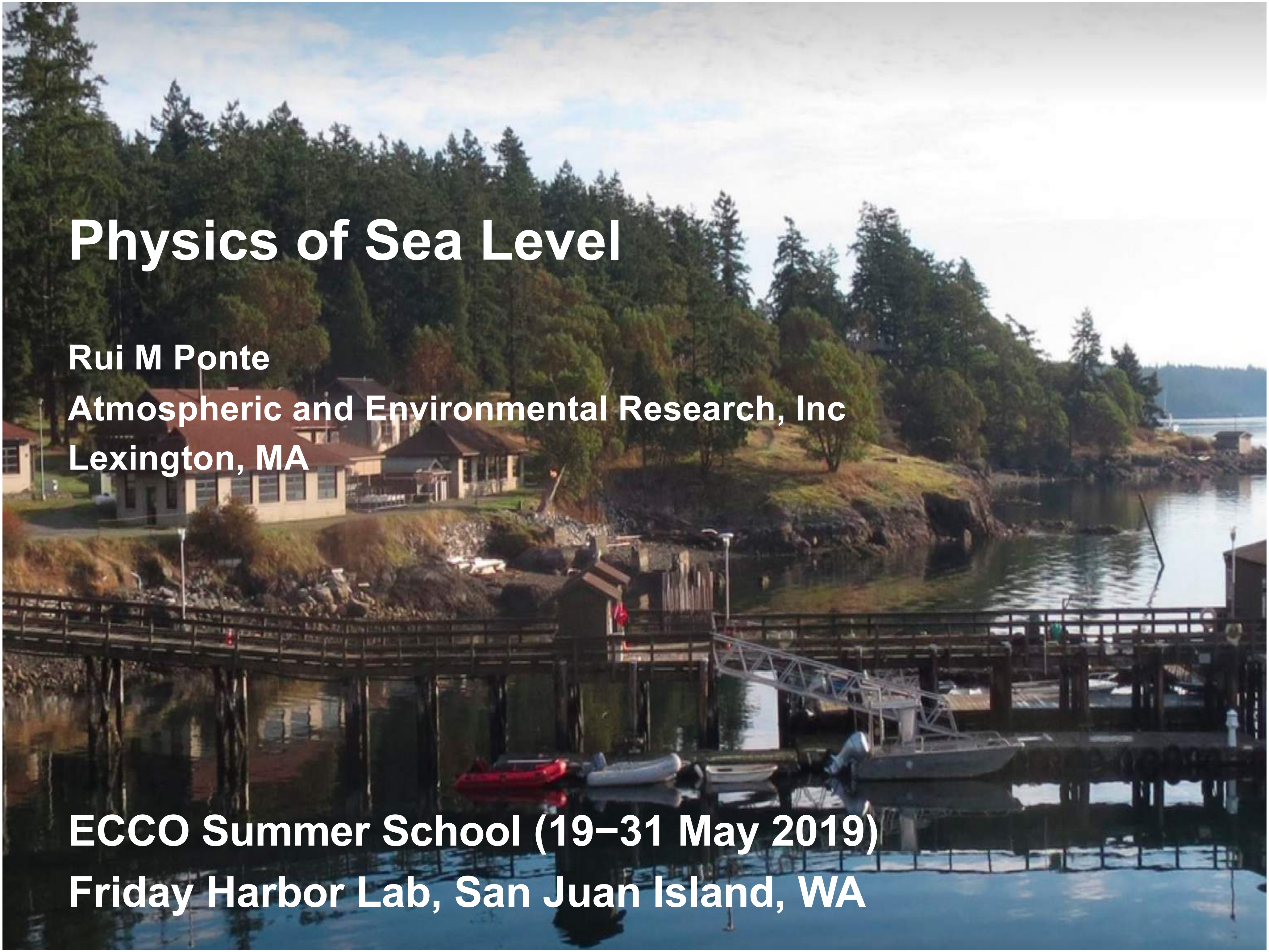

# Physics of Sea Level

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ECCO Summer School (19–31 May 2019)
Friday Harbor Lab, San Juan Island, WA

# Why care about sea level?

Photo credit: Miami Dade DERM

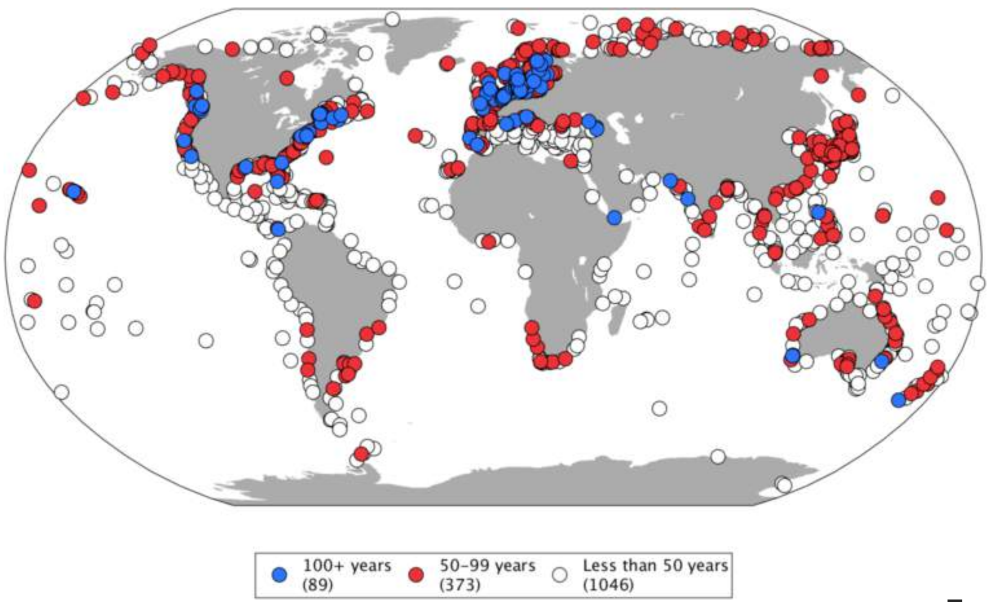
Photo credit: US Coast Guard/Getty Images

- Major societal concern … > 2 million people on US east coast, ~150 million world-wide, live less than 1 m above local mean high water … potential flood costs measured in trillions of dollars under some climate change scenarios

- **Key climate metric …changes in global mean sea level closely reflect changes in ocean heat and freshwater content, which are related to the climate state**
- **Key dynamic variable …sea level gradients contain information about surface geostrophic currents**

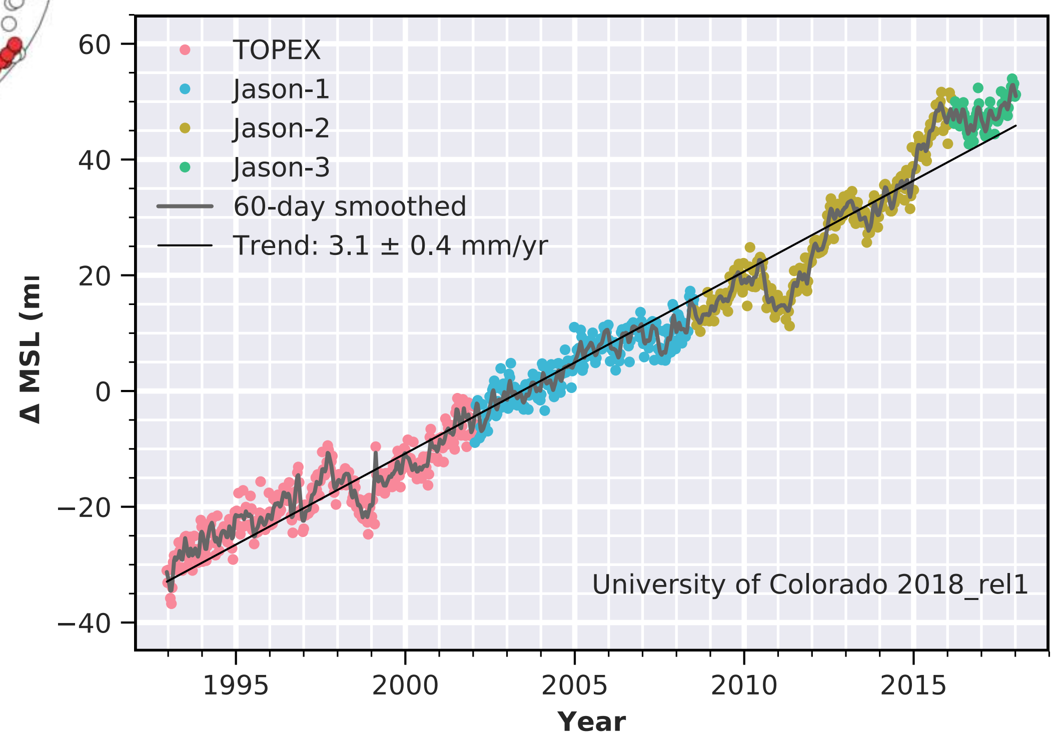
## ➢ Relatively well observed

### Tide gauges (back to 18th century)




Ponte et al. (2019, *Frontiers of Marine Science*)

