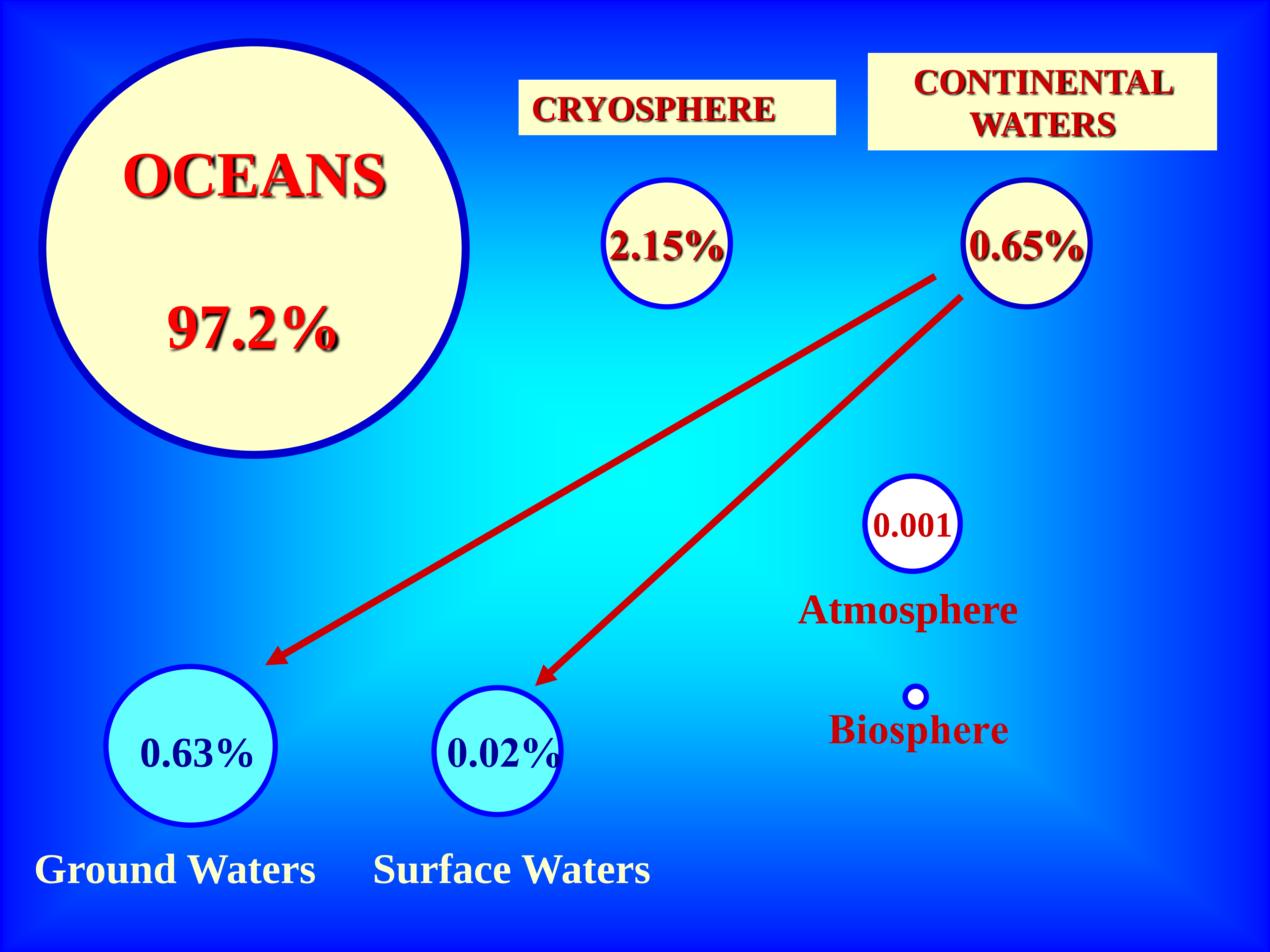
Study of the Water Cycle from Space

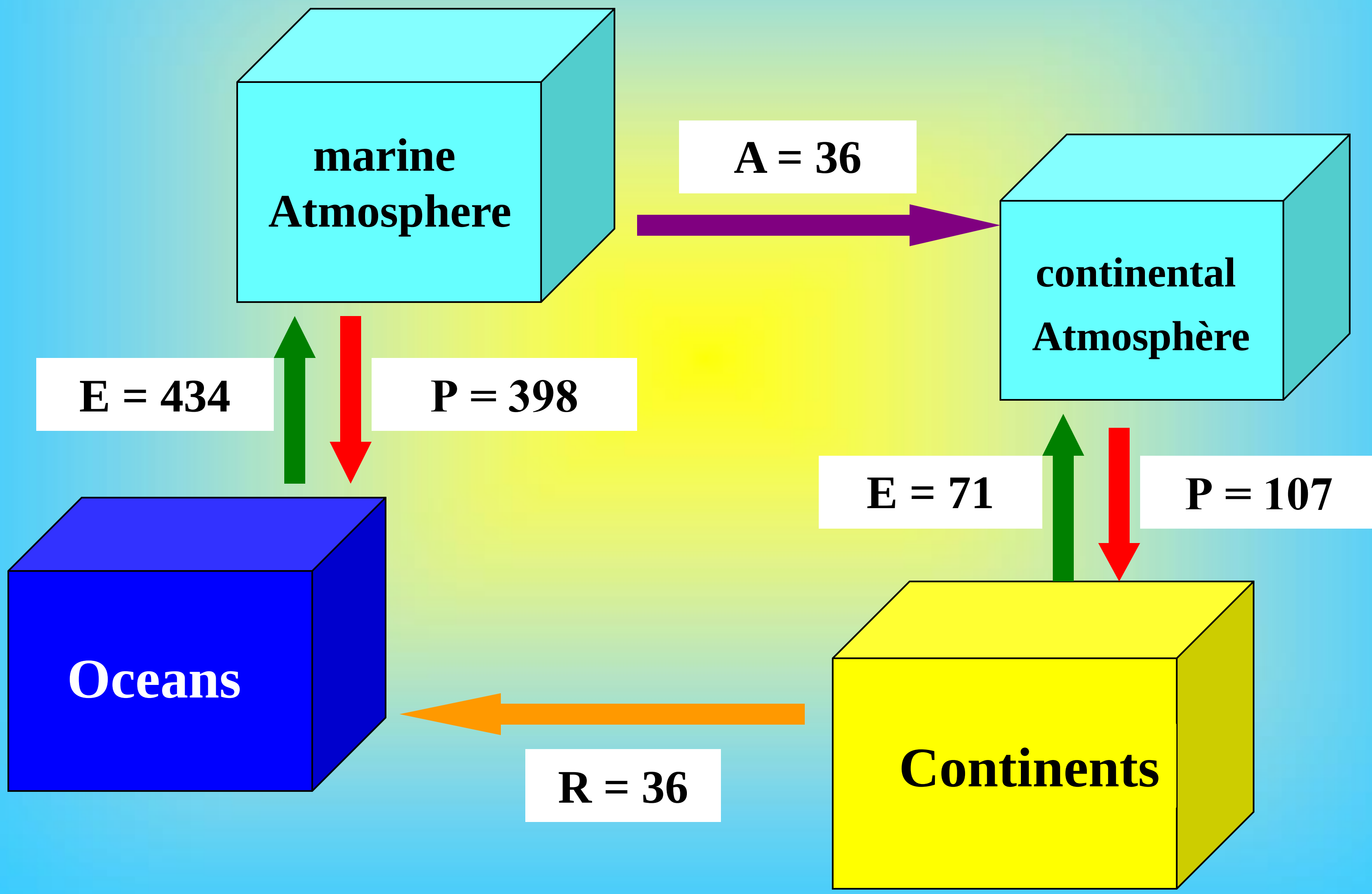
Il bilancio globale delle acque terrestri ed il ciclo dell'acqua

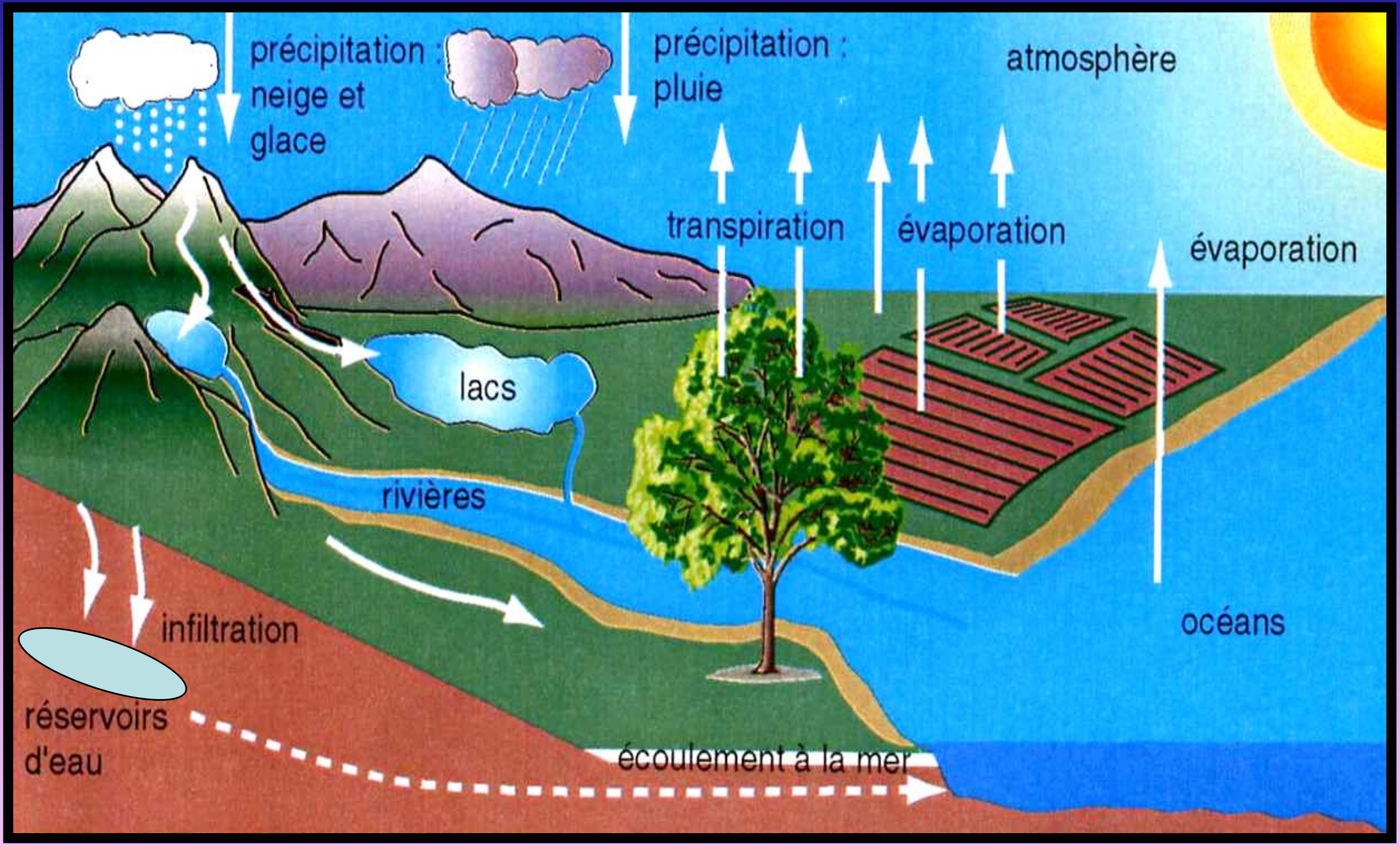
Jérôme Benveniste
European Space Agency

Credits to:
Dr Anny Cazenave, LEGOS, Toulouse, F; Prof. Ph. Berry, DMU, Leicester, UK


OCEANS
97.2%
CRYOSPHERE
2.15%
CONTINENTAL WATERS
0.65%
0.001
Atmosphere
Biosphere
0.63%
0.02%
Ground Waters
Surface Waters

GLOBAL HYDROLOGICAL CYCLE
(units: 10^{12} m^3 per annum)





Surface and Ground Waters

Observations from space for the study of the continental water cycle (stock variations):

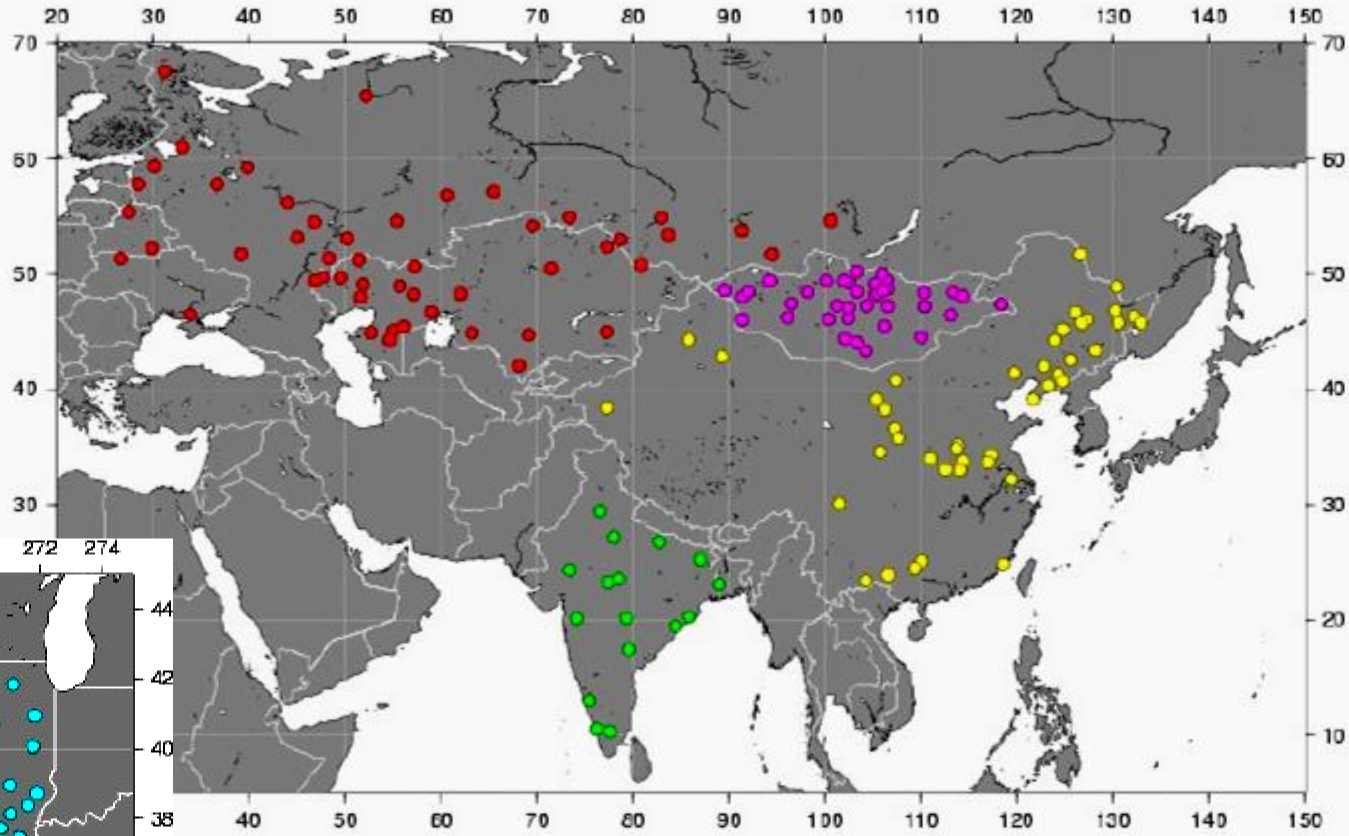
-Space gravimetry mission GRACE (2002-   )

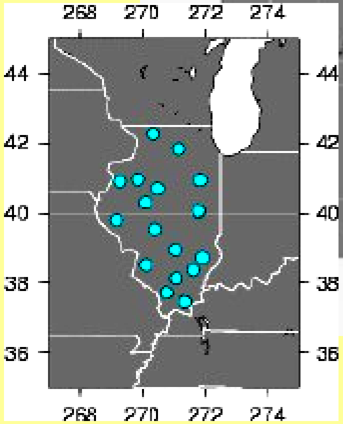
-Space Radar Altimetry missions (Topex/Poseidon, Jason-1, ERS/ENVISAT)

- visible and radar imagery


Part 1
Ground Waters
and
Snow Cover

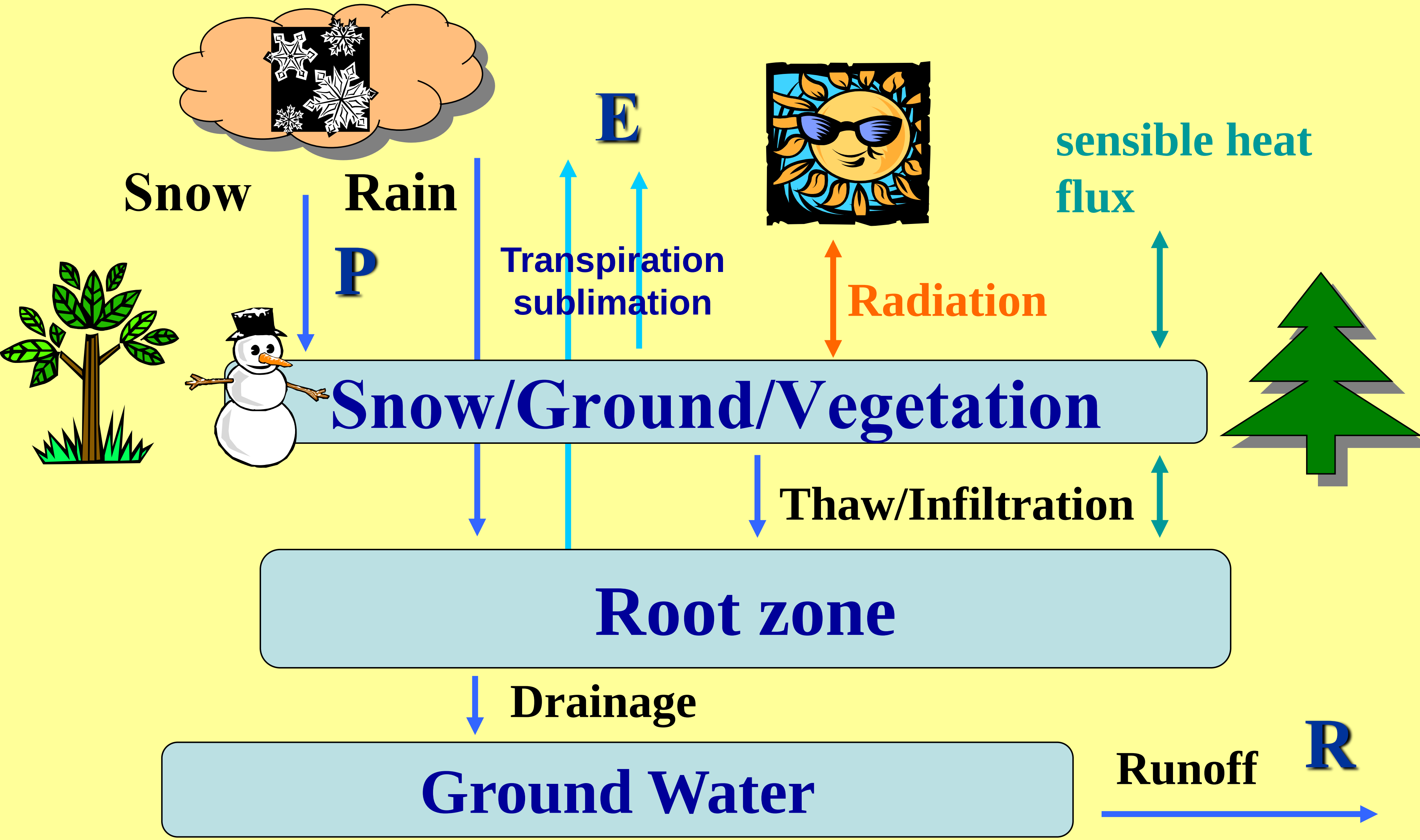
Distribution of Soil Moisture Stations





Global Soil Moisture Data Bank

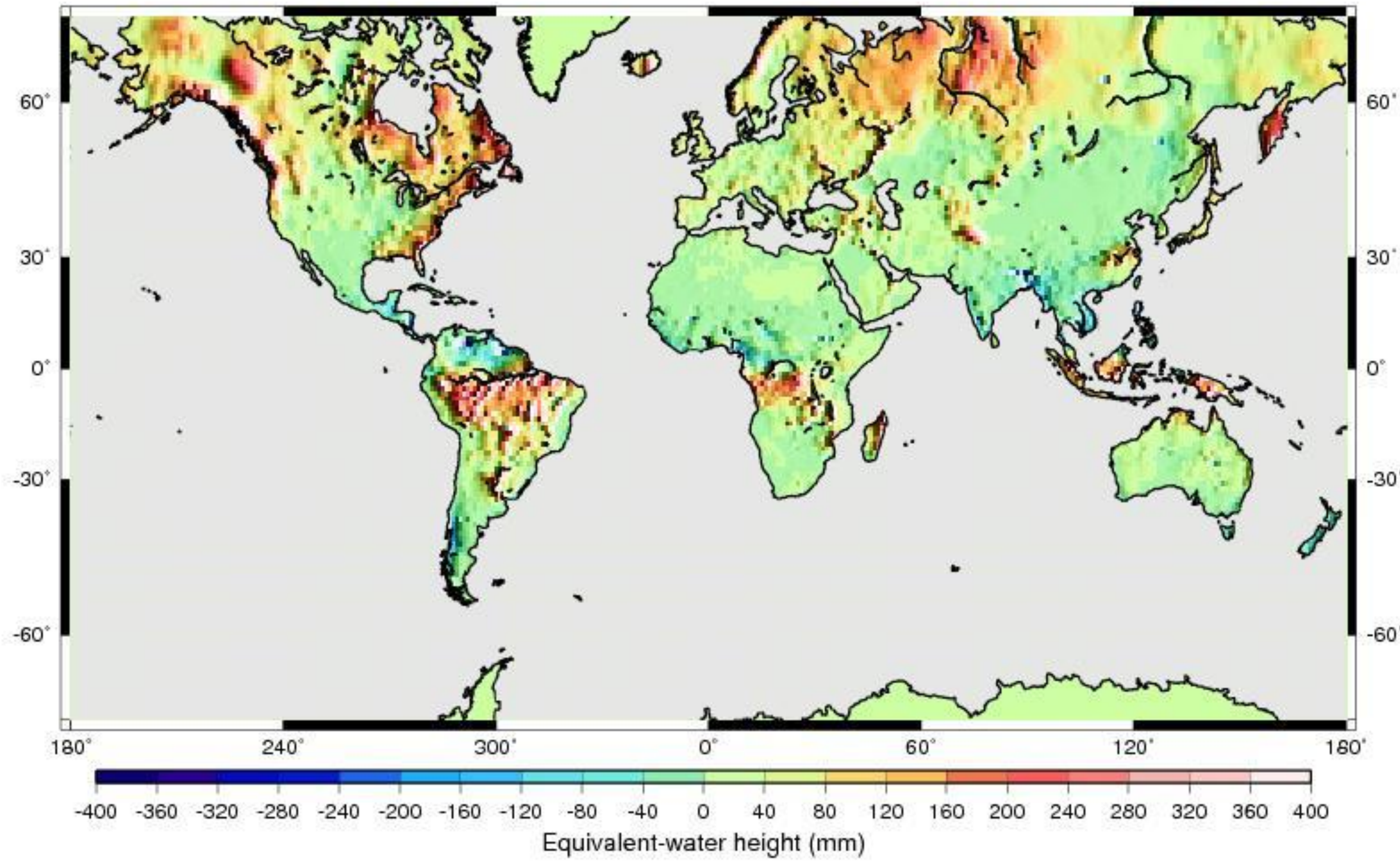
Surface Scheme: modeled processes



$$dW/dt = P - E - R$$

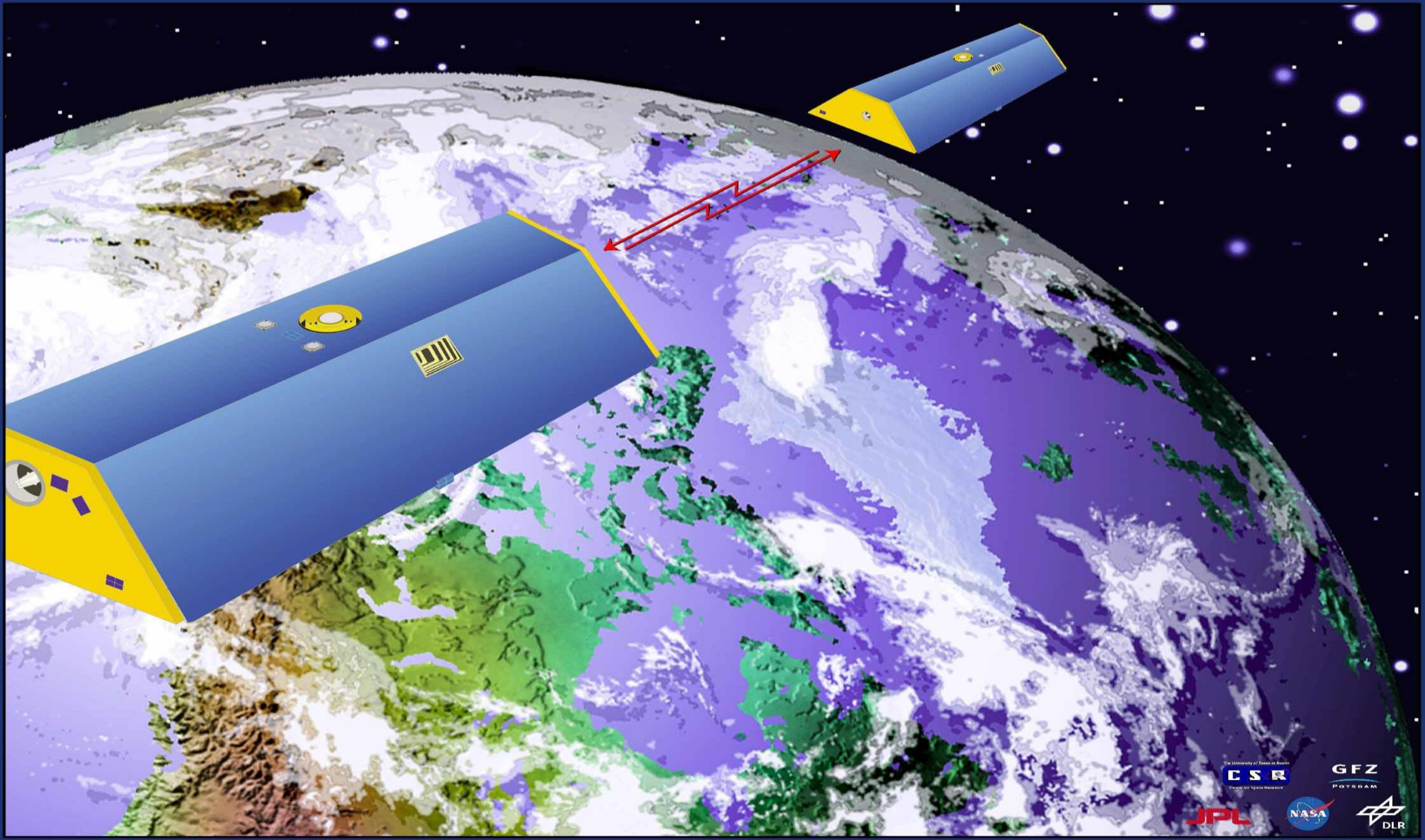
Example: April 2003 - Water and Snow Stock - WGHM Model

(Water global assessment and prognosis Global Hydrological Model; Doll et al.,2003)



Modeling of the continental water cycle

- **Climate Evolution**
- **Water Ressources**



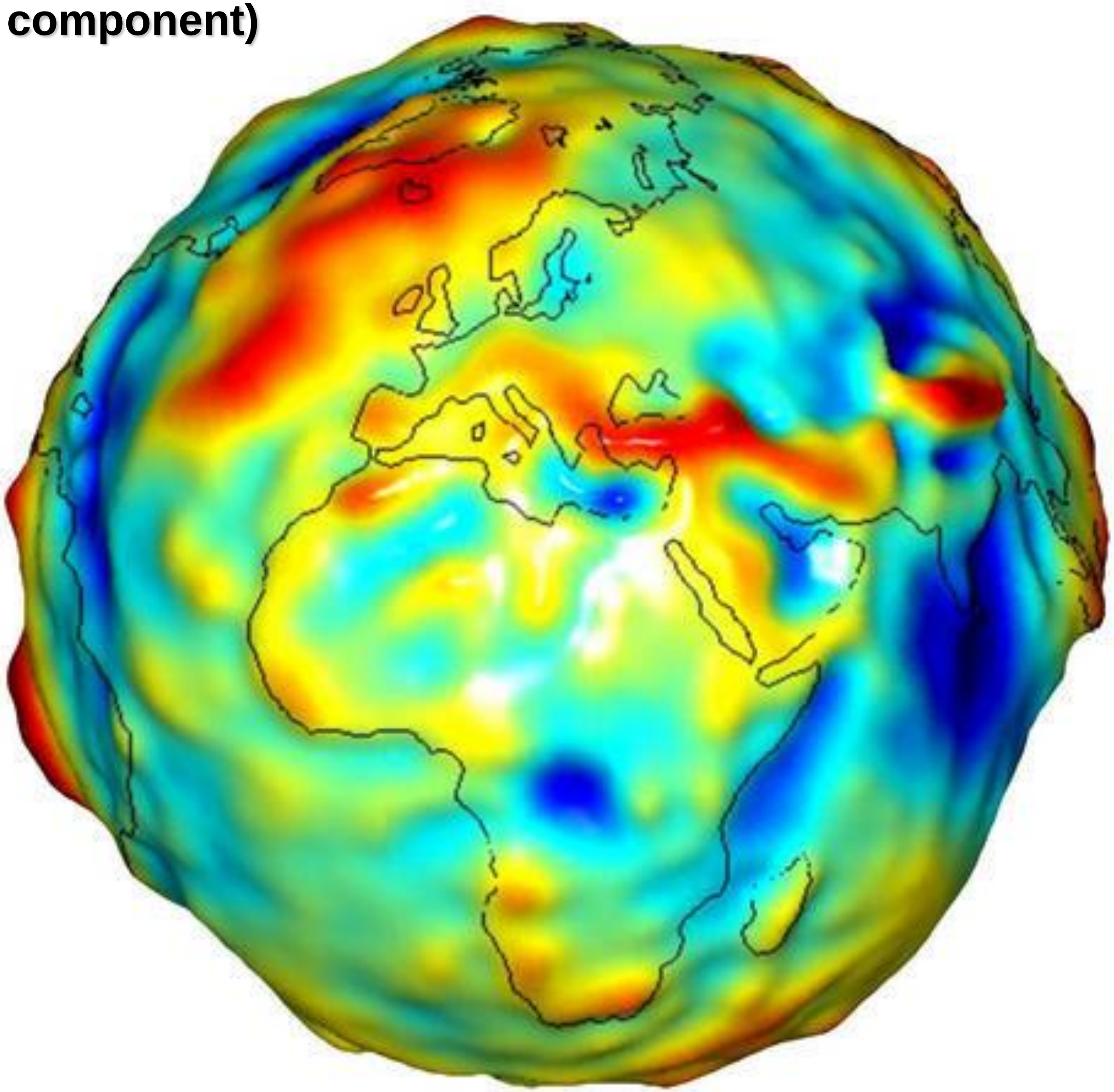
http://www.csr.utexas.edu/grace/

G R A C E

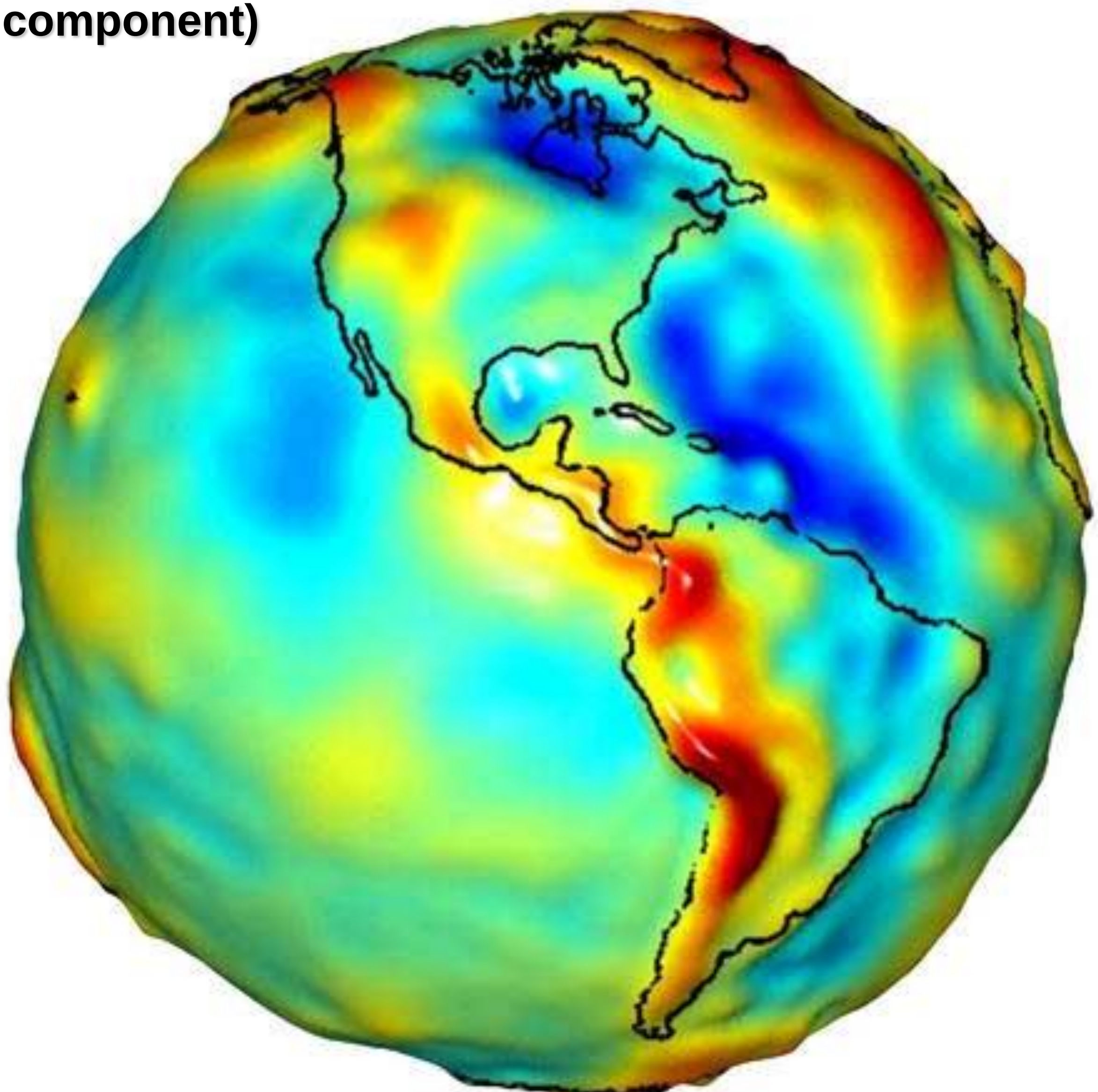
Gravity Recovery And Climate Experiment


GRACE Mission :
Precise mesurements of Earth gravity variations
spatio-temporal Mass Variations
(Temporal resolution=1month
Geographical resolution = 300 km)

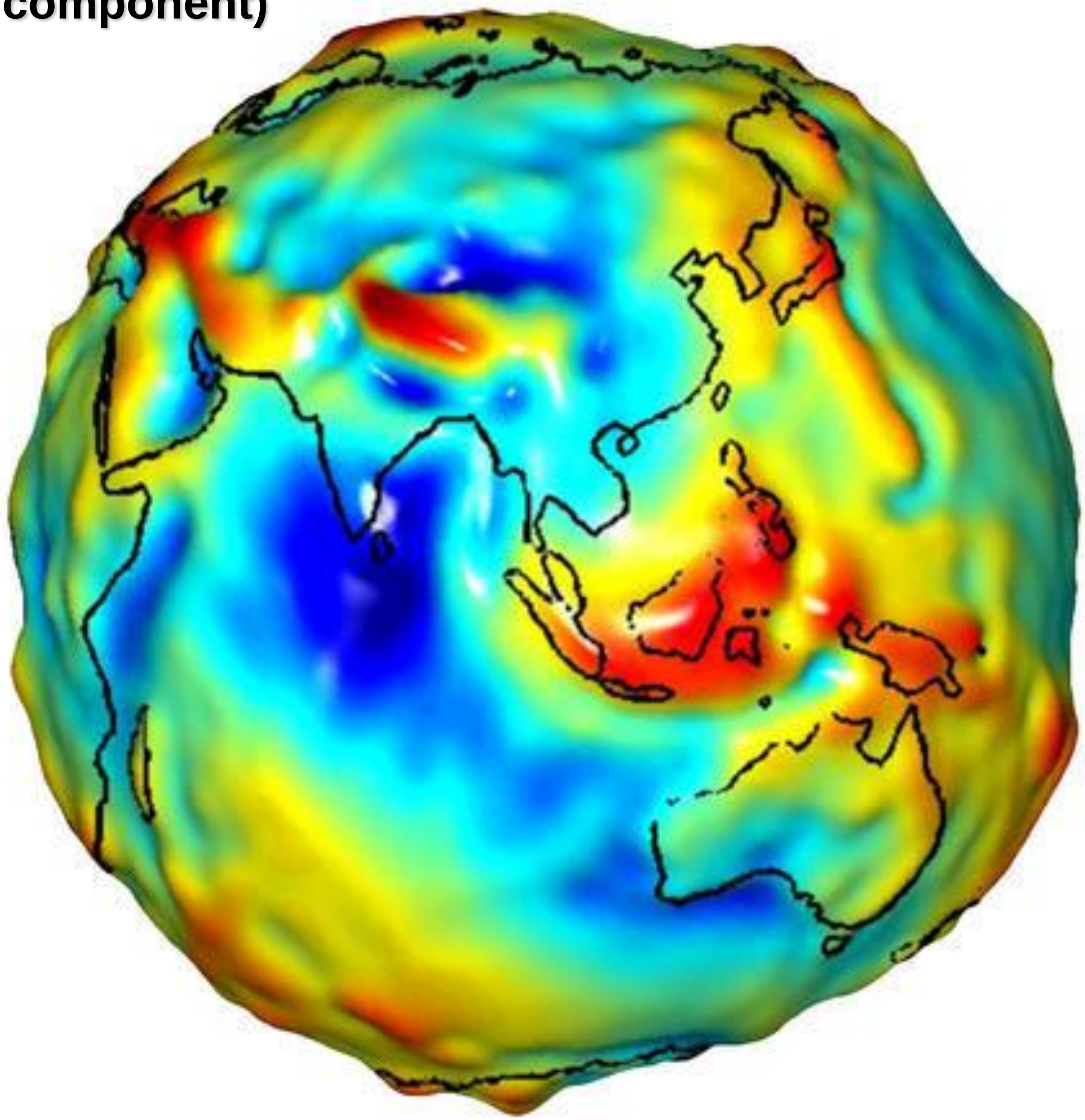
Gravity field
(permanent component)



