Ocean tides after a decade of high precision satellite altimetry

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Overview

1. Ocean tides: the more recent picture
2. Progress over the last decade
   and present state: FES2003 versus GOT2001
3. Recognition of the importance of the internal tides
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   - on the hydrodynamic modelling of ocean tides
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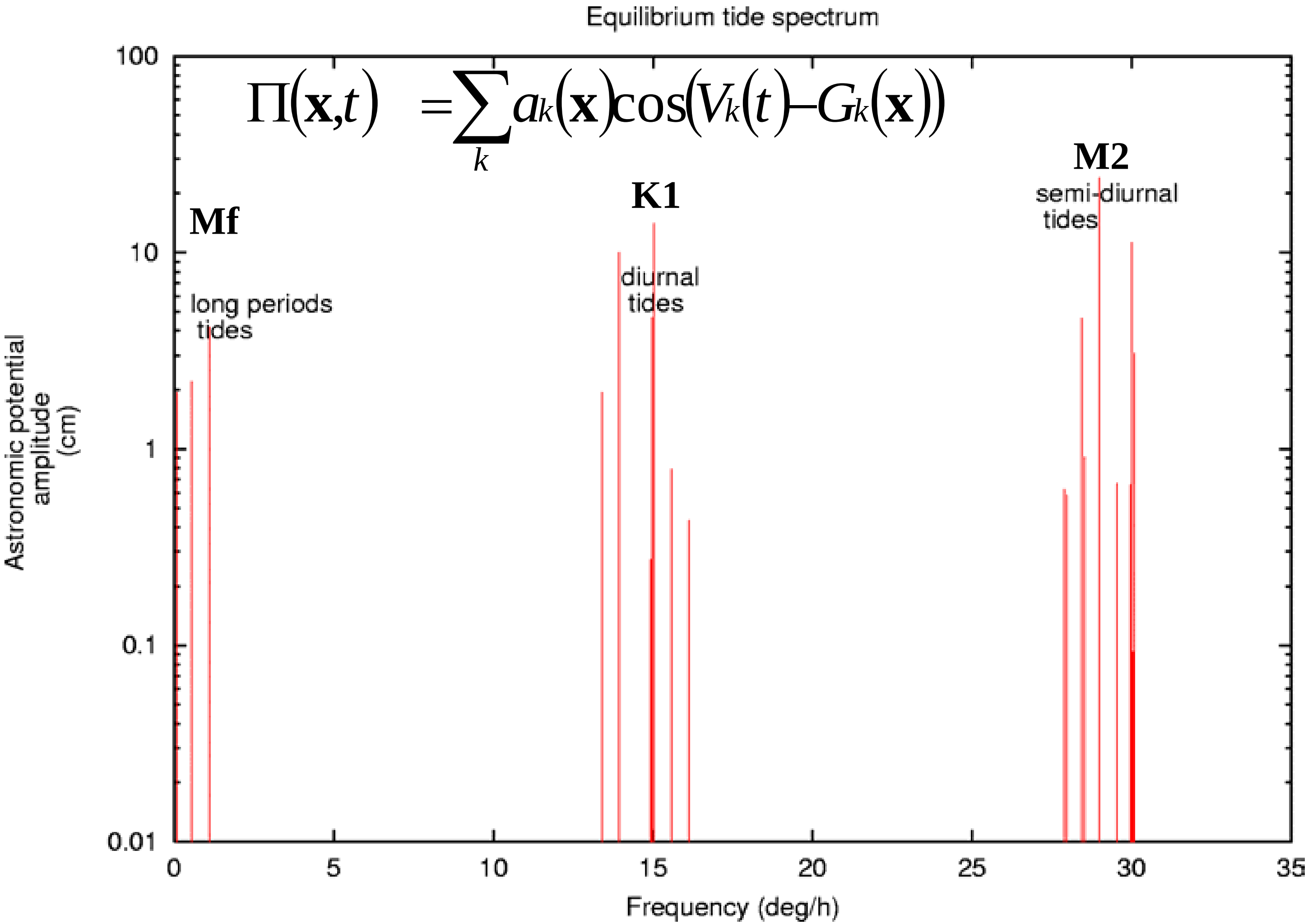
5. Conclusions and outstanding issues

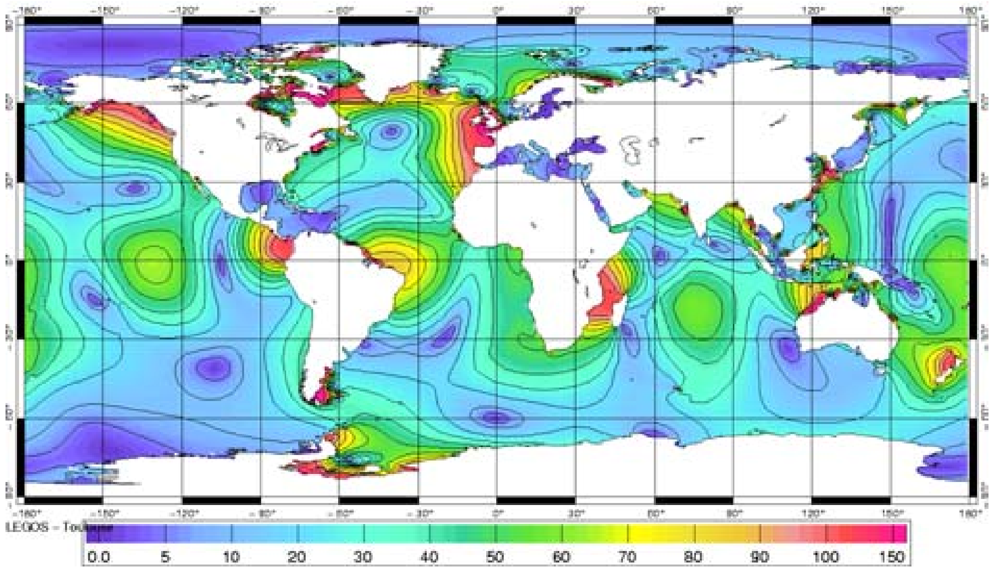
The tidal spectrum

$$\Pi(\mathbf{x},t) = \sum_k a_k(\mathbf{x}) \cos\left(V_k(t) - G_k(\mathbf{x})\right)$$



