How we think about sea level in ocean climate models circa 2012: (a brief version)

Stephen.Griffies@noaa.gov

NOAA/GFDL
Princeton USA

Presentation at the CESM workshop
Breckenridge, Colorado

19 June 2012

Outline

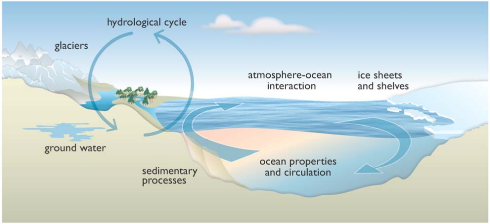
1. Sea level basics
2. Local steric effects
3. Non-Boussinesq steric effects
4. Physics of global mean sea level
5. Sea level in climate models circa 2022
6. Briefing GFDL ocean model development
7. Selected Bibliography

Outline

1. Sea level basics
2. Local steric effects
3. Non-Boussinesq steric effects
4. Physics of global mean sea level
5. Sea level in climate models circa 2022
6. Briefing GFDL ocean model development
7. Selected Bibliography

What impacts sea level?

- Ocean mass: fluxes from rivers, melting continental ice, precip, evap.
- Ocean density: *steric effects* change ocean volume w/o changing mass.
- Ocean currents: redistribute volume; no change to global sea level.
- Gravity and rotation: static equilibrium sea level determined by geophysical factors; e.g., mass distribution of ice sheets and ocean
- Evolving shorelines, ground water changes, post-glacial rebound (glacial isostatic adjustment), land use processes.



From Church et al. (2013) IPCC sea level chapter, in prep.

Three steric effects

- LOCAL STERIC EFFECT: changes sea level through changes in the depth integrated local time tendency of *in situ* density (Gill and Niiler 1973).
  - Commonly used to split sea level evolution into thermosteric, halosteric, and mass changes.
  - Can be use for both Boussinesq and non-Boussinesq oceans.
- GLOBAL STERIC EFFECT: arises from the time tendency of the global mean *in situ* density.
  - Missing in Boussinesq oceans.
  - The *de facto* means for diagnosing global mean sea level in volume conserving Boussinesq ocean model simulations.
  - Little insight regarding how physical processes impact global sea level.
- NON-BOUSSINESQ STERIC EFFECT: contributes to global mean sea level changes through changes in the depth integrated material time derivative of *in situ* density (Greatbatch 1994, Griffies and Greatbatch 2012).
  - Missing in Boussinesq oceans.
  - More complicated to diagnose this steric effect than the global steric.
  - Much insight regarding how physical processes impact global sea level.

Outline

1. Sea level basics
2. Local steric effects
3. Non-Boussinesq steric effects
4. Physics of global mean sea level
5. Sea level in climate models circa 2022
6. Briefing GFDL ocean model development
7. Selected Bibliography

Local steric effect for hydrostatic fluids Gill and Niiler (1973)

Time differentiating the hydrostatic balance $(p_{\mathrm{b}} - p_{\mathrm{a}}) = g \int_{-H}^{\eta} \rho \, \mathrm{d}z$ leads to

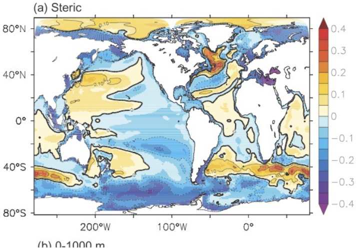
$$\frac{\partial \eta}{\partial t} = \underbrace{\frac{\partial_t \left(p_{\mathrm{b}} - p_{\mathrm{a}}\right)}{g \, \rho(\eta)}}_{\text{mass contribution}} \underbrace{- \frac{1}{\rho(\eta)} \int_{-H}^{\eta} \frac{\partial \rho}{\partial t} \, \mathrm{d}z}_{\text{local steric contribution}}$$