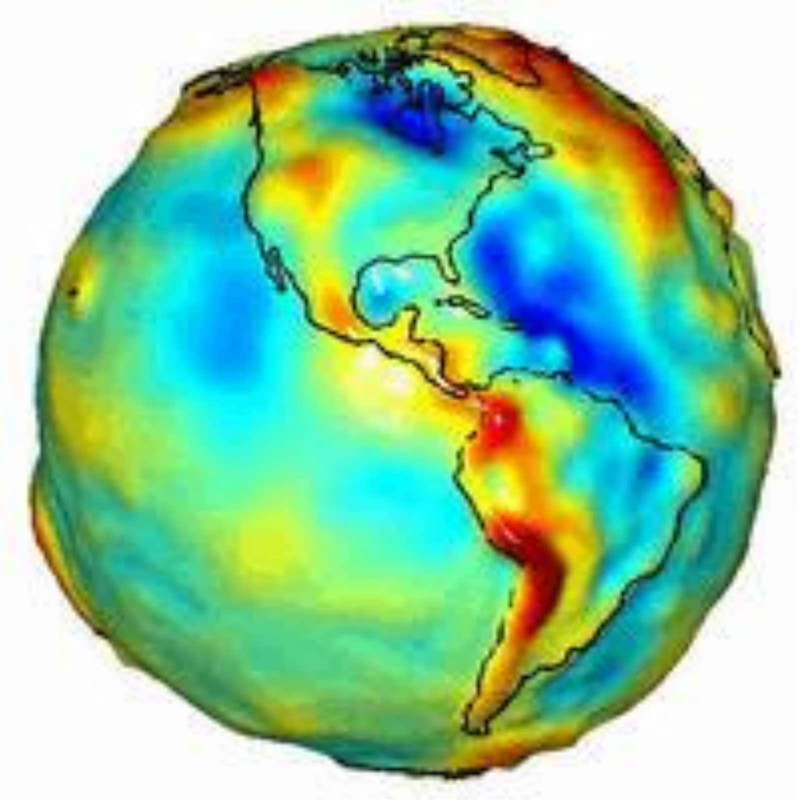
Gravity field (permanent component)

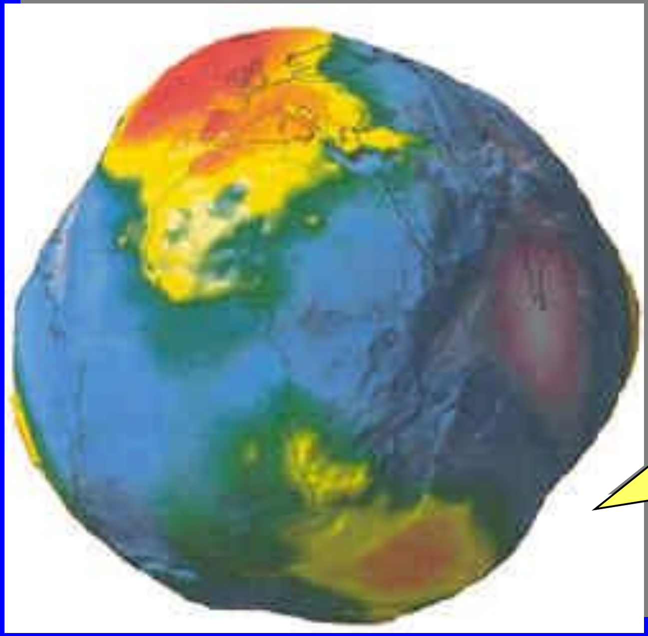


**Gravity field
(permanent component)**



Gravity field
(permanent component)





GEOID HEIGHT

$$\delta N(s,t) = \frac{G}{\gamma} \iiint_V \frac{dm(r,t)}{|r-s|}$$

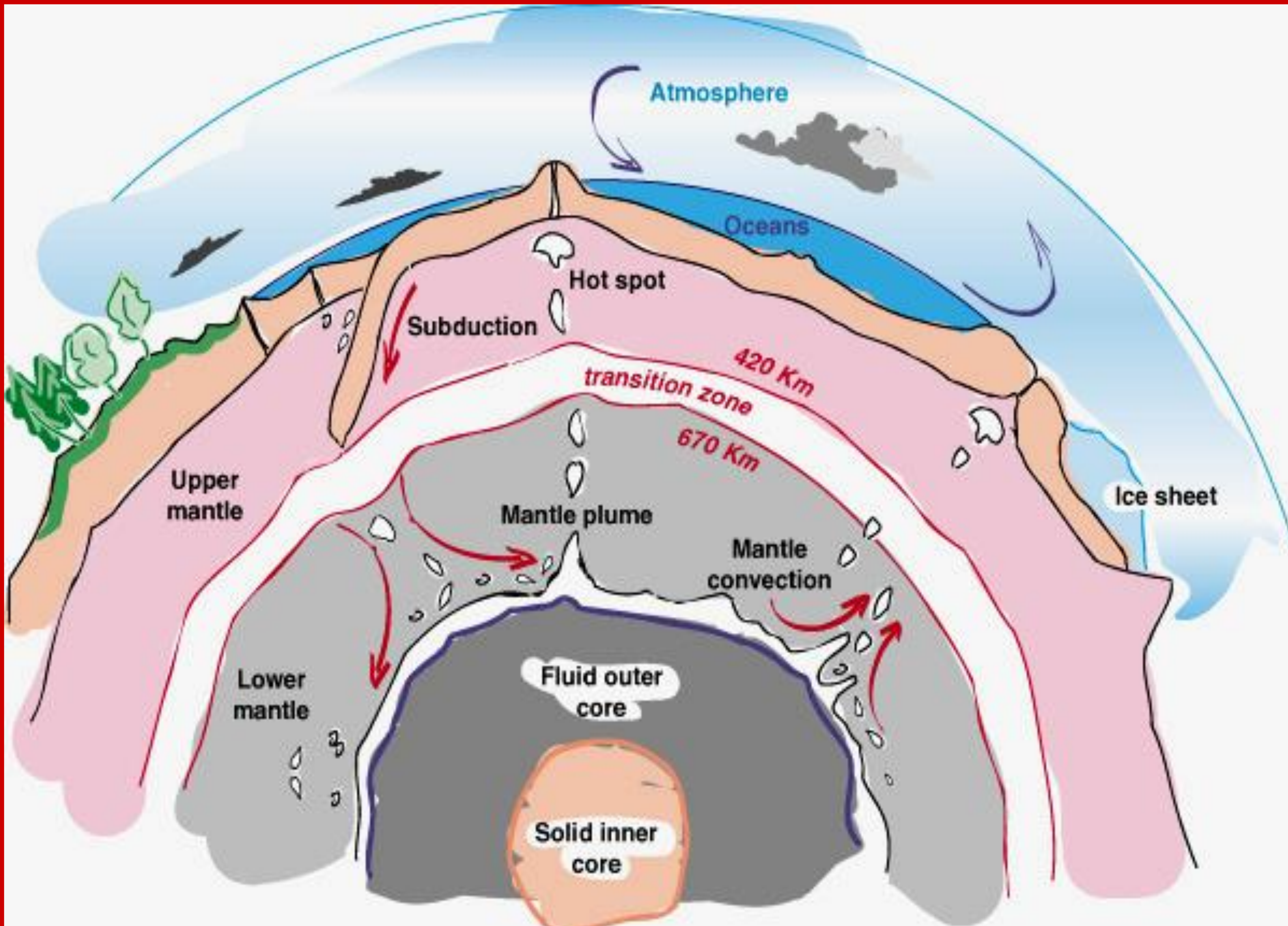
« Static » Contribution + **temporal Variations**

99% of the mesured field

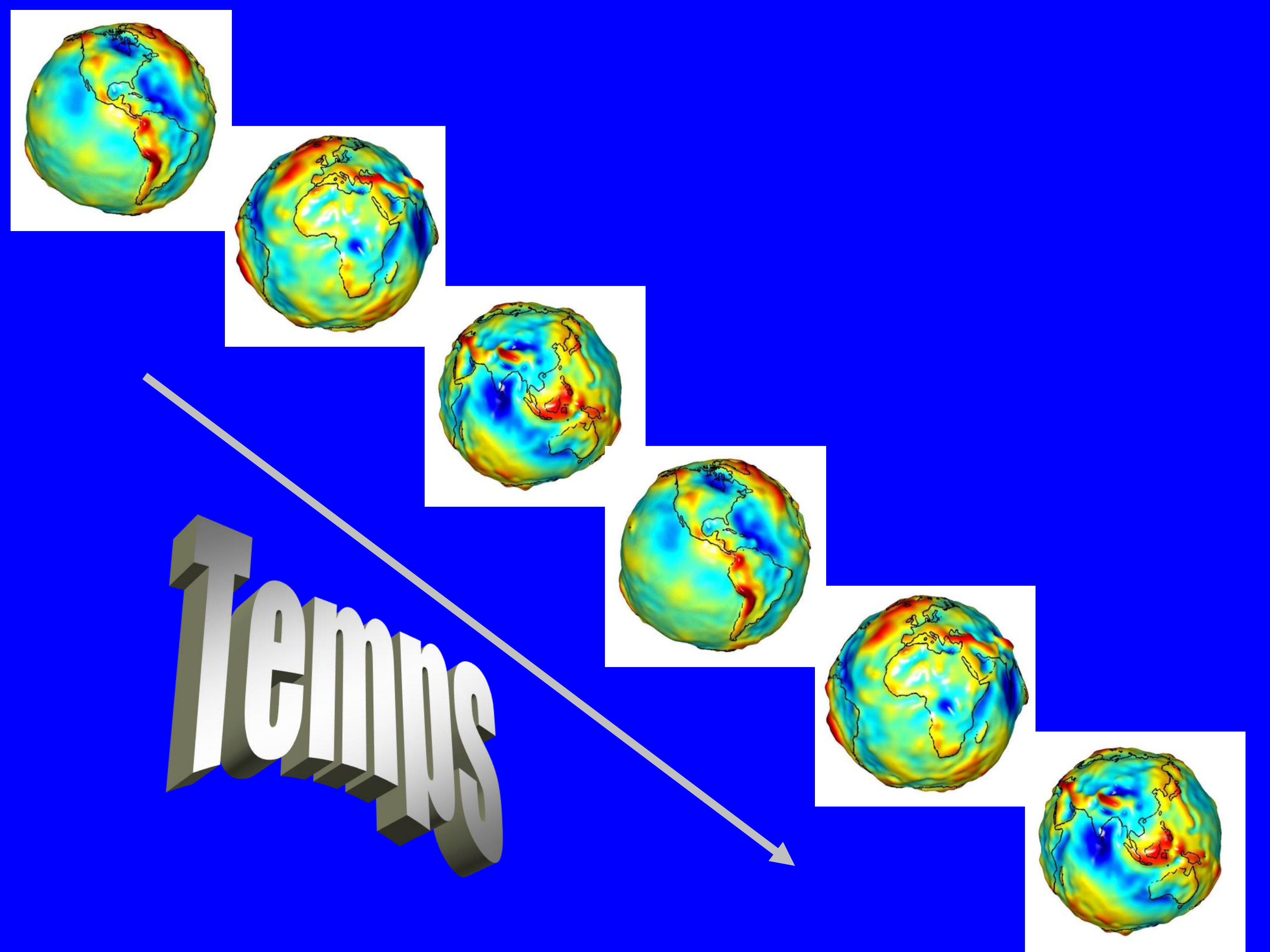
density contrasts in the solid Earth…

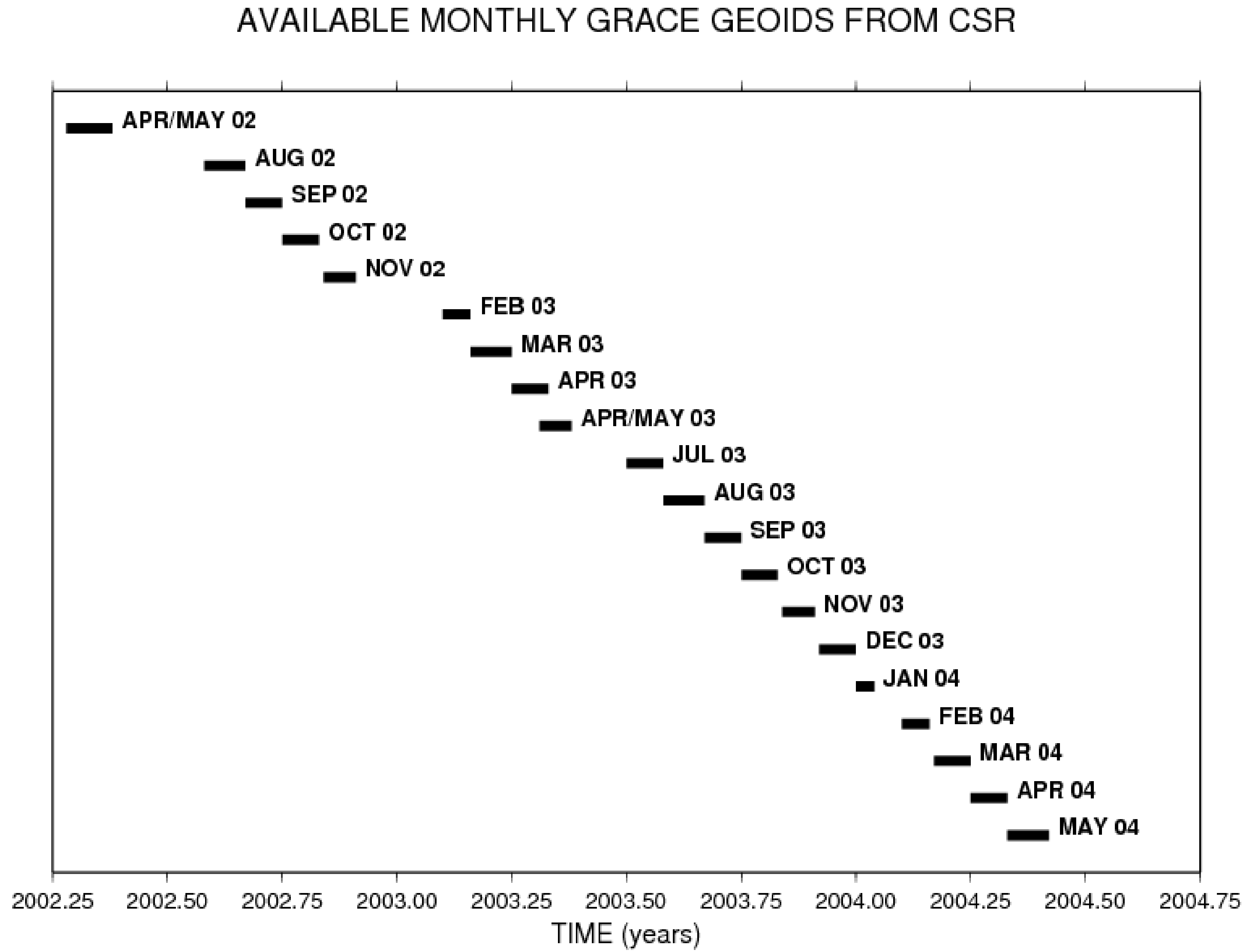
• PGR, redistributions of superficial fluide masses:

atmosphere, oceans, eaux continental waters, polar ice caps



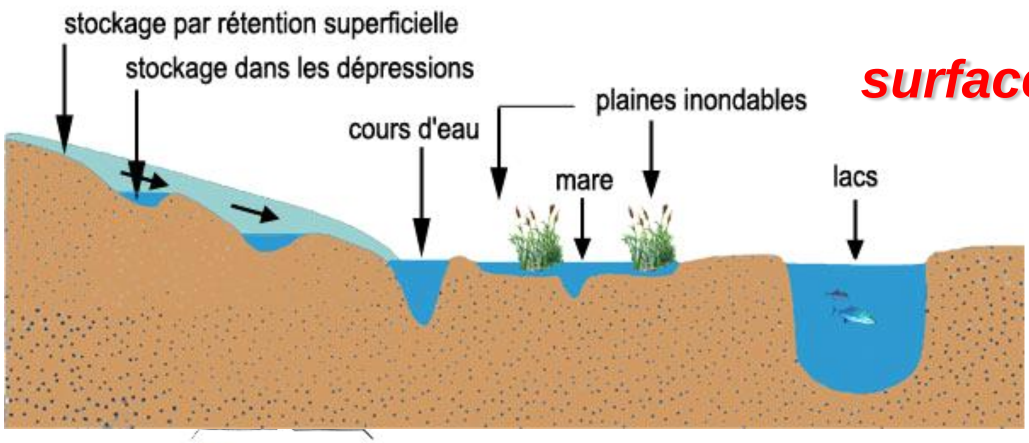
Atmosphere
Oceans
Hot spot
Subduction
420 Km
transition zone
670 Km
Upper mantle
Ice sheet
Mantle plume
Mantle convection
Lower mantle
Fluid outer core
Solid inner core


Temps

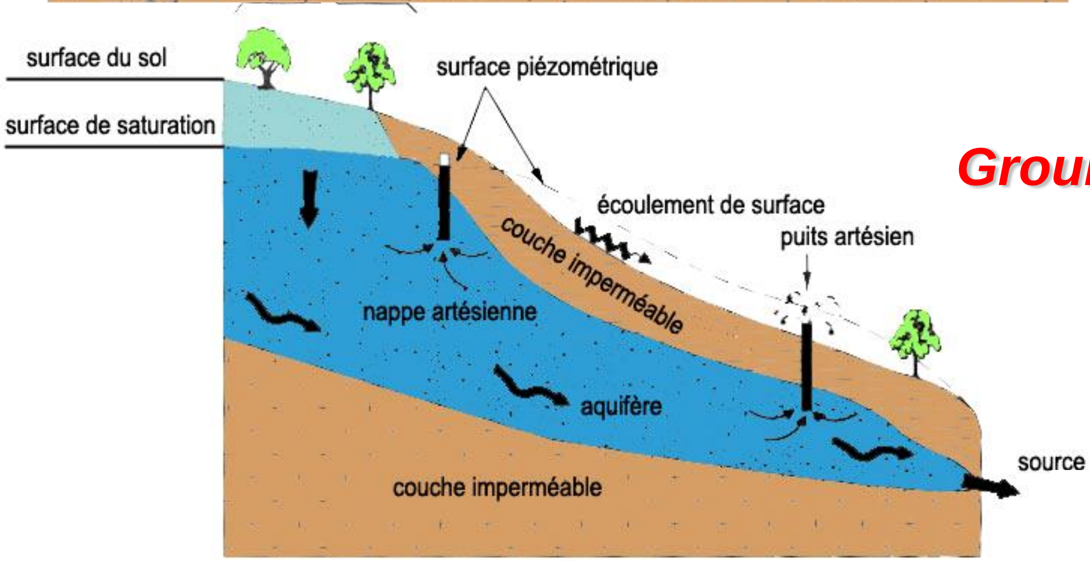


AVAILABLE MONTHLY GRACE GEOIDS FROM CSR
APR/MAY 02
AUG 02
SEP 02
OCT 02
NOV 02
FEB 03
MAR 03
APR 03
APR/MAY 03
JUL 03
AUG 03
SEP 03
OCT 03
NOV 03
DEC 03
JAN 04
FEB 04
MAR 04
APR 04
MAY 04
2002.25
2002.50
2002.75
2003.00
2003.25
2003.50
2003.75
2004.00
2004.25
2004.50
2004.75
TIME (years)

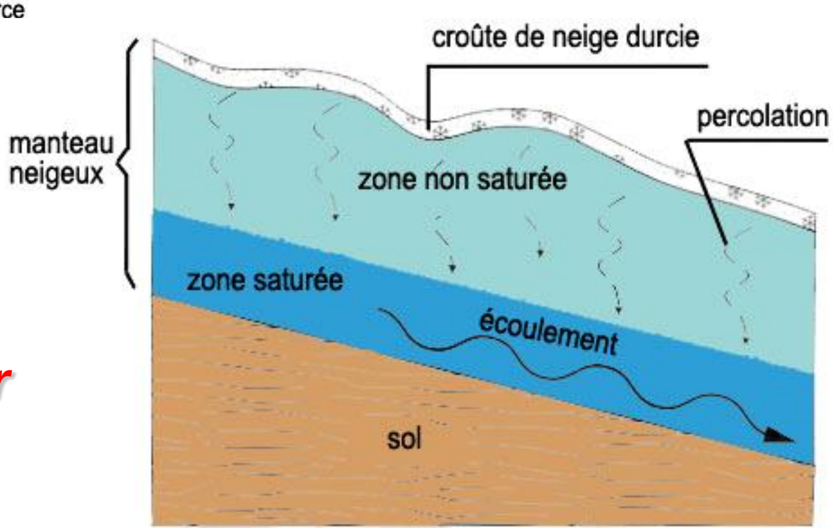
surface waters

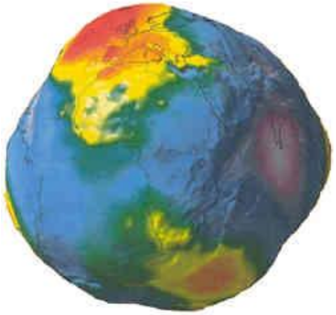


Ground waters



Snow cover





A priori uncertainties of models and GRACE obs.

STEP 1

Inversion of the monthly geoids
(Generalized least-squares inversion)

Maps of geoid anomaly for each surface reservoir

Atmosphere ***Oceans*** ***Soil water*** ***Snow cover***

STEP 2

Predictive filtering of the spherical coefficients
+ compensation (elastic Earth's response to surface loads)

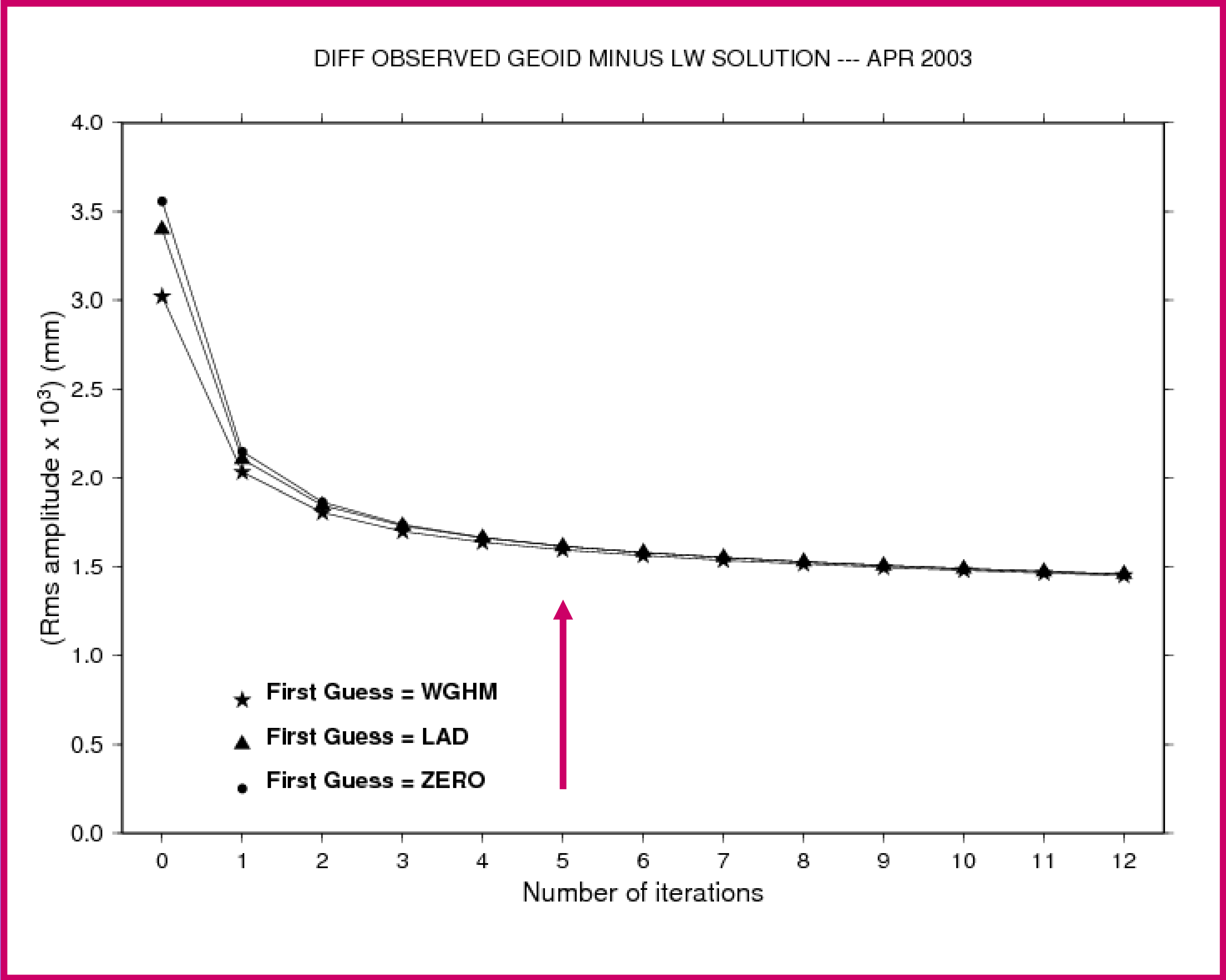
Water mass anomalies for each reservoir

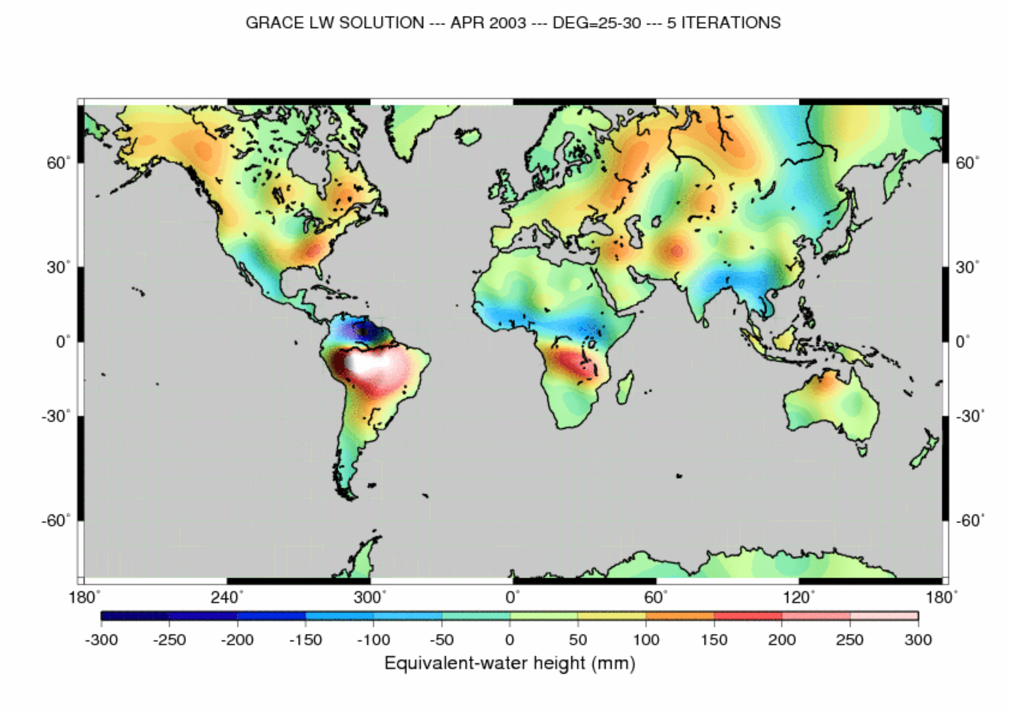
The solution is computed by solving the linear equation:

$$\Gamma_k(t) = \Gamma^0{}_k(t) + C_k A \left[C_D + C_M + A C_k A^T\right]^{-1} \left(\Gamma_{obs}(t) + A\Gamma^0{}_k(t)\right)$$

- $\Gamma_k(t)$: solution vector formed by the list of all spherical harmonic coefficients to be solved
- Γ_{obs} : vector formed with GRACE-derived geoid coefficients
- $\Gamma^0{}_k(t)$: vector formed by the list of all spherical harmonic coefficients of the 'first guess'
- A : matrix composed of 4 diagonal blocks for separating the 4 reservoirs contributions
- C_D and C_M : covariance matrices of the 'a priori' GRACE errors and a priori model uncertainties
- C_k : covariance matrix which describes the statistical properties of the water mass variations in the 'k-th' reservoir

Total Land Waters- Convergence





example : April 2003

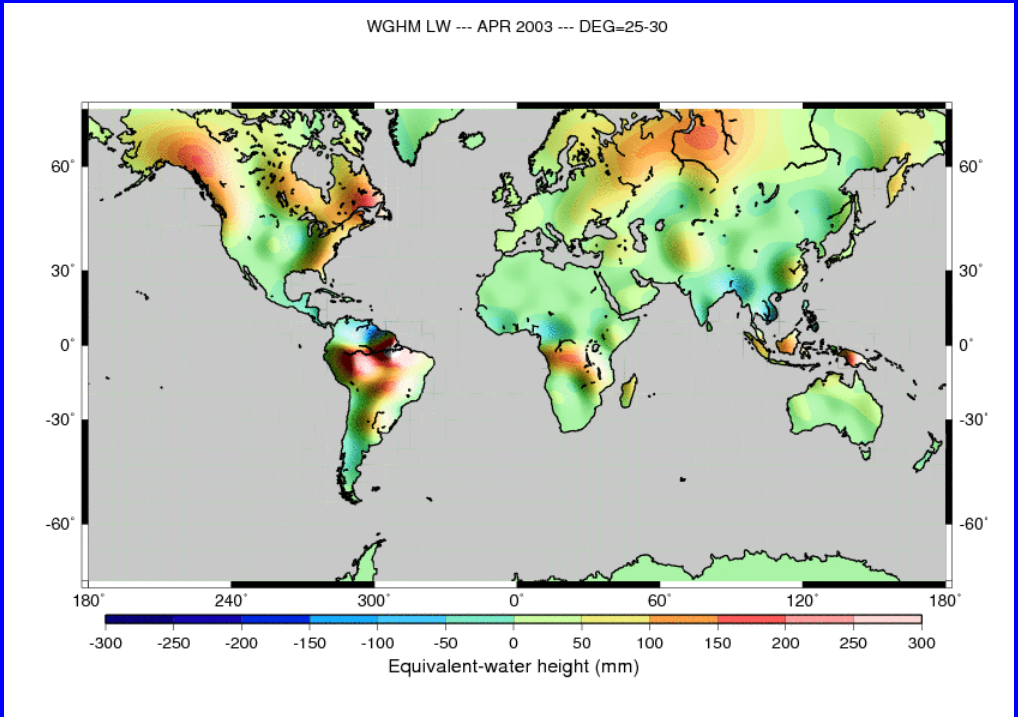
GRACE Solution

(sum of snow+ground waters+ aquifers+surface waters)

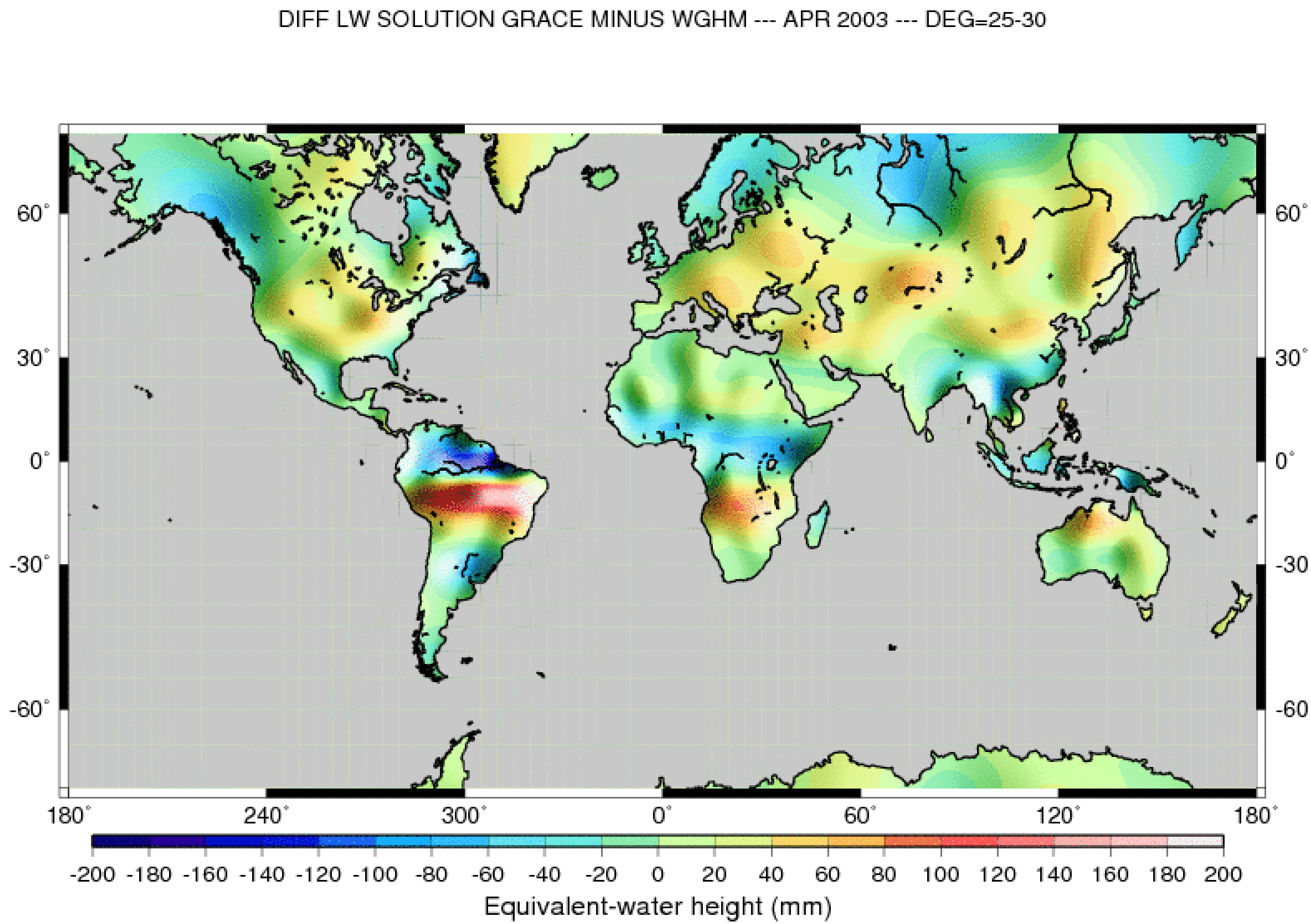
←

Hydrological model (WGHM)

