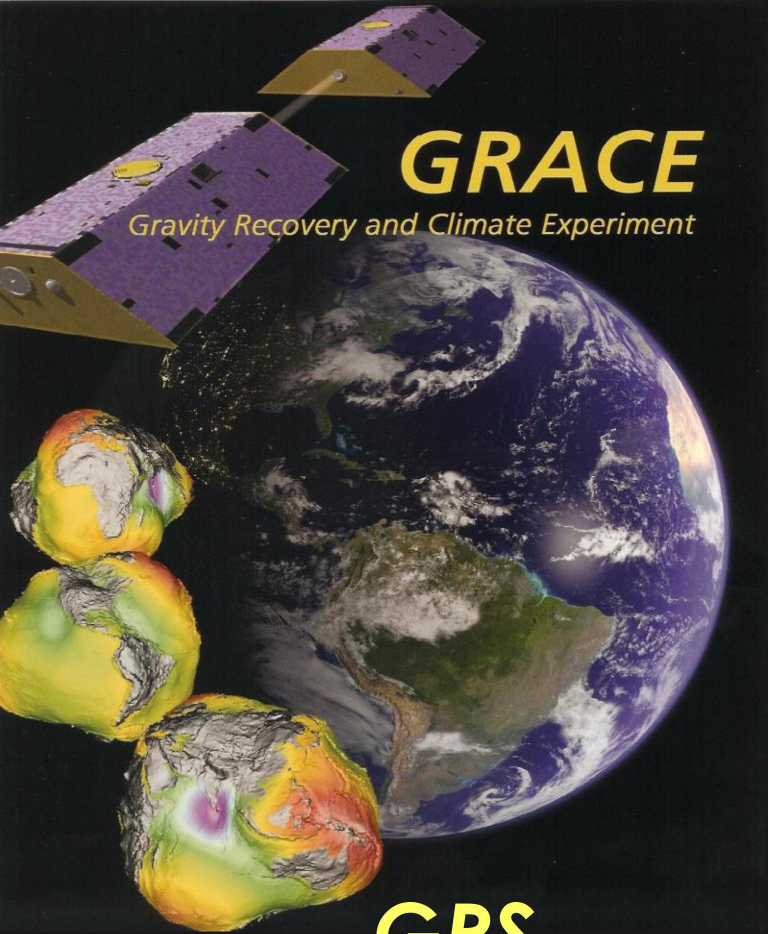


GPS

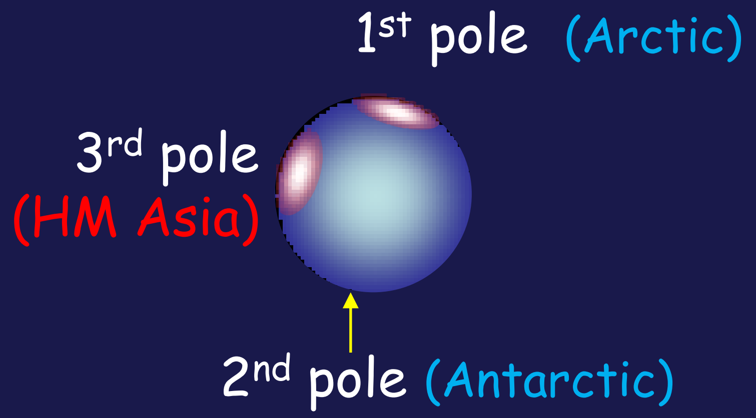
Global Positioning System

Kosuke Heki & K. Matsuo
Dept. Natural History Sci.,
Hokkaido Univ., Sapporo, Japan

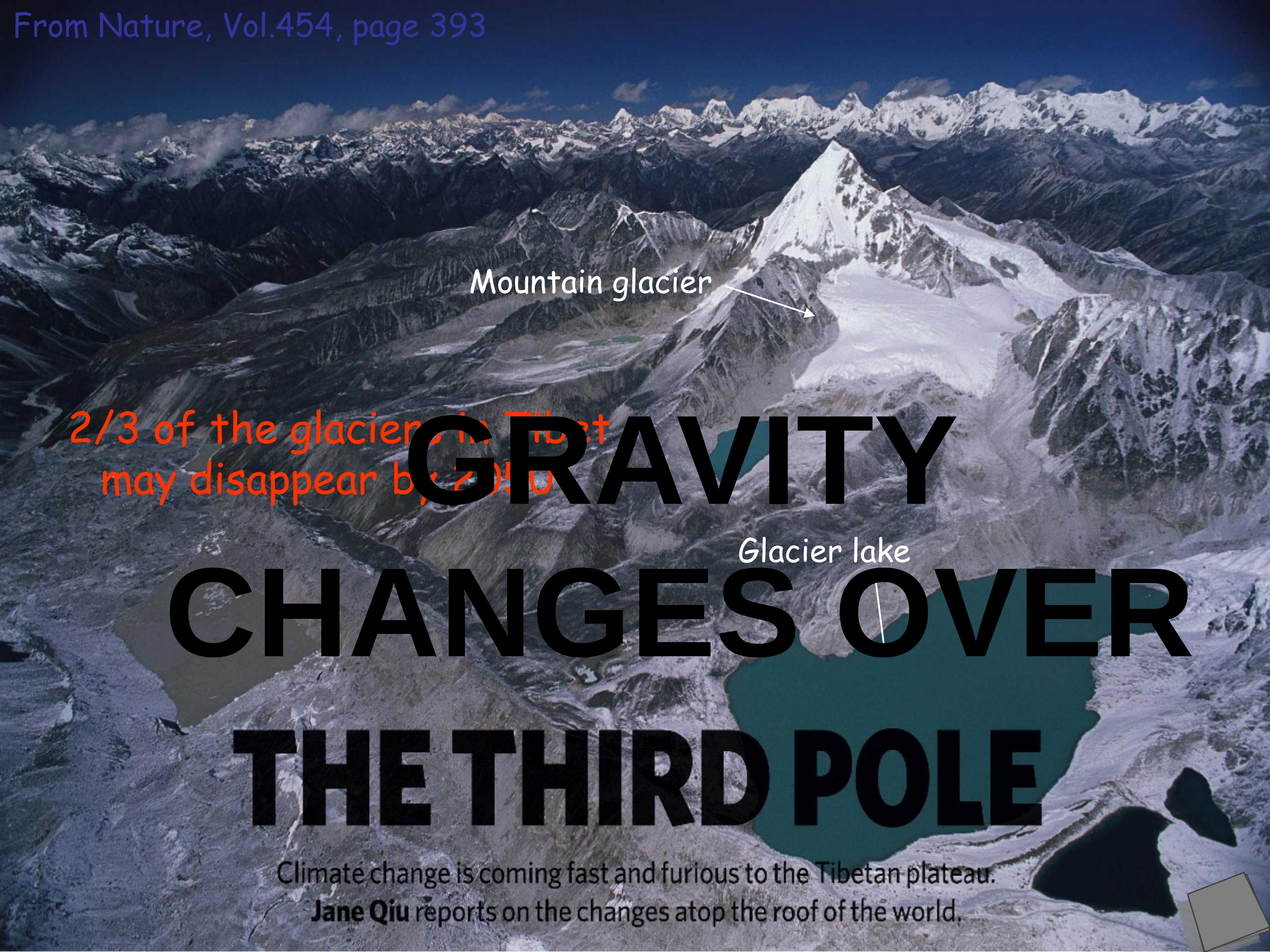
Ice loss versus uplift: Current mass balance in Asian high mountains from satellite gravimetry

Interdisciplinary study on the 3rd pole

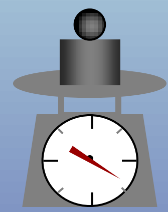
Related fields:
- Glaciology (mass balance of mountain glacior)
- Geodesy (time-variable gravity, crustal movement)
- Tectonics (orogeny)
- Geodynamics (glacial isostatic adjustment)
- Climatology (global warming)



GRAVITY CHANGES OVER



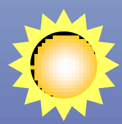
It's not only ice …



Ice melting → negative Δg

Uplift → positive Δg

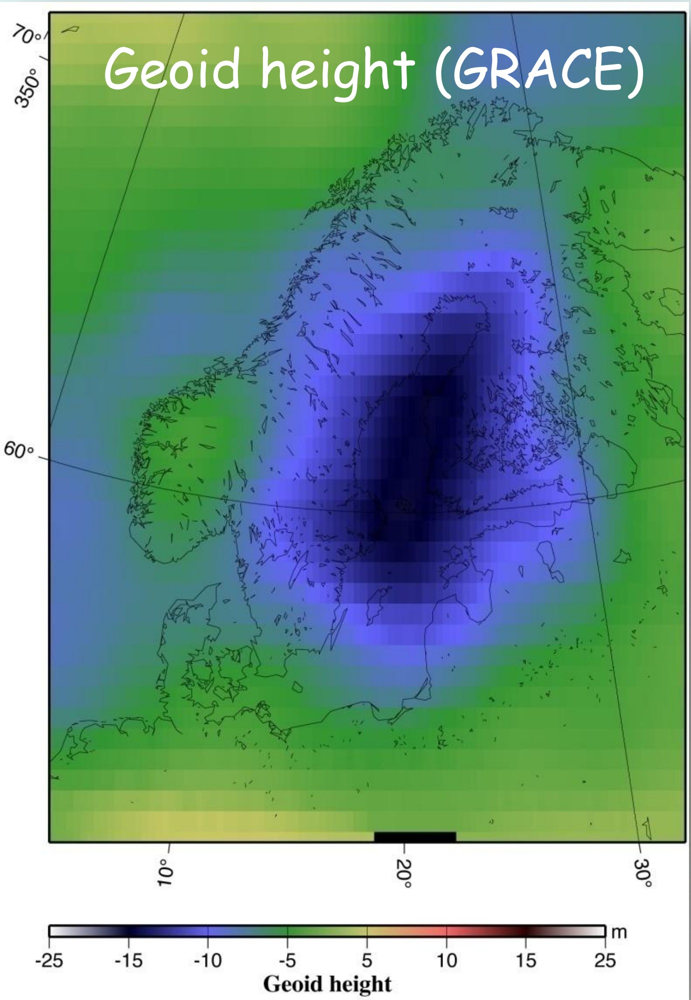
(Tectonic or GIA)

