“Variabilité régionale induite par le phénomène de rebond post glaciaire sur le niveau de la mer”

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“Changement climatique et niveau de la mer; Vulnérabilité côtière et enjeux sociétaux”

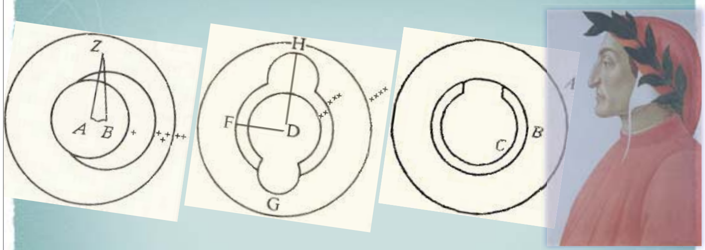
Lundi 10 and mardi 11 juin 2013
h10.45, Lundi

1

The shape of the Earth and of the water masses has been LONG debated:

QUESTIO DE AQUA ET TERRAE, Dante Alighieri (Verona, 1320)

DE FORMA ET SITU DUORUM ELEMENTORUM AQUE VIDELICET ET TERRE



“A question of the water and of the land”

Therefore there is no hump in the water, since God and nature ever doeth and willeth what is better, as is clear from the Philosopher, De Caelo et Mundo, and in the second De Generatione Animalium.

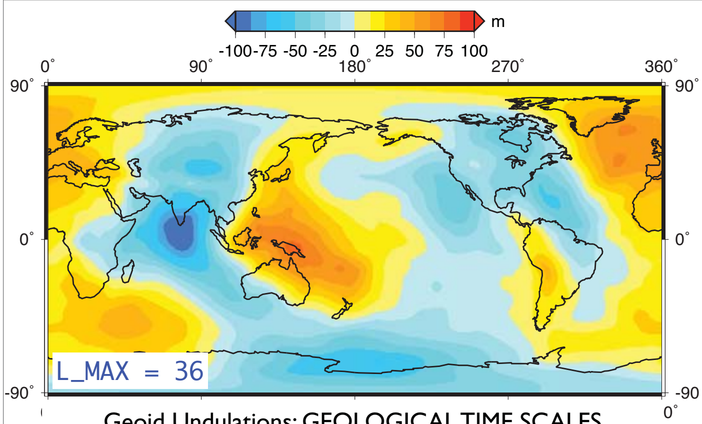
http://alighieri.letteraturaoperaomnia.org/translate_english/alighieri_dante_a_question_of_the_water_and_of_the_land.html

http://www.esri.com/news/arcuser/0703/geoid1of3.html

The geoid approximates mean sea level.

WHAT IS THE “ENGINE” OF GEOID UNDULATIONS, and of the CHANGING SHAPE of the Earth?

3

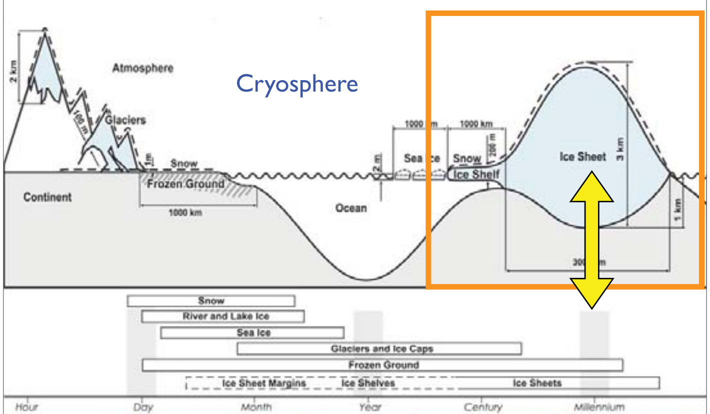


Geoid Undulations: GEOLOGICAL TIME SCALES

“At long wavelength no correlation is observed between *topography* and *geoid undulations*”

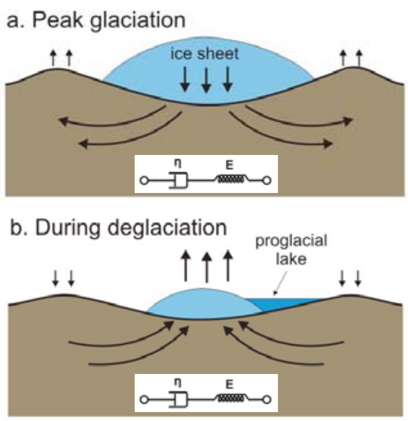
4

MILLENNIUM TIME SCALES



.1 Components of the cryosphere and their typical time scales. Source: Fig. 4.1 of IPCC (2007).

5



“POST GLACIAL REBOUND”

21 kyrs BP

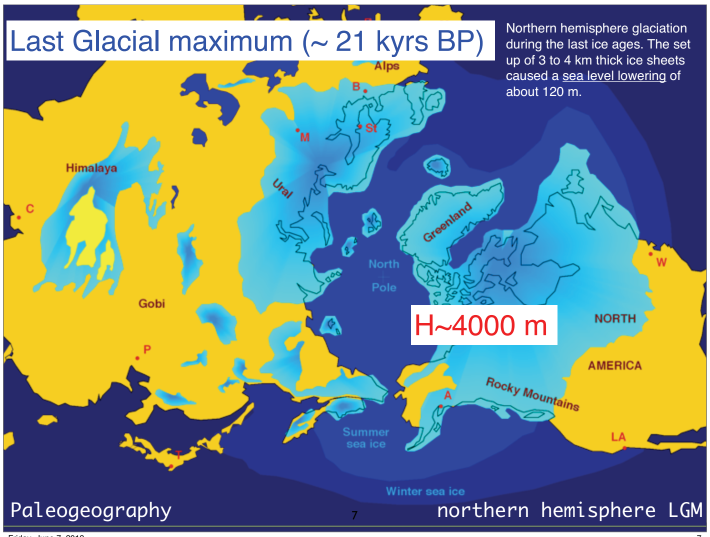
(a) At peak glacial conditions the Earth's surface is depressed beneath the ice sheet and slightly elevated outside the ice sheet owing to mantle flow.

Later on...

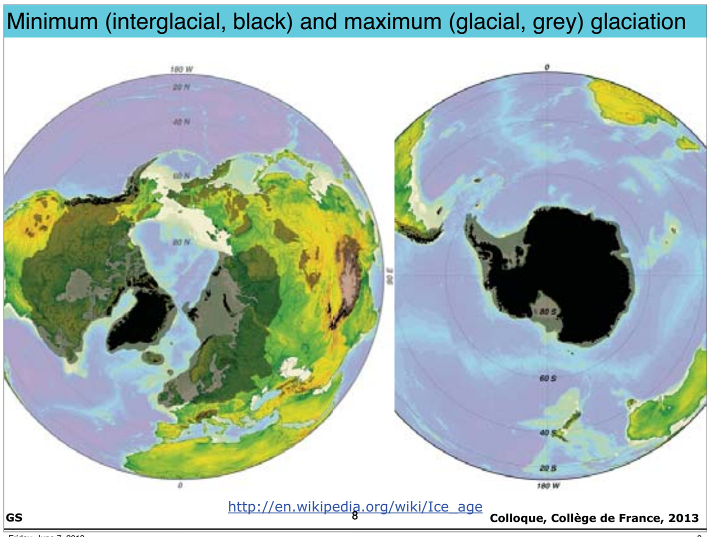
(b) During deglaciation the depressed region rises and peripheral regions subside. Uplift of the Earth's surface is frequently observed as relative sea level fall in recently deglaciated areas.

