NEROGRAV

New Refined Observations of Climate Change from Spaceborne Gravity Missions

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Mass Change of the Oceans

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Mass Change of the Oceans

Warm-up:

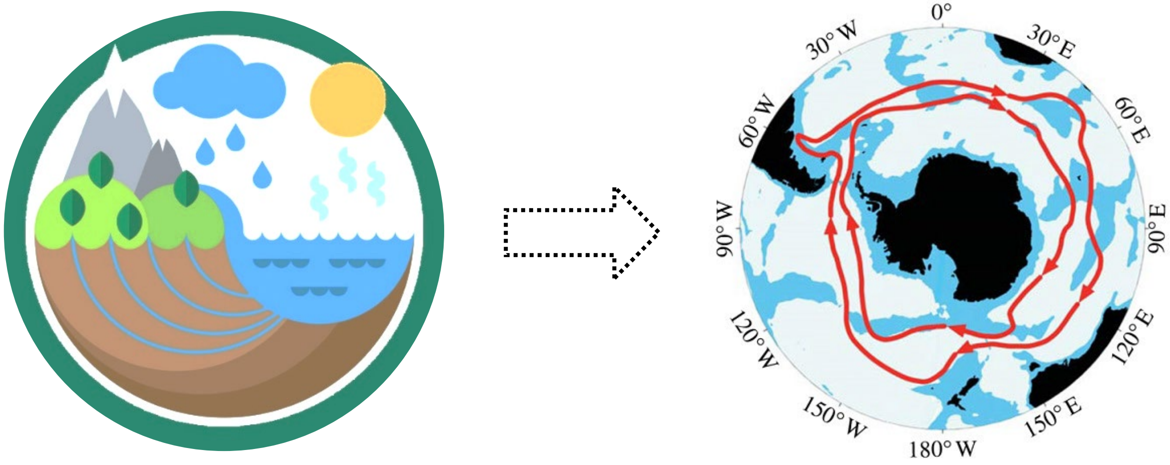
Participate via

or put code **2973 8661** to https://www.slido.com/

Mass Change of the Oceans

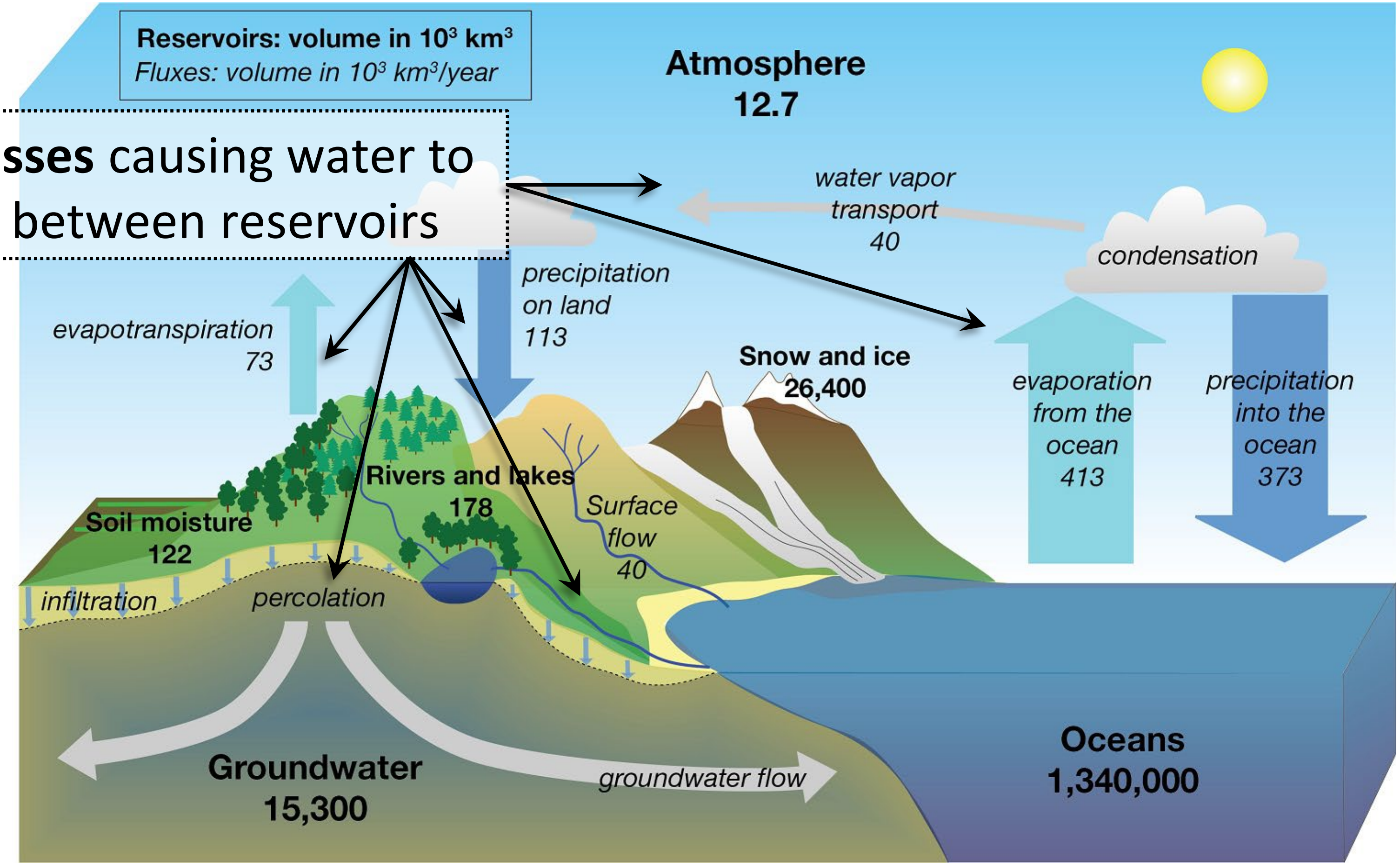
Outline:

1. Basic considerations – hydrological cycle
2. Land-ocean mass transfer
3. Dynamic ocean
4. Ocean bottom pressure



Basic Considerations

Ocean is integral to the hydrological cycle:

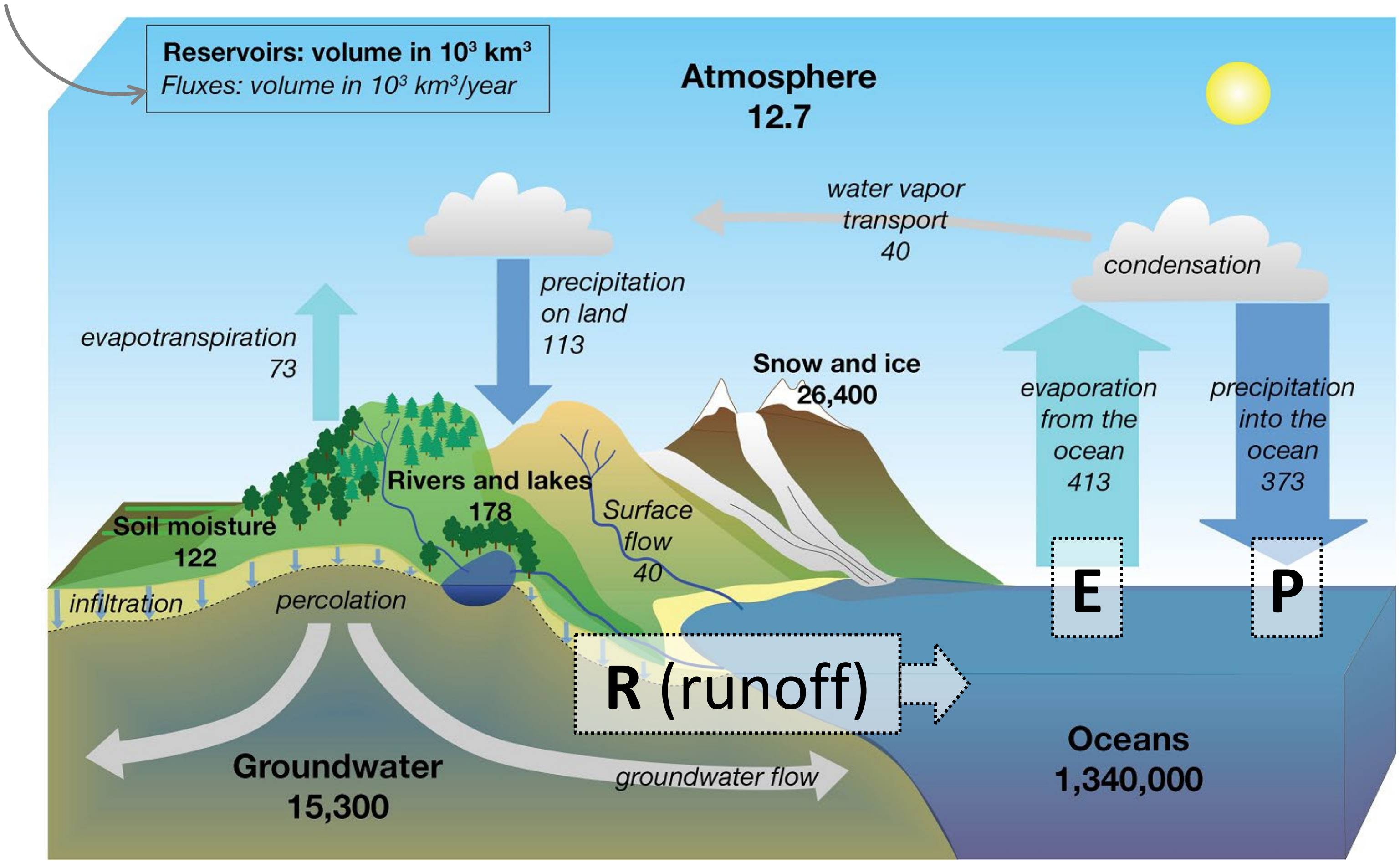


Processes causing water to move between reservoirs

www.visionlearning.com/en/library/Earth-Science/6/The-Hydrologic-Cycle/99

Basic Considerations

Fluxes … sum of transferred water over a nominal year



www.visionlearning.com/en/library/Earth-Science/6/The-Hydrologic-Cycle/99

Basic Considerations

Water balance in the ocean:

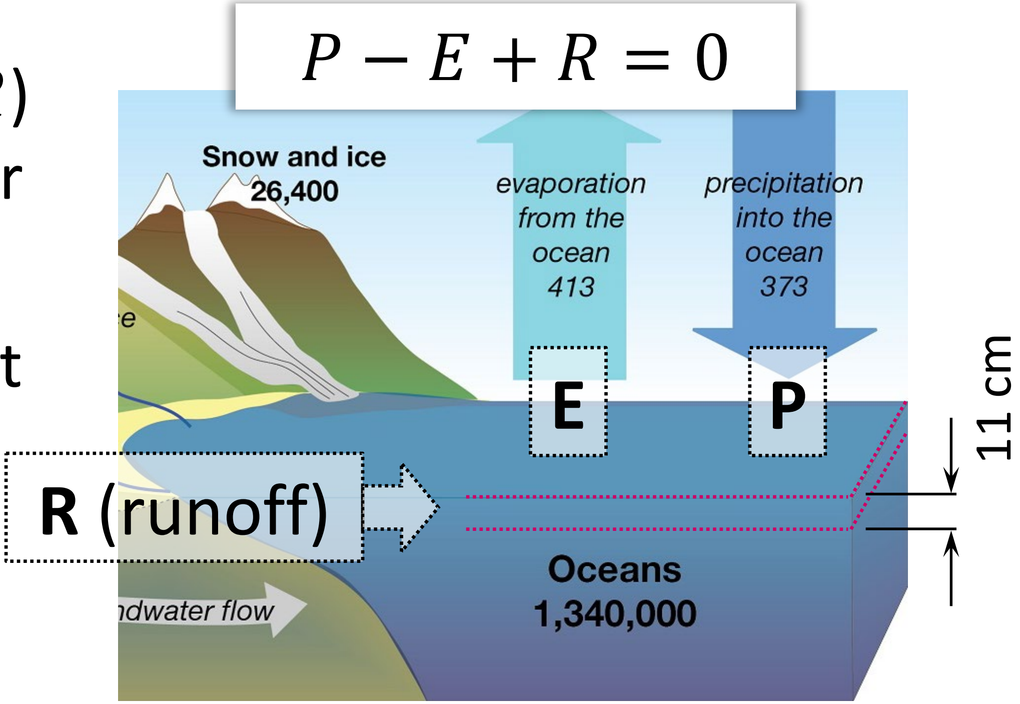
units: $mm\ yr^{-1}$

	P	E	$P-E$	R	$P-E+R$
Global	1066	1176	-110	110	0

- Net fluxes ($E-P$ or R) evenly spread out over ocean ⇒ 11-cm layer
- What goes in, goes out

⇓

No change in ocean mass

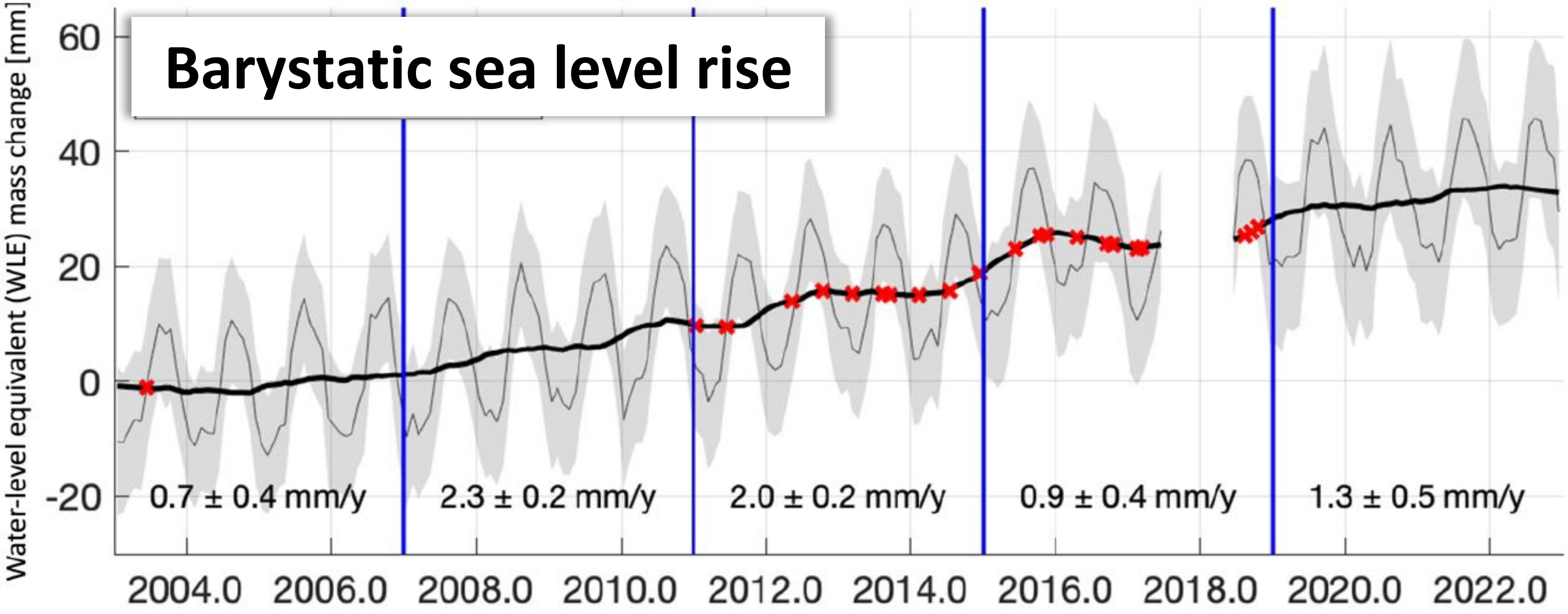


$$P-E+R=0$$

Basic Considerations

What does GRACE/-FO tell us?

Ocean mass increase ⇔ Imbalance of fluxes



Barystatic sea level rise

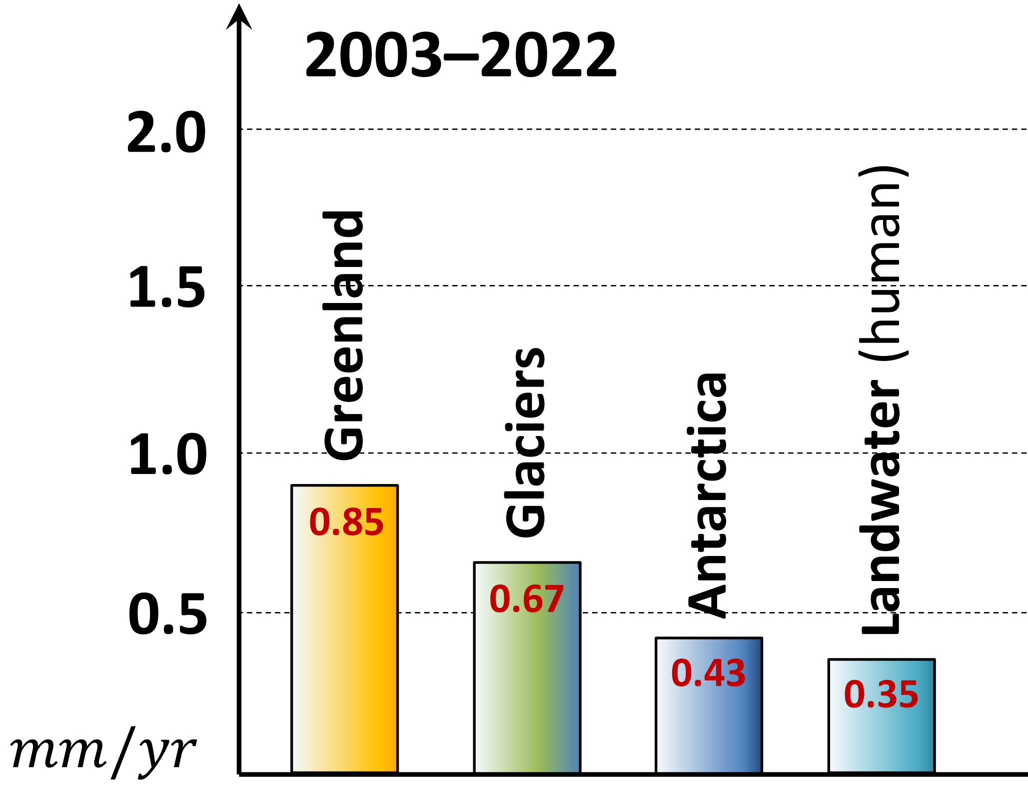
Ludwigsen et al. (2024, Nat. Commun.)