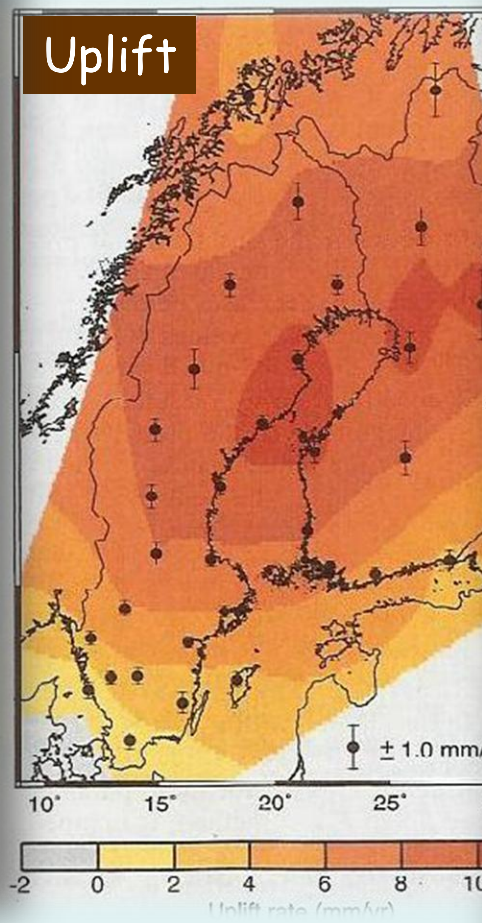


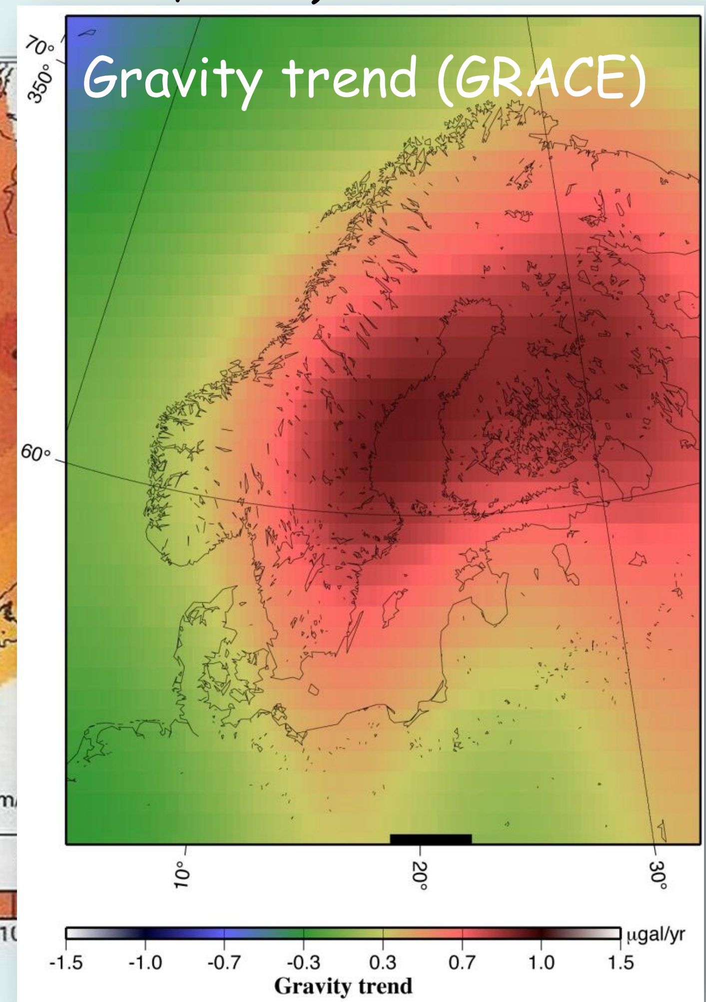
Orogeny does not increase gravity,
but GIA does.

Glacial Isostatic Adjustment in northern Europe

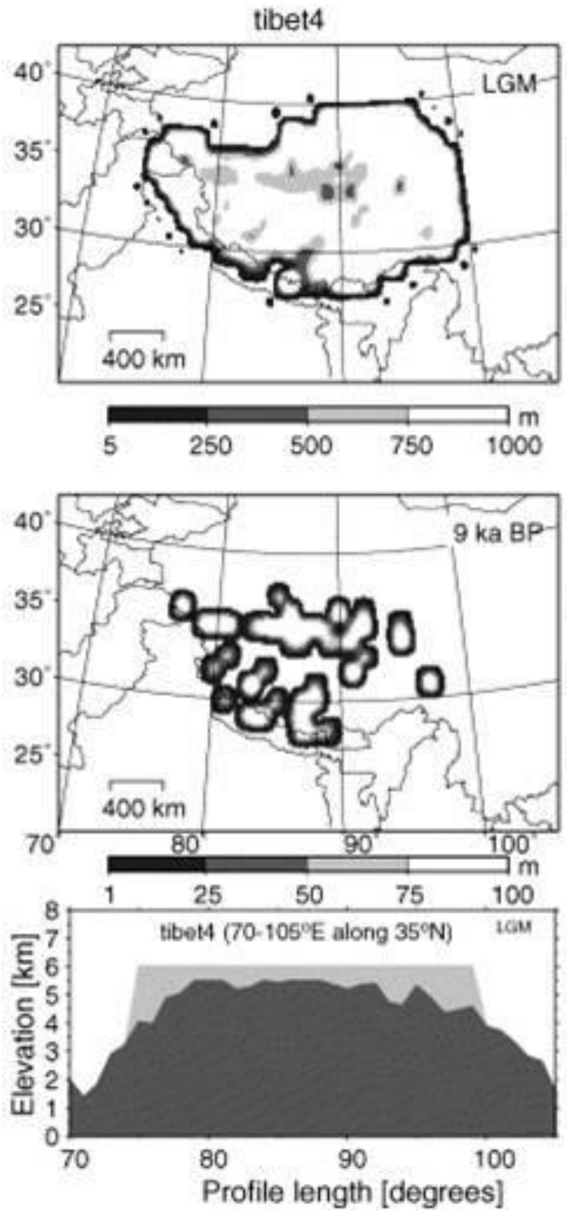
BIFROST (Milne et al., 2001)







A large ice sheet might have been on the 3rd pole …



Last glacial maximum

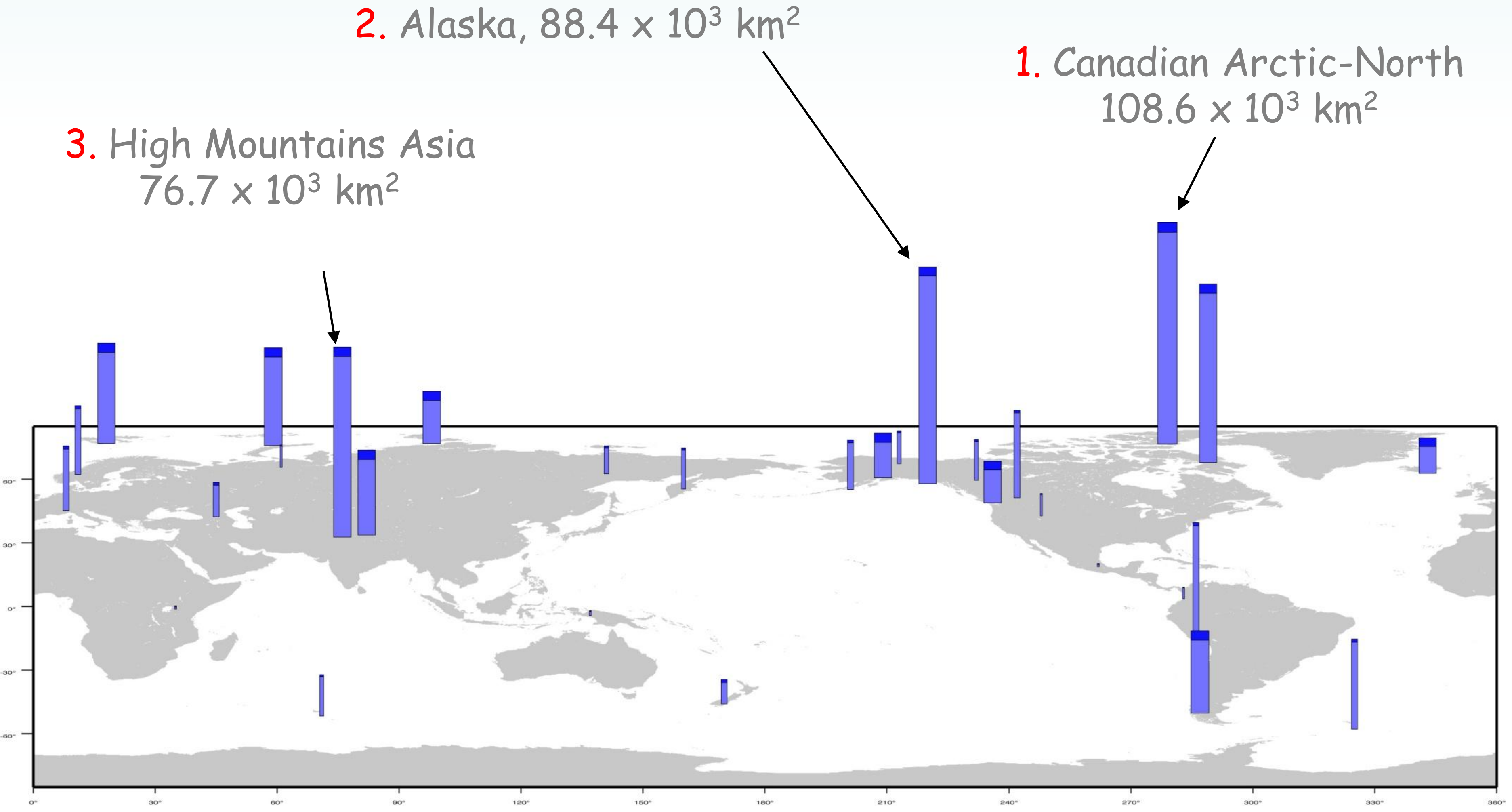
9,000 yrs ago

TIBET-4 GIA model

(Kaufmann, J. Geodyn., 2005)

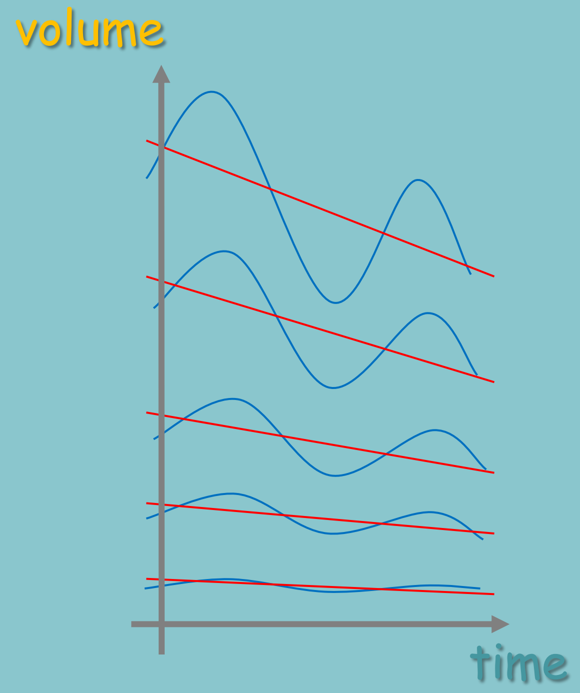
Area of mountain glaciers (Meier, 1984)

But, they are not necessarily melting.



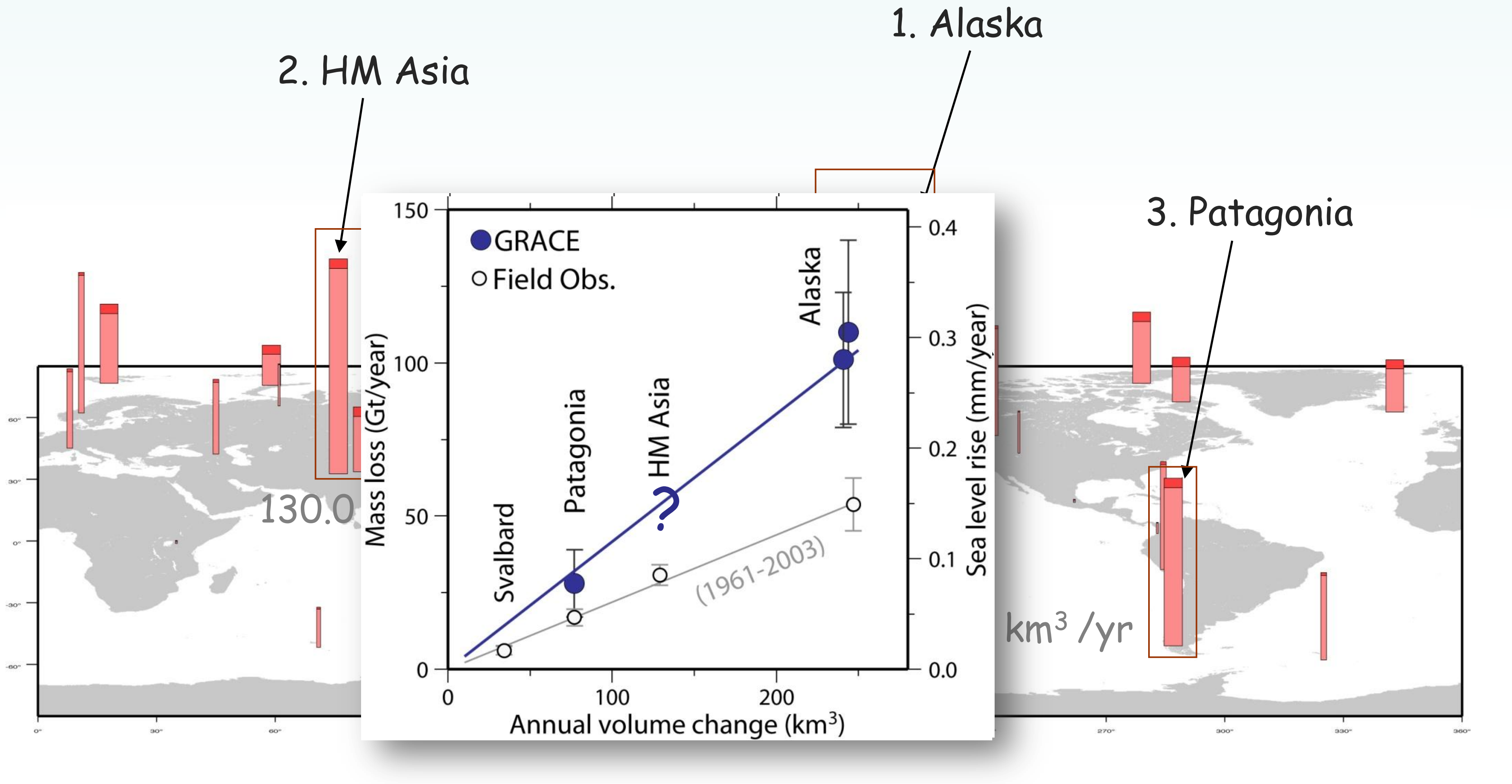
Meier's (1984) rule of thumb:

More seasonal change = More secular change



Annual volume change of mountain glaciers

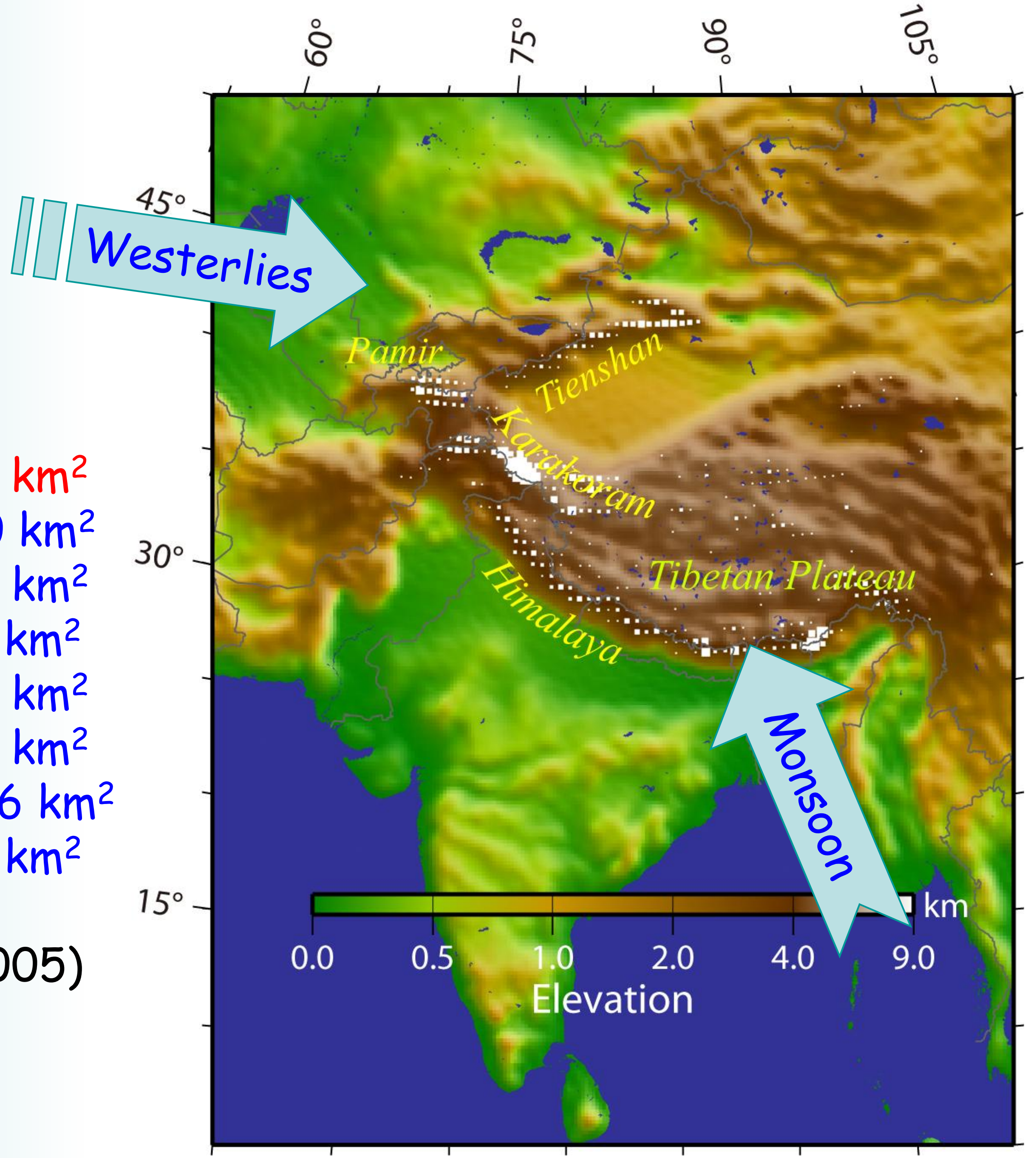
Area x Annual thickness change, after Meier (1984)

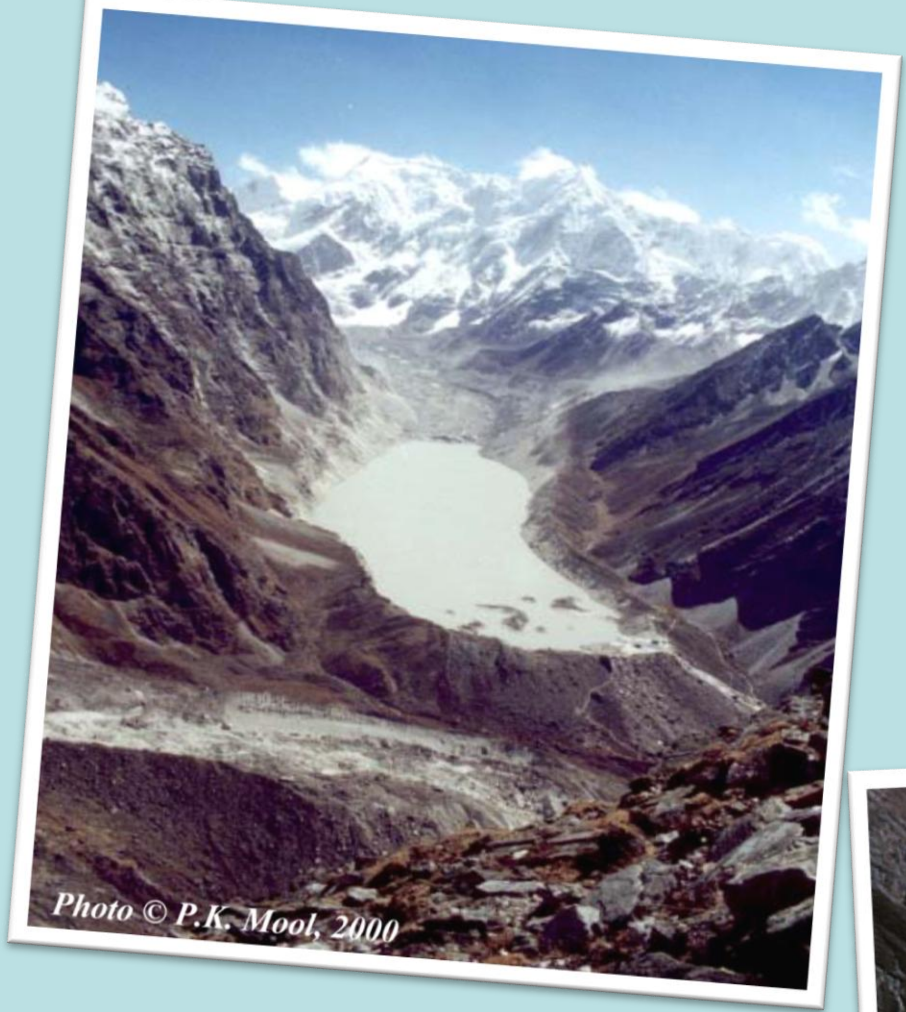


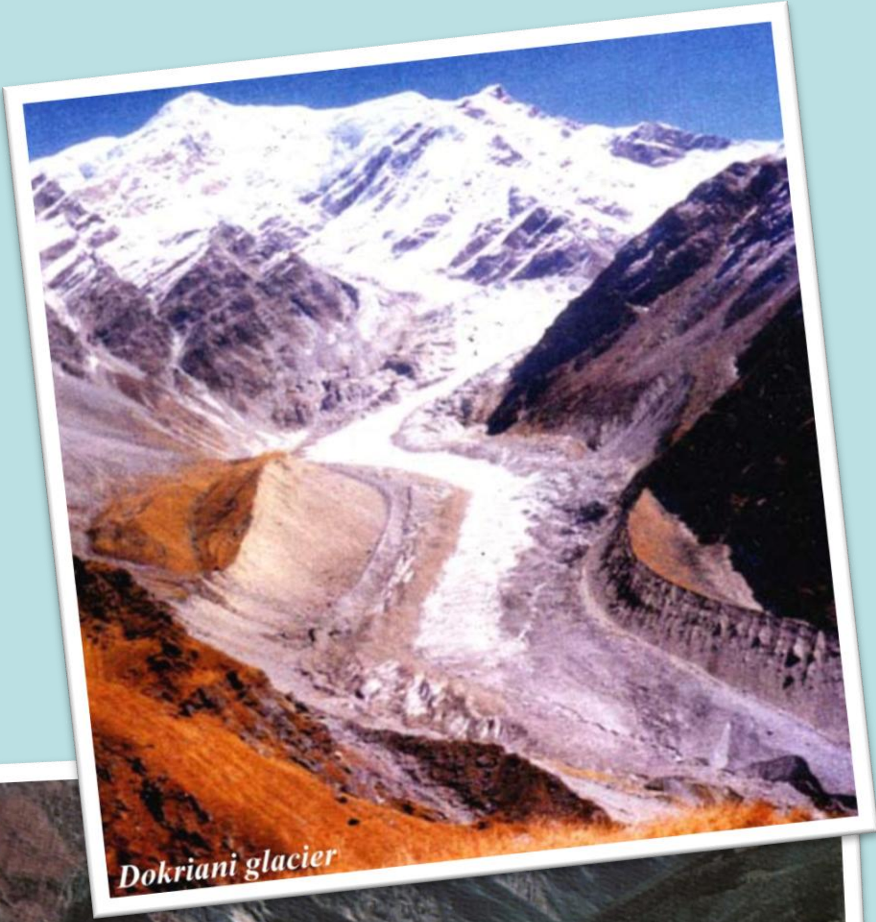
Glaciers in the Asian High Mountains

Total : 116,180 km²
Himalaya : 33,050 km²
Karakoram : 16,600 km²
Tienshan : 15,417 km²
Pamir : 12,260 km²
Kunlun : 12,260 km²
Nyainqentanghla : 7,536 km²
Hindukush : 5,900 km²

(Dyurgerov & Meier, 2005)