M4

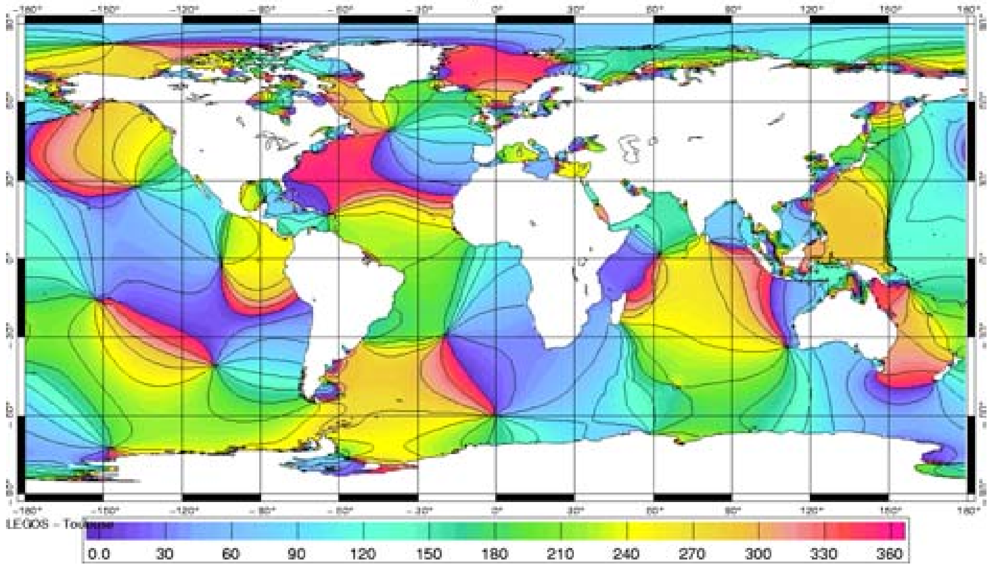
Higher non linear



50 cm 150 cm

Semi Diurnal tides M_2

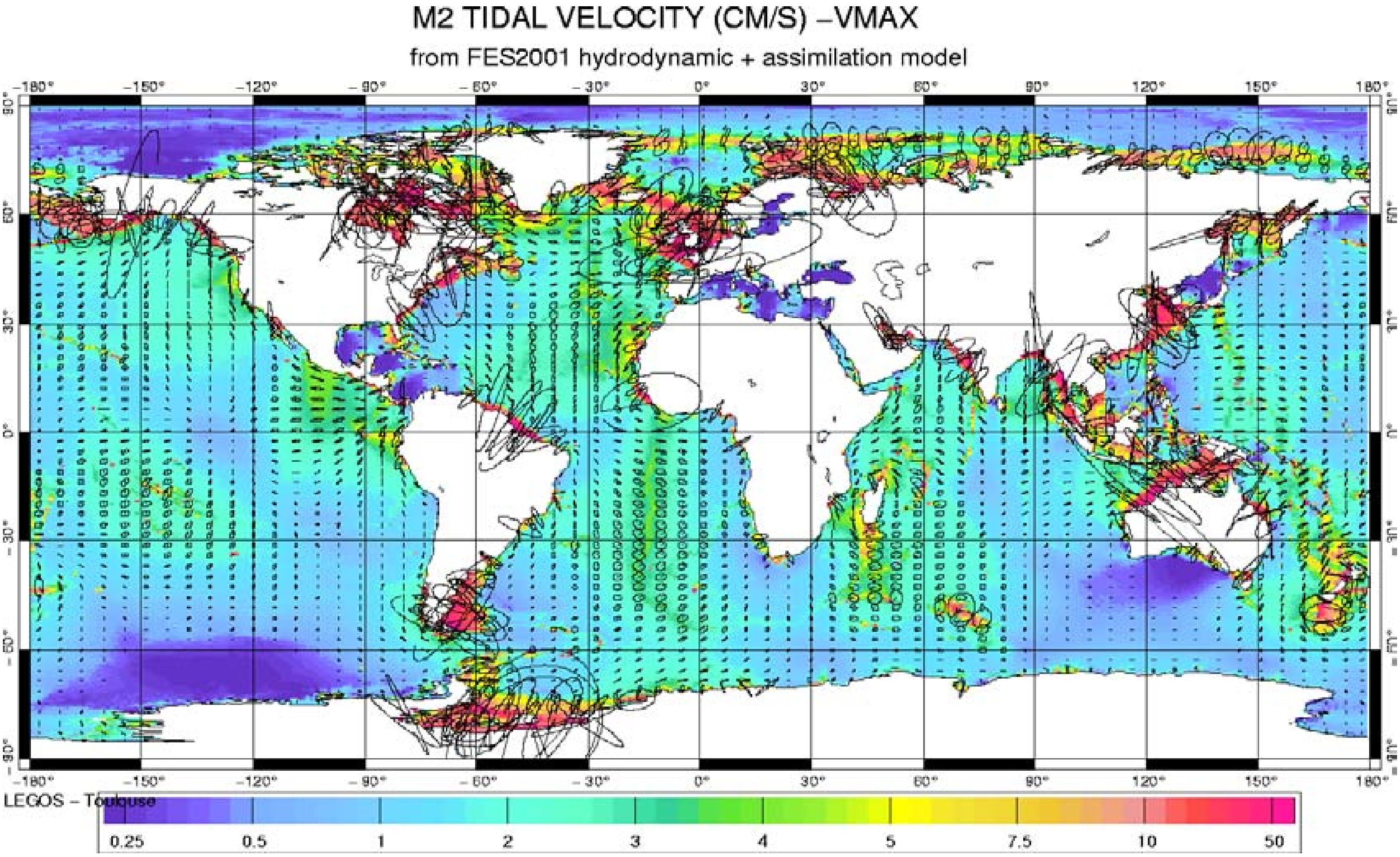
Amplitudes $\boldsymbol{a_{M2}}$



0° 180°

$$h(\mathbf{x},t) = \sum_k a_k(\mathbf{x}) \cos\left(V_k(t) - G_k(\mathbf{x})\right)$$