Basic Considerations

Ludwigsen et al. (2024)

Global ocean mass budget:

- Trends fitted to time series of individual contributions

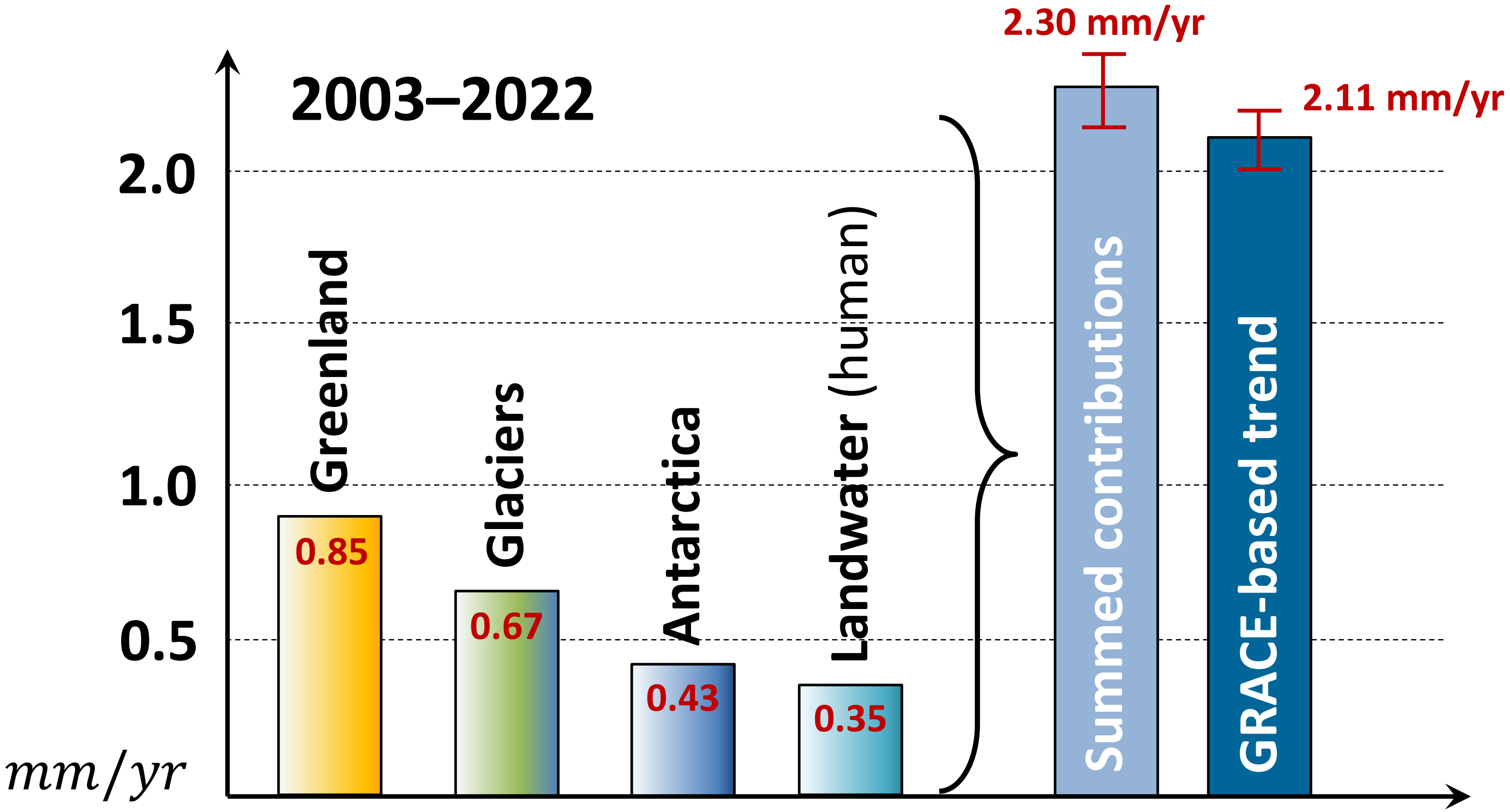


Basic Considerations

Ludwigsen et al. (2024)

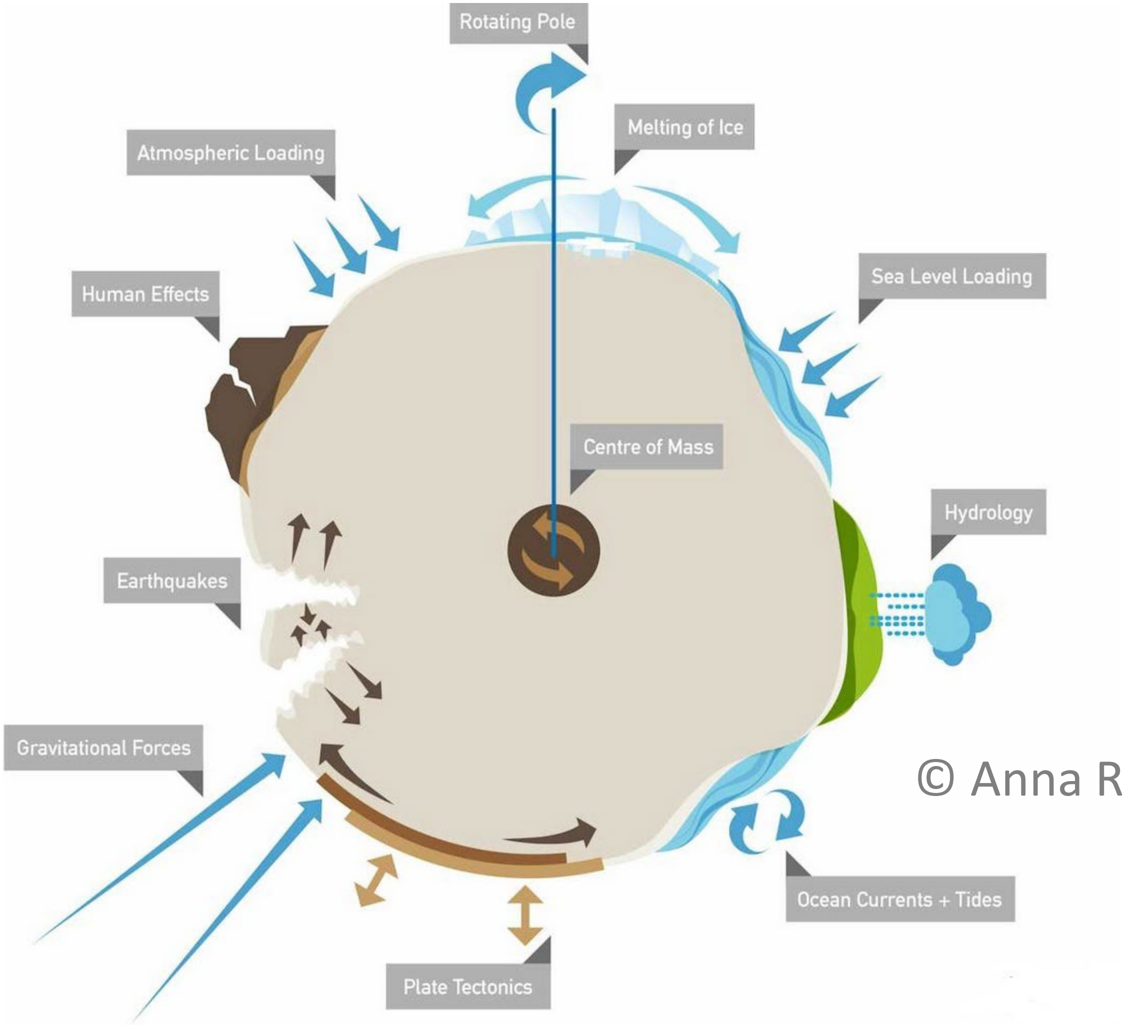
Global ocean mass budget:

- Trends fitted to time series of individual contributions



Mass Change of the Oceans

Bathtub analysis ⟹ realistic Earth: includes …



G: Gravitation

R: Rotation

D: Deformation

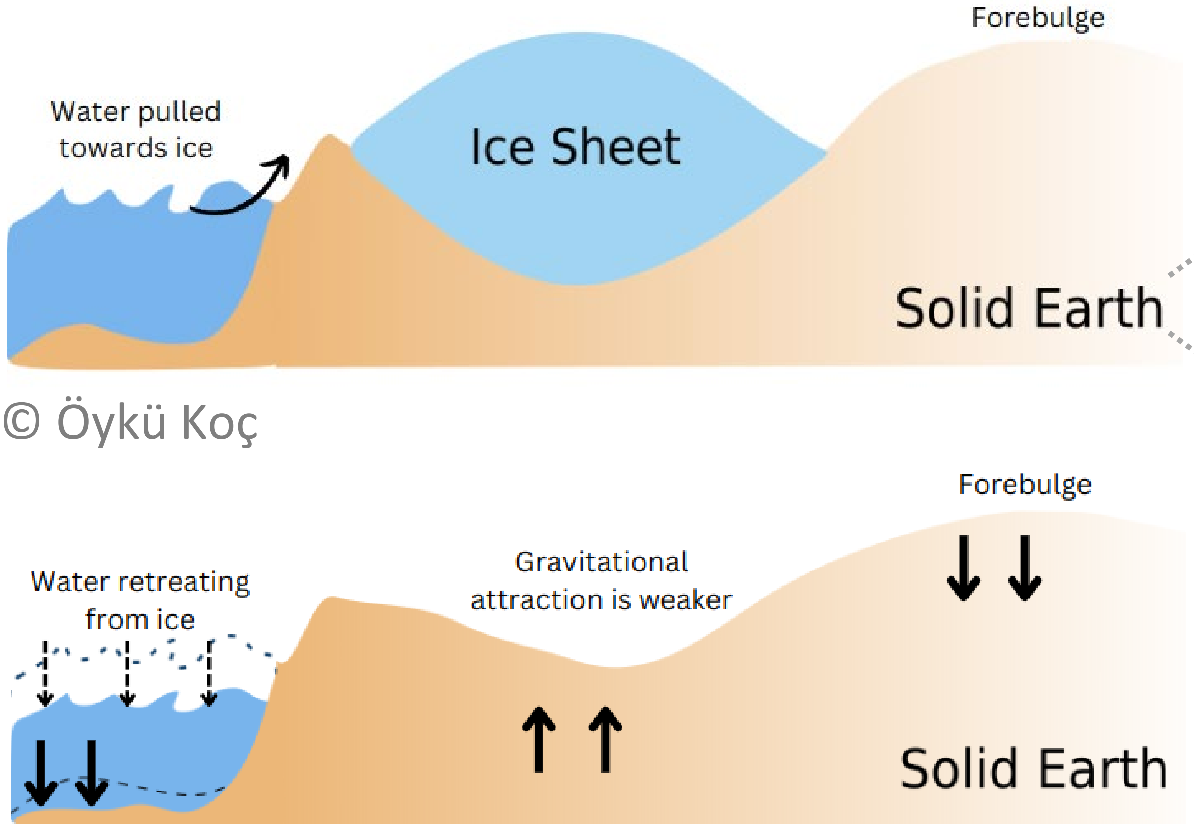
© Anna Riddell

Land-Ocean Mass Transfer

Framework of GRD (I):

- Changing surface loads reconfigure sea surface, crust, …

GIA-specific illustration



© Öykü Koç

Elastic?

Visco-elastic?

Land-Ocean Mass Transfer

Framework of GRD (II):

- Define mass-conserving loading function

$$\sigma(\theta,\lambda,t) = \underbrace{H(\theta,\lambda,t)\mathcal{C}(\theta,\lambda)}_{\text{Change of load on continents with mask } \mathcal{C}} + \underbrace{S(\theta,\lambda,t)\mathcal{O}(\theta,\lambda)}_{\text{Associated change in sea level with ocean mask } \mathcal{O}}$$

- Compute gravitationally consistent sea level change

$$S(\theta,\lambda,t) = \frac{a}{M}\left[\mathcal{G}(\theta,\lambda)\otimes\sigma(\theta,\lambda,t)\right] +$$

Rotational feedback + mass conservation constraint

$$+\frac{1}{g}\sum_{m=0}^{2}\hat{\Lambda}_{2m}(t)\hat{\mathcal{Y}}(\theta,\lambda)_{2m} + E(t)$$

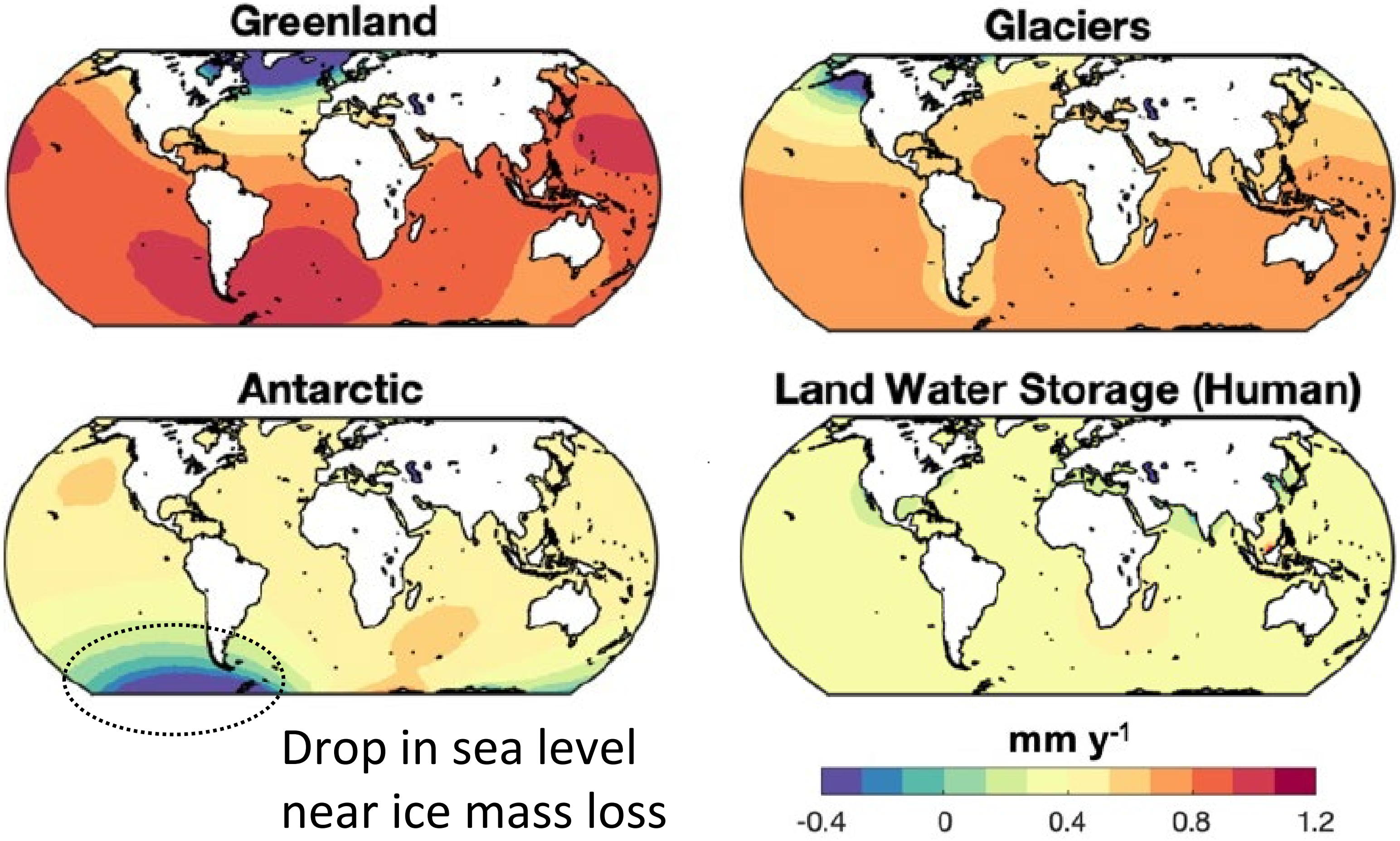
Land-Ocean Mass Transfer

Framework of GRD (III):