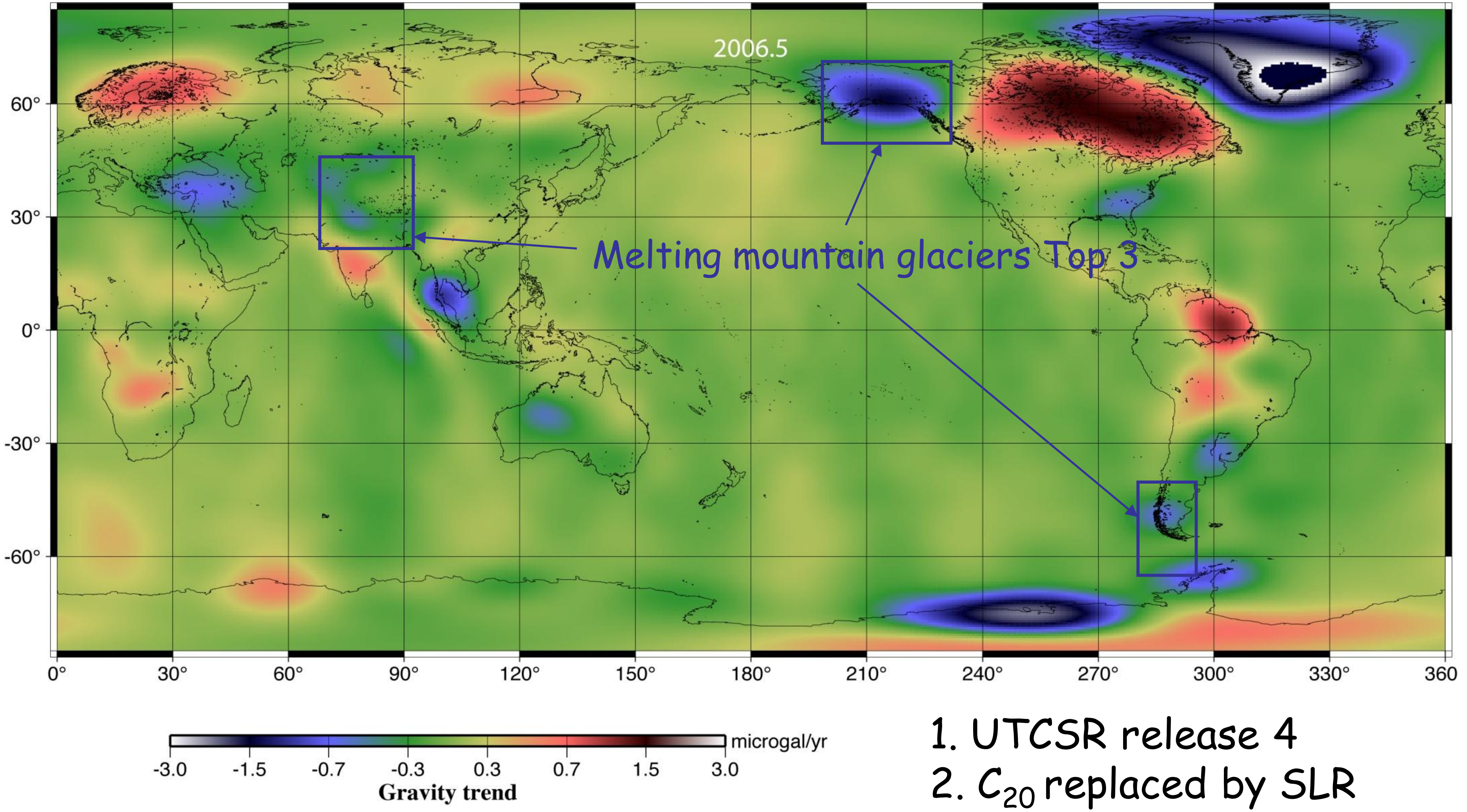




Glaciers fed by summer snows are more sensitive to warming

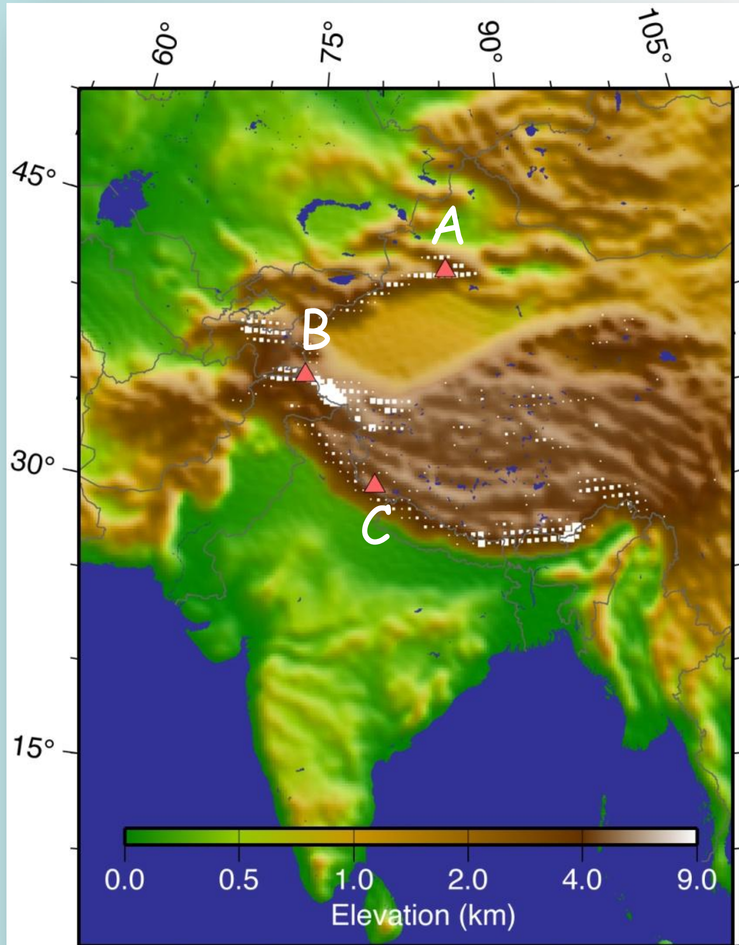
(Fujita & Ageta, J. Glaciol., 2000)

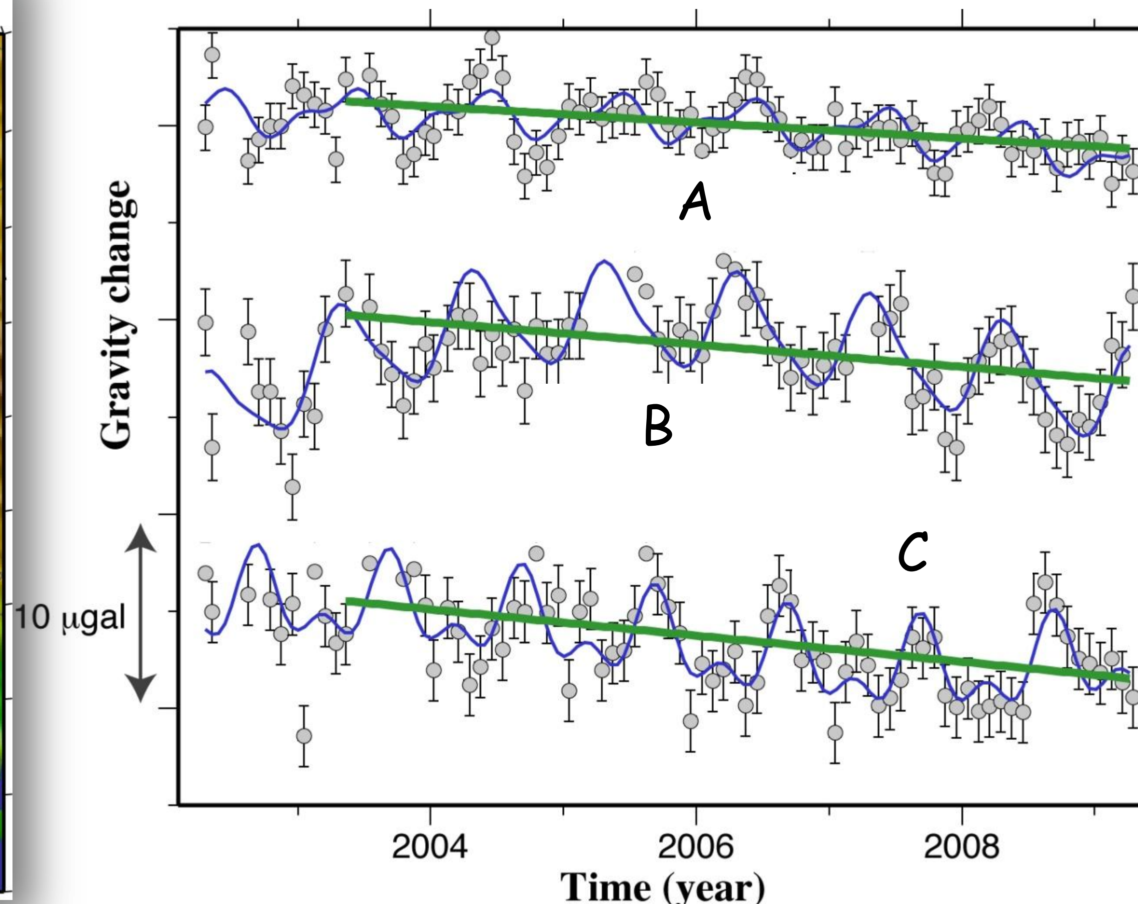
Trend in gravity (2002-2008: epoch 2006.5)



