National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Deep Ocean Warming assessed from altimeters, GRACE, in-situ measurements, and a non-Boussinesq OGCM

Y. Tony Song (JPL)
Frank Colberg (CSIRO)

JGR-Oceans, **116**, doi:10.1029/2010JC006601 (2011).

1. Sea-Level Budget (Closed?)

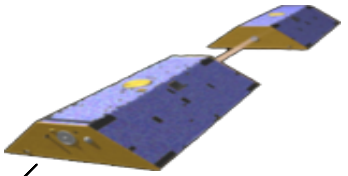
National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

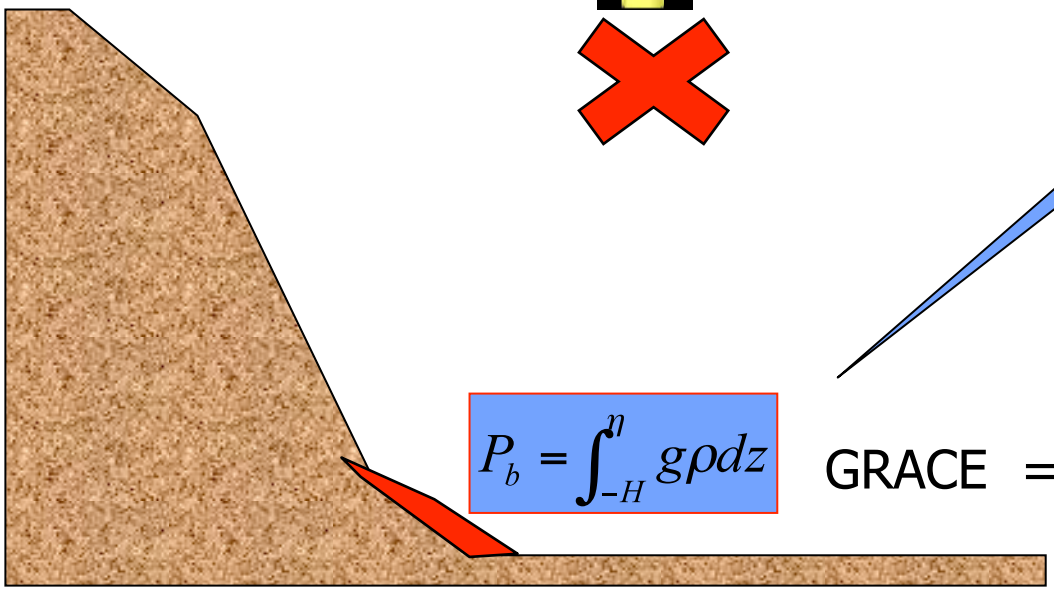
JPL

$$SL_{total} = SL_{steric} + SL_{mass}$$

Grace



Sea Surface Height



$$P_b = \int_{-H}^{\eta} g\rho dz$$

GRACE = mass + EQ + GIA

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

For Example

JPL

For GRACE period (2003-2008) :

- Lombard et al (2007): Altimeter (3.1 mm/yr) >> In-situ (-2.8) + GRACE (1.2)
- Willis et al (2008): Altimeter (3.2 mm/yr) >> Argo (-0.5) + GRACE (0.8)
- Leulliette & Miller (2009) : Altimeter (2.7 mm/yr) = Argo (0.8) + GRACE(0.8)
- Cazenave et al (2009): Altimeter (2.5 mm/yr) = Ago (0.3) + GRACE/Land water(2.0)
- Willis et al (2010): Altimeter (3.2 mm/yr) = Ago (1.2) + GRACE (1.3)

$$\frac{\partial(\eta-\eta^{ib})}{\partial t}=\left(-\frac{1}{\rho_0}\int_{-700m}^{0}\frac{\partial\rho}{\partial t}dz-\frac{1}{\rho_0}\int_{-K}^{-700m}\frac{\partial\rho}{\partial t}dz\right)+\frac{1}{g\rho_0}\frac{\partial P_b}{\partial t}$$

- Wu et al (2010): GRACE (0.5) Deep ocean warming (80% ocean water) has not been accounted for.

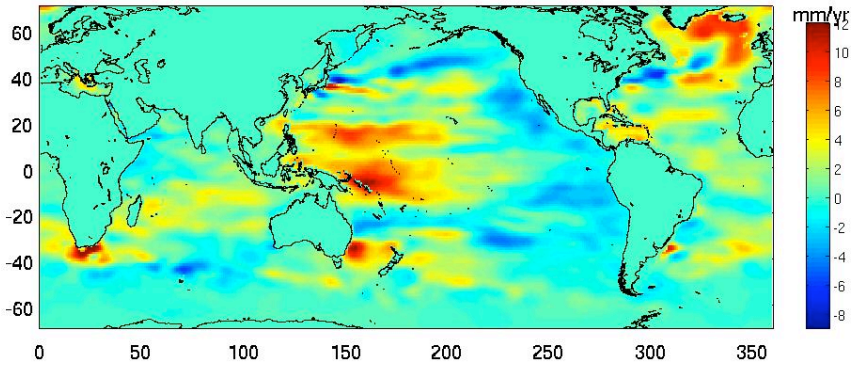
National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