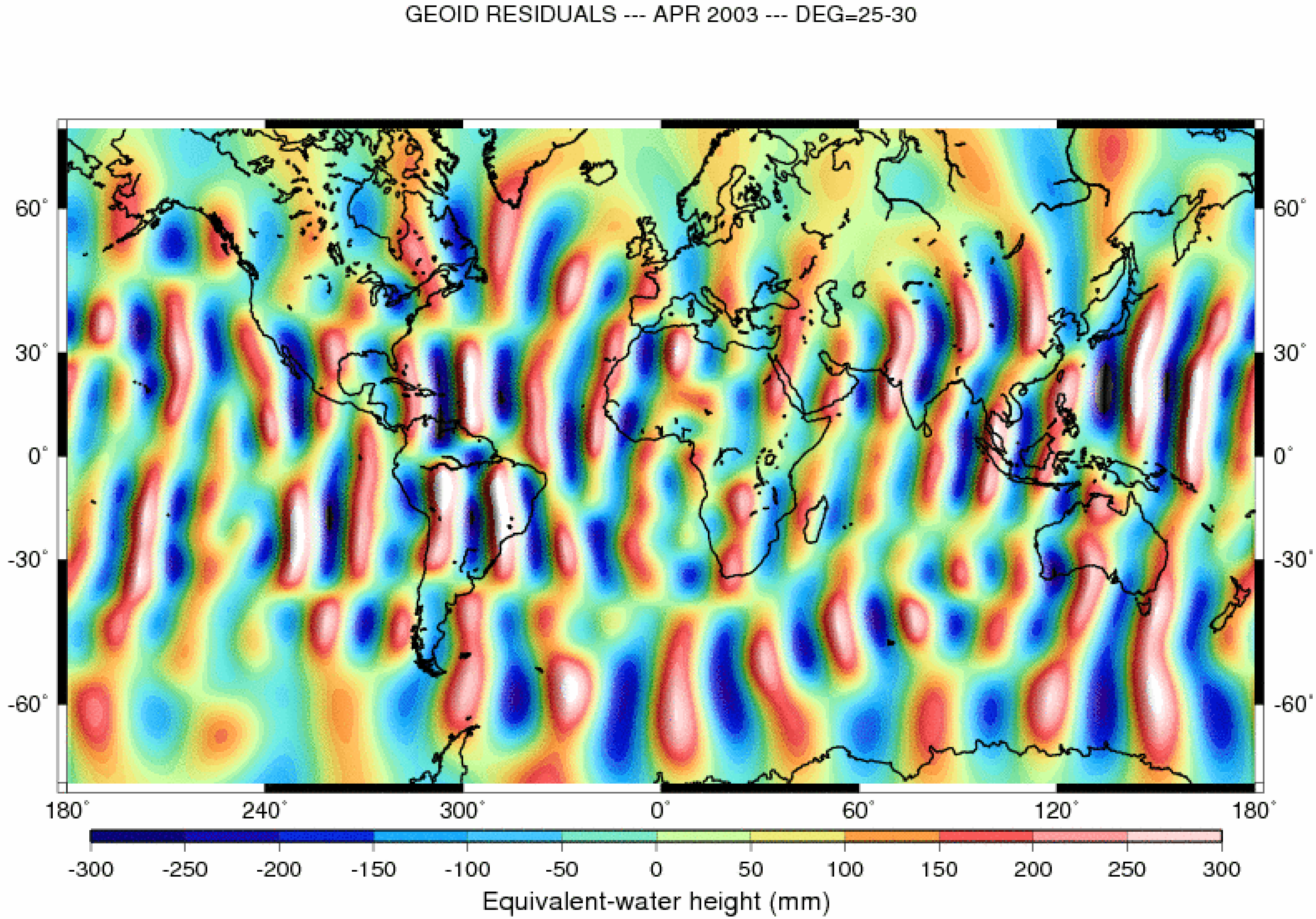
→

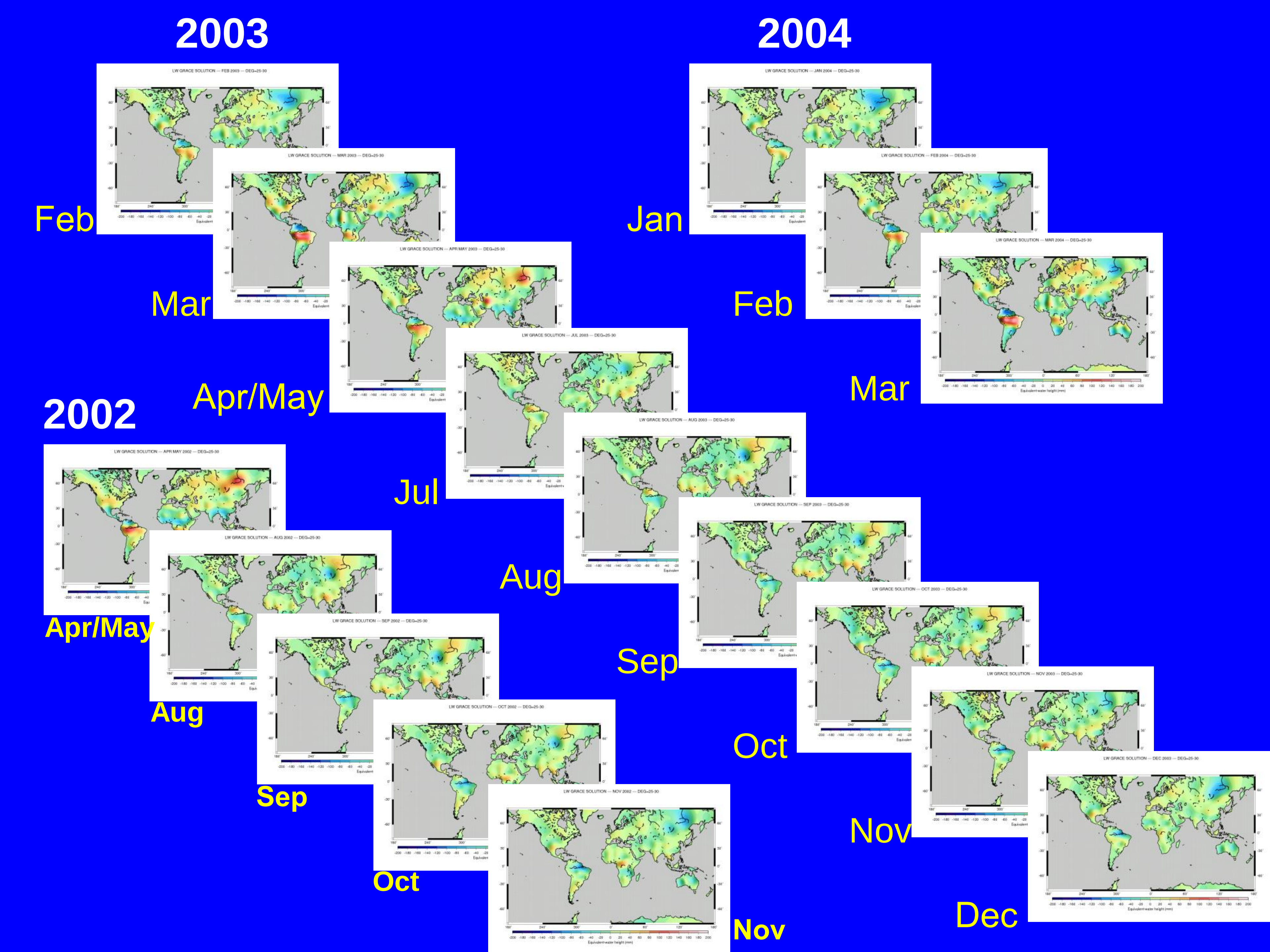


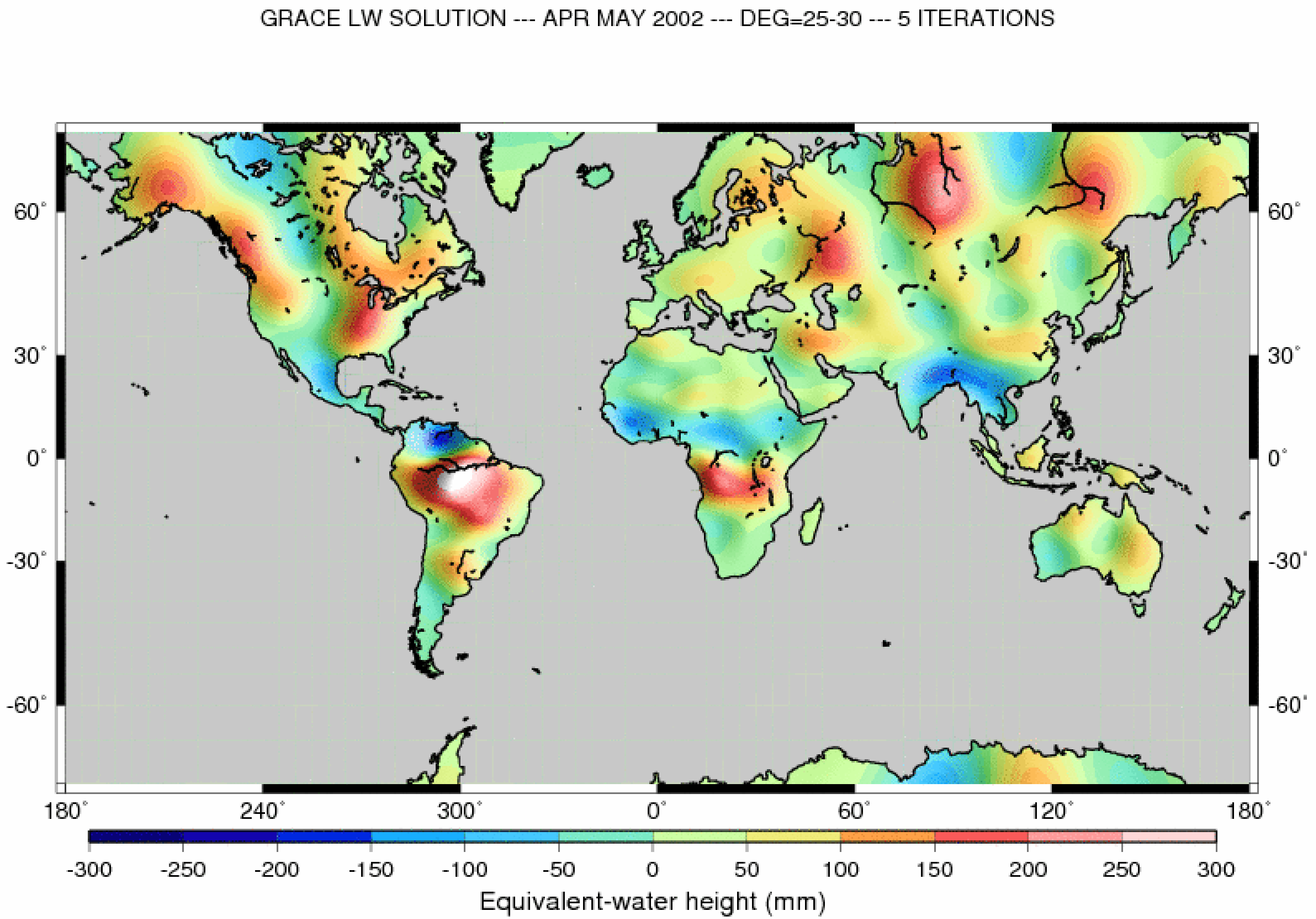
Difference between the GRACE solution and the hydrologcal model



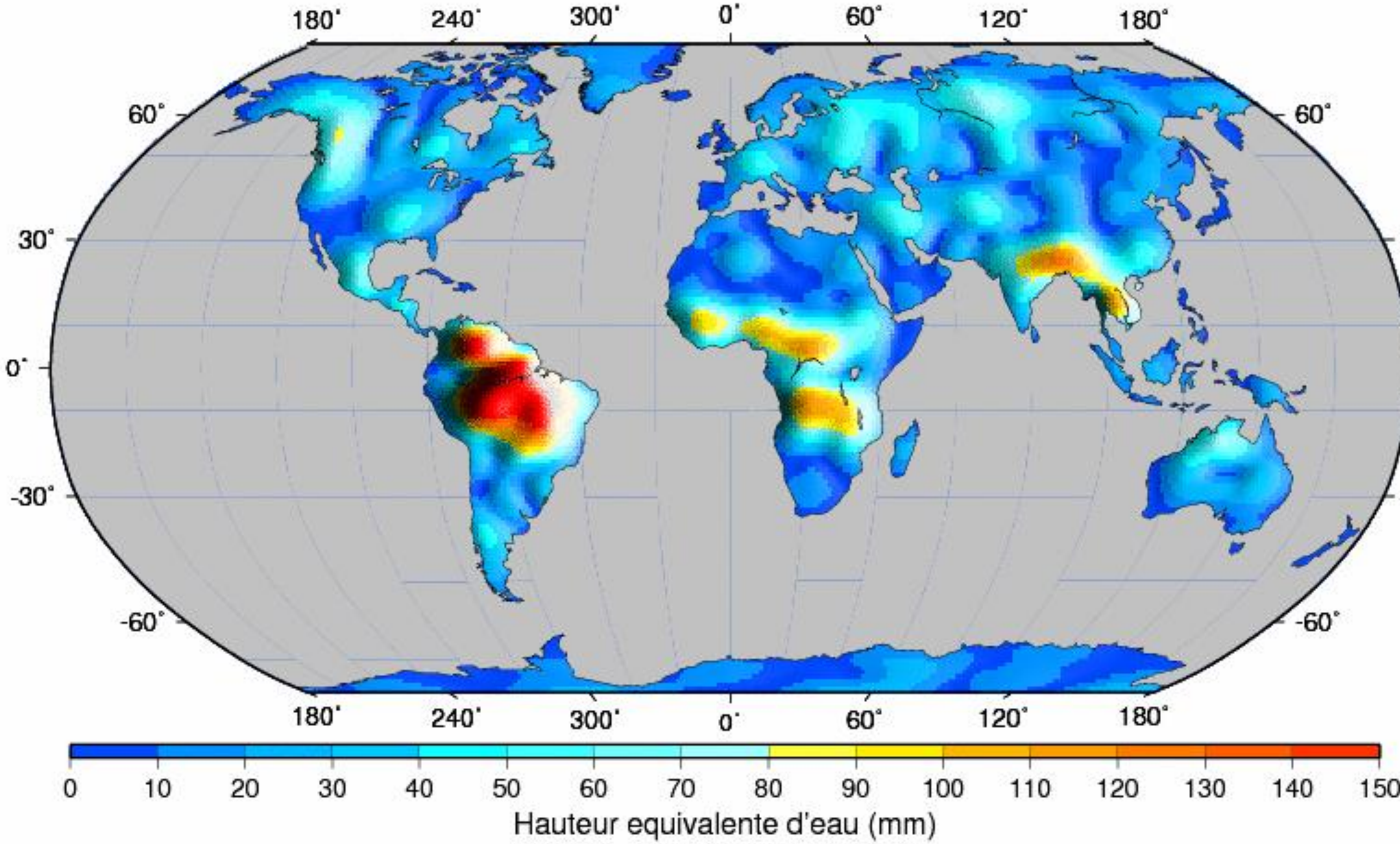
Differences between the observed GRACE geoid and the reconstructed geoid from inversion results

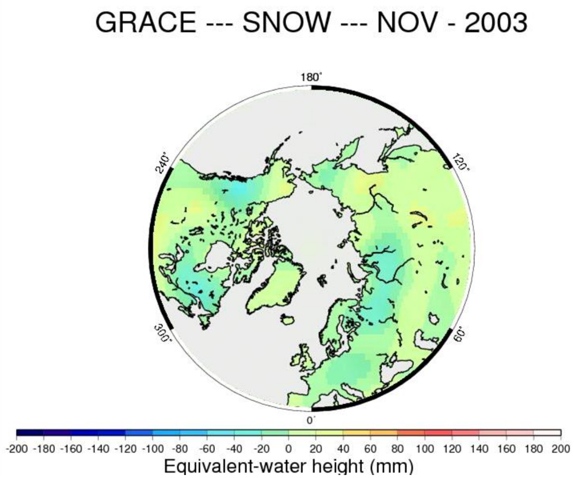


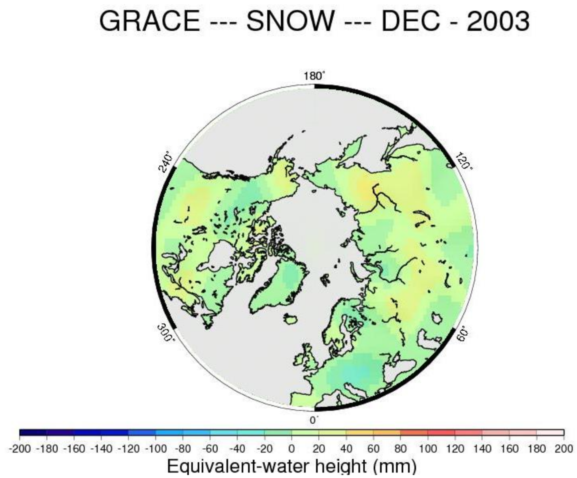

2003
2004
Feb
Mar
Apr/May
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
2002
Apr/May
Aug
Sep
Oct
Nov

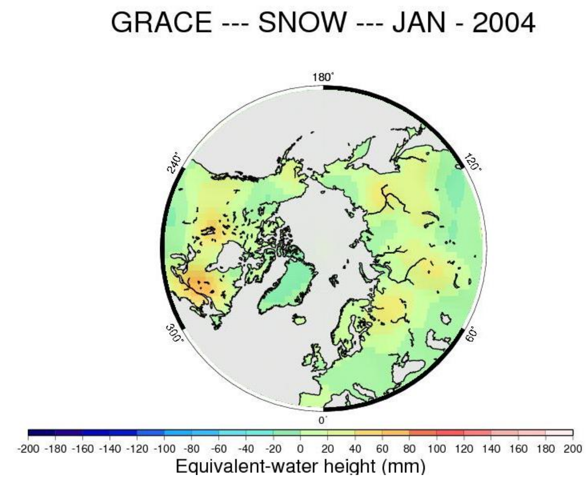

GRACE LW SOLUTION --- APR MAY 2002 --- DEG=25-30 --- 5 ITERATIONS
60°
30°
0°
-30°
-60°
180°
240°
300°
0°
60°
120°
180°
-300
-250
-200
-150
-100
-50
0
50
100
150
200
250
300
Equivalent-water height (mm)

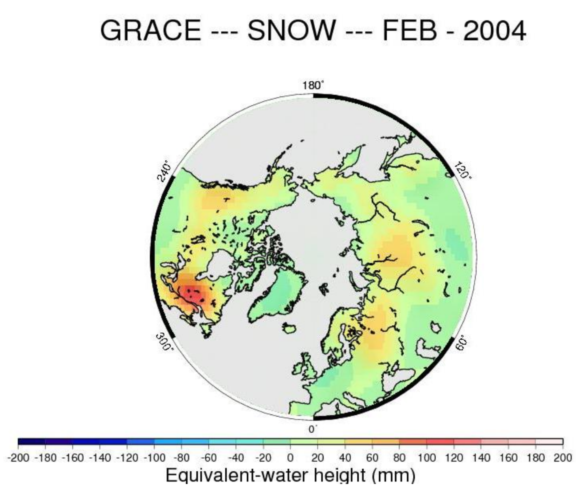
AMPLITUDES SAISONNIERES DES STOCKS D'EAU CONTINENTAUX --- SOLUTIONS INVERSION GRACE

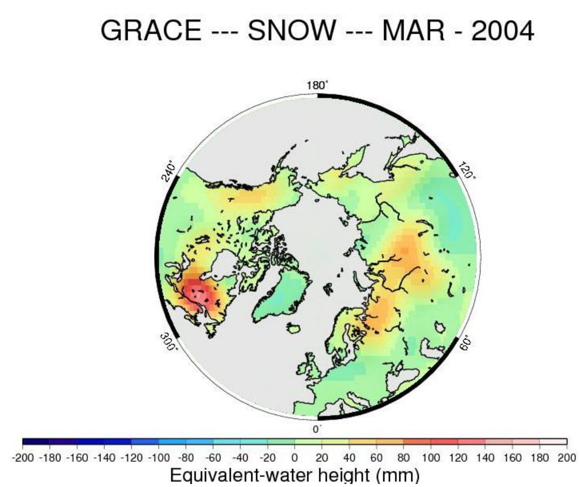


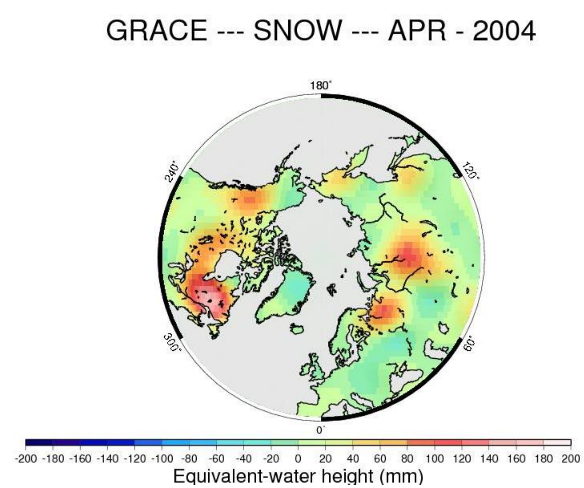

GRACE --- SNOW --- NOV - 2003
180°
120°
240°
300°
60°
0°
-200 -180 -160 -140 -120 -100 -80 -60 -40 -20 0 20 40 60 80 100 120 140 160 180 200
Equivalent-water height (mm)


GRACE --- SNOW --- DEC - 2003
180°
120°
240°
300°
60°
0°
-200 -180 -160 -140 -120 -100 -80 -60 -40 -20 0 20 40 60 80 100 120 140 160 180 200
Equivalent-water height (mm)

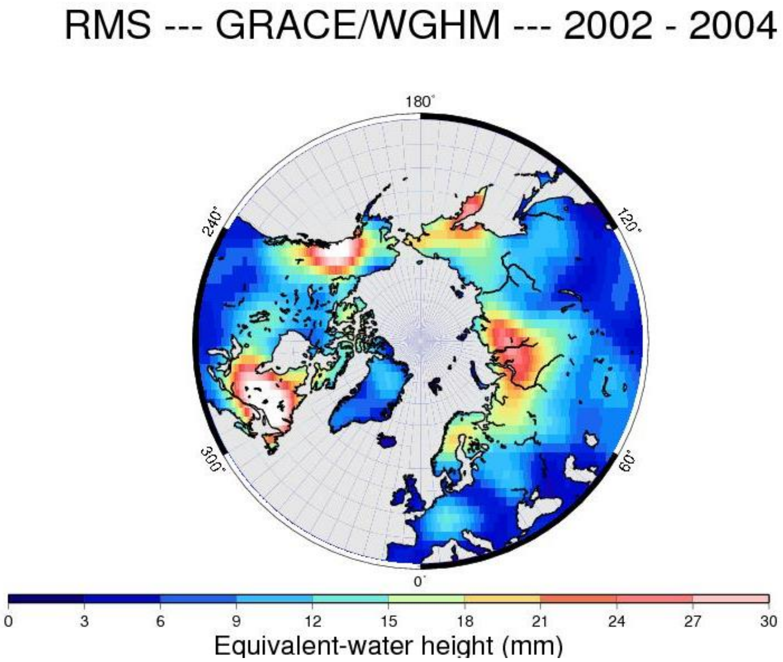

GRACE --- SNOW --- JAN - 2004
180°
120°
240°
300°
60°
0°
-200 -180 -160 -140 -120 -100 -80 -60 -40 -20 0 20 40 60 80 100 120 140 160 180 200
Equivalent-water height (mm)

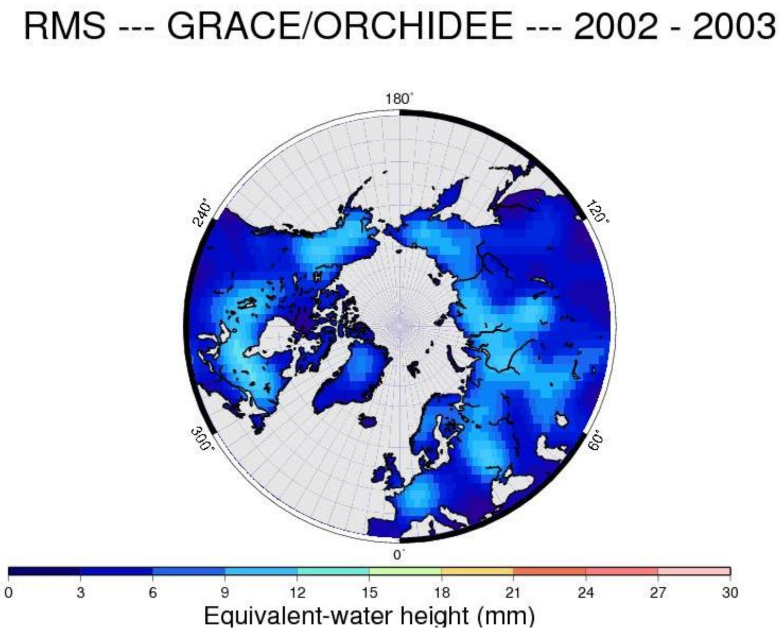

GRACE --- SNOW --- FEB - 2004
180°
120°
240°
300°
60°
0°
-200 -180 -160 -140 -120 -100 -80 -60 -40 -20 0 20 40 60 80 100 120 140 160 180 200
Equivalent-water height (mm)


GRACE --- SNOW --- MAR - 2004
180°
120°
240°
300°
60°
0°
-200 -180 -160 -140 -120 -100 -80 -60 -40 -20 0 20 40 60 80 100 120 140 160 180 200
Equivalent-water height (mm)

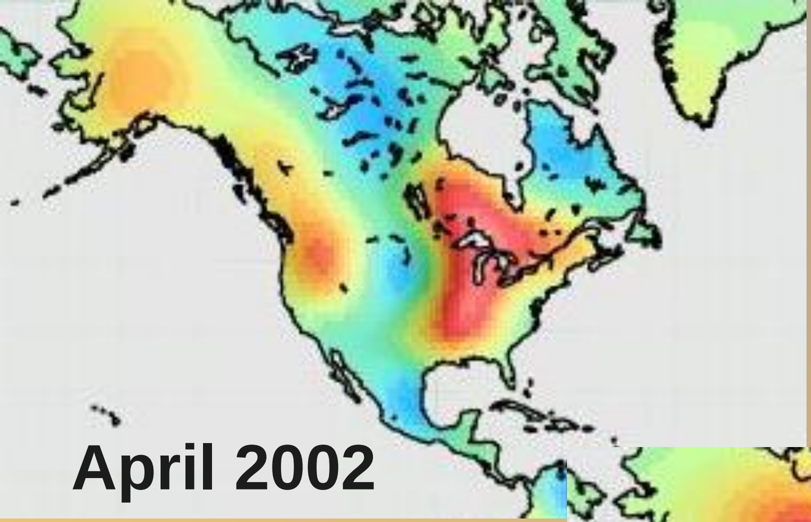

GRACE --- SNOW --- APR - 2004
180°
120°
240°
300°
60°
0°
-200 -180 -160 -140 -120 -100 -80 -60 -40 -20 0 20 40 60 80 100 120 140 160 180 200
Equivalent-water height (mm)

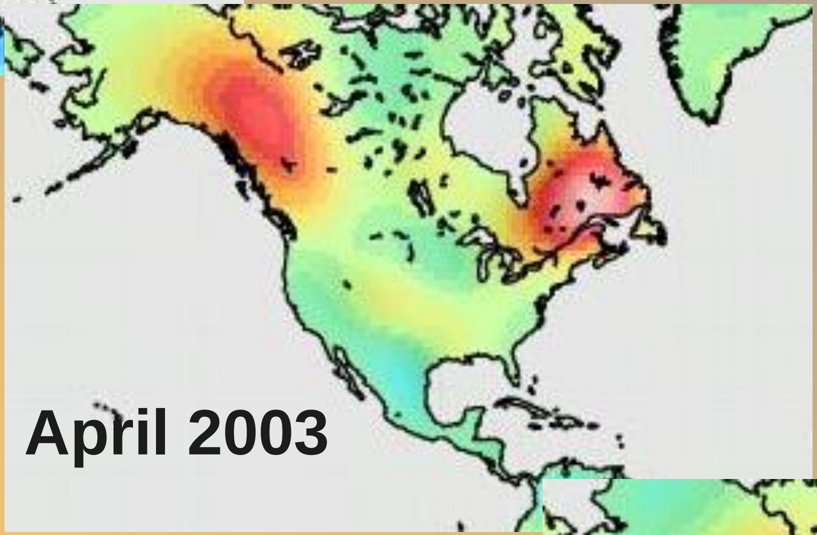
Snow : GRACE - Model difference

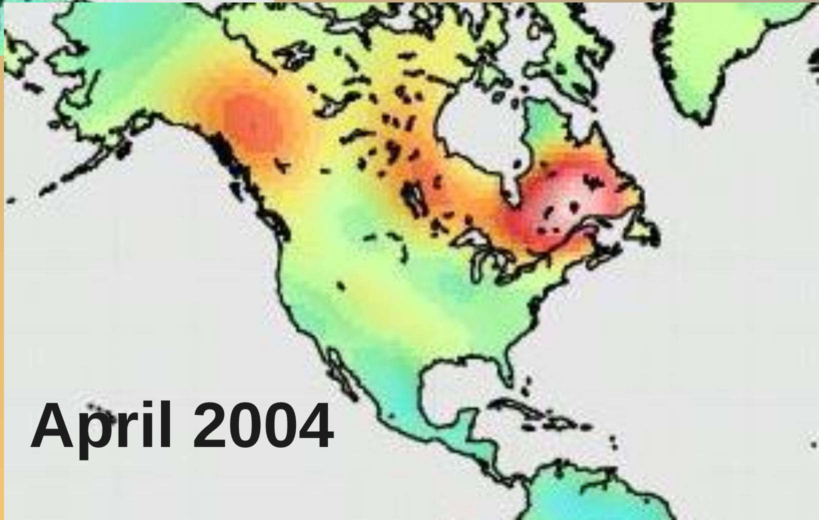




Snow





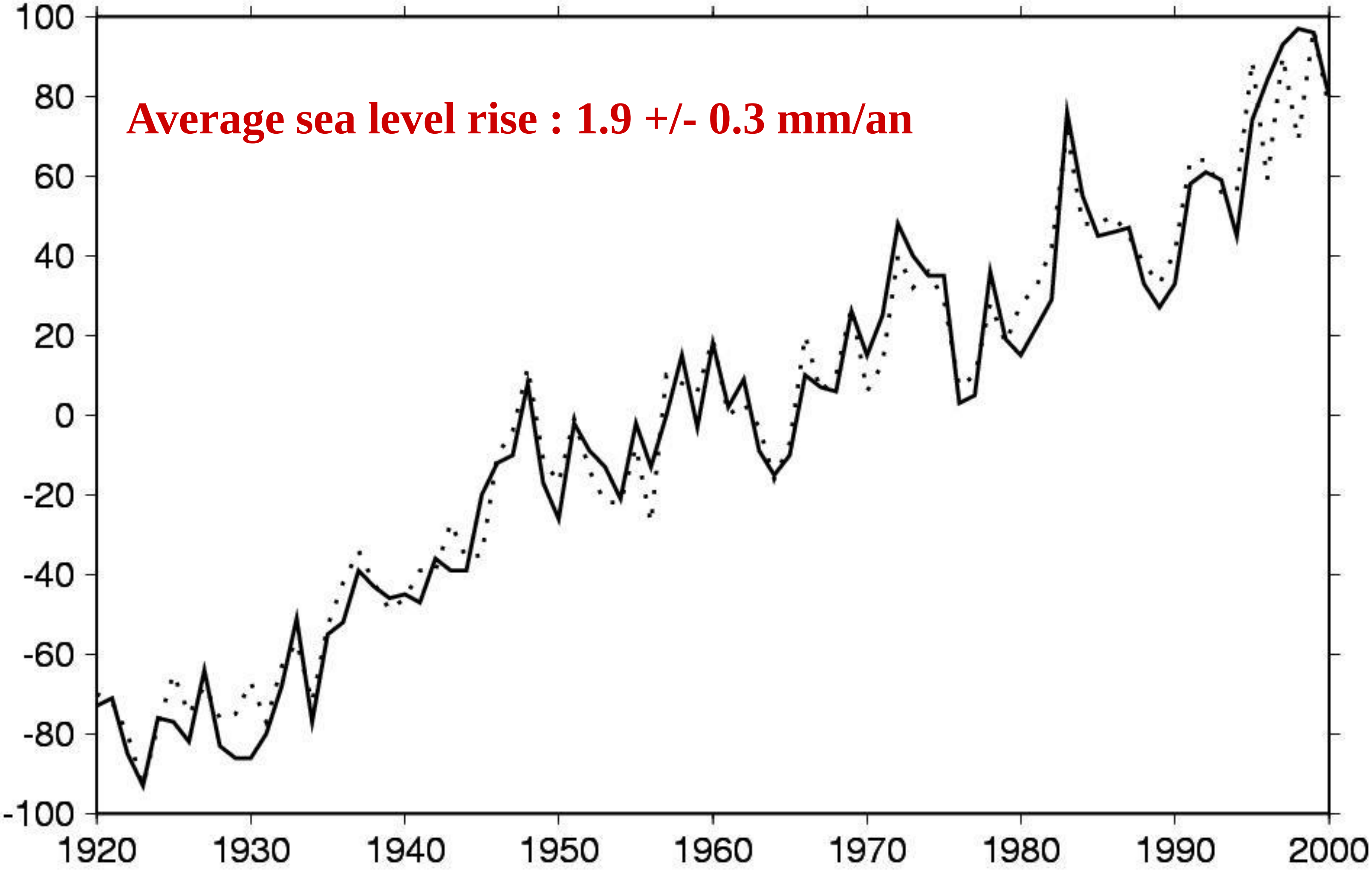


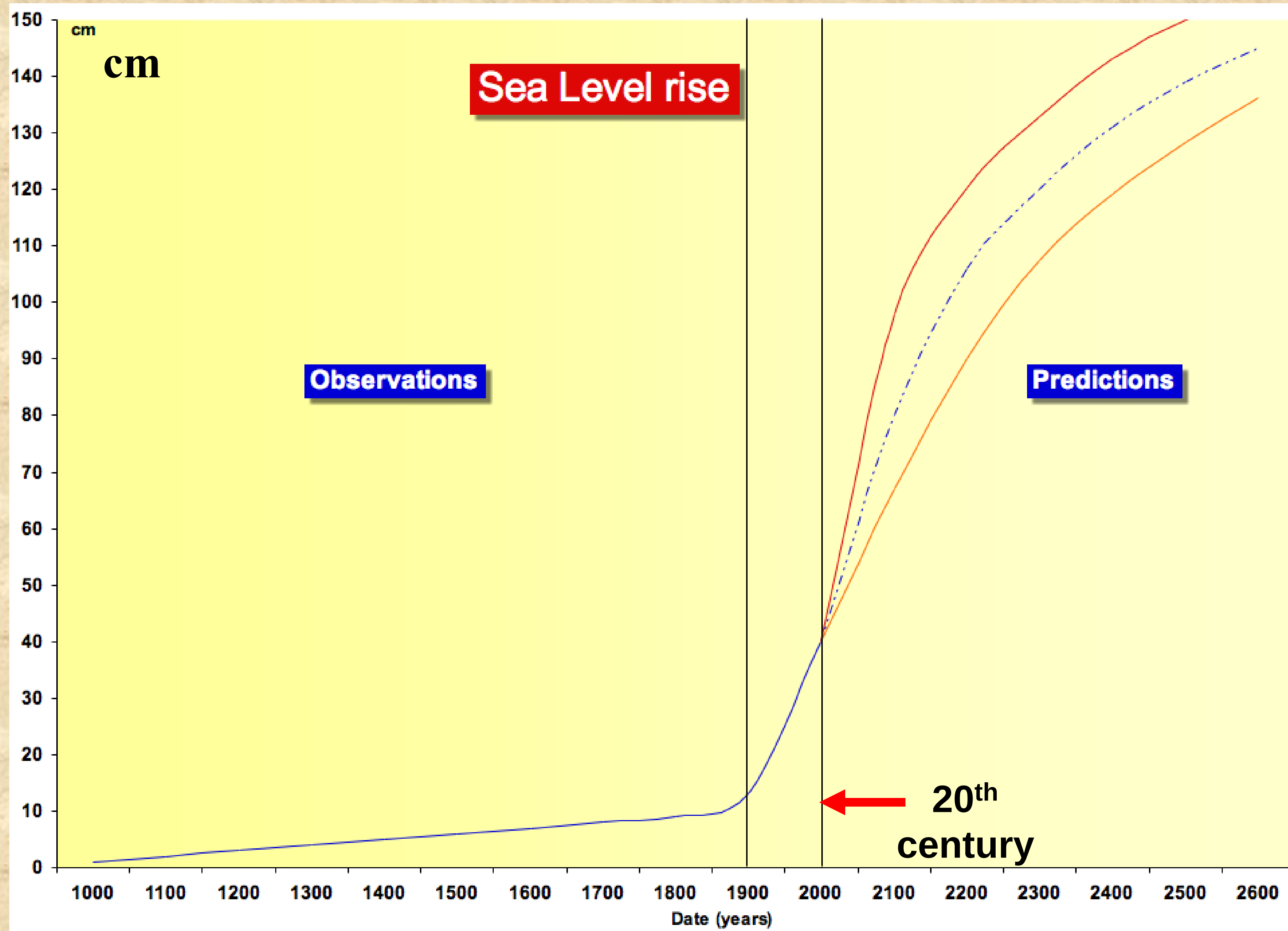
Results from GRACE mission

Other Applications

- ***Sea Level***
- **Geodesy**

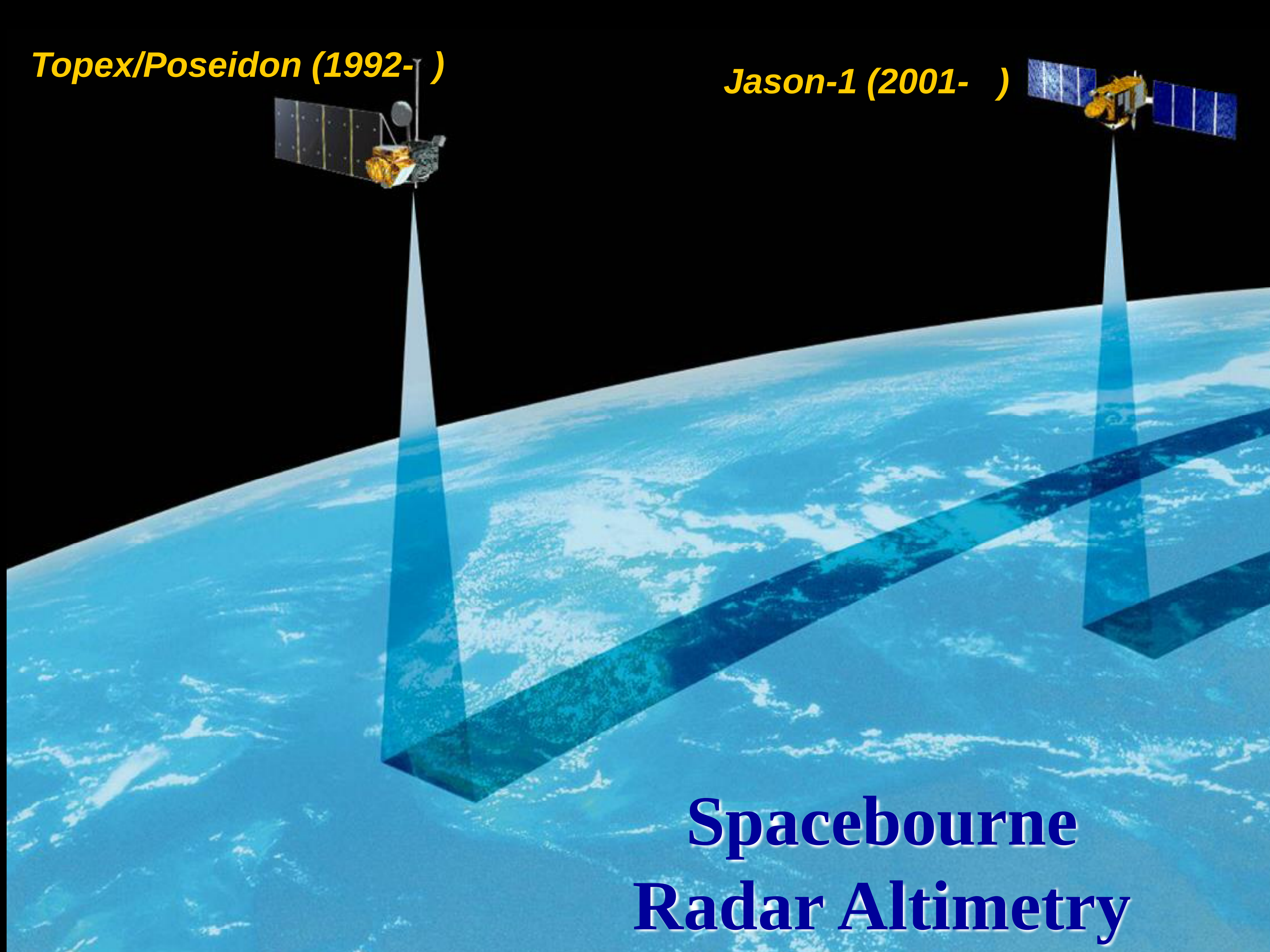
Mean Sea Level from Tide Gauges Observations