Adapted from: *http://www.nrcan.gc.ca/earth-sciences/energy-mineral/geology/geodynamics/earthquake-processes/9593*

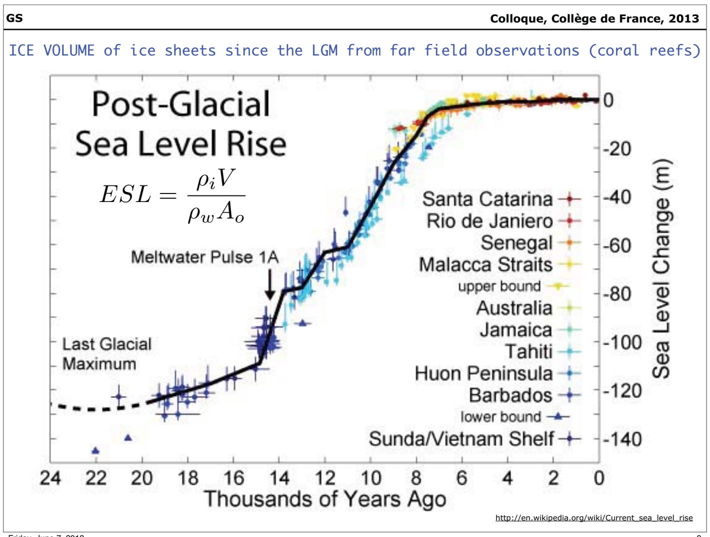
6



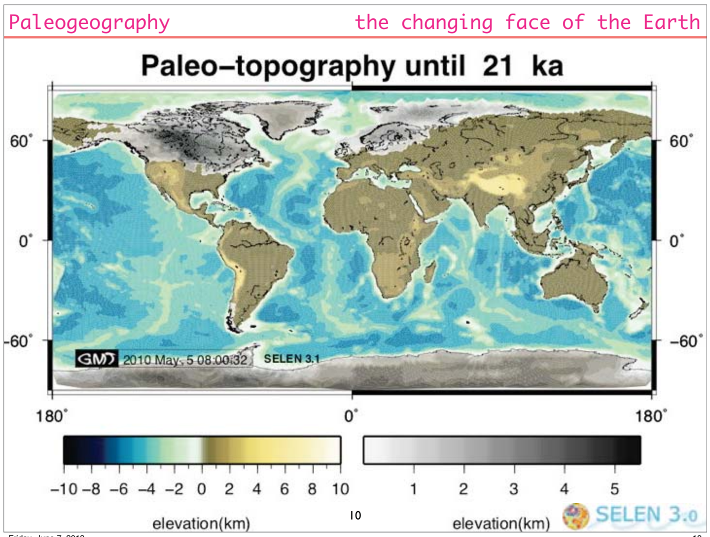
Last Glacial maximum (~ 21 kyrs BP)
Northern hemisphere glaciation during the last ice ages. The set up of 3 to 4 km thick ice sheets caused a sea level lowering of about 120 m.
Alps
Himalaya
Ural
Greenland
North Pole
Gobi
H~4000 m
NORTH AMERICA
Rocky Mountains
Summer sea ice
Winter sea ice
Paleogeography
northern hemisphere LGM



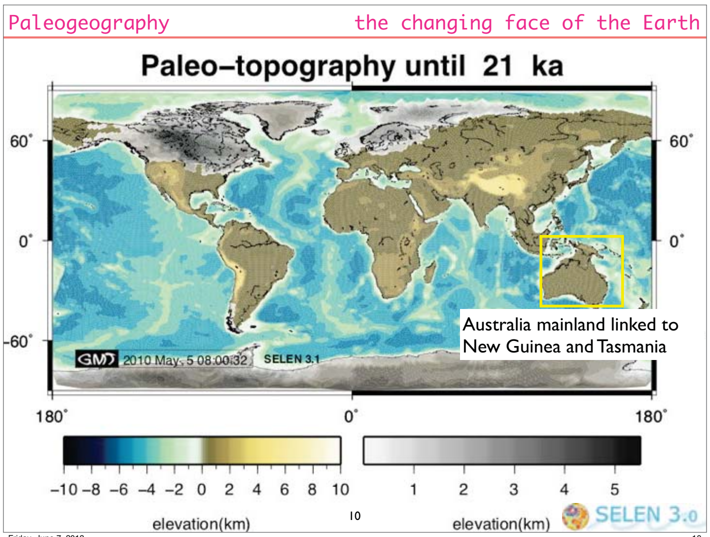
Minimum (interglacial, black) and maximum (glacial, grey) glaciation
GS
http://en.wikipedia.org/wiki/Ice_age
Colloque, Collège de France, 2013



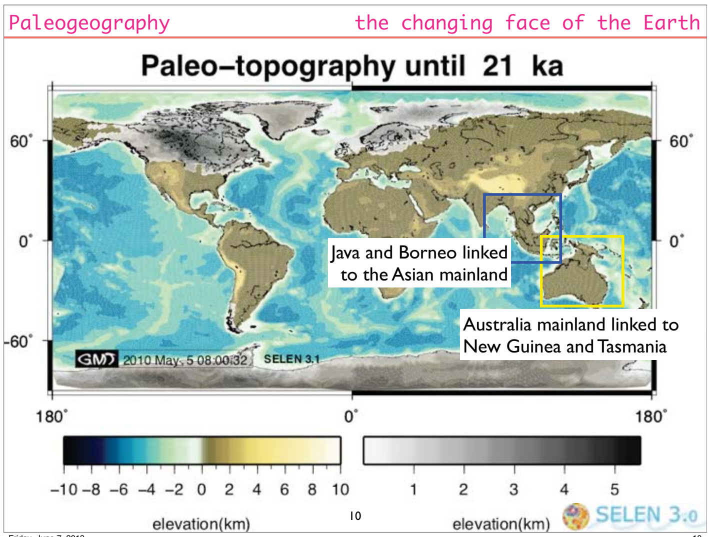
GS
Colloque, Collège de France, 2013
ICE VOLUME of ice sheets since the LGM from far field observations (coral reefs)
Post-Glacial Sea Level Rise
$ESL = \frac{\rho_i V}{\rho_w A_o}$
Meltwater Pulse 1A
Last Glacial Maximum
Santa Catarina
Rio de Janiero
Senegal
Malacca Straits
upper bound
Australia
Jamaica
Tahiti
Huon Peninsula
Barbados
lower bound
Sunda/Vietnam Shelf
Sea Level Change (m)
Thousands of Years Ago
http://en.wikipedia.org/wiki/Current_sea_level_rise