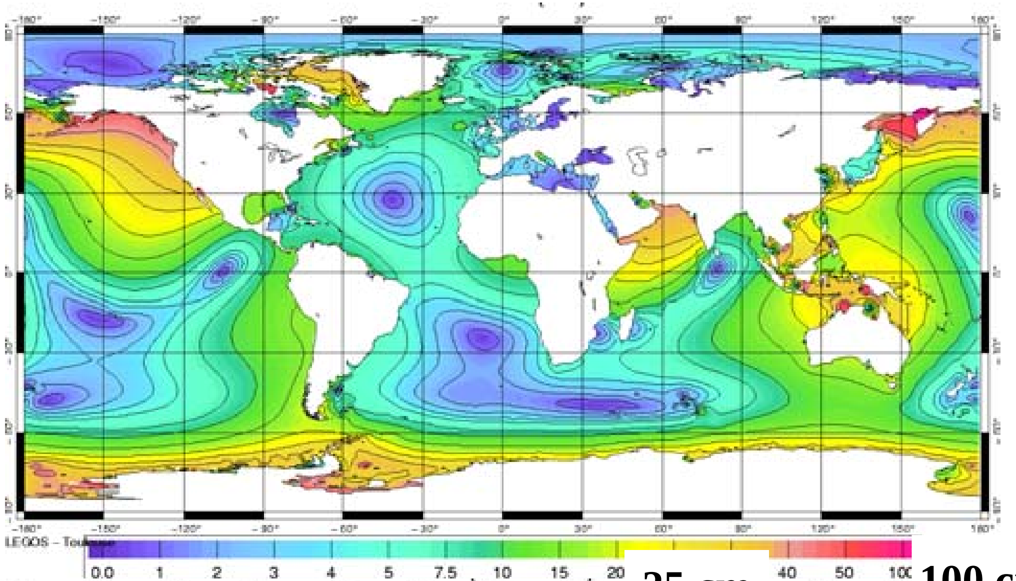
Phases $\boldsymbol{G_{M2}}$



Semi-diurnal tidal currents

Diurnal tides

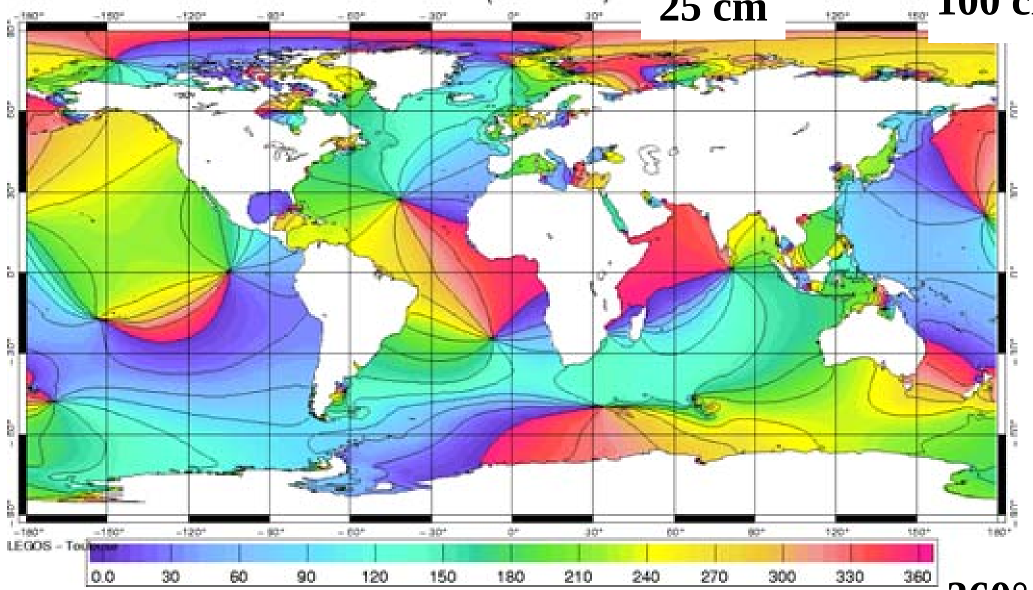
K_1



25 cm

100 cm

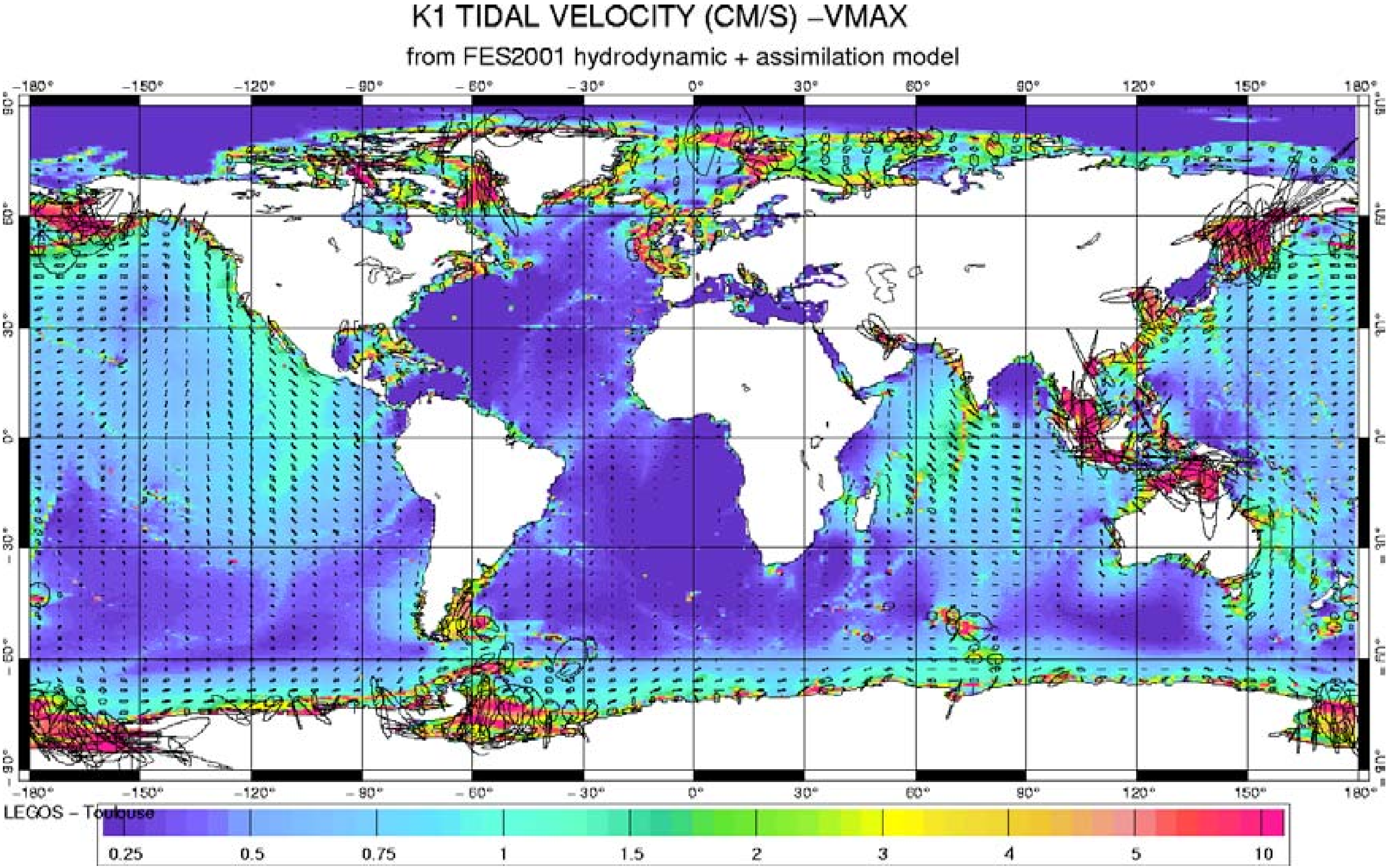
Amplitudes $\boldsymbol{a_{K1}}$



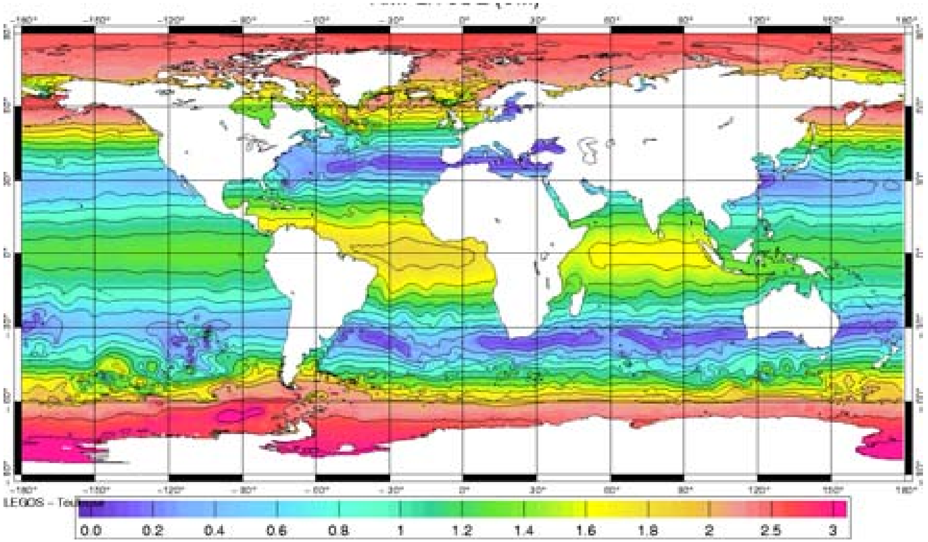
Phases $\boldsymbol{G_{K1}}$

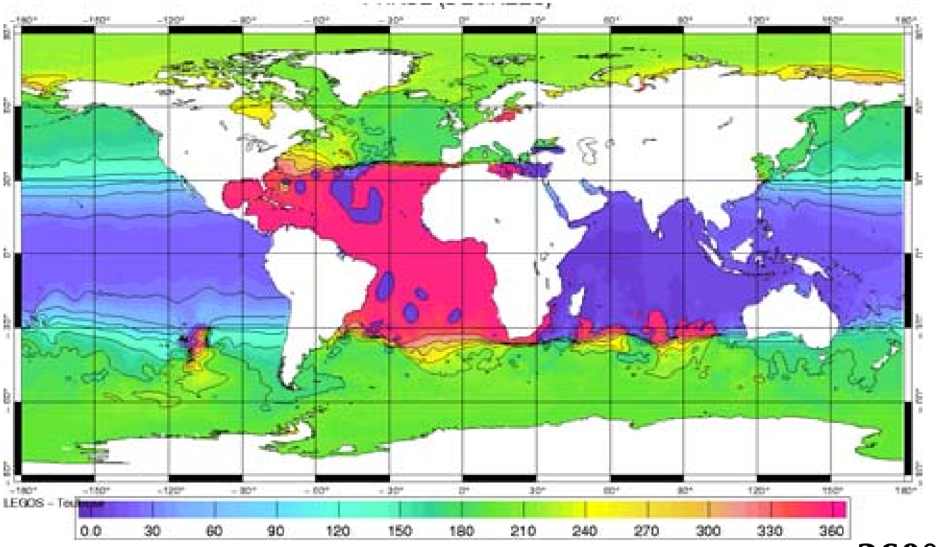
360°

0° 180°



Diurnal tidal currents





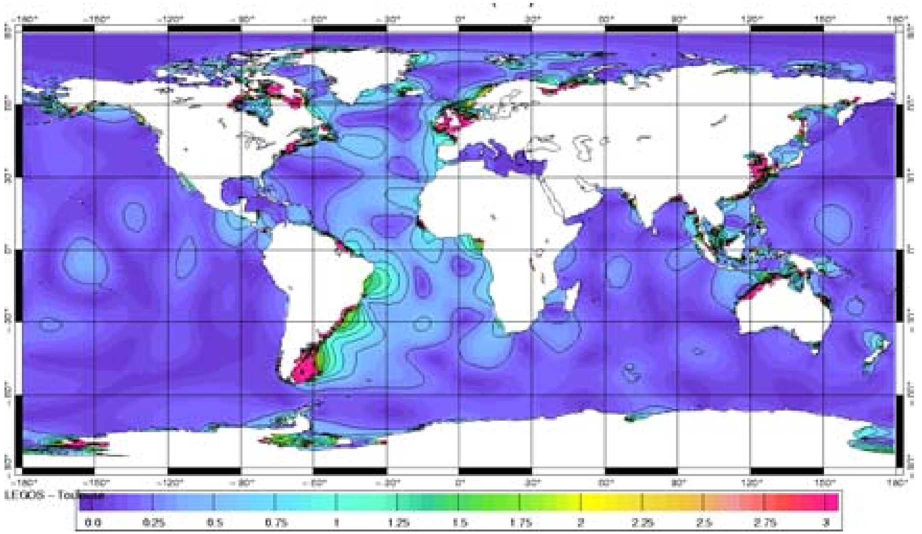
Long period tides Mf

Amplitudes a_{Mf}

Phases G_{Mf}

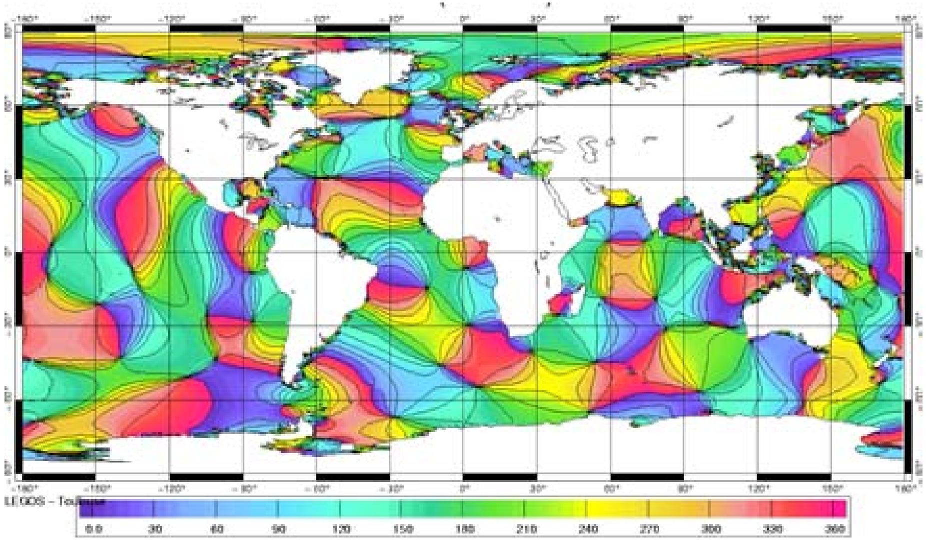
Ref: Egbert & Ray, 2003

Non linear constituents M4



1 cm **2 cm** **3 cm**

Amplitudes $\boldsymbol{a_{M4}}$



0° **180°**

Phases $\boldsymbol{G_{M4}}$

See poster Knudsen et al

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Major steps

a) Before the T/P and ERS era, the standard was **Schwiderski (1980)**

b) 1991- first empirical altimetric solution GEOSAT:
Cartwright and Ray (1991)

c) 1995 – first set of T/P solutions:
empirical: **Schrama and Ray (1994), Eanes / CSR3 (1995), Andersen (1995), Desai-Whar (1995)…**
hydrod.+Assim. : **Egbert et al (1994), Le Provost et al / FES 95(1995), Kantha (1995), ...**

d) 2001: preliminary JASON 1 tide solutions:
empirical: **Ray / GOT 99(2000), Eanes / CSR4 (2001), …**
hydrod.+Assim. : **Egbert (2000), Lefevre et al/ FES 99 (2002), NAO(2002)**

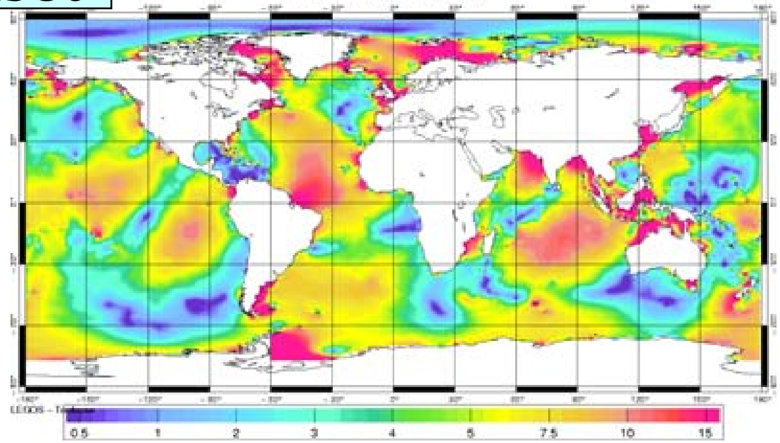
e) 2002: more recent gobal solutions
empirical: **Ray (2002) / GOT2001**
hydrod.+Assim. : **Le Provost et al (2003)/ FES 2002/3**

