EVALUATION OF SHALLOW WATER FRICTIONAL TIDES IN HONG KONG (AND OTHER ANOMALIES) AND PROJECTIONS OF 21ST CENTURY SEA LEVEL RISE IN THE CHINA SEAS

ADAM T. DEVLIN [1], JIAYI PAN [1, 2]

[1]THE CHINESE UNIVERSITY OF HONG KONG

[2]NANJING UNIVERSITY OF INFORMATION SCIENCE AND TECHNOLOGY, MARINE SCIENCE COLLEGE

香港中文大學 The Chinese University of Hong Kong

南京信息工程大學 Nanjing University of Information Science & Technology

香港天文台 HONG KONG OBSERVATORY

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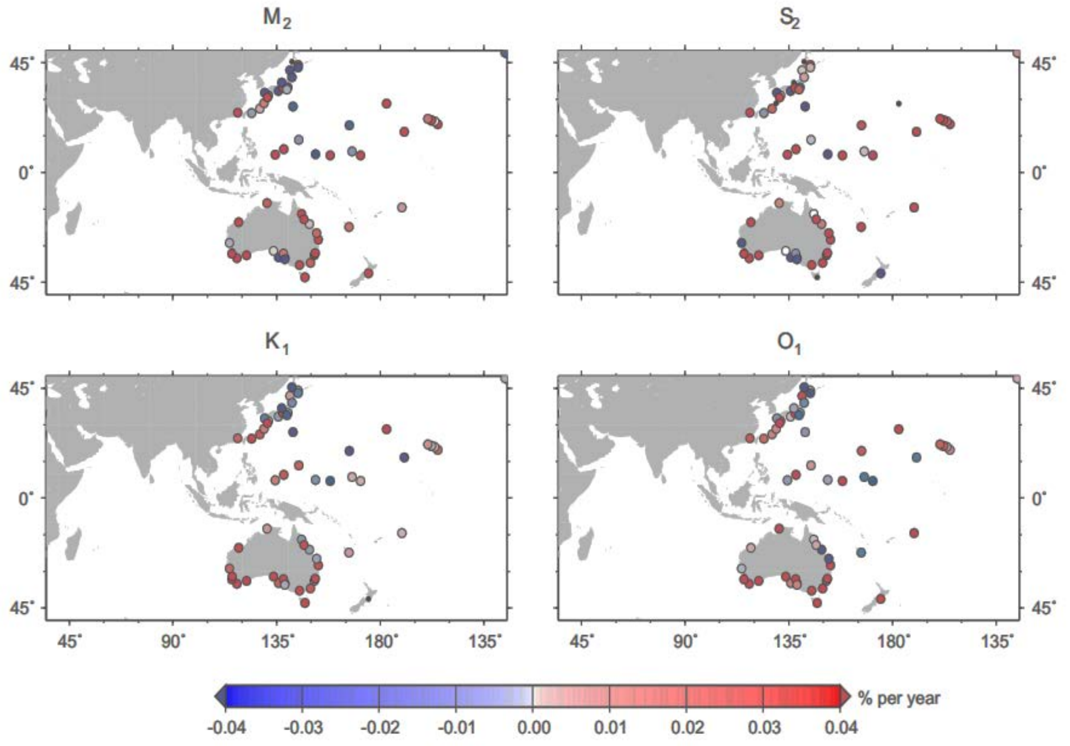
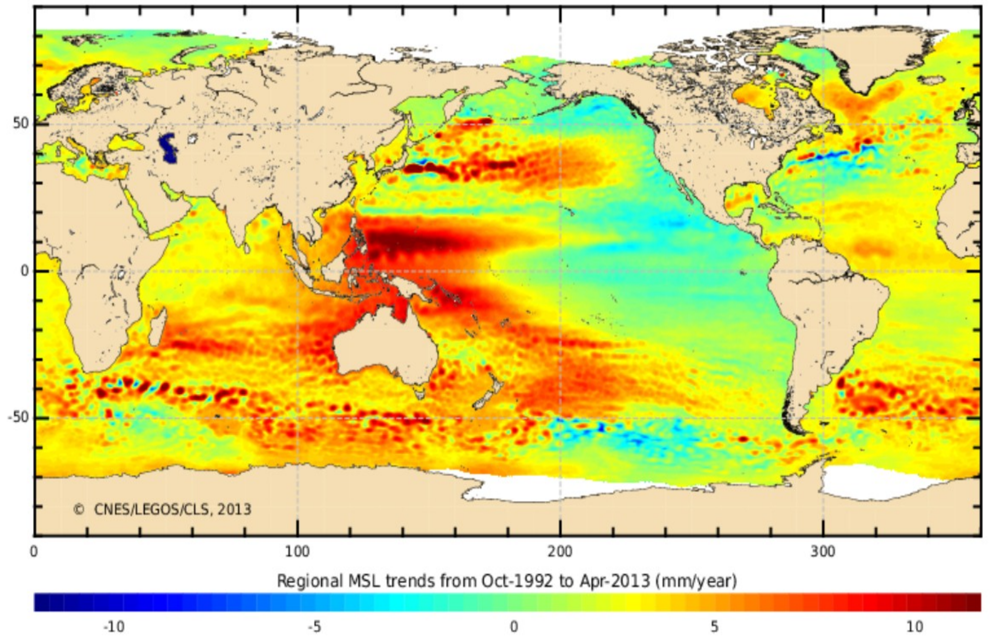
2017年6月26-30日，丹麦 哥本哈根

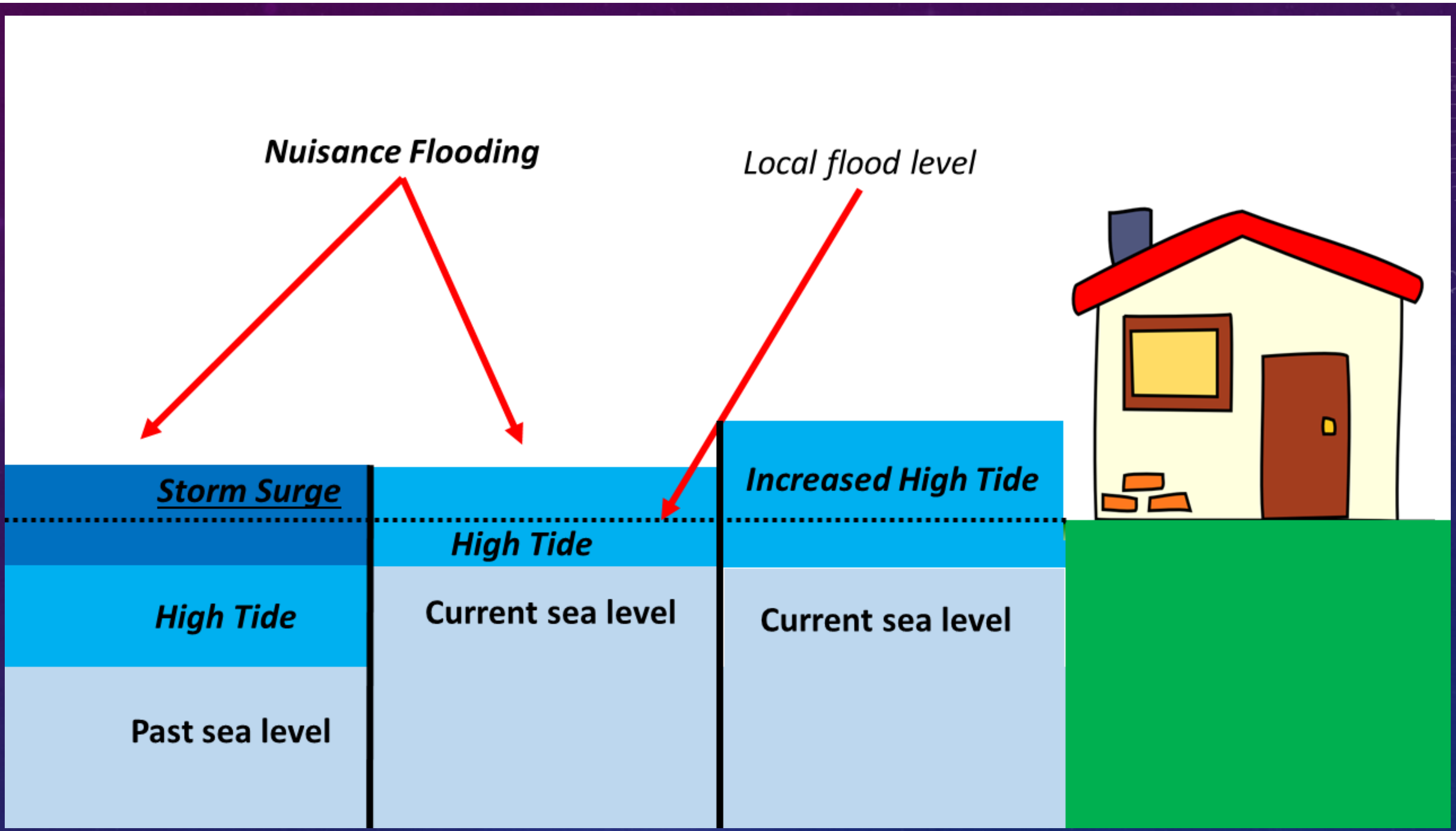
OVERVIEW

- The long-term trends of ocean tides are changing due to non-astronomical reasons (Woodworth, 2010; Jay, 2009)
- The globally-averaged long-term trend in mean sea level (MSL) is +3.4 mm/yr as determined by altimetry (Church et al., 2011), but trends have a regional bias.
- Tides and MSL also exhibit changes at shorter time scales (seasonal to decadal), and these variabilities may be as important as long-term trends in determining the future of total sea levels (TSL).





NUISANCE FLOODING



- Simple cartoon showing the effect of nuisance flooding. In the past, when sea levels were lower, it would take a large storm surge, such as a hurricane or typhoon to cause nuisance flooding, but more recently, as sea levels have risen, nuisance flooding may happen at high tide, and is much more frequent. Furthermore, if tides also change, than inundation will be greater.

PROJECTIONS OF THE 21ST CENTURY SEA LEVEL RISE IN THE CHINA SEAS FROM CMIP5 MODELS

Meixiang Chen, Wenhao Zhang, Qing Xu*

College of Oceanography, Hohai University

Nanjing, Jiangsu, China

*** chenmeixiang@hhu.edu.cn**

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Coupled Sea Level Change Models

CMIP5: includes the latest generation of climate and Earth system models, provides scientific data to support the fifth assessment report (AR5, 2014) of the IPCC.

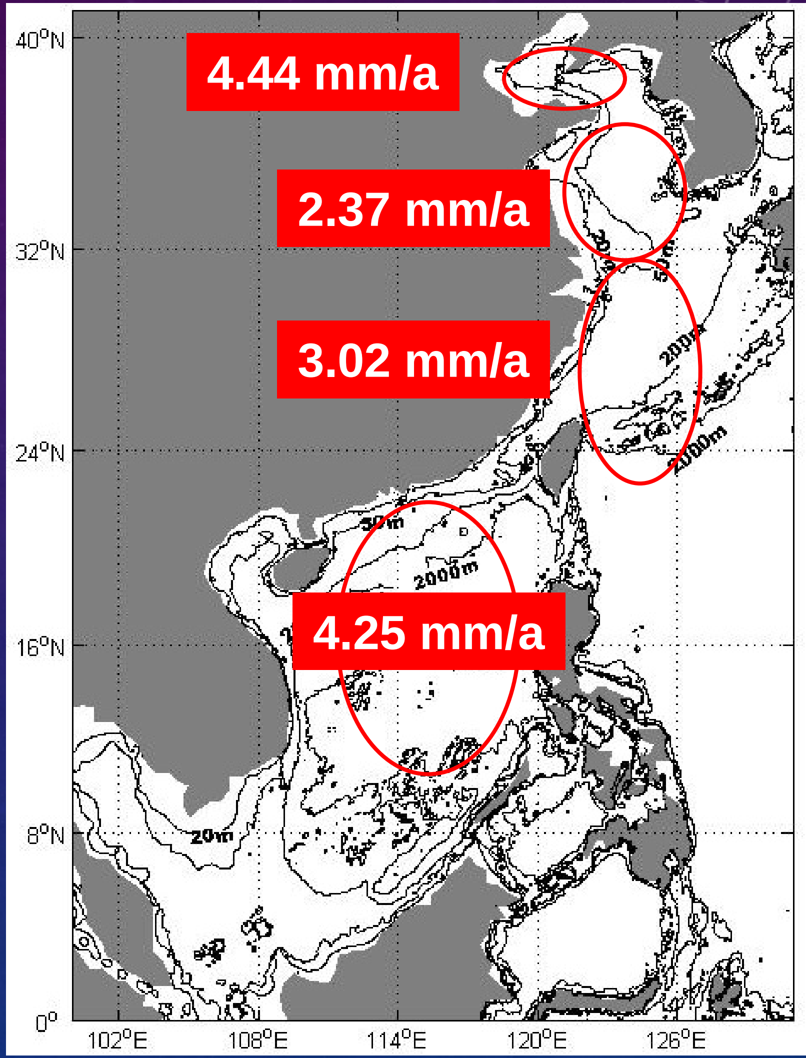
New scenarios called **Representative Concentration Pathways (RCPs)** are used in CMIP5 which describe a wide range of the main drivers of climate change including greenhouse gas and air pollutant emissions and land use (Moss et al., 2010).

Four Representative Concentration Pathways used in AR5 (IPCC)

RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO_2 eq) by 2100.
RCP6	Stabilization without overshoot pathway to 6 W/m^2 (~850 ppm CO_2 eq) at stabilization after 2100
RCP4.5	Stabilization without overshoot pathway to 4.5 W/m^2 (~650 ppm CO_2 eq) at stabilization after 2100
RCP2.6	Peak in radiative forcing at ~3 W/m^2 (~490 ppm CO_2 eq) before 2100 and then decline (the selected pathway declines to 2.6 W/m^2 by 2100).

About 10% of the coastal areas of the China Seas is less than 5m above the sea level (Du et al., 1997), these areas are vulnerable to SLR.

Guo et al. (2015) evaluated the rate of the SLR during 1993-2012 based on altimeter data over the China Seas, showing most of the China Seas exhibits a larger rate of SLR than the global mean (3.4 mm/yr).