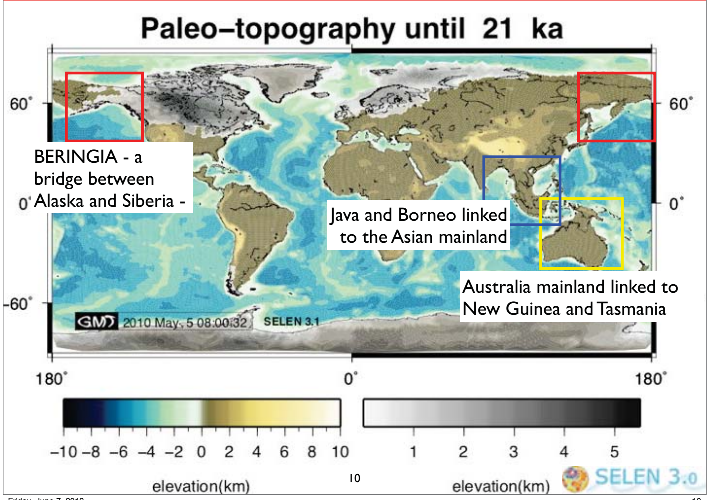
Paleogeography
the changing face of the Earth
Paleo–topography until 21 ka
elevation(km)
elevation(km)
SELEN 3.0



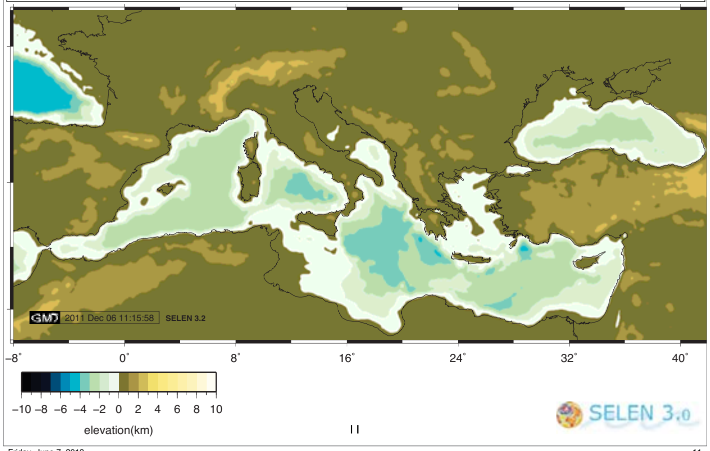
Paleogeography
the changing face of the Earth
Paleo–topography until 21 ka
Australia mainland linked to New Guinea and Tasmania
elevation(km)
elevation(km)
SELEN 3.0

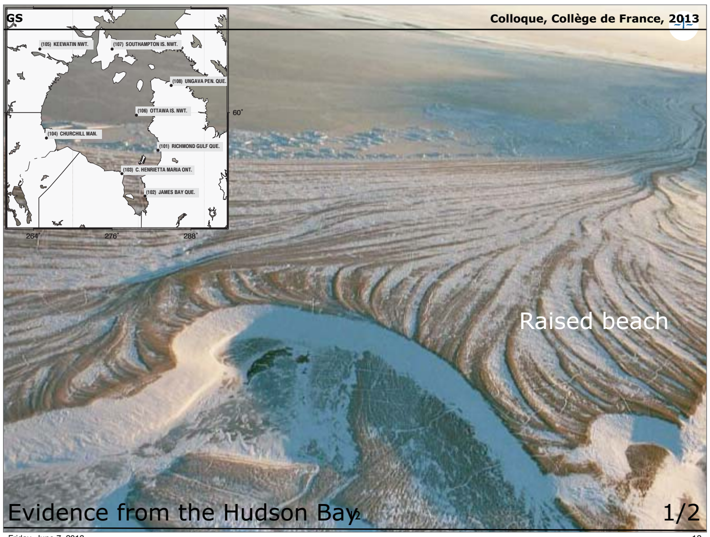


Paleogeography
the changing face of the Earth
Paleo–topography until 21 ka
Java and Borneo linked to the Asian mainland
Australia mainland linked to New Guinea and Tasmania
elevation(km)
elevation(km)
SELEN 3.0

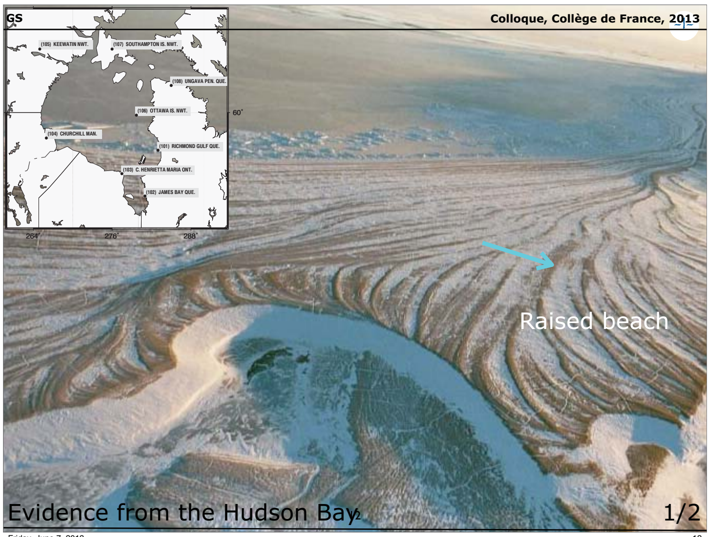


"Gravitationally self-consistent" Mediterranean paleo-topography (LGM, 21 kyrs ago)