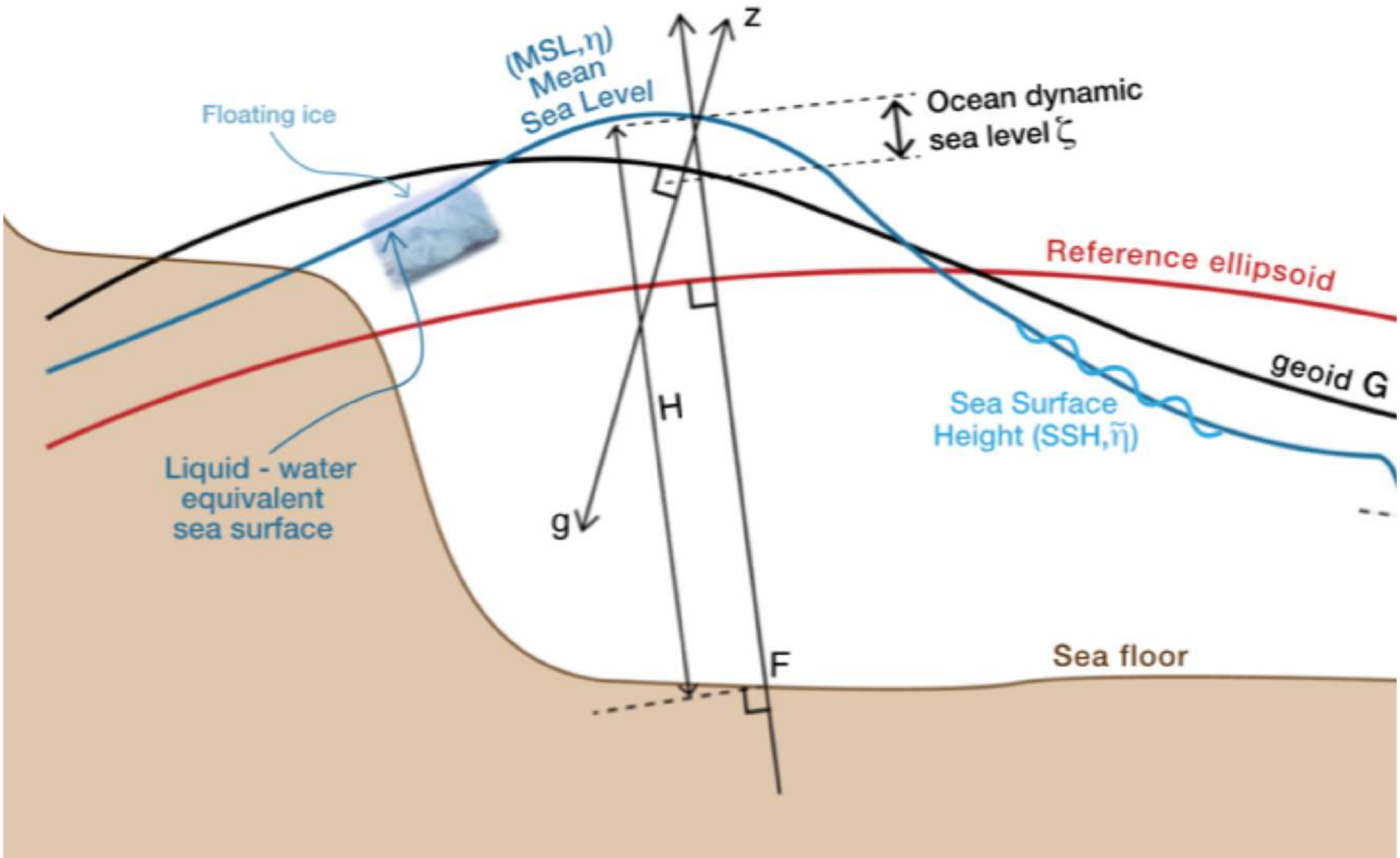
### ~27 years of global altimetry



# Outline

- Basic definitions and processes
- Hydrostatic approximation
- Dynamic vs. static sea level
- Sea level response to various forcing factors
- Influence of nonlinear effects

# Some basic definitions




Gregory et al. (2019, *Surveys in Geophysics*)

# Basic physical processes

- **Volume changes from flow convergence/divergence**
  - **Boussinesq vs. non-Boussinesq model representations of density effects**

- **Boundary fluxes (evaporation, precipitation, land runoff from rivers and other sources, nonfloating ice, sediment)**
  - **Virtual salt vs. real freshwater flux representations**
  - **Some factors poorly treated or ignored**

- **Vertical land motion**
  - **Relative vs. geocentric sea level**

# Forcing factors

- Surface atmospheric winds
- Surface atmospheric pressure
- Evaporation and precipitation
- Freshwater exchange with land (liquid + solid)
- Surface heat flux
- Bottom geothermal flux
- Gravitation : tide potential
- Gravitation : non-tidal (e.g., land ice)
- Self-gravitation
- Bottom motion (e.g. tsunami generation)

# Hydrostatic approximation

**Integrating in the vertical gives**

$$\Delta\zeta = (\Delta p_b - g\int\Delta\rho dz - \Delta p_a) / g\rho_0$$

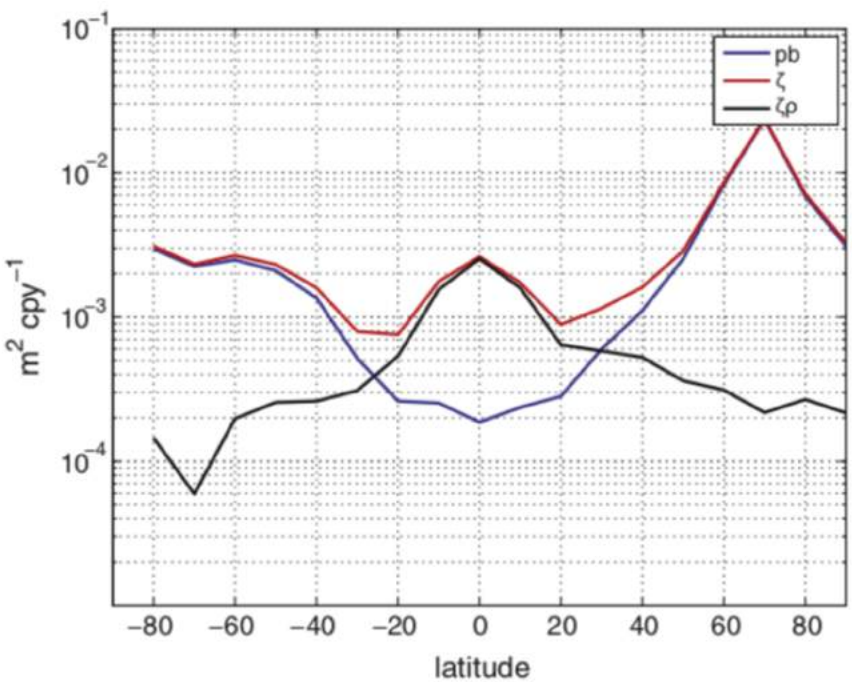
**Variability in $\zeta$ can be diagnosed from**

- **bottom pressure $p_b$ (related to changes in mass of water column)**
- **steric height $-\rho_0^{-1}\int\Delta\rho dz$ (related to changes in density $\rho$)**
- **surface atmospheric pressure $p_a$ (inverted barometer)**

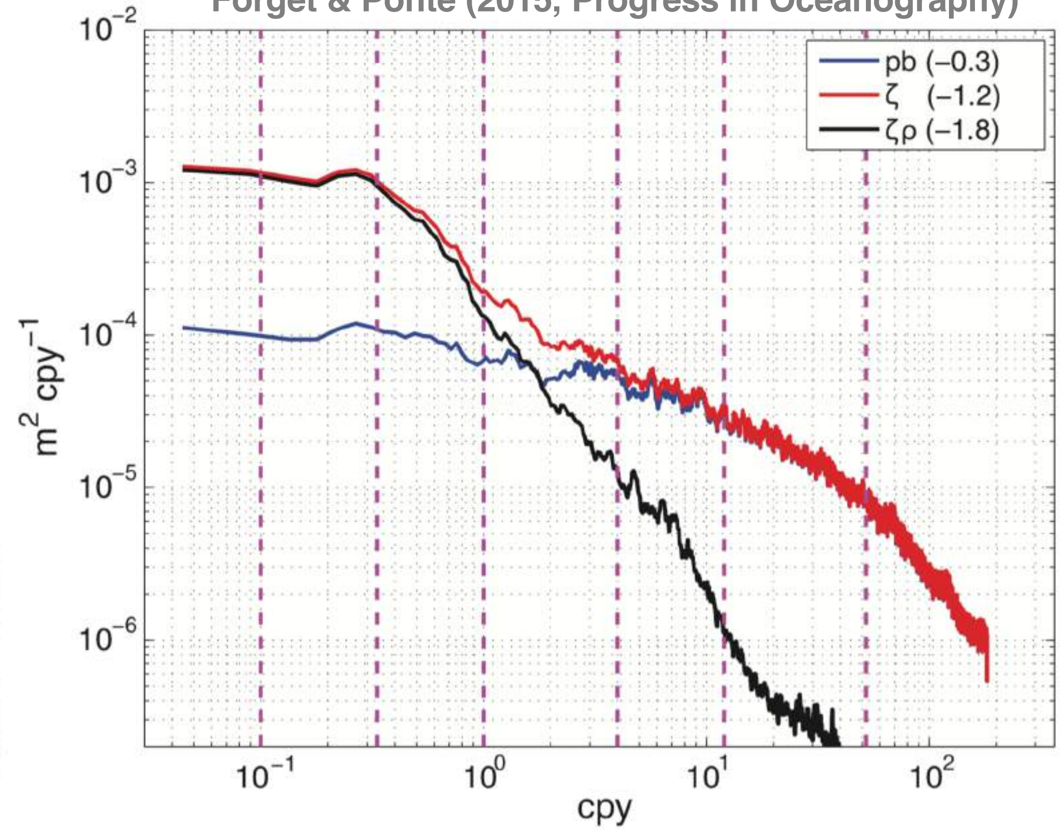
# Relation to steric height, $p_b$

**A global spectral view based on ECCO state estimate…**

- **ζ mostly related to $p_b$ at short periods (≲ 2 months)**
- **ζ mostly related to steric height at long periods (≳ 1yr)**