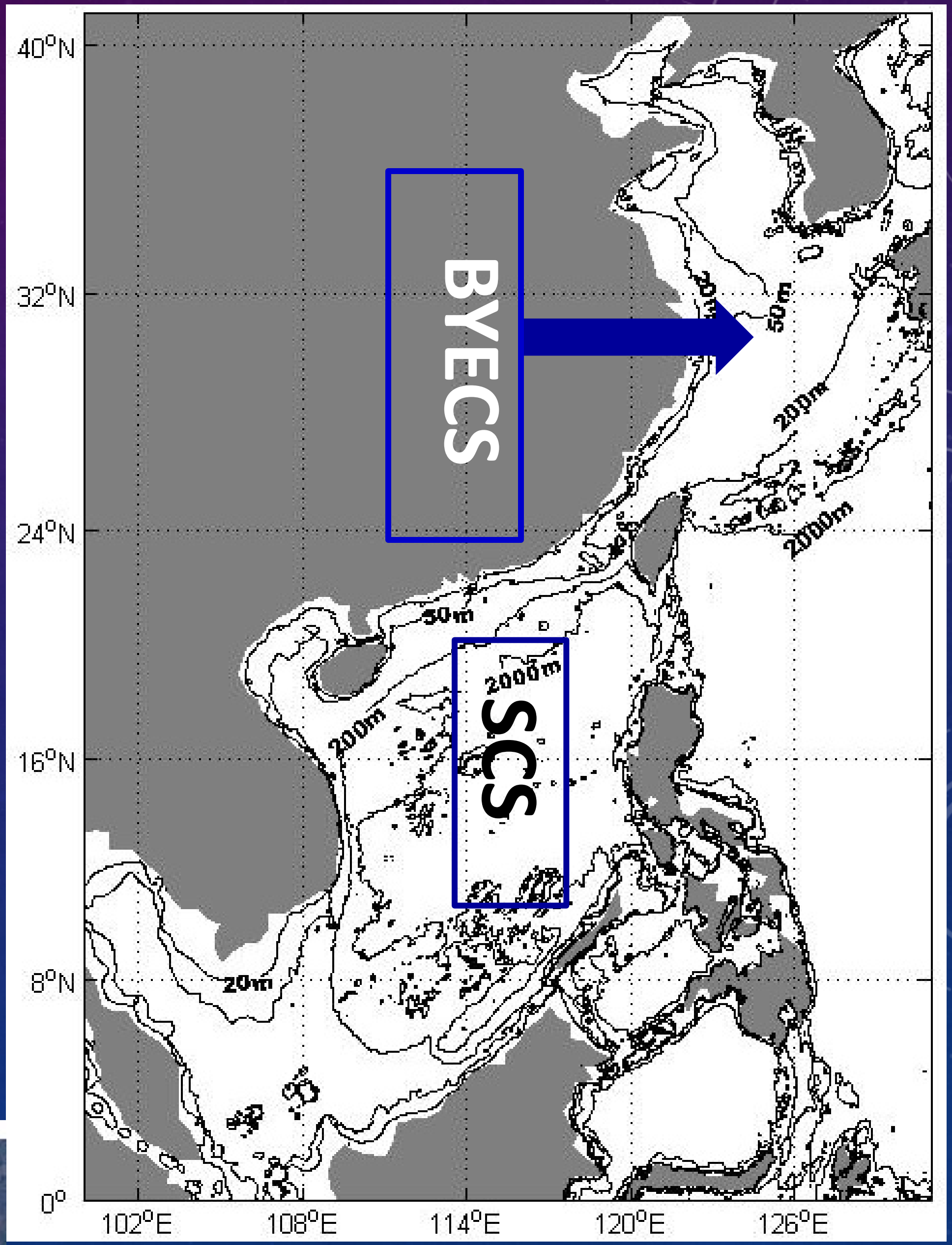
Bathymetry of the China seas. The 20, 50, 200, 2000m isobaths are shown.

Yin (2012) discussed the century to multi-century global sea level rise projections from CMIP5 models, but did not discuss the marginal seas.

<u>We will discuss what will happen in the China seas in the 21st century.</u>

BYECSs: mainly continental shelf, the depth is less than 200m

SCS: marginal sea, has deep basin.



Different forms of sea level change

- *Dynamic sea level (DSL):* approximately is the real sea level, i.e., the sea level deviation from the global mean, and represents the horizontal gradient of the sea level related to sea surface winds and ocean currents, obtained directly from the output of models.

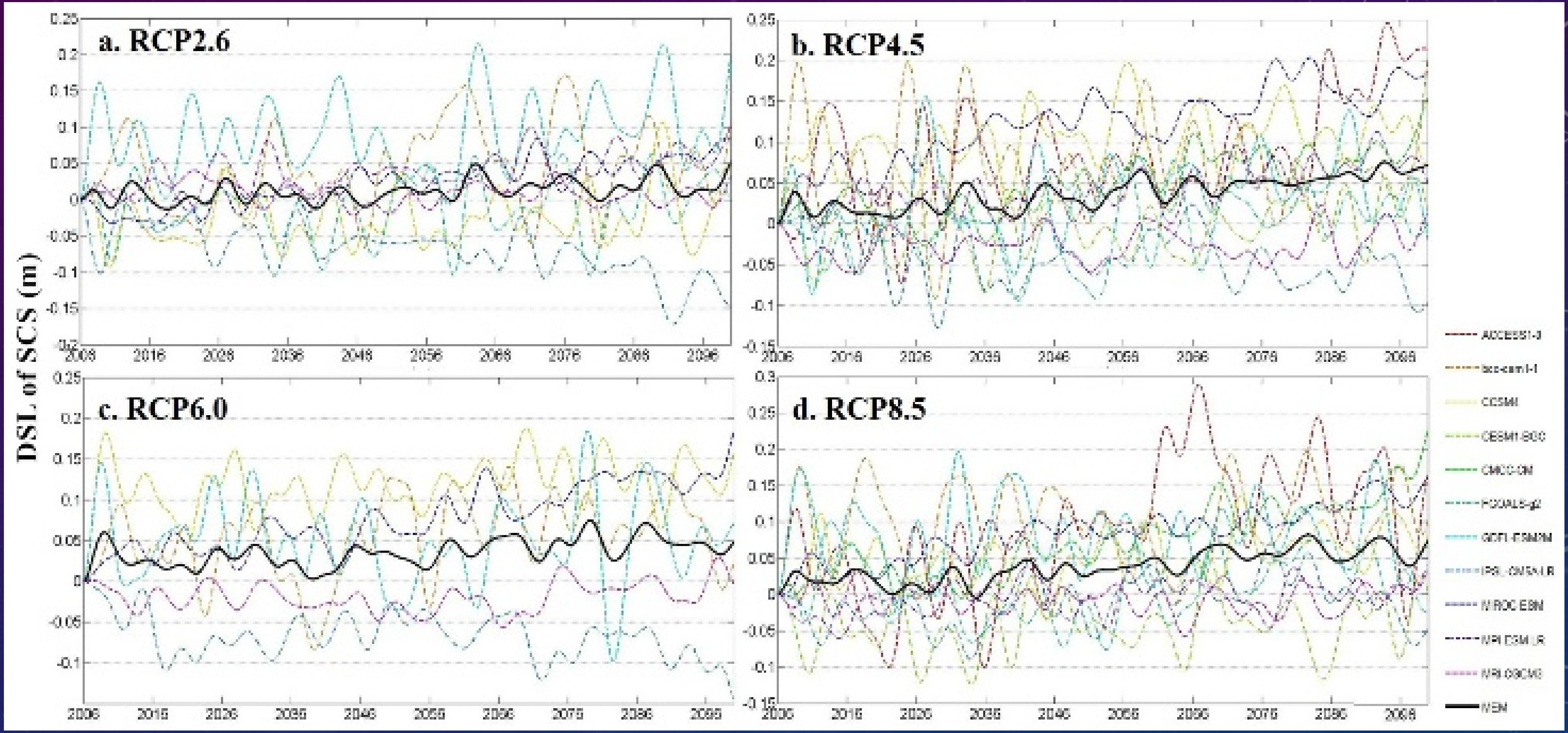
- *Steric sea level (SSL)*: volume change of the seawater induced by the variation of the seawater temperature and salinity from surface to bottom, calculated offline

- The relationship between local DSL and SSL change is :

  DSL+GMSSL(real local SL change)=SSL(expansion)+mass change

- *MEM of the DSL and SSL change: the multi-model ensemble mean.*

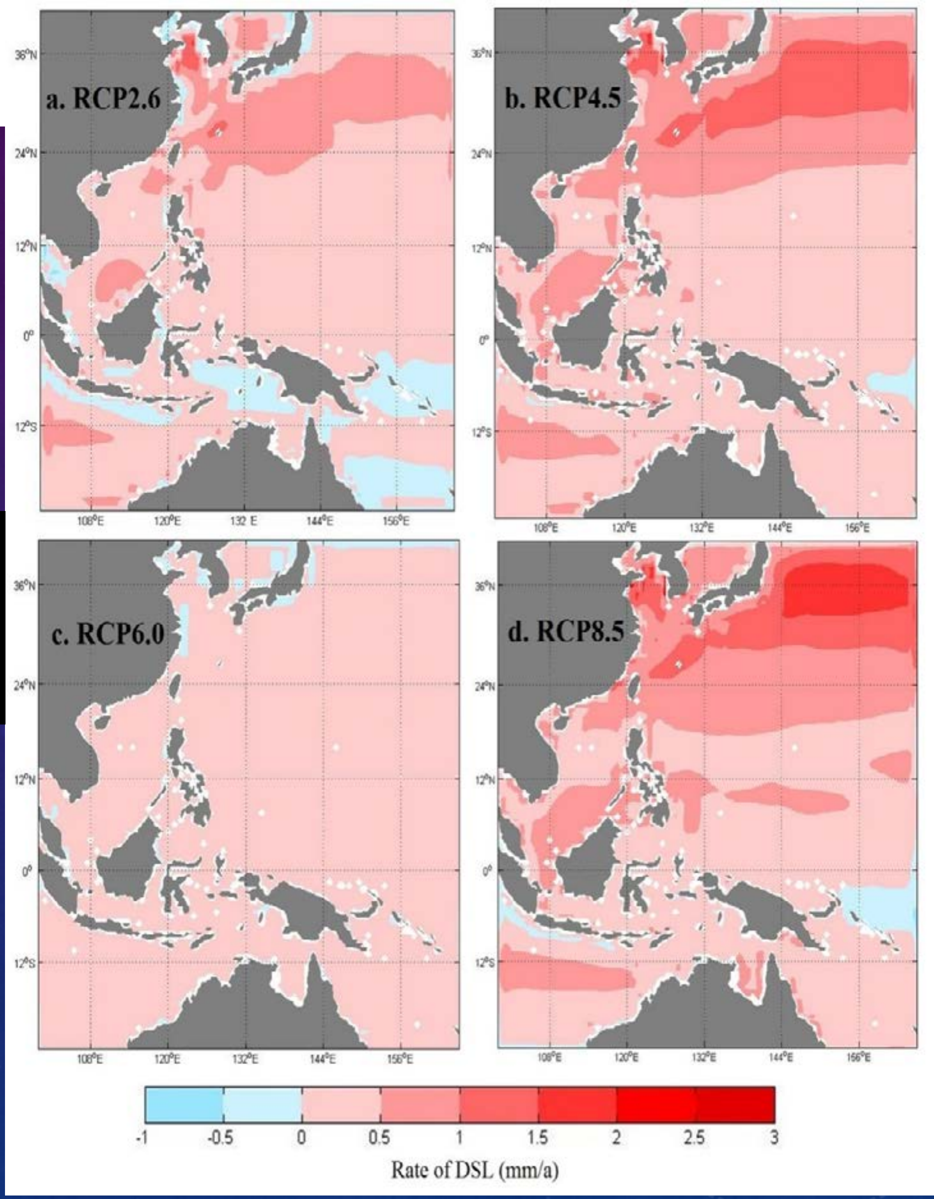
DSL change in the 21st century



Individual and MEM projections of DSL relative to 2006 for (a) RCP2.6, (b) RCP4.5, (c) RCP6.0 and (d) RCP8.5 in the SCS. Five-year low pass filtering is applied to the time series.

DSL change in the 21st century

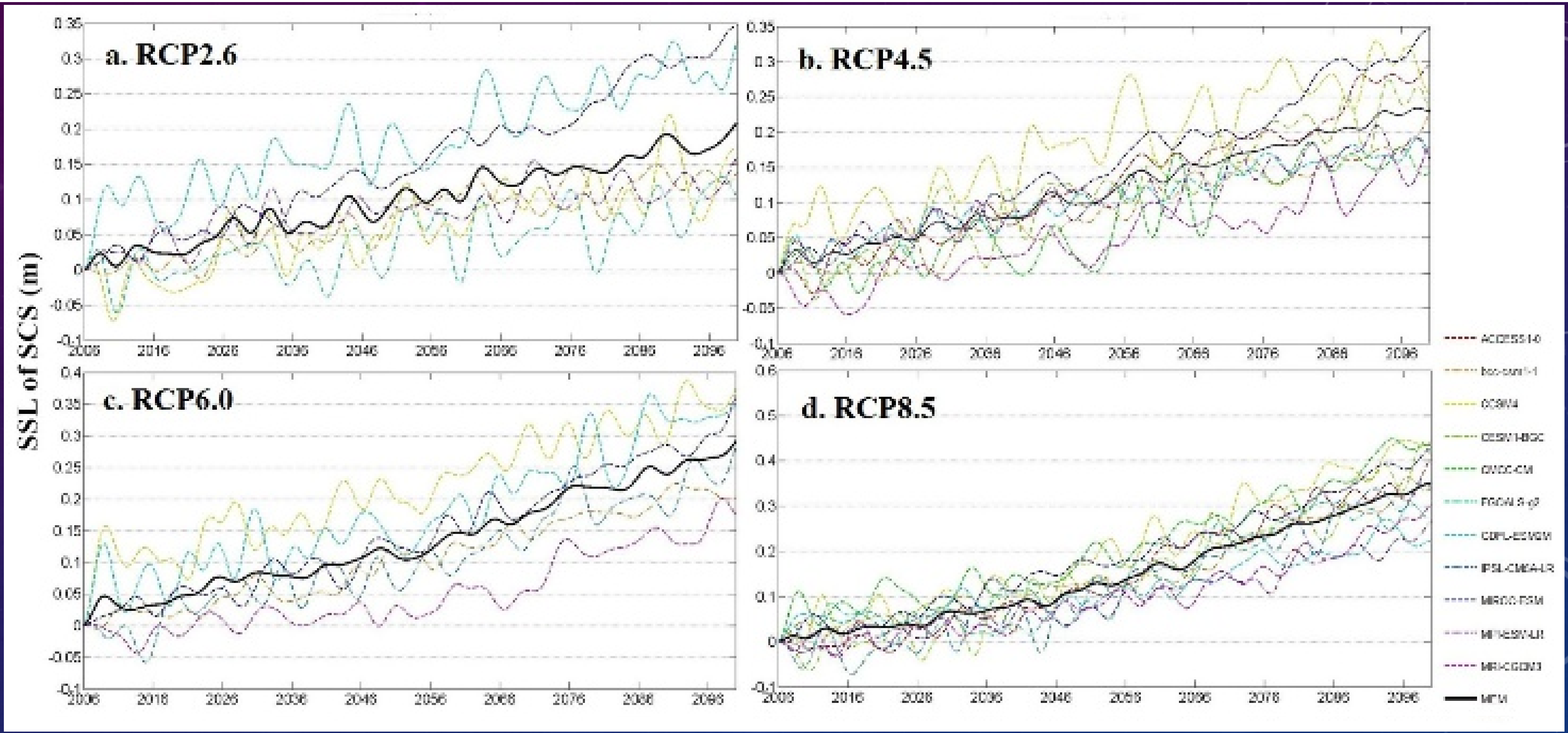
	BYECSs(m)	SCS(m)
RCP2.6	0.04 [-0.01~0.10]	0.06 [-0.03~0.15]
RCP4.5	0.09 [0.03~0.15]	0.07 [0~0.14]
RCP6.0	0.03 [-0.08~0.15]	0.05 [-0.07~0.17]
RCP8.5	0.12 [0.05~0.20]	0.08 [0.02~0.14]



Rising rate of the projected MEM DSL in the China seas.