Successive improvements on the M2 tide

1980

M2 TIDAL WAVE: NSWC Versus FES2001

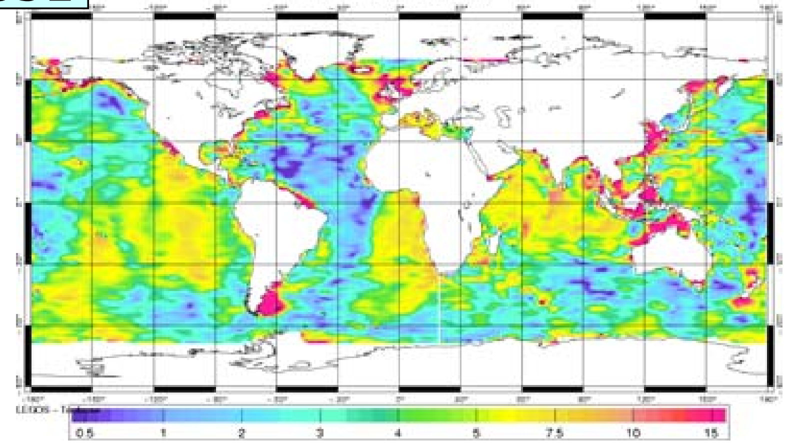
COMPLEX MISFITS (CM)



1991

M2 TIDAL WAVE: CR91 Versus FES2001

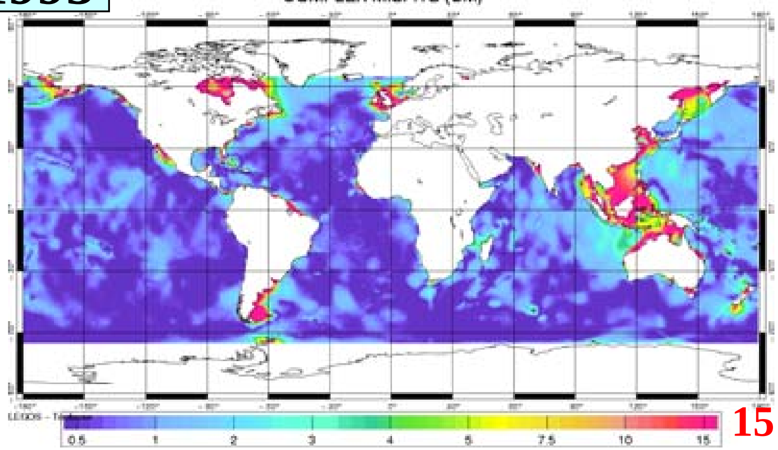
COMPLEX MISFITS (CM)



1995

M2 TIDAL WAVE: SR95 Versus FES2001

COMPLEX MISFITS (CM)



15 cm

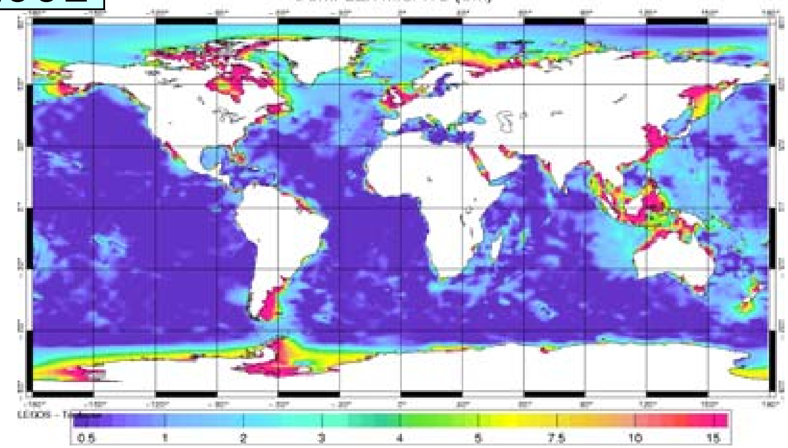
15 cm

0.5 cm **2 cm** **4 cm** **10 cm**

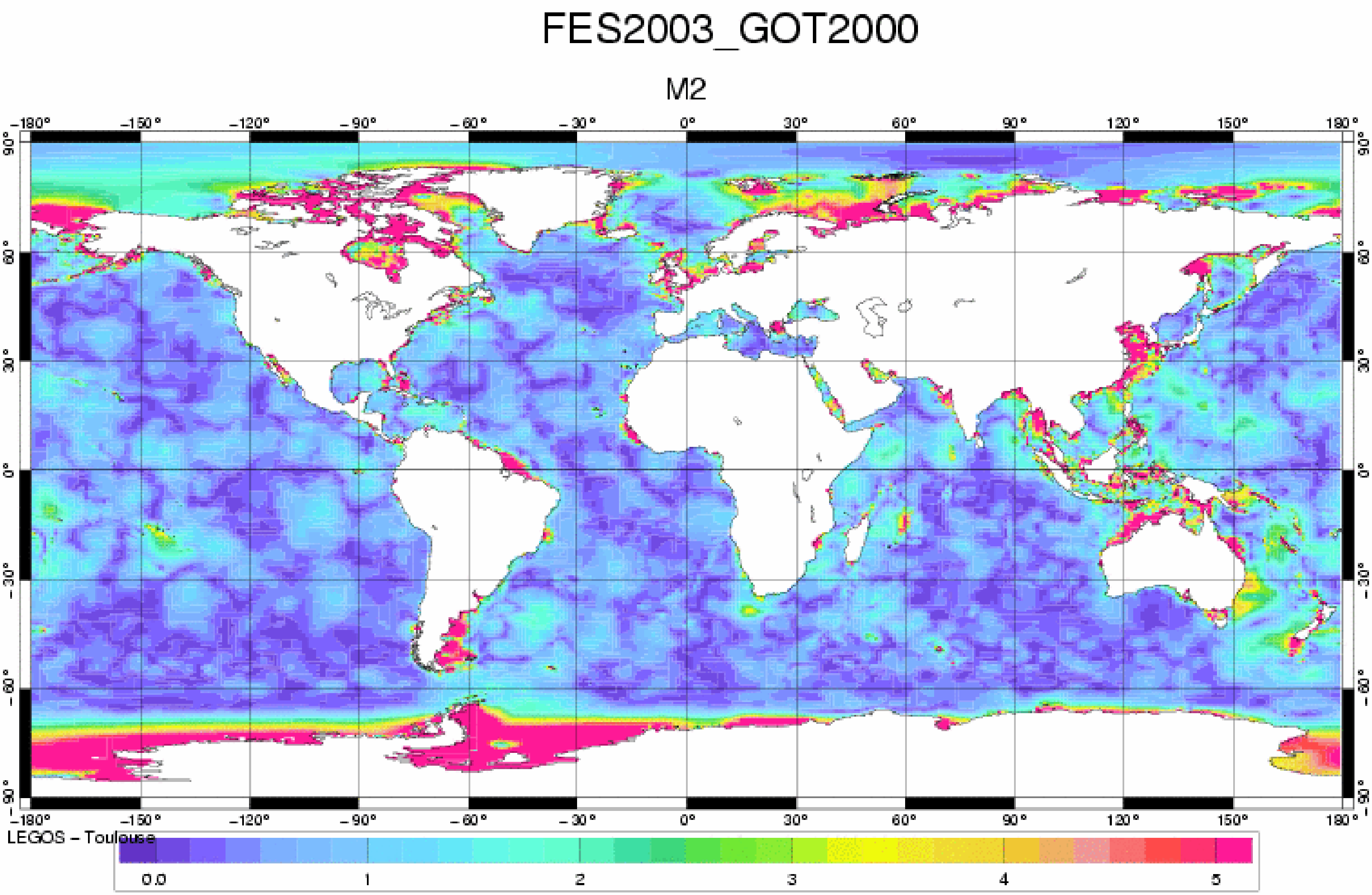
2001

M2 TIDAL WAVE: GOT00 Versus FES2001

COMPLEX MISFITS (CM)



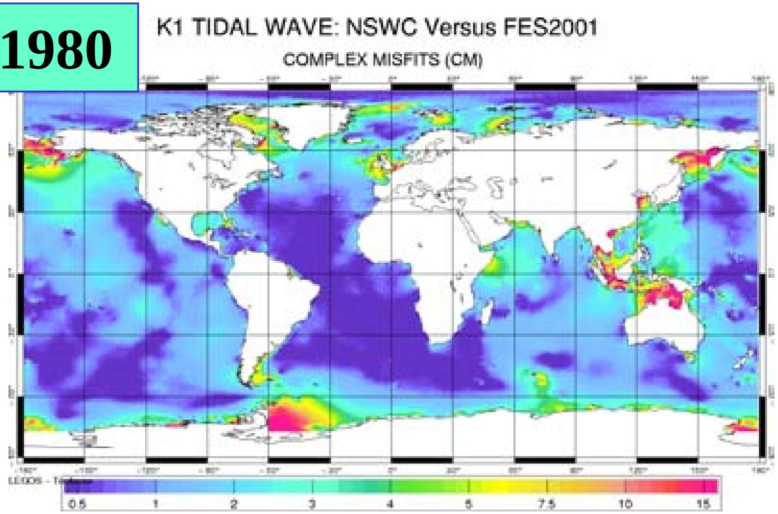
Ref: FES2001


FES2003_GOT2000
M2
−180°
−150°
−120°
−90°
−60°
−30°
0°
30°
60°
90°
120°
150°
180°
90°
60°
30°
0°
−30°
−60°
−90°
LEGOS – Toulouse
0.0
1
2
3
4
5