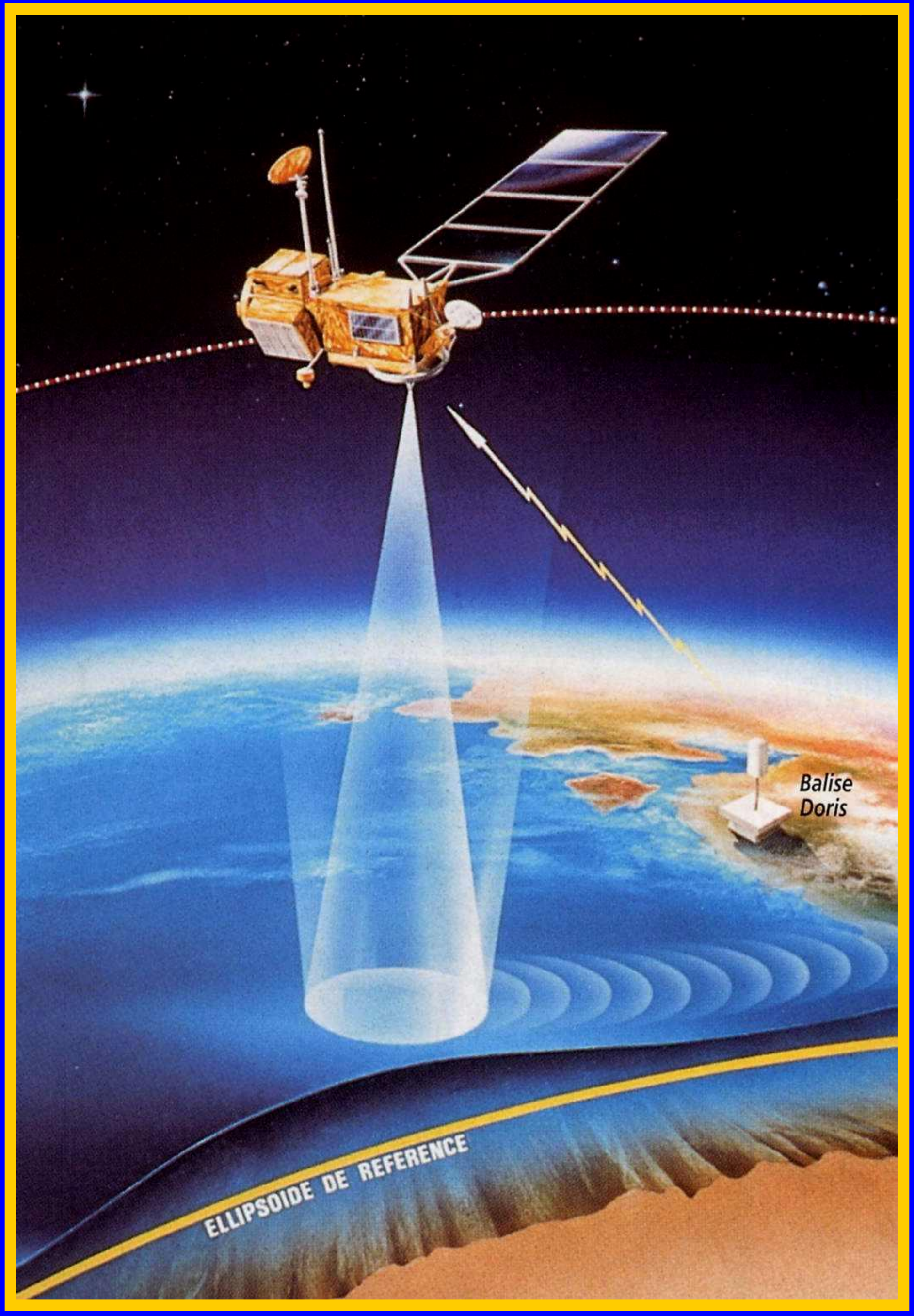



cm
cm
Sea Level rise
Observations
Predictions
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
2500
2600
Date (years)
20th
century

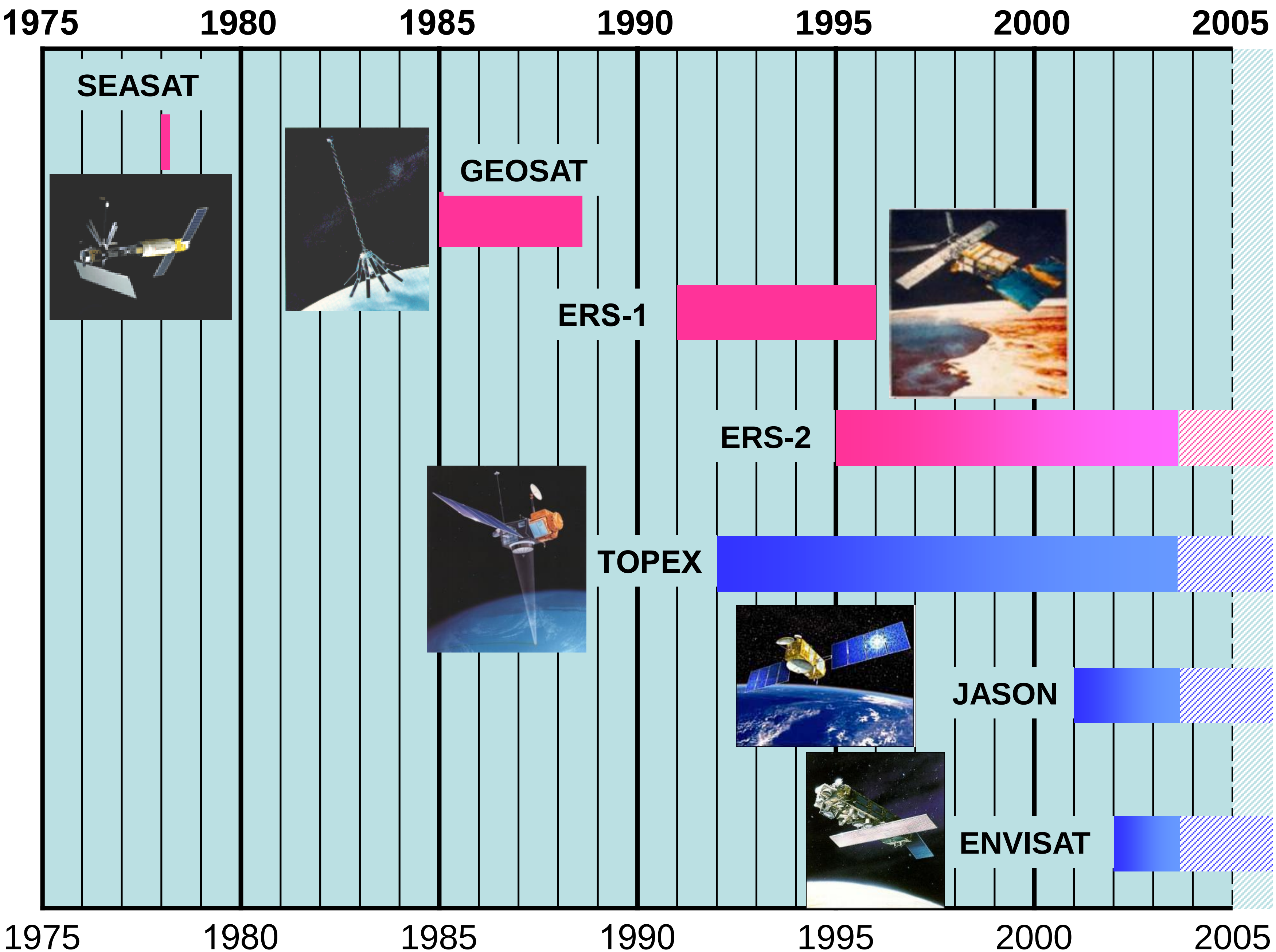
Date (Years)

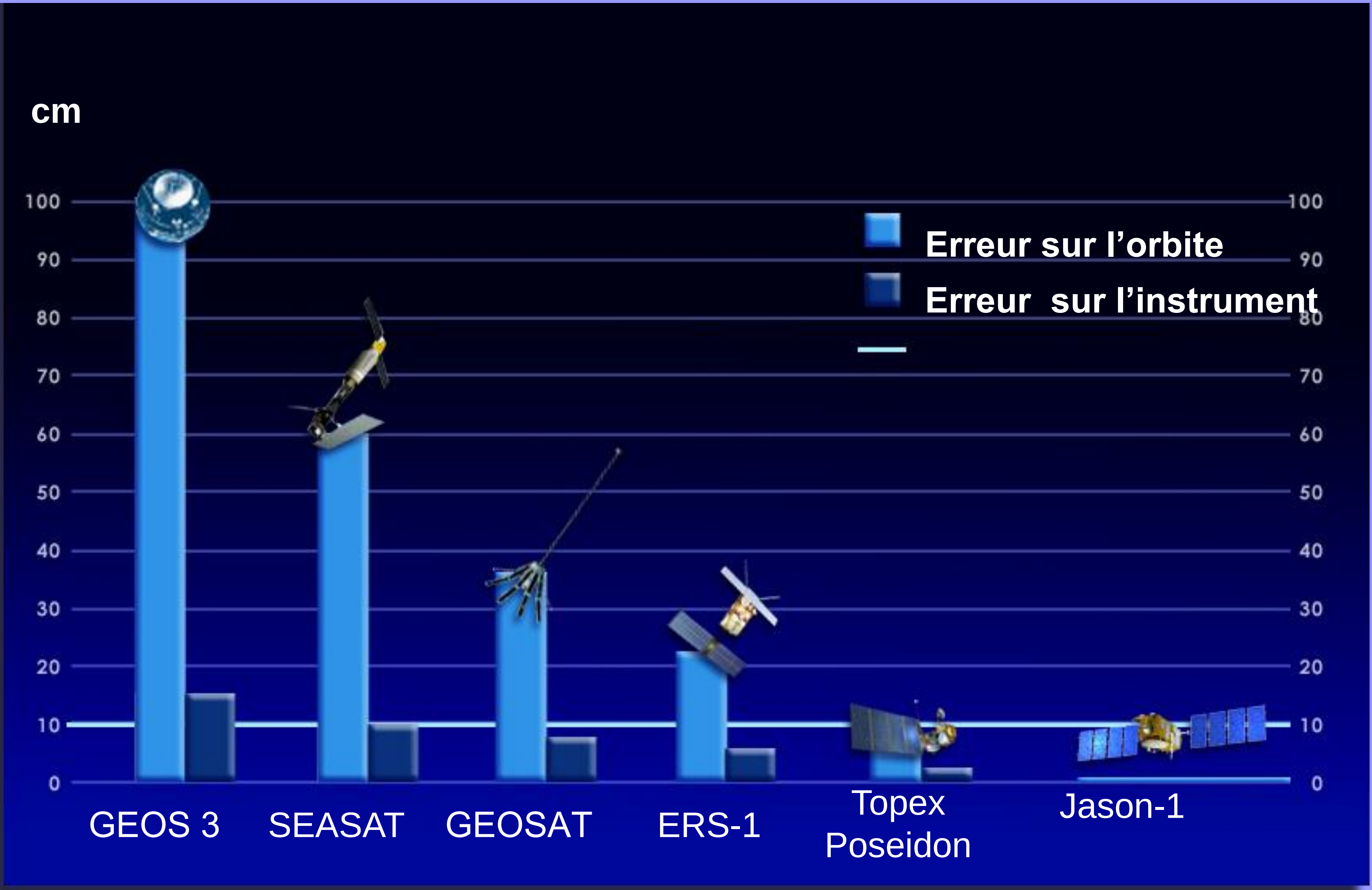
Spacebourne Radar Altimetry





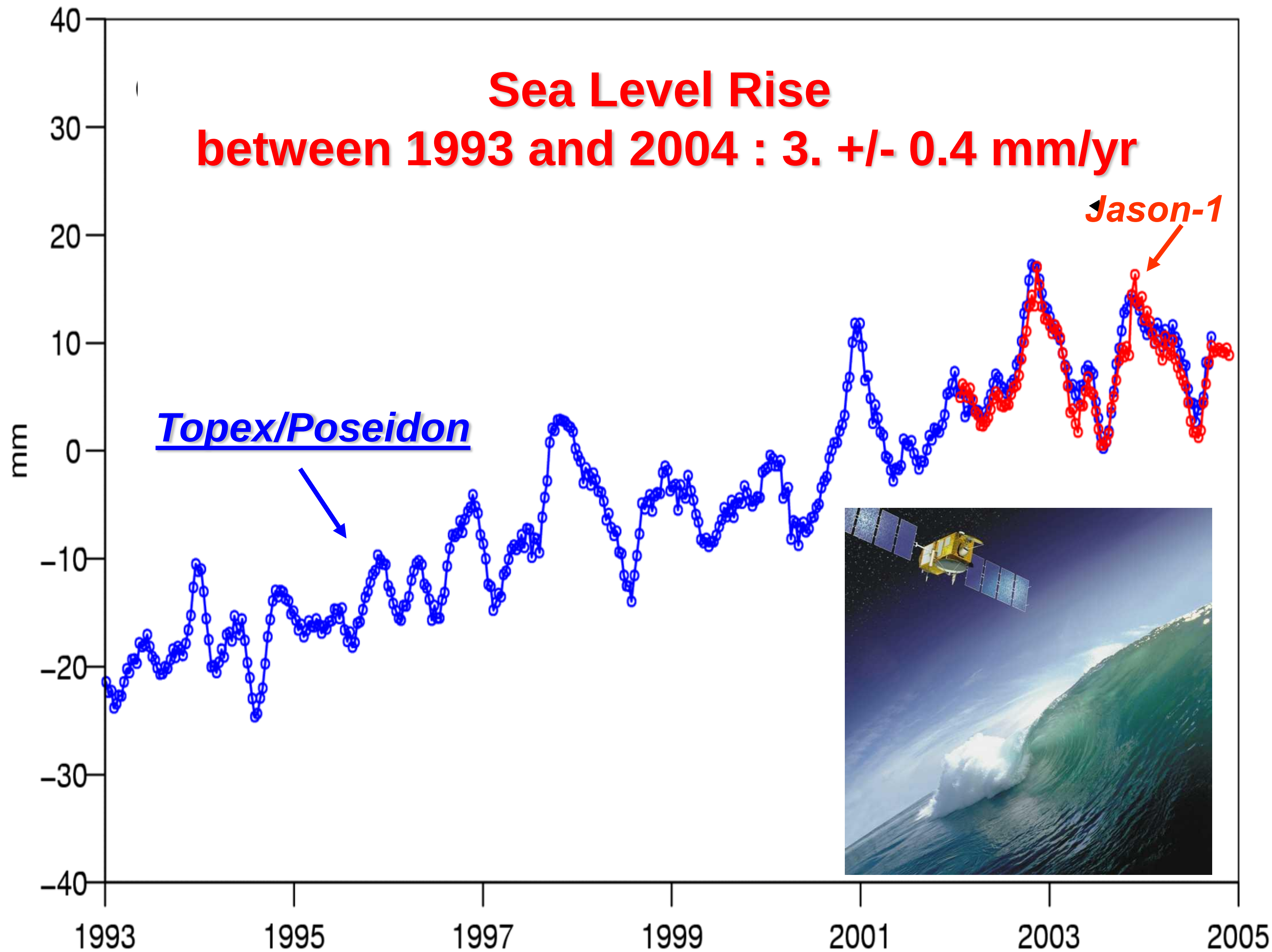
Radar Altimetry Measurement Principle


1975
1980
1985
1990
1995
2000
2005
SEASAT
GEOSAT
ERS-1
ERS-2
TOPEX
JASON
ENVISAT
1975
1980
1985
1990
1995
2000
2005



cm
100
90
80
70
60
50
40
30
20
10
0
Erreur sur l'orbite
Erreur sur l'instrument
GEOS 3
SEASAT
GEOSAT
ERS-1
Topex Poseidon
Jason-1

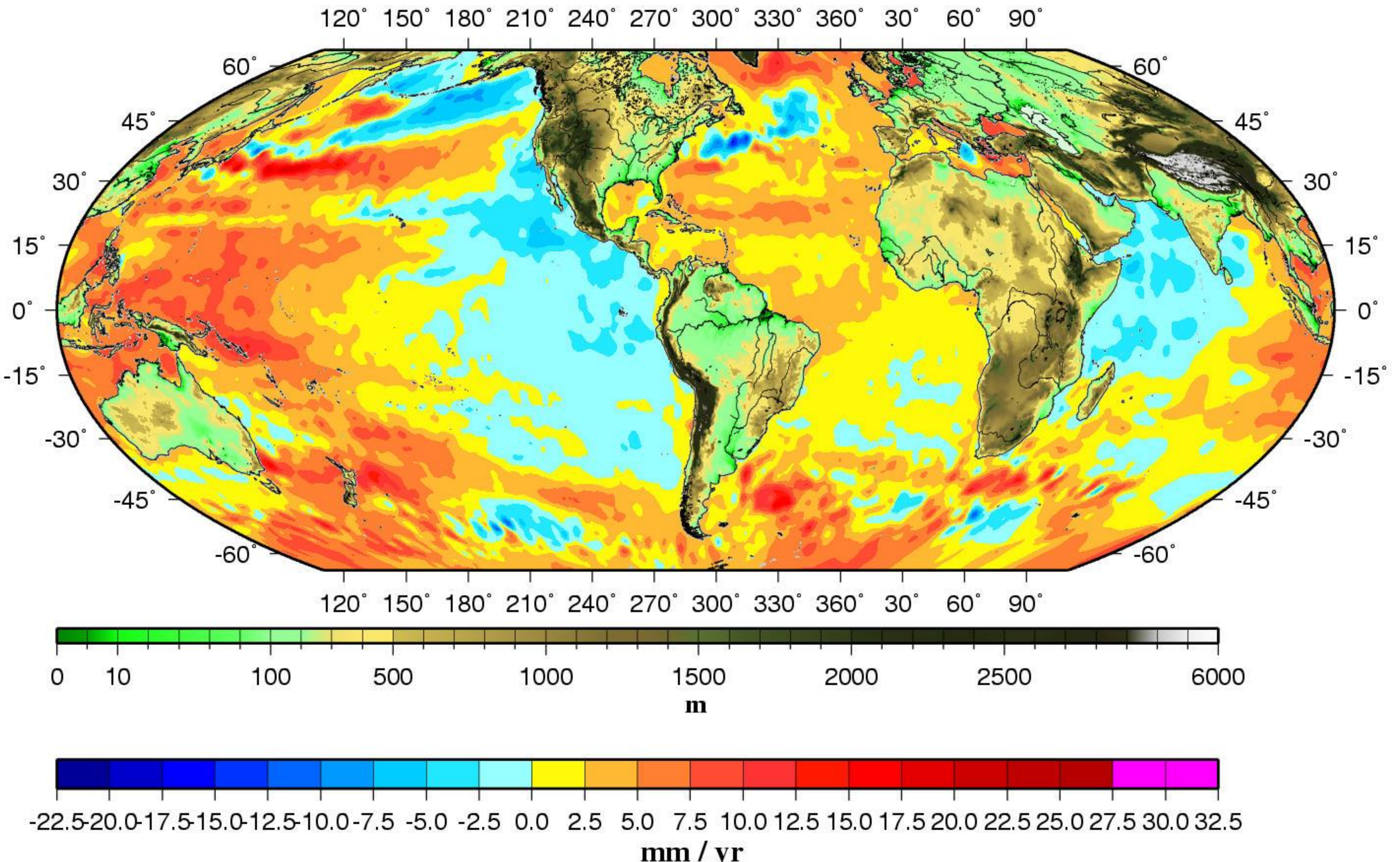
Global Mean Sea Level / Niveau Moyen de la Mer



Sea level trends from Topex-Poseidon

(Jan. 1993 - Dec. 2004)

LEGOS/CNES (Mar 2005) (MOG2D 11a450 ppalix)



Sea Level Rise

- 1950-2000 : 1.9 +/- 0.3 mm/yr (tide gauges)

- 1993-2004 : 3. +/- 0.4 mm/yr (radar altimetry)

↓

Acceleration?

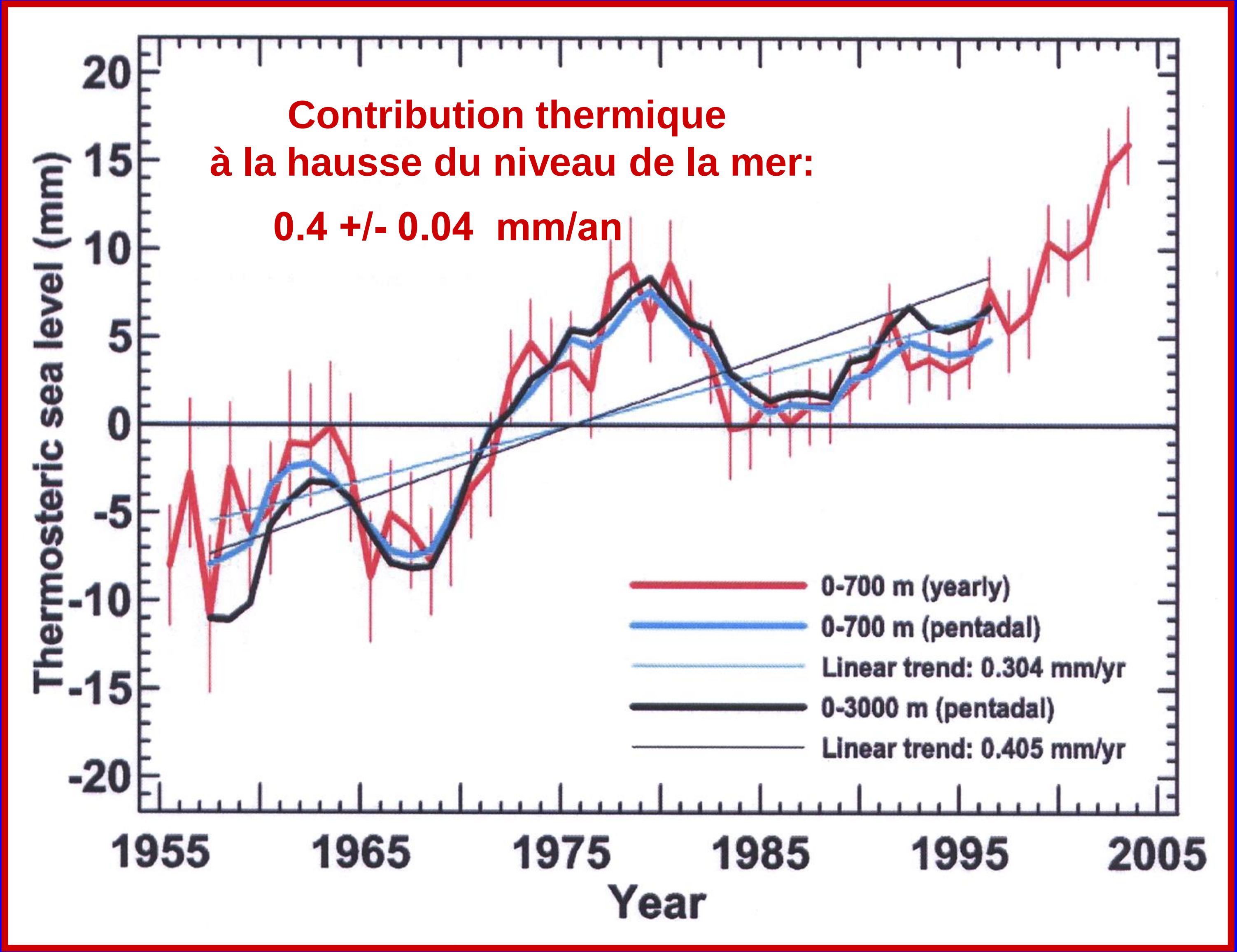
Causes des variations du niveau de la mer (échelle de temps 1-100 ans):

• Variations de température et de salinité de l'eau de mer :

Expansion thermique

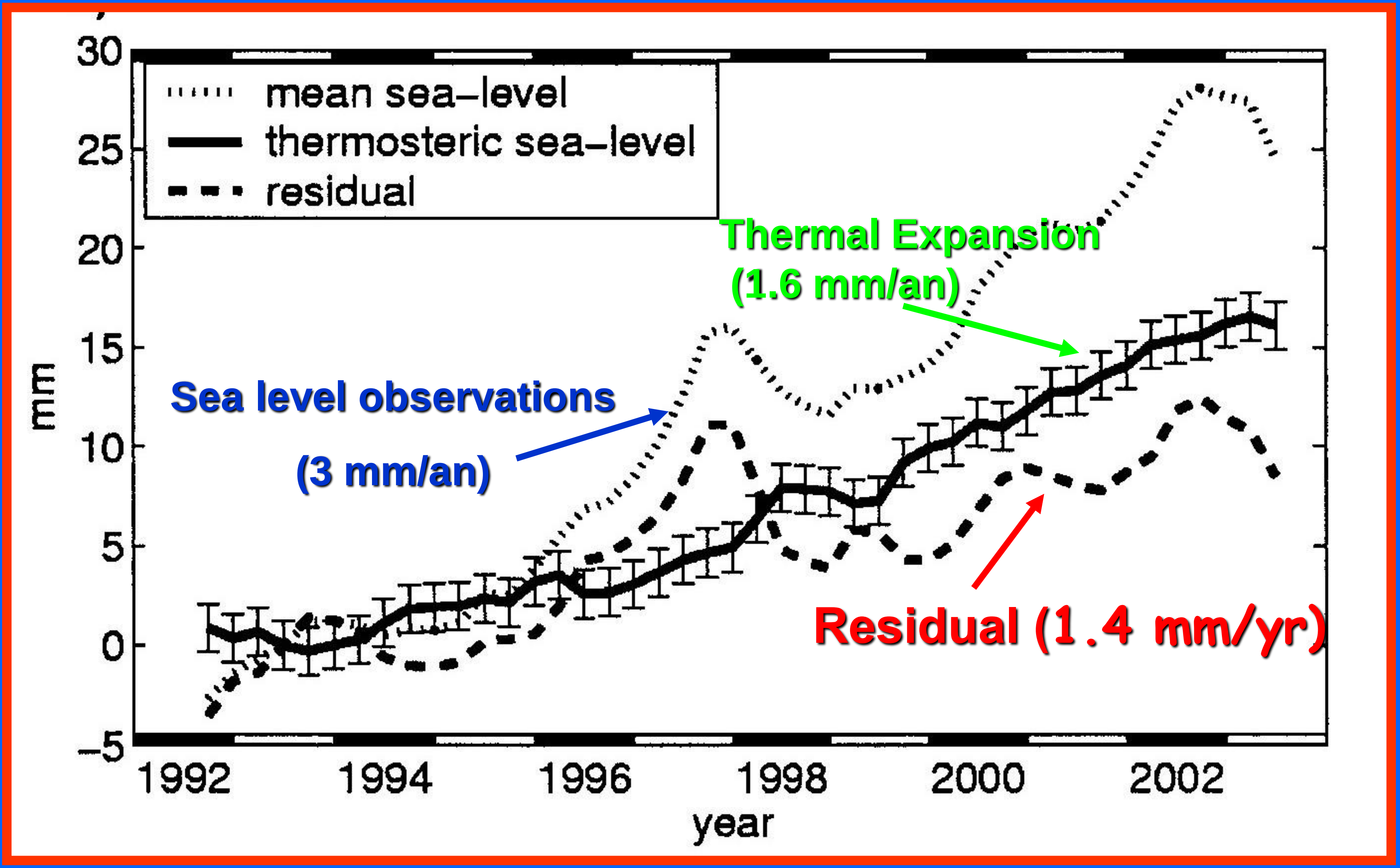
• Echanges de masse d'eau entre les océans et les différents réservoirs continentaux, les glaciers et les calottes polaires

Expansion thermique de l'océan mondial

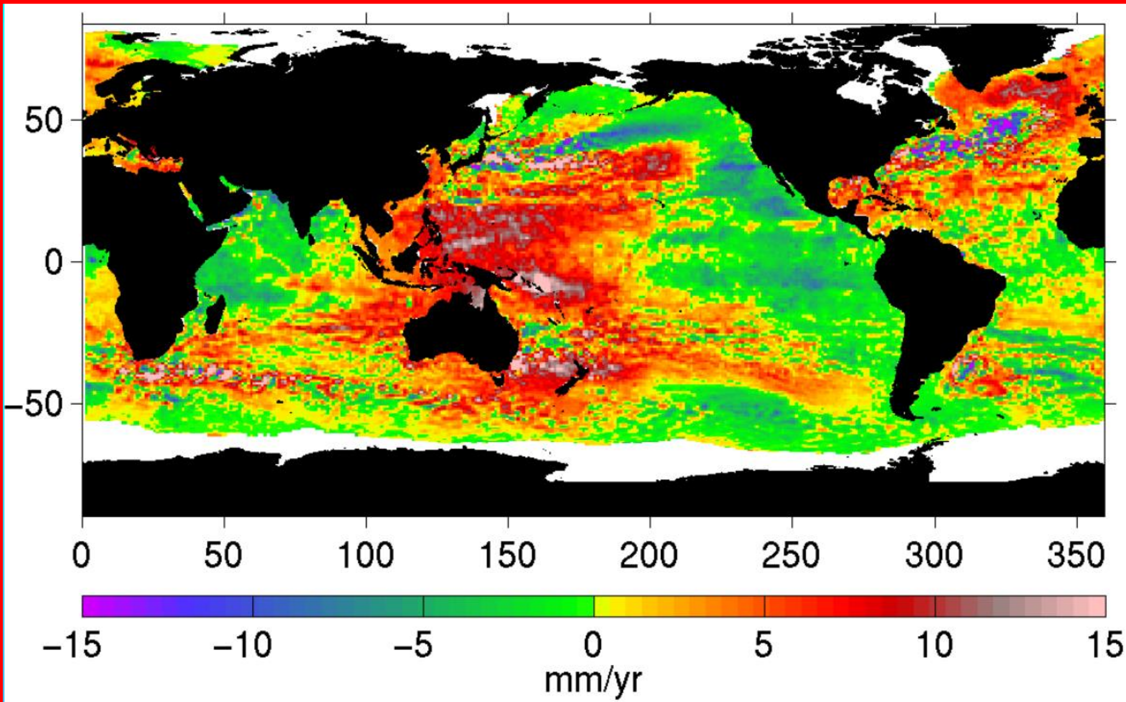


Levitus et al., 2005

SEA LEVEL RISE (1993-2003)



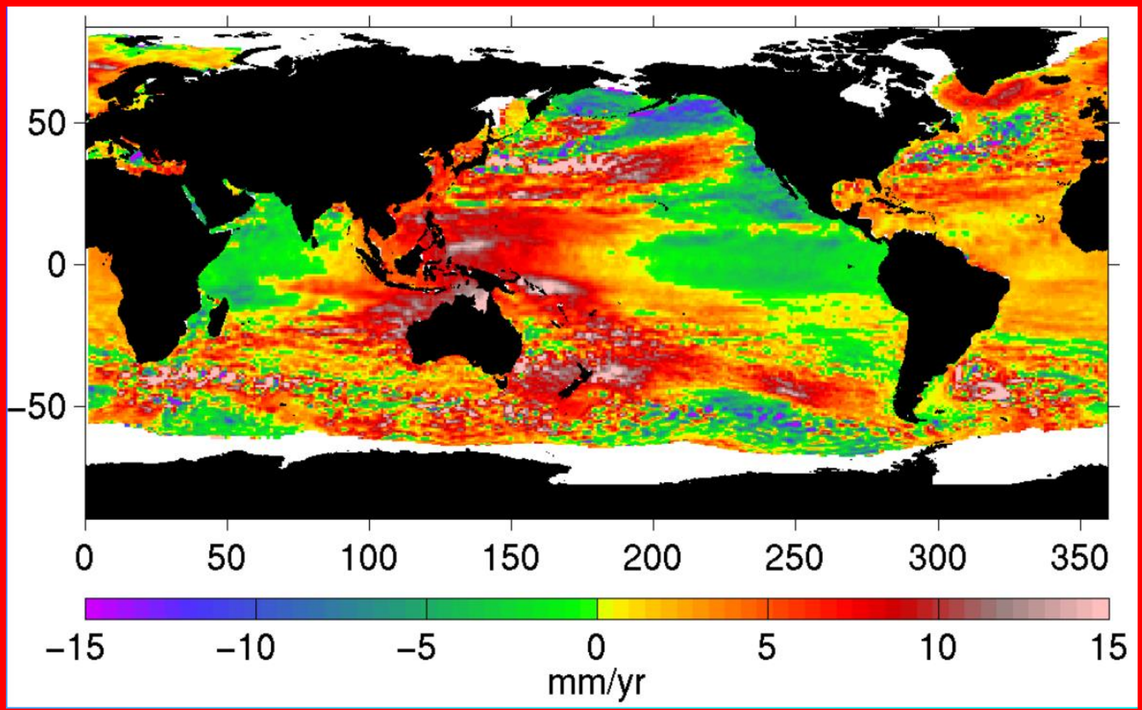
Willis et al., 2004



Variabilité régionale des vitesses de variation du niveau de la mer 1993-2003

Expansion thermique

Observations de Topex/Poseidon

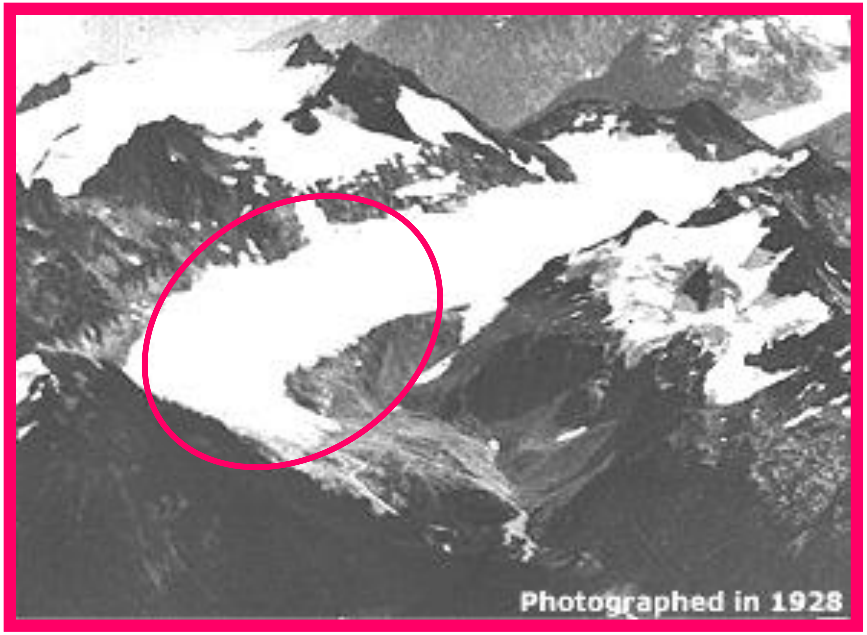


- Thermal expansion explains only 25% of the sea level rise during the last 50 years (0.4 out of 1.8 mm/yr)

- For the period 1993-2004, thermal expansion explains 60% of observed sea level rise (1.6 out of 3 mm/yr)

- But for both periods , the difference 'observation minus thermal expansion' is 1.4 mm/yr (+/- 0.3 mm/yr)
  --→ significative contribution of continental water and ice

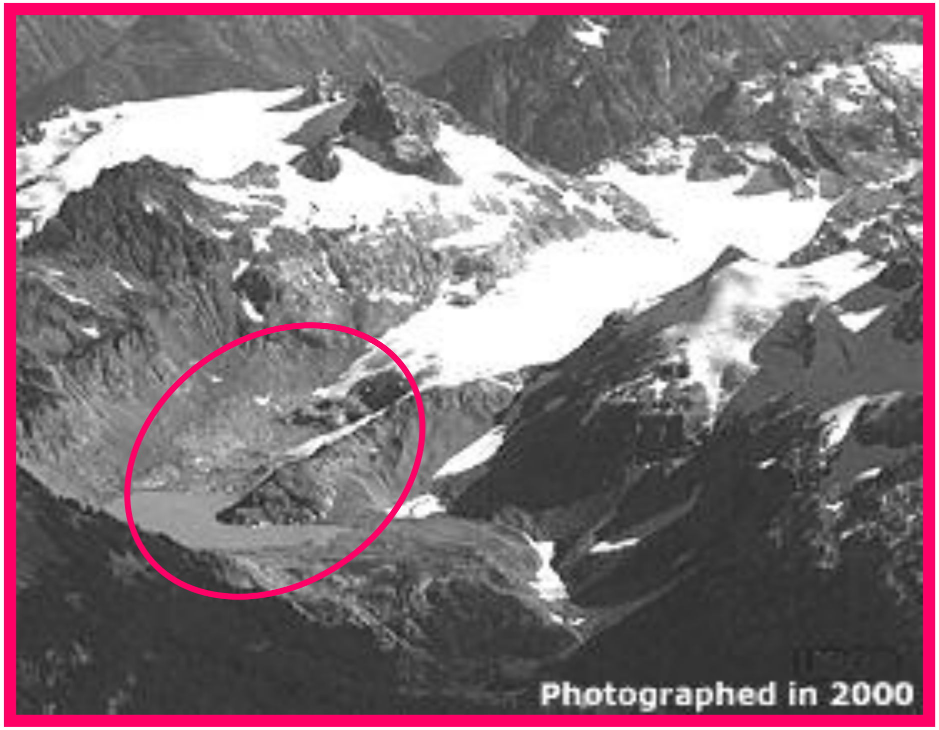
- Meltdown of mountain glaciers and polar ice cap
- Transfer of water from continental reservoirs to the ocean