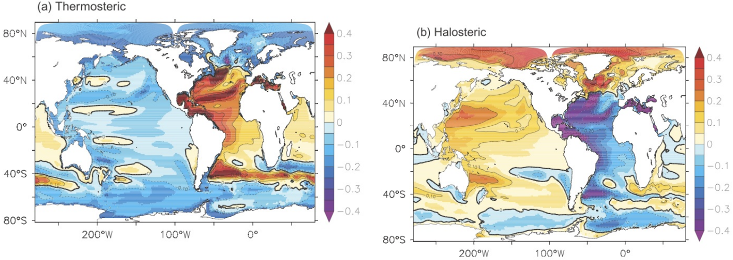
- Relates fluctuations in sea level to fluctuations in water mass (through bottom pressure) and fluctuations in density (local steric).
- Valid for Boussinesq and non-Boussinesq fluids.
- Partition into thermosteric and halosteric wrt a reference state

$$\eta^{\text{thermo}}(\tau) = \eta(\tau^r) - \frac{1}{\rho_o} \sum \mathrm{d}z \, [\rho(\Theta, S^r, p^r) - \rho(\Theta^r, S^r, p^r)],$$

$$\eta^{\text{halo}}(\tau) = \eta(\tau^r) - \frac{1}{\rho_o} \sum \mathrm{d}z \, [\rho(\Theta^r, S, p^r) - \rho(\Theta^r, S^r, p^r)],$$

GFDL/CM2.1 thermo & halo steric Yin, Griffies, Stouffer (2010)





- Lots of compensation
- Similar Atlantic pattern seen in obs (Paul Durack, personal comm).

Mass loading on shelves and ocean warming

Landerer et al. (2007) and Yin, Griffies, and Stouffer (2010)

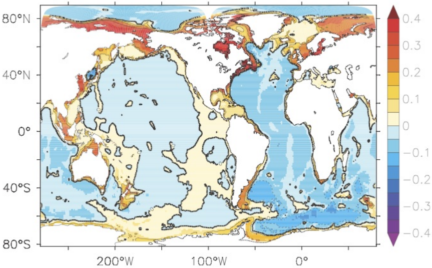


FIG. 12. The SLR (m) induced by ocean mass redistribution during 2091–2100 in the A1B scenario run of CM2.1. The values are calculated as $\Delta(p_b - p_a)/\rho_0 g$.

- Heat penetration to deep ocean leads to larger local steric effect than shallow shelves: simply more water to warm.
- Associated higher dynamic topography in deep ocean.
- Mass adjusts to compensate dynamic topography gradients, leading to more mass on shelves.
- An intriguing fingerprint of deep ocean warming is the corresponding increase in mass on continental shelves.

Outline

1. Sea level basics
2. Local steric effects
3. Non-Boussinesq steric effects
4. Physics of global mean sea level
5. Sea level in climate models circa 2022
6. Briefing GFDL ocean model development
7. Selected Bibliography

Oceanographer's kinematic sea level equation

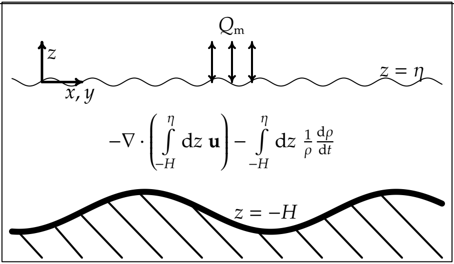
Greatbatch 1994; Griffies & Greatbatch 2012

Lagrangian form of mass conservation

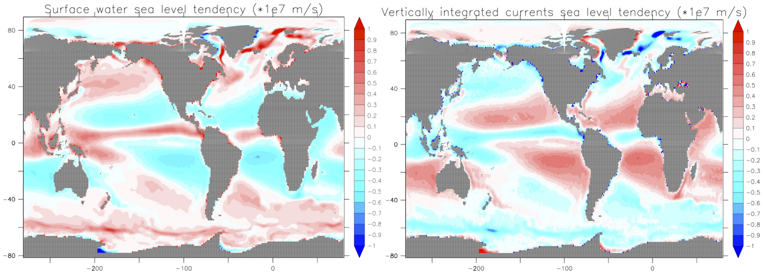
$$\frac{1}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\nabla \cdot \mathbf{v}.$$