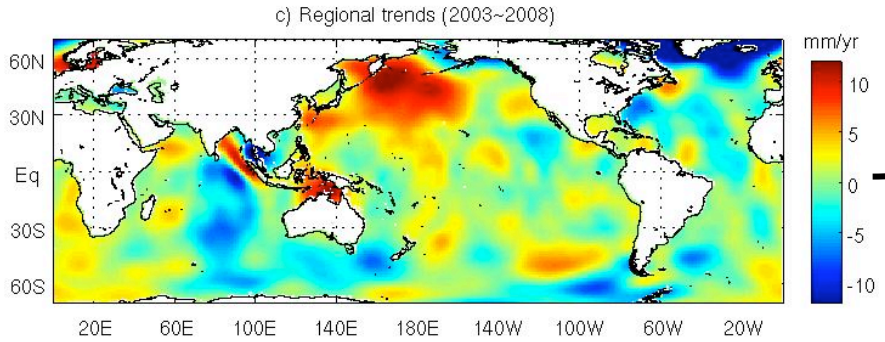
Another Example

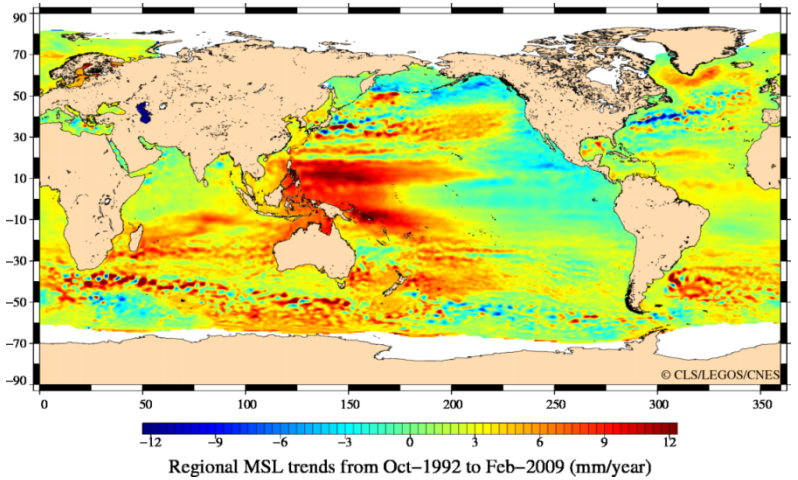
(linear trends do not close)

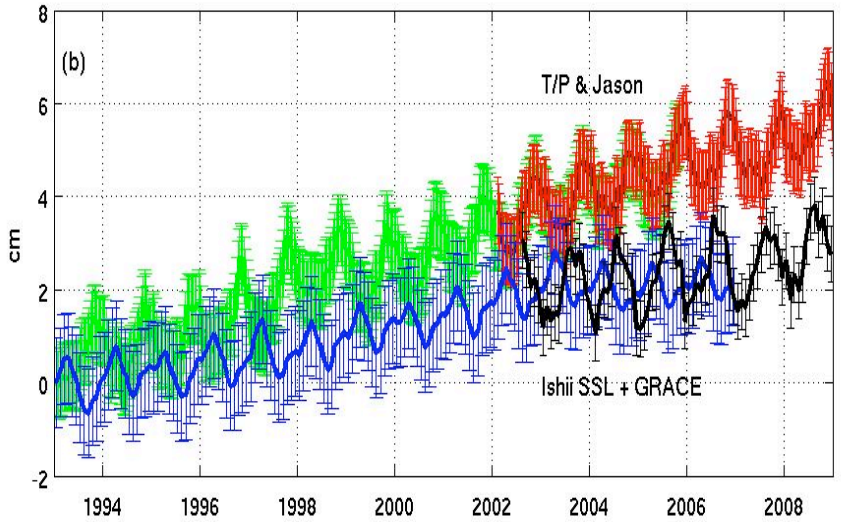
Regional SSL trends (1993-2008)



Regional GRACE trends (2003-2008)





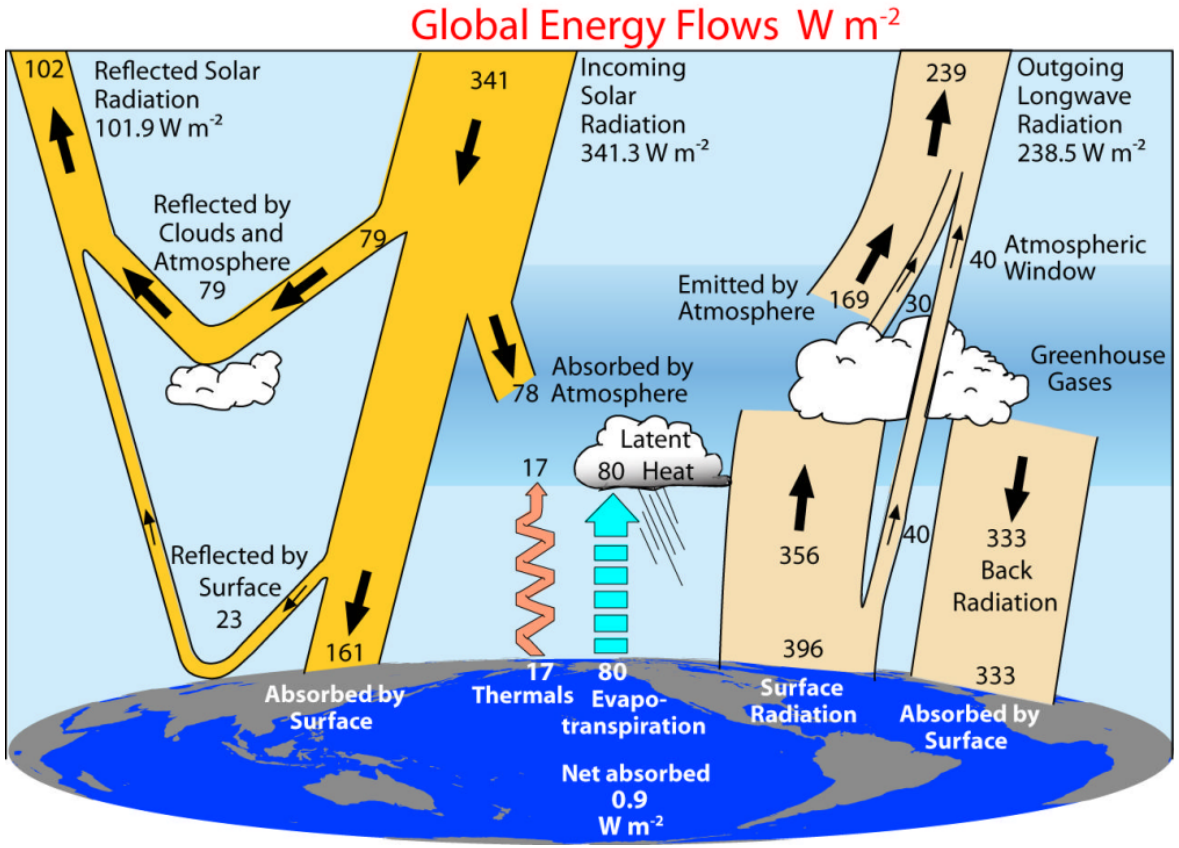


National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

2. Energy/Heat Budget (Closed?)

JPL



Heat flux: 0.9 ± 0.5 Wm-2 (Trenberth et al . 2008)