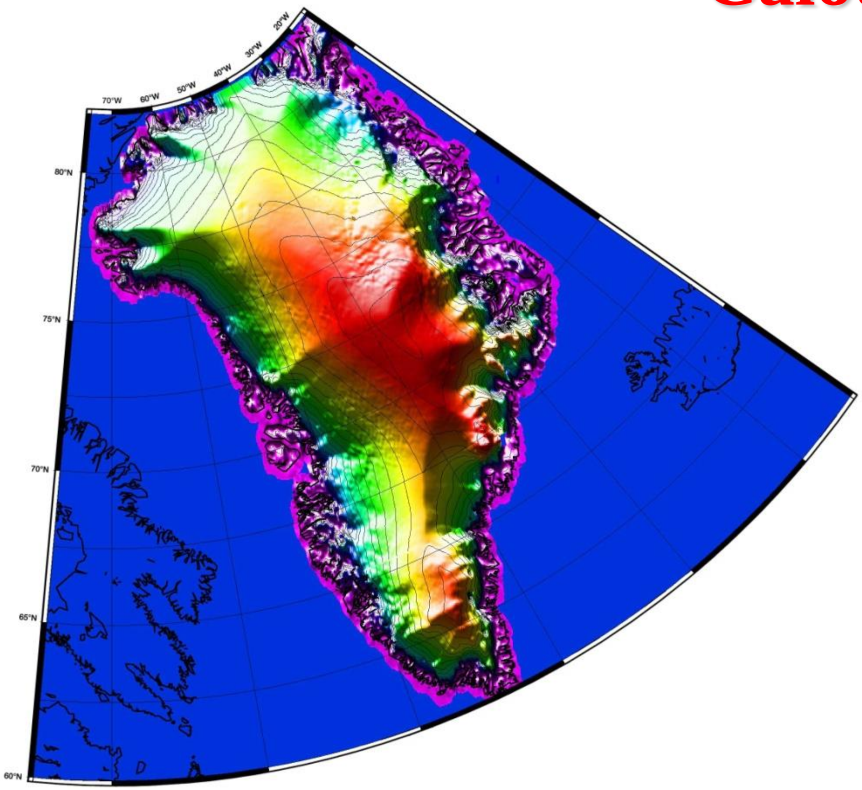
1928

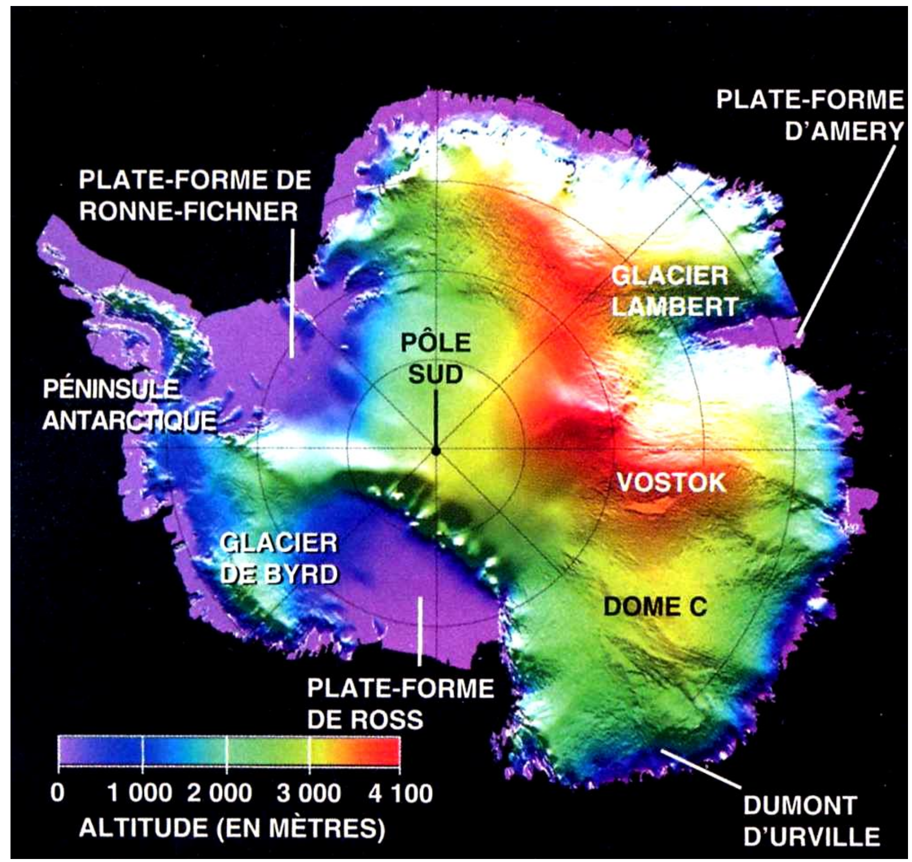
A glacier in Alaska

2000



Calottes polaires





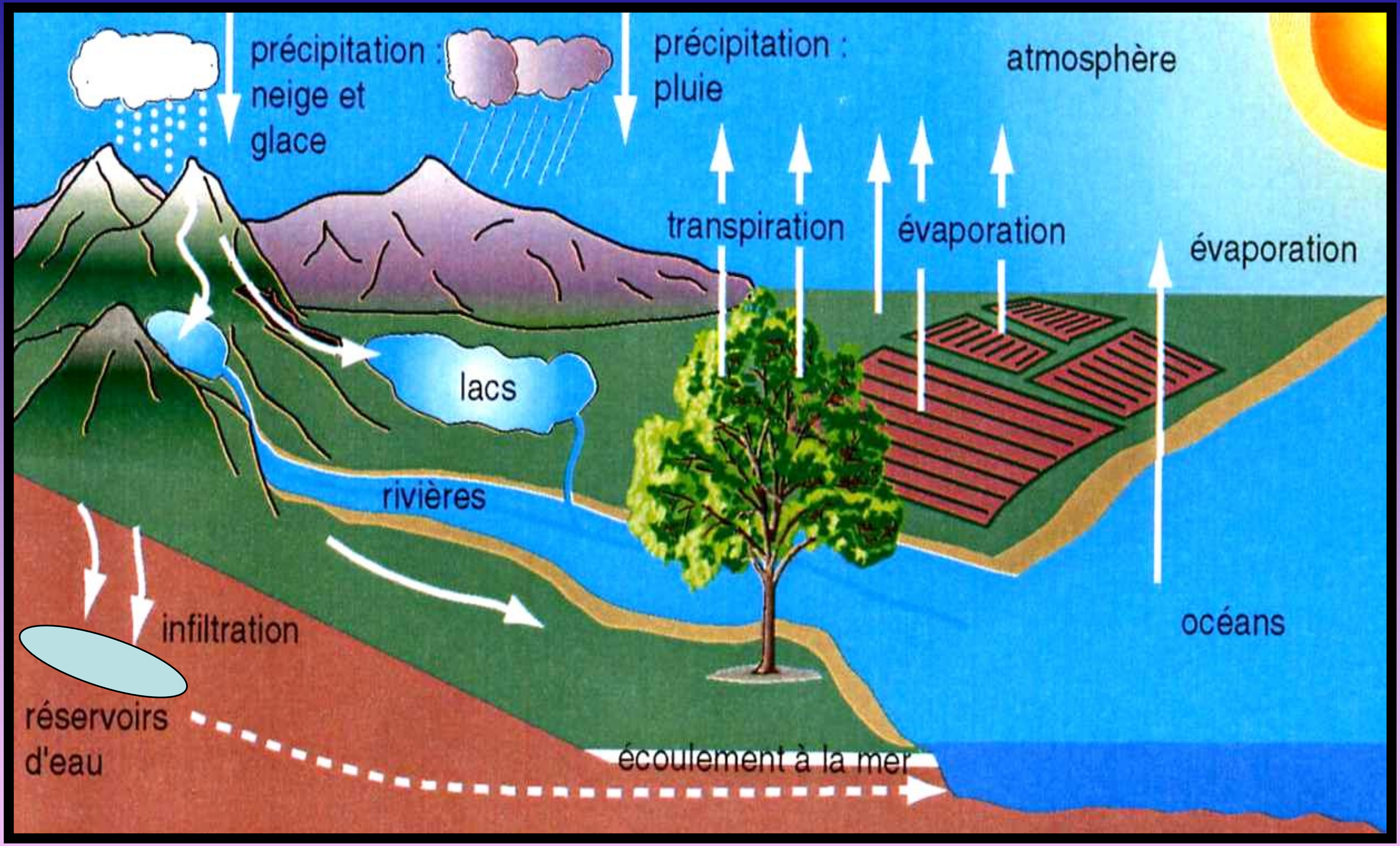
Contribution des glaciers, calottes polaires à la hausse du niveau de la mer au cours des années 1990

(Sources :IPCC, 2005)

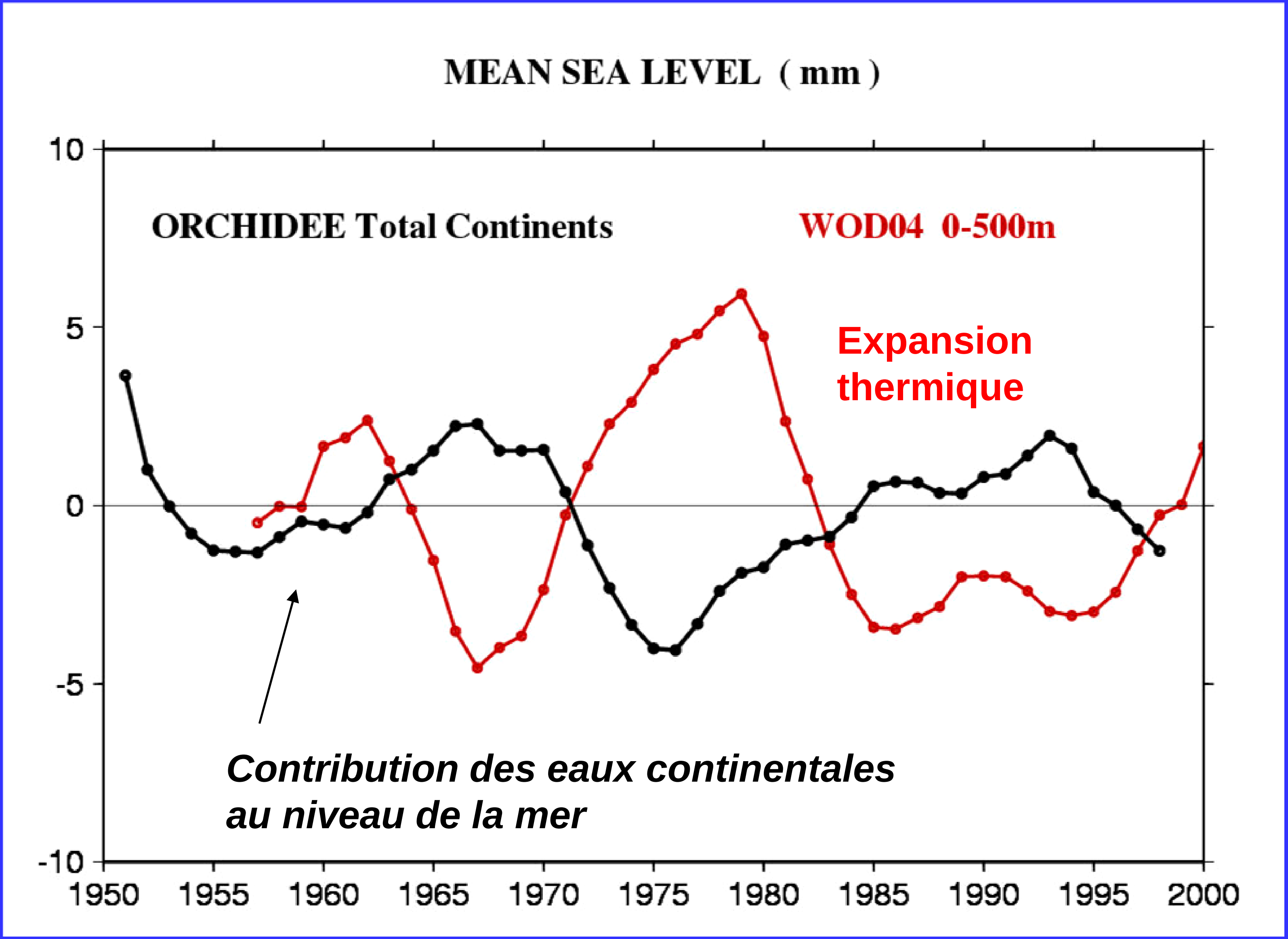
- **Mountain GLACIERS : 0.4 mm/yr**
- **POLAR ICE CAPS :**
  - **Groenland : 0.1-0.2 mm/yr**
  - **Antarctique ouest : 0.1-0.2 mm/yr**
  - **Total glaces polaires = 0.2-0.4 mm/yr**

~0.7 mm/an dû à la fonte des glaces

Can the contribution of continental waters explain the missing part ?

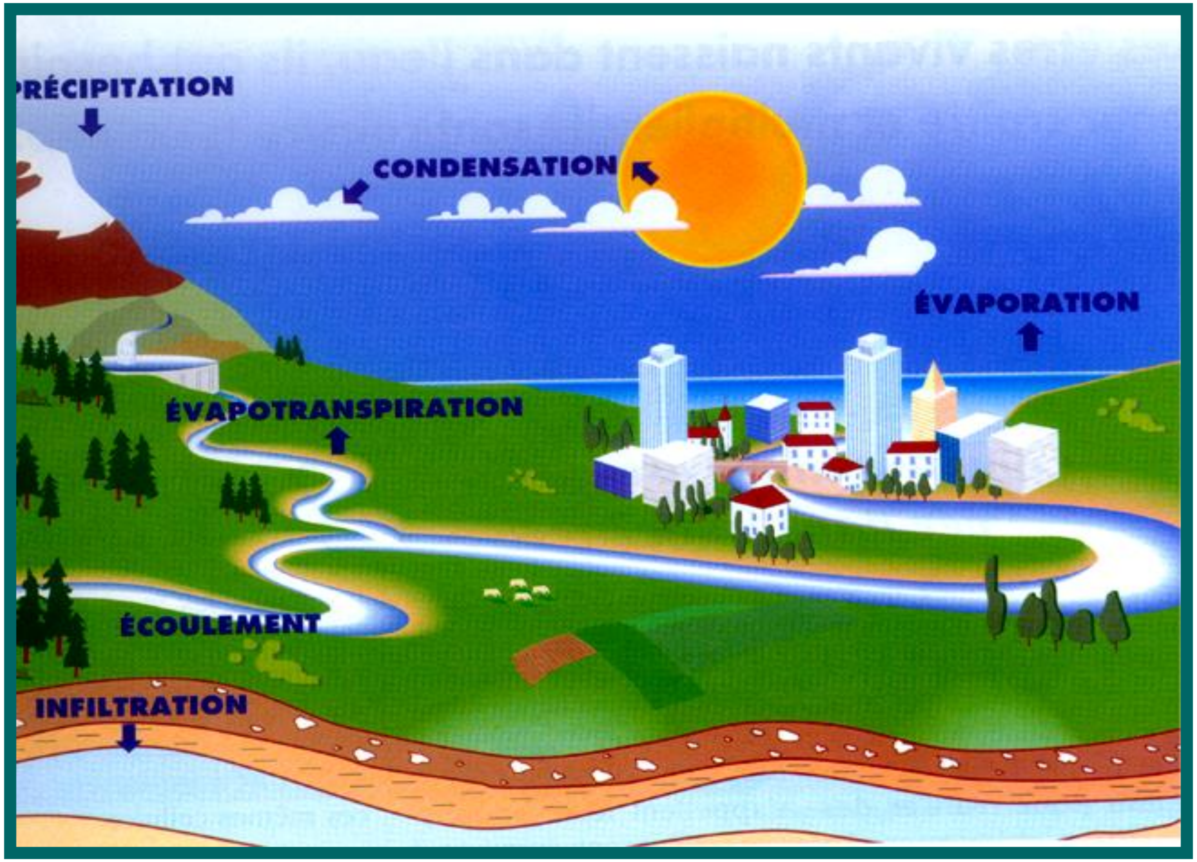


Eaux de surface et eaux des sols



Ngo-Duc et al., 2005

Modification du cycle hydrologique par les activités humaines



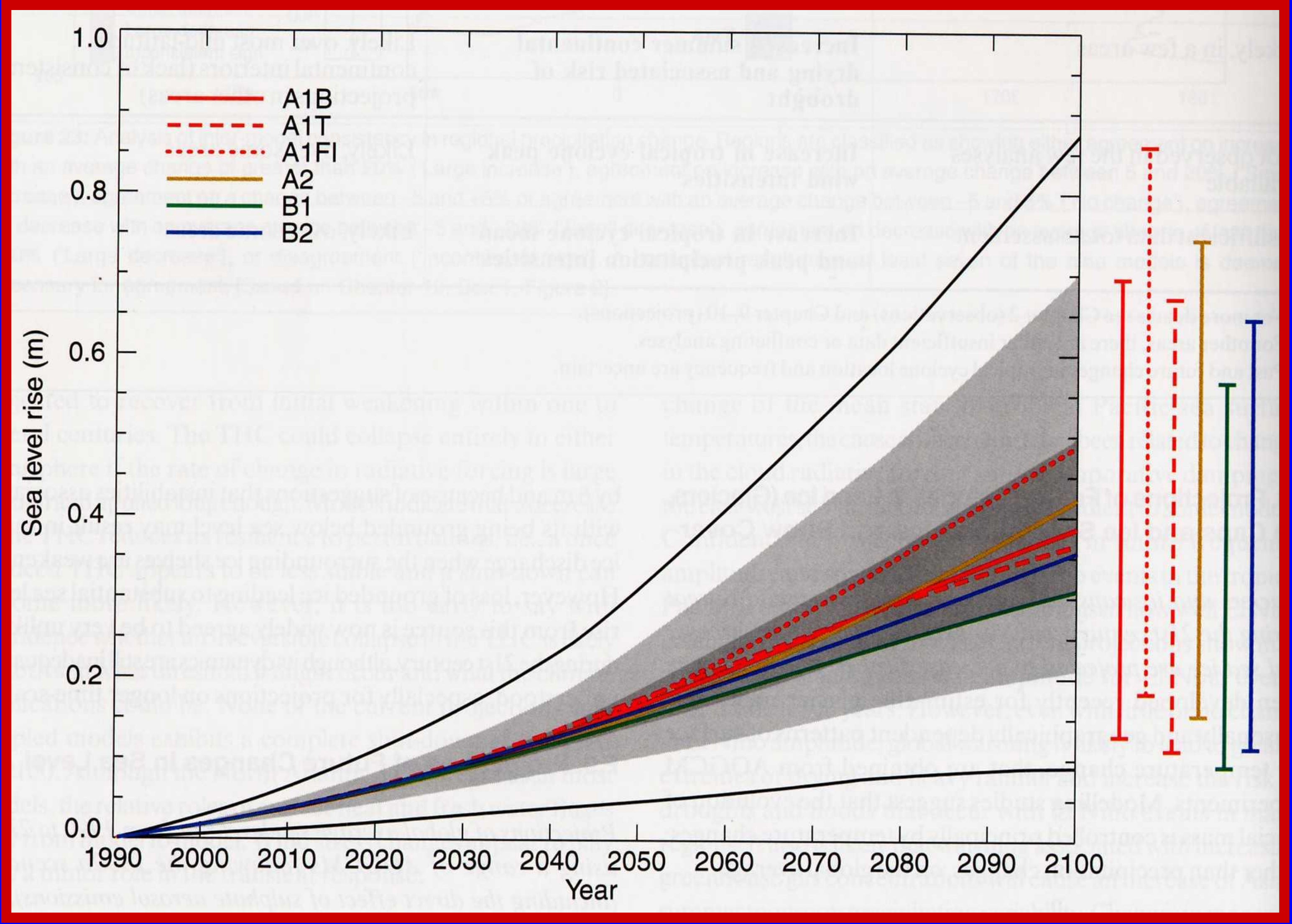
Contribution
au niveau de la mer
↓
entre 0 et - 1 mm/an

▬ ruissellement ↘

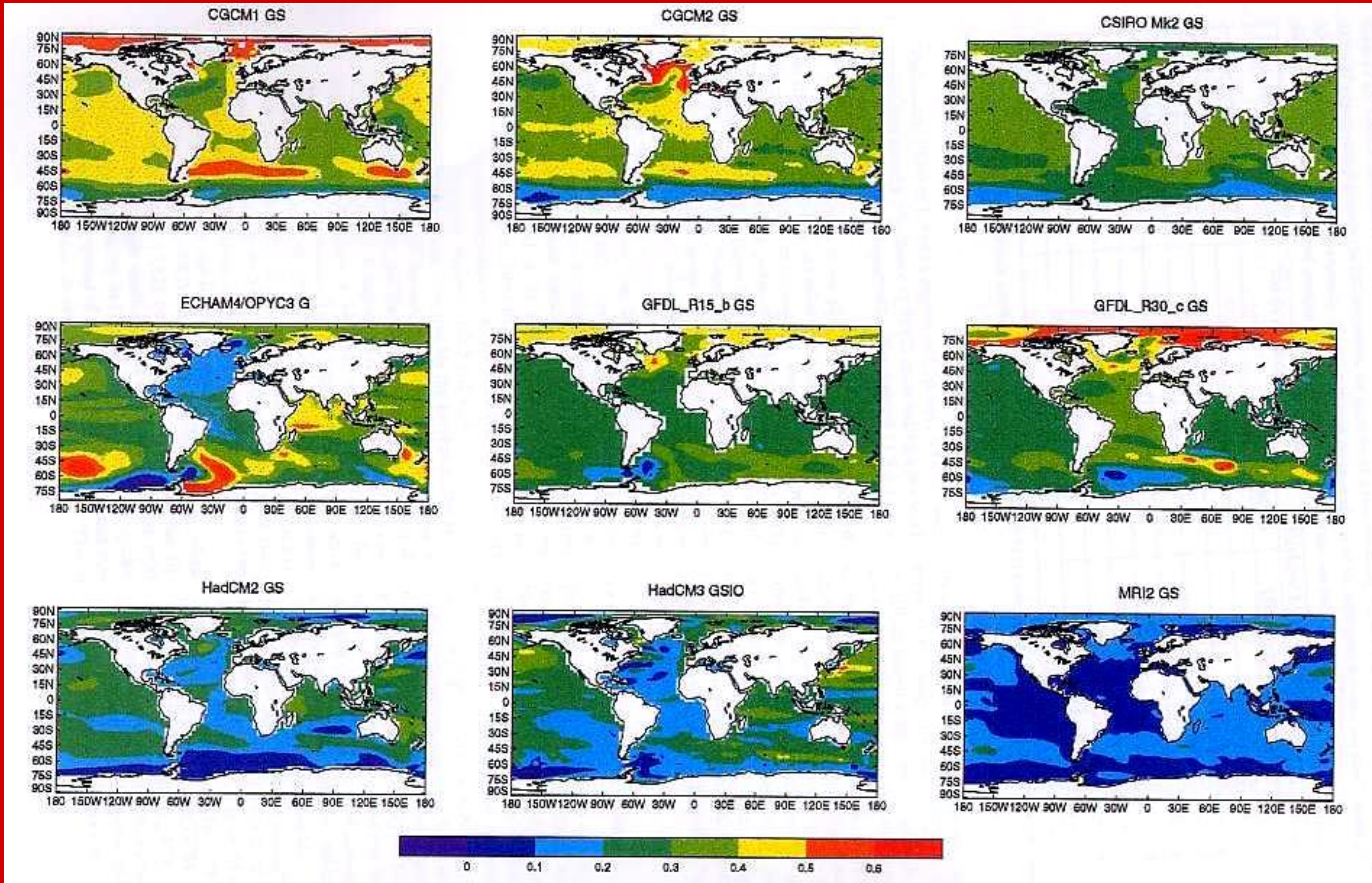
▬ ruissellement ↗

- Construction de barrages et de réservoirs
- Utilisation de l'eau des fleuves pour l'irrigation
- Pompage des eaux souterraines, déforestation, urbanisation

ELEVATION DU NIVEAU DE LA MER AU 21ème SIECLE : PREDICTIONS DE l 'IPCC



Elévation du niveau de la mer en 2100

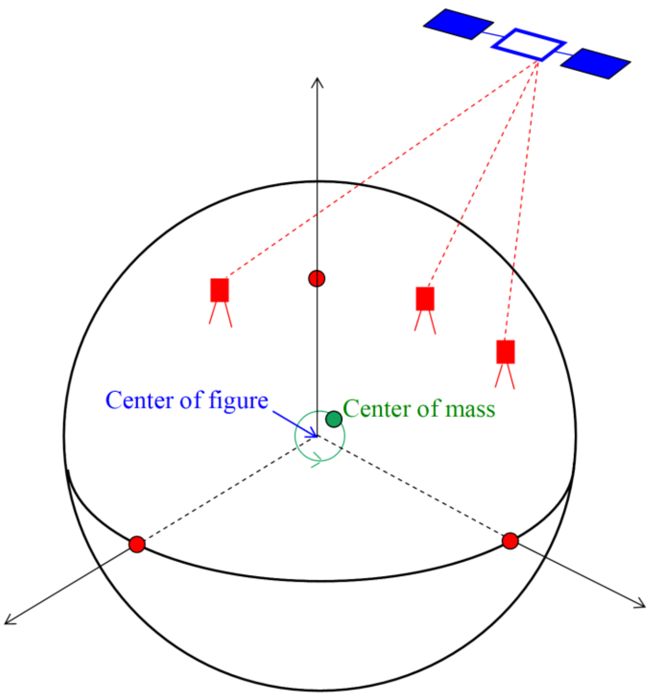


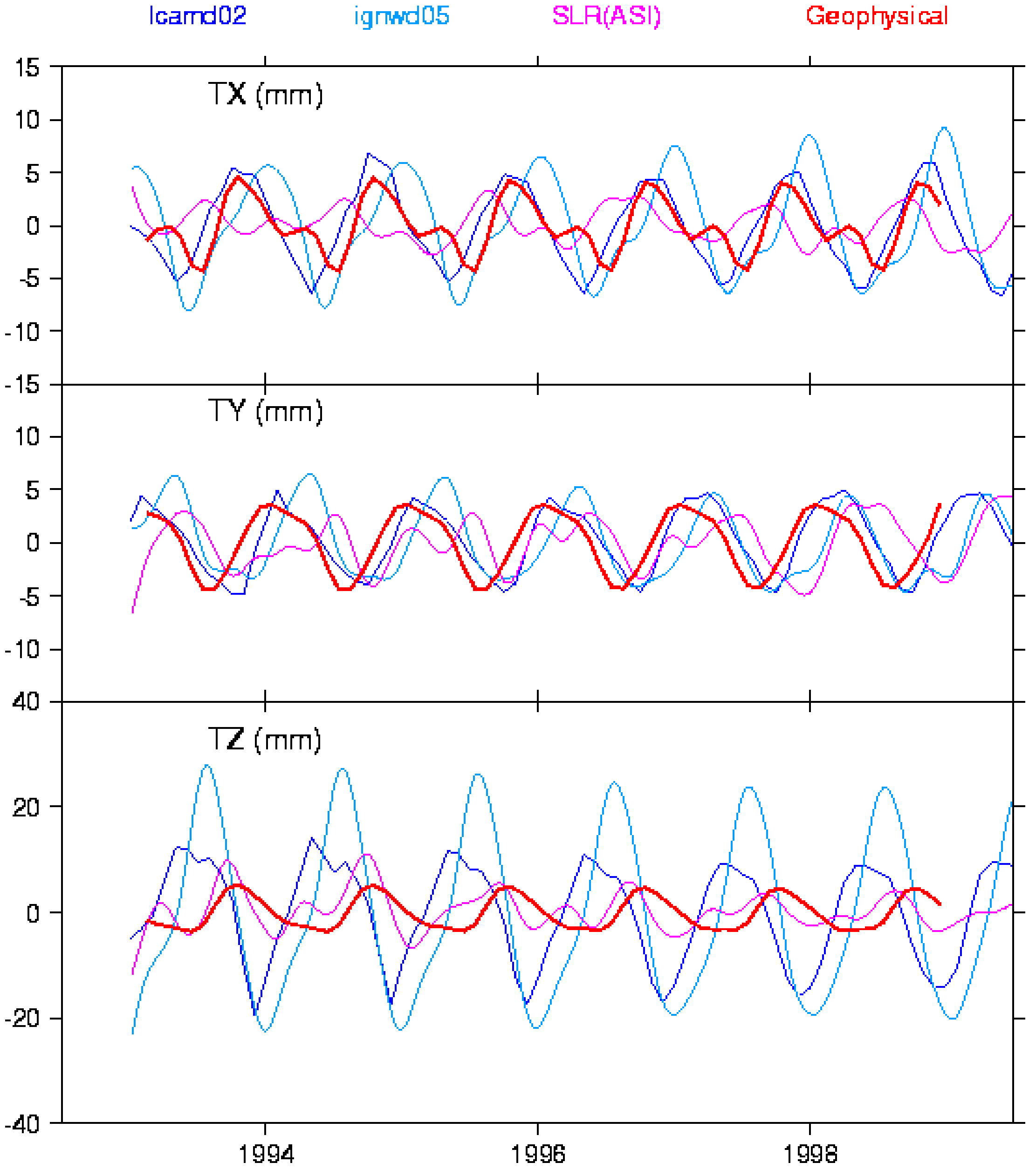
0 30 cm 60 cm

Other Applications

- ***Sea Level***
- **Geodesy**

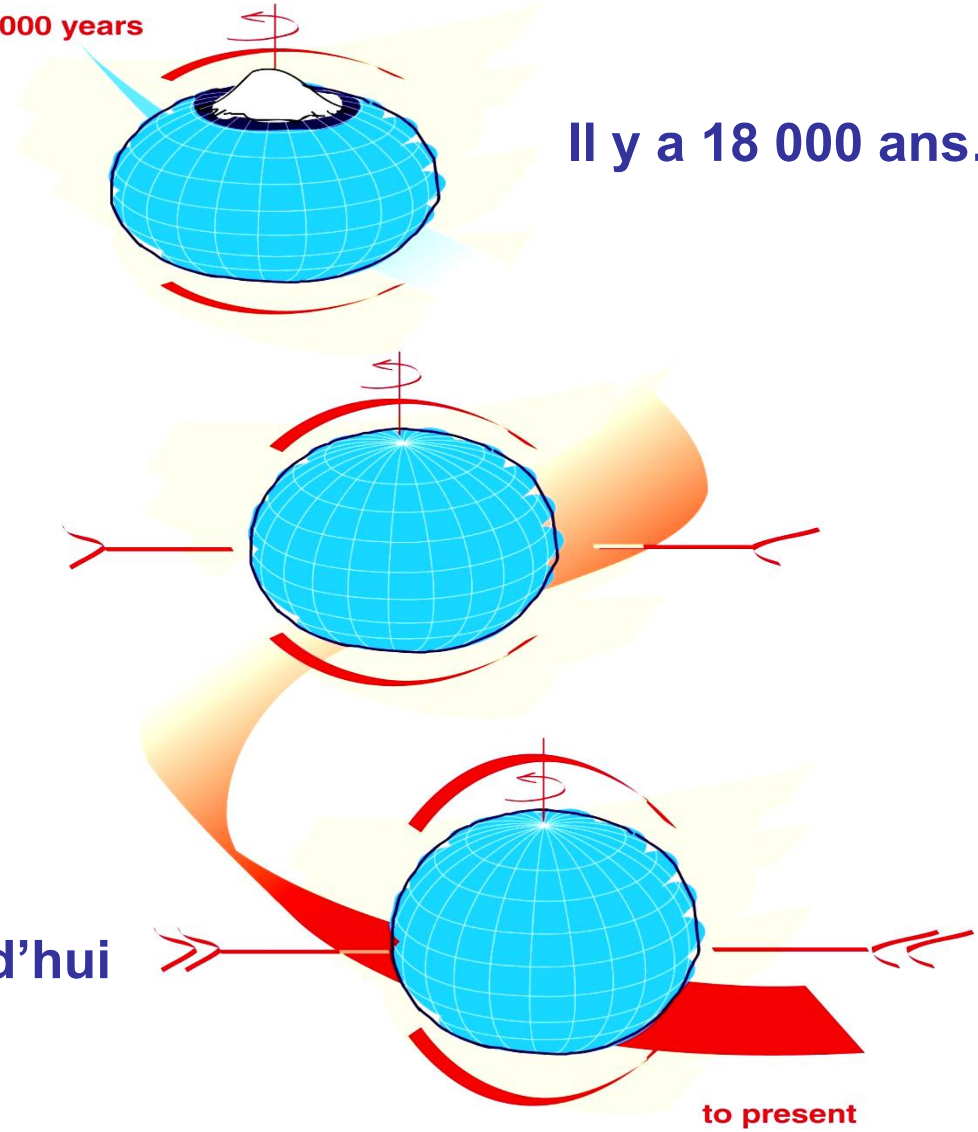
Oscillations du centre de masse de la Terre





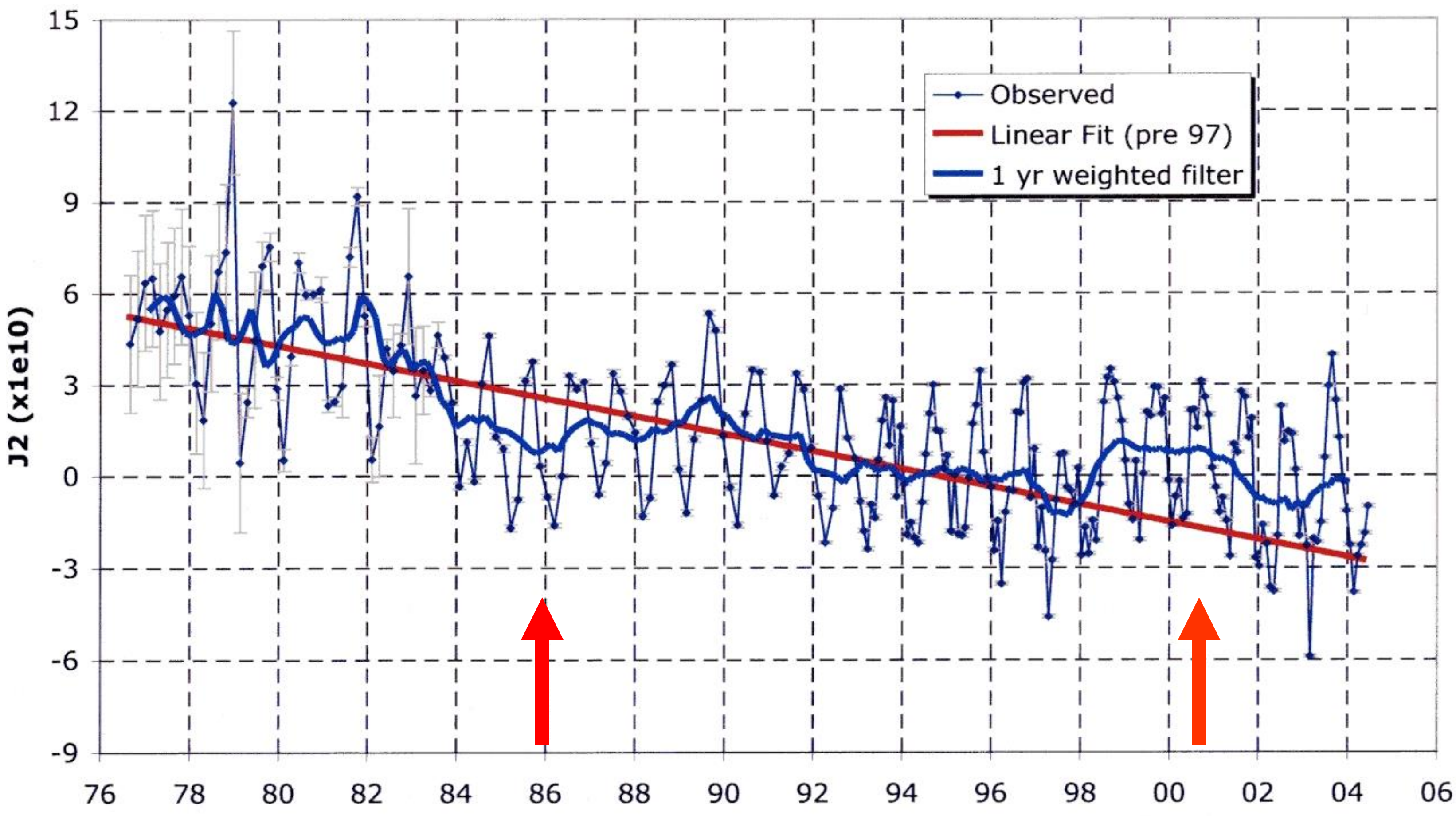
Variation séculaire de l'aplatissement de la Terre

Il y a 18 000 ans…..