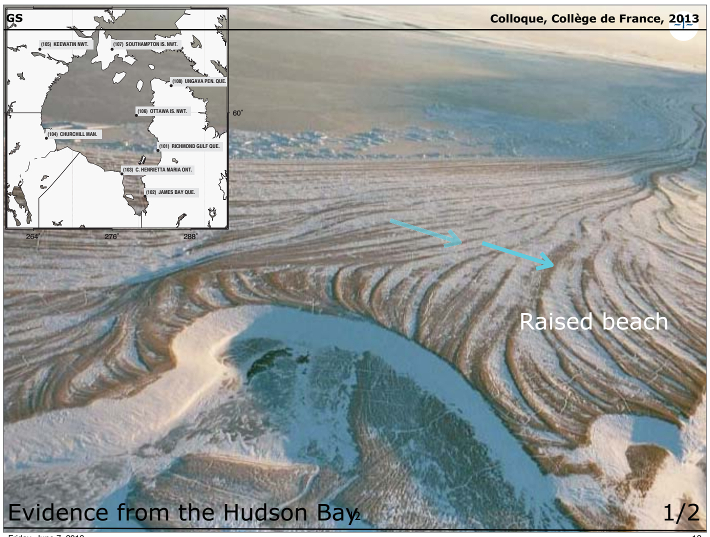


GS Colloque, Collège de France, 2013



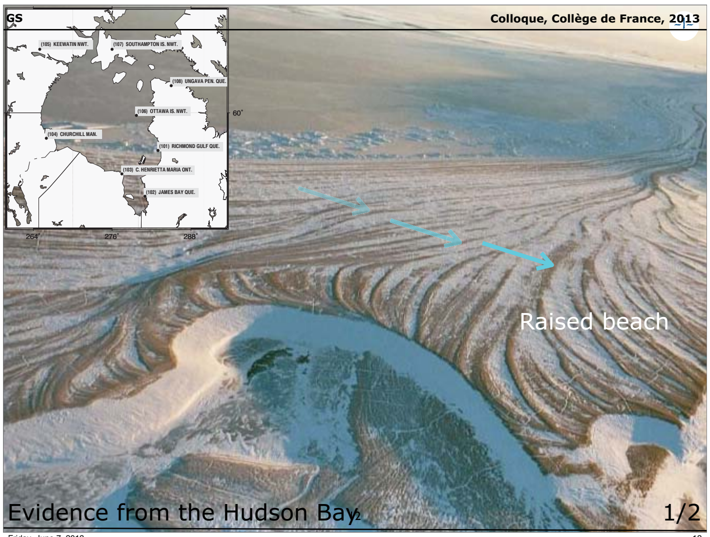
Friday, June 7, 2013 12

GS Colloque, Collège de France, 2013

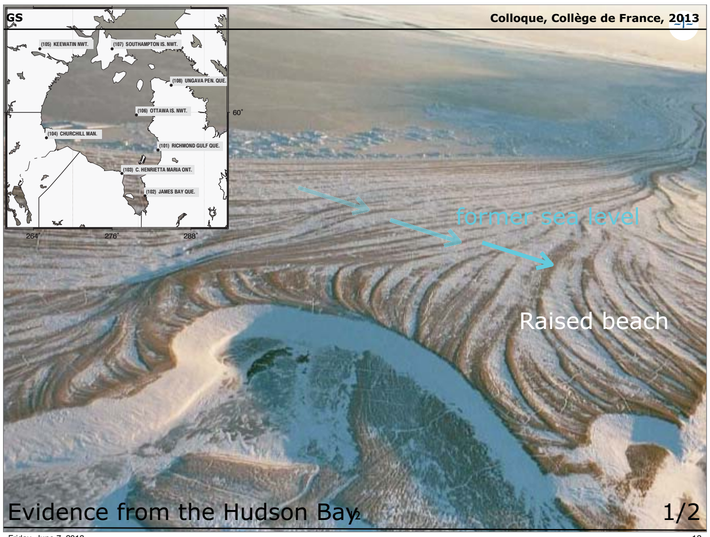


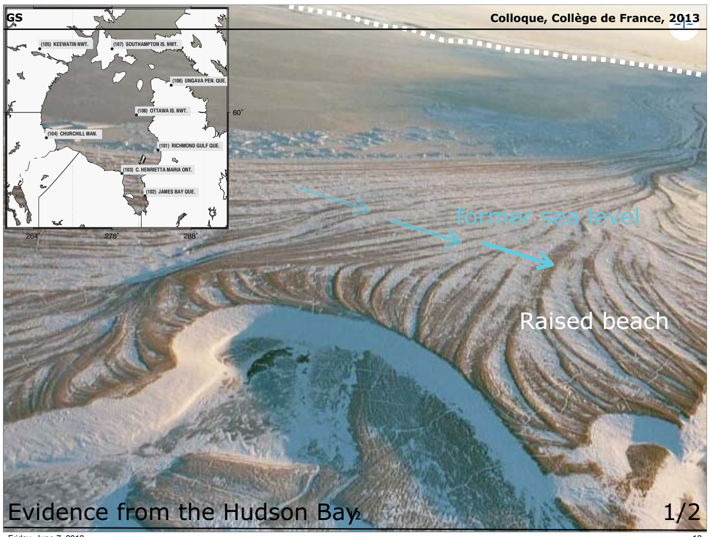
Friday, June 7, 2013 12

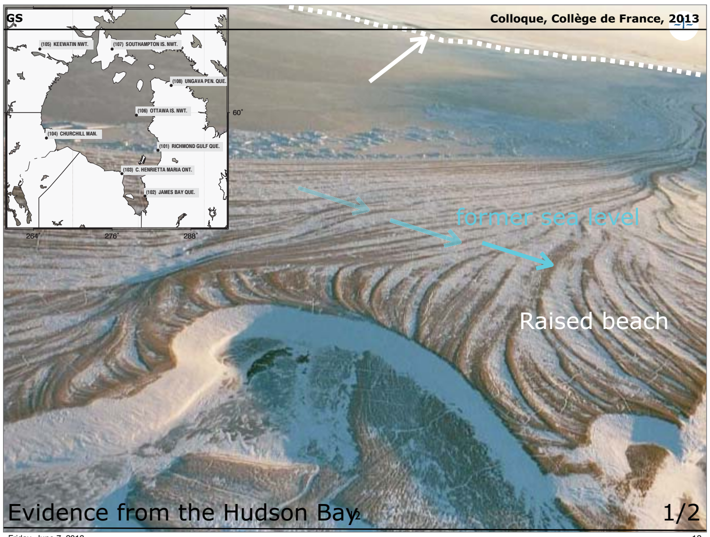
GS Colloque, Collège de France, 2013

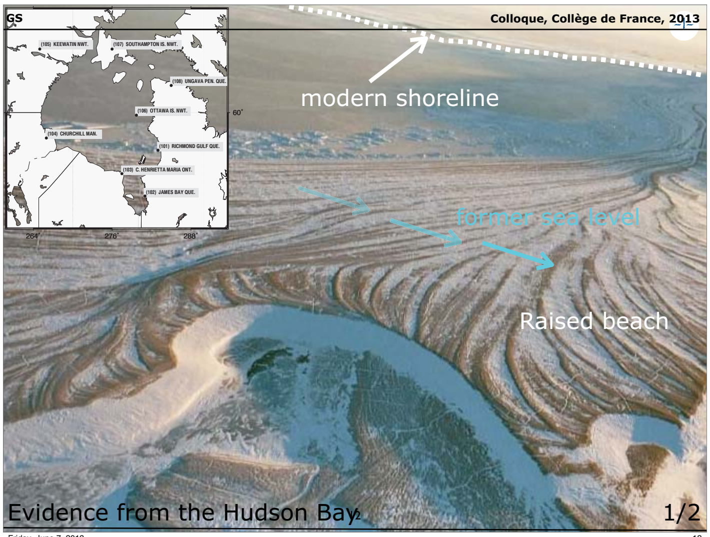


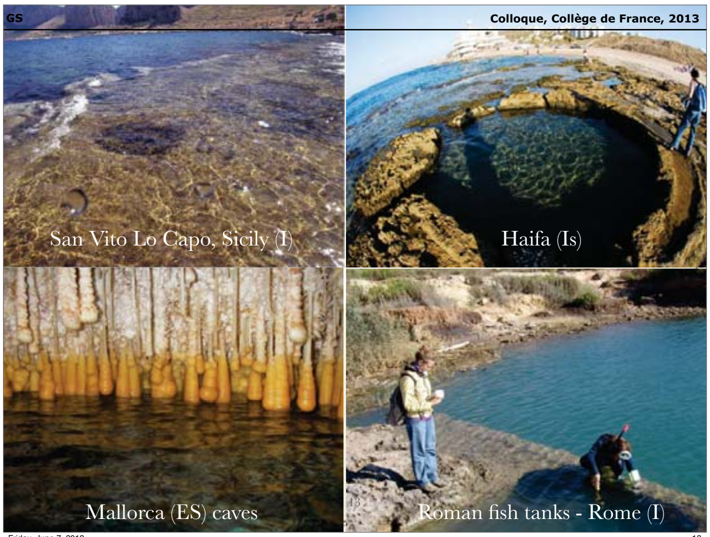
Friday, June 7, 2013 12

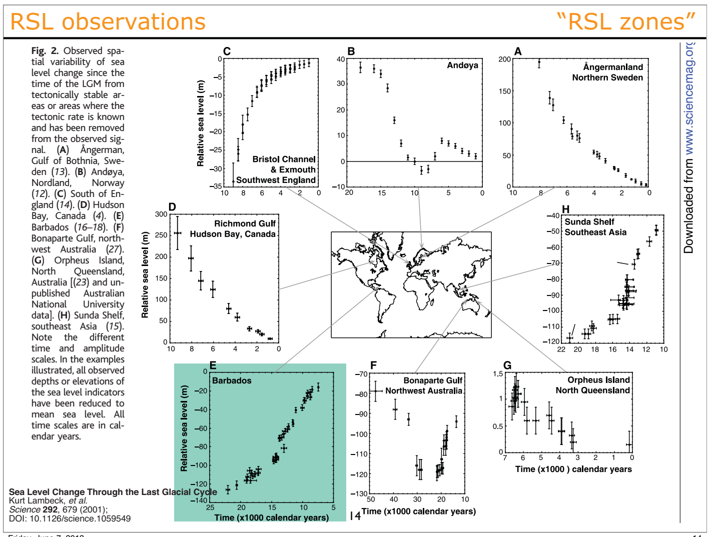

GS
Colloque, Collège de France, 2013
(105) KEEWATIN NWT.
(107) SOUTHAMPTON IS. NWT.
(108) UNGAVA PEN. QUE.
(106) OTTAWA IS. NWT.
(104) CHURCHILL MAN.
(101) RICHMOND GULF QUE.
(103) C. HENRIETTA MARIA ONT.
(102) JAMES BAY QUE.
60°
264°
276°
288°
former sea level
Raised beach
Evidence from the Hudson Bay
1/2


GS
Colloque, Collège de France, 2013
former sea level
Raised beach
Evidence from the Hudson Bay
1/2

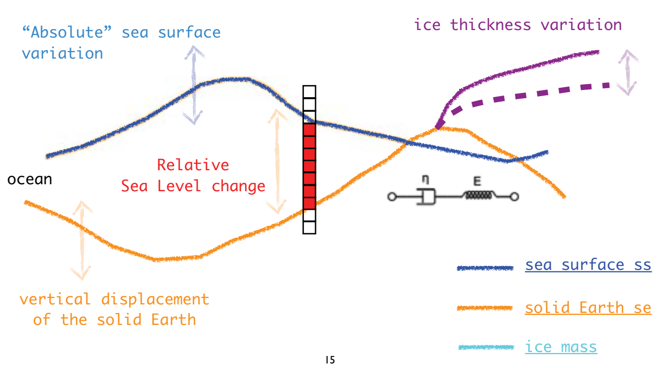

GS
Colloque, Collège de France, 2013
former sea level
Raised beach
Evidence from the Hudson Bay
1/2


GS
Colloque, Collège de France, 2013
modern shoreline
former sea level
Raised beach
Evidence from the Hudson Bay
1/2


GS
Colloque, Collège de France, 2013
San Vito Lo Capo, Sicily (I)
Haifa (Is)
Mallorca (ES) caves
Roman fish tanks - Rome (I)


RSL observations
"RSL zones"