Spatial pattern of DSL rise shows large rising rates in the region of Kuroshio, revealing an strengthening of the Kuroshio current, which can carry more water to the China seas (especially the BYECSs) from the tropical Pacific Ocean.

SSL change in the 21st century

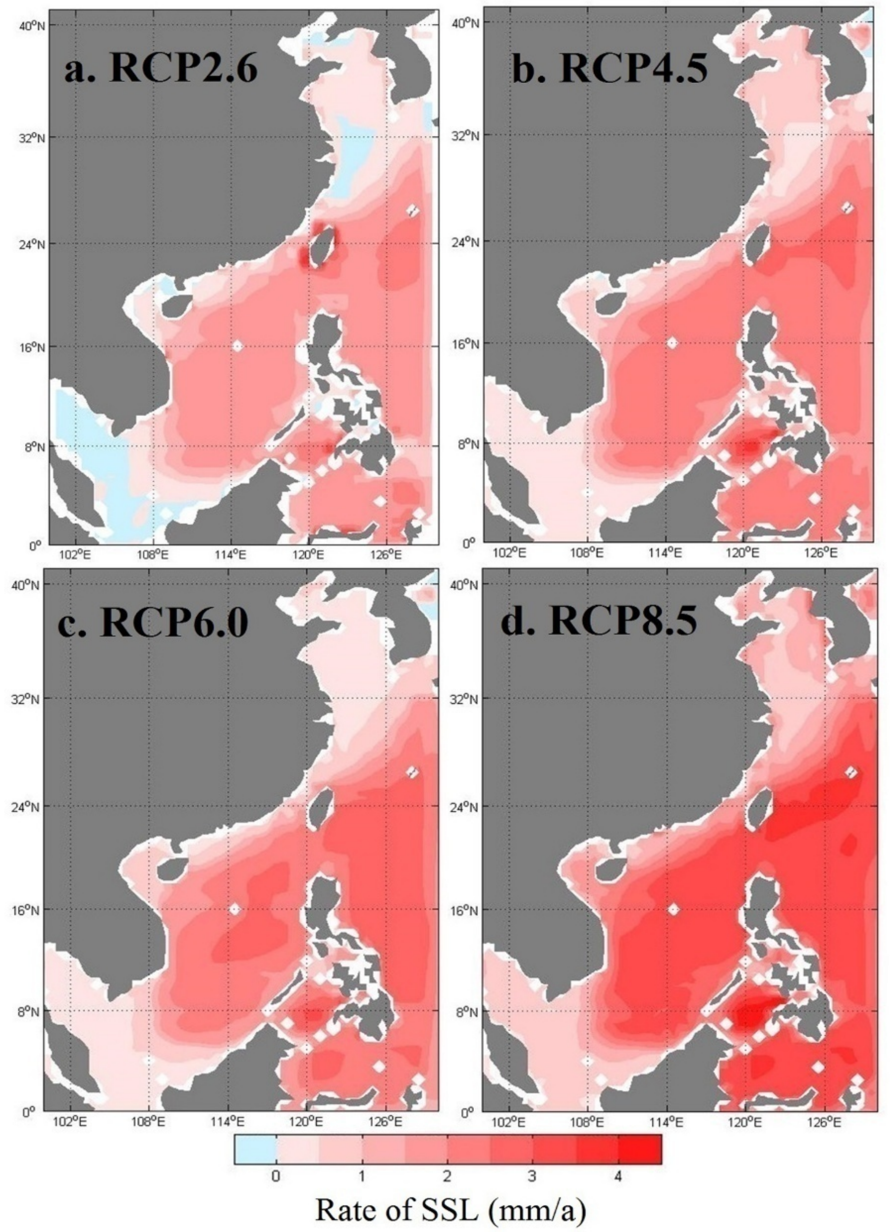


Individual and MEM projections of SSL relative to 2006 for (a) RCP2.6, (b) RCP4.5, (c) RCP6.0 and (d) RCP8.5 in the SCS. **All the RCPs show faster SSL rise than BYECSs.**

SSL change in the 21st century

	BYECSs(m)	SCS(m)
RCP2.6	0.03 [-0.04~0.11]	0.21 [0.11~0.31]
RCP4.5	0.06 [0.01~0.10]	0.23 [0.18~0.28]
RCP6.0	0.02 [0~0.05]	0.30 [0.21~0.38]
RCP8.5	0.09 [0.04~0.15]	0.35 [0.31~0.40]

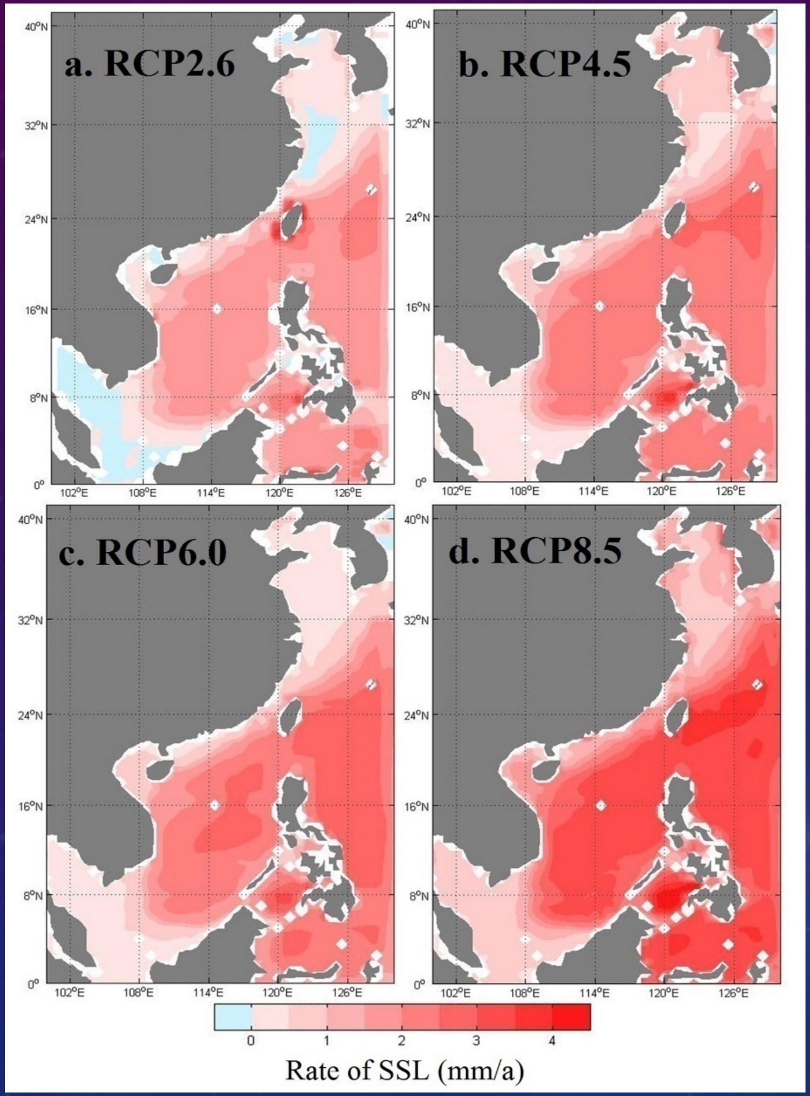
Rising rate of projected MEM SSL in the China seas.



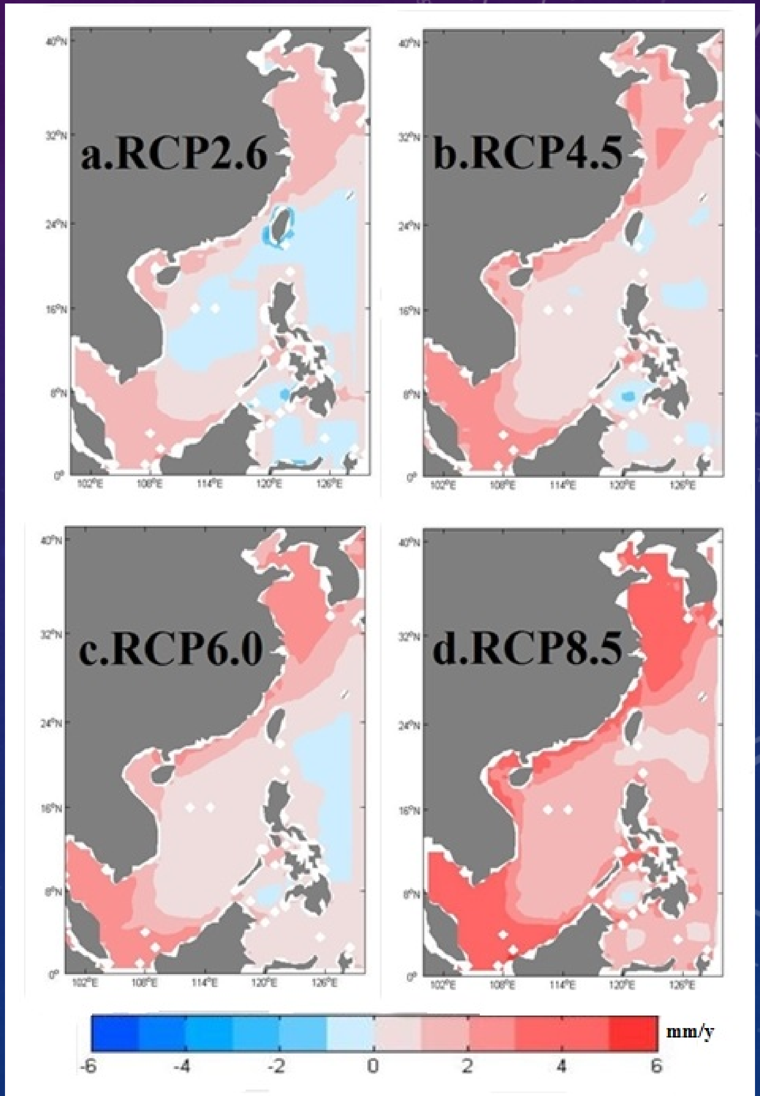
The projected SSL in the SCS rises faster than the BYECSs as the SCS has more water.

CONTRIBUTION OF MASS CHANGE TO SLR

SLR caused by steric change



SLR caused by mass change



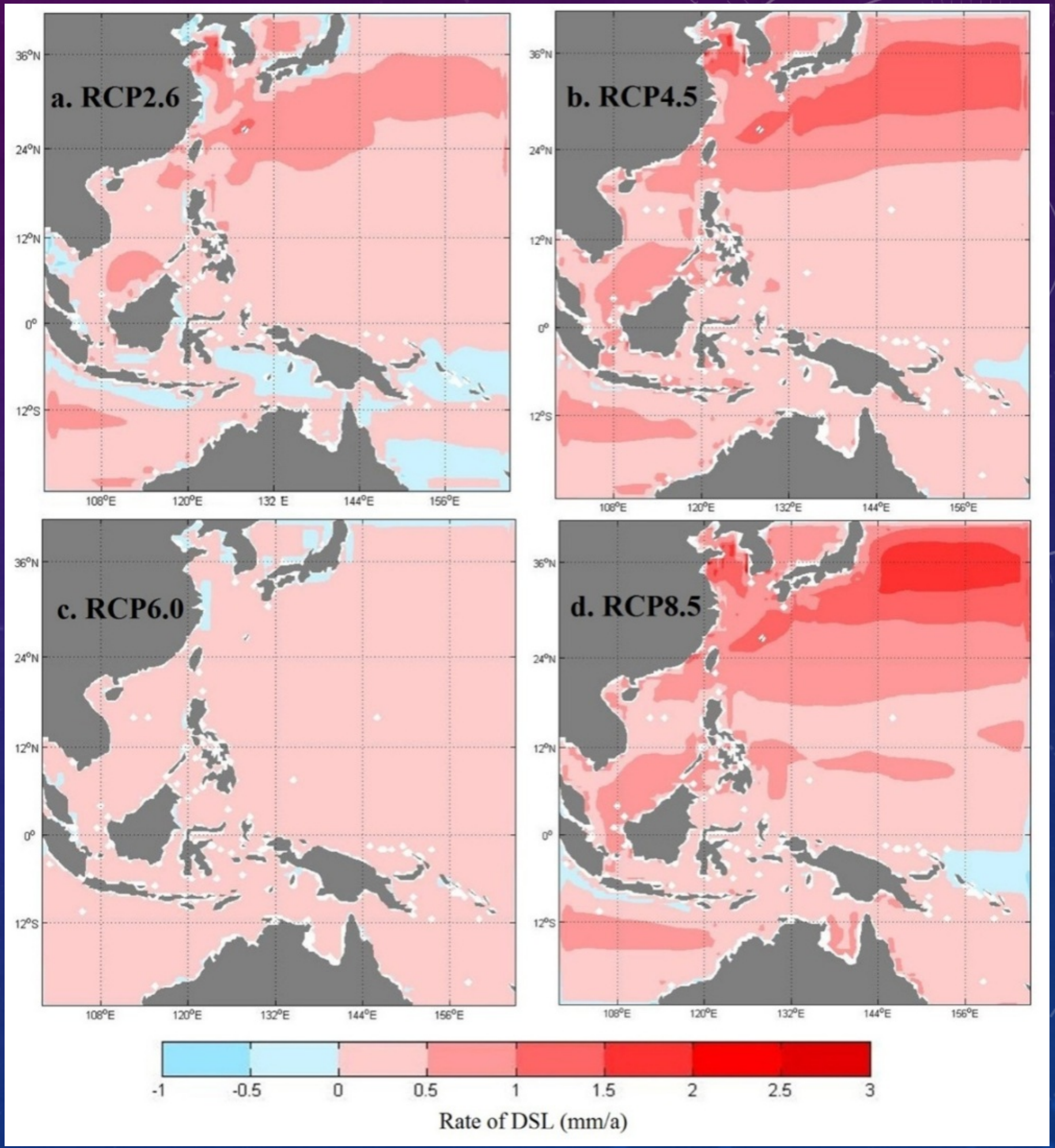
BYECSs: mass gain is more important; SCS: steric change dominates the SLR

CONCLUSIONS

The Kuroshio strengthening may be the main reason for the SLR in the China seas by carrying more water to the BYECSs.

BYECSs: mass change dominates the SLR.

SCS: steric change dominates the SLR.



Conclusions

- In terms of uncertainty, the model-to-model disagreement in the rate of the projected SLR is significant, especially under RCP6.0 due to bad stability and few available databases.
- The limitation of the quantity of selected models is another source of uncertainty, especially compared with the result of IPCC AR5 based on 21 coupled models.
- The bathymetry of large areas of the continental shelf in the China seas is also an important source of uncertainty as the OGCM in the coupled models may not behave well in the shallow waters. Inadequate resolution of the OGCMs in the coastal region in the studied area should also be considered in the uncertainty of the result.