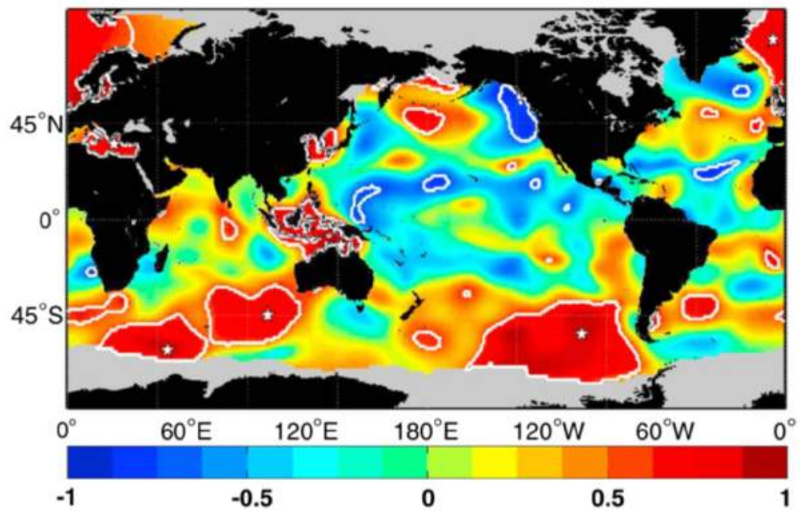



Forget & Ponte (2015, Progress in Oceanography)

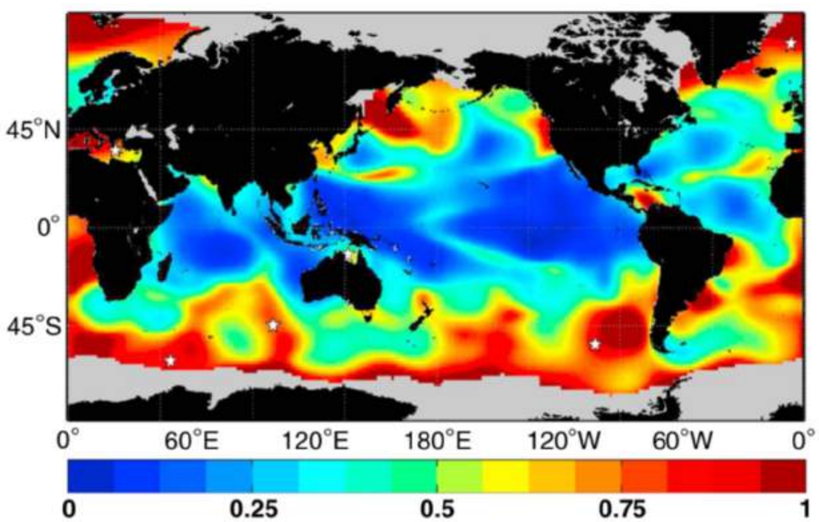



- **…but there is considerable spatial dependence**

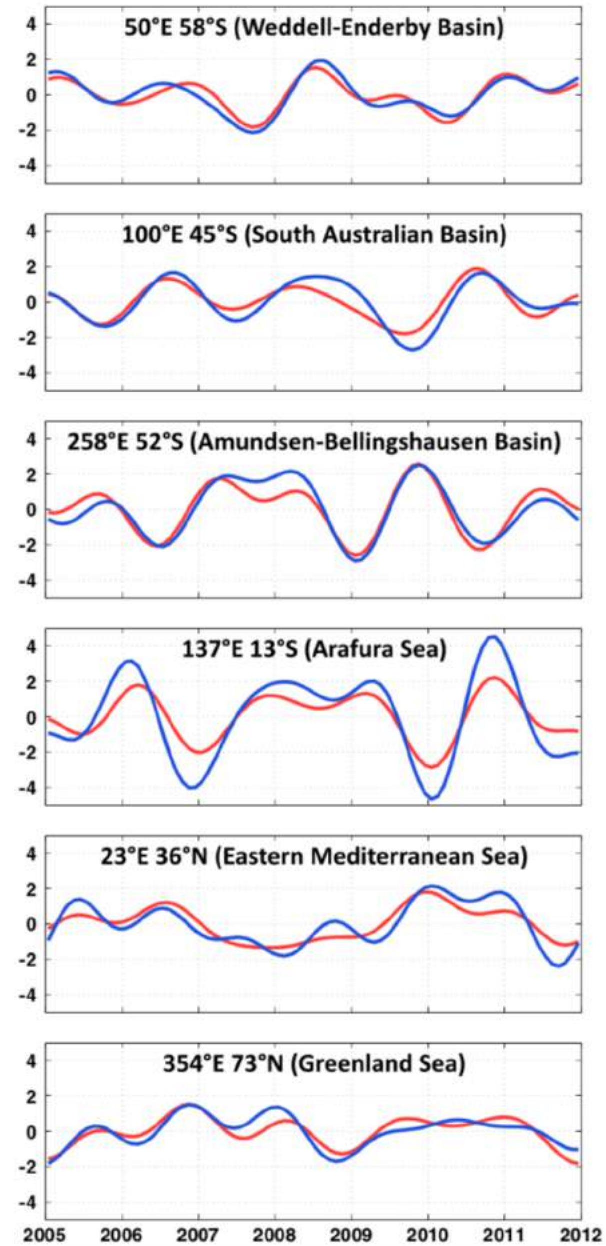
# Importance of $p_b$ at long timescales




**Correlation of ζ (altimetry) and $p_b$ (GRACE) at interannual time scales**



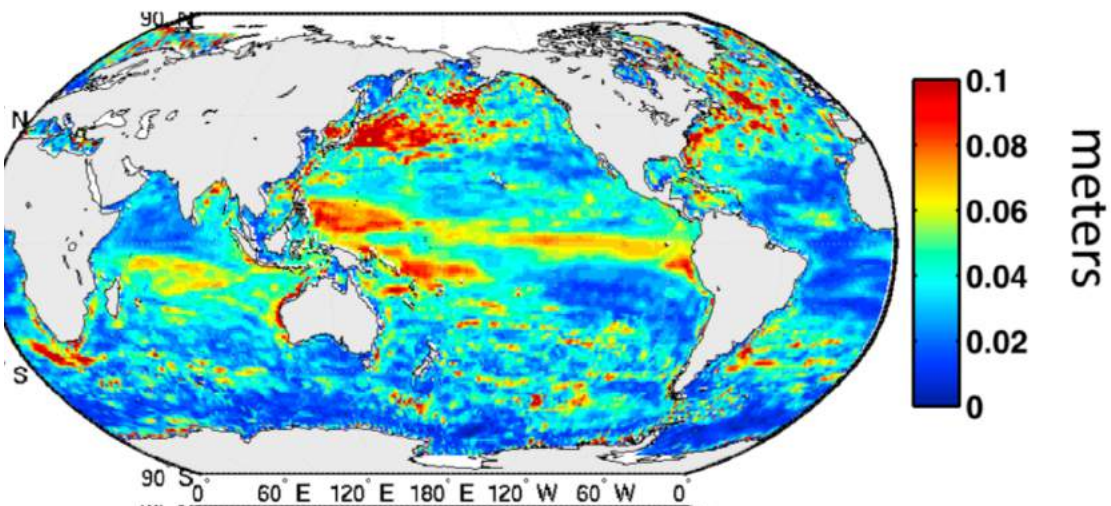

**Ratio of $p_b$ (GRACE) and ζ (altimetry) standard deviations**



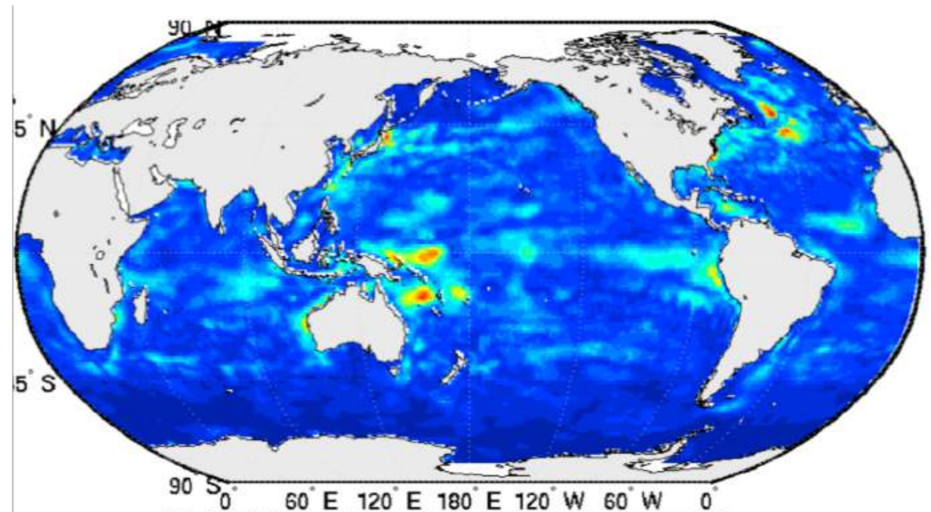

Piecuch et al. (2013, Geophysical Research Letters)