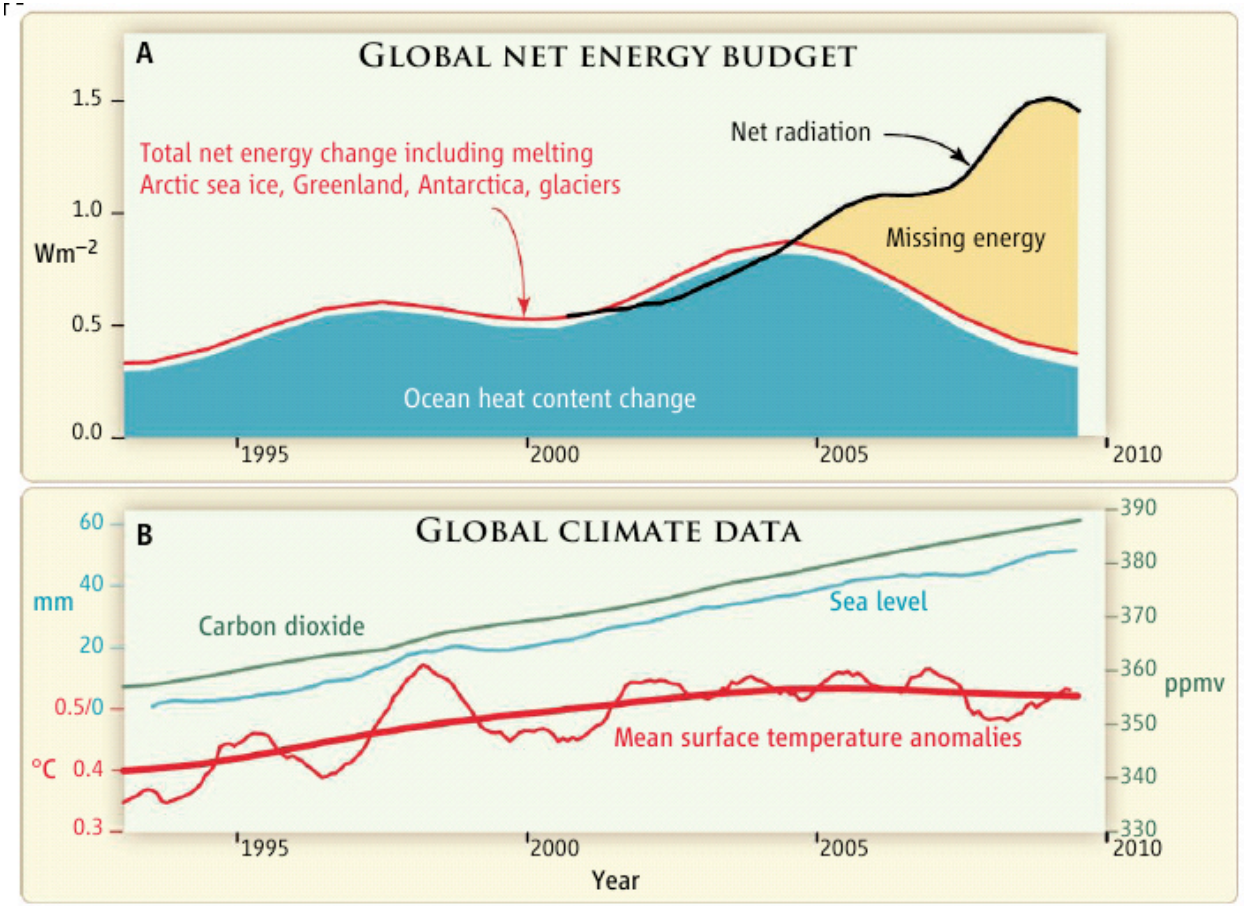
Gregory & Lowe (2000): 0.5~2.5

Hansen et al (2005): 0.85 ± 0.15

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

For Example



Trenberth et al (2008)

Trenberth & Fasullo (2010) : "Energy budget closure over the past 5 years is elusive".

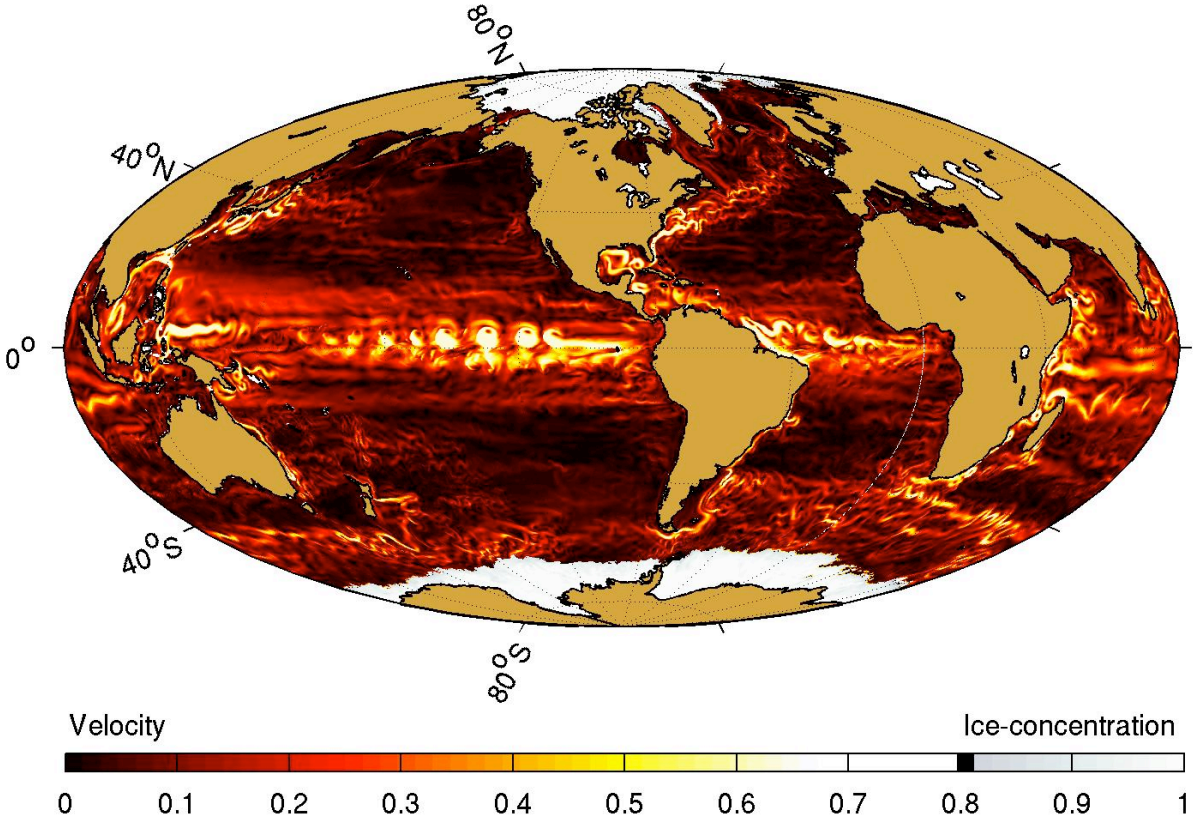
Murphy et al. (2009)