AND NOW, THE TIDES…

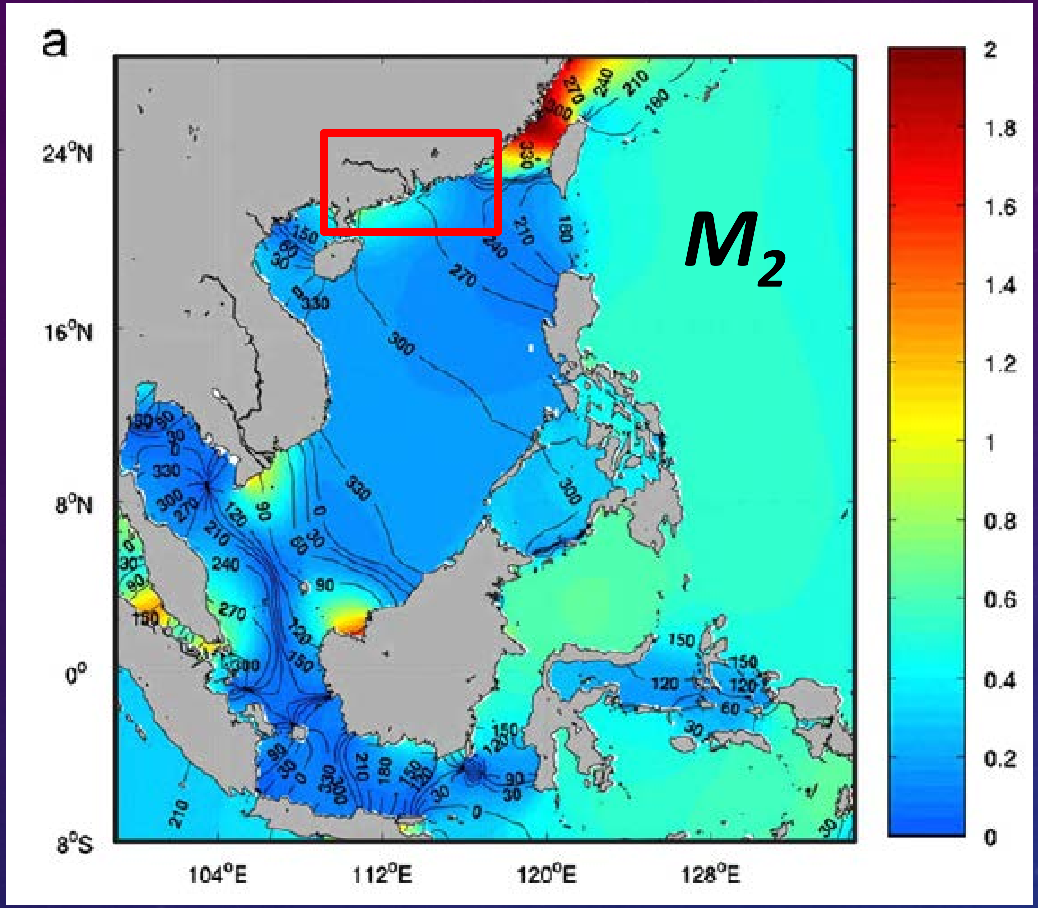
"Despite the sea being wild and the waves rolling away from the shore, the tide always returns."

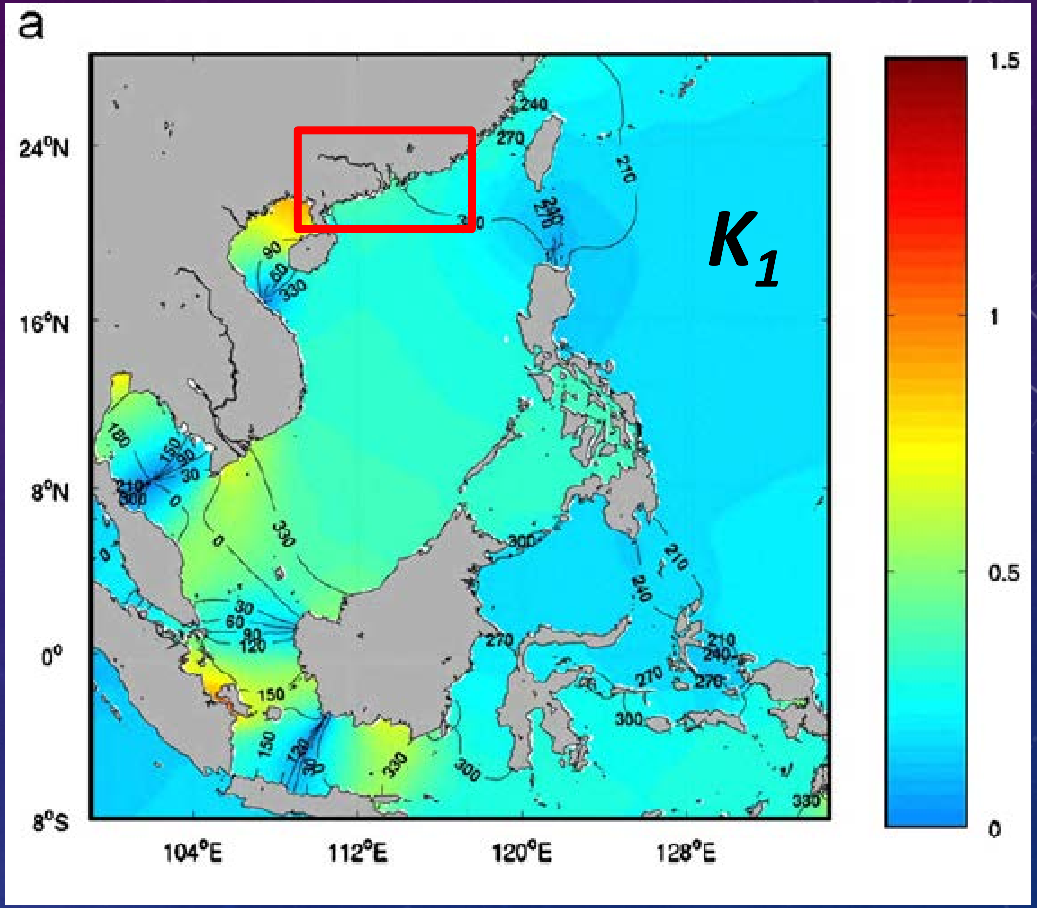
— Katherine McIntyre, By the Sea

ANOMALOUS TIDES IN HONG KONG

- ***Of two varieties:***
- First, a statistical treatment showing that when considering the long-term variability of MSL and all tides, the TSL and nuisance flooding probabilities in Hong Kong have increased.
- Second, there are short-term fluctuations, particularly in the 2000’s, that are unique.
- ***Hypotheses for observed anomalies:***
- The changes are due to basin-scale changes in the South China Sea due to climate change.
- Alternatively, the changes are more local in origin, are forced by changes in resonance and/or friction, and may be due to changing coastal morphology due to land reclamation projects over the past century or so.

TIDES IN THE SOUTH CHINA SEA

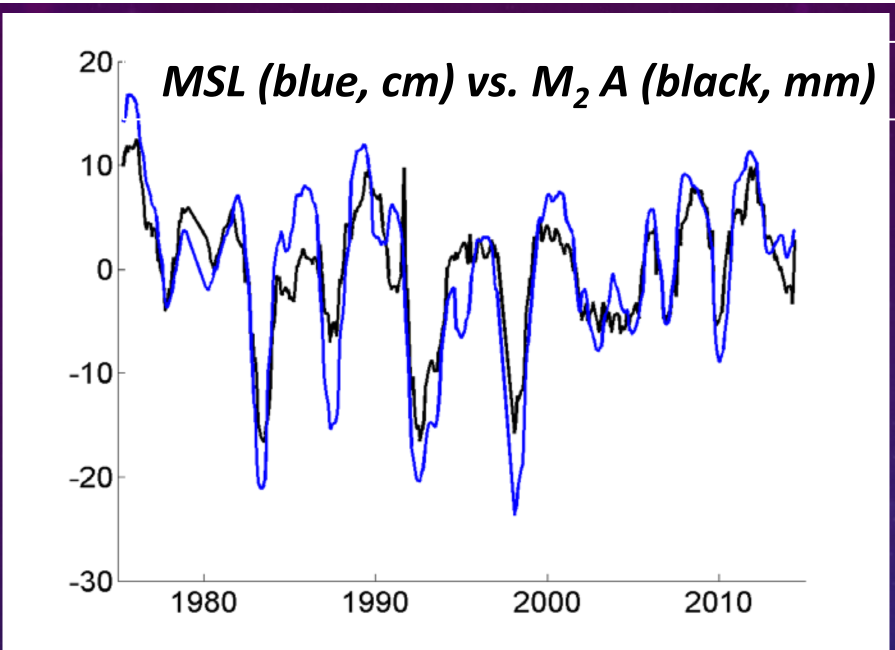


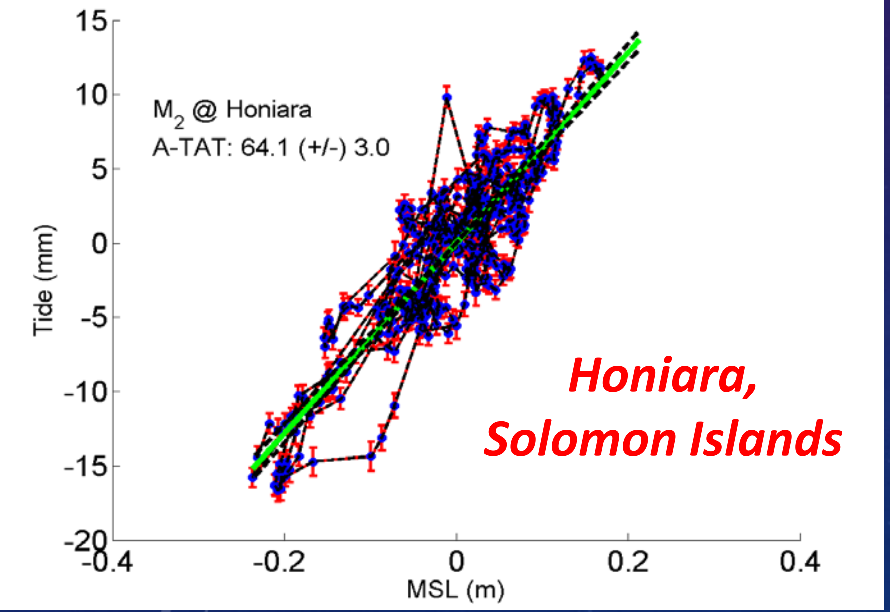


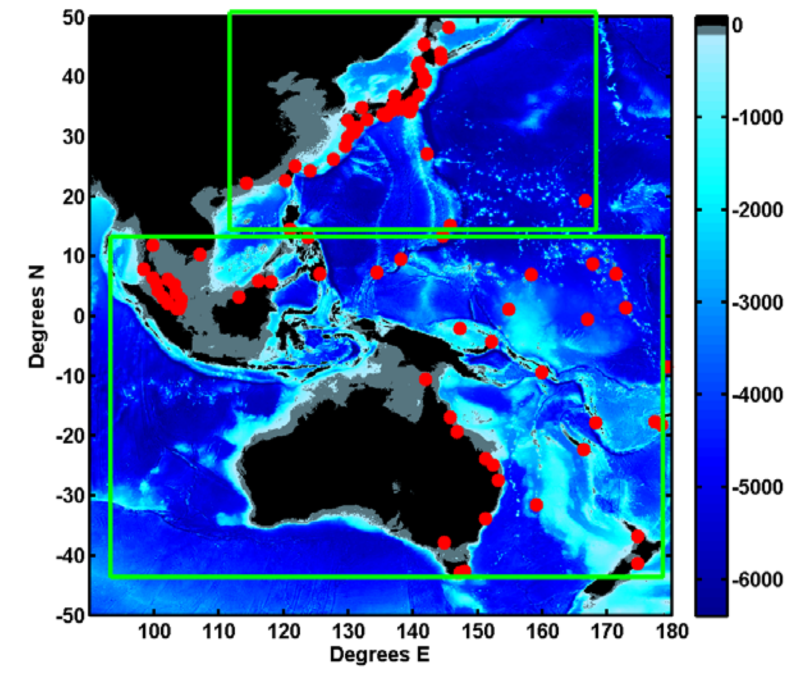
Zu et al., 2008

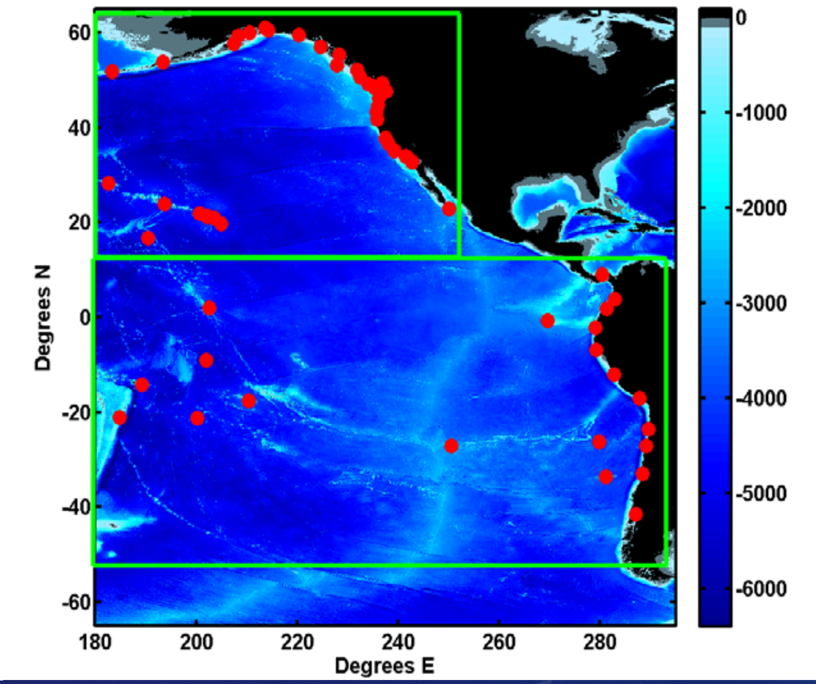
- Tides are composed of twice-daily (*semidiurnal;* D2) components (M_2, S_2, N_2, etc.)
- And once-daily (*diurnal;* D1) components (K_1, O_1, Q_1, etc.)