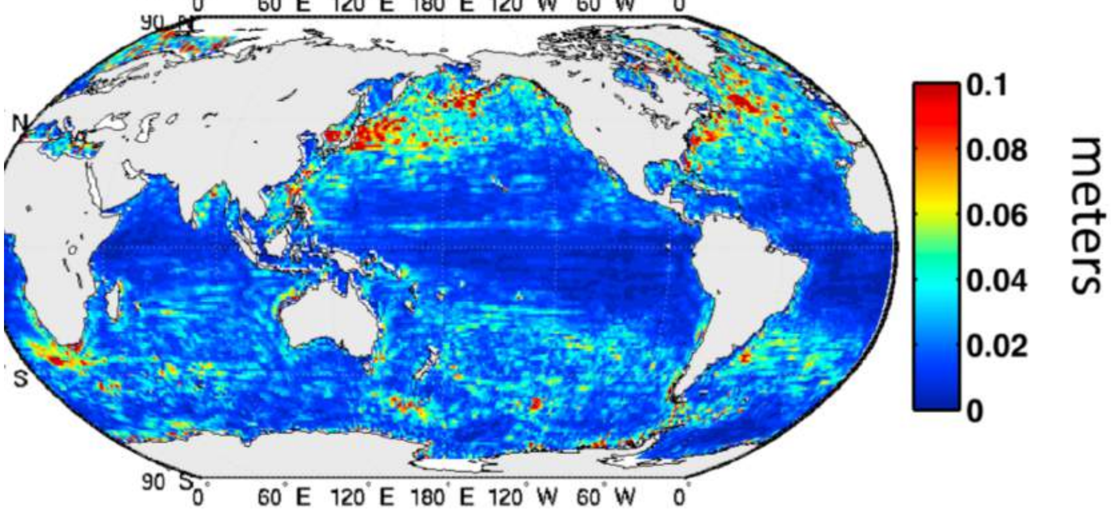
# Steric height budgets

**advection**

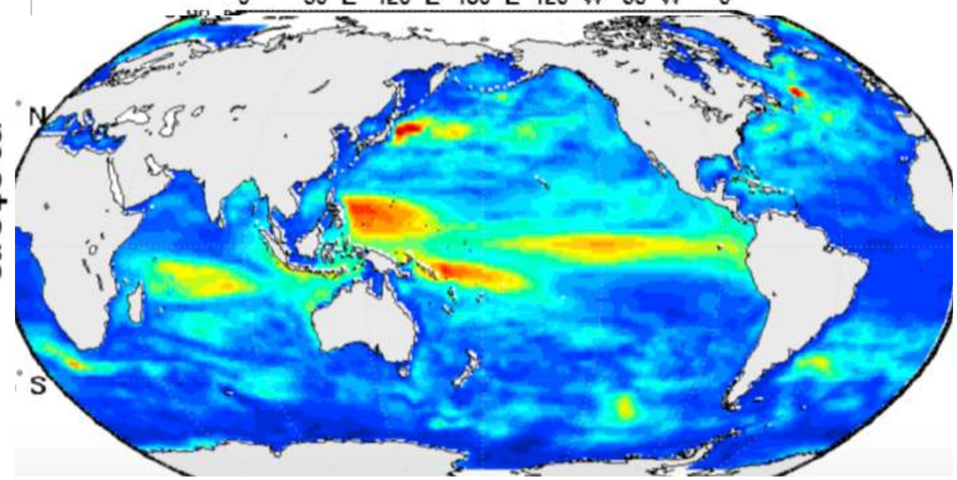



**surface buoyancy forcing**




**diffusion**




**steric height**

Piecuch and Ponte (2011, Geophys. Res. Lett.)

# Exploring forcing mechanisms

**Interannual variability**

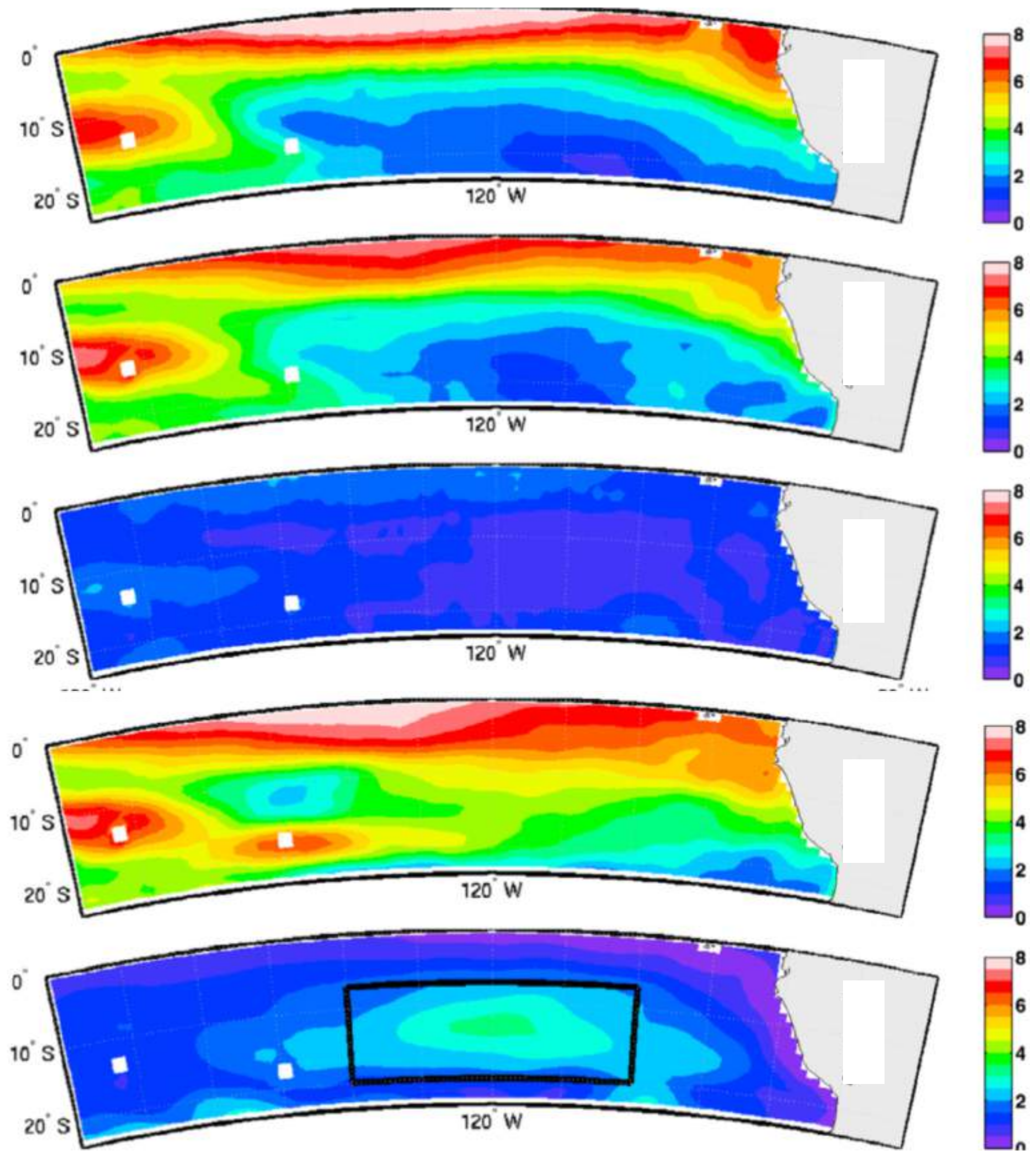
**Sea level (altimetry)**

**Sea level (ECCO)**

**RMS difference**

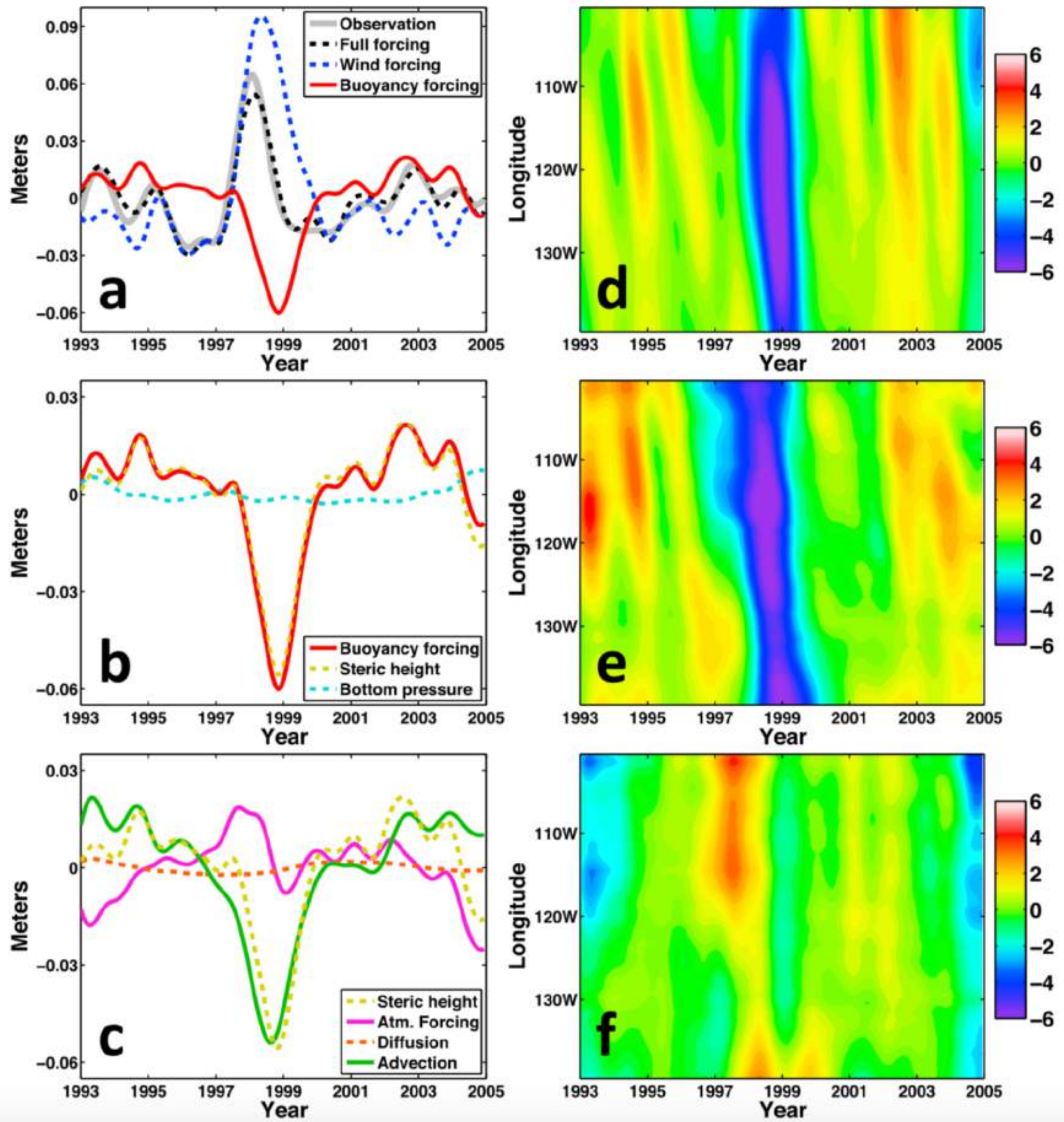
**Wind forcing**

**Buoyancy forcing**




Piecuch and Ponte (2012, Geophys. Res. Lett.)