1. UTCSR release 4
2. C_{20} replaced by SLR
3. P5M11 de-striping
4. 400 km Gaussian filter

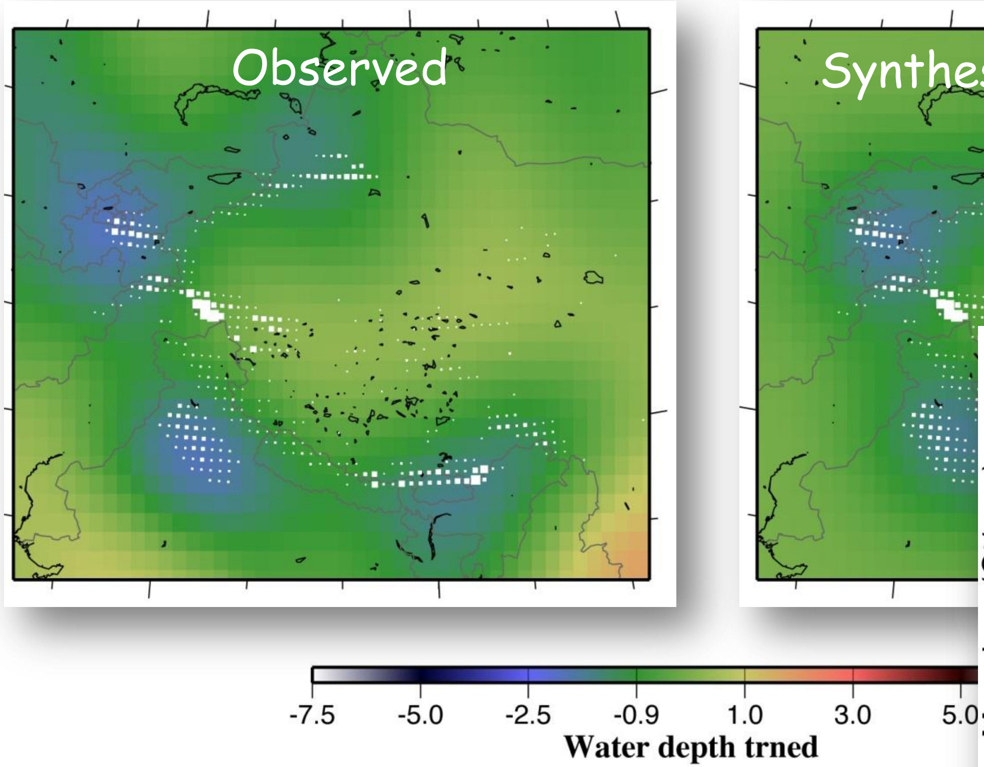
2003-2009 average trends show decreases

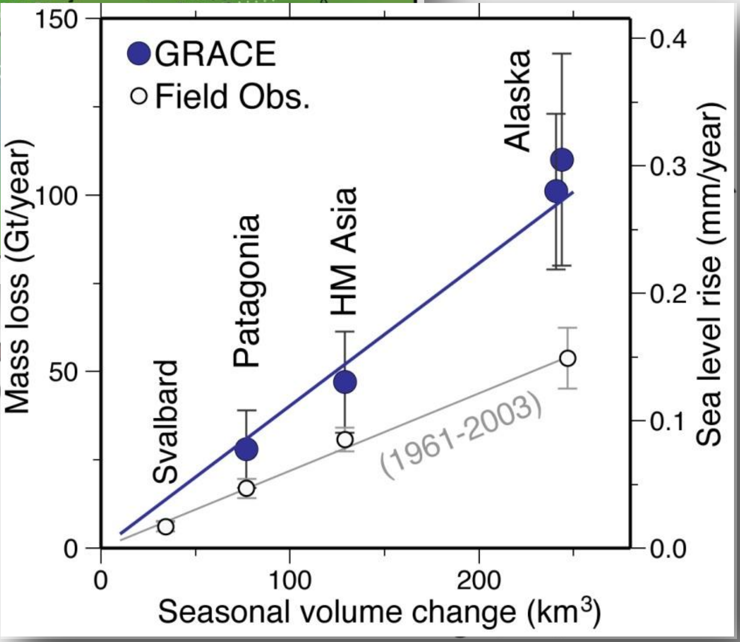


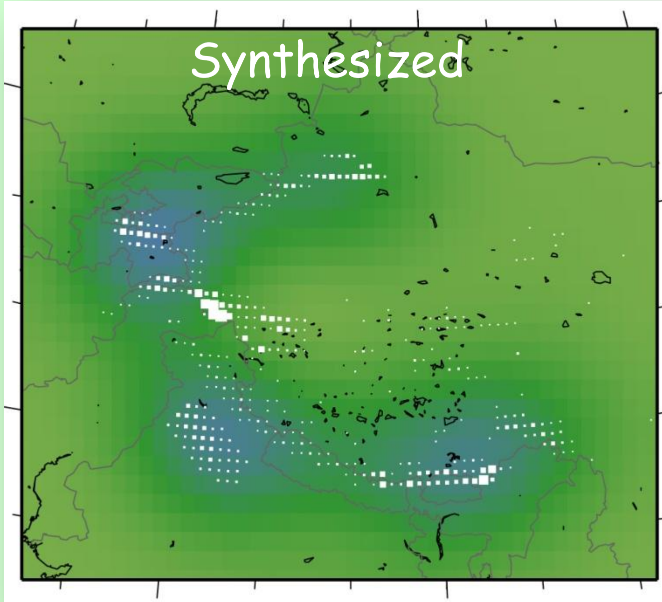


$$\Delta\sigma(\theta,\phi) = \frac{R\rho_{ave}}{3}\sum_{n=0}^{\infty}\sum_{m=0}^{n}\frac{2n+1}{1+k_n}(\Delta C_{nm}\cos m\phi + \Delta S_{nm}\sin m\phi)P_{nm}(\sin\theta)$$

From Stokes' coefficients to surface mass distribution [*Wahr et al.*, 1998]



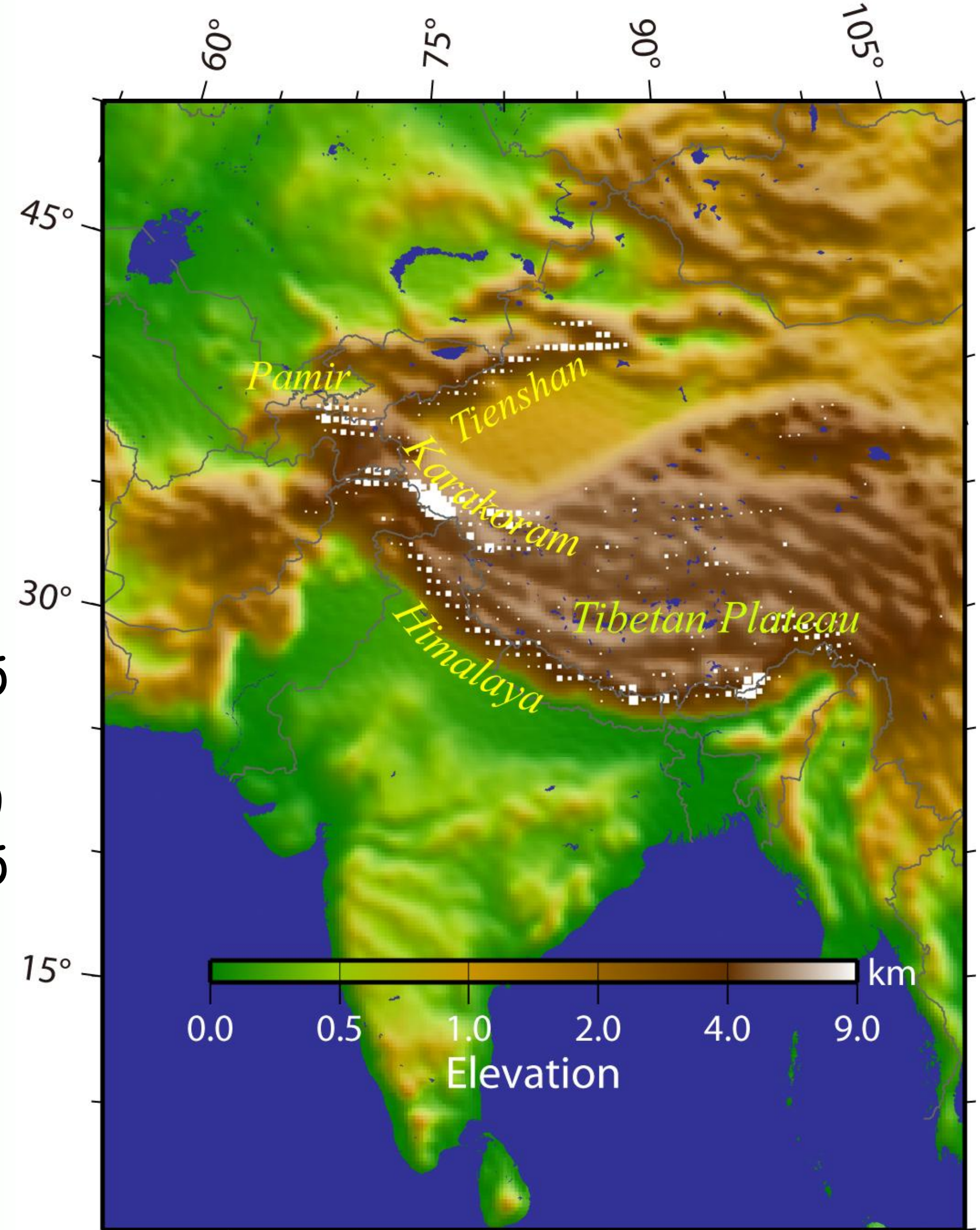




Total :	116,180 km^2	
Himalaya :	33,050 km^2	× 1.0
Karakoram :	16,600 km^2	× -0.5
Tienshan :	15,417 km^2	× 1.5
Pamir :	12,260 km^2	× 2.0
Kunlun :	12,260 km^2	× -0.5
Nyainquentanghla :	7,536 km^2	× 1.0
Hindukush :	5,900 km^2	× 1.0

(Dyurgerov & Meier, 2005)

+ Groundwater loss in northern India
10 Gt/yr



Two recent papers

1. Rodell et al., Satellite-based estimate of groundwater depletion in India, Nature, 2009
2. Tiwari et al., Dwindling groundwater resources in northern India, from satellite gravity observations, GRL, in press.

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...ssIndia, Dec.09, 2008)

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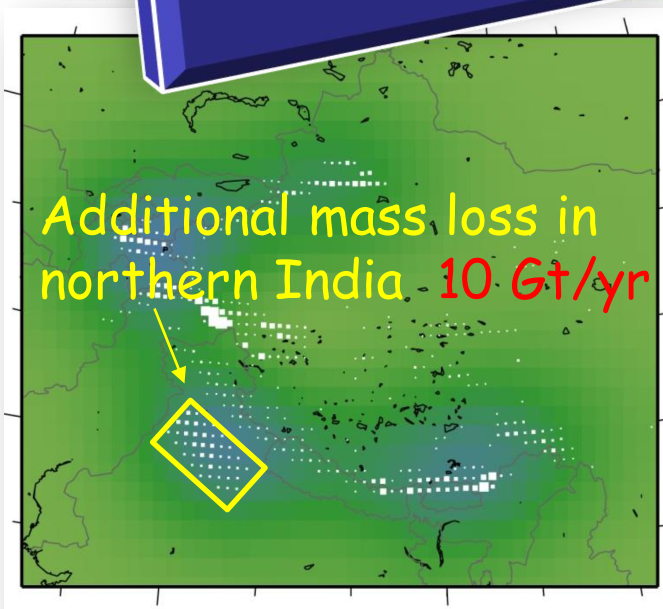
...country is different from ...
...country is different from ...
...ants to inspect terror boat ...
... a 25-year high

...r groundwater replenishments due ...western part faced problems of arid

...tershed projects which would cover ...s were undertaken.

There would be other Central government projects too, including the Integrated Wasteland Development Project Scheme.

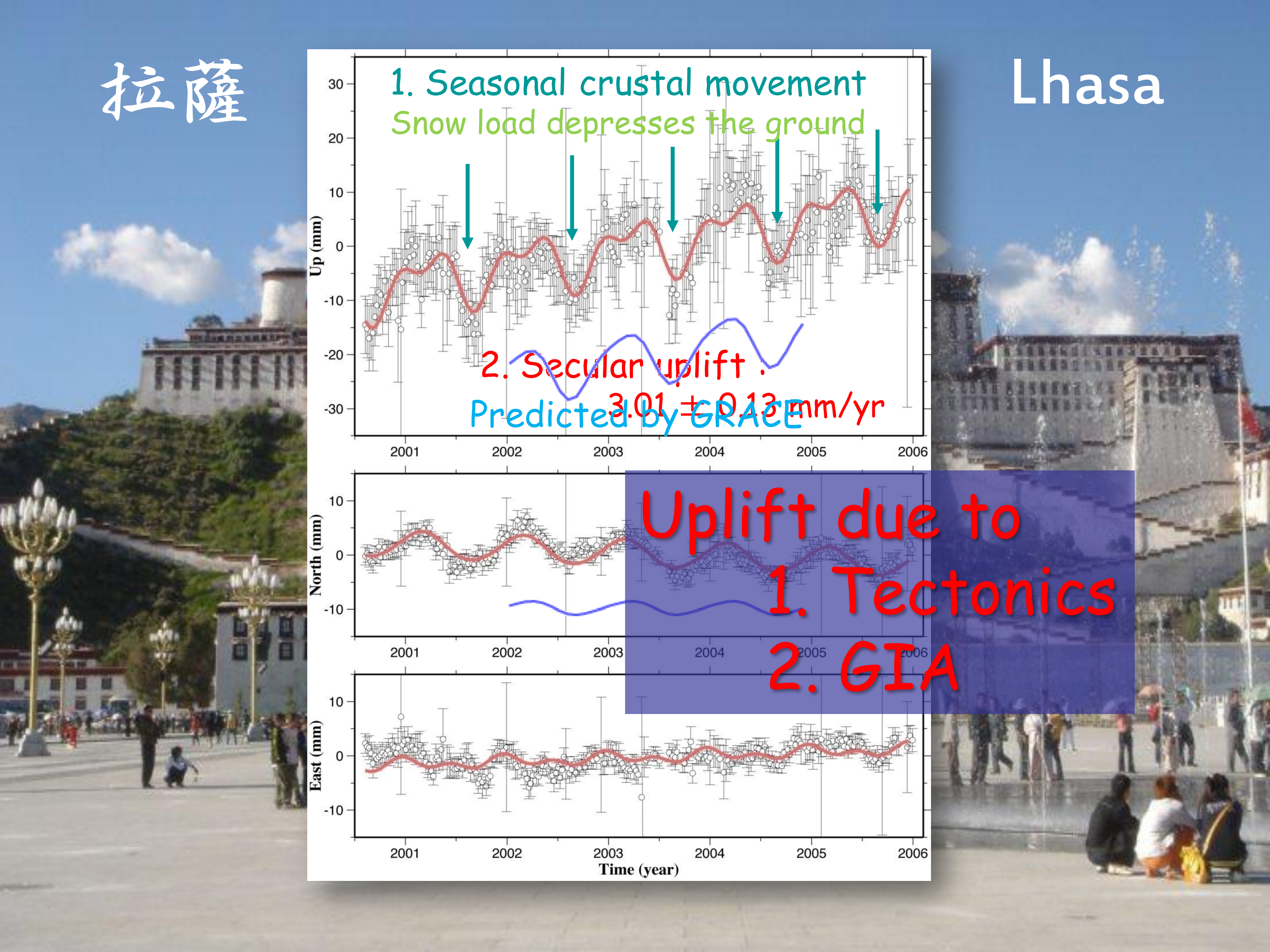
Punjab produces 13 per cent of the total rice, 22 per cent of the total wheat and 13 per cent of total cotton output of India. State's cropping intensity is as high as 189 per cent. But state's agriculture pre-eminence is threatened by groundwater depletion and soil erosion. It is estimated that of the total 141 blocks in the state, 100 are facing critical groundwater depletion.