TIDAL ANOMALY CORRELATIONS (TACS)







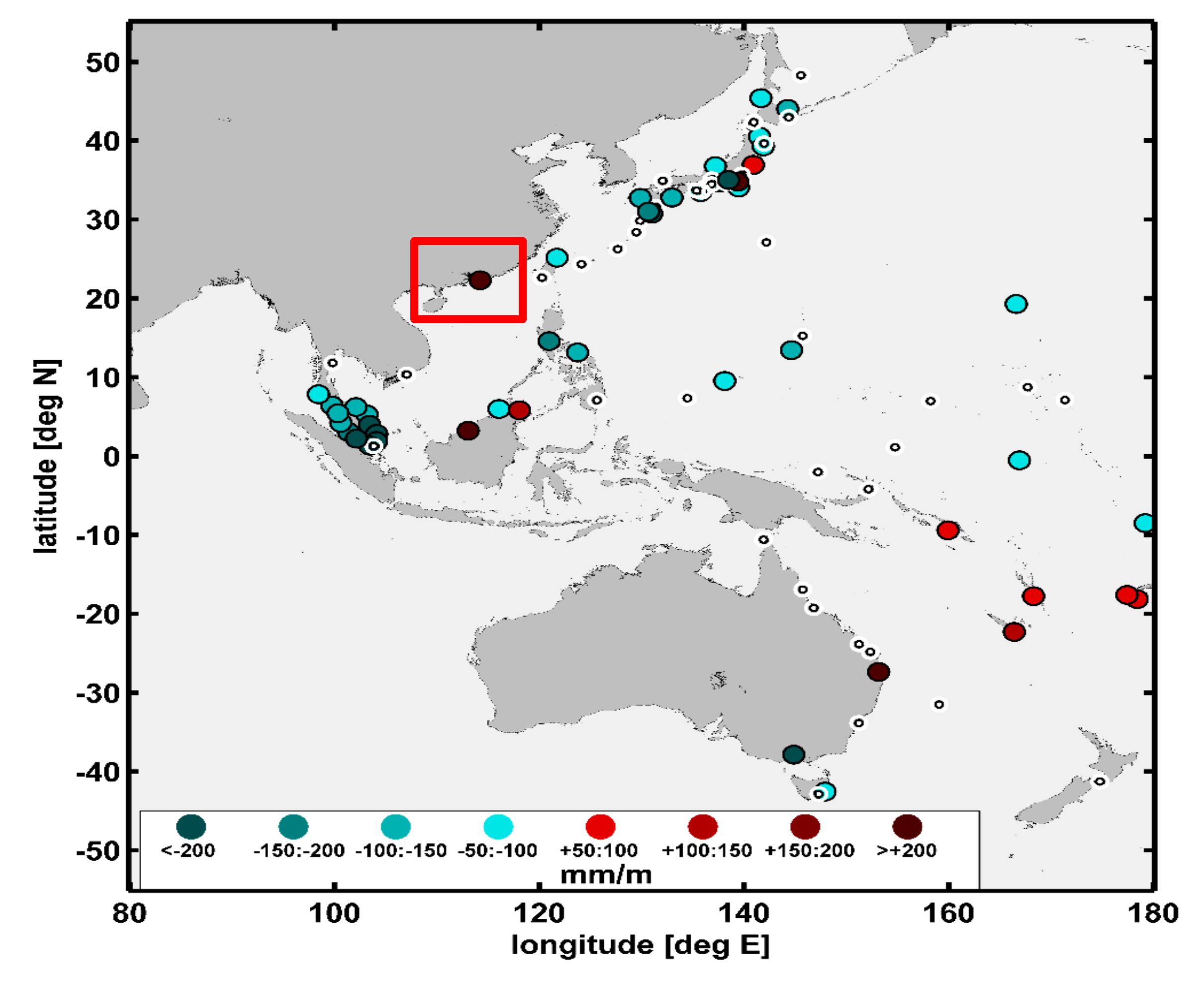


- ***Survey of TACs of major tides*** (M_2, S_2, K_1, O_1)
- Performed at 152 Pacific Ocean tide gauges
- (*Devlin et al., 2017b, Submitted to JGR-Oceans*)
- ***The combined TACs of four major tides is a proxy for δ-HAT (change in highest astronomical tide)***

-A very large positive δ-HAT is seen at the Hong Kong NPQB gauge (+575 mmm^{-1})!?!?

-How might this affect total sea levels and nuisance flooding?

-Consider a statistical analysis using PDFs, and including all resolvable tidal components!

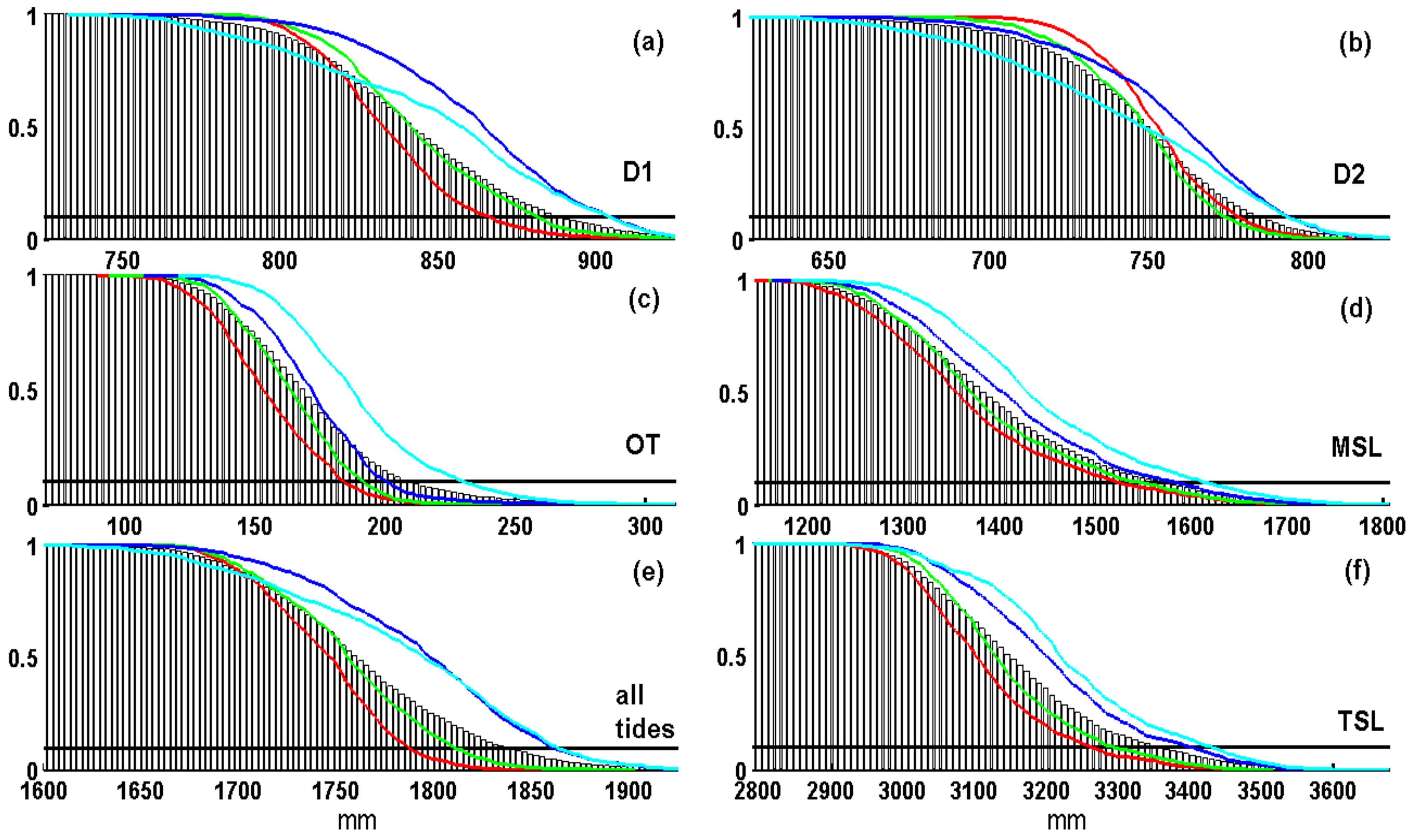


TSL = MSL + D1 + D2 + OT

We examine the PDFs in 20-year chunks at 10-year steps to see the change in *exceedance levels*, meaning the probability that the quantity in question will be above or below a certain threshold

We look at the trends in 90%, 95%, and 99% exceedance levels…

NUISANCE FLOODING



Probability density functions (PDFs) of: (a) diurnal (D1) tides, (b), semidiurnal tides (D2), (c) overtides, (d) MSL, (e) all tidal components, and (f) total sea level (TSL) for the Hong Kong tide gauge. The black bar graph shows the distribution of all data, red lines are 1965-1985, green lines are 1975-1995, dark blue lines are 1985-2005, and light blue lines are1995-2015. The solid horizontal black line on each subplot shows the 90% exceedance level.

(Devlin et al., 2017a)

THE PUNCHLINE…

-Changes in MSL are steadily increasing, as would be expected based on MSL rise and climate change.

-Changes in D1 and D2 are smaller but significant, and more importantly, *unexpected*!

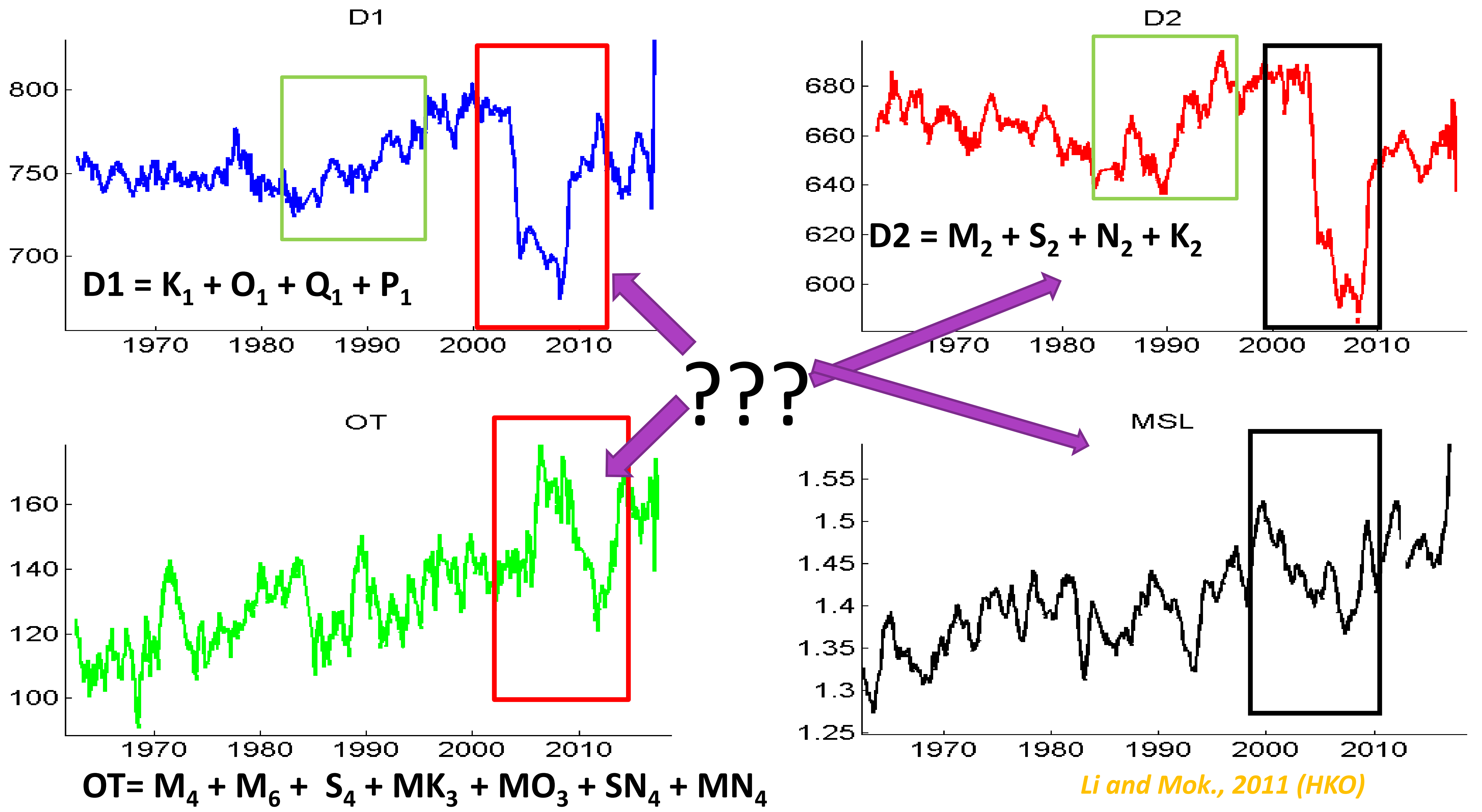
-Changes in overtides (OT) are larger in terms of percentage change.

-Comparisons of changes in TSL to changes in MSL show increases in 90, 95, and 99% exceedance levels of:

<u>180%, 192%, and 126%</u>

	1965-1985 level (mm)	1995-2015 level (mm)	Change in level (mm)
D1 90% exceedance level	866	904	+38
D1 95% exceedance level	877	913	+36
D1 99% exceedance level	900	938	+38
D2 90% exceedance level	775	793	+18
D2 95% exceedance level	782	804	+22
D2 99% exceedance level	797	820	+23
OT 90% exceedance level	185	232	+47
OT 95% exceedance level	194	245	+51
OT 99% exceedance level	213	272	+59
MSL 90% exceedance level	1521	1611	*+90*
MSL 95% exceedance level	1584	1662	*+78*
MSL 99% exceedance level	1665	1740	*+75*
ALL 90% exceedance level	1787	1863	+76
ALL 95% exceedance level	1800	1880	+80
ALL 99% exceedance level	1825	1920	+95
TSL 90% exceedance level	3260	3430	***+170***
TSL 95% exceedance level	3330	3480	***+150***
TSL 99% exceedance level	3435	3557	***+122***

- This shows that the statistical probability of nuisance flooding in Hong Kong is increasing…
- But there is more to the story!