Integrate over a fluid column & surface & bottom boundary conditions:

$$\boxed{\frac{\partial \eta}{\partial t} = \underbrace{\left(\frac{Q_{\mathrm{m}}}{\rho(\eta)}\right) - \nabla \cdot \left(\int_{-H}^{\eta} \mathrm{d}z\,\mathbf{u}\right) - \int_{-H}^{\eta} \mathrm{d}z\,\frac{1}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}t}.}_{\text{surface mass flux + converging horz currents + non-Bouss steric effect}}}$$



Low frequency balance: mass flux + convergence ≈ 0

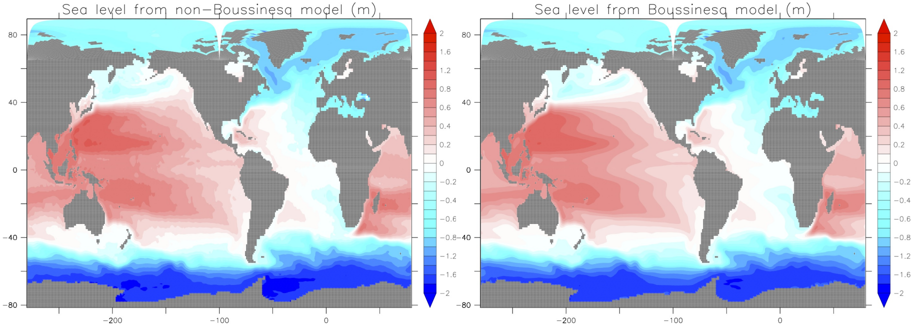


$$\frac{Q_{\mathrm{m}}}{\rho(\eta)} \qquad\qquad -\nabla\cdot\left(\int_{-H}^{\eta}\mathrm{d}z\,\mathbf{u}\right)$$

Balance suggests the utility of the Boussinesq approximation, in which we drop non-Boussinesq steric effect

$$\boxed{\frac{\partial\eta^{\mathrm{B}}}{\partial t} = \underbrace{\left(\frac{Q_{\mathrm{m}}}{\rho_o}\right) - \nabla\cdot\left(\int_{-H}^{\eta}\mathrm{d}z\,\mathbf{u}\right)}_{\text{mass flux + converging currents}}.}$$

Non-Boussinesq pattern ≈ Boussinesq pattern



Non-Boussinesq steric term acts on sea level similarly to surface mass flux.

- Both mass flux and non-Boussinesq steric effect initiate a barotropic response that adjusts global mean sea level (e.g., Greatbatch 1994).
- Low frequency patterns largely unaffected by non-Boussinesq steric.

Outline

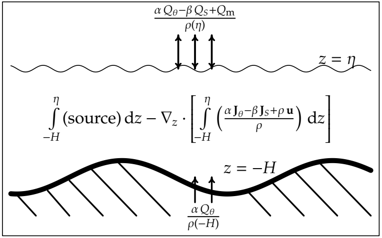
1. Sea level basics
2. Local steric effects
3. Non-Boussinesq steric effects
4. **Physics of global mean sea level**
5. Sea level in climate models circa 2022
6. Briefing GFDL ocean model development
7. Selected Bibliography

Unpacked global sea level equation Griffies & Greatbatch 2012

$$\mathcal{A}\,\partial_t\,\overline{\eta} = \underbrace{\int_{\text{globe}} \left(\mathbf{J}^{(\Theta)} \cdot (\alpha/\rho) - \mathbf{J}^{(S)} \cdot (\beta/\rho) - \frac{\omega}{\rho\, c^2_{\text{sound}}} \right) \mathrm{d}V.}_{\text{source term from SGS fluxes plus motion across pressure surfaces}}$$

$$+ \underbrace{\int_{\text{globe}(z\,=\,\eta)} \mathrm{d}A \left(\frac{\alpha\, Q^{(\Theta)} - \beta\, Q^{(S)} + Q_{\text{m}}}{\rho} \right)}_{\text{surface buoyancy plus mass fluxes}} + \underbrace{\int_{\text{globe}(z\,=\,-H)} \mathrm{d}A \left(\frac{\alpha\, Q^{(\Theta)}}{\rho} \right)}_{\text{geothermal heating}}$$

All terms, except mass flux Q_{m}, arise from non-Boussinesq steric effect.