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

3. Diagnose deep-ocean Warming (Non-Boussinesq OGCM)

Song & Hou, *Ocean Modell*. 2006
Song et al, *AdGeo*. 2011



Heat flux (B. Barnier 1998):

- SST data
- NCEP flux

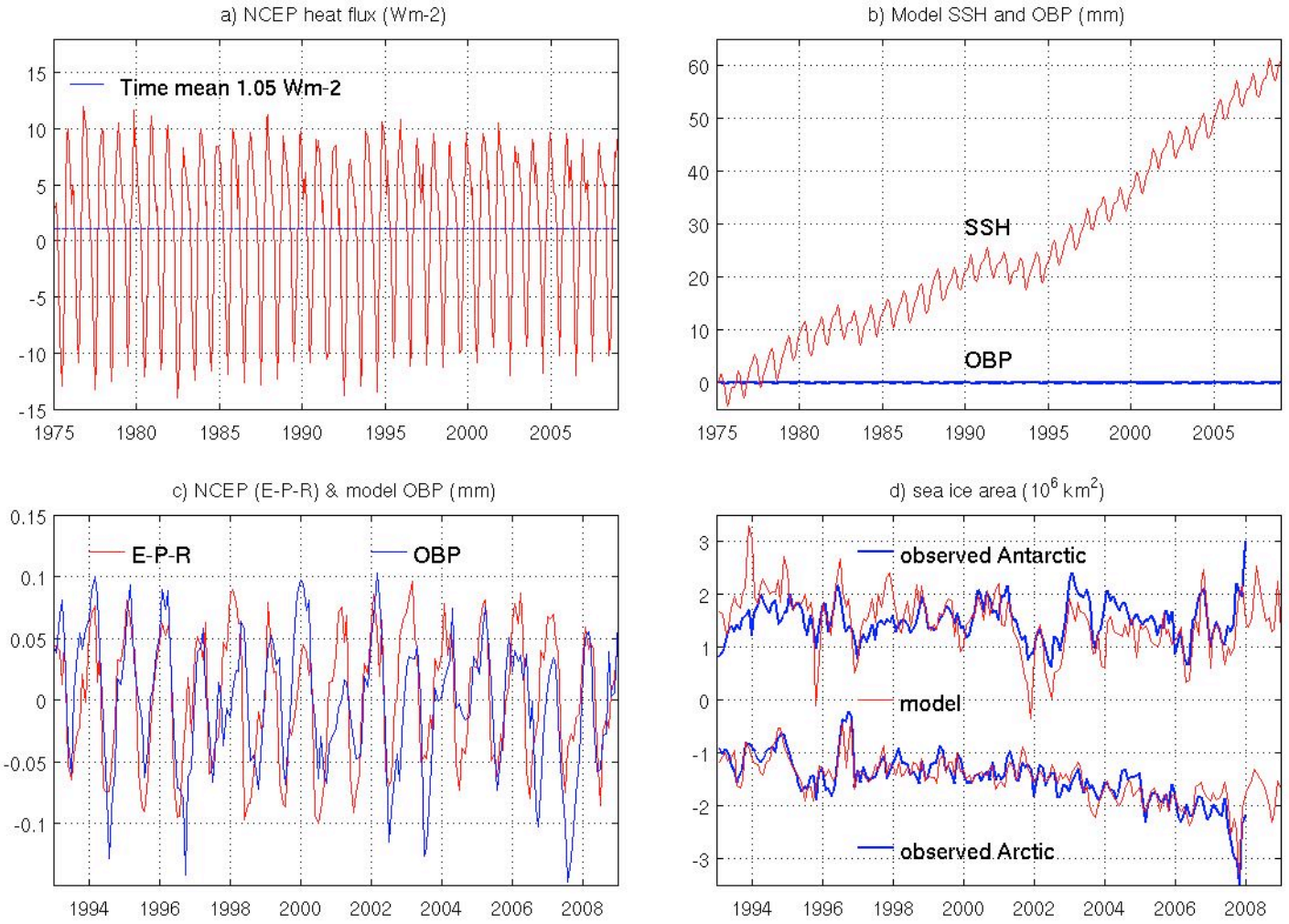
Freshwater flux:

- E-P+R=0;
- No land-based water

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technolog
Pasadena, California