# Steric height budgets




**Buoyancy-driven steric height**

**Steric term from ocean advection**

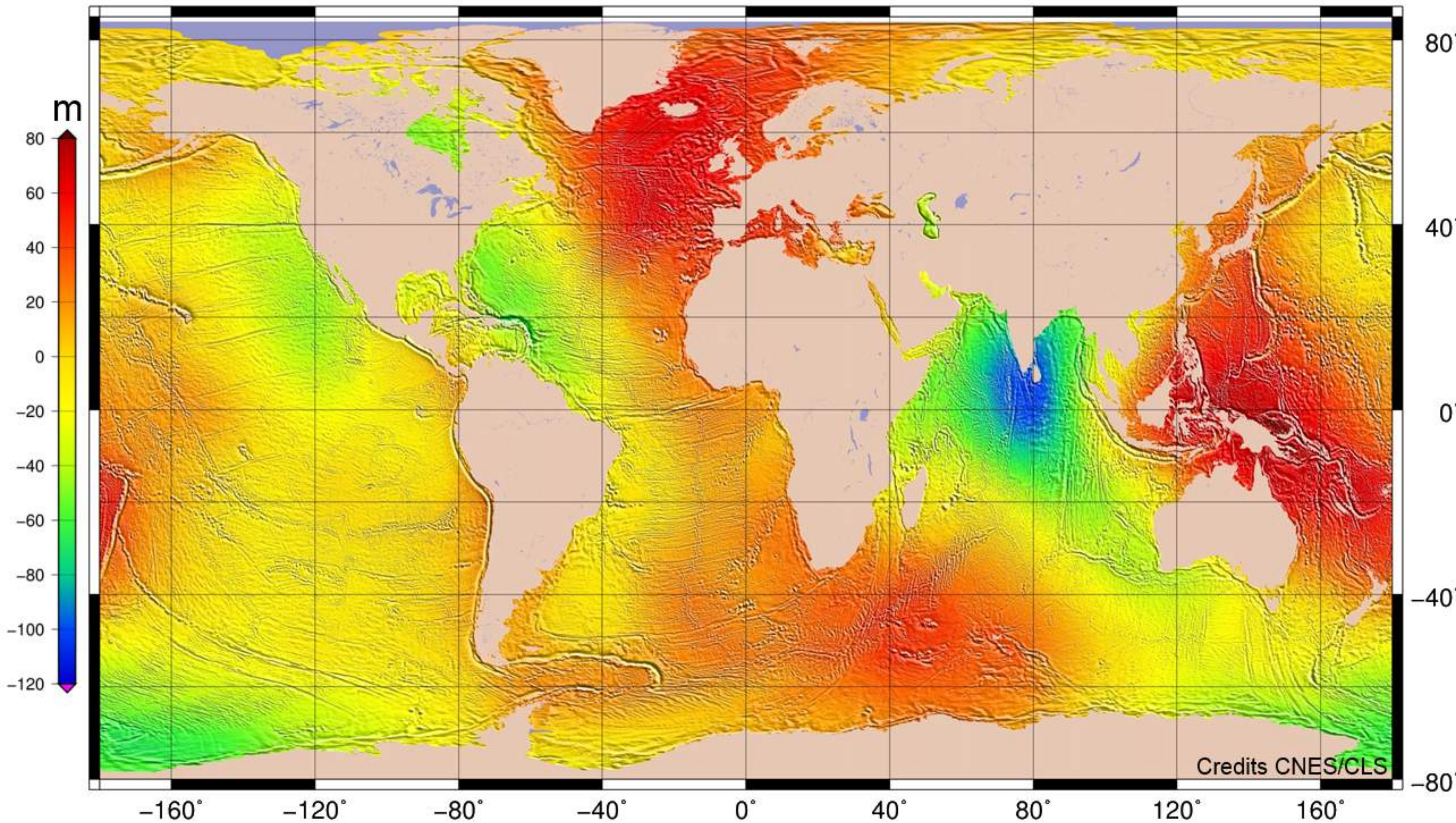
**Steric term from local forcing**

Piecuch and Ponte (2012, Geophys. Res. Lett.)

# Dynamic vs. static sea level

## Some sea level gradients have little dynamical relevance…

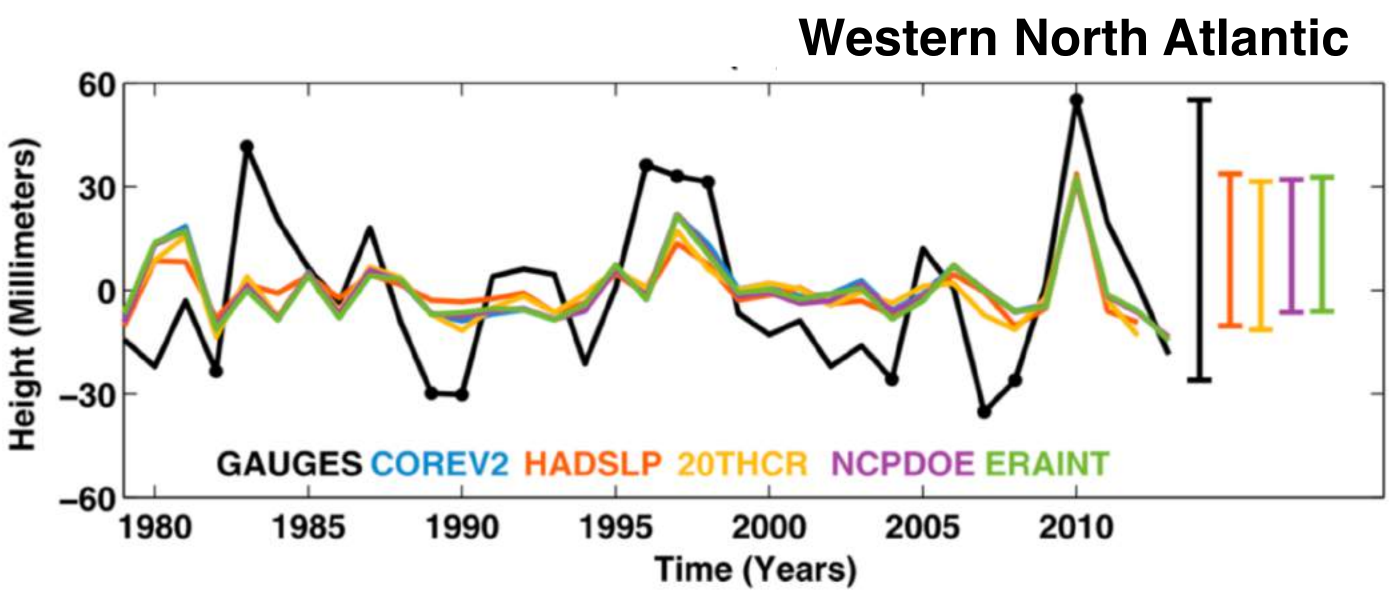
Mean Sea Surface (mapped by satellite altimeters)



# Static signals (inverted barometer)

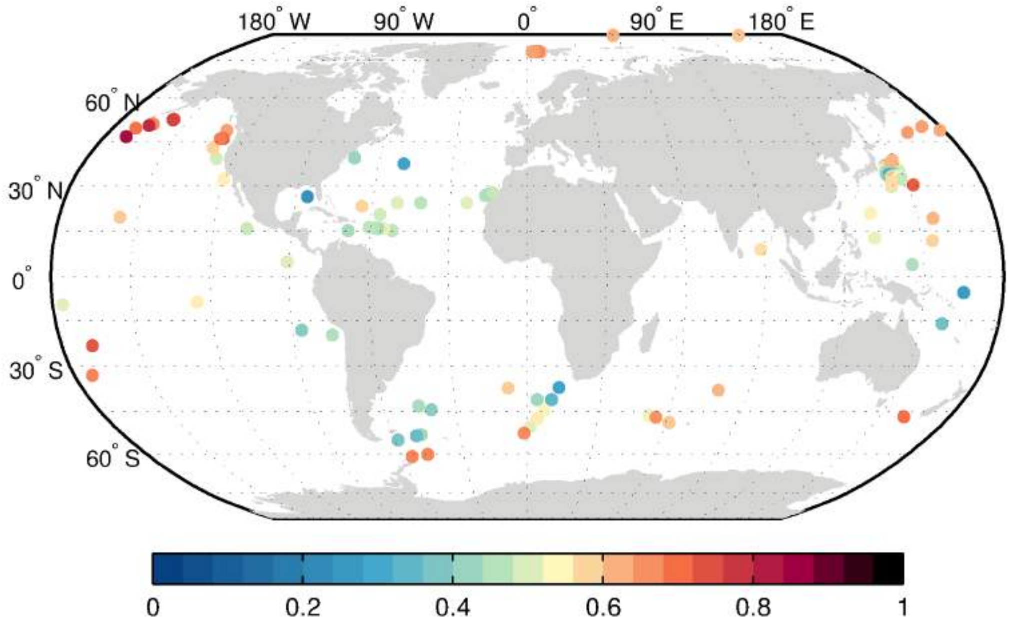
**…the case of the sea level response to surface atmospheric pressure ($p_a$) at long timescales**

$$\Delta\zeta = -\,\Delta p_a / g\rho_0$$



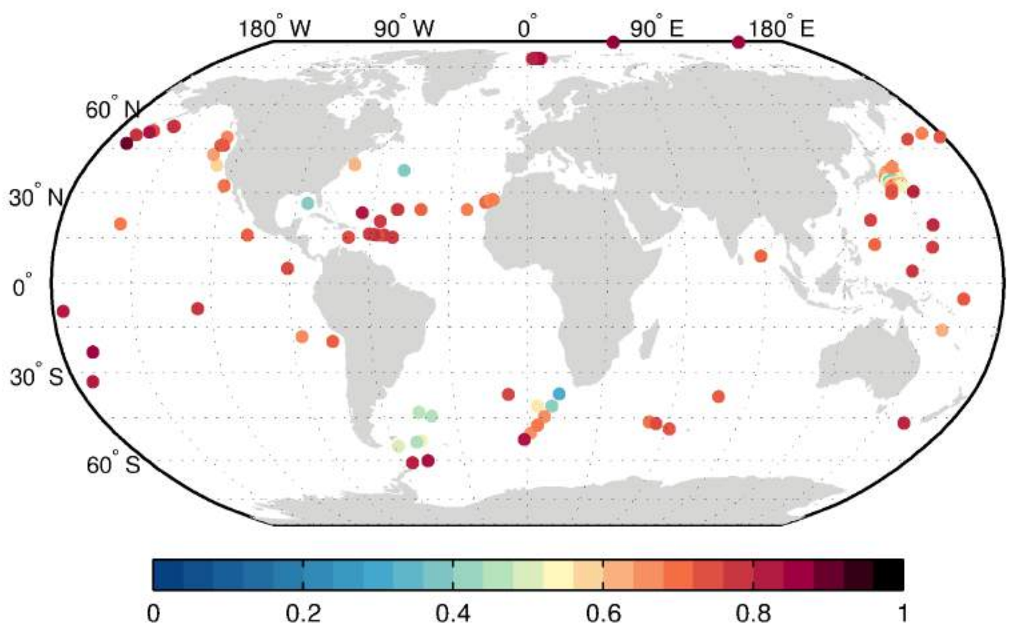

Piecuch & Ponte (2015, GRL)