Effects on global mean sea level from SGS processes

- FLUX PROJECTION FORM

$$\boxed{\text{sgs source} = \mathbf{J}^{(\Theta)} \cdot \nabla(\alpha/\rho) - \mathbf{J}^{(S)} \cdot \nabla(\beta/\rho)}$$

  - Most important term is temperature, due to large variations in α.
  - Poleward heat transport moves heat to regions of smaller α, as does vertical diffusion into the abyss

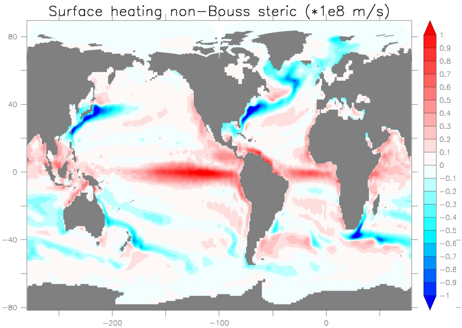
$$\boxed{\mathbf{J}^{(\Theta)} \cdot \nabla(\alpha/\rho) < 0.}$$

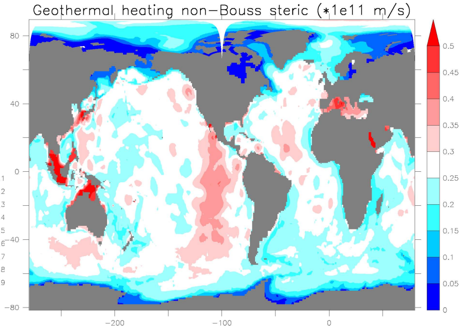
- WEIGHTED FLUX DIVERGENCE FORM

$$\boxed{\text{sgs source} = -(\alpha/\rho)\, \nabla \cdot \mathbf{J}^{(\Theta)} + (\beta/\rho)\, \nabla \cdot \mathbf{J}^{(S)}}$$

  - Differs by a total divergence from the flux projection form.
  - Useful to analyze both forms.

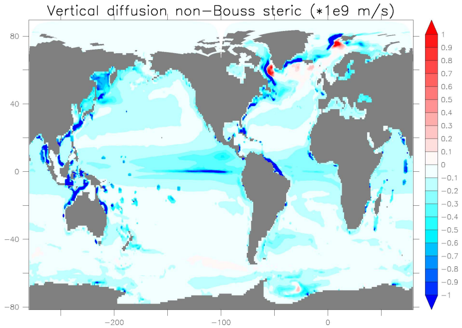
Boundary heat fluxes


Surface heating non−Bouss steric (∗1e8 m/s)


Geothermal heating non−Bouss steric (∗1e11 m/s)

- Boundary currents and tropics are key regions.
- Geothermal heating is locally $\approx$ 1000 smaller than surface heating.
- Thermal expansion coefficient $\approx$ 10 times larger in tropics than high latitudes
  - Tropical heating is more effective at increasing sea level than high latitude cooling is at reducing.
  - Ocean physical processes (e.g., eddy transport and mixing) close budget by moving heat to regions of smaller α.

Vertical diffusion (including convection)