Fig. 2. Observed spatial variability of sea level change since the time of the LGM from tectonically stable areas or areas where the tectonic rate is known and has been removed from the observed signal. (A) Ångerman, Gulf of Bothnia, Sweden (13). (B) Andøya, Nordland, Norway (12). (C) South of England (14). (D) Hudson Bay, Canada (4). (E) Barbados (16–18). (F) Bonaparte Gulf, northwest Australia (27). (G) Orpheus Island, North Queensland, Australia [(23) and unpublished Australian National University data]. (H) Sunda Shelf, southeast Asia (15). Note the different time and amplitude scales. In the examples illustrated, all observed depths or elevations of the sea level indicators have been reduced to mean sea level. All time scales are in calendar years.
Bristol Channel & Exmouth Southwest England
Andøya
Ångermanland Northern Sweden
Richmond Gulf Hudson Bay, Canada
Sunda Shelf Southeast Asia
Barbados
Bonaparte Gulf Northwest Australia
Orpheus Island North Queensland
Relative sea level (m)
Time (x1000 calendar years)
Time (x1000) calendar years
Sea Level Change Through the Last Glacial Cycle
Kurt Lambeck, et al.
Science 292, 679 (2001);
DOI: 10.1126/science.1059549
Downloaded from www.sciencemag.org

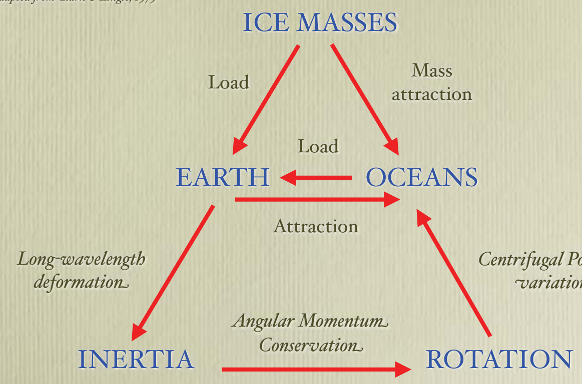
Causes of regional variability in TIM - induced sea level change (i)



15

Causes of regional variability in TIM - induced sea level change (ii)

Adapted from Clark & Lingle, 1979



$$S \neq -\frac{\Delta m_{ice}}{\rho_w A_{oc}}$$

G. Spada ice2sea Forum London, May 2013

16

the "Sea Level Equation"

Farrell & Clark (1976)

$$S = \frac{\rho_i}{\gamma} G_s \otimes_i I + \frac{\rho_w}{\gamma} G_s \otimes_o S - \frac{m_i}{\rho_w A_o} - \frac{\rho_i}{\gamma}\overline{G_s \otimes_i I} - \frac{\rho_w}{\gamma}\overline{G_s \otimes_o S}$$

with:

$S =$ sea level change

$m_i =$ ice mass variation

$\rho_i, \rho_w =$ ice and water density

$A_o =$ area of the oceans

$G_s =$ sea level Green function

$\otimes_i, \otimes_o =$ 3(2+1)D convolutions

$I =$ ice thickness variation

$\overline{(\ldots)} =$ ocean average

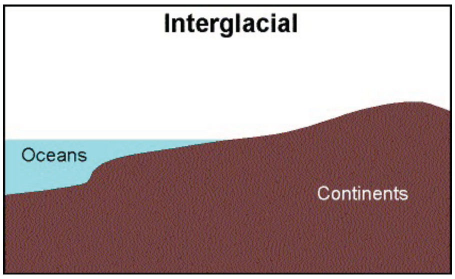
$$\left\{ \begin{array}{c} U_i \\ \Phi_i \end{array} \right\} (\omega, t) \equiv \left\{ \begin{array}{c} G_u \\ G_\phi \end{array} \right\} \otimes_i \rho_i I, \quad \text{and} \quad \left\{ \begin{array}{c} U_o \\ \Phi_o \end{array} \right\} (\omega, t) \equiv \left\{ \begin{array}{c} G_u \\ G_\phi \end{array} \right\} \otimes_o \rho_w S$$

17

The sea level equation (SLE) - basic ideas

Dropping some terms in the SLE.

$$S = \frac{\rho_i}{\gamma} G_s \otimes_i I + \frac{\rho_w}{\gamma} G_s \otimes_o S - \frac{m_i}{\rho_w A_o} - \frac{\rho_i}{\gamma}\overline{G_s \otimes_i I} - \frac{\rho_w}{\gamma}\overline{G_s \otimes_o S}$$



Eustatic solution!

$$S = S^E(t) = -\frac{m_i(t)}{\rho_w A_o}$$

solves the SLE in the very special case:

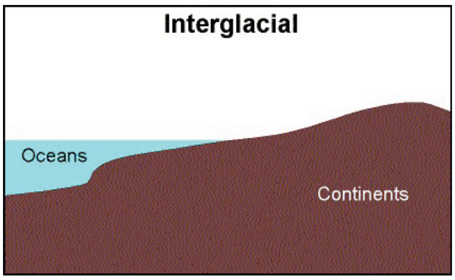
the EARTH is RIGID
and
Newton constant is =0

18

The sea level equation (SLE) - basic ideas

Dropping some terms in the SLE.

$$S = \cancel{\frac{\rho_i}{\gamma} G_s \otimes_i} I + \frac{\rho_w}{\gamma} G_s \otimes_o S - \frac{m_i}{\rho_w A_o} - \frac{\rho_i}{\gamma}\overline{G_s \otimes_i I} - \frac{\rho_w}{\gamma}\overline{G_s \otimes_o S}$$



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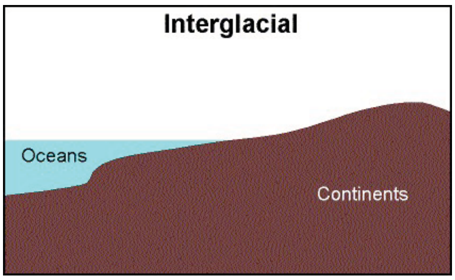

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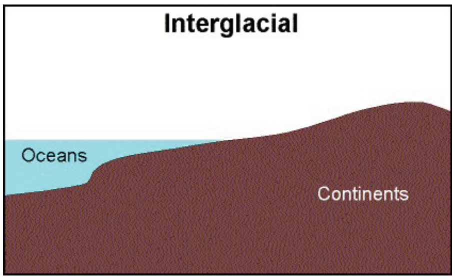

Eustatic solution!

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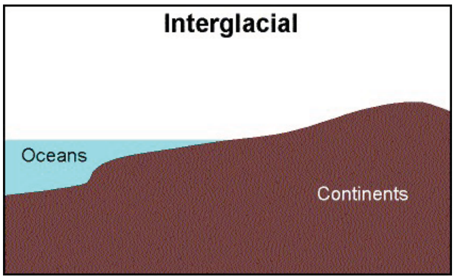

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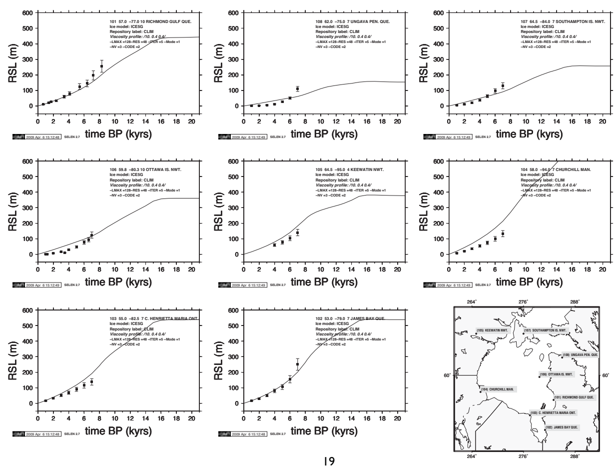
18

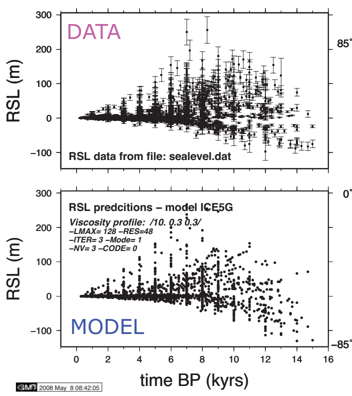
Friday, June 7, 2013 18

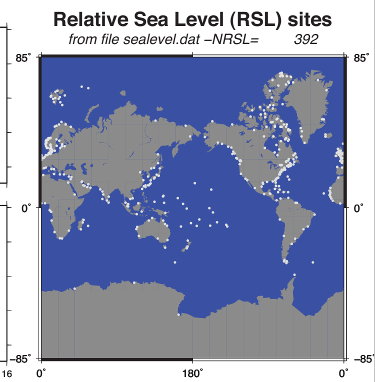
Model vs RSL observations - full theory Hudson bay



19

Model vs RSL observations the global scale





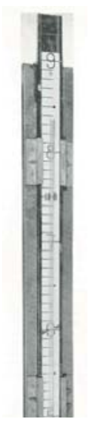
T/P database

http://gcmd.nasa.gov/records/GCMD_EARTH_LAND_NGDC_PALEO_SEALEVEL1.html

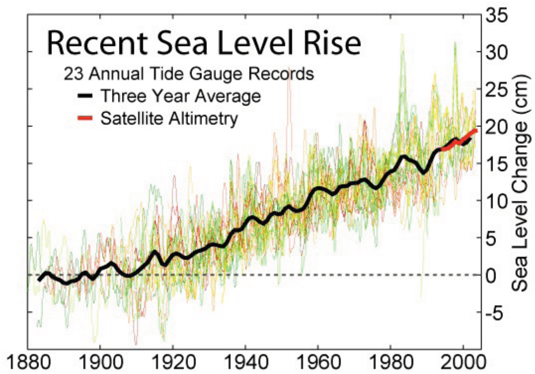
20

Sea level rise from tide gauges

"viewpoint of the solid Earth"



"A tide staff"