D1
D1 = $K_1 + O_1 + Q_1 + P_1$
D2
D2 = $M_2 + S_2 + N_2 + K_2$
???
OT
MSL
OT= $M_4 + M_6 + S_4 + MK_3 + MO_3 + SN_4 + MN_4$
Li and Mok., 2011 (HKO)

***-North Point/Quarry Bay* (NPQB; 1962-present)**

-Kwai Chung, Terminal 8 (**CT8**; 2001-present)

-Chi Ma Wan (**CMW**, 1963-1997)

-Cheung Chau (**CHC**, 2005-present)

-Ma Wan (**MWC**, 2004-present)

***-Tai Po Kau* (TPK; 1963-present)**

-Ko Lau Wan (**KLW-HKO**, 1974-1995; **KLW**, 1999-present))

-Tai Miu Wan (**TMW**, 1996-present)

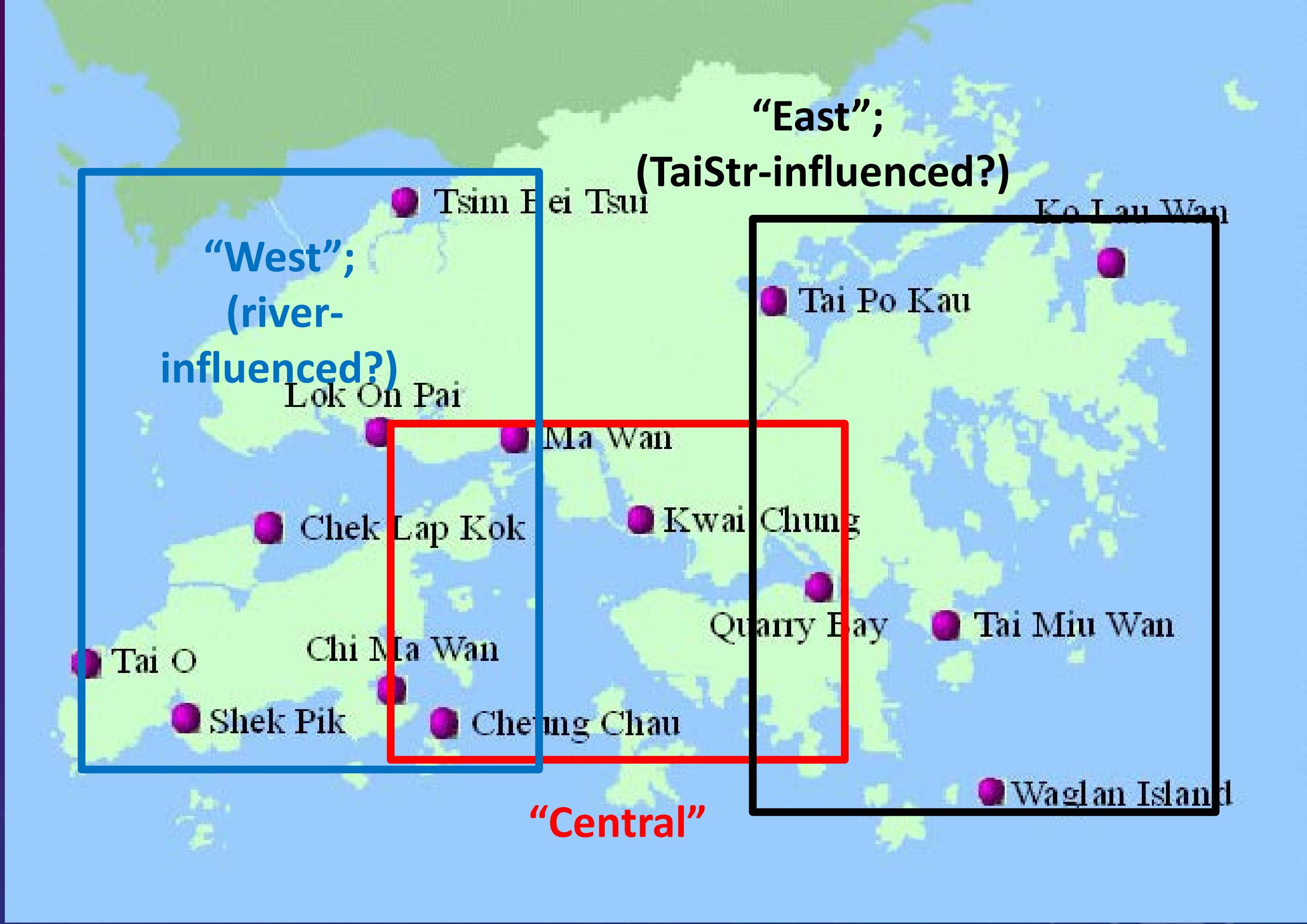
-Waglan Island (**WAG**, 1976-present)

***-Tsim Bei Tsui* (TBT; 1974-present; *Lots of gaps!*)**

-Lok On Pai (LOP, 1981-1999)

-Shek Pik (**SPW**, 1997-present)

-Tai O (**TAI,** 1985-1997, but… **So many gaps!)**

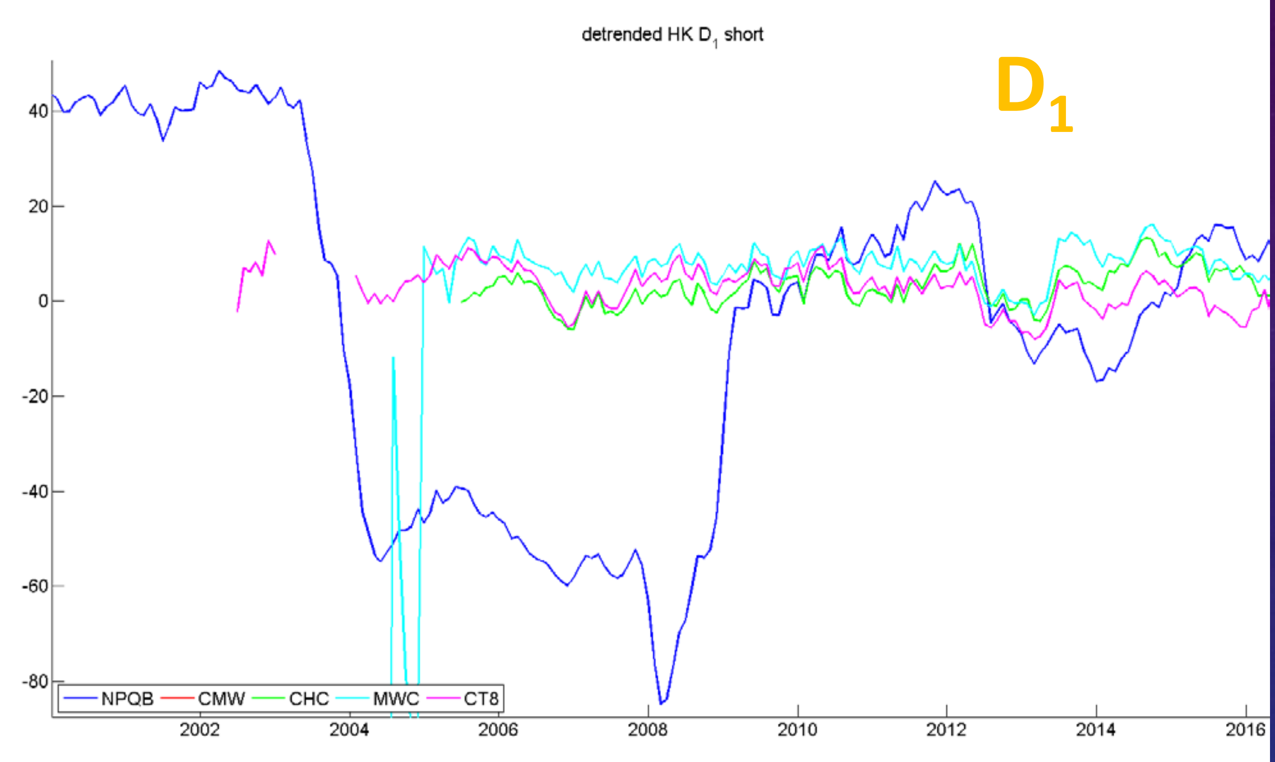


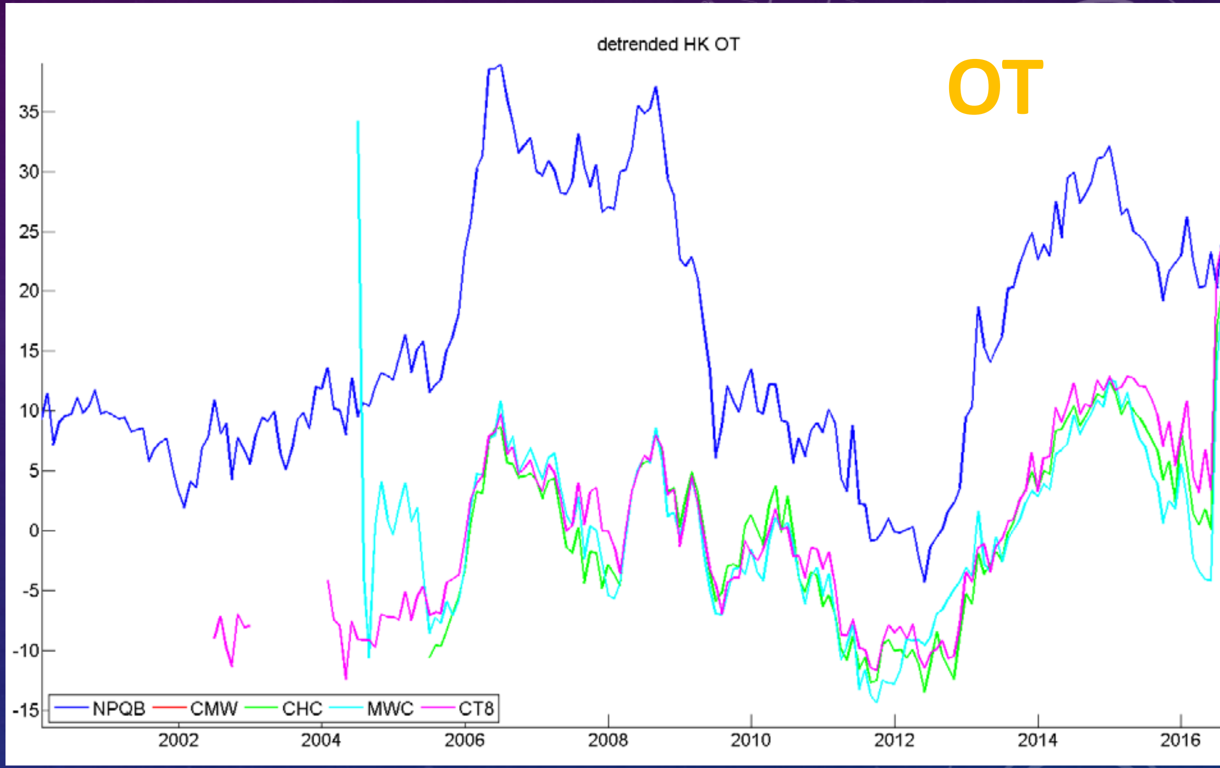
-A selection of tide gauges are provided by the Hong Kong Observatory, and by the HK Marine Department.

-Some locations are current, and some historical.

-An exhaustive analysis of all gauges look at all tidal variability, looking for similar anomalies as seen at NPQB, or any other commonalities.

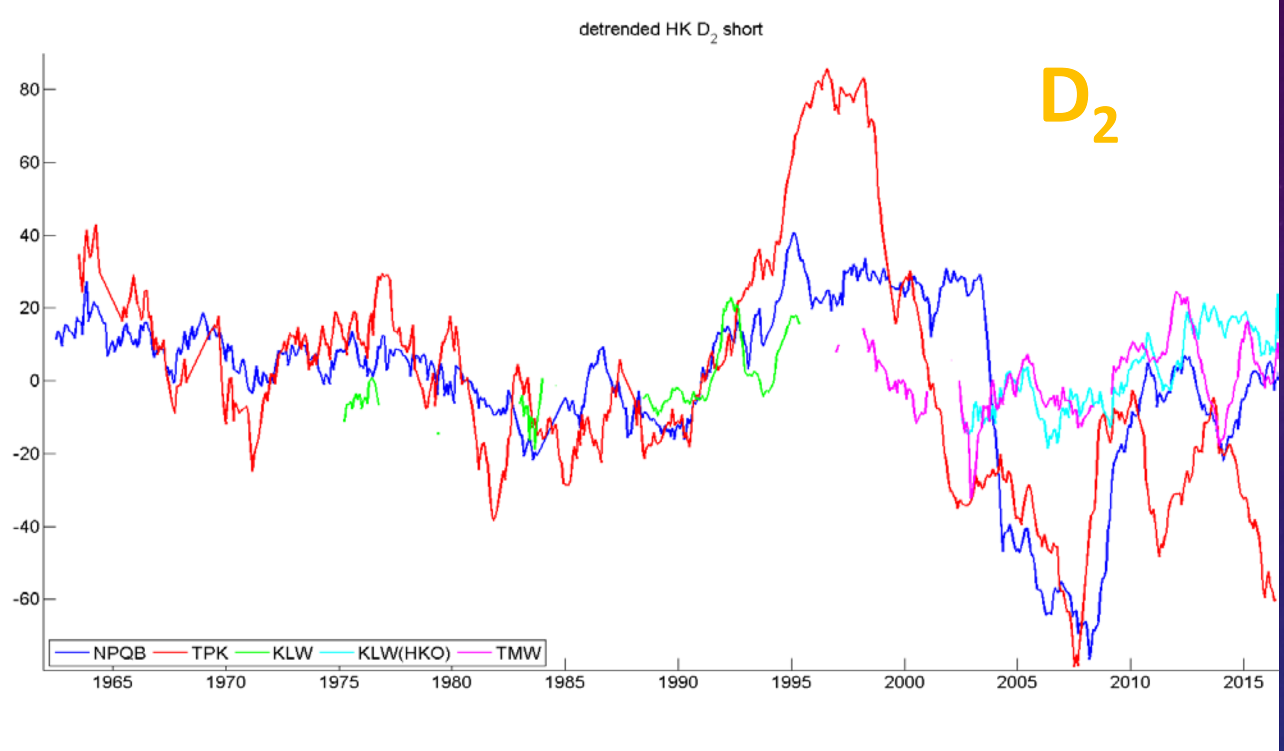
HK (CENTRAL)

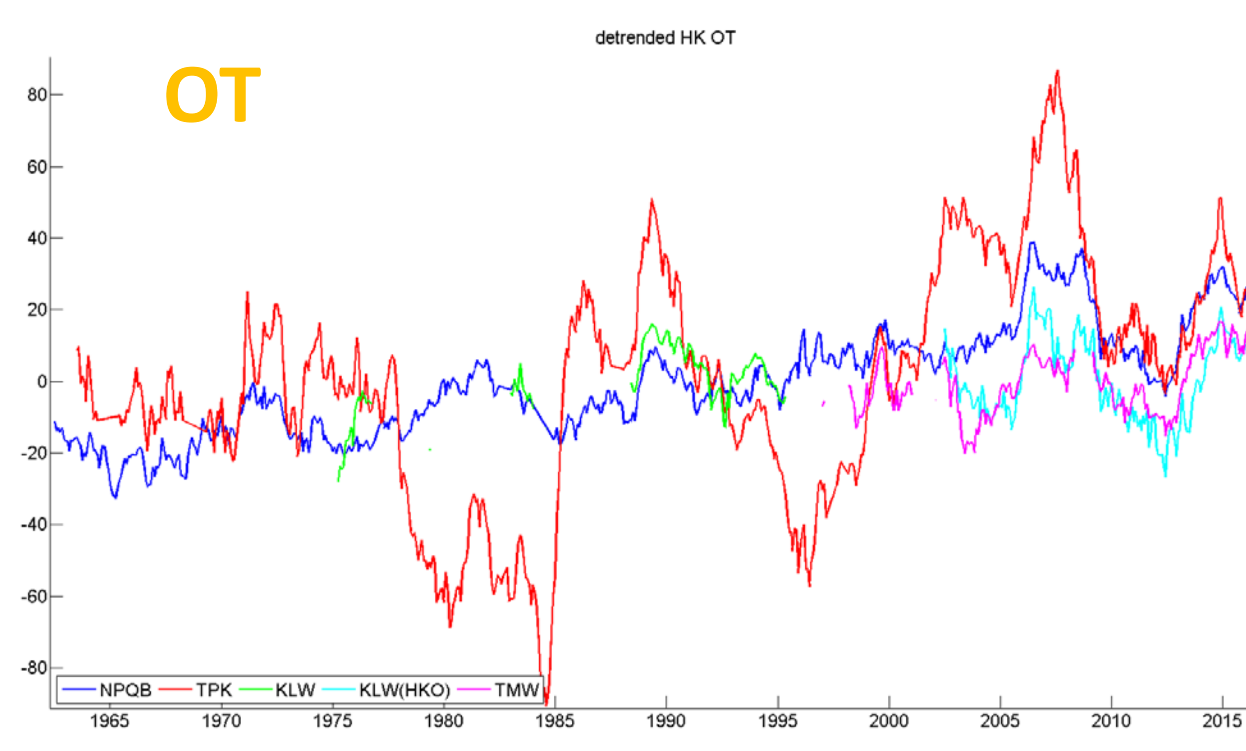




- The large anomaly in question is not re-produced at other gauges for D1 or D2
- But, there is a similarity of records after this event.
- And, strong correlations in the OT band, with anomalies anti-correlated to D1 and D2