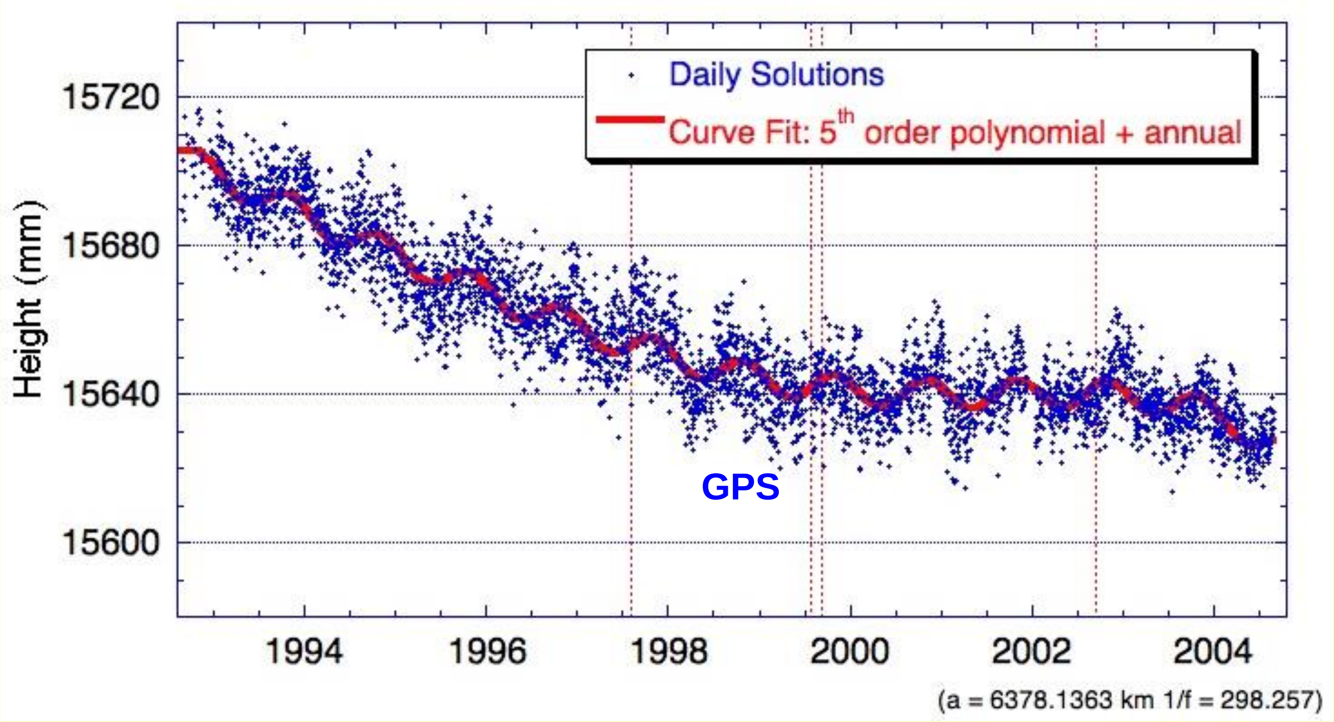


Aujourd'hui

Variations séculaire, interannuelles et saisonnières de l'aplatissement terrestre observées par les satellites 'Laser'

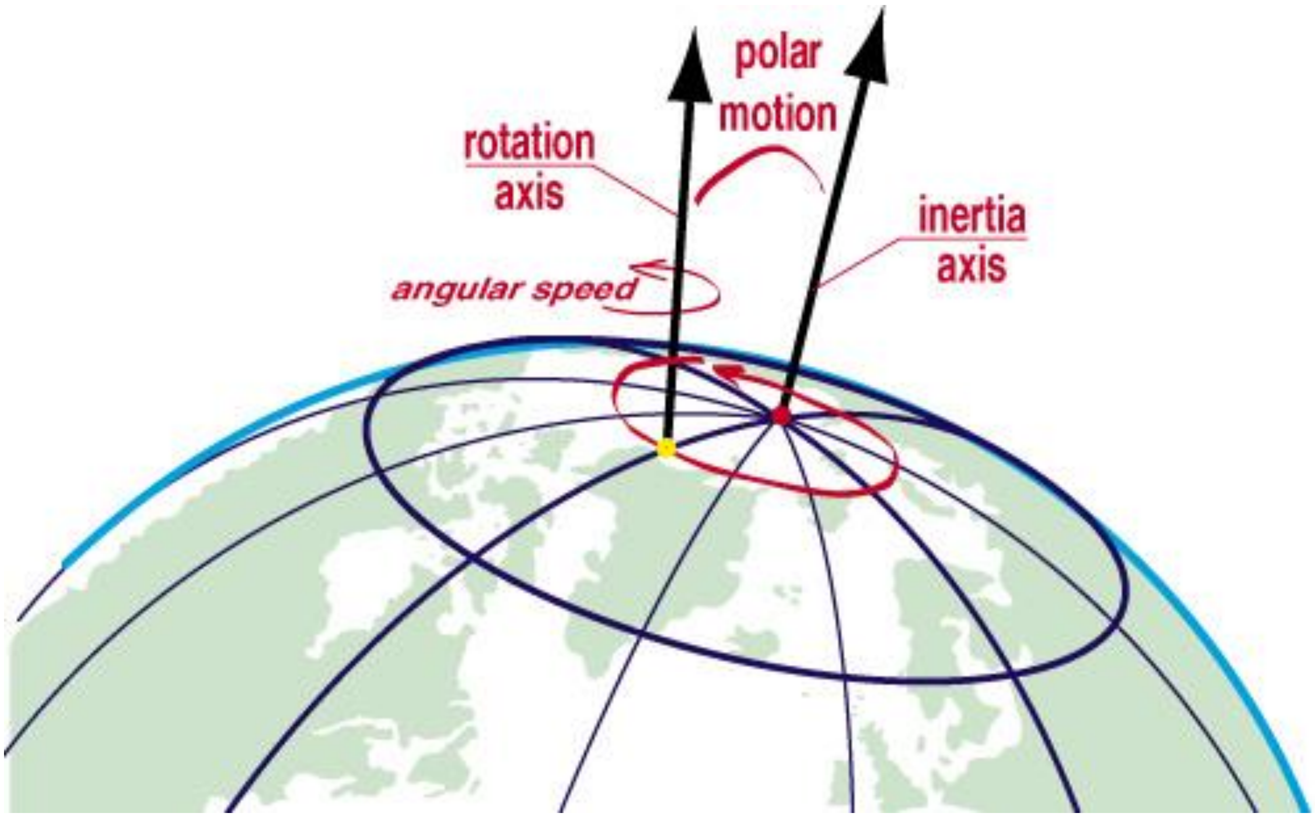


Mouvements verticaux de la croûte terrestre



Station de Harvest (Californie)

Variations de la rotation terrestre

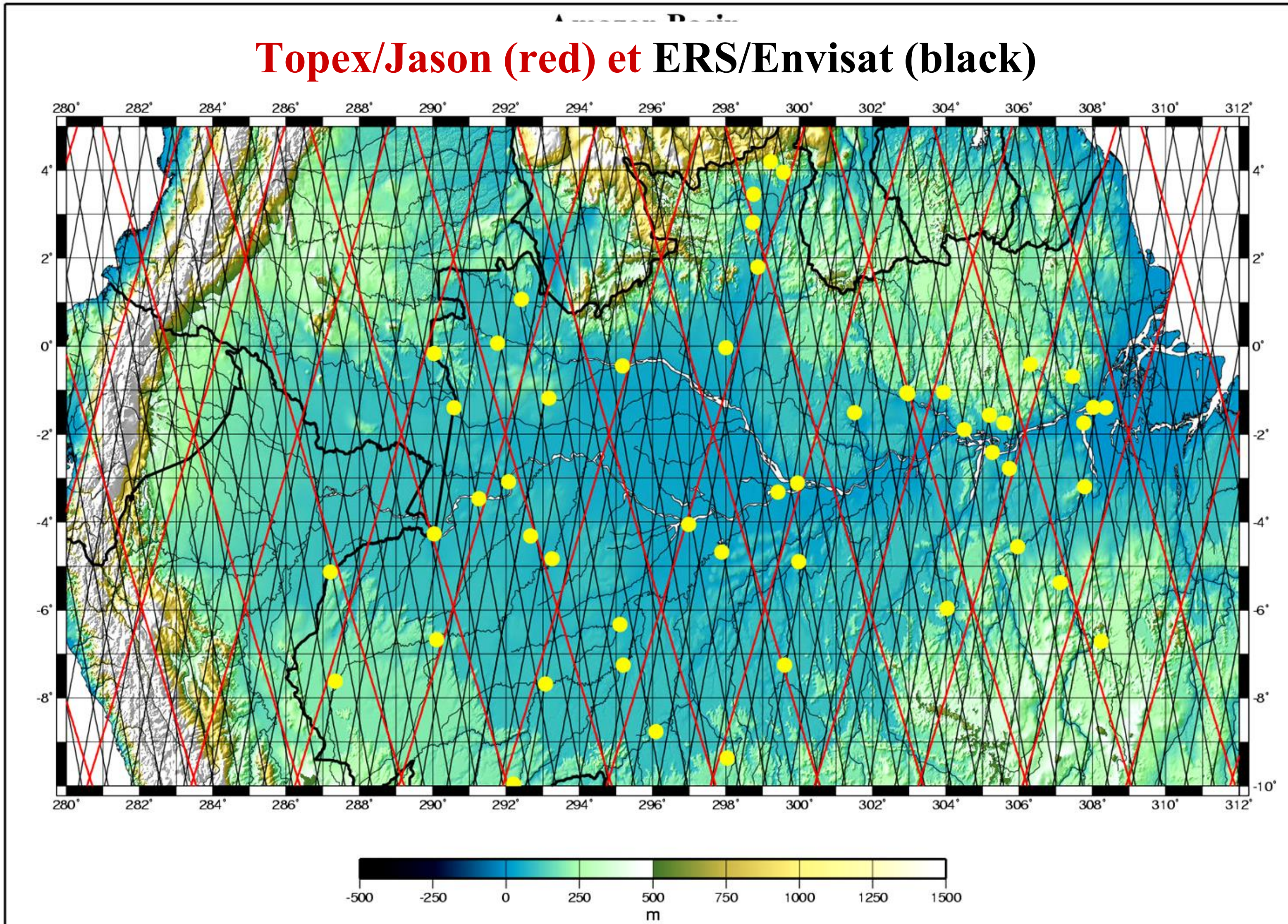


Part 2

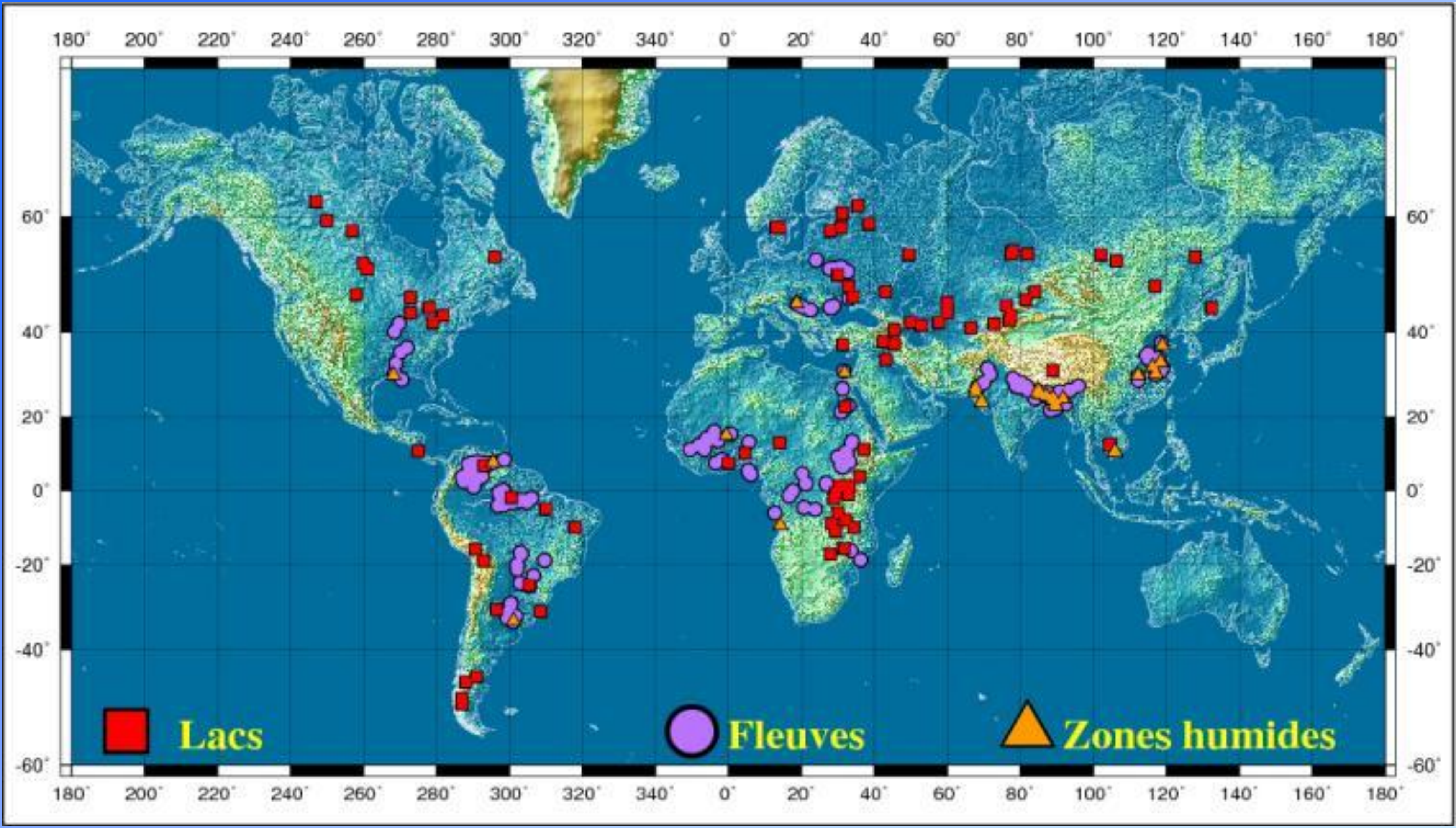
Surface Waters: Rivers, lakes, flood zones


Eaux de surface

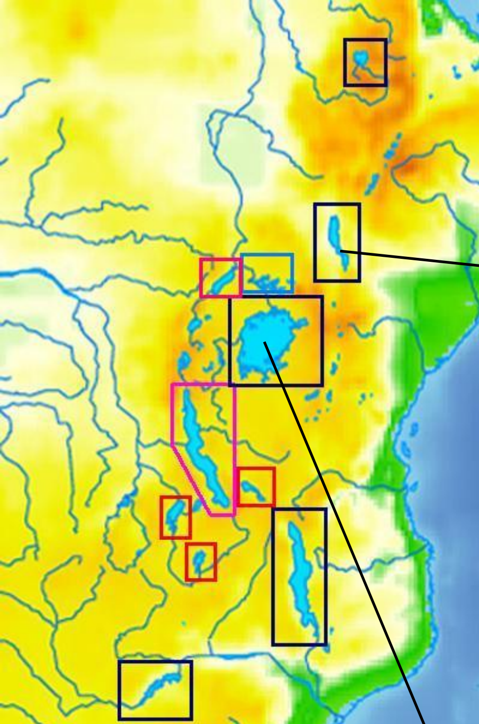
Amazon Bassin

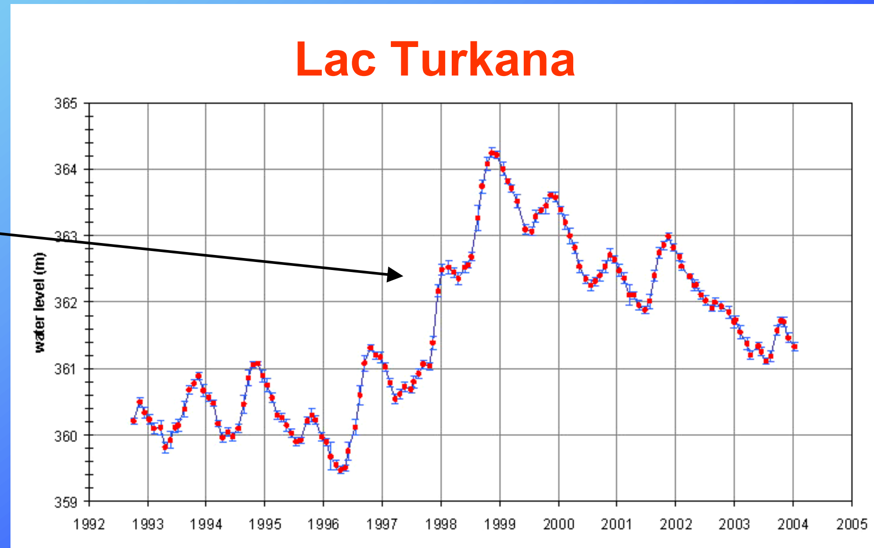


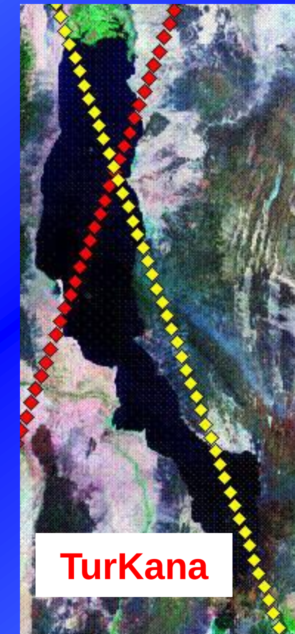
• in situ hydrographic stations

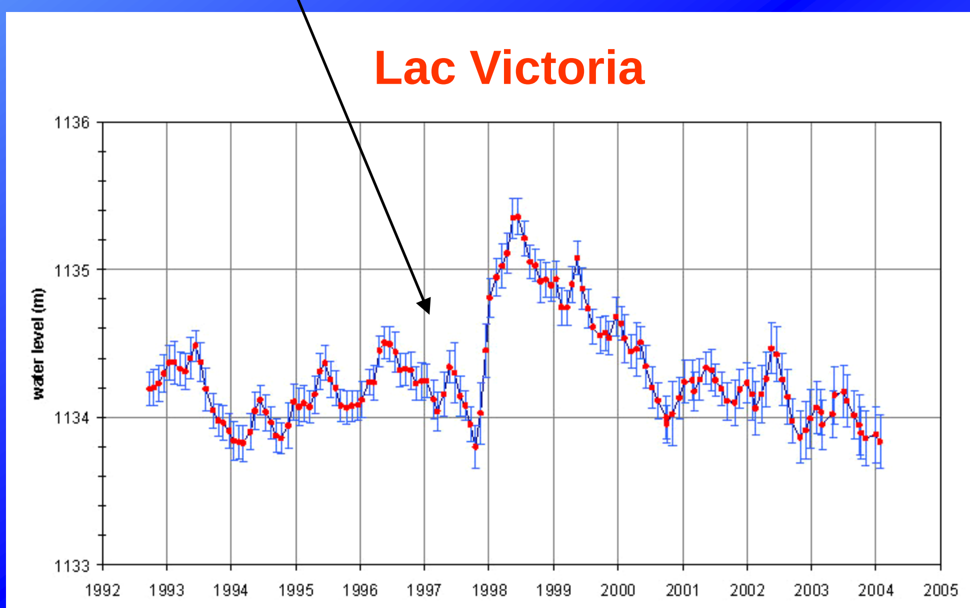


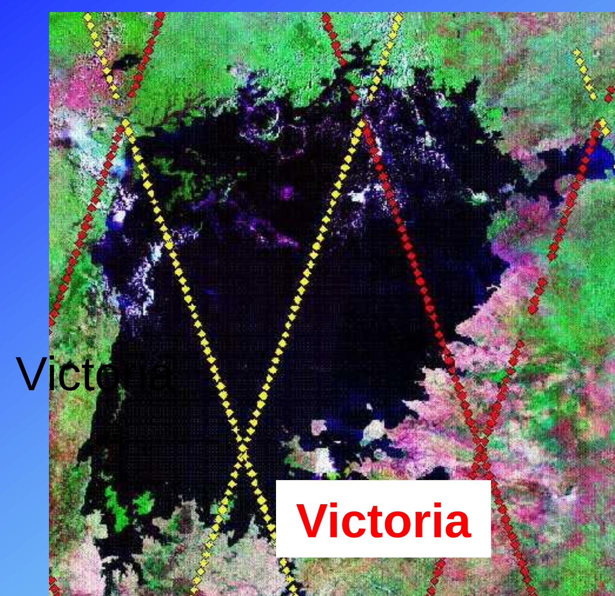
http://www.legos.obs-mip/soa/hydrologie/hydroweb
http://earth.esa.int/riverandlake



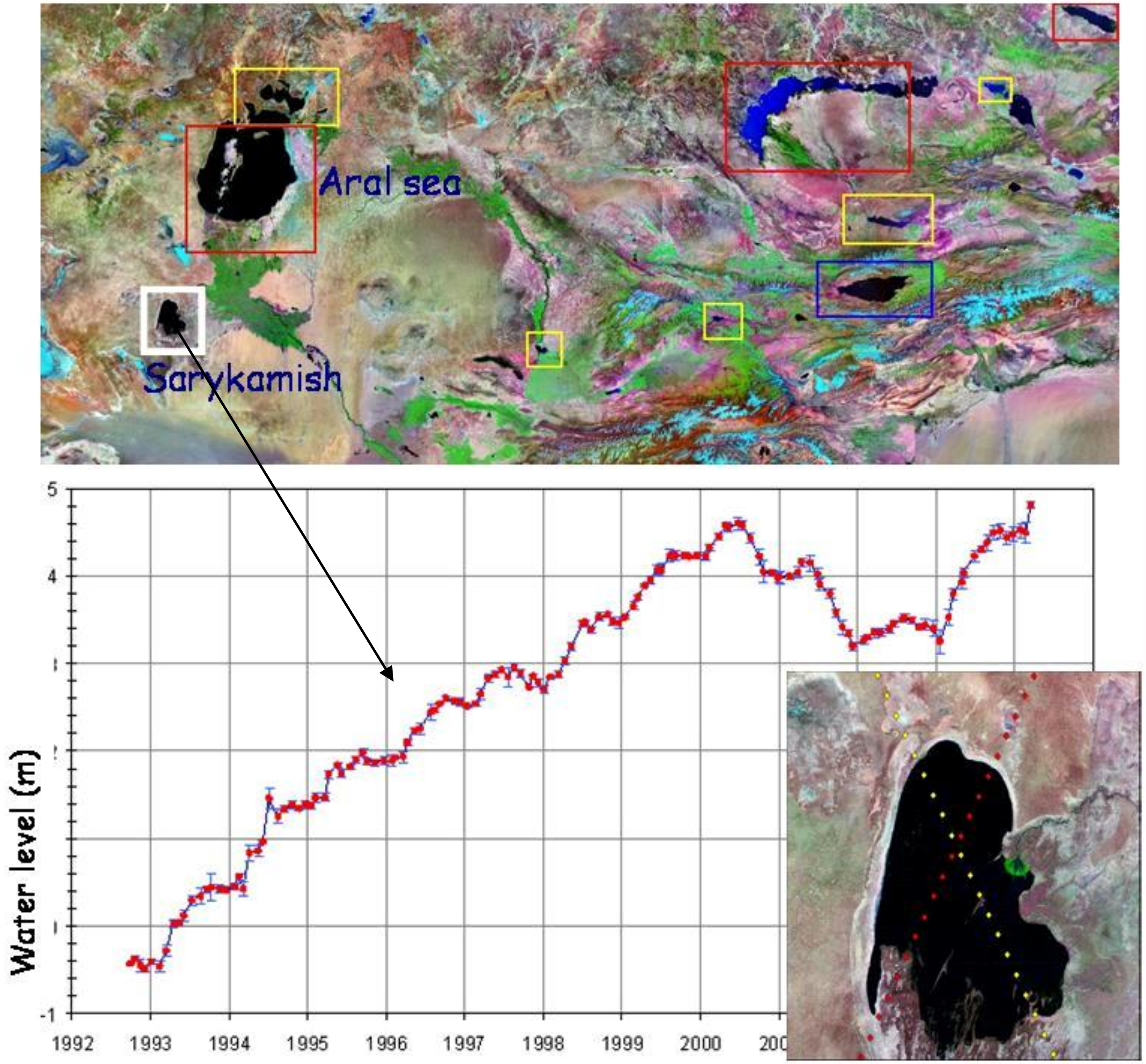

Lac Turkana
water level (m)
365
364
363
362
361
360
359
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005

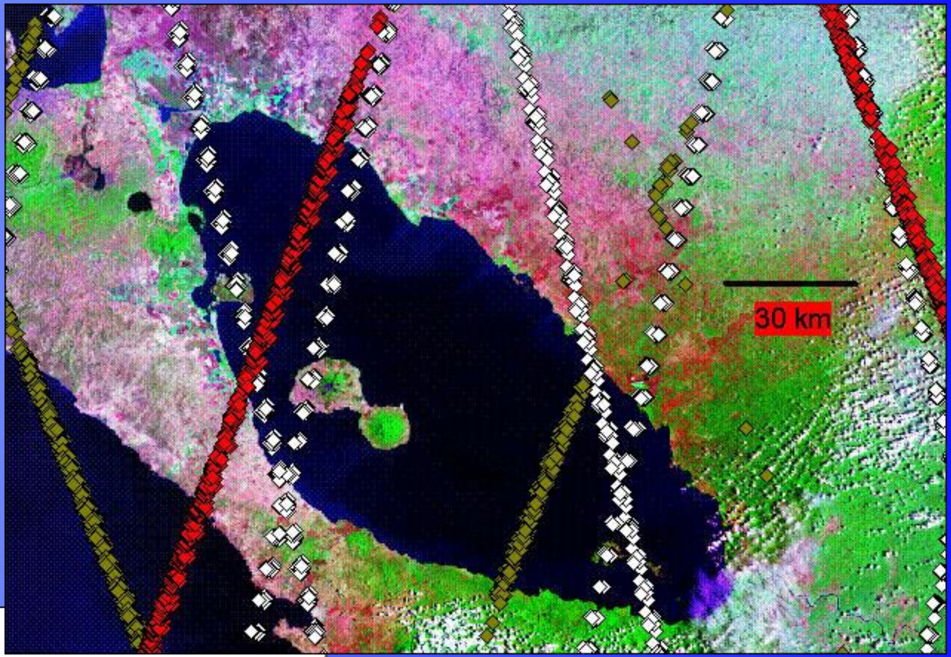

TurKana

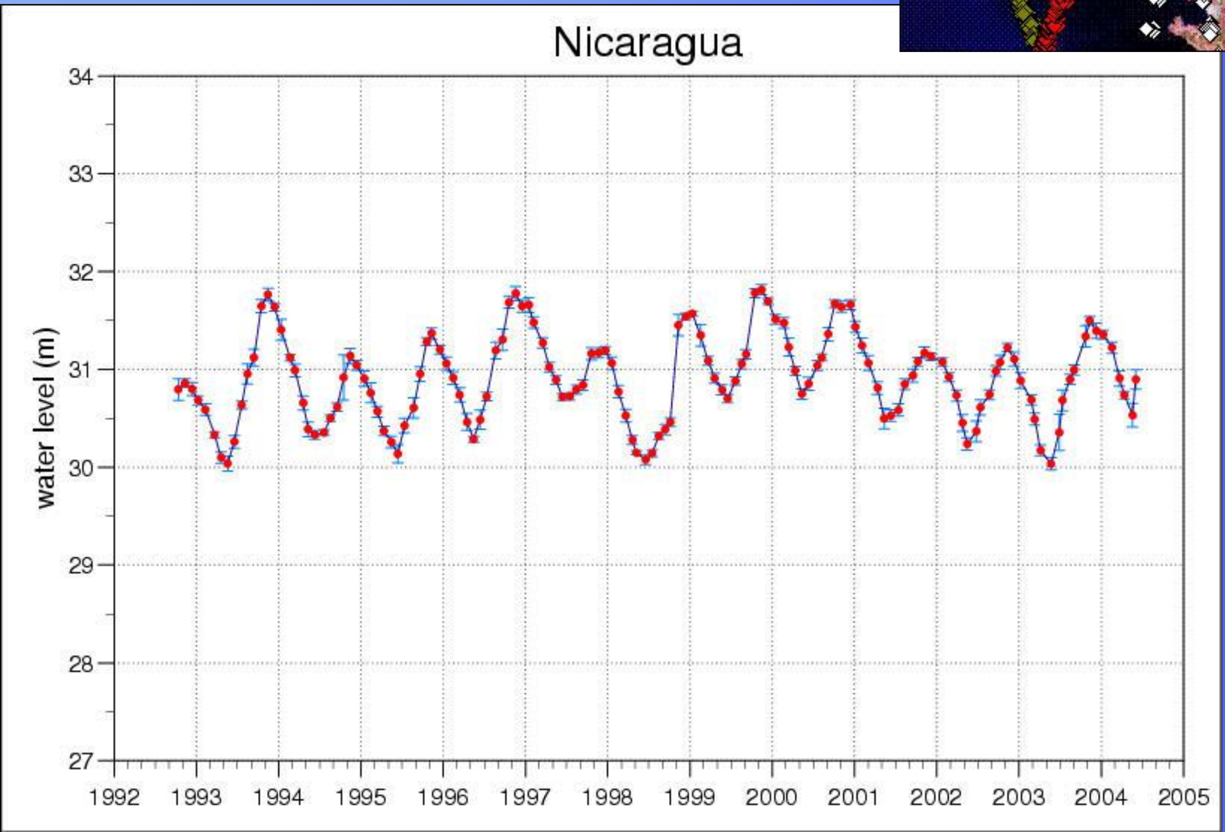

Lac Victoria
water level (m)
1136
1135
1134
1133
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005


Victoria
Victoria

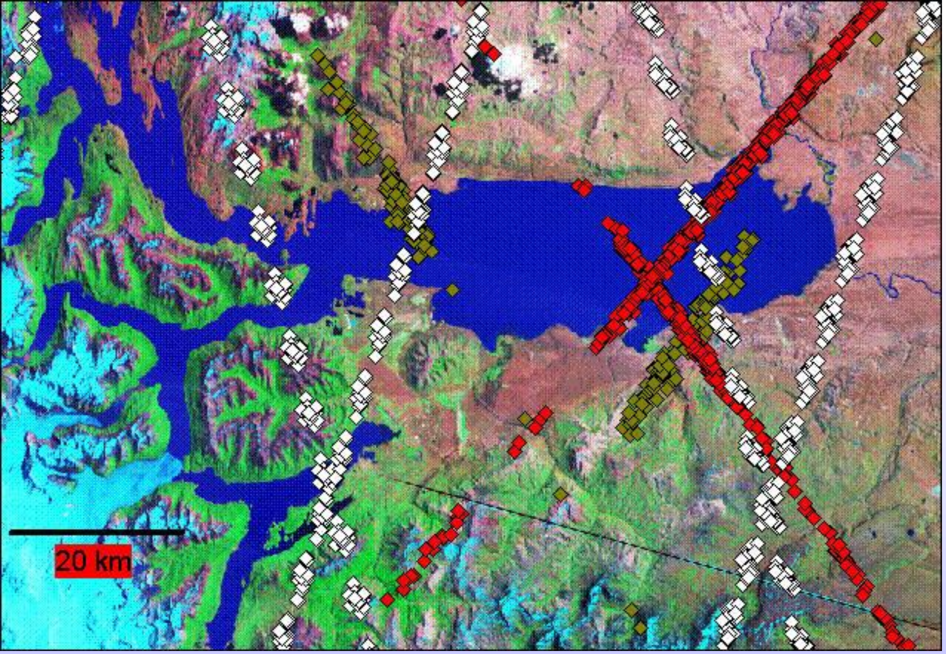
Lac Sarykamish (Asie centrale)