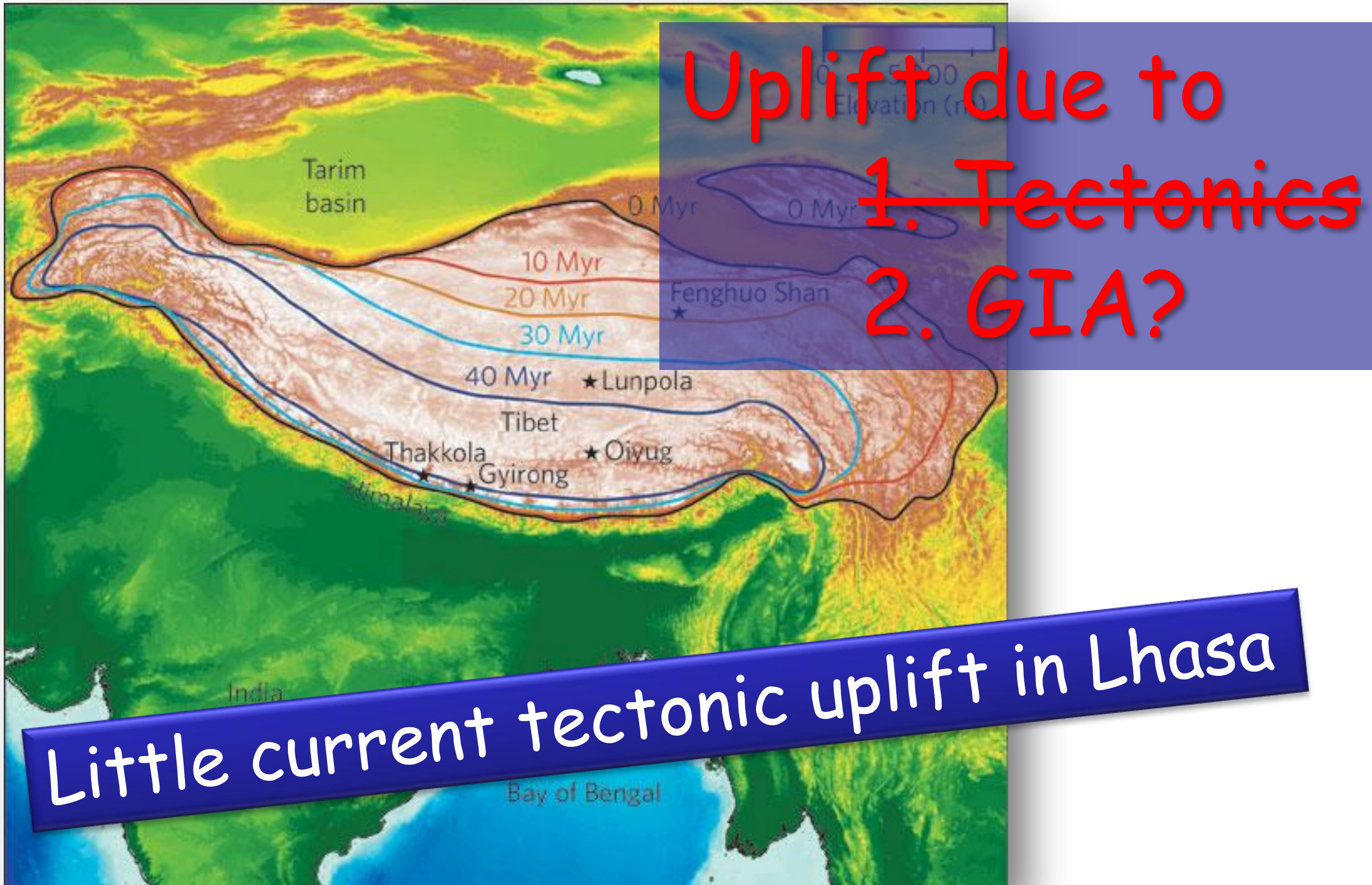
GPS

Global Positioning System

Crustal uplift in HM Asia



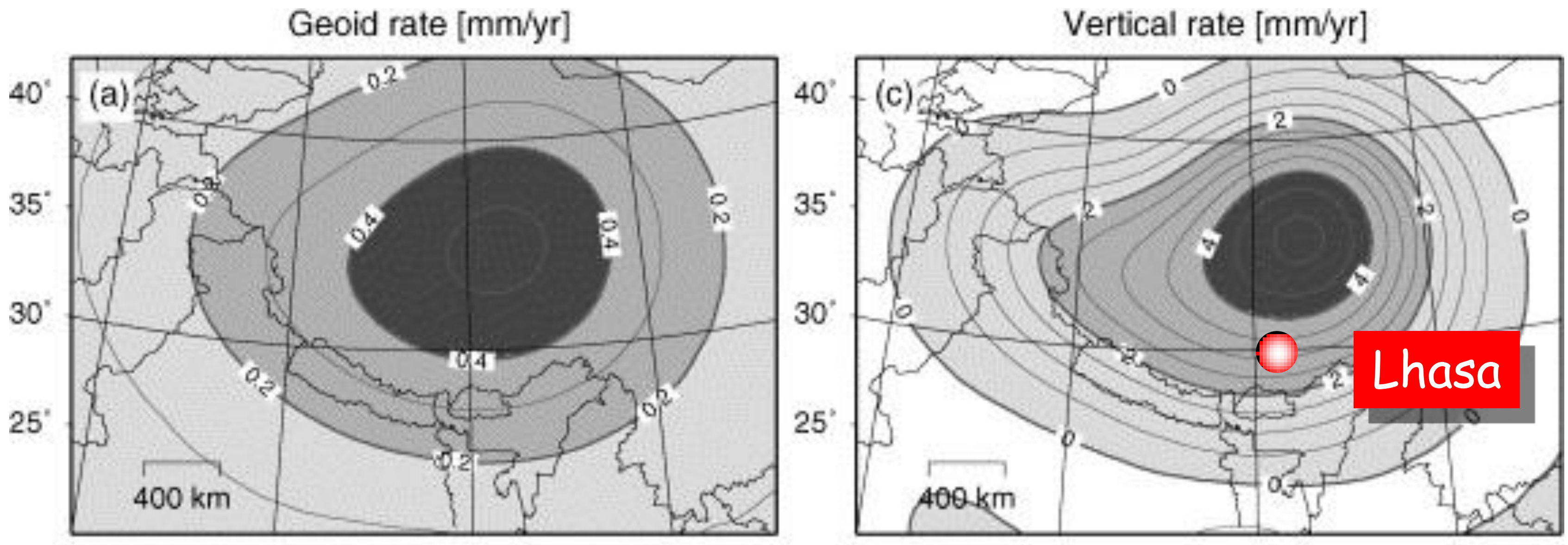
拉薩
Lhasa
1. Seasonal crustal movement
Snow load depresses the ground
2. Secular uplift :
3.01 ± 0.13 mm/yr
Predicted by GRACE
Uplift due to
1. Tectonics
2. GIA
Up (mm)
North (mm)
East (mm)
Time (year)
2001
2002
2003
2004
2005
2006

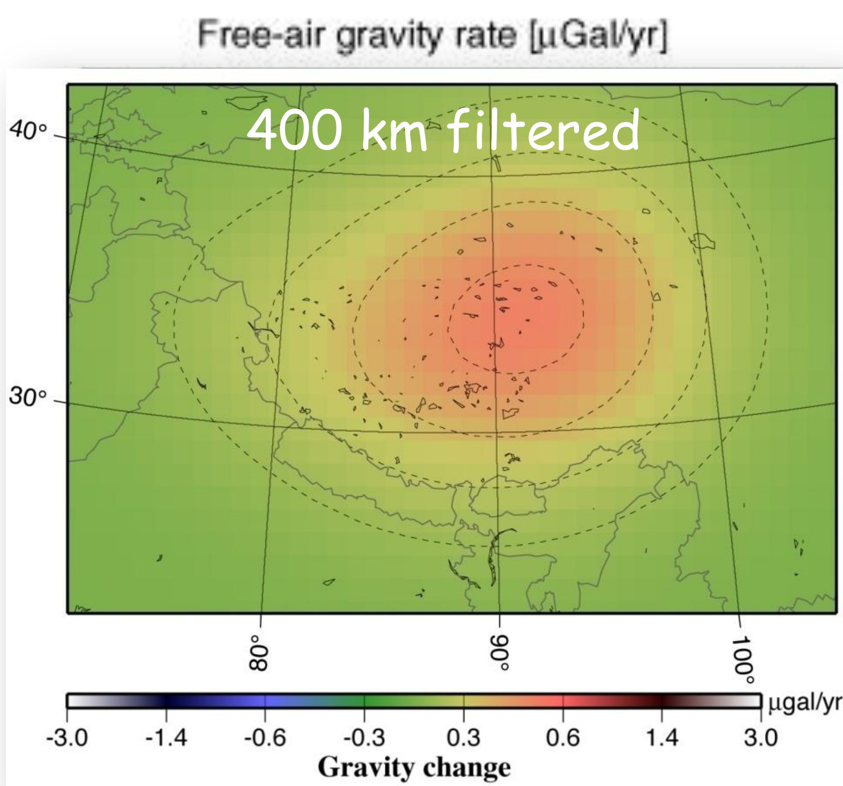


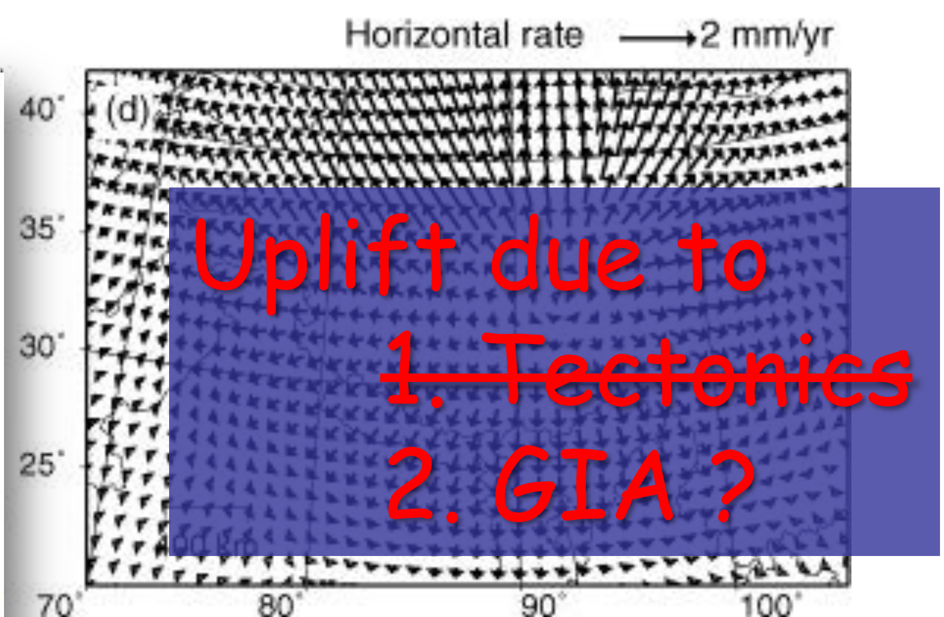
R. A. Spicer et al., Constant elevation of southern Tibet over the past 15 million years, Nature, 421, 622 (2003)

D.B. Rowley, B.S. Currie, Palaeo-altimetry of the late Eocene to Miocene Lunpola basin, central Tibet, Nature, 439, 677 (2006).

Uplift due to GIA?
Then, gravity change should be corrected.