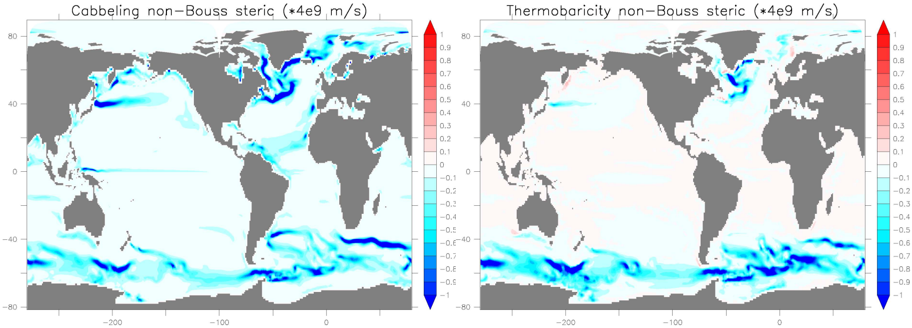


For vertical diffusion, the non-Boussinesq steric effect source term is

$$\boxed{\mathbf{J}^{(\Theta)} \cdot \nabla \nu_{,\Theta} + \mathbf{J}^{(S)} \cdot \nabla \nu_{,S} = -D\,N^2\,\left((N/g)^2 + c_{\text{sound}}^{-2}\right) - D\,(\partial_z \alpha\,\partial_z \Theta - \partial_z \beta\,\partial_z S).}$$

- Most regions see reduction of sea level upon vertical mixing.
- Dominant term is $\partial_z \alpha\,\partial_z \Theta$.
- Note mixing raises column center of mass but reduces sea level.

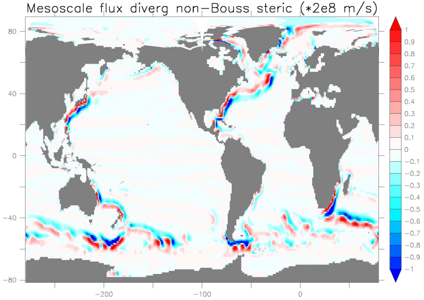
Neutral diffusion (cabbeling and thermobaricity)



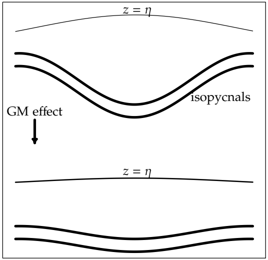
$$\boxed{\mathbf{J}^{(\Theta)} \cdot \nabla \nu_{,\Theta} + \mathbf{J}^{(S)} \cdot \nabla \nu_{,S} = \underbrace{-\mathcal{C}\, A_{\text{nd}}\, (\nabla_\gamma \Theta)^2}_{\text{cabbeling}} \underbrace{-\mathcal{T}\, A_{\text{nd}}\, \nabla_\gamma p \cdot \nabla_\gamma \Theta}_{\text{thermobaricity}} .}$$

- Cabbeling coefficient $\mathcal{C} > 0$, so cabbeling reduces global mean sea level.
- Thermobaricity is not sign definite, yet mostly reduces sea level.

Gent-McWilliams



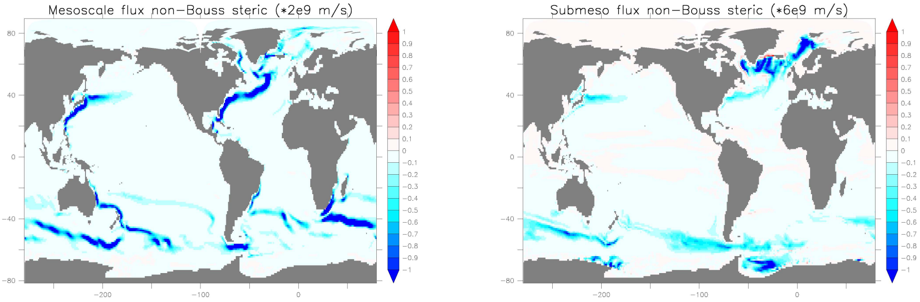
Mesoscale flux diverg non−Bouss steric (*2e8 m/s)



$$\boxed{\text{GM source} = -\left(\frac{N^2}{\rho\, g}\right) \nabla_\gamma \cdot (\rho\, A_{\text{gm}}\, \nabla_\gamma\, z)}$$

- GM diffuses isopycnal depth (generally distinct from thickness diffusion).
- Erodes curvature in depressed isopycnals by raising γ surfaces, which produces a negative non-Boussinesq steric effect.

Downgradient α for GM and submesoscale



Diagnosed as flux projected into gradients of α and β

$$\mathbf{J}^{(\Theta)} \cdot \nabla(\alpha/\rho) - \mathbf{J}^{(S)} \cdot \nabla(\beta/\rho)$$

- Reduces global mean sea level.
- Largely a result of heat fluxes directed down the gradient of α.