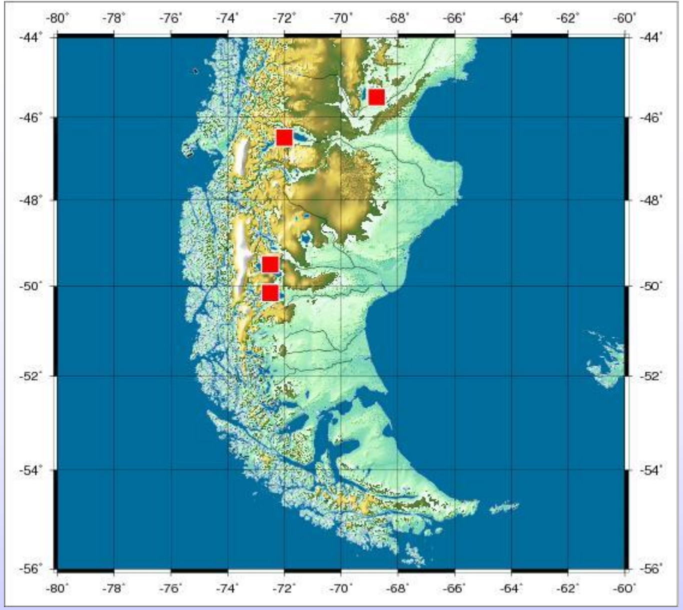




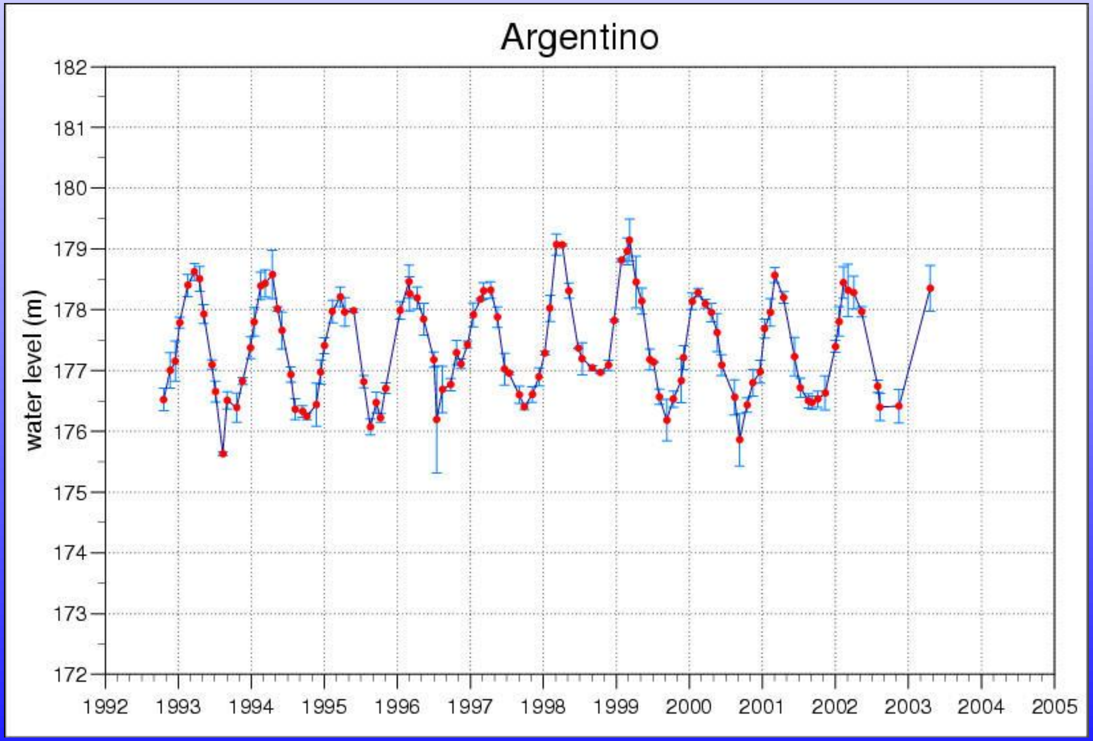


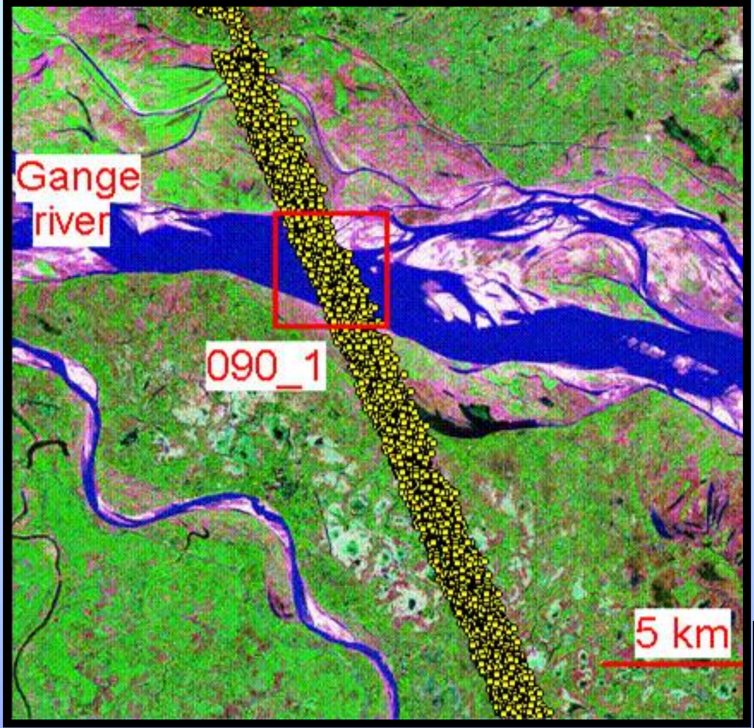
Lac Nicaragua

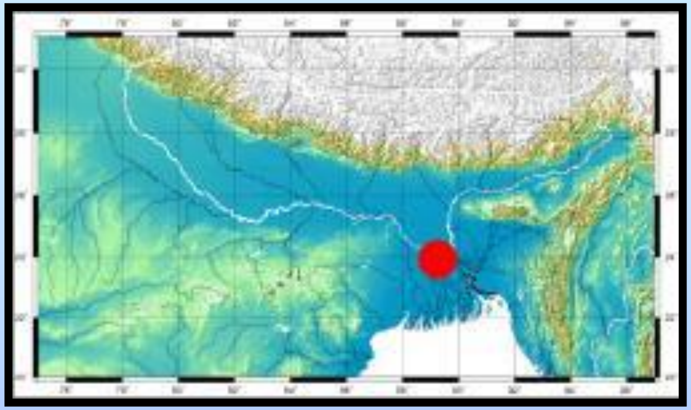


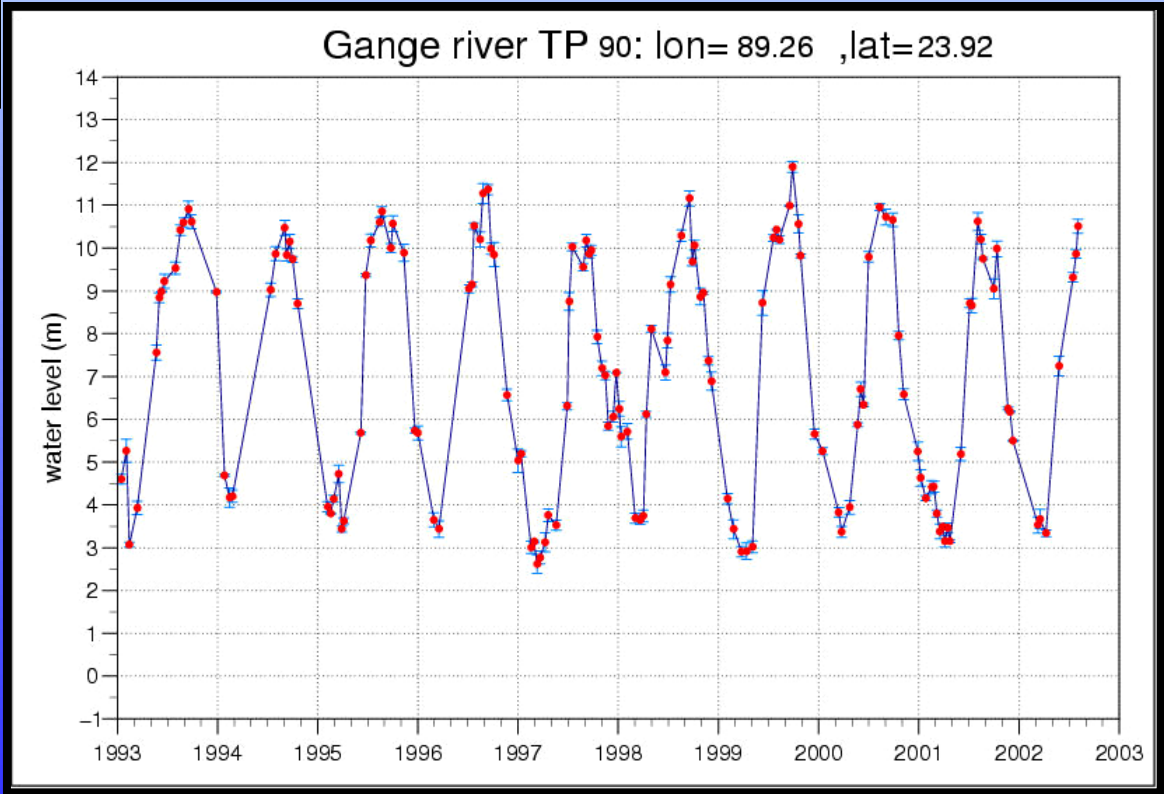


Lac Argentino

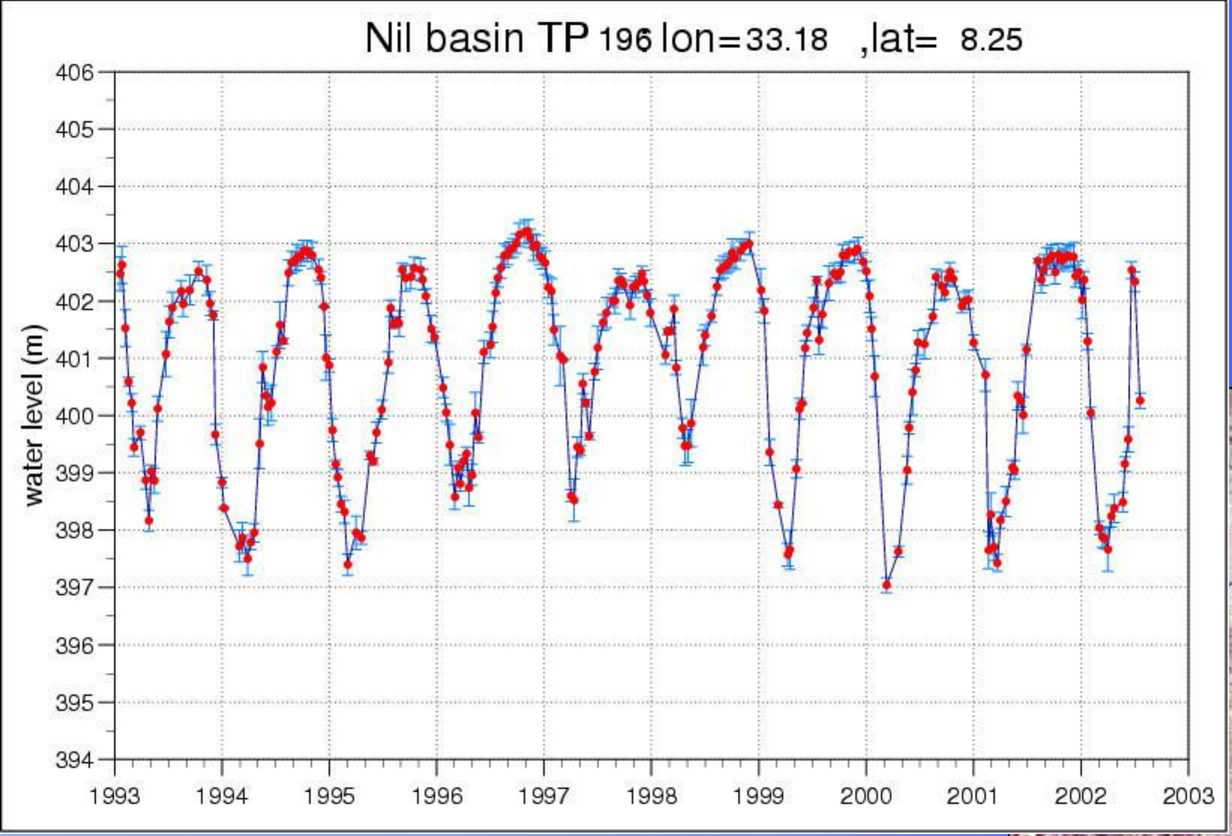


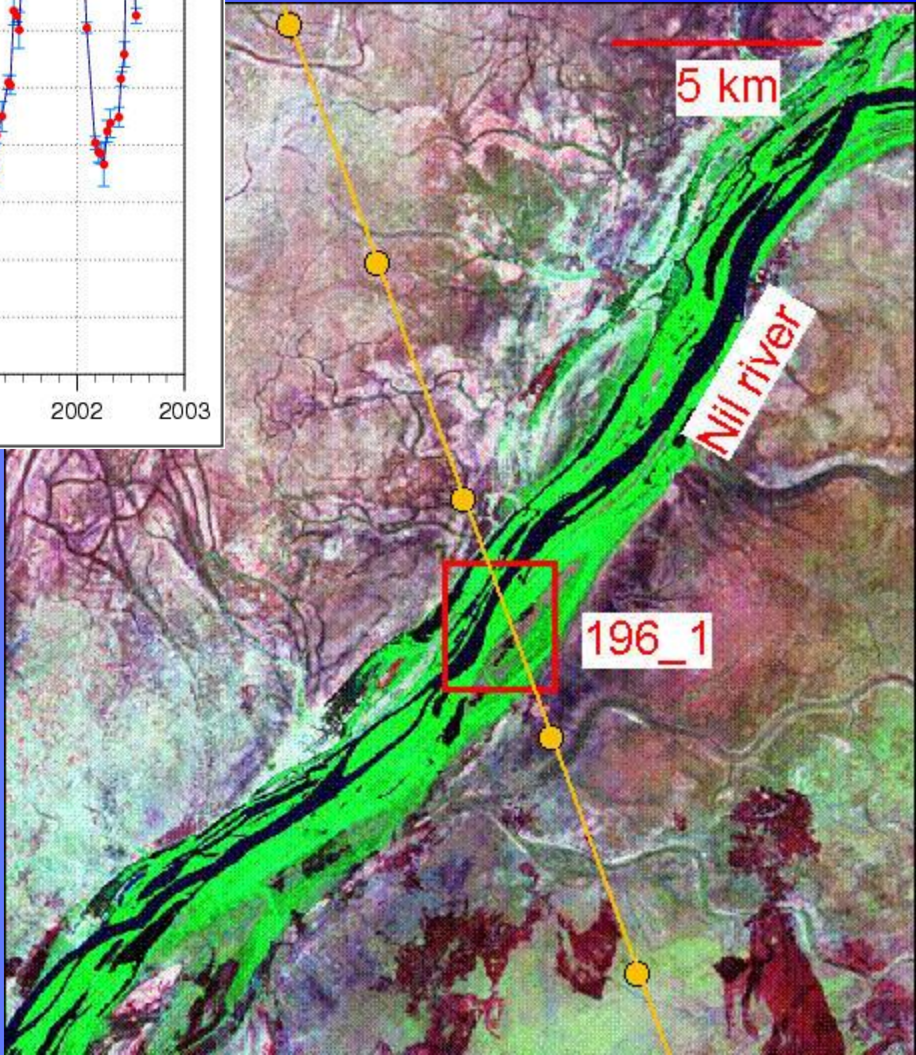

Gange
river
090_1
5 km




Gange river TP 90: lon= 89.26 ,lat=23.92
water level (m)
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
−1
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003

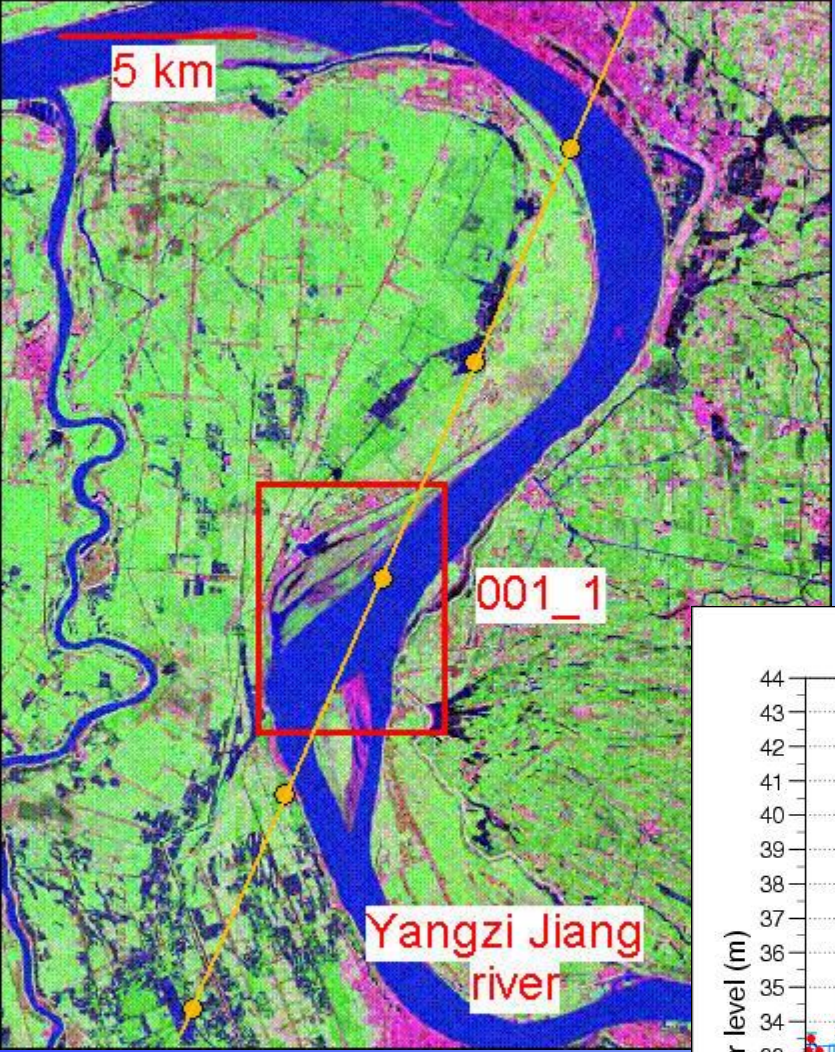
Le Gange

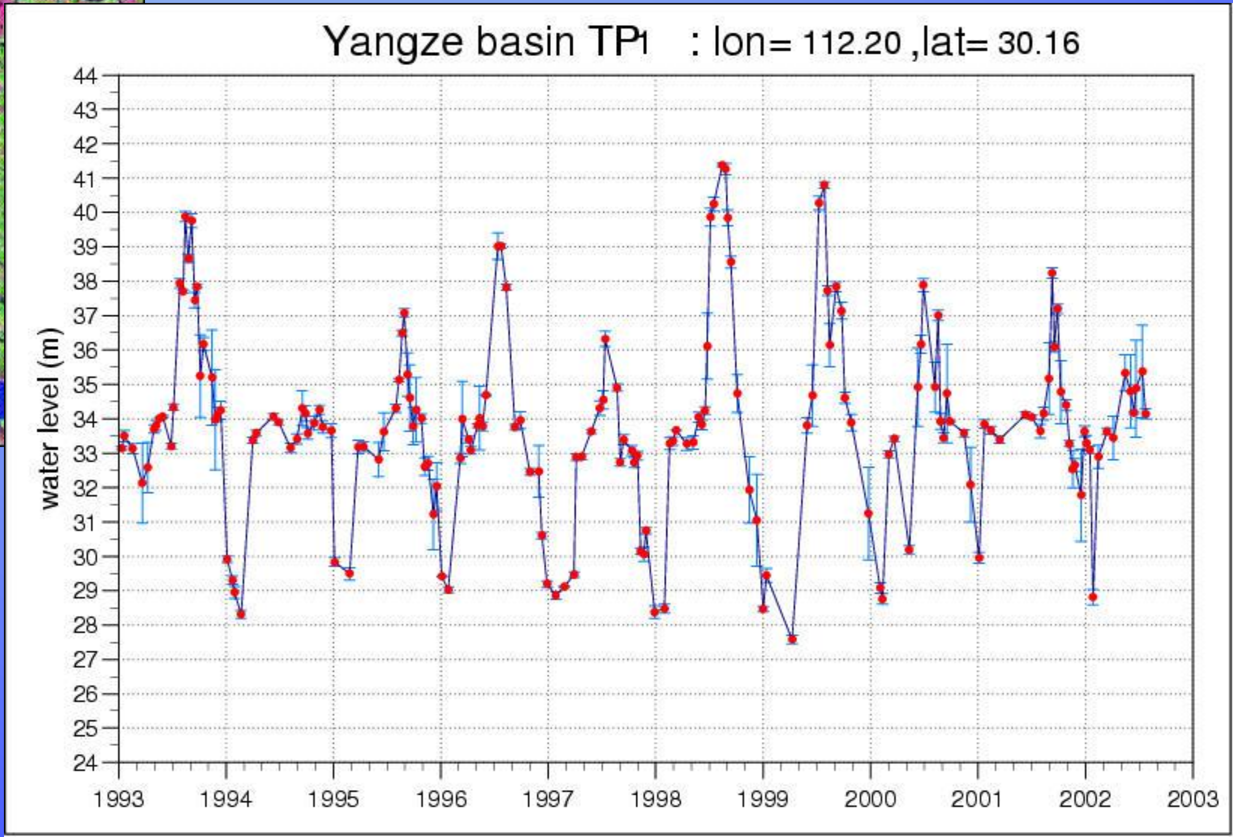

Nil basin TP 196 lon=33.18 ,lat= 8.25
water level (m)
406
405
404
403
402
401
400
399
398
397
396
395
394
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003

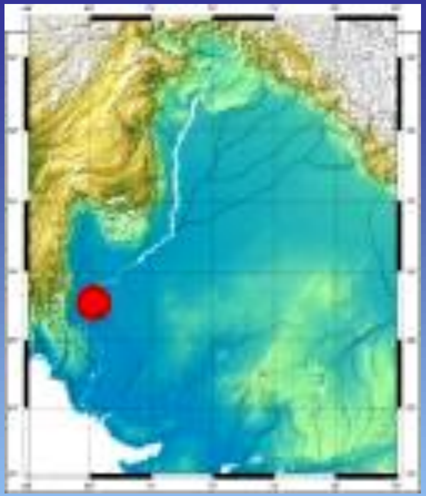

5 km
Nil river
196_1

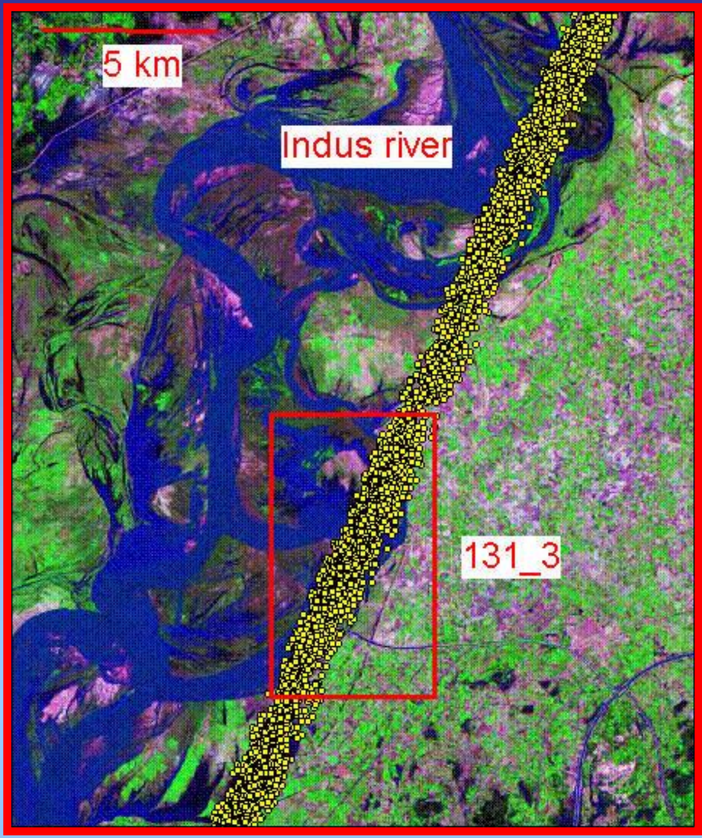
Le Nil

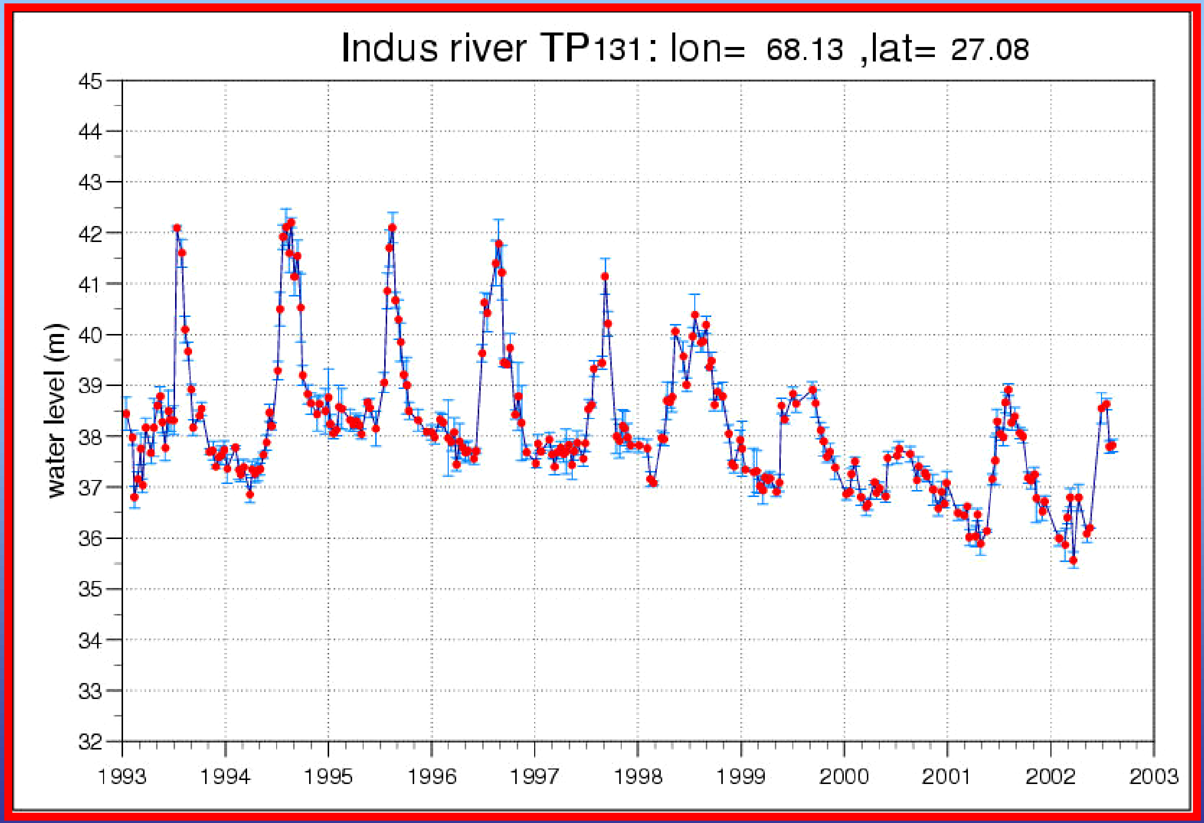
Fleuve Yangze





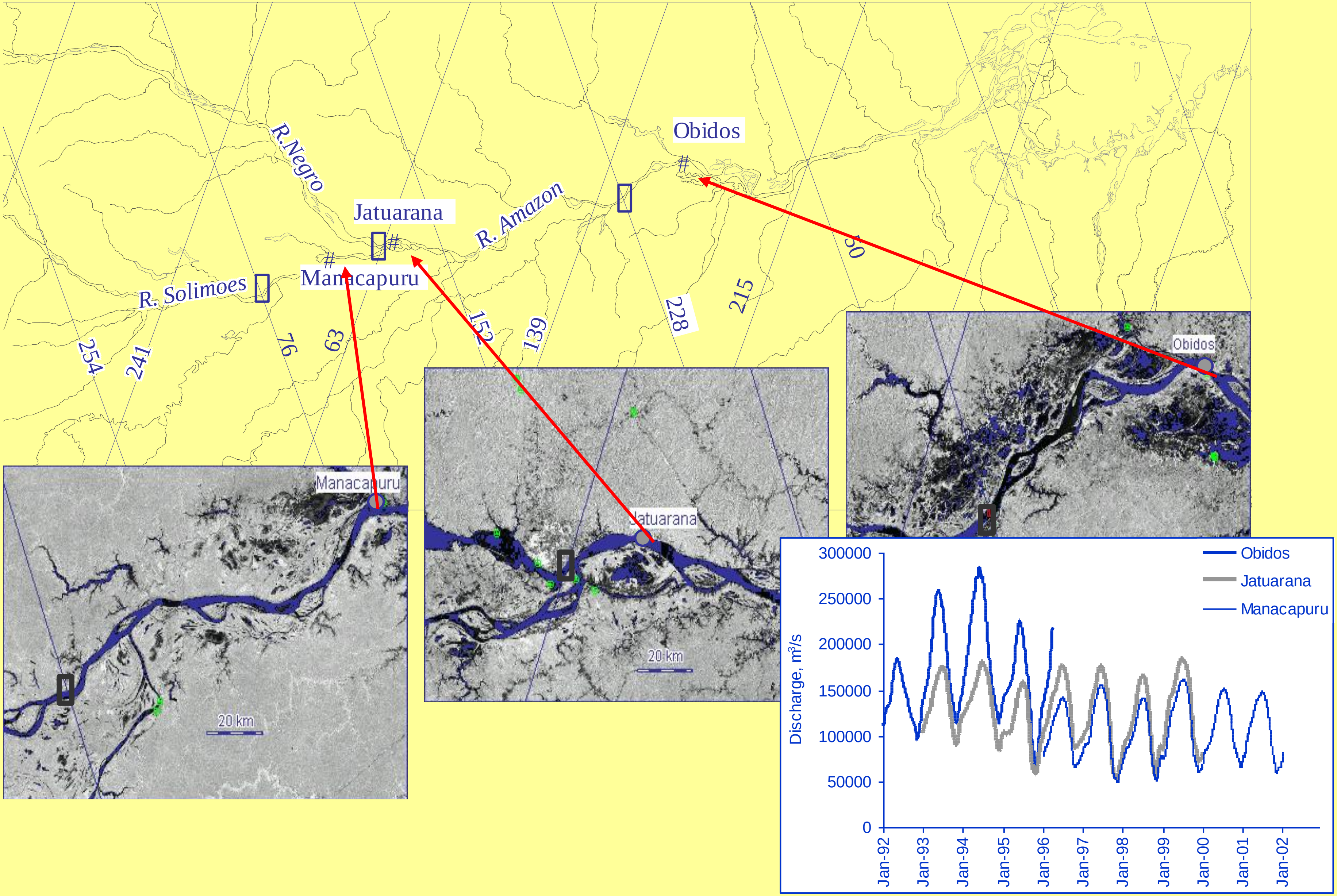






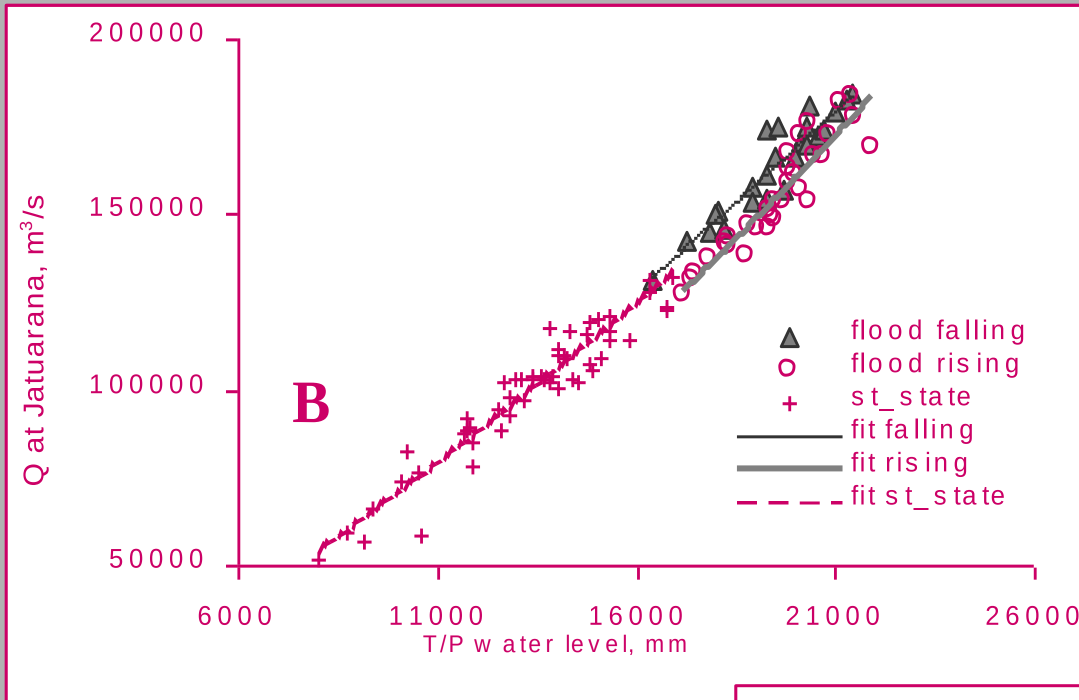
Fleuve Indus

AMAZONE



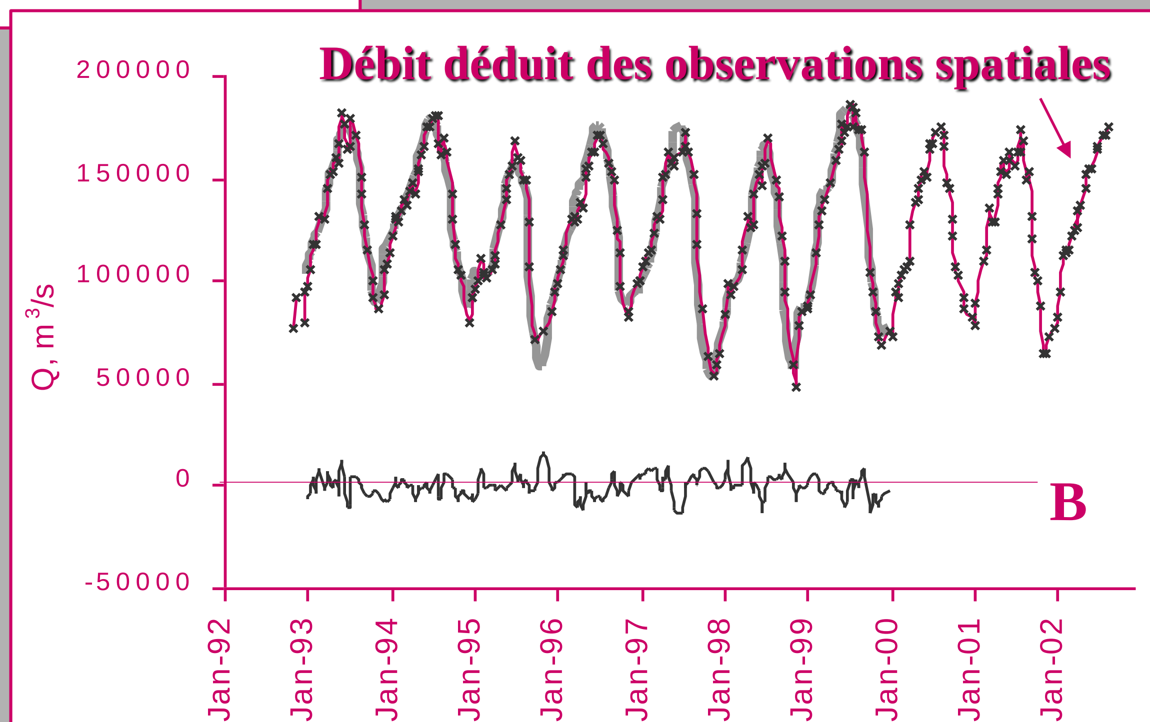
Obidos
R.Negro
Jatuarana
R. Amazon
Manacapuru
R. Solimoes
254
241
76
63
152
139
228
215
Manacapuru
20 km
Jatuarana
20 km
Obidos
Discharge, m³/s
300000
250000
200000
150000
100000
50000
0
Obidos
Jatuarana
Manacapuru
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02

Courbe de calibration

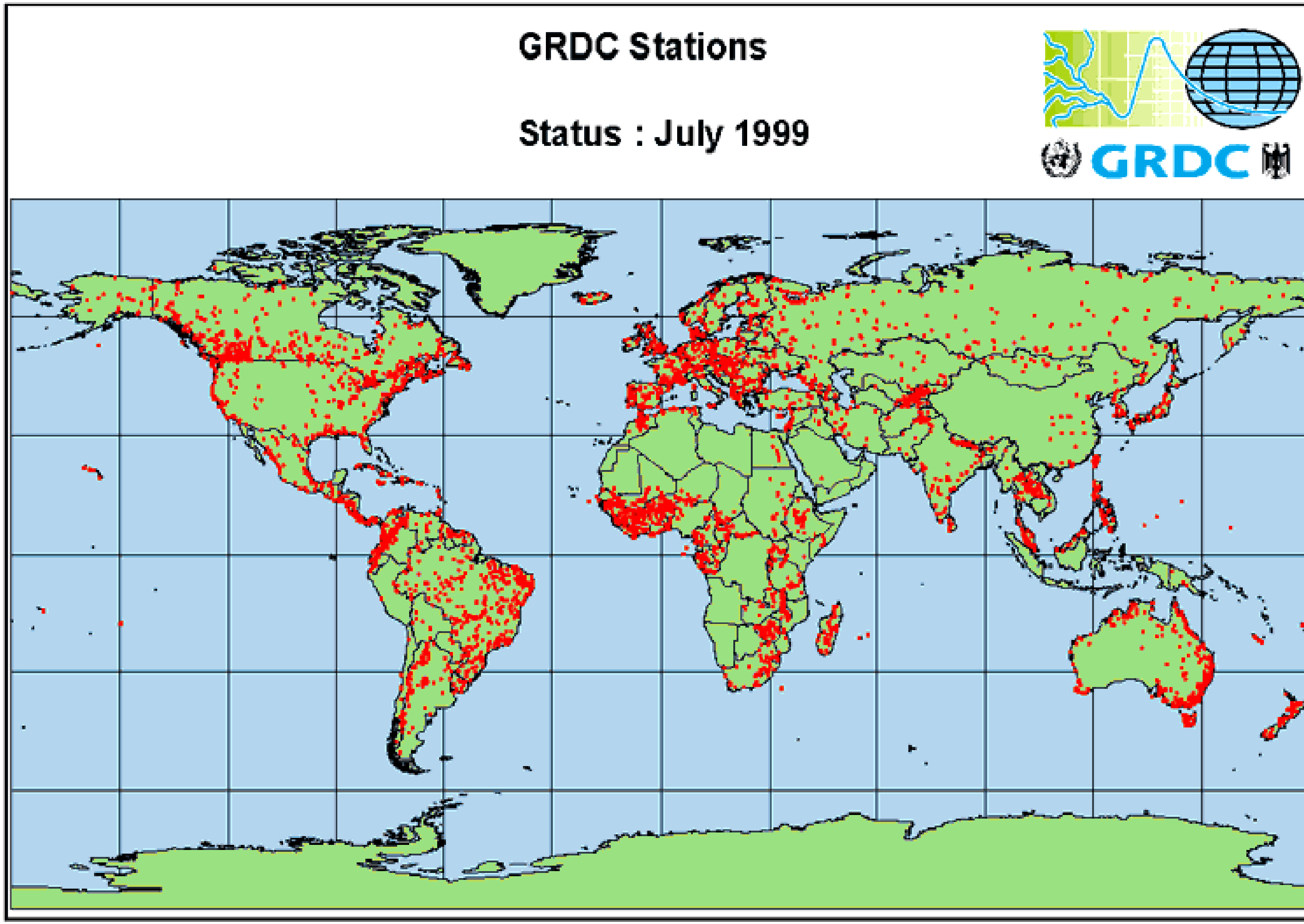


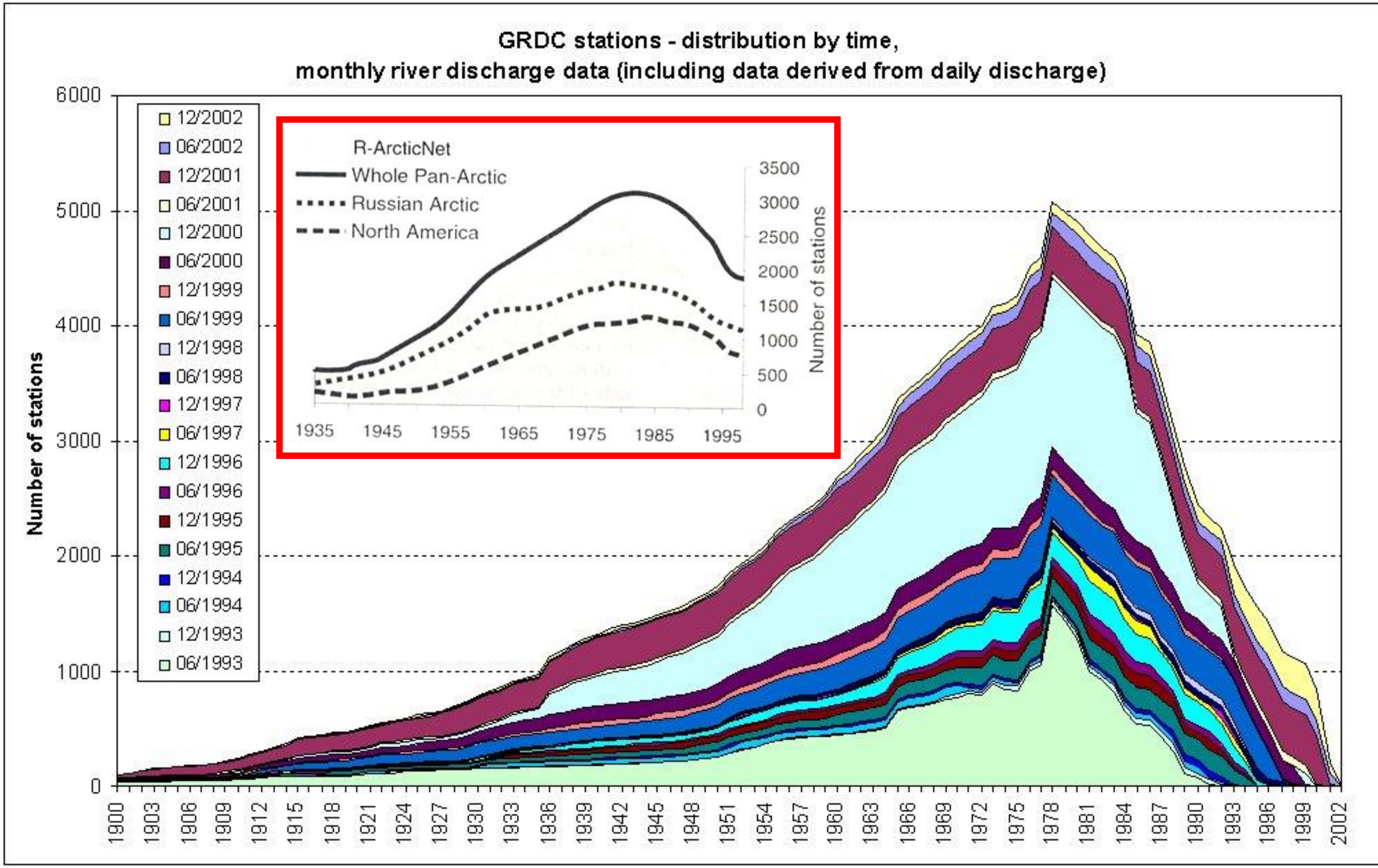
débit observé en fonction du niveau d'eau mesuré par le satellite Topex/Poseidon

Débit (m^3/s)

