14.0%	-12.3% to 13.6%	-11.6% to 13.3%	

RCP8.5	ESL_{lower} (10^3 km^2)	ESL_{mean} (10^3 km^2)	ESL_{upper} (10^3 km^2)	Uncertainty span
$RSLR_{lower}$ (10^3 km^2)	661	700	750	-5.5% to 7.2%
$RSLR_{mean}$ (10^3 km^2)	779	819	874	-4.9% to 6.8%
$RSLR_{upper}$ (10^3 km^2)	915	956	1,009	-4.3% to 5.6%
Uncertainty span	-15.1% to 17.5%	-14.5% to 16.8%	-14.2% to 15.4%	

RESULTS
Population and Asset Exposure

- Inundation extent increases by **6%** with **WS** contribution only for the present conditions
- For RCP 8.5, **16%** increase by **2050** and **48%** increase by **2100**
- Potential affected population will increase by **17%** by **2050** and **52%** by **2100**
- Exposure of assets increase **15%** by **2050** and **46%** by **2100**

Inundation extent and Population and Asset Exposure		Inundated Area without WS (10^3 km^2)	Inundated Area with WS (10^3 km^2)	Population Exposed (million people)	Asset Exposed (10^9 US$2011)
Present Day		521	553	148	7,761
2050	*RCP4.5*	593	631	171	8,848
	RCP8.5	601	640	173	8,961
2100	*RCP4.5*	702	737	202	10,222
	RCP8.5	779	819	225	11,301

$$A=2.8*P*G$$

where

P= population count & G= Gross Domestic Product (GDP)

Note: Population and GDP data is based on year 2015

DISCUSSION and CONCLUSION

- Increase in coastal flood risk requires a global assessment to **highlight high risk coastal zones/hotspots for the upcoming century**
- Number of datasets adopted to determine from the time series of sea levels to reach to the potential exposure of coastal areas
- *Wave setup contribution is considered here, which was given less attention in previous studies*
- *Two different wave setup calculation approaches are analysed and found insignificant difference wrt ESLs*
- *On the other hand, WS is a significant contributor while extremes happen*
- Both historical timeseries and the derived ESLs are validated with wide extent of global TG data
- Number of EVA methods compared and best fitting is determined (GPD 98)
- Regional-Relative Sea Level Rise is considered as SLR shows significant difference along coastal locations
- Uncertainty analysis is conducted wrt the EVA method used as well as the upper-lower bounds of the SLR scenarios (RCP 4.5 and RCP 8.5)

DISCUSSION and CONCLUSION

- A GIS based bathtub approach is applied for determining the inundation extent, with an enhanced version of topography (MERIT DEM)
- Potential exposure of the population and as correlated, the exposed assets are determined.
- By **2100**, with **RCP 8.5**, we estimate **52%** increase among the affected population and 46% increase of the global assets comparing with the present ESL conditions.
- For **RCP8.5**, **0.6%** of the world's land area will be at risk of episodic coastal flooding by 2100 from a **1 in 100-year return period event**, impacting **3%** of the world's population and threatening assets worth up to **18%** of global GDP.
- Tide and storm surge will account for **63%** of the global area inundated by 2100, with relative sea level rise accounting for **32%** and wave setup accounting for only approximately **5%**.
- Projected sea level rise will significantly increase the frequency of coastal flooding by 2100, with results herein showing that for most of the world, flooding associated with a present day **1 in 100-year event** could **occur as frequently as once in 10 years**, primarily as a result of sea level rise

THANK YOU