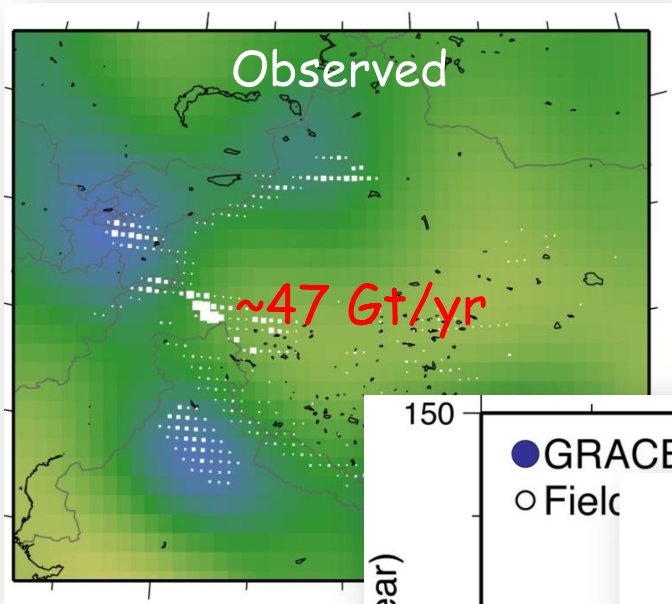


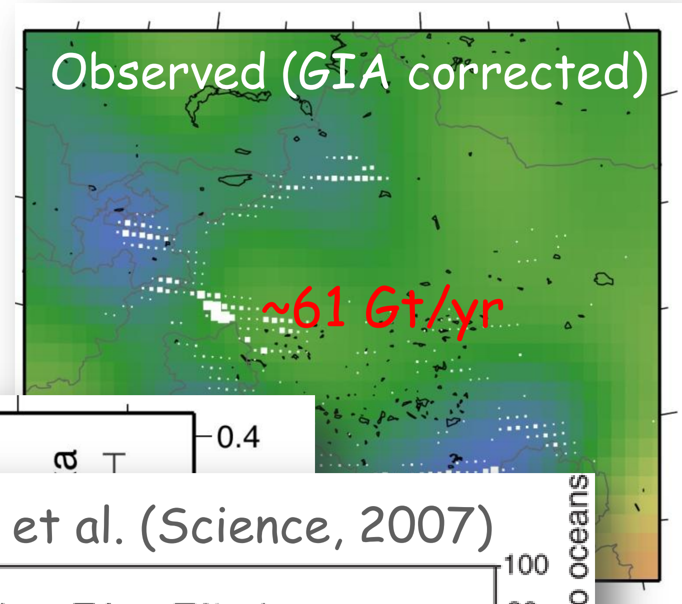


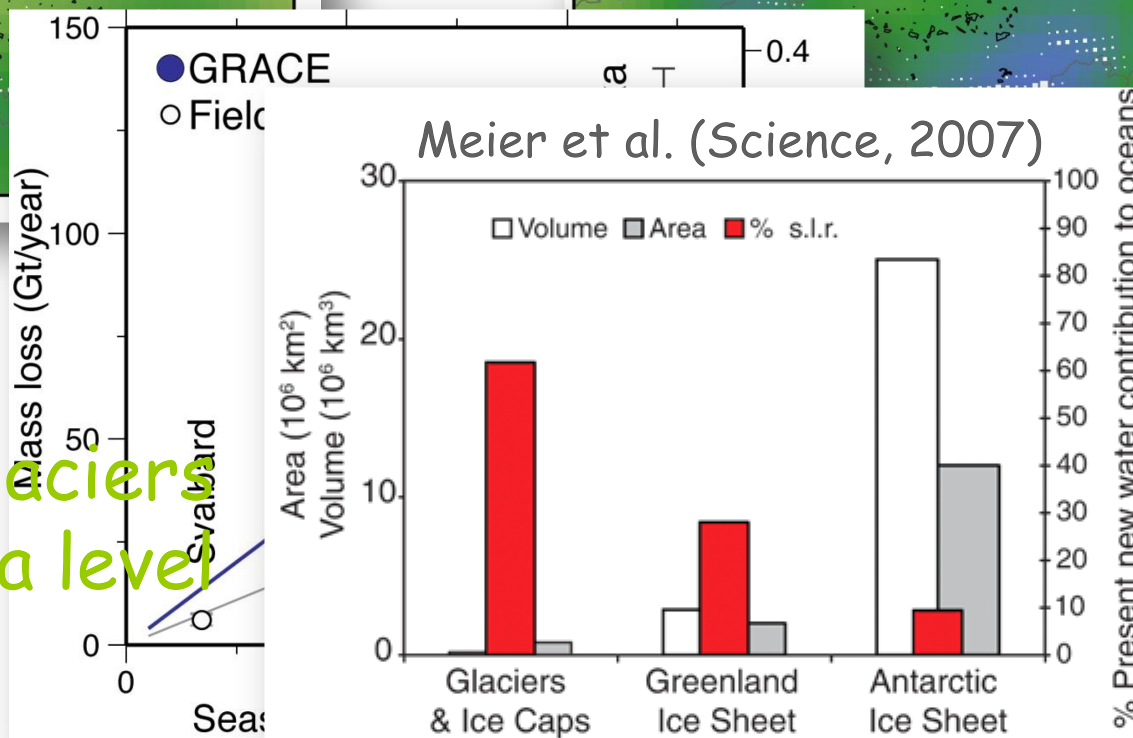
TIBET- 4 GIA model

(Kaufmann, J. Geodyn., 2005)

Ice loss estimated after GIA correction







Mountain glaciers raise sea level

Ice melting rate of the three major glacial systems

Alaska

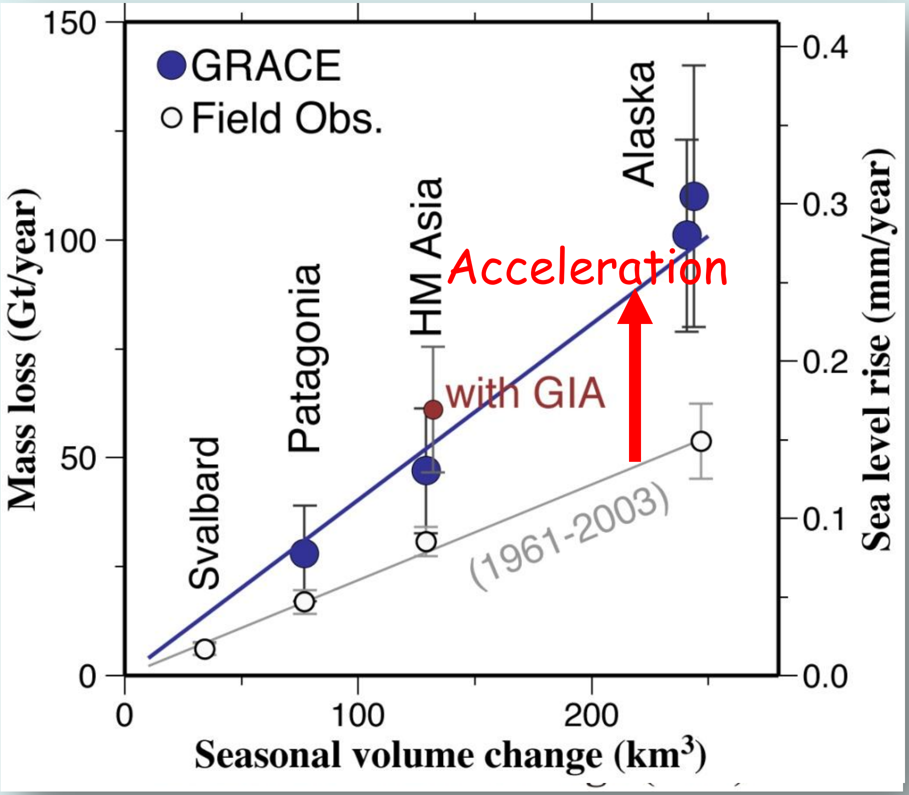
-110±30 Gt/yr
(Tamisiea et al., 2005)
-101±22 Gt/yr
(Chen et al., 2006)

HM Asia (This study)

-47±13 Gt/yr
0.13 mm/yr as Sea Level Rise

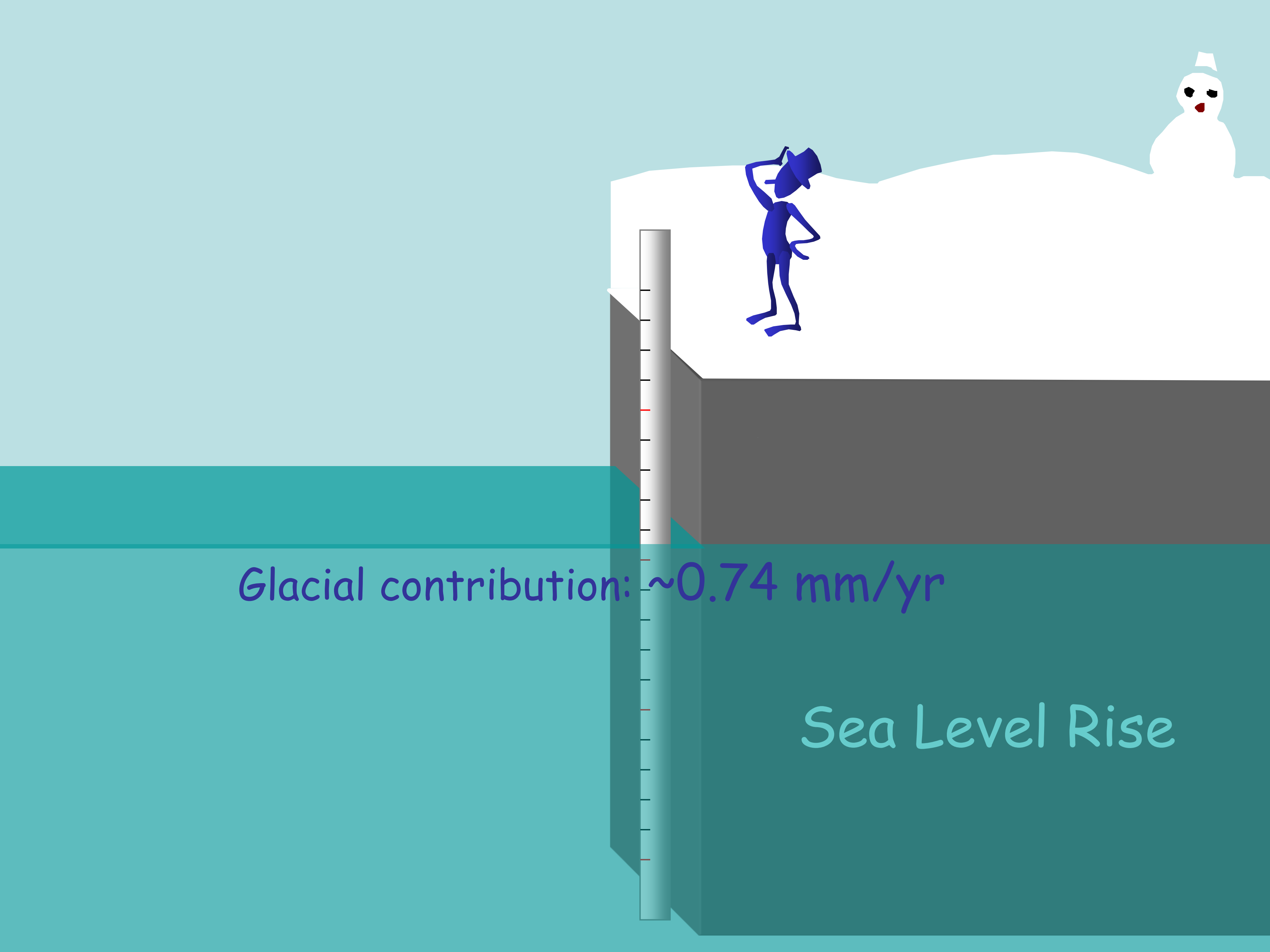
Patagonia (Chen et al., 2007)