# Dynamic signals (T < 60 days)




Bottom pressure recorder comparisons from M. Schindelegger (U. Bonn)

**ECCO v4r3**

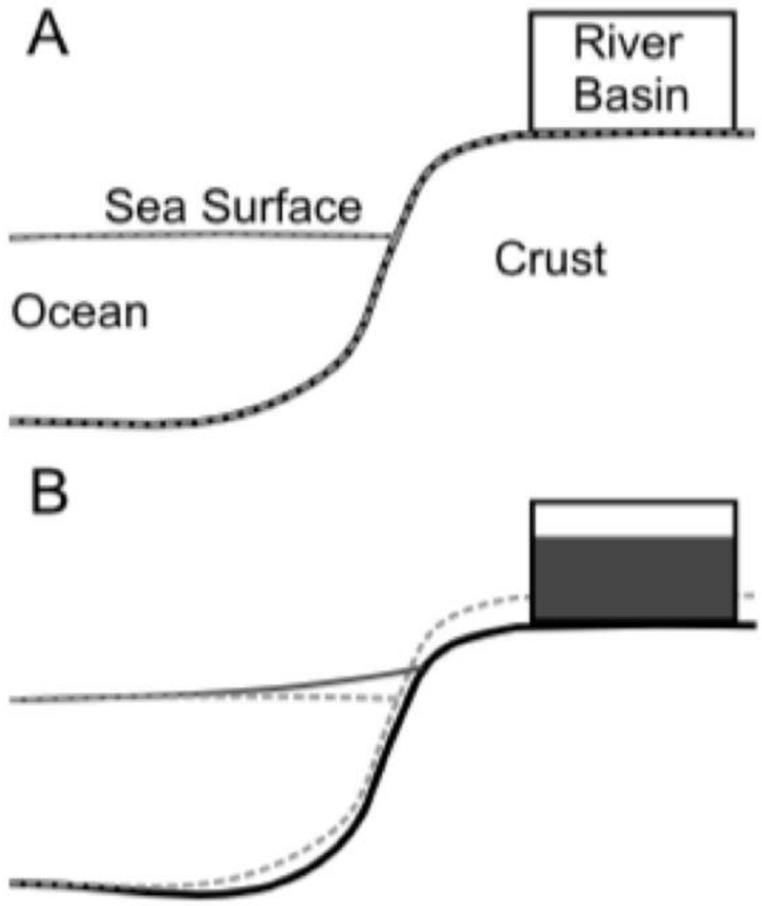



**ECCO v4r3 + atmospheric pressure forcing**

# Other static signals

- Long-period tides mostly static or equilibrium, in contrast with short-period tides…the case for resonance
- Response to gravitational forcing from changes in land water and ice
- Surface mass loading from freshwater fluxes (e.g., river runoff)

# Non-tidal gravitational forcing

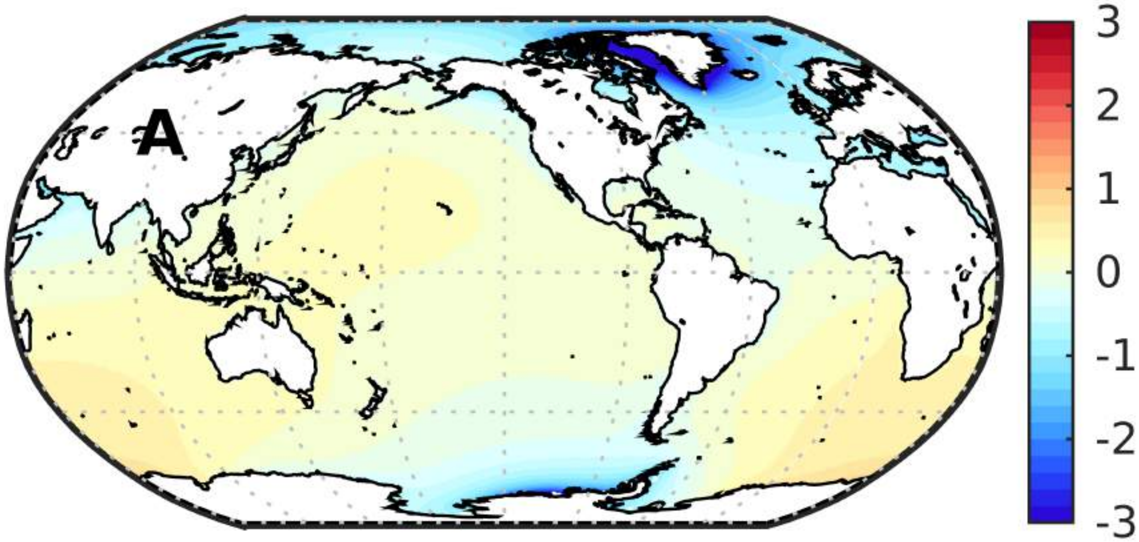



Tamisiea et al. (2010, J. Geophys. Res.)

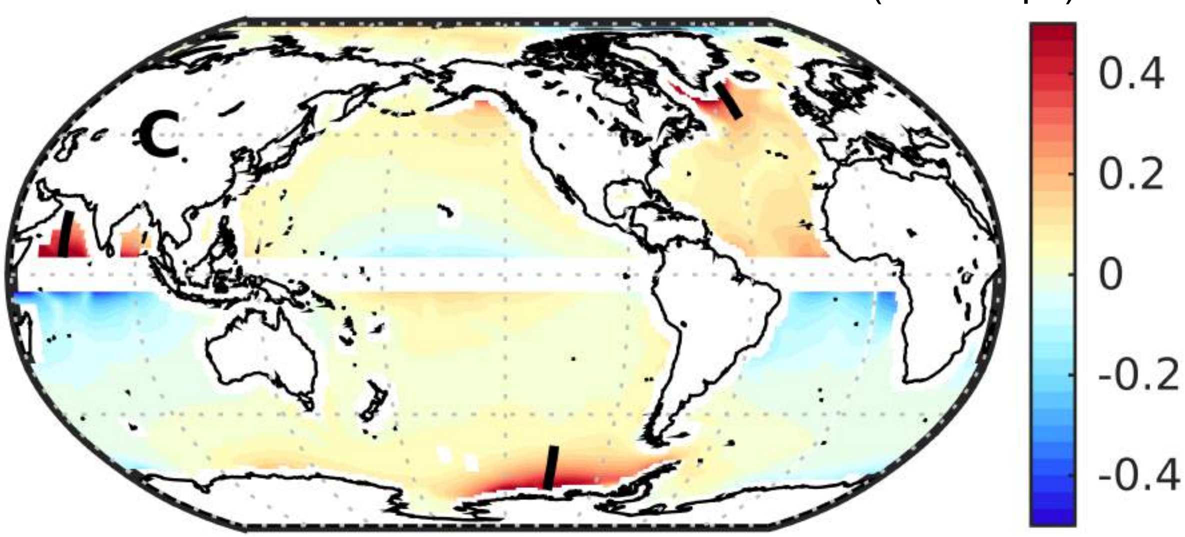
- Changes in the mass field over land, even without involving mass transfer to the oceans, affect sea level through the physics of gravitational attraction and loading (GAL):
  - Surface atmospheric pressure and distribution of air mass over land
  - Terrestrial water storage
  - Land ice (glaciers and ice sheets)
- At monthly and longer time scales, response associated with GAL effects is expected to be nearly static in nature

# GAL-related sea level trends

(Trends for 2005-2015) (mm/yr)