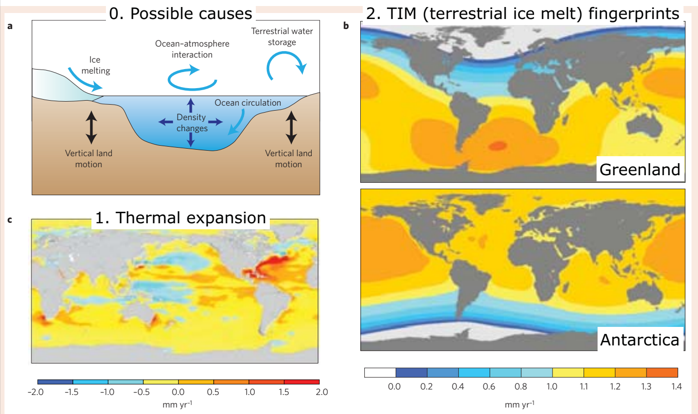
Rate is ~ 20 cm/century

Now we move to present time with TWO points

21

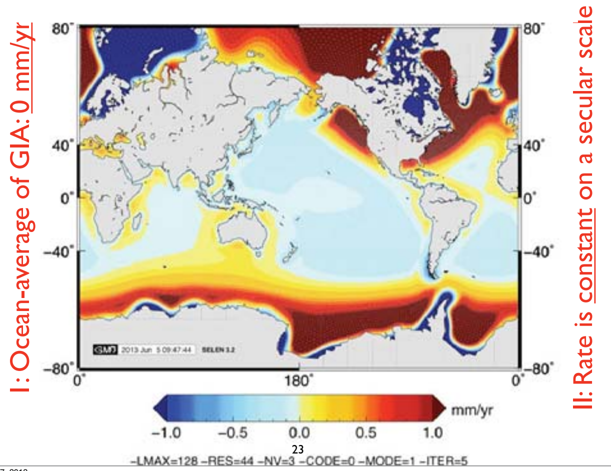
Identifying the causes of sea-level change

Glenn A. Milne, W. Roland Gehrels, Chris W. Hughes and Mark E. Tamisiea, NATURE GEOSCI 2009



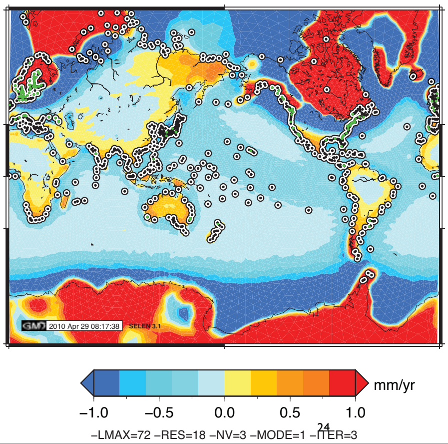
22

PRESENT DAY GIA component of SLR: ICE-5G (VM2) Peltier, 2004



Rate of vertical displacement today

−Ice model: ICE5G −ALMA rheology: ./VSC/vsca_BENCH.dat



All PSMSL tide gauges (~ 1200)

All PSMSL tide gauges with T > 60 years (~ 140)

Most (all?) tide gauges are in regions of considerable GIA disequilibrium

SELEN 3.0

The GLOBALLY AVERAGED RATE of SEA LEVEL RISE

is estimated using long series of T/G data
after GIA correction!

Table 3.1
Recent Determinations of Global Sea Level Rise from Tide Gauge Data

Author	Estimate (mm/yr)	Comments
Peltier and Tushingham (1989, 1991)	2.4 ± 0.9[a]	Global data
Barnett (1990)	1–2	Global data
Nakiboglu and Lambeck (1990)	1.15 ± 0.38	Global data
Trupin and Wahr (1990)	1.75 ± 0.13	Global data
Douglas (1991)	1.8 ± 0.1	Global data
Shennan and Woodworth (1992)	1.0 ± 0.15	U.K. and Europe
Mitrovica and Davis (1995)	1.1–1.6	Global data
Davis and Mitrovica (1996)	1.5 ± 0.3	U.S. east coast
Peltier (1996)	1.94 ± 0.6[a]	U.S. east coast
Peltier and Jiang (1997)	1.8 ± 0.6[a]	U.S. east coast
Douglas (1997)	1.8 ± 0.1	Global data

[a] Standard deviation of trends about their mean. The formal SE is a few tenths.

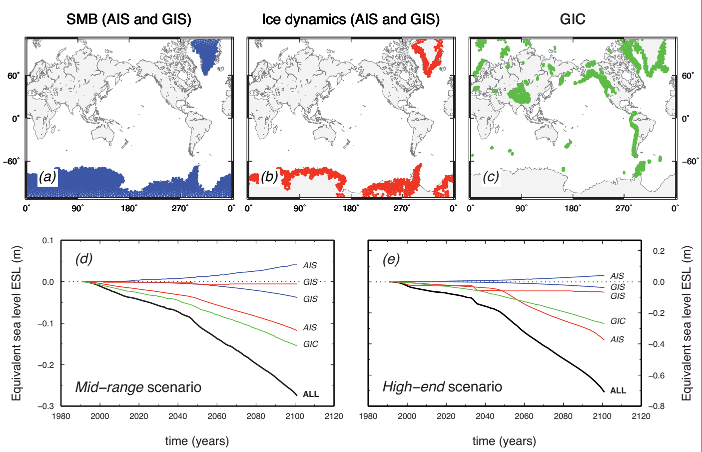
What is the color of sea level change?

and regional (future) signals

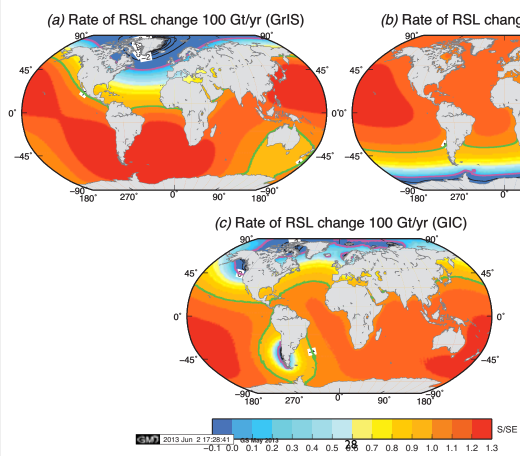
http://www.ice2sea.eu/

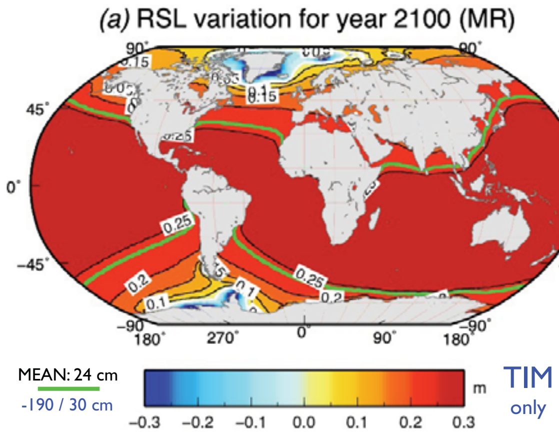
Ice2sea is a science programme that is funded by the European Union Framework-7 scheme.