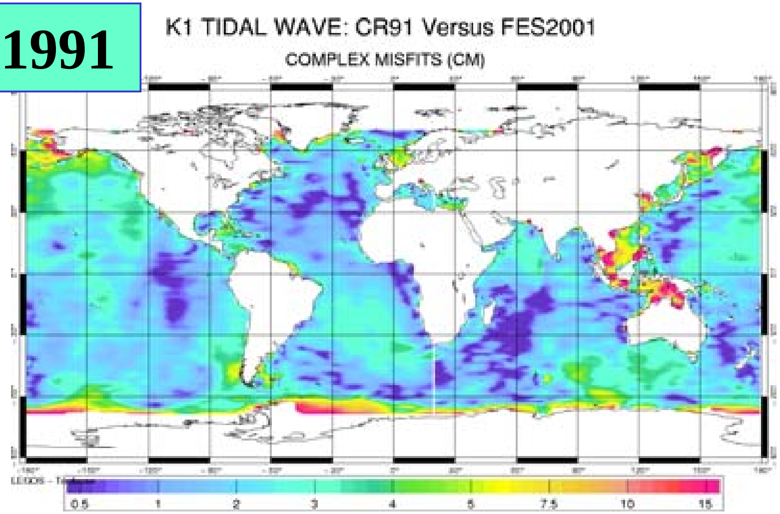
1 cm **3 cm** **5 cm**

Successive improvements on the K1 tide

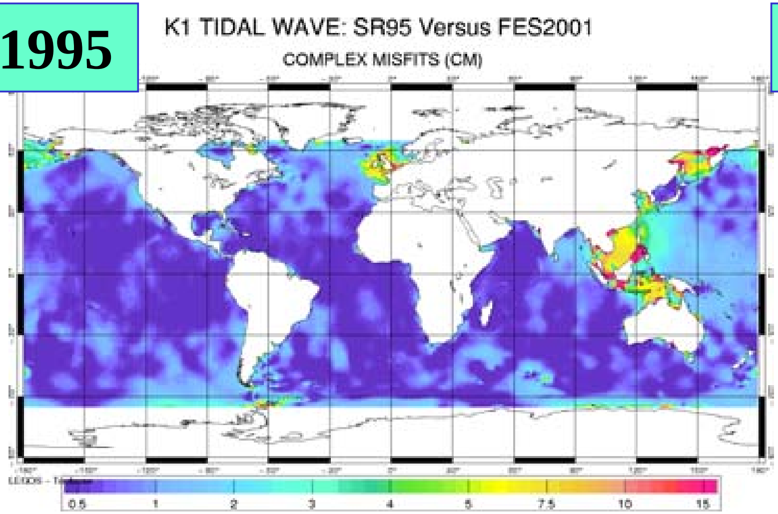
1980



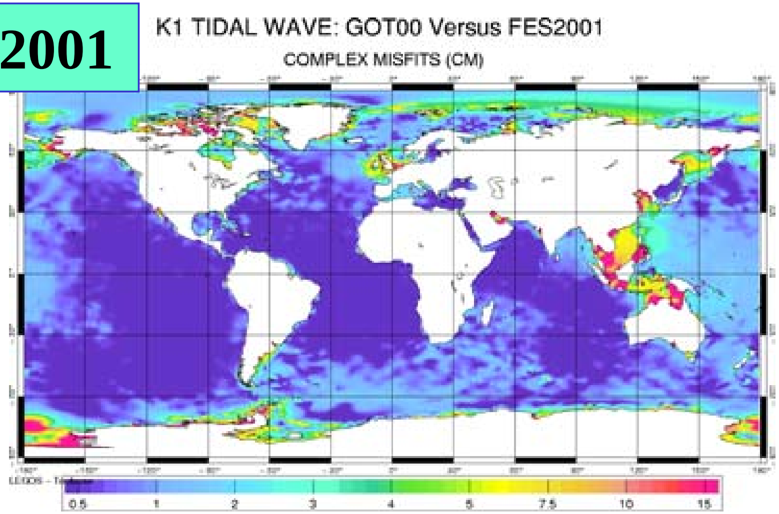
1991



1995

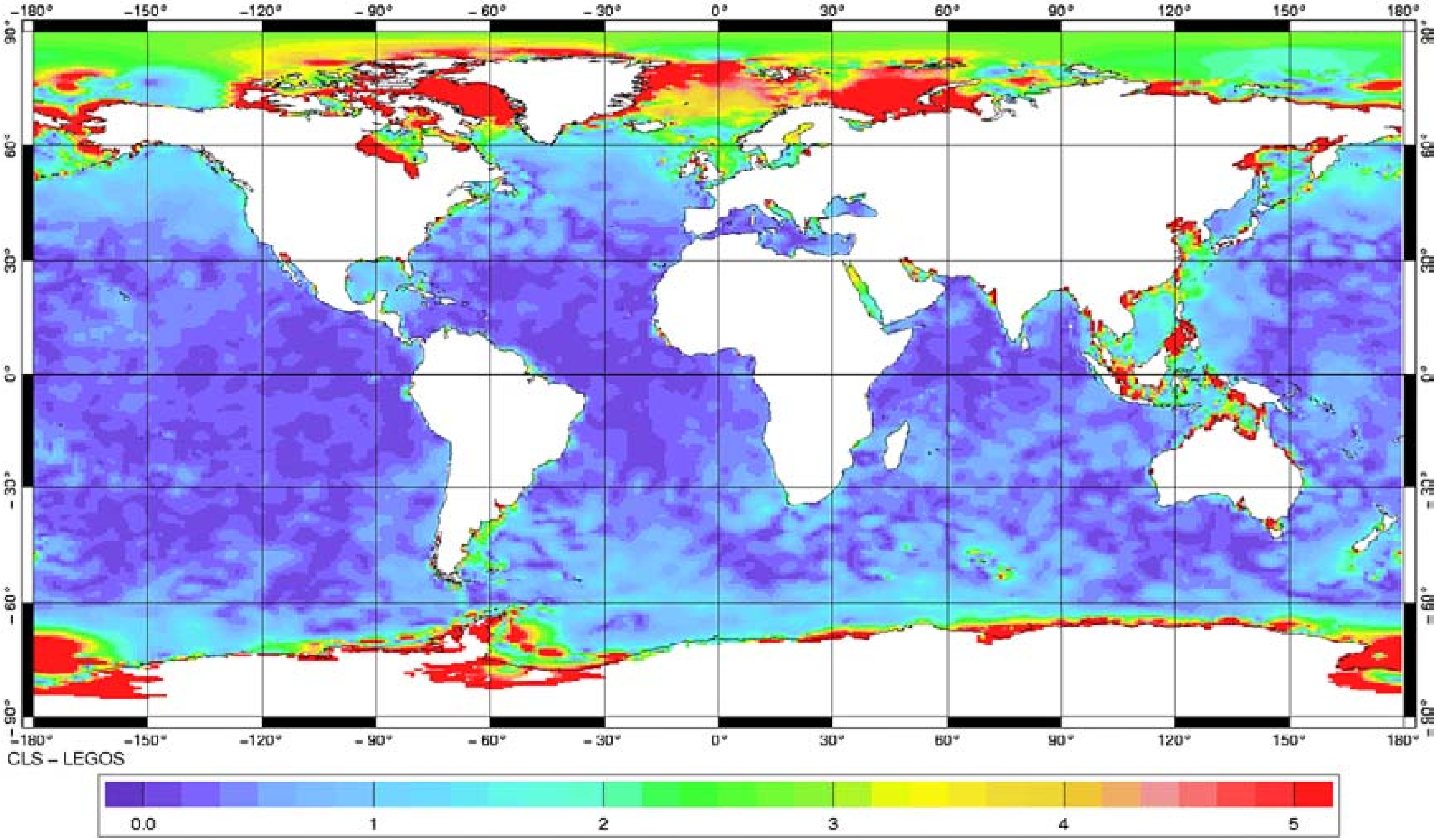


2001



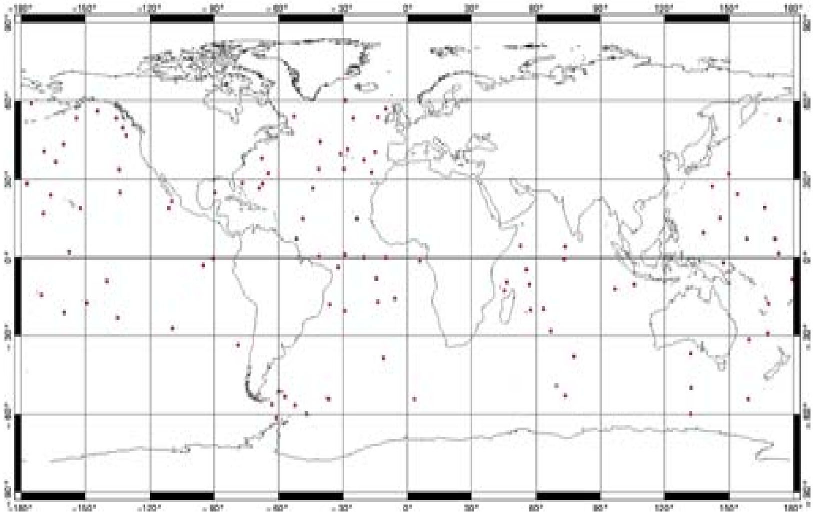
K1 TIDAL WAVE: FES2002 vs GOT00

COMPLEX MISFITS (CM)