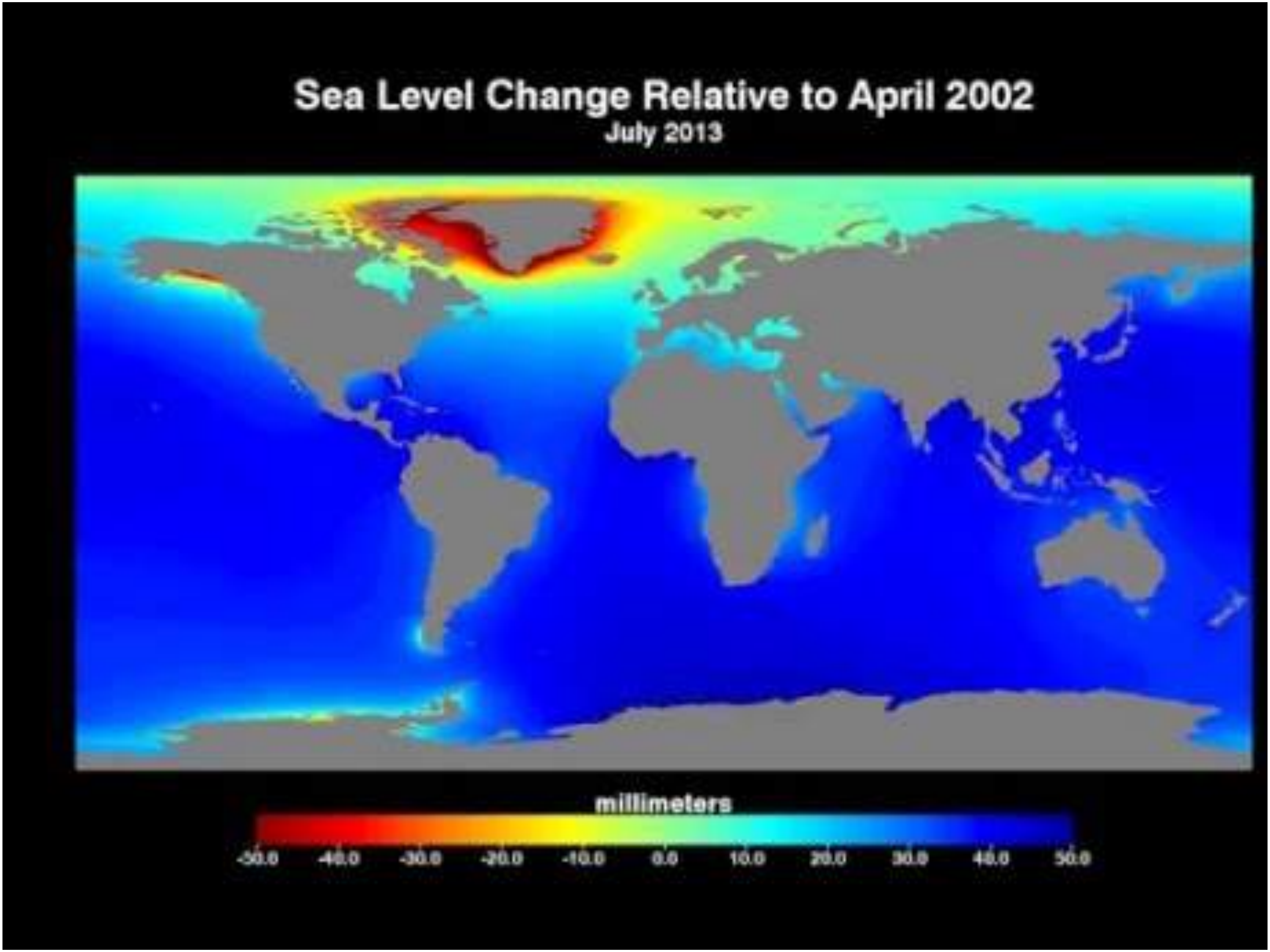



Decadal changes in zonal geostrophic transport per degree latitude (Sverdrups)




- **Typical effects of order 1mm/yr, larger (negative) trends and strongest spatial gradients near the ice sheets**
- **Largest transport changes near ice sheets, with accumulated transport errors ~ 5 Sv across sections in Southern Ocean, subpolar North Atlantic**

Ponte et al. (2010, J. Atmos. Oce. Tech.)


Sea Level Change Relative to April 2002
July 2013
millimeters
-50.0
-40.0
-30.0
-20.0
-10.0
0.0
10.0
20.0
30.0
40.0
50.0

# Freshwater loading

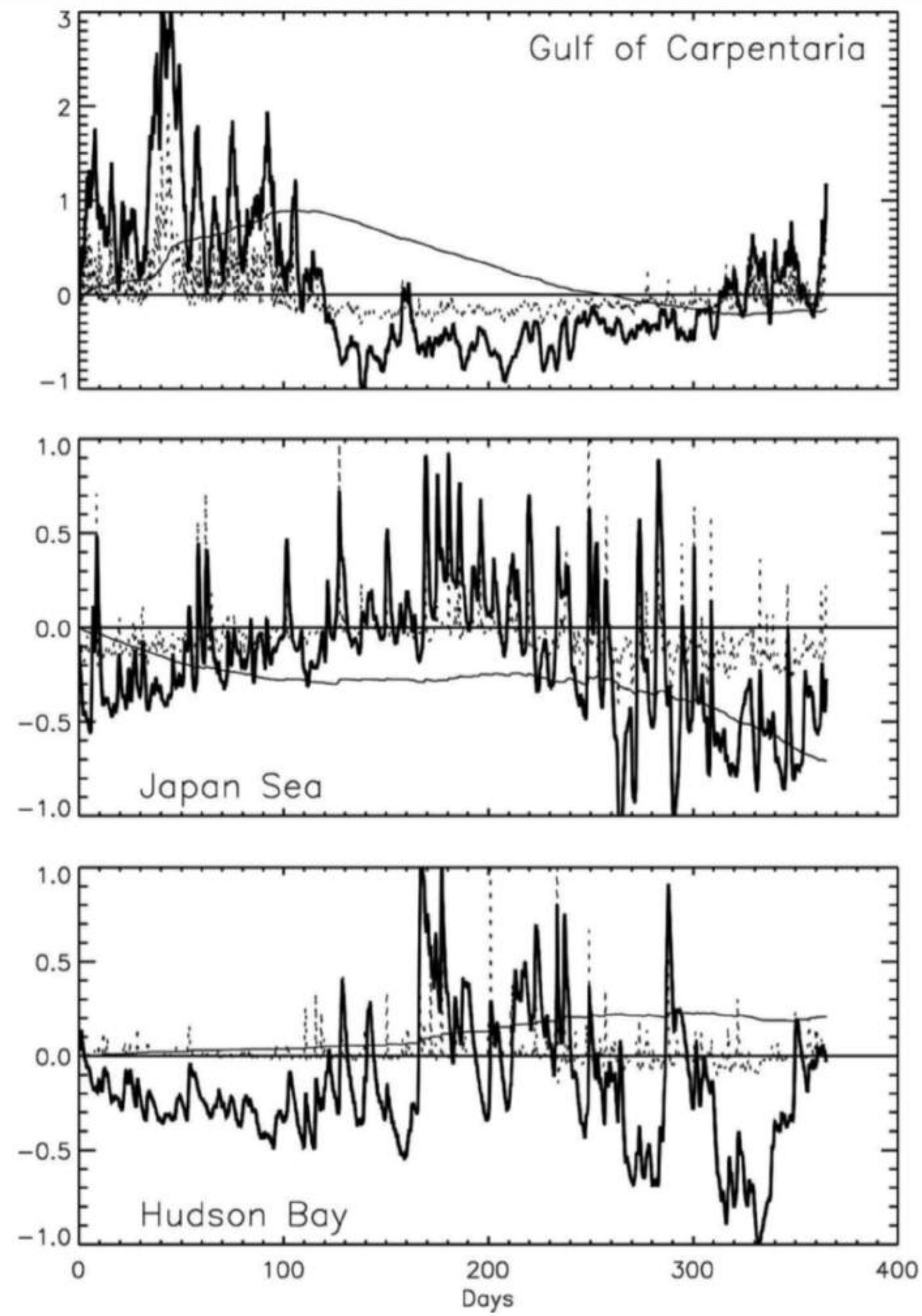
**E−P**

- **Static response to freshwater loading involves quasi-instantaneous* spread of the load homogeneously over the global ocean**

- **Mostly valid but not always**
  - **Resonant forcing**
  - **Very shallow water (slow adjustment)**
  - **Frictionally or geometrically constricted flows**
  - **Barotropic/baroclinic coupling**

***quasi-instantaneous = fast compared with the time scale of the anomalous load**

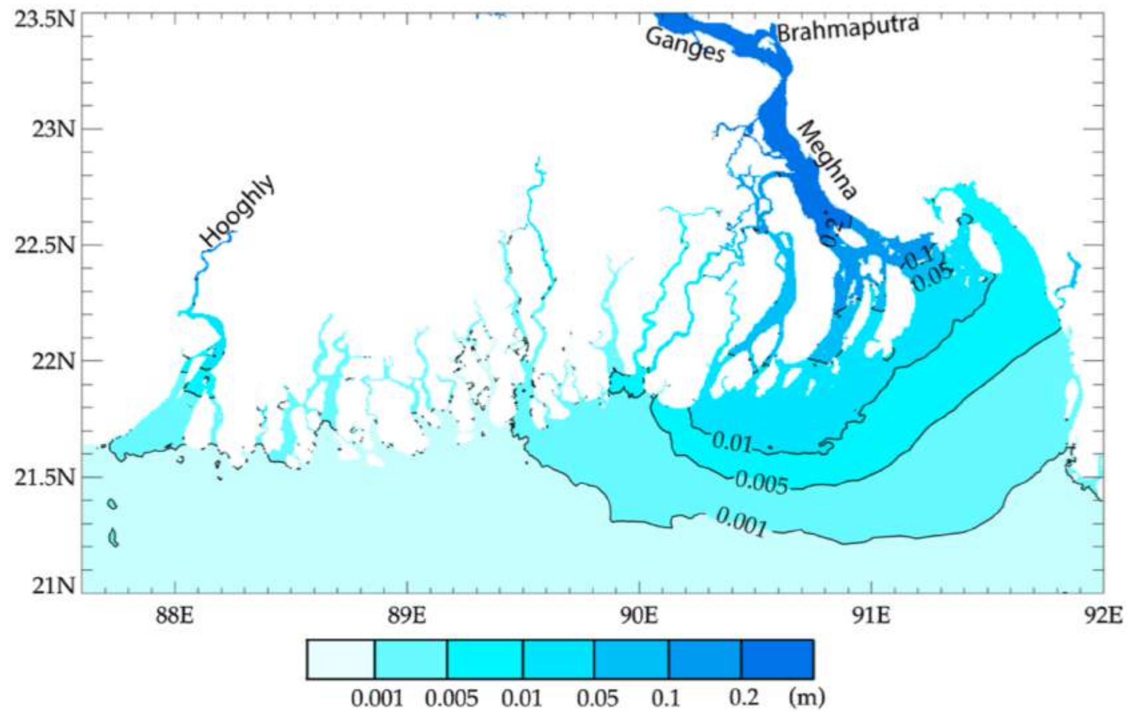
Ponte (2006, J. Phys. Oceanogr.)