Ice2sea will improve projections of the contribution of ice to future sea-level rise.



FUTURE component of SLR: Terrestrial Ice Melt (TIM) fingerprints



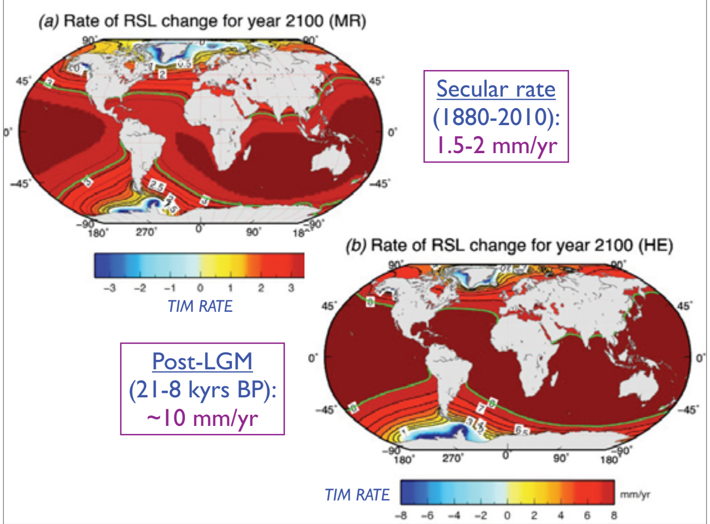


SUMMARY

- ✓ Sea level change associated with GIA (Glacial Isostatic Adjustment) have a marked regional character,
- ✓ The causes are: Earth deformations and gravity field variations, the complex geometry of ocean floors, rotational variations, time-dependency of the ice loads and rheological effects,
- ✓ The interpretation of secular sea level rise by instrumental observations is only possible when these regional changes are accounted for,
- ✓ Future sea level changes (to year 2100) will strongly depend on the contribution of terrestrial ice melt. From the ice2sea project, we now better know what their regional pattern will be.

THANK YOU

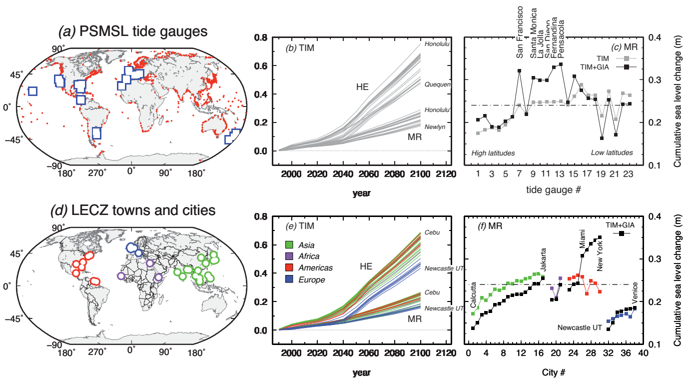
BACKUP SLIDES
(e.g. for questions..., ETC)



Secular rate
(1880-2010):
1.5-2 mm/yr

Post-LGM
(21-8 kyrs BP):
~10 mm/yr

RSL Projections on specific sites: Tide gauges and LECZs / cities

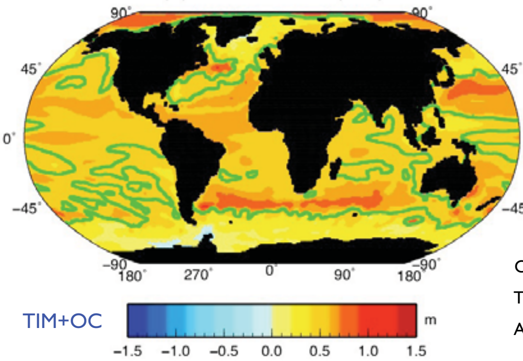


Low Elevation Coastal Zone (LECZ) data: all land area that is contiguous with the coast and 10 meters or less in elevation, see http://sedac.ciesin.columbia.edu/data/set/lecz-low-elevation-coastal-zone and McGranahan et al . 2007

PSMSL tide gauges observations: http://www.psmsl.org/

year 2100

(a) TIM + ocean (MR)



50 cm

TIM+OC

OC: 27 cm

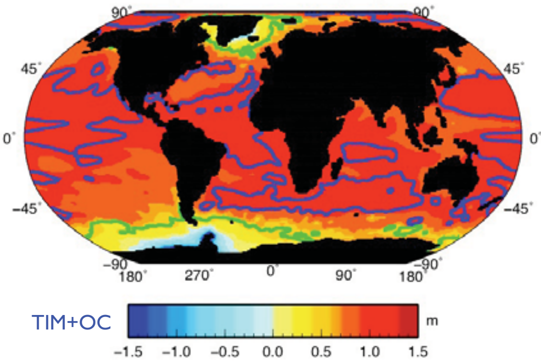
TIM: 24 cm

AVE=51cm

<u>TIM</u> is combined with the <u>OCEAN</u> response (OC: steric+ocean circulation) (ECHAM5 MPI-OM A1B, *Meehl et al., 2007*) - NO GIA here

Note: NOT a fully coupled TIM + OC experiment

(b) TIM + ocean (HE)



50 cm

100 cm

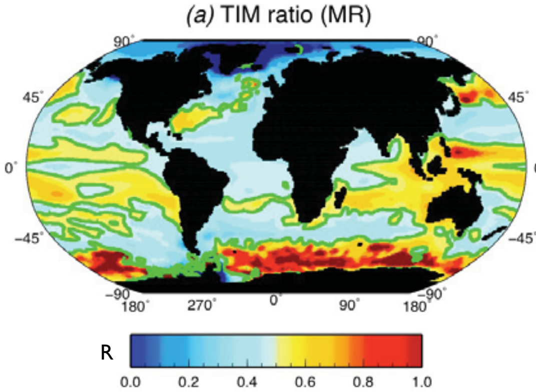
TIM+OC

<u>ECHAM5 A1B: 27 cm</u> <u>TIM: 61 cm</u> <u>AVE: 89 cm</u>

year 2100

Comparing TIM to OC: TIM ratio R = TIM/(TIM+OC)

(a) TIM ratio (MR)

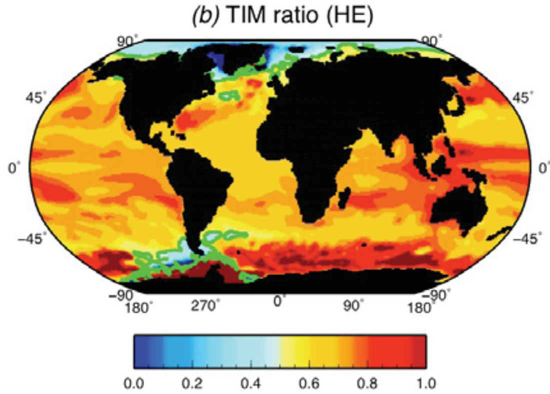


R

TIM<OC TIM=0 TIM>OC

Comparing TIM to OC: TIM ratio R = TIM/(TIM+OC)

(b) TIM ratio (HE)



TIM<OC TIM=0 TIM>OC