-28±11 Gt/yr

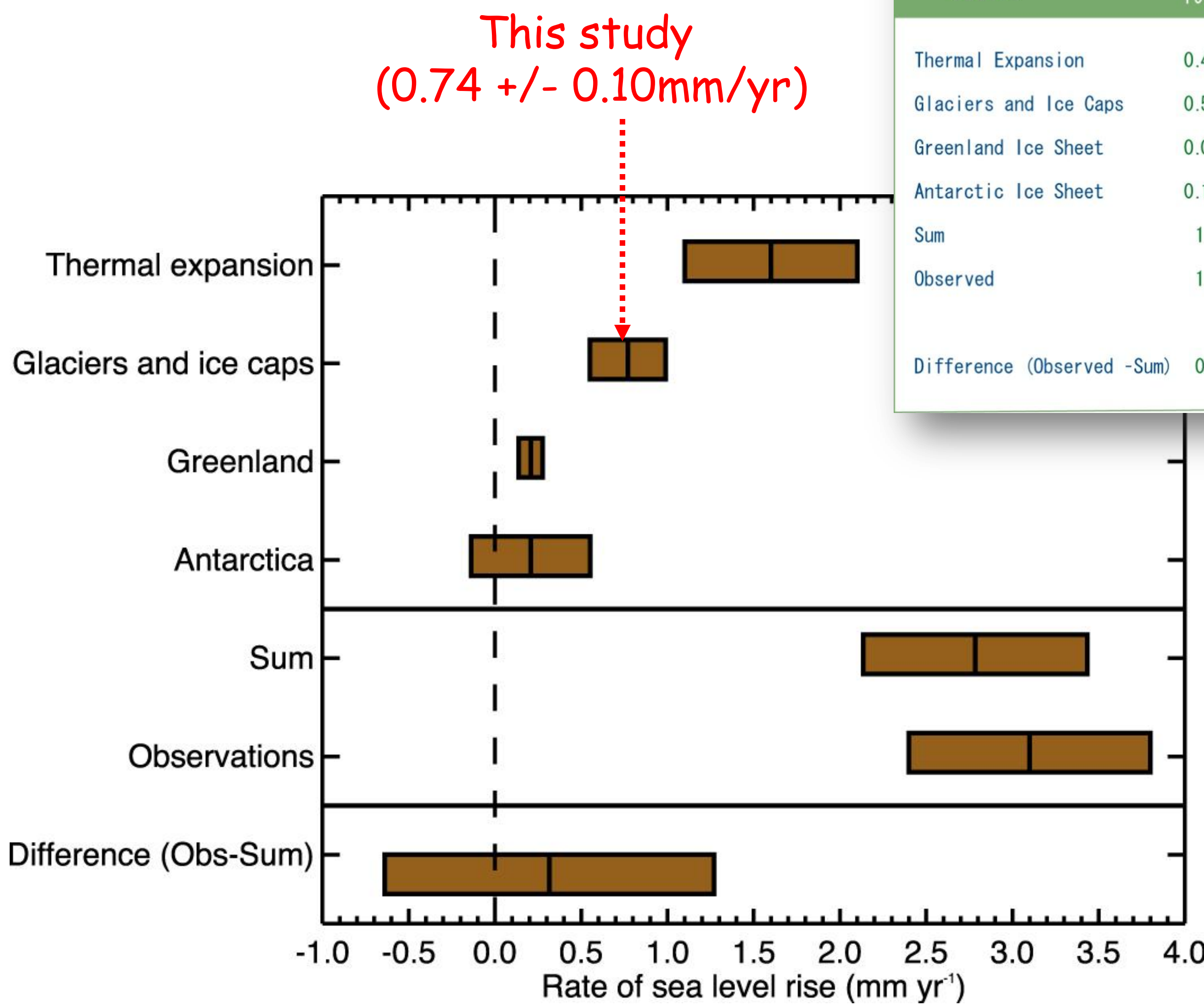


Worldwide

-266±34 Gt/yr 0.74 mm/yr as Sea Level Rise

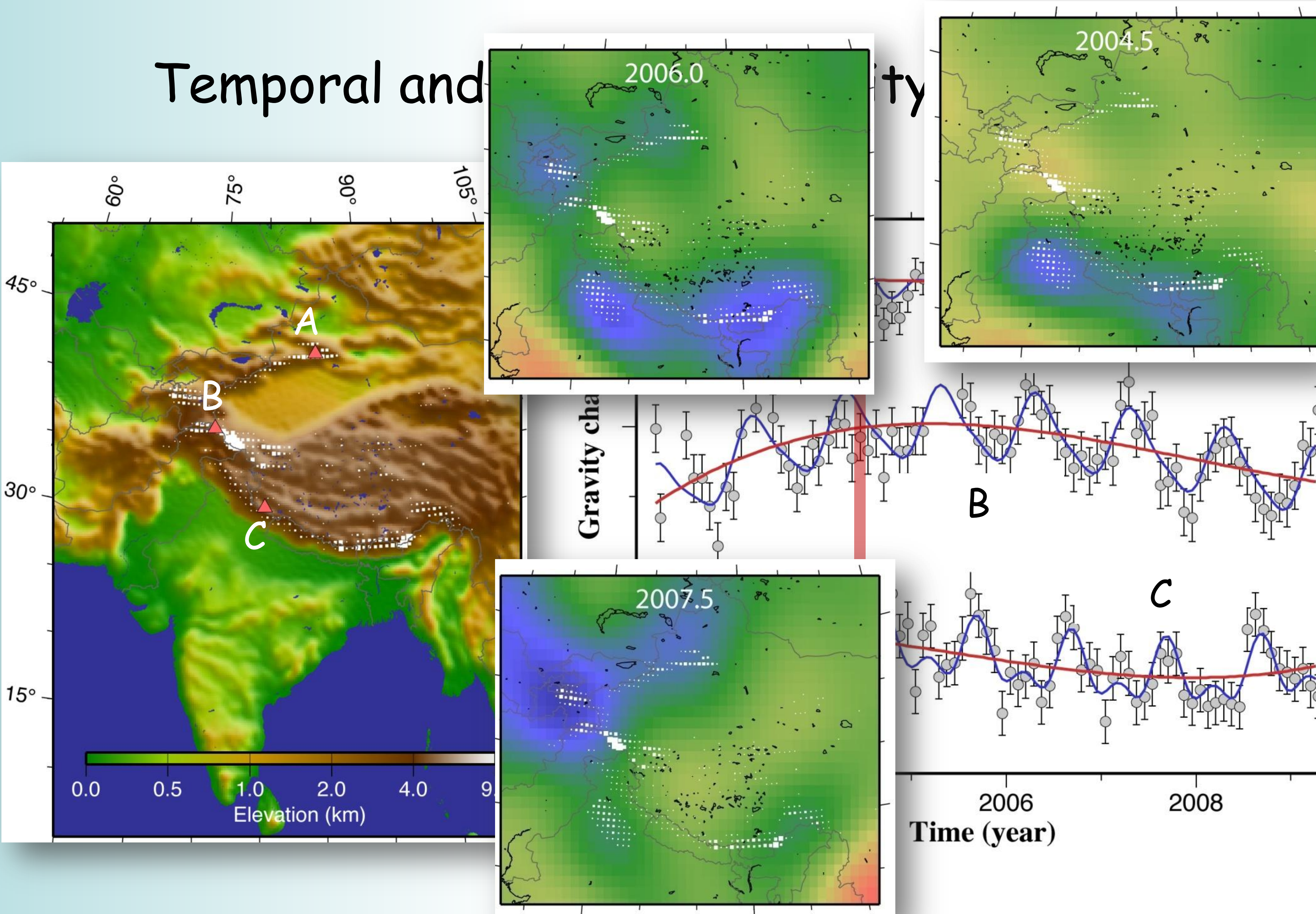

Glacial contribution: ~0.74 mm/yr
Sea Level Rise

IPCC Archive 4 WG-1 Chapter 5 (Bindoff et al., 2007)

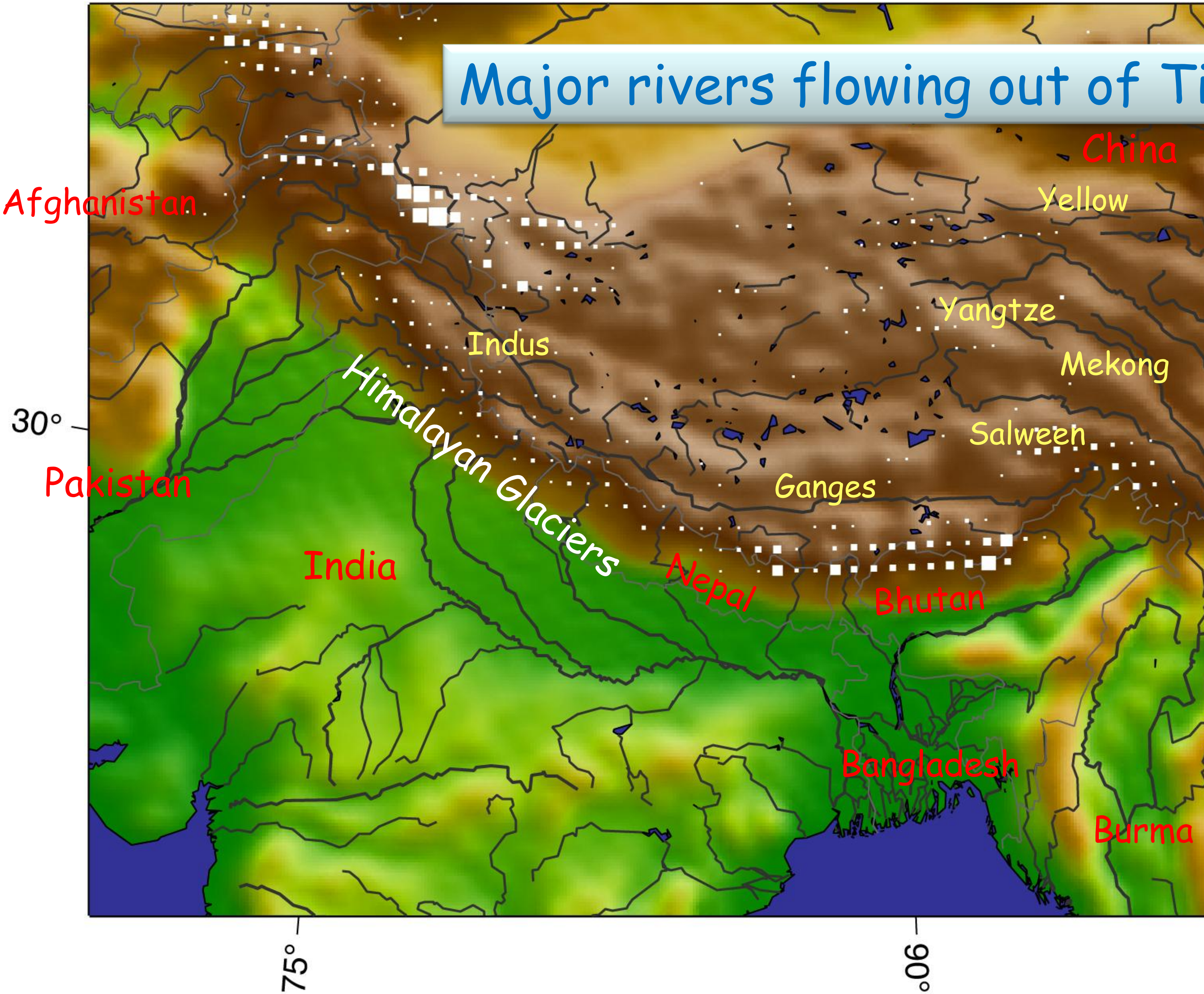


Source	Sea Level Rise (mm yr^{-1}) 1961-2003	1993-2003	Reference
Thermal Expansion	0.42 ± 0.12	1.6 ± 0.5	Section 5.5.3
Glaciers and Ice Caps	0.50 ± 0.18	0.77 ± 0.22	Section 4.5
Greenland Ice Sheet	0.05 ± 0.12	0.21 ± 0.07	Section 4.6.2
Antarctic Ice Sheet	0.14 ± 0.41	0.21 ± 0.35	Section 4.6.2
Sum	1.1 ± 0.5	2.8 ± 0.7	
Observed	1.8 ± 0.5		Section 5.5.2.1
		3.1 ± 0.7	Section 5.5.2.2
Difference (Observed -Sum)	0.7 ± 0.7	0.3 ± 1.0	

Temporal and ... ity



Major rivers flowing out of Tibet



Summary

1. Gravity decrease in HM Asia from GRACE
   Highly variable in time and space

2. Worldwide acceleration of glacial melting
   Alaska > HM Asia (47Gt/yr) > Patagonia

3. Does crustal uplift contribute to Δg?
   More melting (61 Gt/yr) if GIA goes on

4. Glacial contribution to SLR (~0.74 mm/yr)
   Consistent with IPCC report (~0.77 mm/yr)

Thank you for your attention