3.1 Model Caliberation



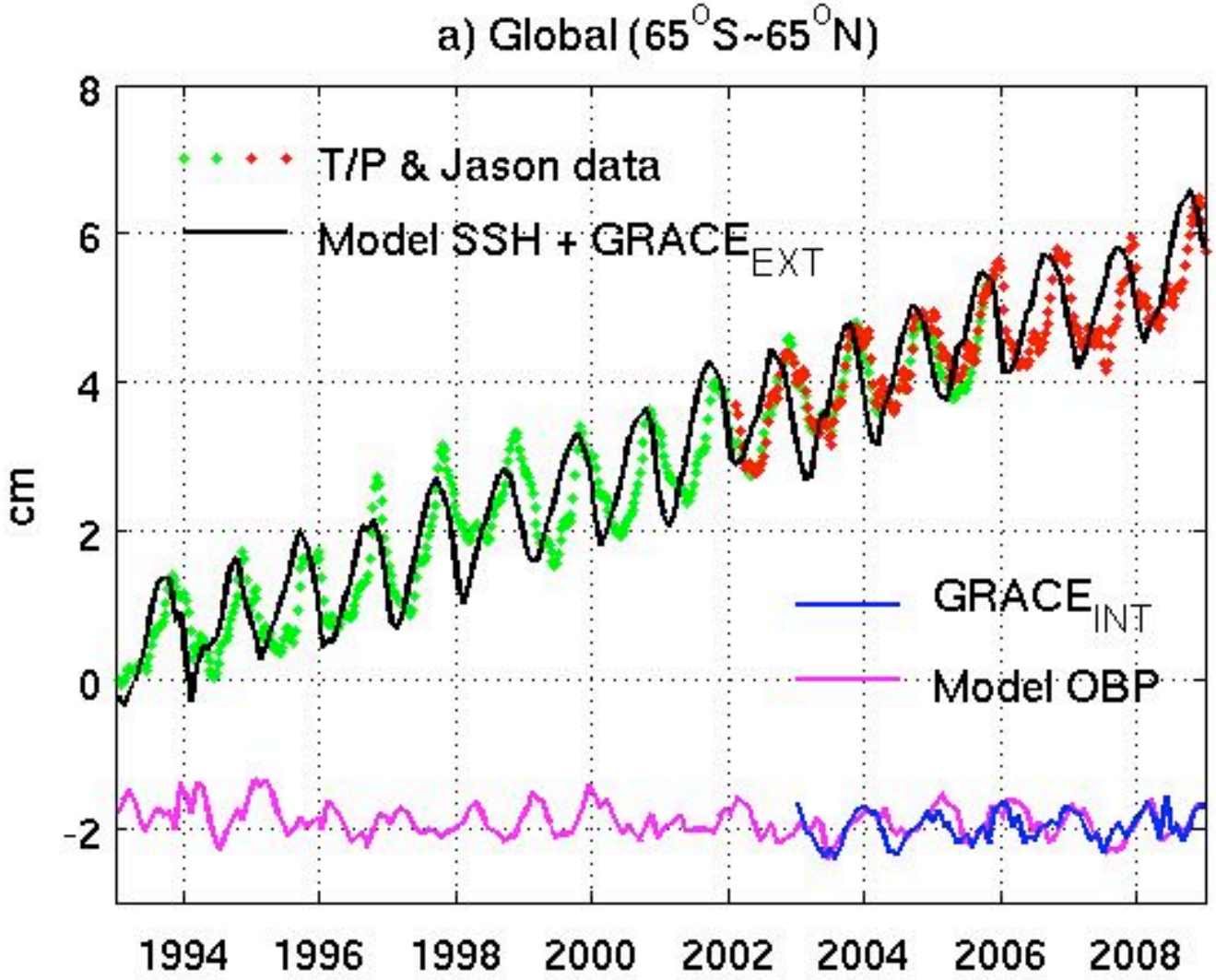
- Heat flux consistency: 1 Wm-2 ~ 1.3 mm/yr (Church et al 2010)
- Mass-conservation: accuracy 0.1 mm/yr (Wunsch et al 2007)
- Sea ice consistency

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

3.2 Compare with Altimetrs & GRACE

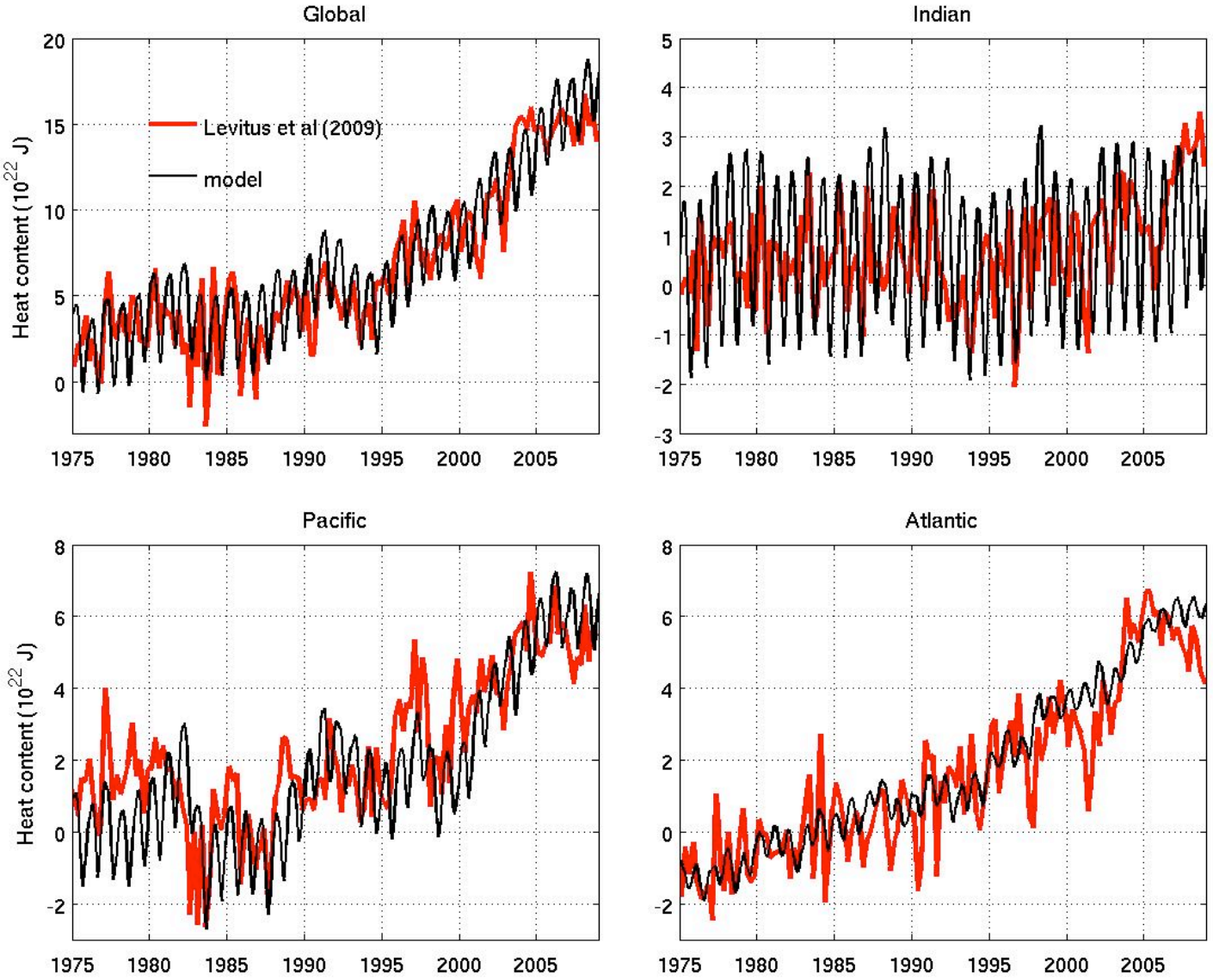
SSH = SSL + OBP_Ext + OBP_Int



National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technolog
Pasadena, California