Global budget for sea level (or global volume)

- Conserved ocean scalars: mass, heat, salt
  - Volume is not a conserved scalar in the ocean.
  - Diagnosing terms contributing to volume budget is not straightforward.
- Global sea level budget in a non-Boussinesq ocean-ice CORE simulation
  - Long-term mean balance between sea level rise from surface fluxes and sea level drop from heat fluxes moving down gradient of α:

$$\boxed{\text{surface heat fluxes} \approx \text{SGS fluxes down } \alpha \text{ gradient}}$$

- Time for reaching this balance depends on multiple physical processes.
- How will physical processes respond under climate change and thus impact global mean sea level?
  - Changes in boundary forcing impart changes to physical processes (e.g., eddies and mixing).
  - Sea level budget altered even without changes to water fluxes.
  - Ongoing research

Details of sea level global budget

CONTRIBUTION	SECTION	FIGURE	GLOBAL OCEAN MEAN TENDENCY (M/YEAR)
precipitation	2.3	2	1×10^{0}
surface shortwave + penetration	3.4.1	7	3×10^{-1}
river runoff	2.3	2	1×10^{-1}
vertical motion	3.2	4	7×10^{-4}
river mixing	3.4.1	-	6×10^{-4}
geothermal heat	3.4.1	8	8×10^{-5}
Joule heat (not in model)	3.4.1	-	4×10^{-6}
frazil sea ice	3.4.1	7	6×10^{-7}
ice/ocean salt flux	3.4.2	9	6×10^{-7}
evaporation	2.3	2	-1×10^{0}
surface latent	2.3	2	-2×10^{-1}
surface longwave	2.3	2	-1×10^{-1}
surface sensible	2.3	2	-2×10^{-2}
vertical diffusion	5.1	10	-5×10^{-3}
meoscale param	7	13	-2×10^{-3}
cabbeling	6.6	12	-8×10^{-4}
boundary horiz diffusion	6.8	12	-7×10^{-4}
thermobaricity	6.7	12	-5×10^{-4}
KPP non-local mixing	5.2	10	-3×10^{-4}
numerical B-grid smoothing	B2	-	-3×10^{-4}
submesoscale	7	13	-2×10^{-4}
overflow and exchange mixing	B2	-	-1×10^{-4}
salt restoring	B1	9	-3×10^{-5}
net surface buoyancy	3.4.1	7	9×10^{-3}
net subgrid scale	-	-	-9×10^{-3}
net surface water	3.4.1	2	8×10^{-4}
vertical motion	3.2	4	7×10^{-4}
sea level trend	-	-	3×10^{-4}
residual=buoy+water+sgs+vert motion-trend	-	-	1×10^{-3}

Outline

1. Sea level basics
2. Local steric effects
3. Non-Boussinesq steric effects
4. Physics of global mean sea level
5. Sea level in climate models circa 2022
6. Briefing GFDL ocean model development
7. Selected Bibliography

Maturity feasible in coupled climate models circa 2022

order of increasing difficulty

- non-Boussinesq
  - capture full steric effects
  - useful for analysis and coupling to gravity models
  - not critical, but reasonably simple and convenient
- Inverse barometer
  - sea ice: now done by many free surface models (e.g., GFDL)
  - atmosphere: not done by any coupled model (perhaps I am wrong).
- Ocean surface gravity waves
  - of interest for coastal planning and impacts (e.g., beach erosion)
  - changes in wave climate can impact sea-ice barriers buffering land ice
- ice shelves: as per Bill Lipscomb's talk
  - gravitational effects from ice-sheets (self-attraction and loading effects); may have feedbacks to ocean circulation and grounding lines
  - ocean-ice shelf interactions with moving land-sea boundary
- Other effects perhaps sufficient to do *a posteriori*
  - Glacial isostatic adjustment; slow and small
  - Ground water extraction and dams; societal modeling/scenarios