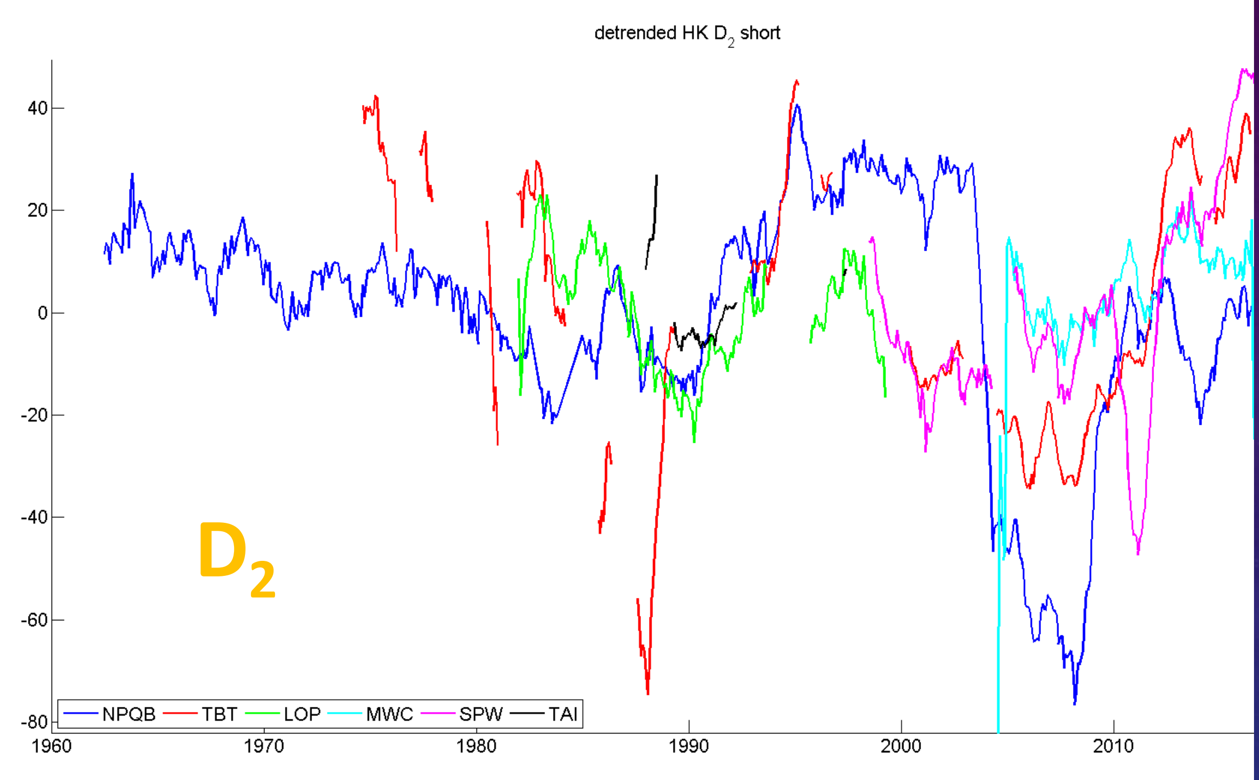
HK(EAST)

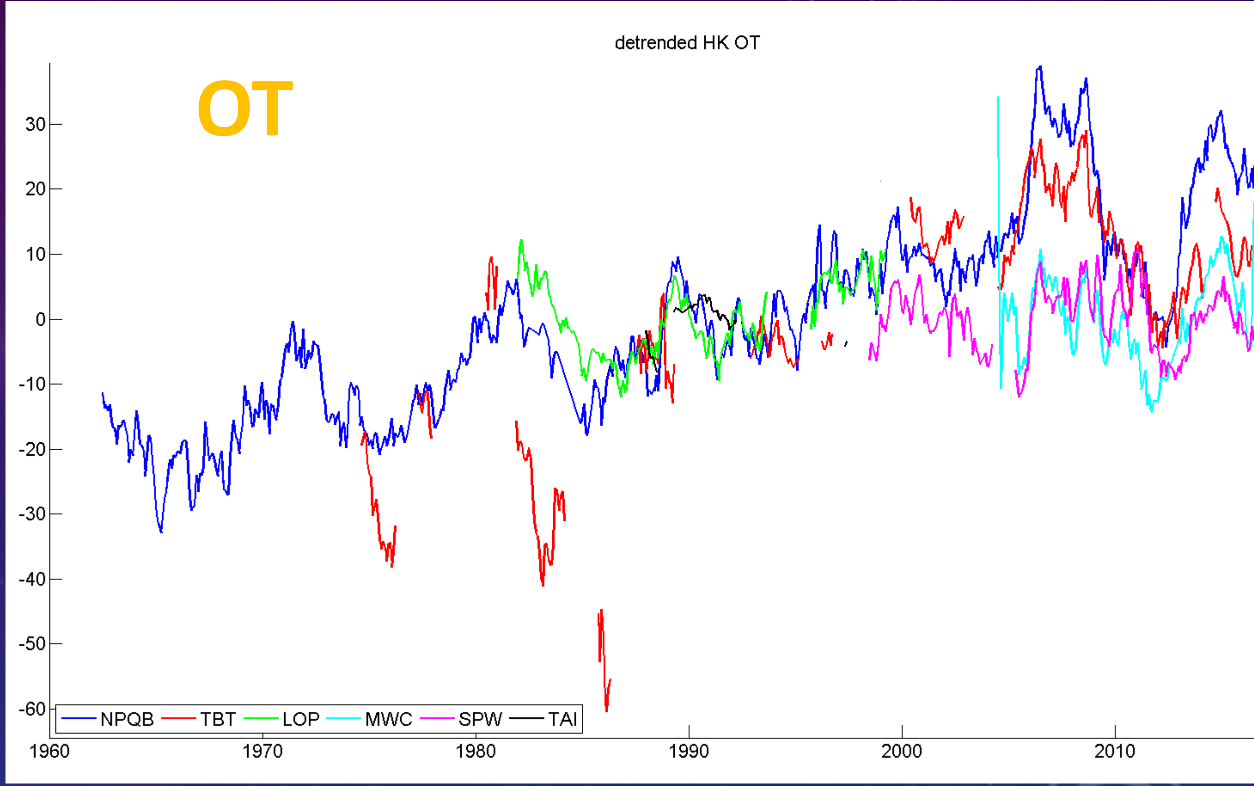




- The large anomaly in question is not exactly re-produced at other gauges in D1 or D2
- But, there is a similar (but not identical) set of events at Tai Po Kau (red line) for D1 and D2
- And, like at NPQB, an opposed OT record (also highly variable, and increasing over time)

HK(WEST)





- Also, there is a similar (but not identical) set of events at Tsim Bei Tsui(red line) in D2
- And, like elsewhere, an opposed OT record that is well-correlated between gauges

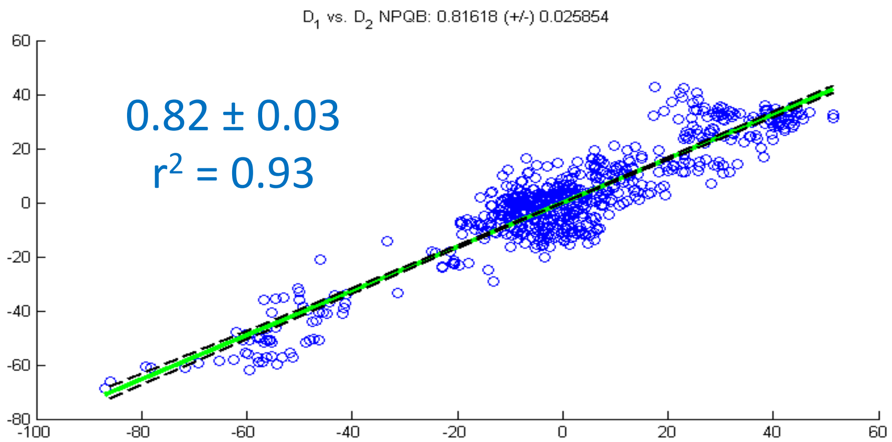
COMMONALTIES OF HK GAUGES

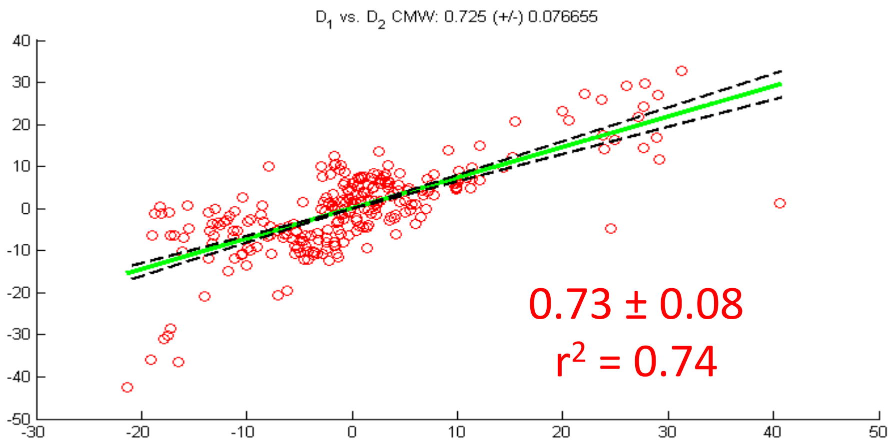
- Anti-correlations of D1 vs. OT, D2 vs. OT, and (D1 + D2) vs. OT
- Strong correlations of D1 vs. D2

(this is a not a "common" trait of tide gauge records)

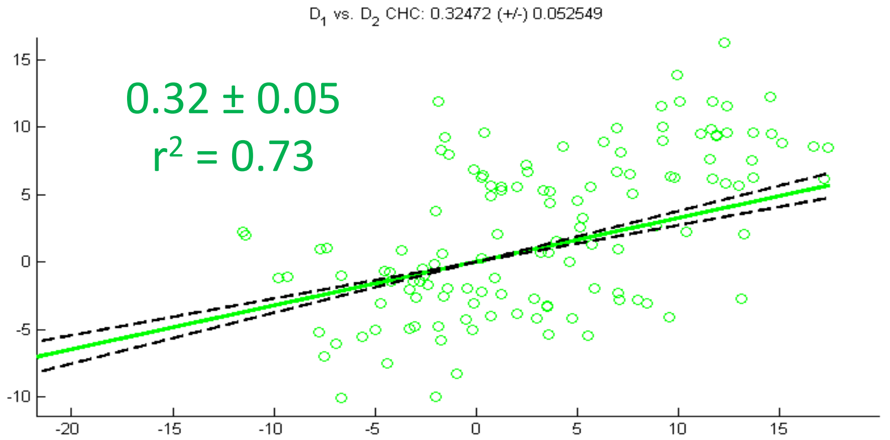
- ***<u>The "Major Anomaly" not observed elsewhere for major tides</u>***
  - But, looking at some lesser constituents DOES show a similar behavior!
    - N_2, Q_1, M_3, e.g.

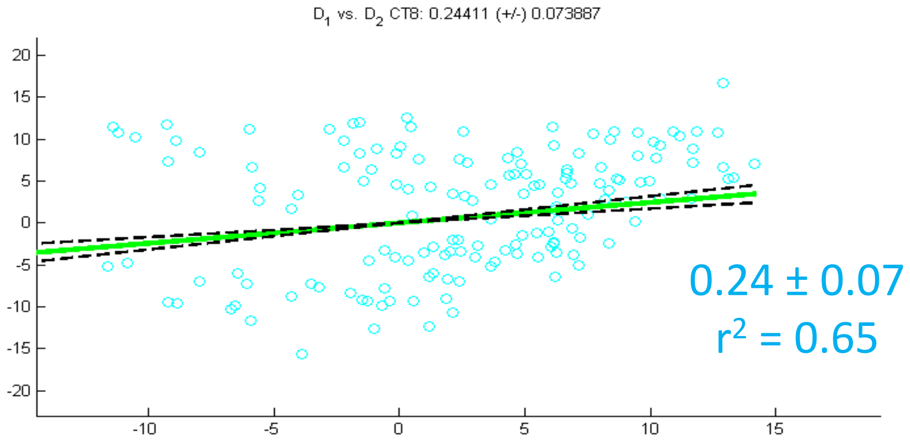
D1 VS. D2: HK CENTRAL





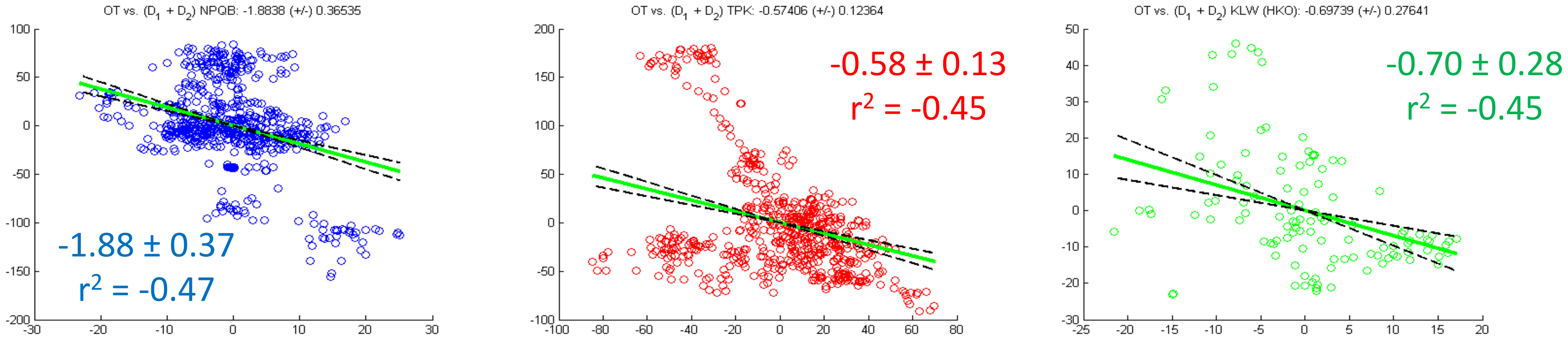
<u>Units of mm change in D2 per mm change in D1</u>