3.3 Compare with heat content data

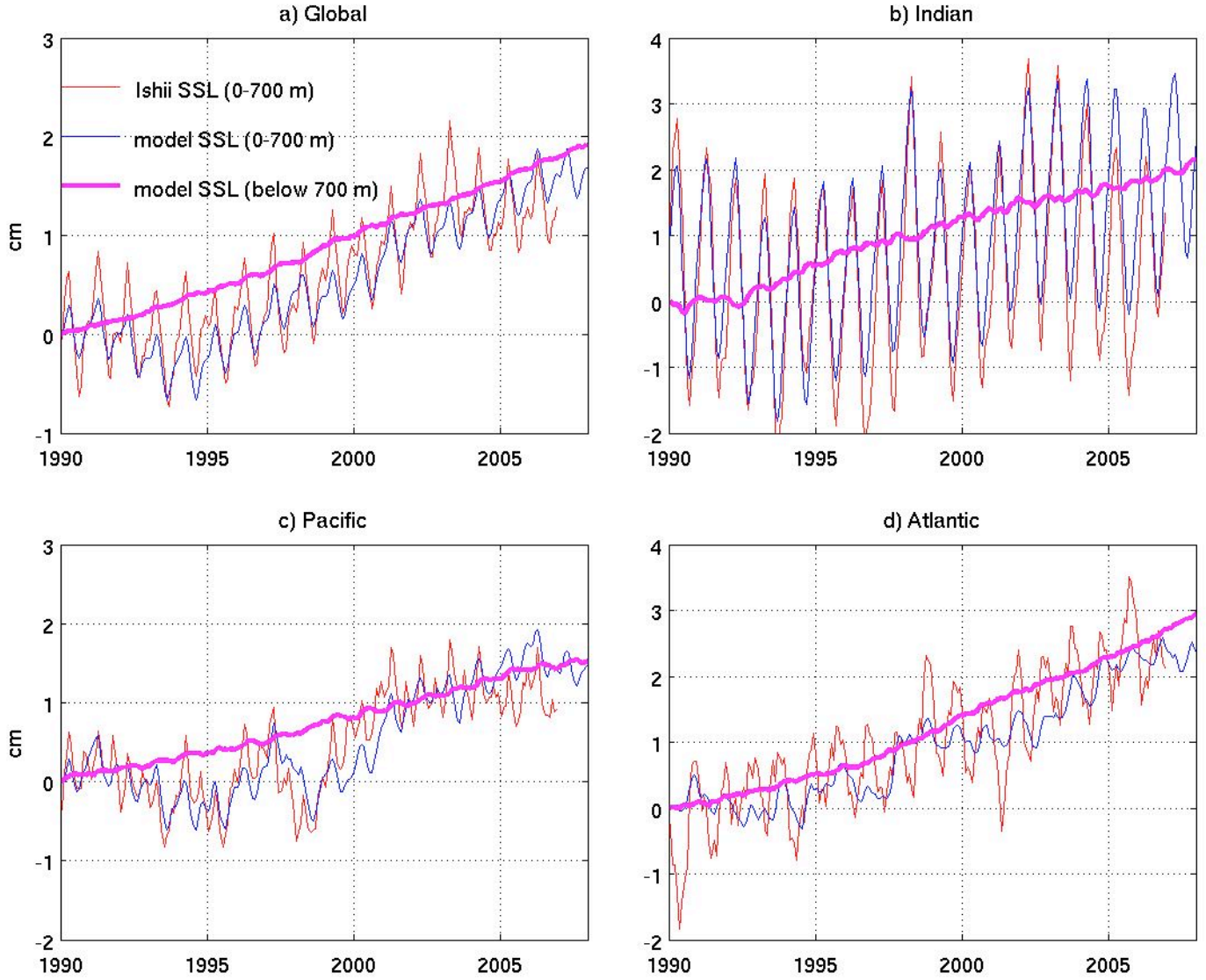


National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

3.4 Compare with Ishii SSL

$$SSL = \left(-\frac{1}{\rho_0}\int_{-700m}^{0} \frac{\partial \rho}{\partial t} dz - \frac{1}{\rho_0}\int_{-H}^{-700m} \frac{\partial \rho}{\partial t} dz \right)$$



3.5 Compare with Deep-Ocean measurements

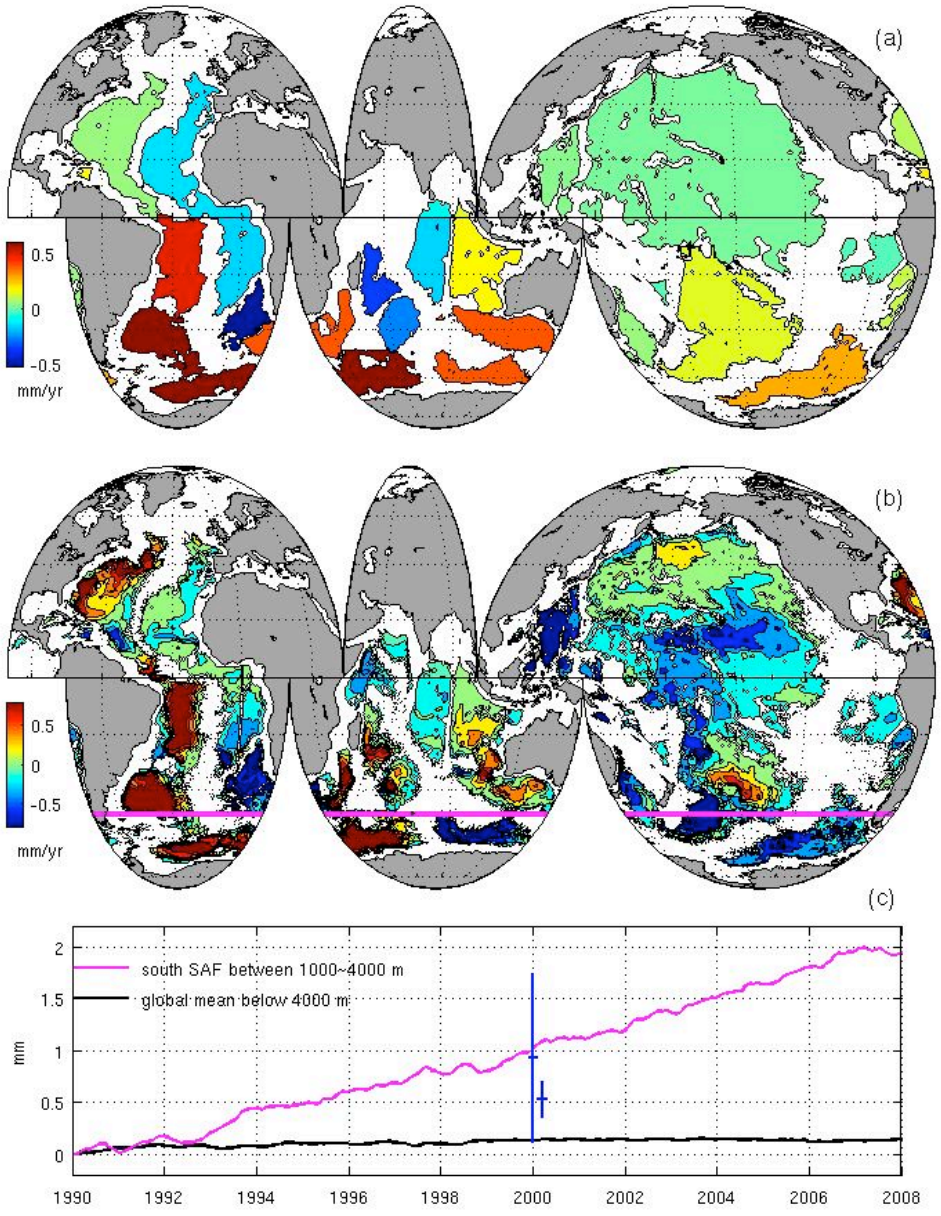
National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Purkey&Johnson