# Other examples

- **Possible dynamic response in semi-enclosed basins, e.g.,**
  - **Black Sea (Volkov et al. 2016, GRL)**
  - **Arctic (Peralta-Ferriz and Morison, 2010, GRL)**

**Barotropic model response to river runoff (annual cycle)**




Durand et al. (2019, Surv. Geophys.)

# Modeling/estimation issues

- **Most models do not represent static sea level processes (e.g., no tidal and non-tidal gravitational forcing, no $p_a$ forcing)**

- **Appropriate corrections need to be applied to data before sea level constraints can be used**

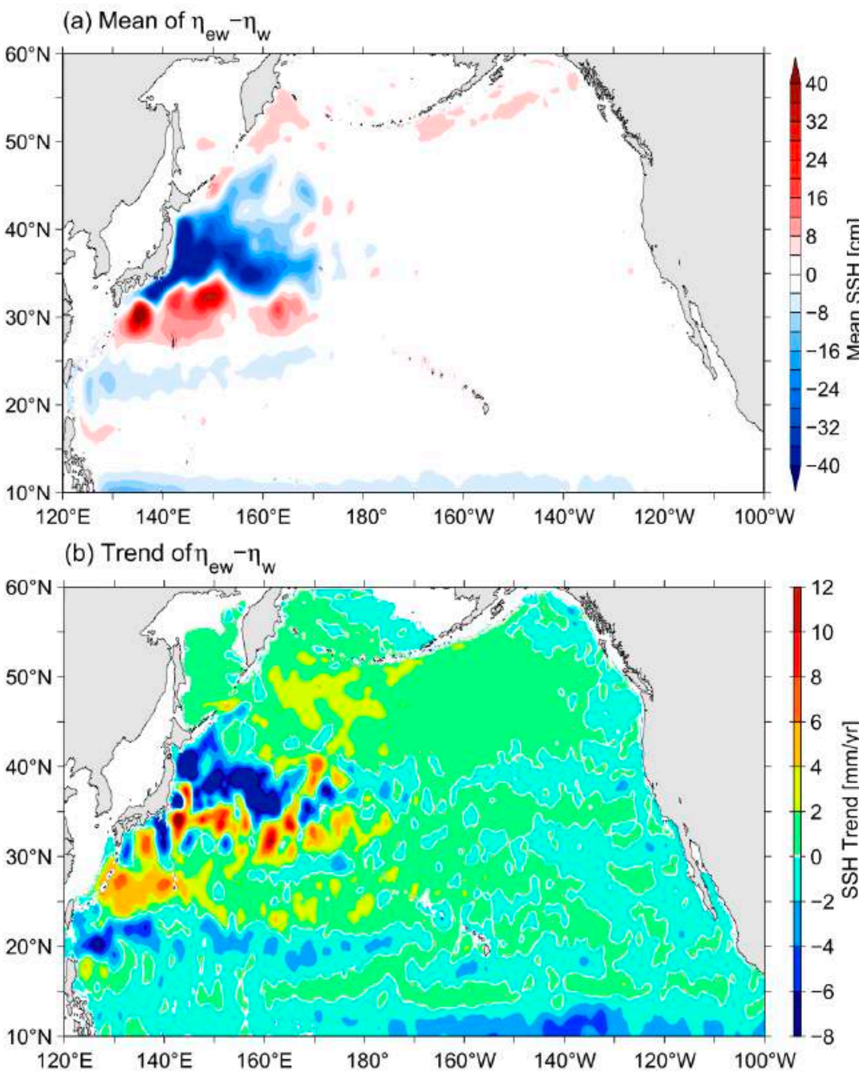
- **Problems arise when assumptions of static response break down (resonance, flow constraints, fast timescales/long spatial scales relative to wave adjustment scales,…)**

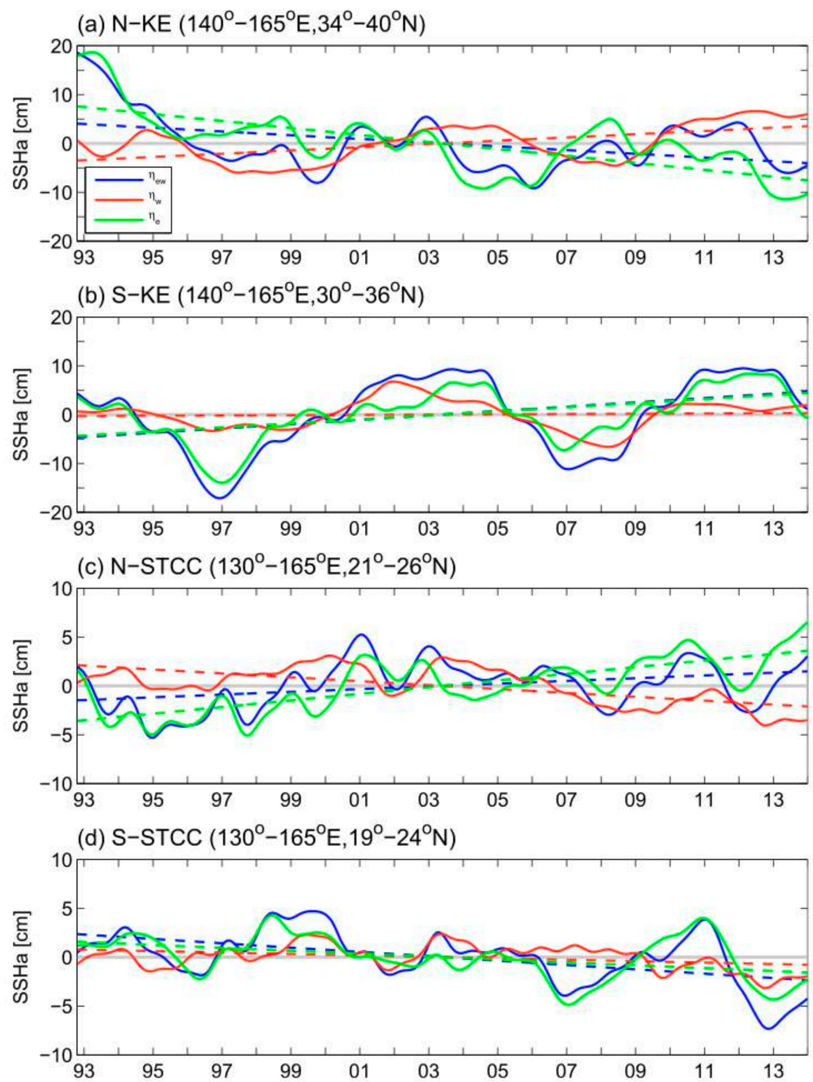
- **Best to represent as many processes as possible in the model physics**

# Nonlinear processes

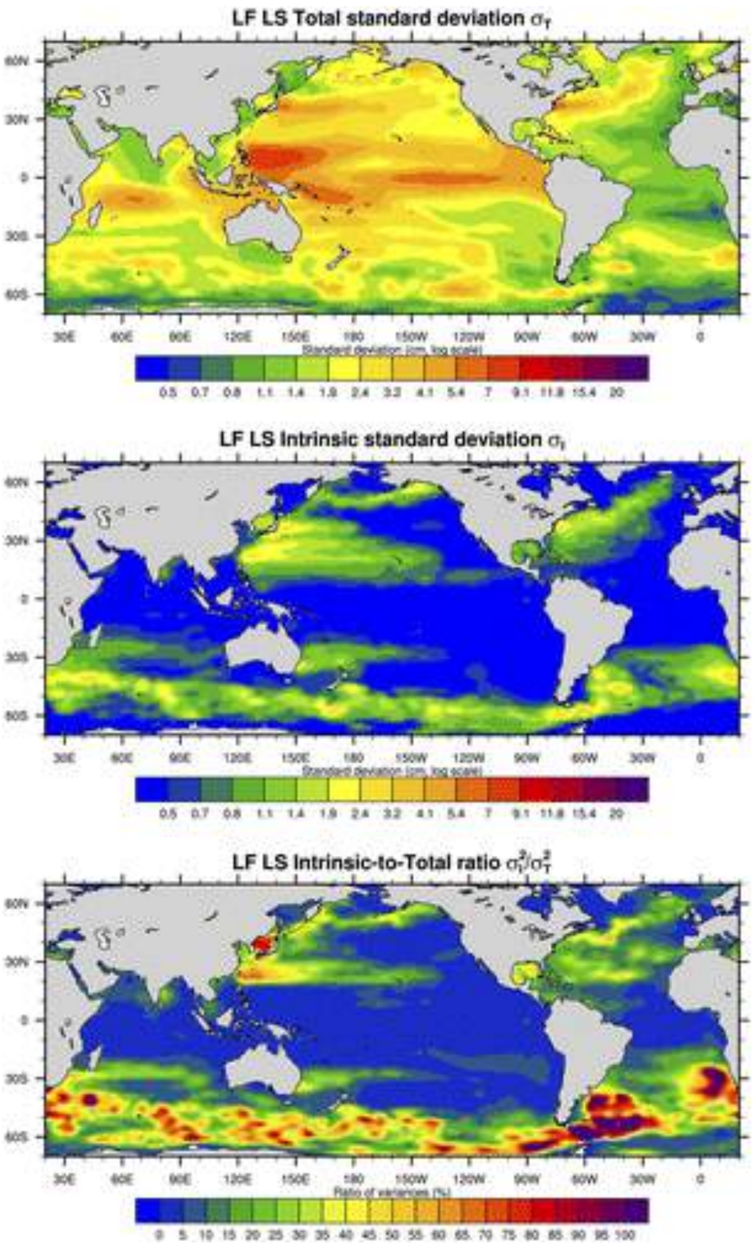
Qiu et al. (2015, J. Climate)

blue: wind+eddies; red: wind; green: difference



# Nonlinear processes




Results for T > 18 months, L > 12 degrees

- **Model-based results from running 1/12º experiments with and without atmospheric forcing effects**
- **Substantial intrinsic sea level variability at low frequency, large scale**

**Serrazin et al. (2015, J. Climate)**

# Summary

- …