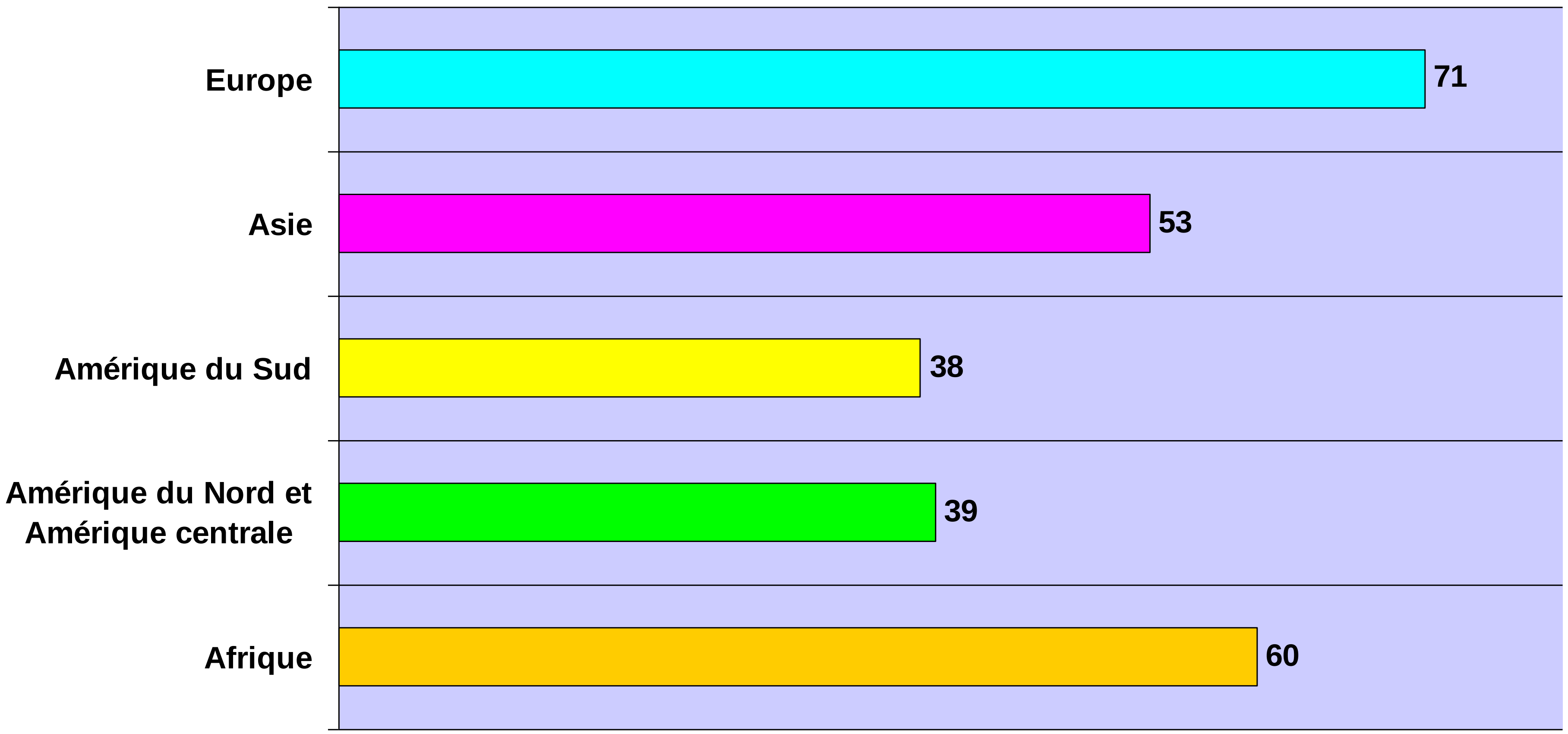


GLOBAL RUNOFF DATA CENTER

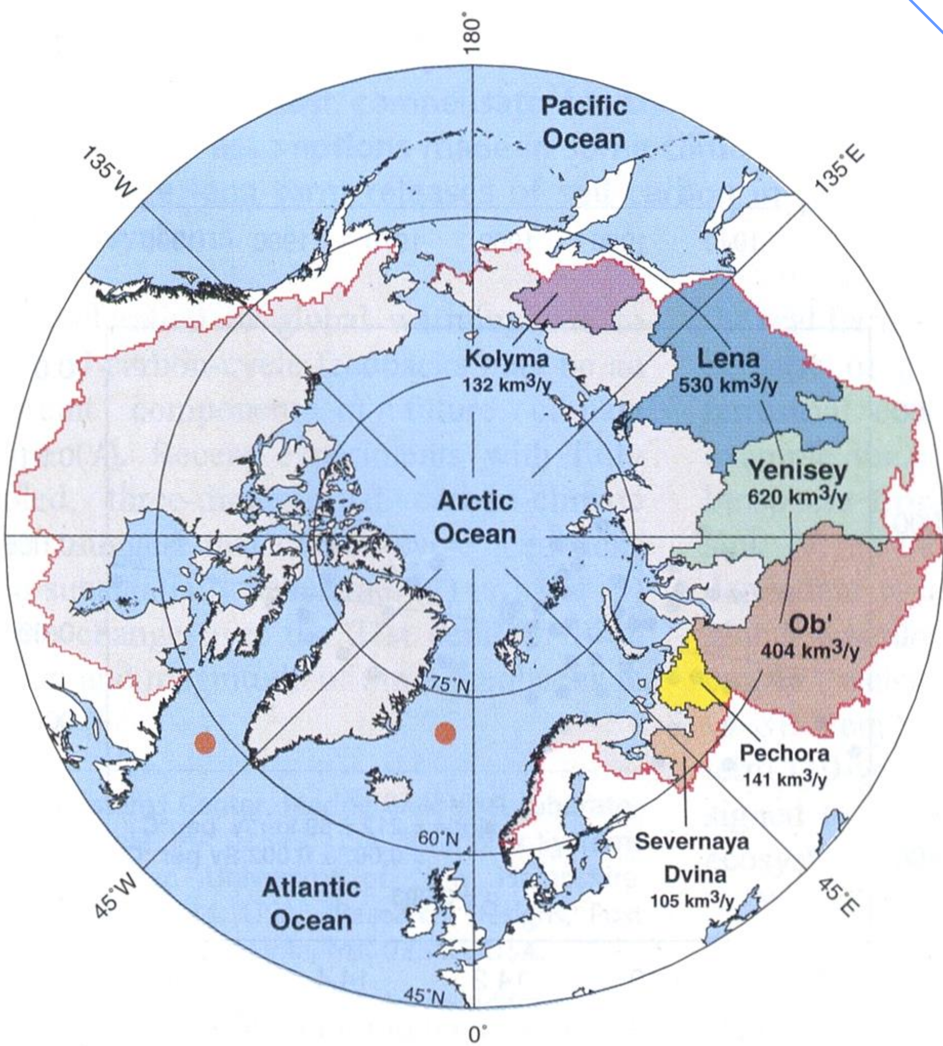


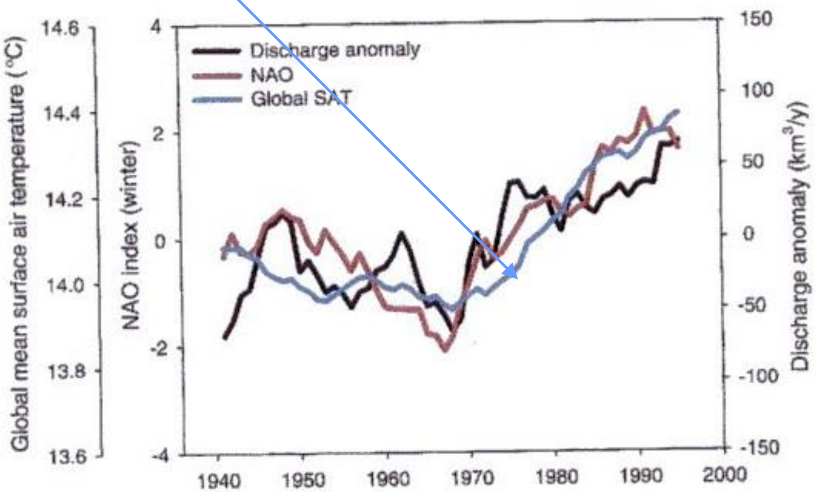

GRDC stations - distribution by time,
monthly river discharge data (including data derived from daily discharge)
Number of stations
12/2002
06/2002
12/2001
06/2001
12/2000
06/2000
12/1999
06/1999
12/1998
06/1998
12/1997
06/1997
12/1996
06/1996
12/1995
06/1995
12/1994
06/1994
12/1993
06/1993
R-ArcticNet
Whole Pan-Arctic
Russian Arctic
North America
Number of stations

Nombre de bassins fluviaux internationaux



Augmentation observée du débit des rivières arctiques (1940-2000)



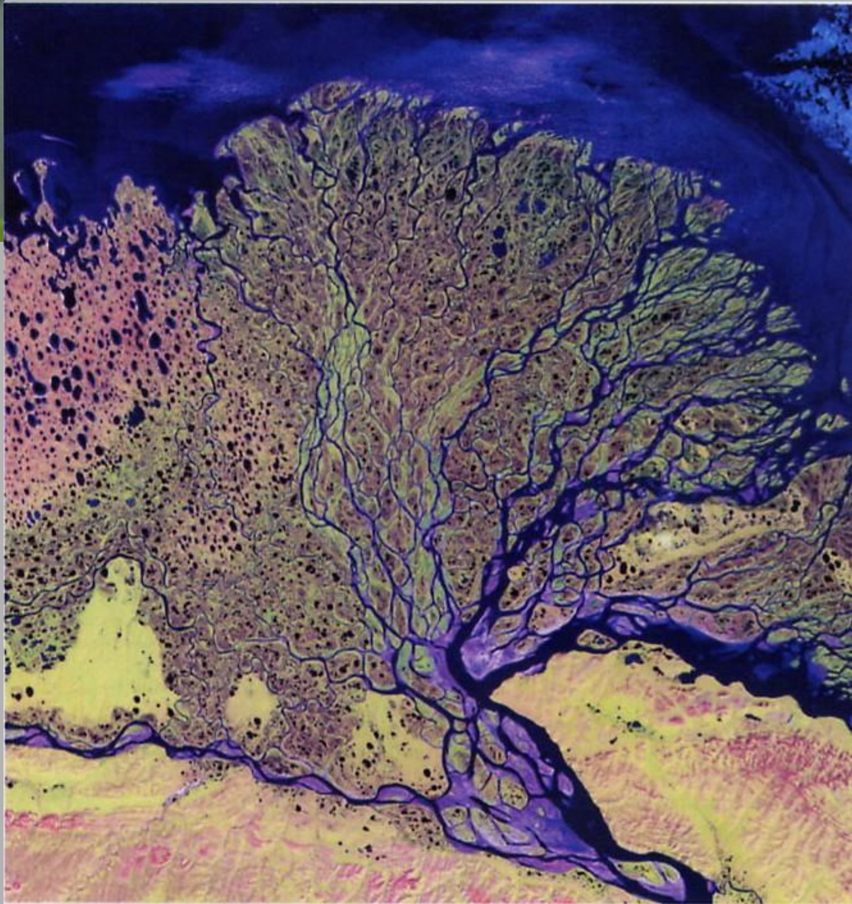


Peterson et al., 2002

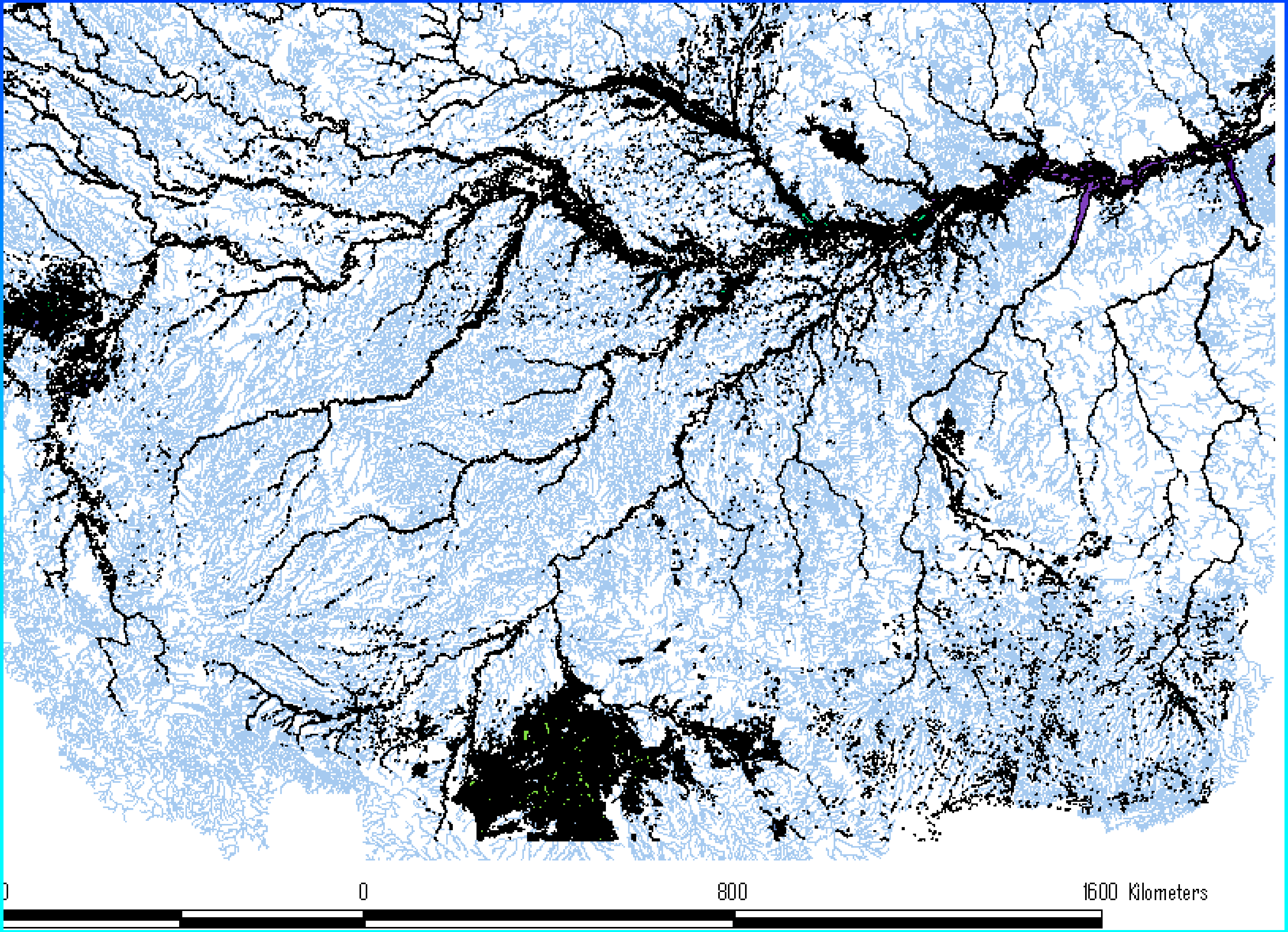
Le problème des mesures in situ

Zone inondée en Amazonie

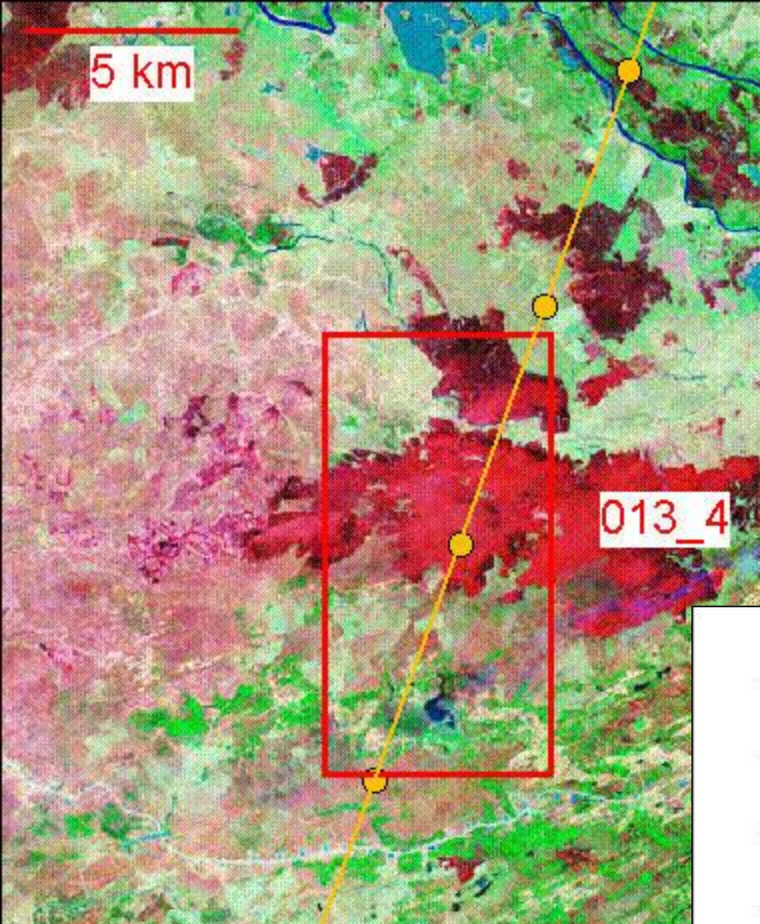
Delta du fleuve Lena (Sibérie)

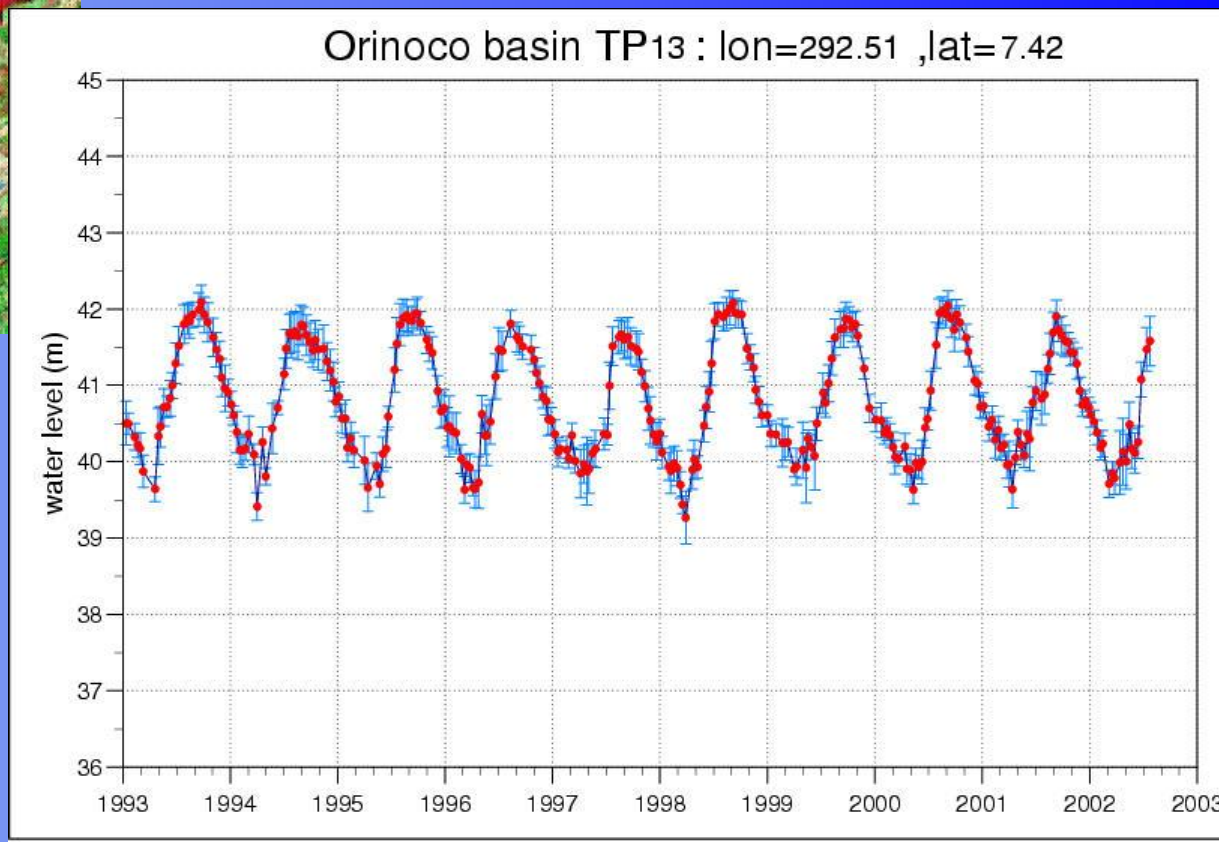


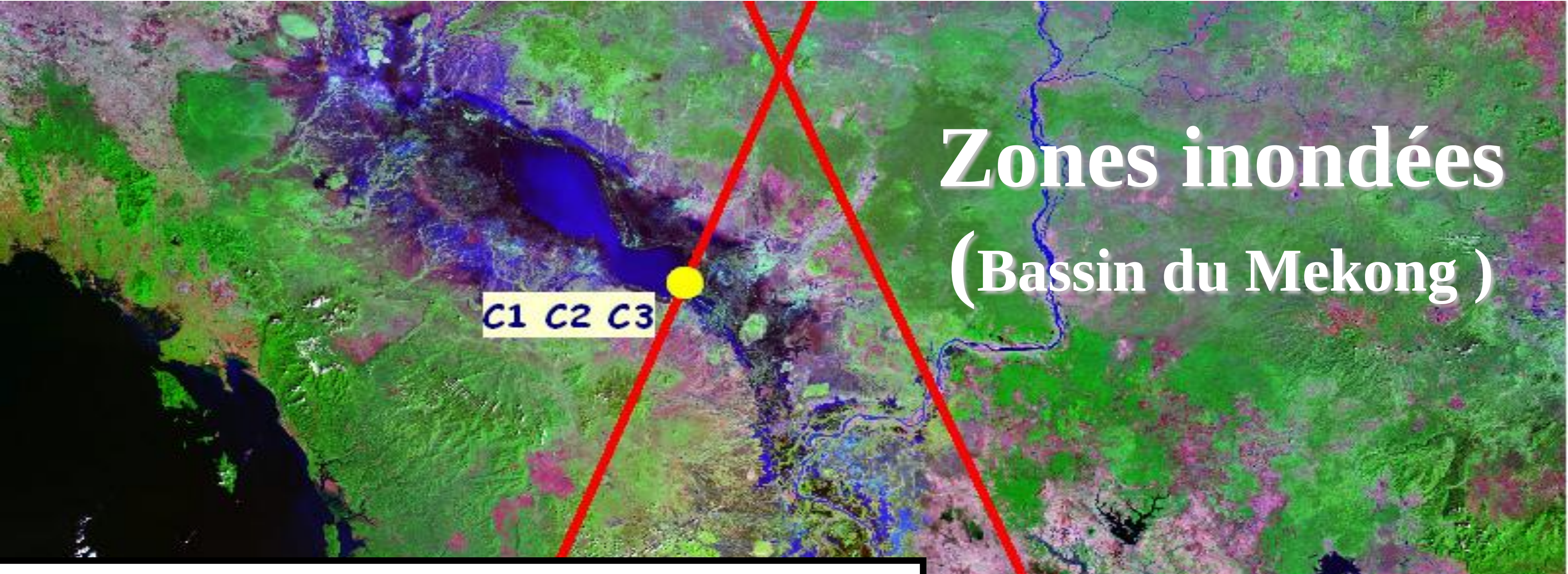
Extension of flood zones during the seasonal hydrological cycle in the Amazon bassin

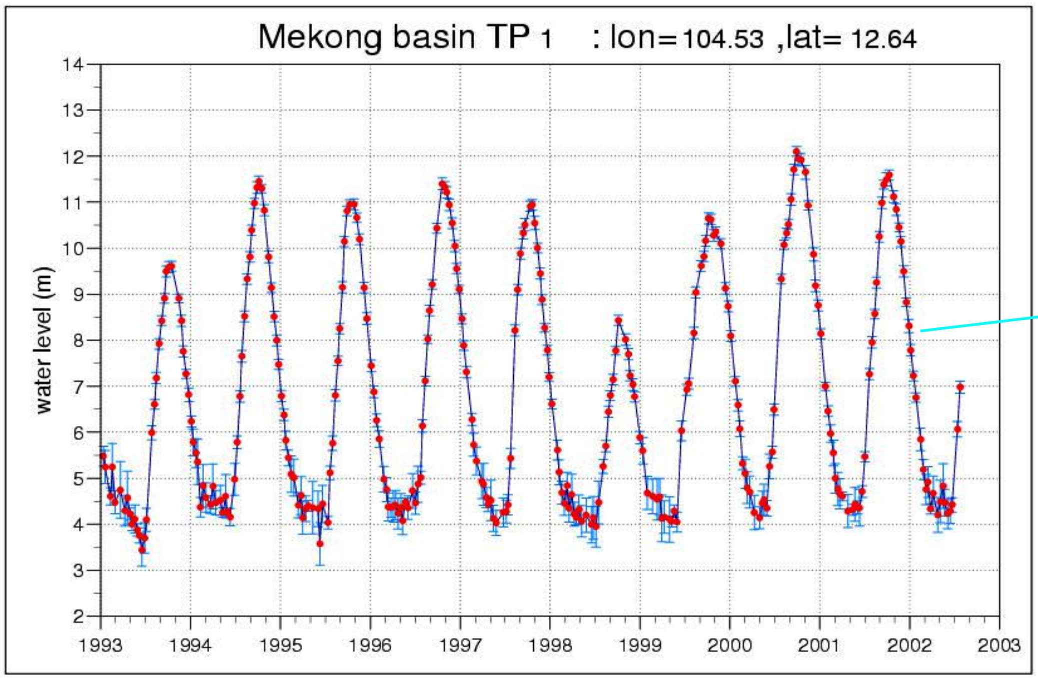


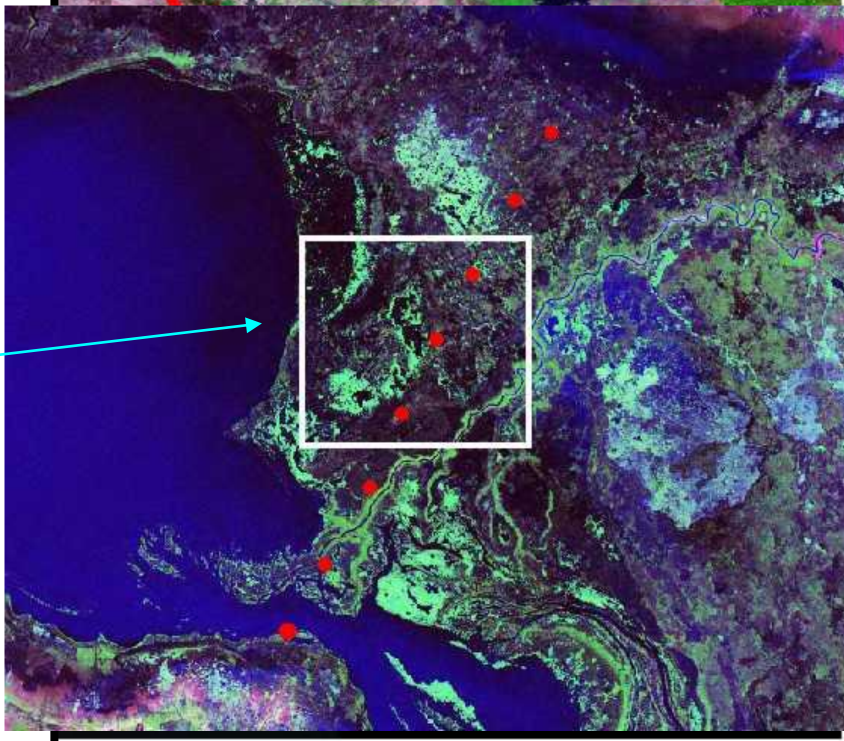
Bassin de l'Orénoque





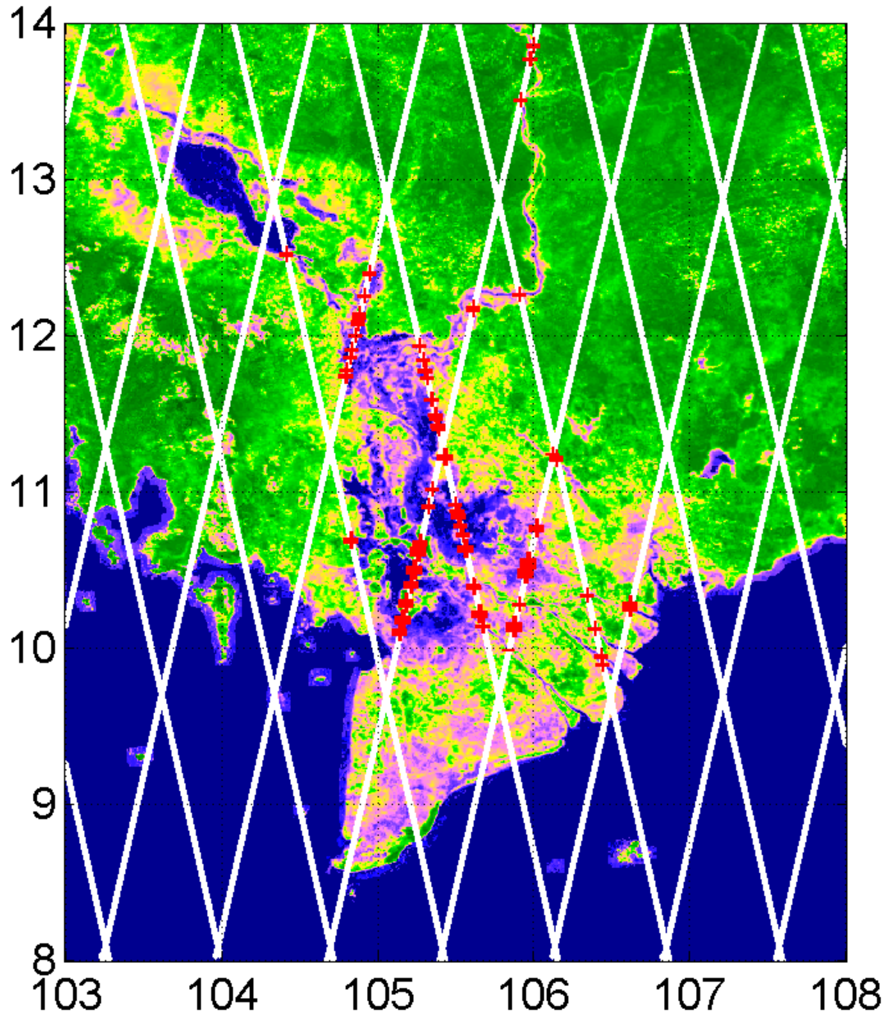

Zones inondées
(Bassin du Mekong)
C1 C2 C3


Mekong basin TP 1 : lon=104.53 ,lat= 12.64
water level (m)
14
13
12
11
10
9
8
7
6
5
4
3
2
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003

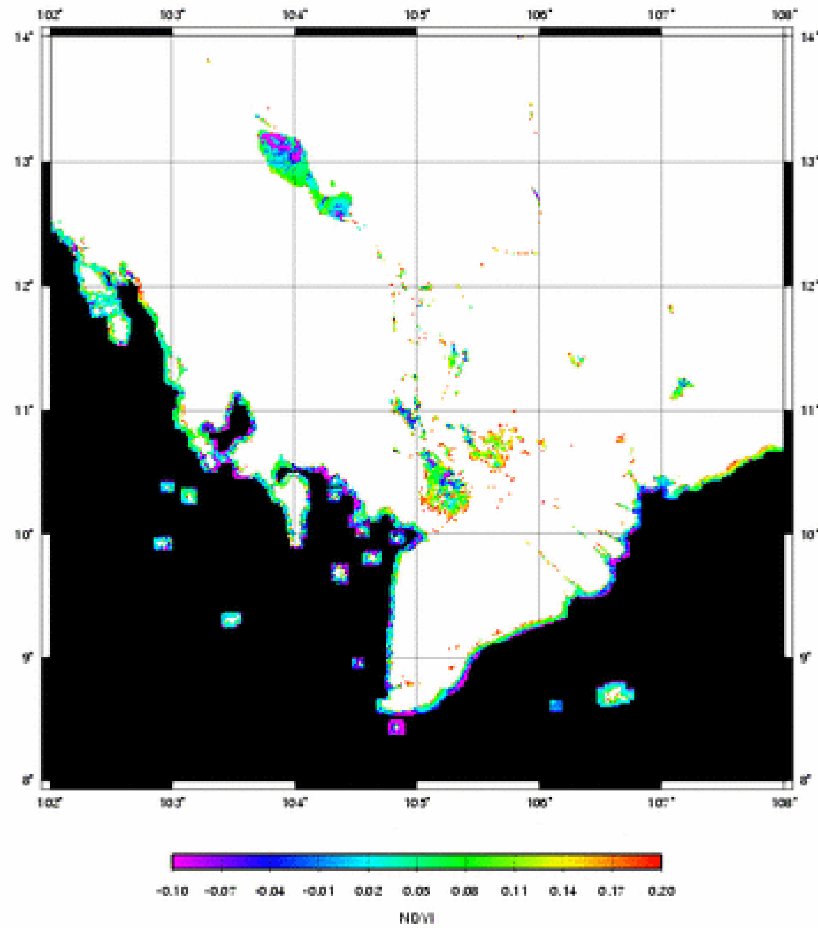


Bassin du MEKONG

Couverture du satellite altimétrique ENVISAT



NDVI of Mekong basin : 2000_00011



Perspectives

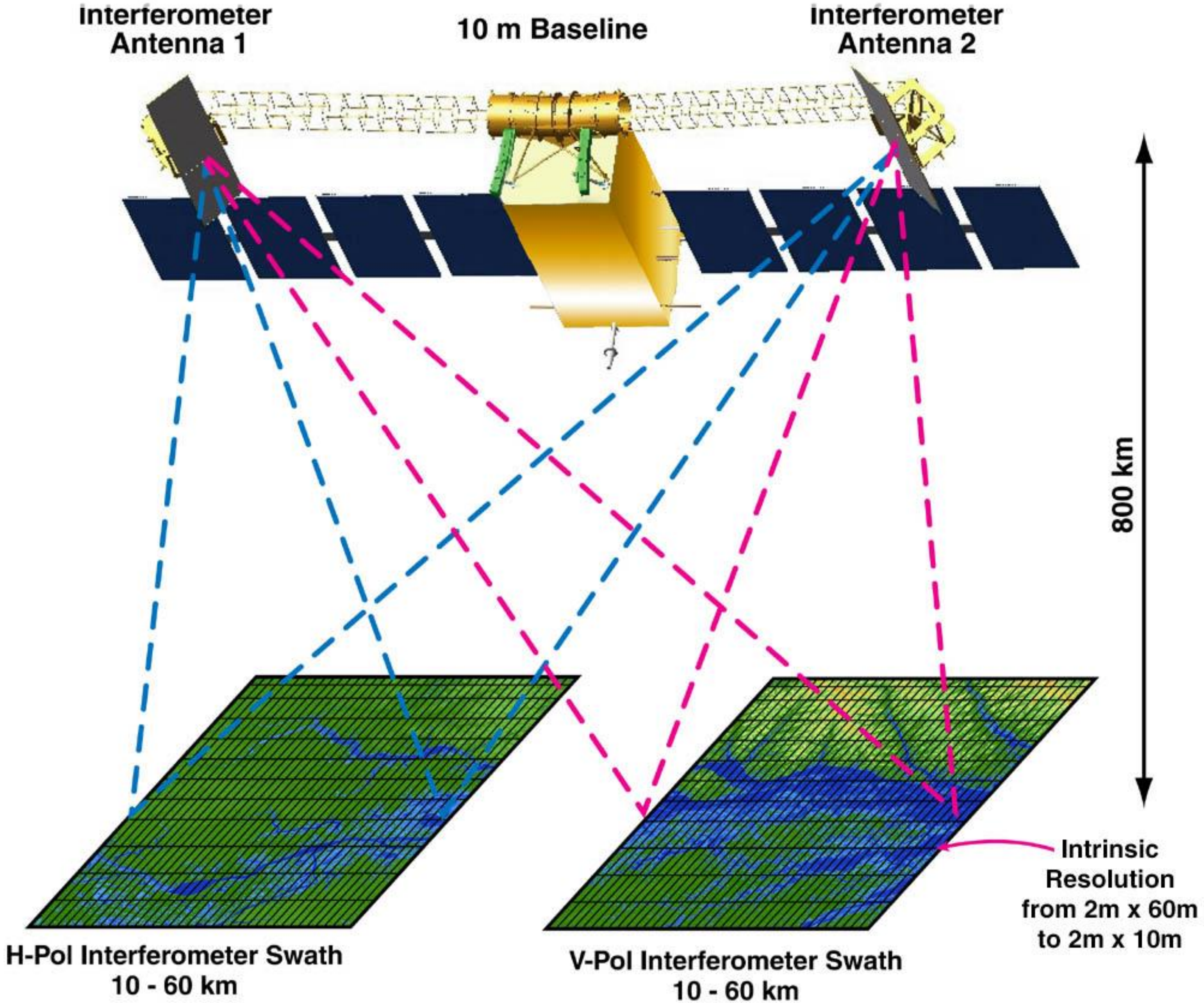
- Improve GRACE resolution résults

- Use GRACE for the study of Antarctica and Greenland masse balance

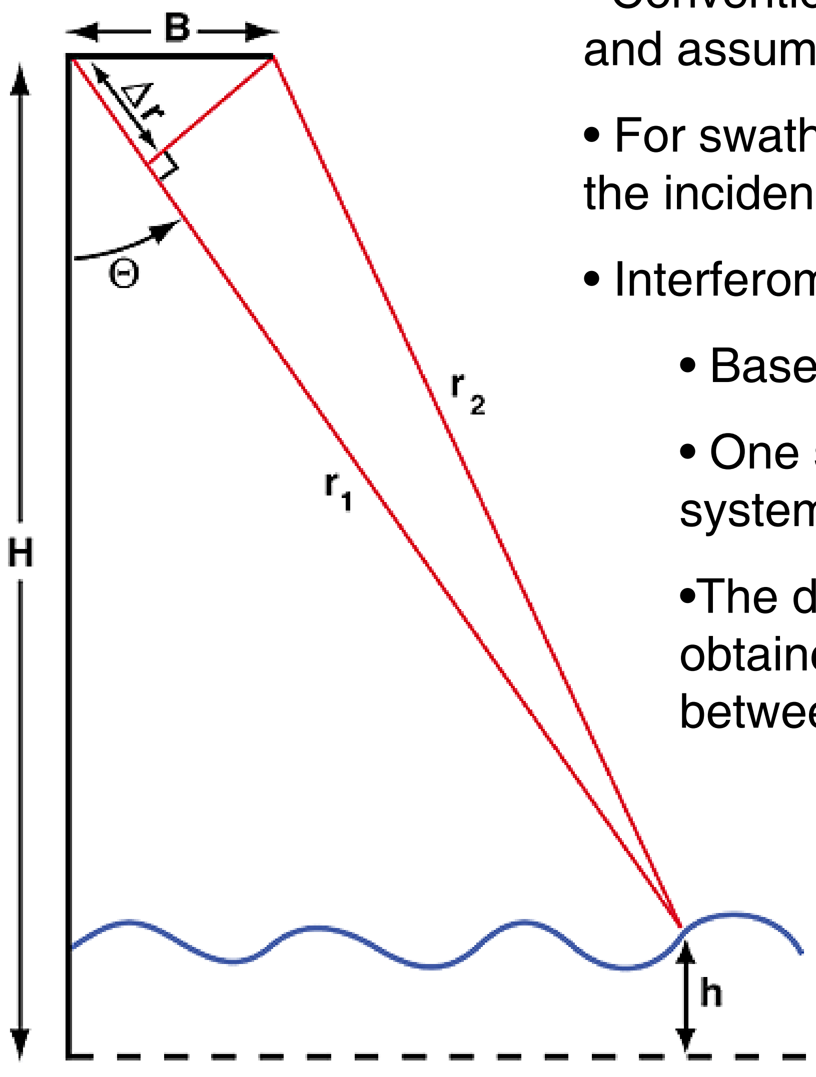
- Assimilate GRACE data in global hydrological models

- A space mission dedicated to the study of surface waters based on new technology (imaging interférometric altimeter
-> h, dh/dt, dh/dx) :
mission proposed in 2005 to ESA & NASA

"WaTER" Space Mission



Mission WATER



- Conventional altimetry measures a single range and assumes the return is from the nadir point
- For swath coverage, additional information about the incidence angle is required to geolocate
- Interferometry is basically triangulation
  - Baseline B forms base (mechanically stable)
  - One side, the range, is determined by the system timing accuracy
  - The difference between two sides (Δr) is obtained from the phase difference (Φ) between the two radar channels.

$$\Phi = 2\pi \, \Delta r/\lambda = 2\pi B \sin \Theta/\lambda$$

$$h = H - r \cos \Theta$$


THE END