5 cm

Name	M2	S2	N2	K2	K1	O1	P1	Q1	RSS	2N2
CSR4.0	1.7	1.1	0.7	0.5	1.1	0.9	0.4	0.3	**2.6**	0.2
FES2002	1.7	1.1	0.7	0.5	1.0	0.8	0.4	0.3	**2.6**	0.2
FES99	1.4	0.8	0.6	0.4	1.0	0.9	0.4	0.3	**2.3**	0.3
GOT00	1.5	1.0	0.6	0.4	1.0	0.9	0.4	0.3	**2.4**	
GOT99	1.6	1.1	0.7	0.4	1.0	0.9	0.4	0.3	**2.5**	
NAO99	1.8	1.1	0.7	0.5	1.2	0.9	0.4	0.3	**2.7**	0.2



ST 102 sea truth tide gauge data base

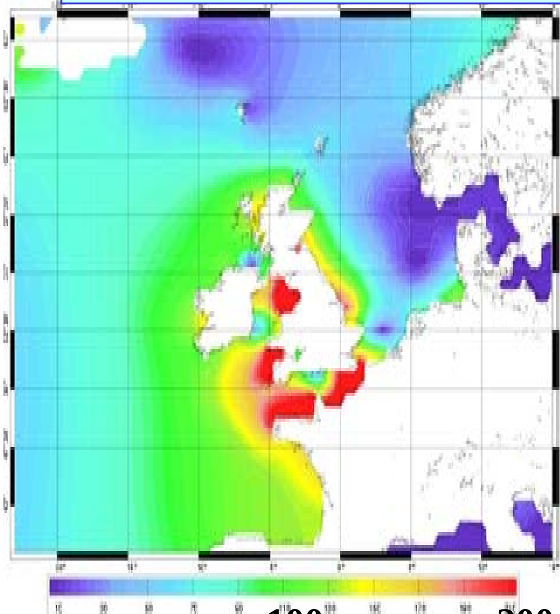
Present state:

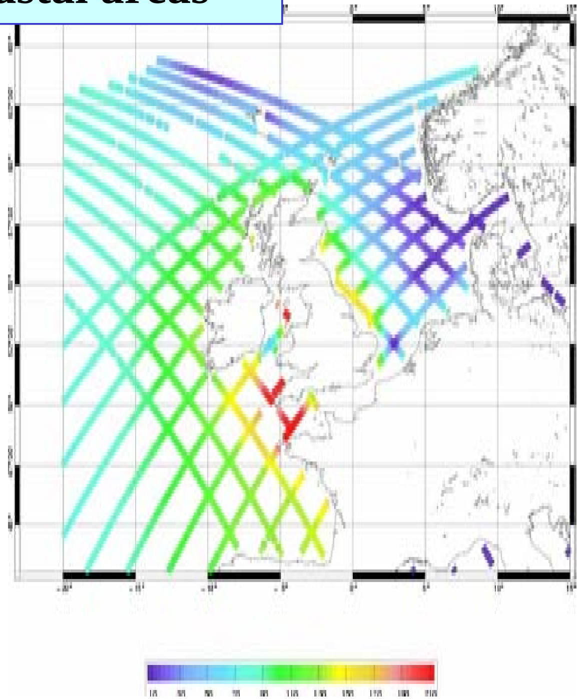
1. over the deep ocean:
   model solutions are converged at the cm level

2. Accuracy of the predictions over the deep ocean at 2.5 cm level or better

3. Large difference between solutions:
   - at high latitudes
   - over the coastal areas

Difficulties over shelves and coastal areas





M2

➔input of altimetry limited

➔model accuracy limited by bathymetry,…

➔ used of T/P + Jason+ ERS+ ENVISAT

➔Assimilation of altimeter and in situ data

Non linear constituents

M2 non linear dynamics ➔M4 (35 cm), M6 (15 cm)

M2 and S2 non linear interactions ➔MSf, 2MS2, 2SM2, MS4, 2MS6

Still to under investigation

(Andersen, 1999)

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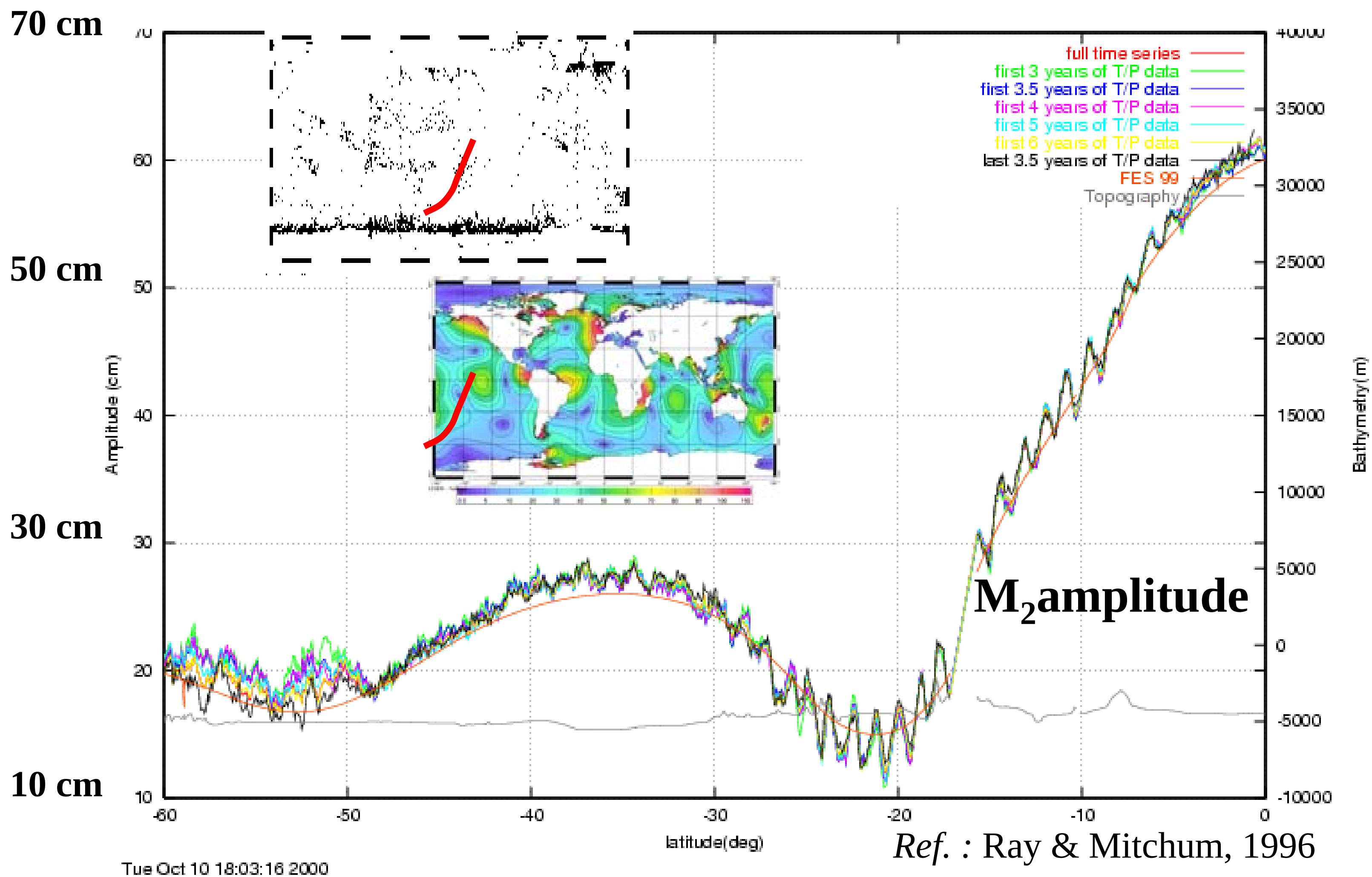
Internal tidal waves are observed by satellite altimetry

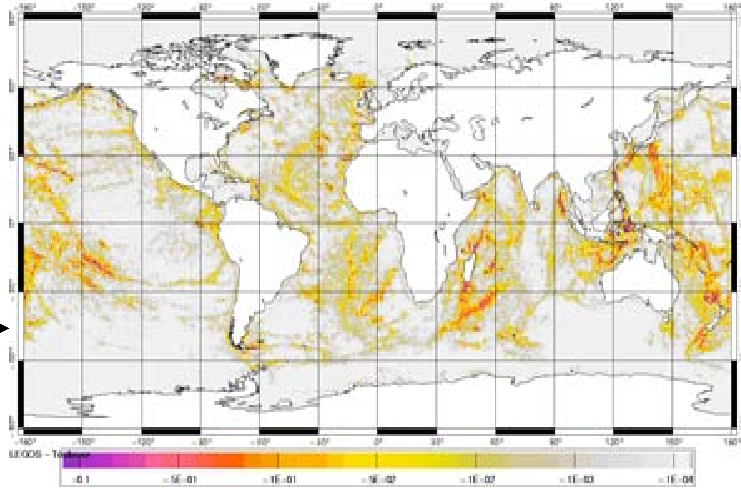


Ref. : Ray & Mitchum, 1996

Energy transfered from barotropic to baroclinic tides

computed from assimilation of T/P data in models

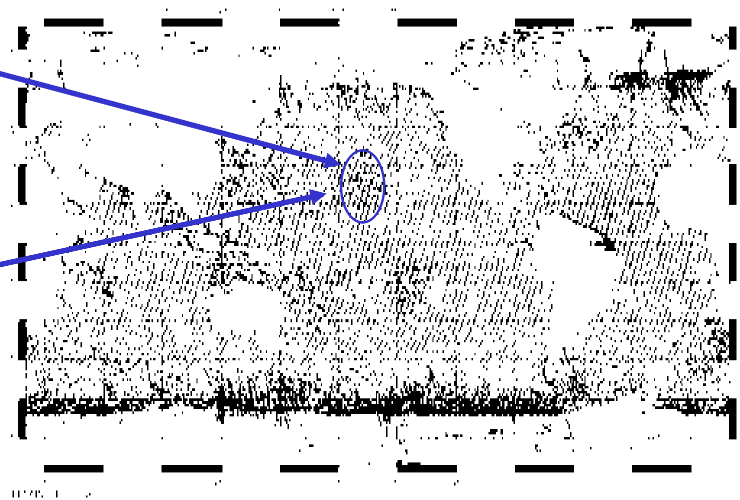
Egbert & Ray, 2001
Lyard & Le Provost, 2002



W/m²

Part of this energy locally dissipated / part radiated ?