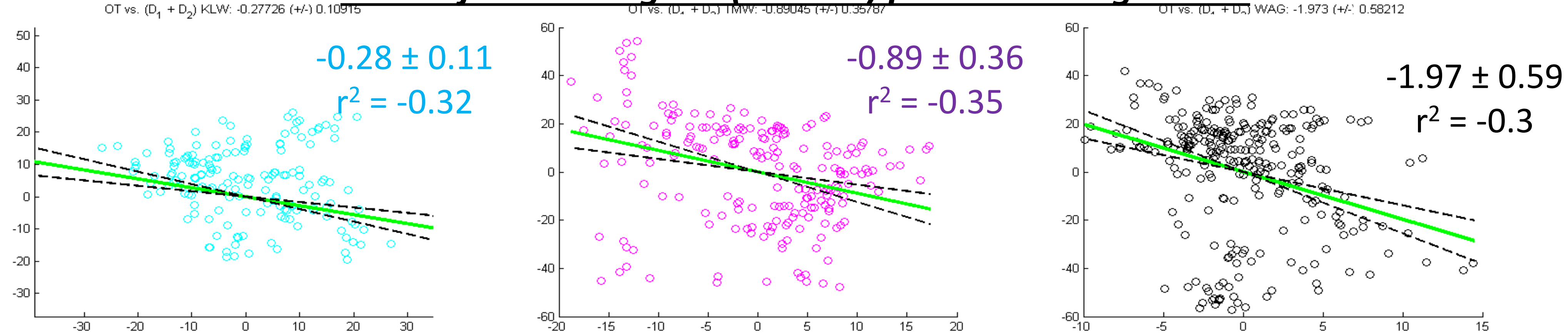


-Similar correlations seen at West HK, East HK, and in the northwest SCS

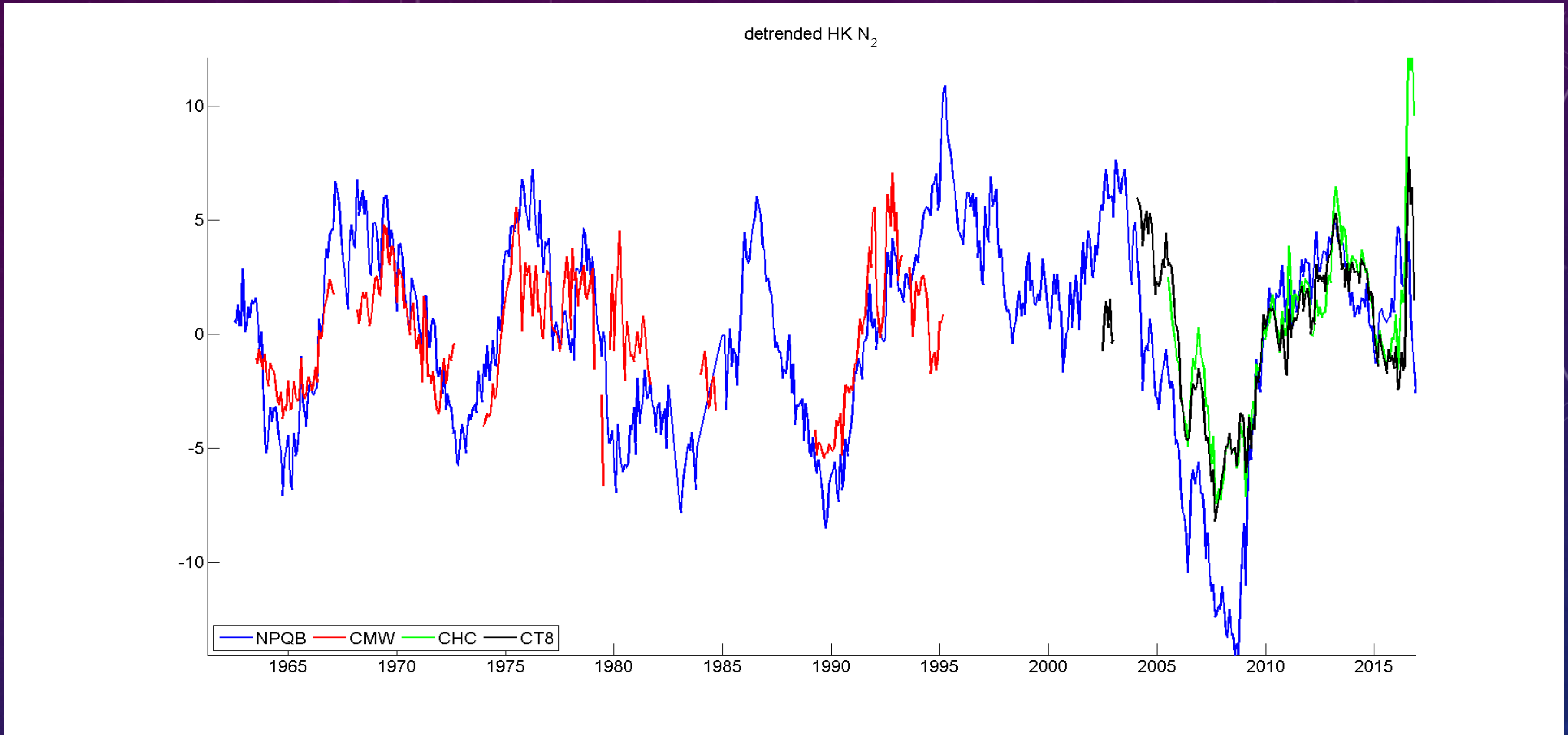
(D1+D2) VS. OT: HK EAST

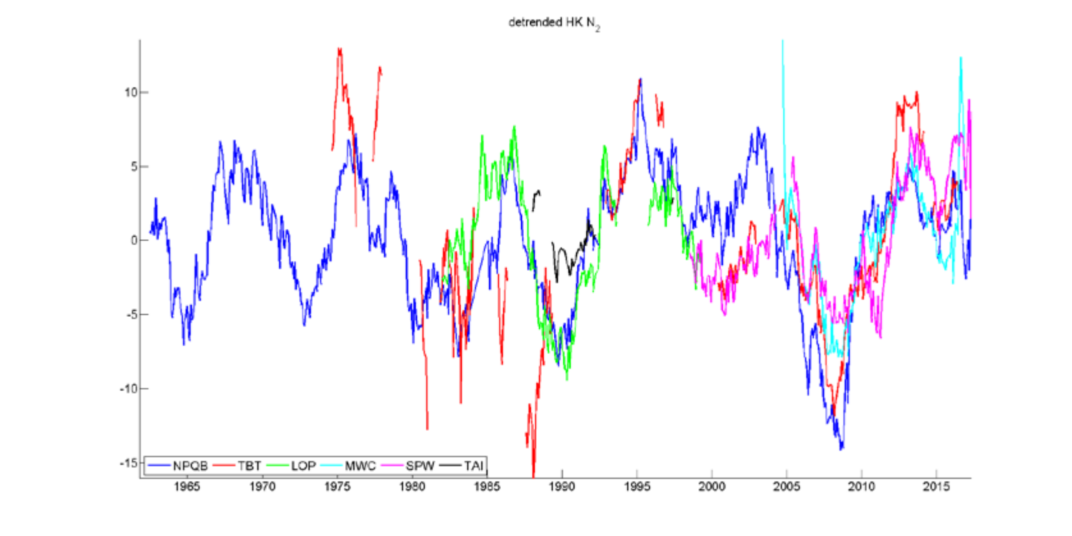


Units of mm change in (D1 +D2) per mm change in OT

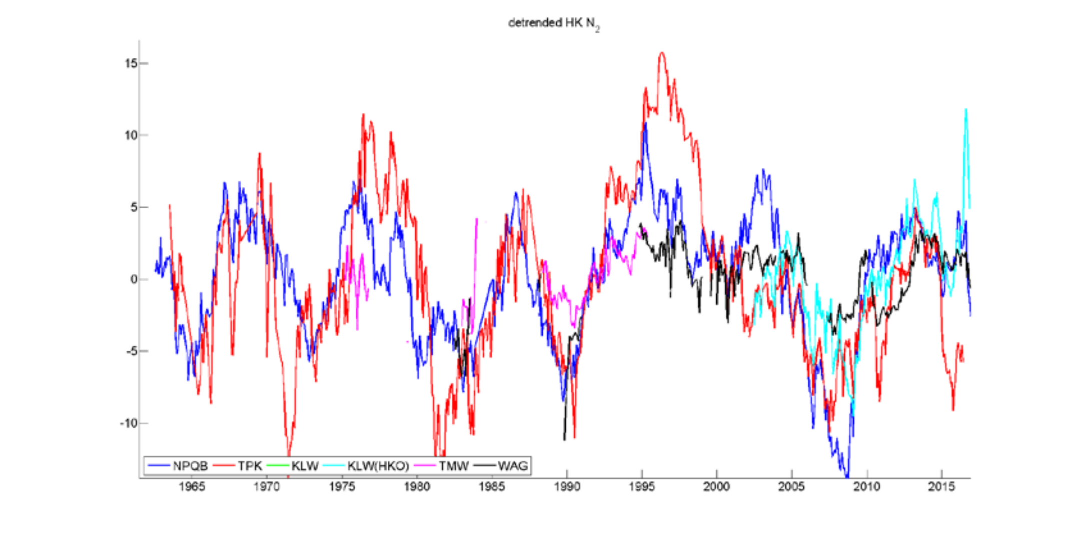


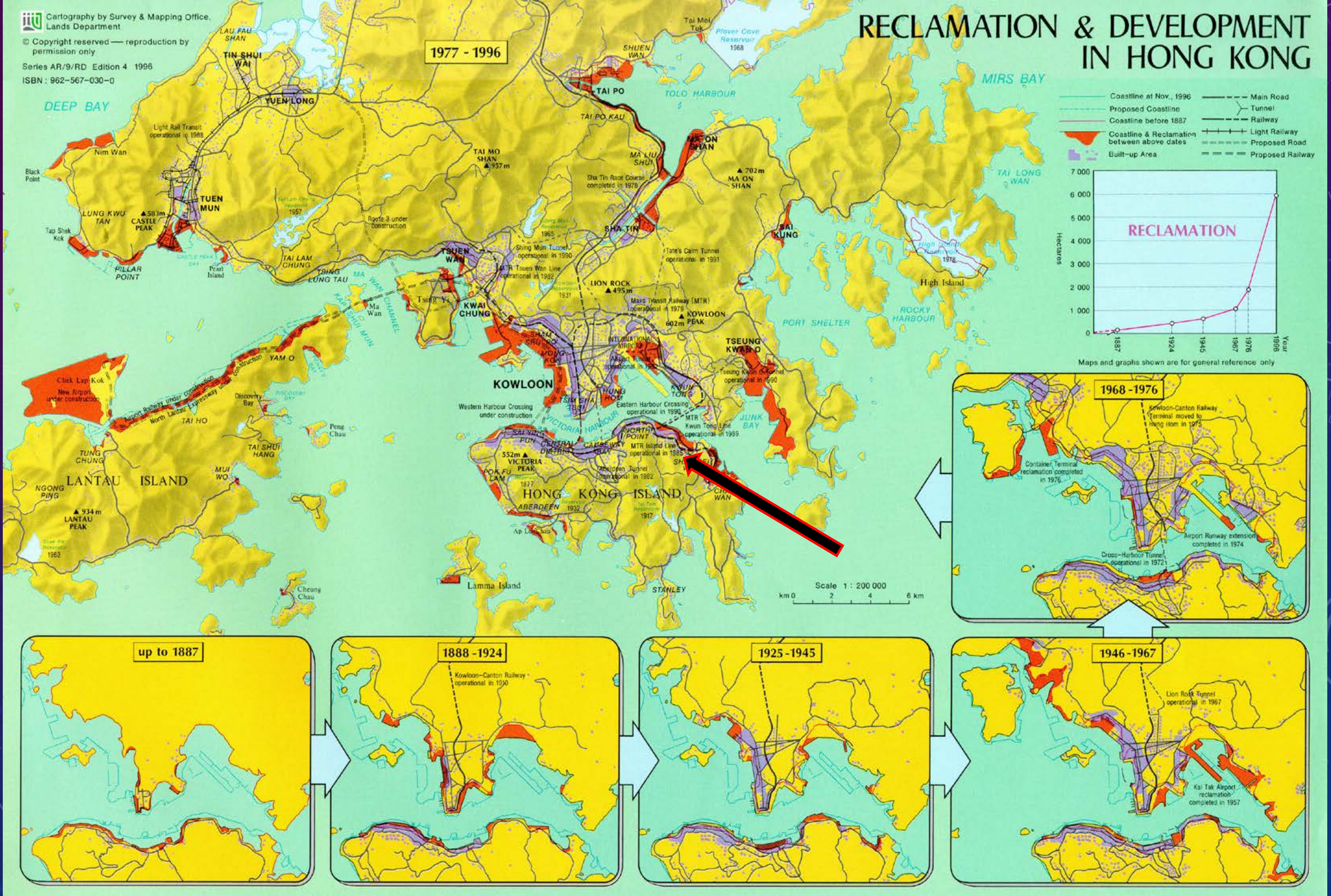
-Similar correlations seen at Central HK, West HK, and in the northwest SCS





• $\underline{N_2}$





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1977 - 1996
Coastline at Nov., 1996
Proposed Coastline
Coastline before 1887
Coastline & Reclamation between above dates
Built-up Area
Main Road
Tunnel
Railway
Light Railway
Proposed Road
Proposed Railway
RECLAMATION
Hectares
Year
Maps and graphs shown are for general reference only
Scale 1 : 200 000
km 0 2 4 6 km
DEEP BAY
MIRS BAY
TOLO HARBOUR
PORT SHELTER
JUNK BAY
YUEN LONG
TIN SHUI WAI
TUEN MUN
TAI PO
SHA TIN
MA ON SHAN
SAI KUNG
TSUEN WAN
KWAI CHUNG
TSEUNG KWAN O
KOWLOON
VICTORIA HARBOUR
HONG KONG ISLAND
LANTAU ISLAND
Lamma Island
Chek Lap Kok
New Airport under construction
Airport Railway under construction
North Lantau Expressway under construction
Western Harbour Crossing under construction
Eastern Harbour Crossing operational in 1990
MTR Island Line operational in 1985
Aberdeen Tunnel operational in 1982
Sha Tin Race Course completed in 1978
Light Rail Transit operational in 1988
Shing Mun Tunnel operational in 1990
Tate's Cairn Tunnel operational in 1991
Mass Transit Railway (MTR) operational in 1979
MTR Tsuen Wan Line operational in 1982
MTR Kwun Tong Line operational in 1989
Tseung Kwan O Tunnel operational in 1990
Route 3 under construction
VICTORIA PEAK
LION ROCK
KOWLOON PEAK
TAI MO SHAN
ABERDEEN
STANLEY
1968 -1976
Kowloon-Canton Railway Terminal moved to Hung Hom in 1975
Container Terminal reclamation completed in 1976
Airport Runway extension completed in 1974
Cross-Harbour Tunnel operational in 1972
up to 1887
1888 -1924
Kowloon-Canton Railway operational in 1910
1925 -1945
1946 -1967
Lion Rock Tunnel operational in 1967
Kai Tak Airport reclamation completed in 1957

Google Earth Engine Timelapse

WHAT TO MAKE OF THIS? (SUMMARY)

- Large anomalous events at HK in D1, D2, OT.
- Most prevalent at NPQB circa 2002-3009. Not observed elsewhere to same degree.
- However, it is reproduced in some minor constituents (M_3, N_2, Q_1)
- ***D1/D2 "lock":***
  - Exists at all HK gauges, and in NWSCS
- ***Anti-correlation of D1/OT, D2/OT, (D1+D2)/OT***
  - Exists at all HK gauges…
  - *And* most northern SCS gauges to some measure!
- ***Friction appears to be important!***
- ***So does resonance of enclosed harbours!***

  - ***NEXT STEPS: MODELS TO EXPLORE RESONANCE AND FRICTION MECHANISMS in HK and the SCS!***

Questions???

- Thank you for your time and attention!
- 谢谢你的关注！
- Tak for din tid og opmærksomhed!

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