Outline

1. Sea level basics
2. Local steric effects
3. Non-Boussinesq steric effects
4. Physics of global mean sea level
5. Sea level in climate models circa 2022
6. **Briefing GFDL ocean model development**
7. Selected Bibliography

Briefing on GFDL ocean model development

- Single ocean code
  - GFDL no longer has two distinct ocean code development paths.
  - MOM and GOLD developers (Adcroft, Griffies, and Hallberg) initiating core, physics, and diagnostics merger.
  - Starting point is MOM5.0.0 (release Jul2012); ending point is MOM6.0.0.
- Various intermediate versions of MOM5 on path to MOM6
  - B and C grid options
  - Software engineering: restructure for efficiency, anticipated computer platforms, and needs of bringing in the GOLD core
  - Parameterizations, such as work with NCAR/LANL on vertical physics
  - Diagnostics and documentation
- Mature merged MOM/GOLD cores and physics will define MOM6.0.0.
  - Full documentation
  - Many test cases
  - Functionality of MOM4 and GOLD plus more, given the inevitable improvements associated with code rewrites and head banging.
- Priorities and timelines remain to be determined.
  - Heaps of large and small details to be fleshed out.
  - Requirements: mindful research and coding as well as some mindless recoding.

Outline

1. Sea level basics
2. Local steric effects
3. Non-Boussinesq steric effects
4. Physics of global mean sea level
5. Sea level in climate models circa 2022
6. Briefing GFDL ocean model development
7. Selected Bibliography

Selected Bibliography

1. Gent, P.R., J. Willebrand, T. J. McDougall, and J. C. McWilliams, 1995: Parameterizing eddy-induced tracer transports in ocean circulation models, *Journal of Physical Oceanography*, **25**, 463–474.
2. Gill, A.E. and P.P. Niiler, 1973: The theory of the seasonal variability in the ocean, *Deep-Sea Research*, **20**, 141–177.
3. Greatbatch, R.J., 1994: A note on the representation of steric sea level in models that conserve volume rather than mass, *Journal of Geophysical Research*, **99**, 12767–12771.
4. Griffies, S.M., and R.J. Greatbatch, 2012: Physical processes that impact the evolution of global mean sea level in ocean climate models, *Ocean Modelling*, **51**, 37–72, doi:10.1016/j.ocemod.2012.04.003.
5. Kopp, R.E., J. X. Mitrovica, S.M. Griffies, J. Yin, C. C. Hay, R. J. Stouffer, 2010: The impact of Greenland melt on regional sea level: a preliminary comparison of dynamic and static equilibrium effects, *Climatic Change Letters*, **103**, 619–625.
6. Landerer, F.W., J.H. Jungclaus, and J. Marotzke, 2007: Regional dynamic and steric sea level change in response to the IPCC-A1B Scenario, *Journal of Physical Oceanography*, **37**, 296–312.
7. Lorbacher, K., S. J. Marsland, J. A. Church, S. M. Griffies, and D. Stammer, 2012: Rapid barotropic sea level rise from simulated ice-sheet melting scenarios, doi:10.1029/2011JC007733, *Journal of Geophysical Research*.
8. Mitrovica, J. X., 2001: Recent mass balance of polar ice sheets inferred from patterns of global sea-level change. *Nature*, **409**, 1026–1029.
9. Stammer, D., 2008: Response of the global ocean to Greenland and Antarctic ice melting, *Journal of Geophysical Research*, **113**, doi:10.1029/2006JC004079.
10. J. Yin, M. Schlesinger, and R.J. Stouffer, 2009: Model projections of rapid sea-level rise on the northeast coast of the United States Century Projections, *Nature Geosciences*, **2**, 262–266.
11. J. Yin, S.M. Griffies, and R.J. Stouffer, 2010: Spatial Variability of Sea-Level Rise in 21st Century Projections, *Journal of Climate*, **23**, 4585–4607.
12. Different magnitudes of projected subsurface ocean warming around Greenland and Antarctica, 2011: J. Yin, J.T. Overpeck, S.M. Griffies, A. Hu, J.L. Russell, and R.J. Stouffer, *Nature Geosciences*, doi:10.1038/NGEO1189.