Global energy transfer:
Egbert & Ray (2000) ➔ 20 GW



Internal tide energy flux :
Ray & Cartwright, 2001 ➔ 6 GW
Merrifield & Holloway, 2000 ➔ 9.7 GW

Local mixing ➔ 10 –14 GW ??????

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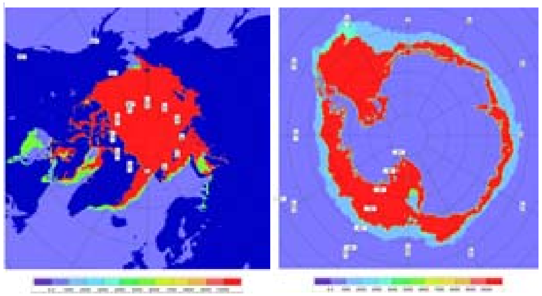
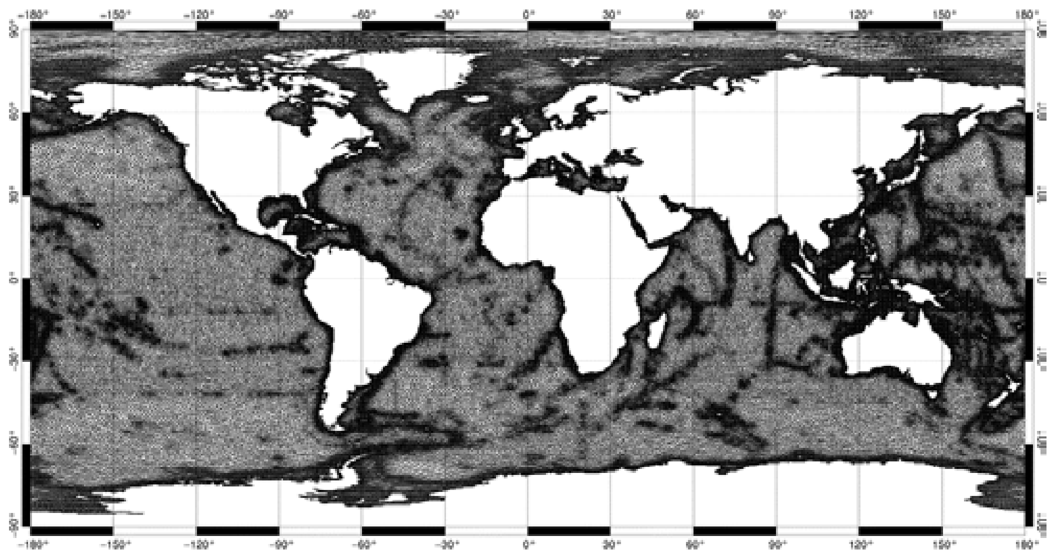
New hydrodynamic model: FES 2002-free

physically self consistent and energetically (almost) coherent

1- Bottom drag x 2 under the ice



Ice cover



2- Internal wave drag:

$$F_{wd} = - C_D \, \rho_0 \, K^{-1} \, N \, (\overrightarrow{grad} \, H \cdot \vec{U}) \, \overrightarrow{grad} \, H$$

3- FE mesh (P2)

3 times denser than previous mesh (FES94-free)

7 km resolution on coastal areas,

75 km resolution on the deep ocean,

mesh refinement controlled following a criterion based on the topographic gradient

4- Compound bathymetry

ETOPO5, DBDB5

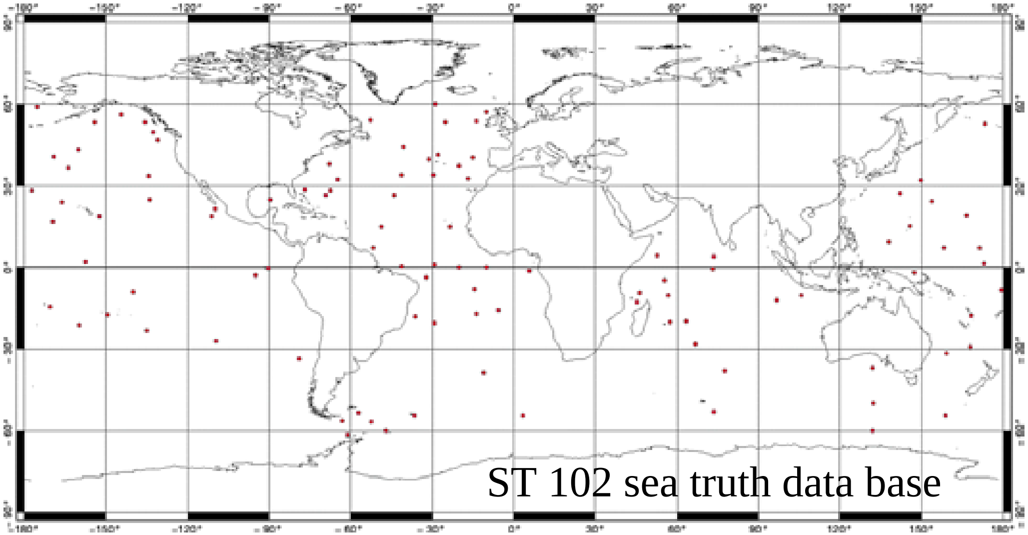
Smith & Sandwell

WVS, 1989

GEBCO 97

13 local bathymetries

Solution physically self consistent



	Biais M2	**RMS/ST102 M2**	**K1**
FES99-free*	+8 cm	13.1 cm	2.4 cm
•Lefevre, Lyard, Le Provost and Schrama, 2002 (solution without internal wave parameterisation)			
FES2002-free	+1 cm	5.8 cm	1.2 cm
FES2002-Assim.	0	1.7 cm	1.1 cm

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Global energetic of the ocean tides

- P = P1 + P2 : local rate of energy input

  P1 : rate of work due to astro. forcing and earth tides

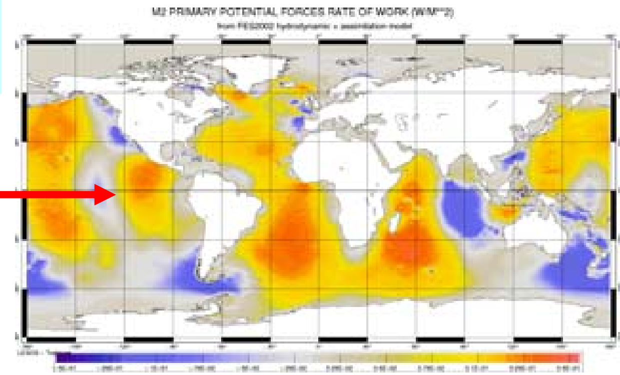
  P2: rate of work due to loading and self attraction

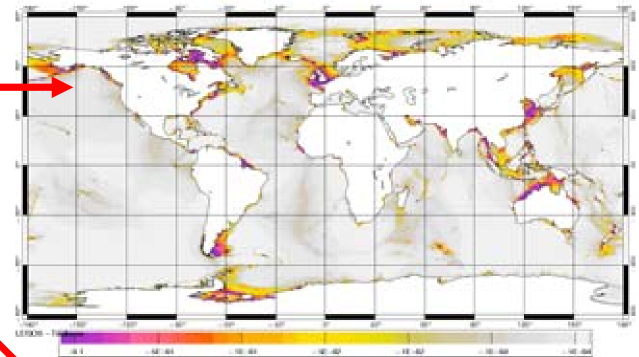
- D = D1 + D2 : local rate of dissipation

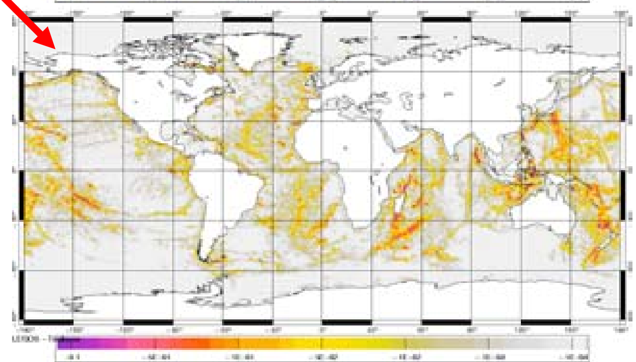
  D1: rate of dissipation by bottom friction