Model ⟶

Time series



National Aeronautics and Space Administration

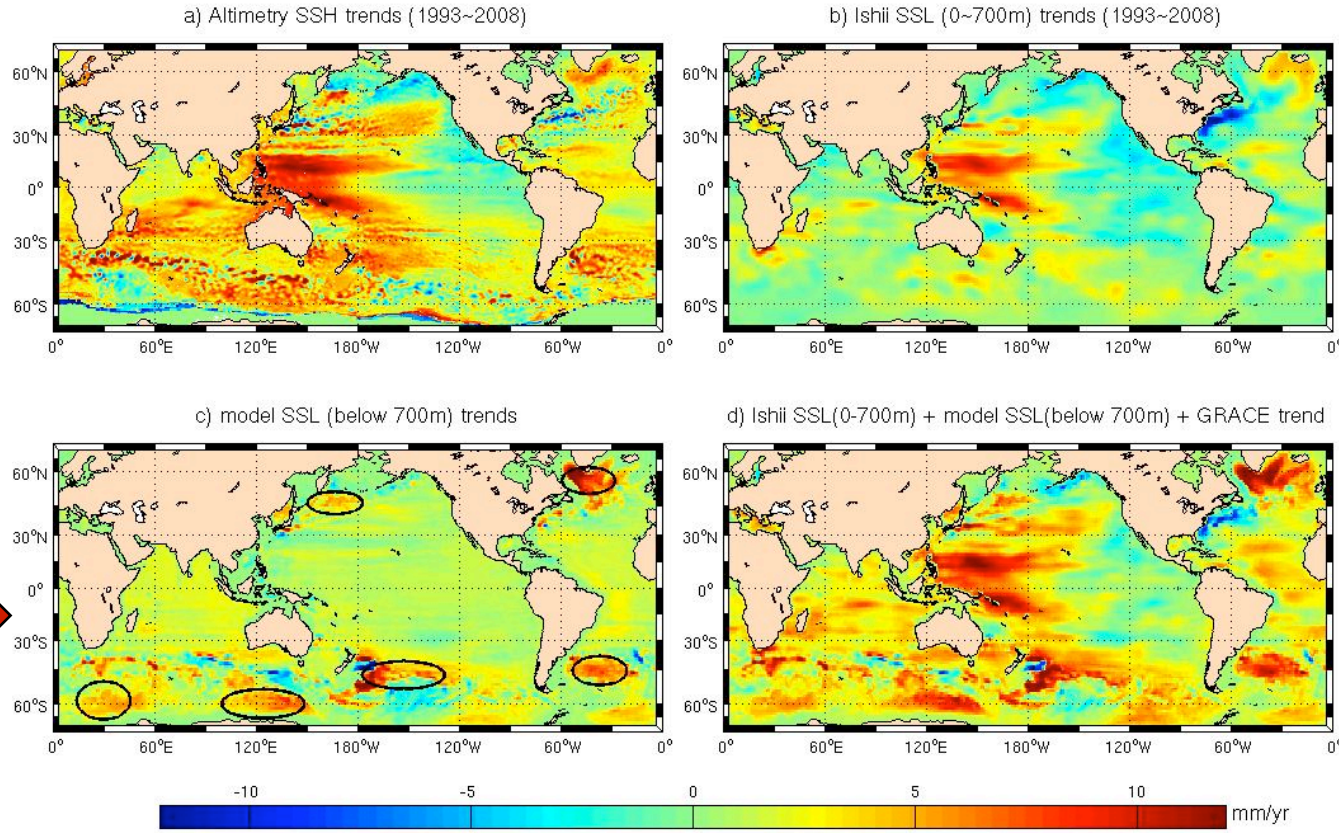
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

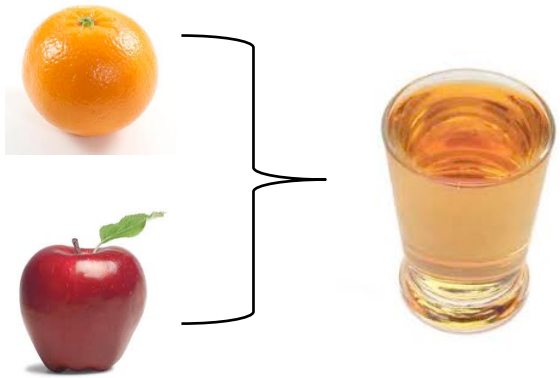
Regional Sea-Level Budget with Deep Oceans

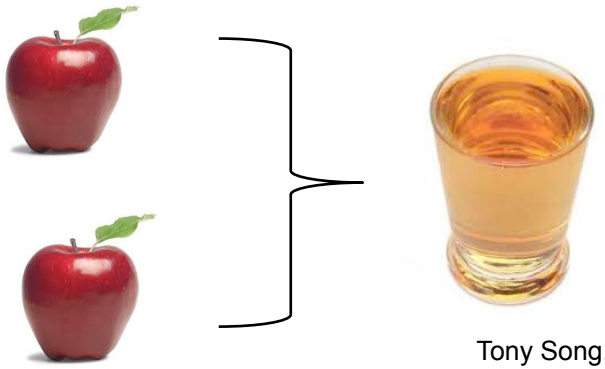
JPL

Altimetry (total)

Causes (with deep ocean)







National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Sea Level Budget

$$\frac{\partial(\eta-\eta^{ib})}{\partial t}=\left(-\frac{1}{\rho_0}\int_{-700m}^{0}\frac{\partial\rho}{\partial t}dz-\frac{1}{\rho_0}\int_{-H}^{-700m}\frac{\partial\rho}{\partial t}dz\right)+\frac{1}{g\rho_0}\frac{\partial P_b}{\partial t}$$

1. **2.** **3.**

Altimeter:		**3.1±06 mm/yr**
1.	0-700m:	1.2±0.8 mm/yr
2.	**Below 700m:**	**1.1 mm/yr**
3.	GRACE:	0.8±0.5 mm/yr

Purkey, S.G. and G.C. Johnson (2010). Warming of Global Abyssal and Deep Southern Ocean Waters between the 1990s an 2000s: Contributions to Global Heat and Sea Level Rise Budgets. *J. Climate*, **23**.