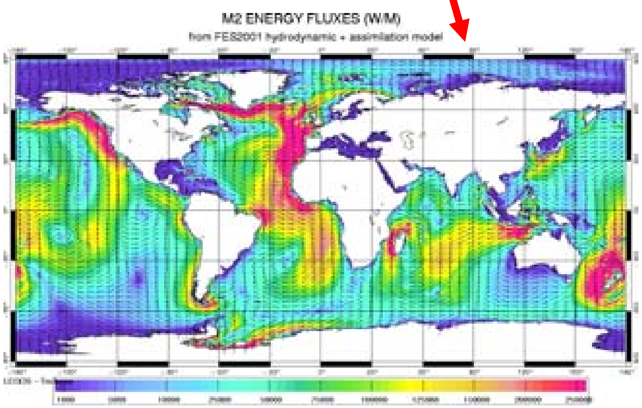
  D2: rate of work of internal wave drag

- F : local energy flux F = P + D









(W / m)

(W/m^2)

tidal dissipation and transfer from barotropic to baroclinic

For the M2 tide,

2/3 of the energy is dissipated by bottom friction,
mainly over continental shelves
1/3 of the energy is transferred to internal tides

M2(TW)	Total						
Egbert & Ray, 2003: TPXO.5	2.431	SW	1.649	(0.68)	Deep Ocean	0.782	(0.32)
GOT99				(0.74)			(0.26)
Lyard & Le Provost, 2002:	2.5	BF	1.8	(0.72)	Int.WaveDrag	0.7	(0.28)

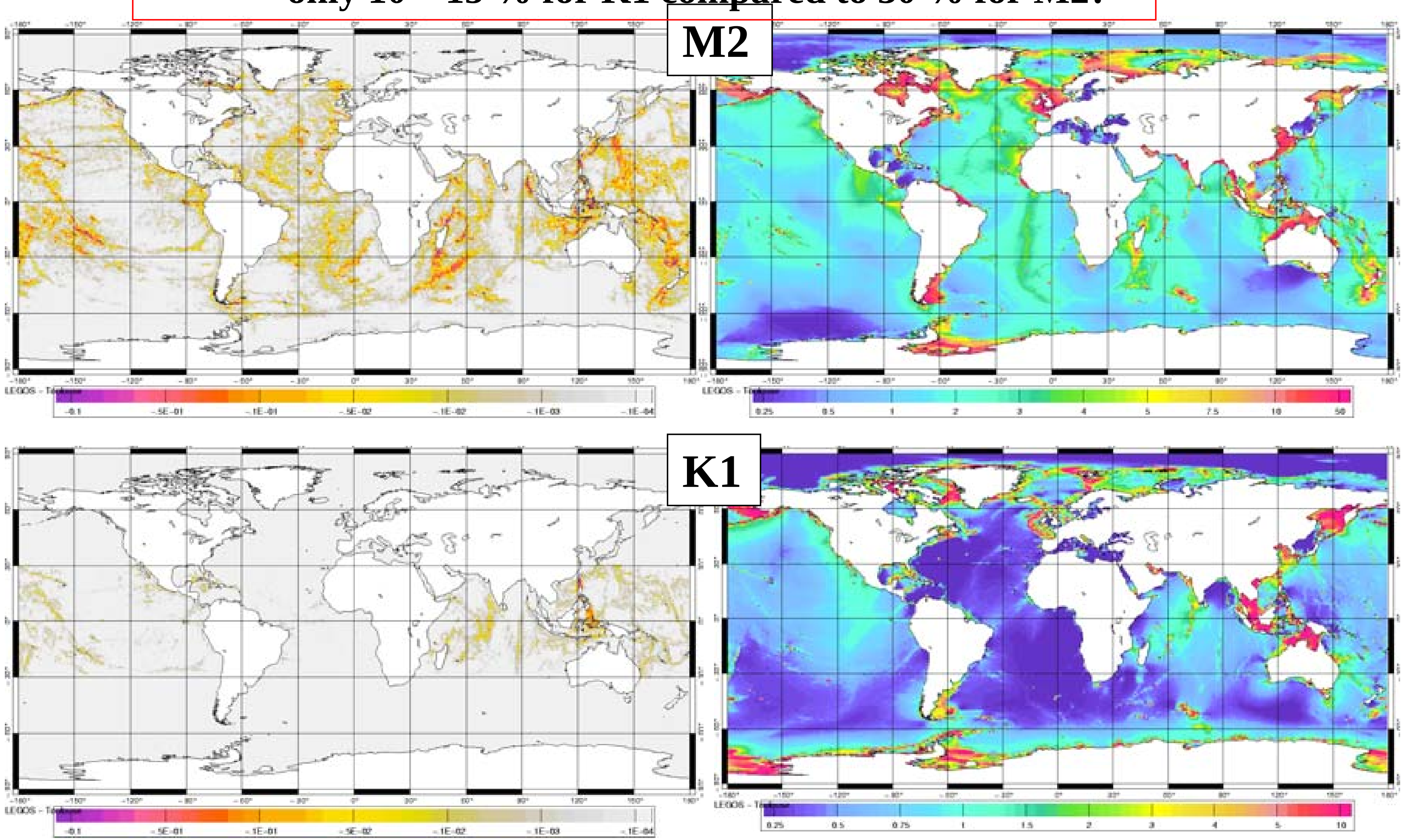
For the K1 tide,

85 - 90% of the energy is dissipated by bottom friction,
mainly over continental shelves

Only 10 - 15 % of the energy is transferred to internal tides

K1(TW)	Total						
Egbert & Ray, 2003: TPXO.5	0.343	SW	0.304	(0.89)	Deep Ocean	0.039	(0.113)
GOT99				(0.83)			(0.169)
Lyard & Le Provost, 2002:	0.3	BF	0.25	(0.83)	Int.Wave Drag	0.05	(0.17)

WHY , for barotropic to baroclinc energy transfer only 10 – 15 % for K1 compared to 30 % for M2?



For internal wave drag

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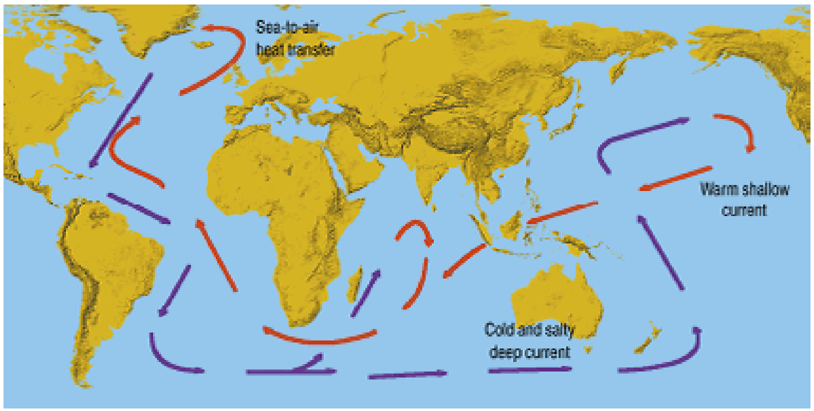
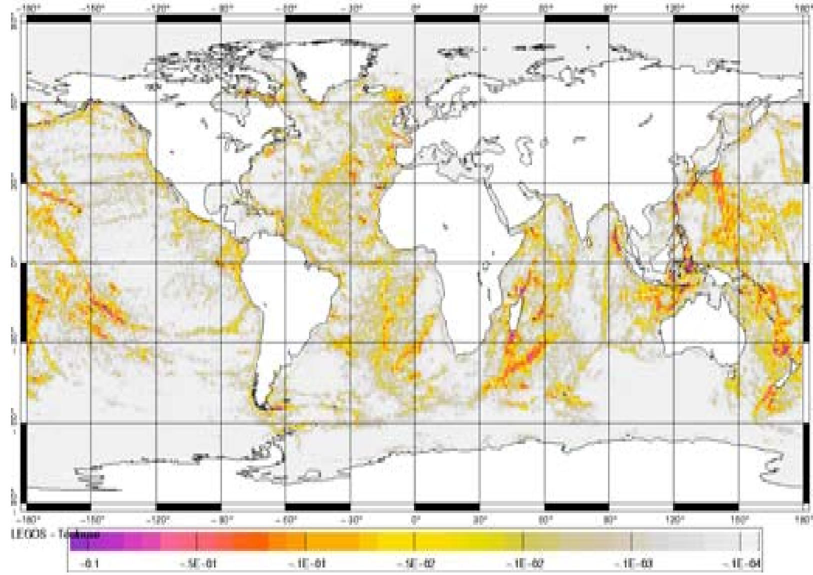
Ocean tides and Ocean general circulation

Munk and Wunsch (1998): *tidally induced ocean vertical mixing*





Preliminary studies on the impact of tidal mixing in ocean circulation models:

Schiller (2002) ➔ through bottom friction

water mass transformation in the Indonesian through flows

Simmons et al (2003) ➔ through internal waves

positive impact on global overturning, on the meridionl heat transport

on the global distribution of temperature and salinity

Conclusions: outstanding issues

Improvements at high latitudes needed

Improvements over continental shelf and coastal areas needed

Science

- topographic trapped waves: diurnal and long period (smaller scales)
- tides over shallow water areas: smaller scales and non linear constituents

Applications

- better predictions of sea level variations and currents (shipping, engineering)
- better tidal corrections for satellite altimetry

Investigations on internal tides need more work

Science : better understanding and parameterisation of global ocean mixing

Applications: baroclinic tidal currents (coastal modelling, offshore oil industry,…)

long time series (T / P + JASON 1) + (ERS + ENVISAT) & HR satellite altimetry