Kouketsu, S. et al (2011). Deep ocean heat content changes estimated from observations and reanalysis product and their influence on sea level change. *JGR-Oceans*, **116**.

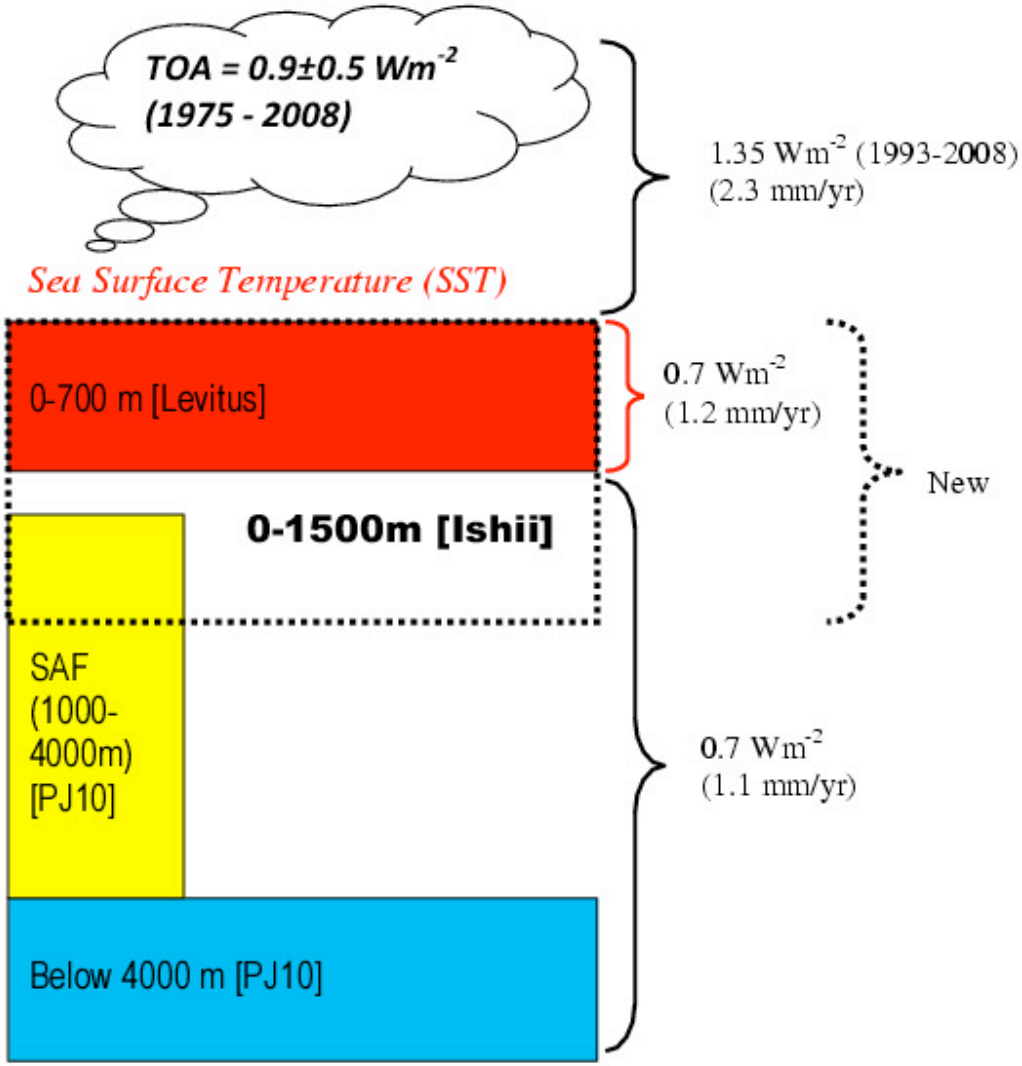
Church et al. (2011). Revising the Earth's sea-level and energy budgets from 1962-2008, GJR

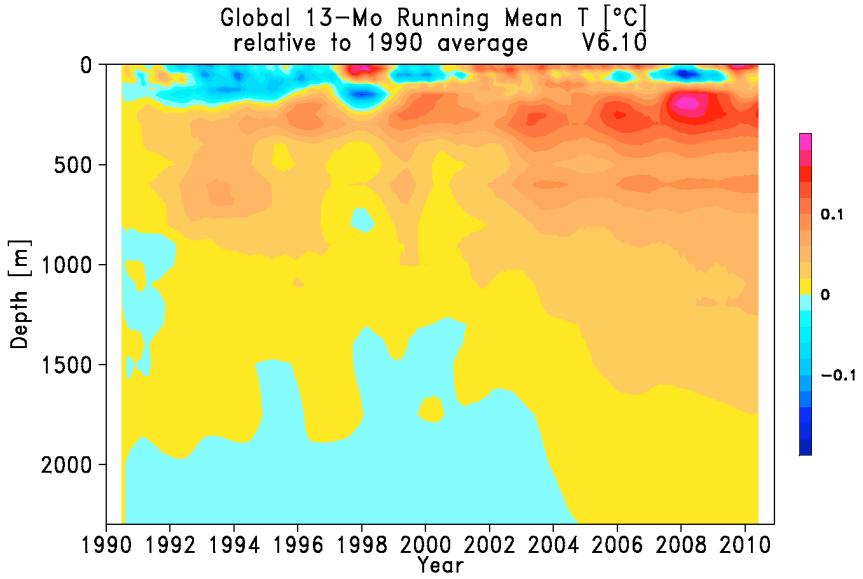
National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Summary

(Both sea-level and energy budgets have to be closed!)





Courtesy of Ishii