- Terms and parameters:
  - a … Earth radius, M … total mass of Earth, g … gravity acc.
  - $\mathcal{G}(\theta, \lambda)$ … Green’s function that parameterizes the perturbations in the gravitational potential and the associated solid Earth deformation (SED, elastic)
  - $\widehat{\Lambda}_{2m}$ … Degree-2 spherical harmonic coefficients related to perturbations in rotational potential and associated SED
  - $\hat{\mathcal{Y}}_{2m}$ … Degree-2 spherical harmonics, both sine/cosine
  - $E(t)$ … Eustatic term for mass conservation

Land-Ocean Mass Transfer

Relative sea level trends (GRD-based): **2003–2022**

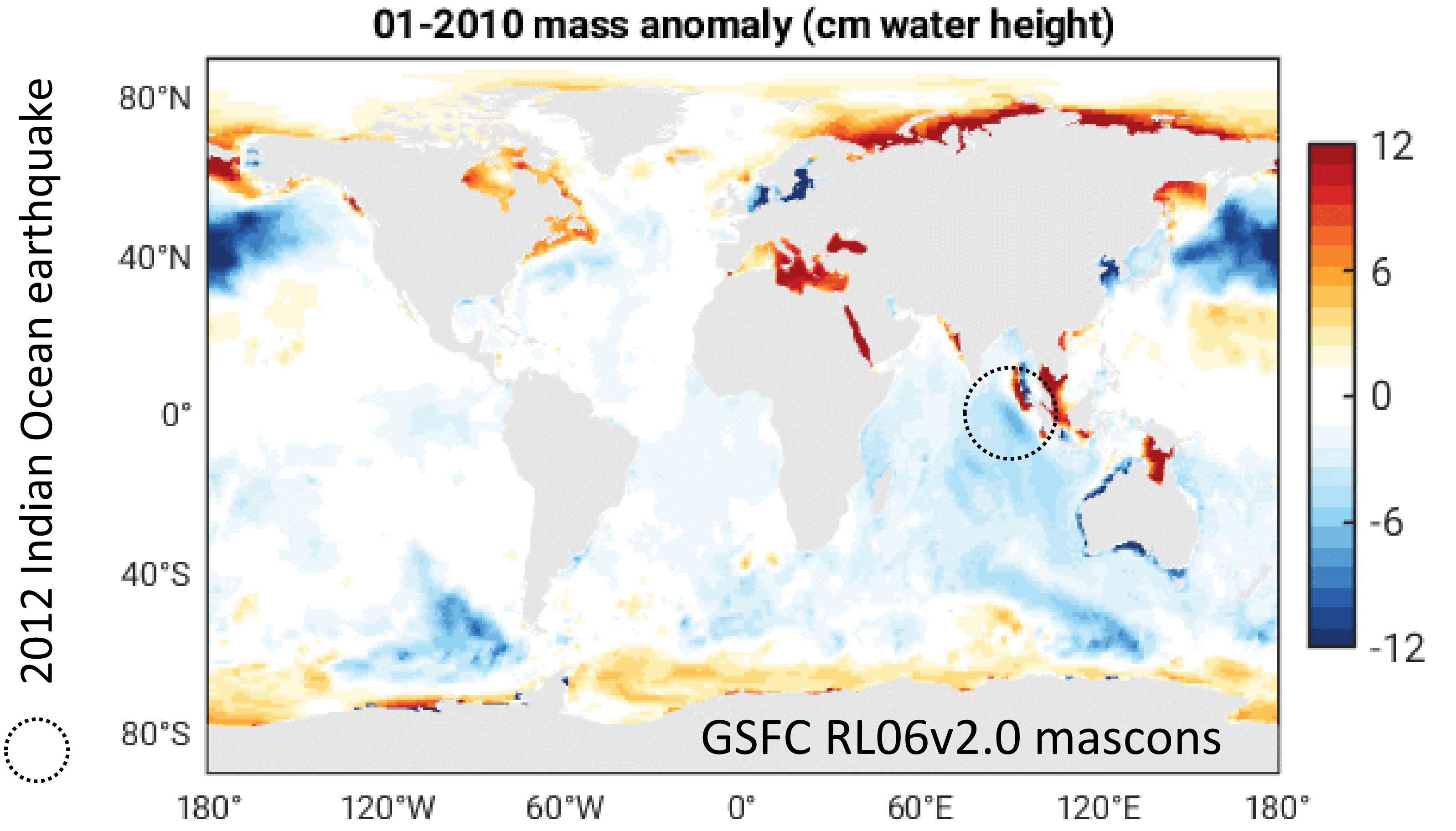


Drop in sea level near ice mass loss

Ludwigsen et al. (2024)

Mass Change of the Oceans

Is this consistent with what GRACE is seeing?

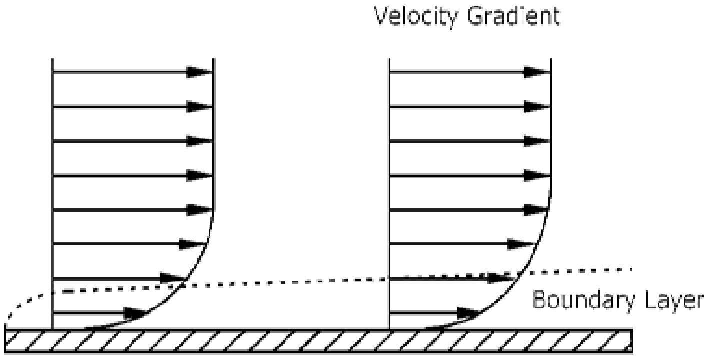


2012 Indian Ocean earthquake

Mass Change of the Oceans

What is missing from the picture?

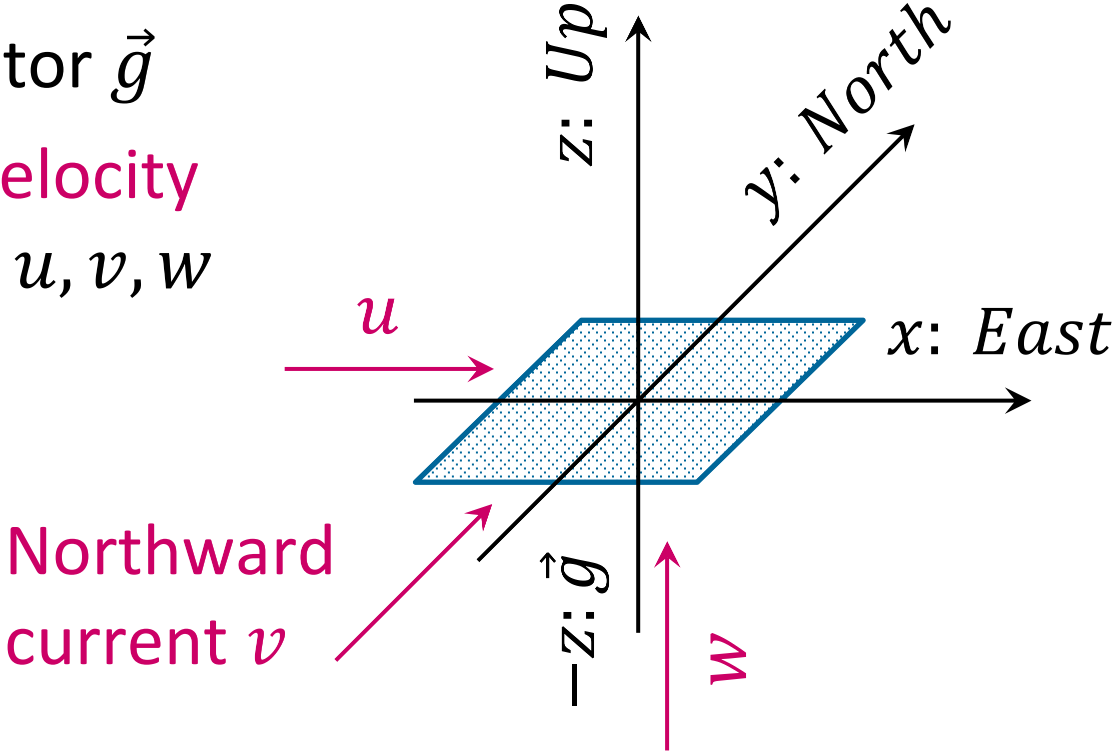
A: Currents! ⟹ Dynamic ocean



Dynamic Ocean

Coordinate system and some variables:

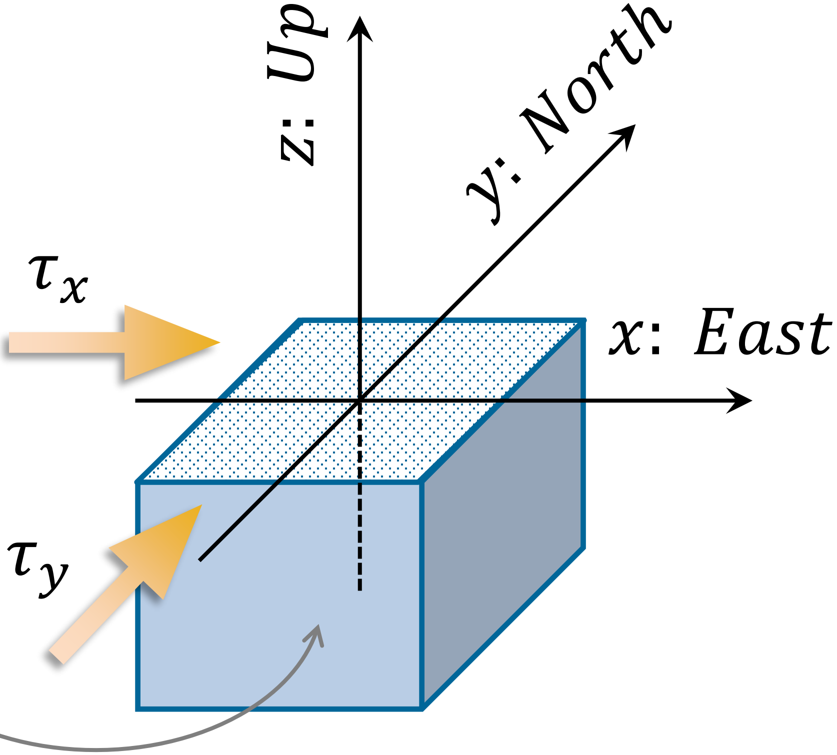
- „Flat-Earth“, i.e., xy plane is a **tangential plane**
- z points opposite to the gravitational vector $\vec{g}$
- Corresponding velocity components are u, v, w



Dynamic Ocean

Coordinate system and some variables:

- State variables in 3D: density (ρ), **pressure** (p), …
- Also consider **wind stress**:
  - x, y components of wind stress are τ_x, τ_y (= force per unit area Nm^{-2})
  - Quadratic in the near-surface wind speed



ρ, p for each parcel

Dynamic Ocean

Water is set in motion by forces F:

(1) Pressure gradient

(2) Coriolis

(3) Gravity

(4) Friction

Newton's second law in u direction:

$$\frac{\partial u}{\partial t} = \frac{1}{m}\sum F$$

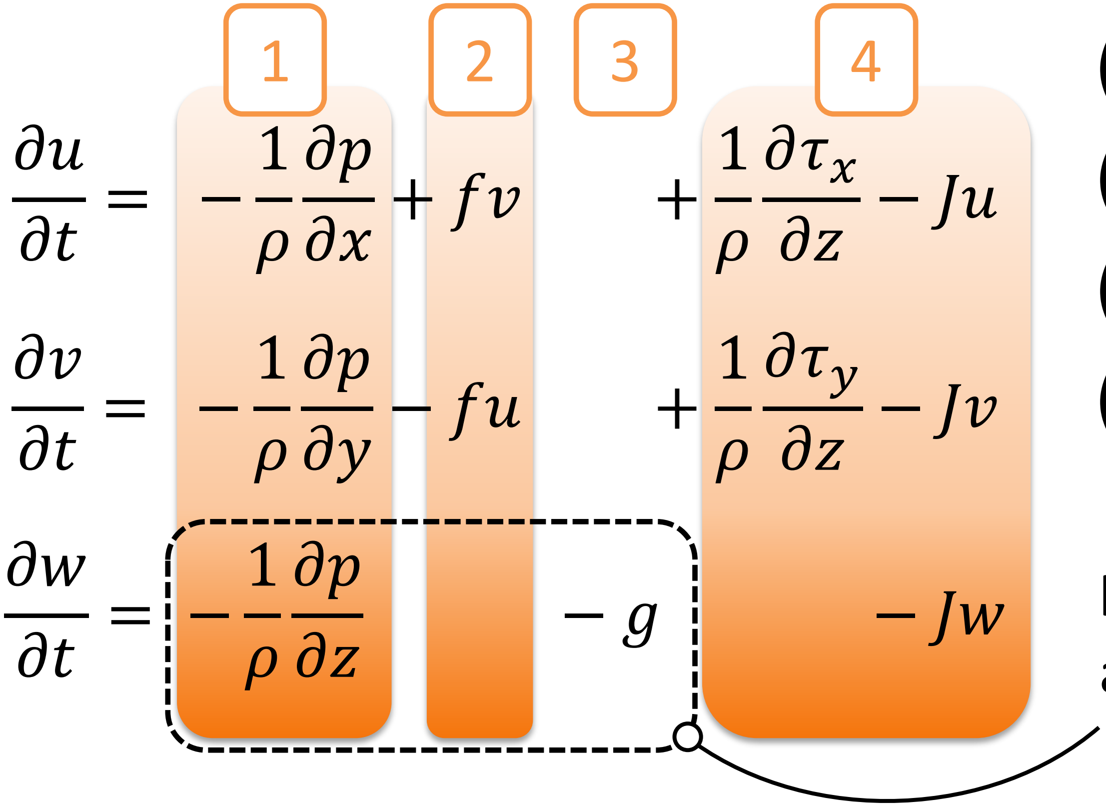
m … mass, t … time

$$\begin{gathered} density \cdot particle\ acceleration = \\ = pressure\ gradient + Coriolis \\ + gravity + friction \end{gathered}$$

Dynamic Ocean

Momentum equations – in fuller form:

- The discussed forces balance the acceleration term:



$$\frac{\partial u}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + fv + \frac{1}{\rho}\frac{\partial \tau_x}{\partial z} - Ju$$

$$\frac{\partial v}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial y} - fu + \frac{1}{\rho}\frac{\partial \tau_y}{\partial z} - Jv$$

$$\frac{\partial w}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g - Jw$$

(1) Press. gradient

(2) Coriolis

(3) Gravity

(4) Friction

Hydrostatic equation appears here

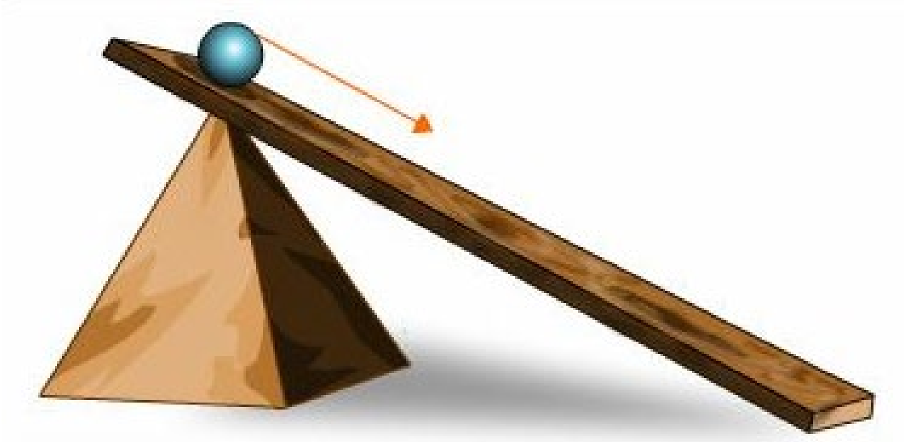
Dynamic Ocean

Horizontal **pressure gradient force**:

- Particles move **from high to low pressure**
- Mechanical analogue: ball on frictionless inclined plane

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x}$$

$$\frac{\partial v}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial y}$$



Contribution of p to equations of motion in (x, y)

Dynamic Ocean

Coriolis force – general remarks:

- An acceleration occurring when objects are moving …
- … in a non-inertial frame of reference:
  - Spinning disk
  - Rotating sphere or
  - The local reference frame we adopted (⟶ slide no. 17)

Earth's angular velocity

Latitude

- Coriolis parameter $\boldsymbol{f = 2\Omega sin\varphi}\ [rad\ s^{-1}]$

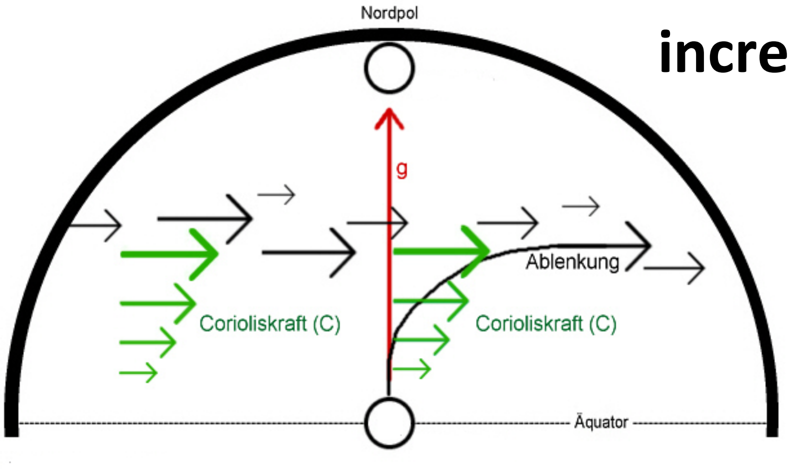
Dynamic Ocean

Coriolis force – basic findings:

Acceleration **increases with increasing latitude**

$$\frac{\partial u}{\partial t} = +vf$$

$$\frac{\partial v}{\partial t} = -uf$$



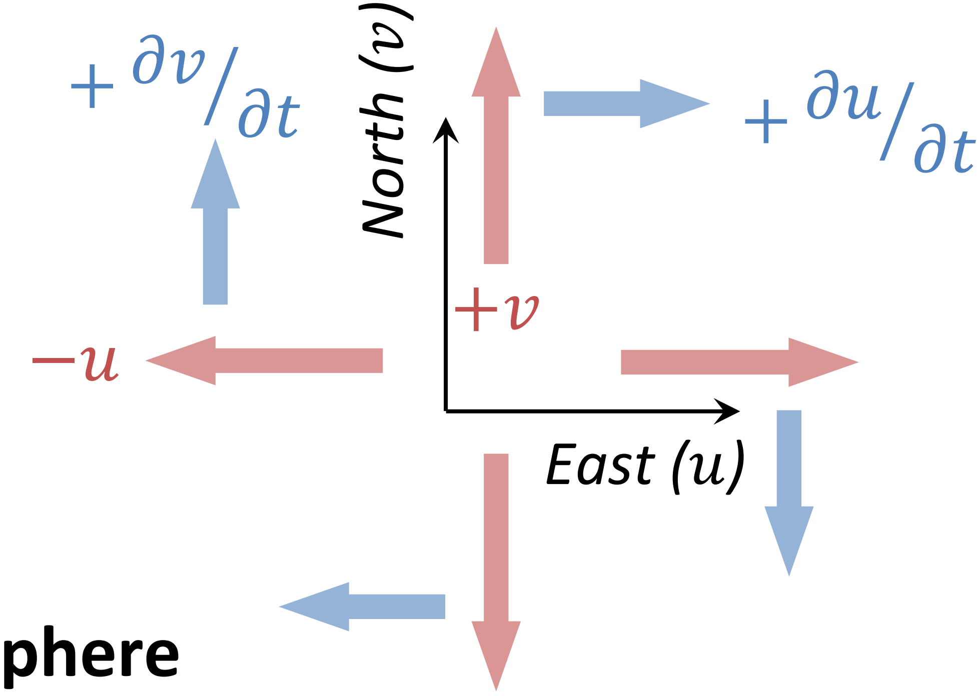
- As (u, v) are orthogonal, the Coriolis force always acts at right angles to the direction of motion:
  - N-Hemisphere: deflection to the right
  - S-Hemisphere: deflection to left (as f will be negative)

Dynamic Ocean

Moving at right angles to the direction of motion:

$$\frac{\partial u}{\partial t} = +vf$$

$$\frac{\partial v}{\partial t} = -uf$$



- Picture in **N-Hemisphere**
- Motion in v direction triggers deflection in u direction
- Particles will follow a clockwise path in this case

Dynamic Ocean

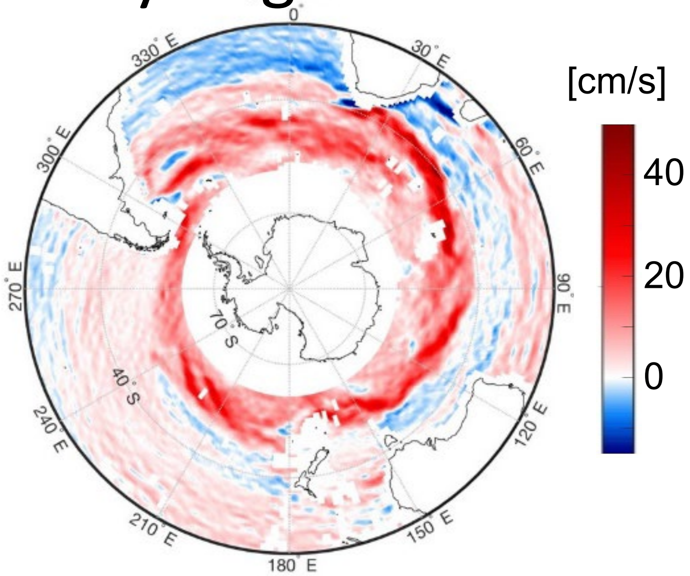
Subsetting the momentum equations:

- Assume that all currents are horizontal and steady-state
- No wind stress is acting and friction is negligible
- Processes of interest have sufficiently large scales

$$\Downarrow$$

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + fv + \frac{1}{\rho}\frac{\partial \tau_x}{\partial z} - Ju$$

$$\frac{\partial v}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial y} - fu + \frac{1}{\rho}\frac{\partial \tau_y}{\partial z} - Jv$$



Dynamic Ocean

Result = **Geostrophic equation**:

- The momentum equations are reduced to a simple balance relationship between the …
- **Pressure force** and the **Coriolis accelerations** (l.h.s.)

$$fv = \frac{1}{\rho}\frac{\partial p}{\partial x}$$

$$fu = -\frac{1}{\rho}\frac{\partial p}{\partial y}$$

- (u, v) are geostrophic currents
- Forces involved very small, but still largest in the ocean’s interior
- Good approximation for *Gulf Stream, Antarctic Circumpolar Current (**ACC**), etc.*

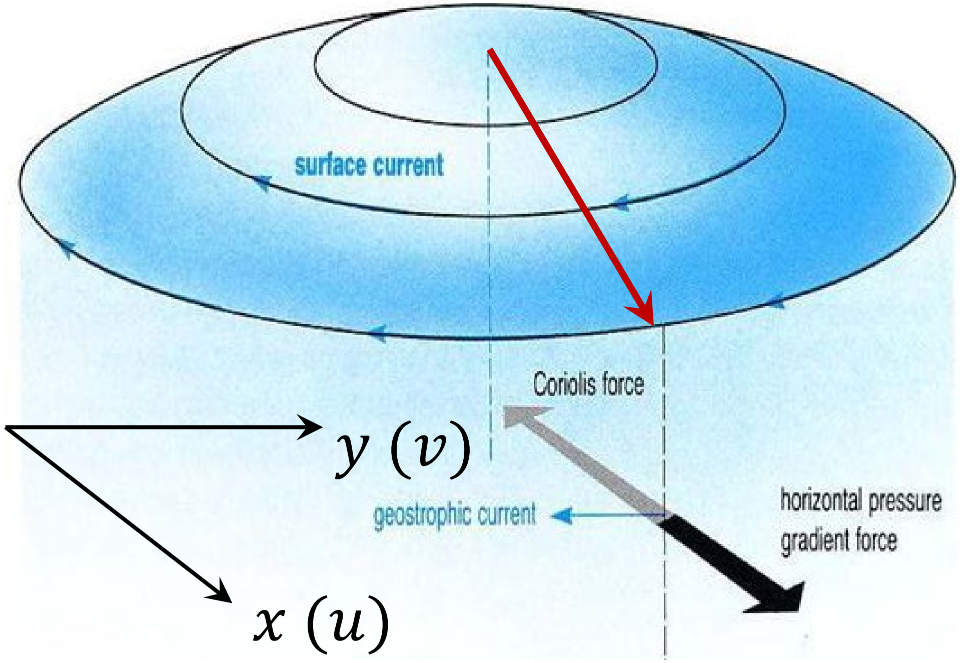
Dynamic Ocean

Consequences of the geostrophic equation:

Elevated pressure surface **N-Hemisphere**

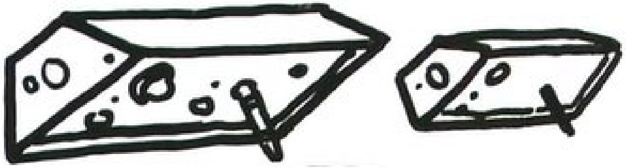
$$fv = \frac{1}{\rho}\frac{\partial p}{\partial x}$$

$$\boxed{fu = -\frac{1}{\rho}\frac{\partial p}{\partial y}}$$

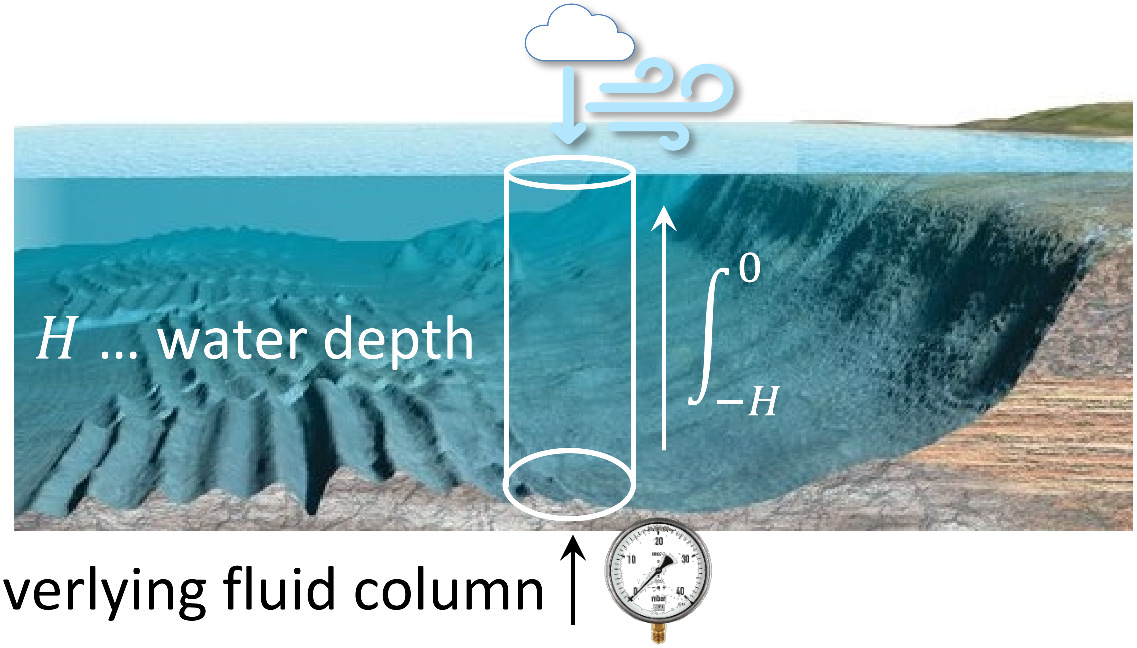


- $\partial p/\partial x$ is negative in this configuration
- With $f > 0$, a negative v current follows
- **Clockwise motion** in N-Hemisphere

Mass Change of the Oceans



OBP = Ocean Bottom Pressure (→ mass)

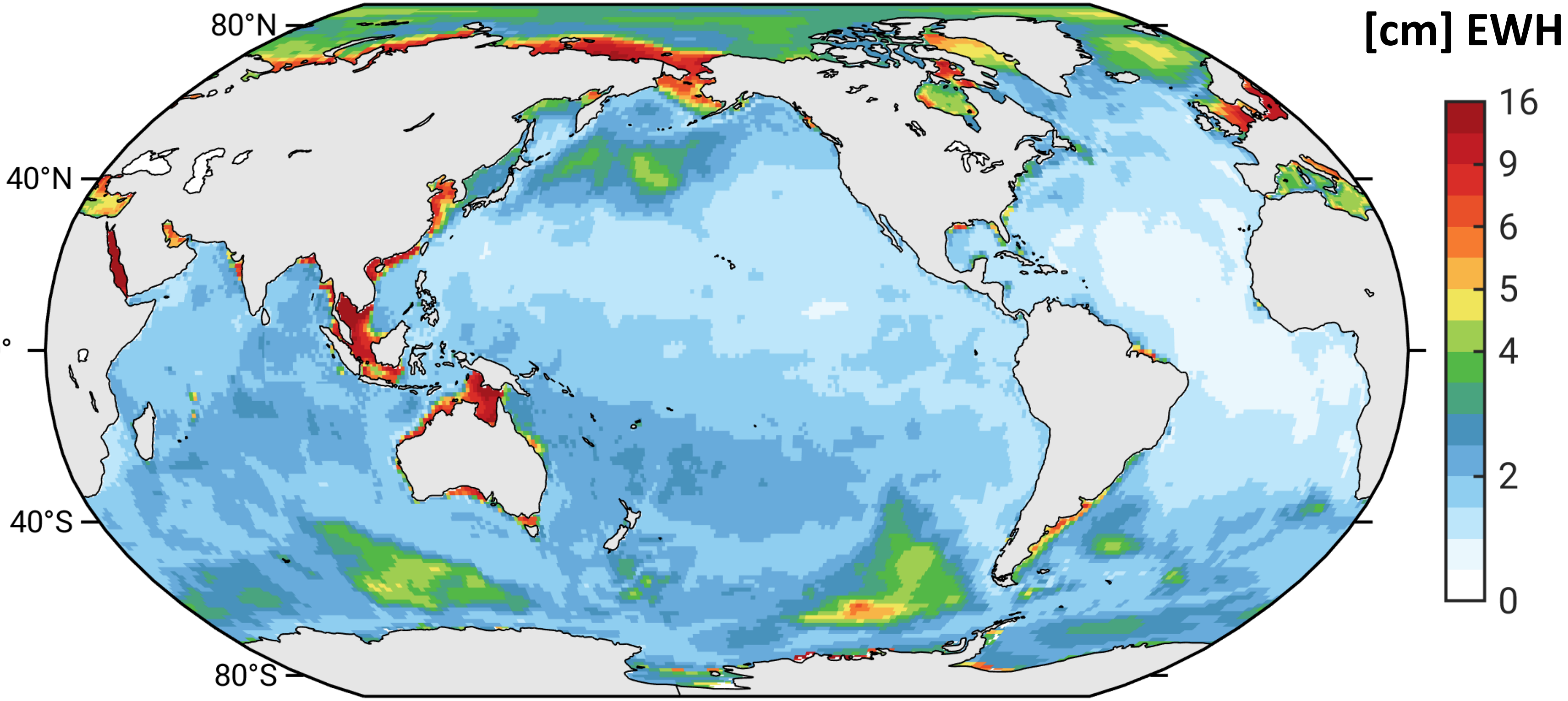


Weight of overlying fluid column

Ocean Bottom Pressure

Global view of observed OBP signals:

- σ of anomalies (spatial mean & trend reduced)



Ocean Bottom Pressure

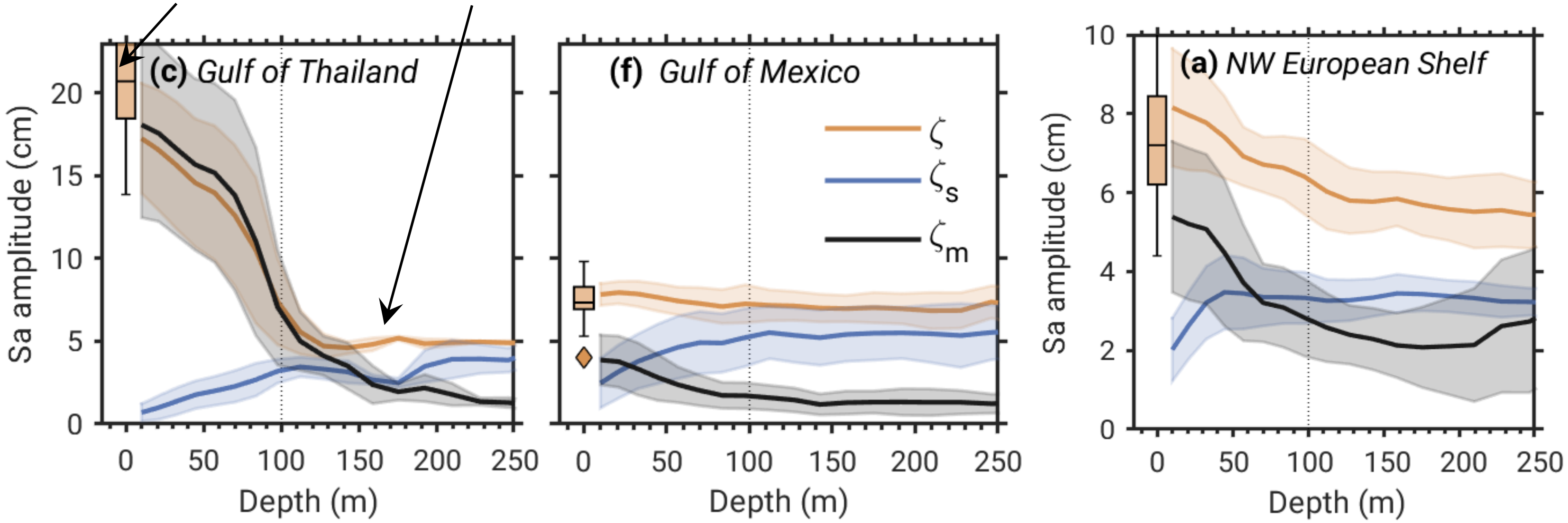
GRACE/-FO & ocean applications (I):

- Partitioning of sea level (ζ) variability
  - **Manometric** (ζ_m) vs. **steric** (ζ_s) variability: $\boxed{\zeta = \zeta_m + \zeta_s}$
  - E.g., for annual cycle, plotted over depth

ζ: Tide gauges, altimetry

ζ_m: GRACE/-FO

ζ_s: Hydrographic profiles

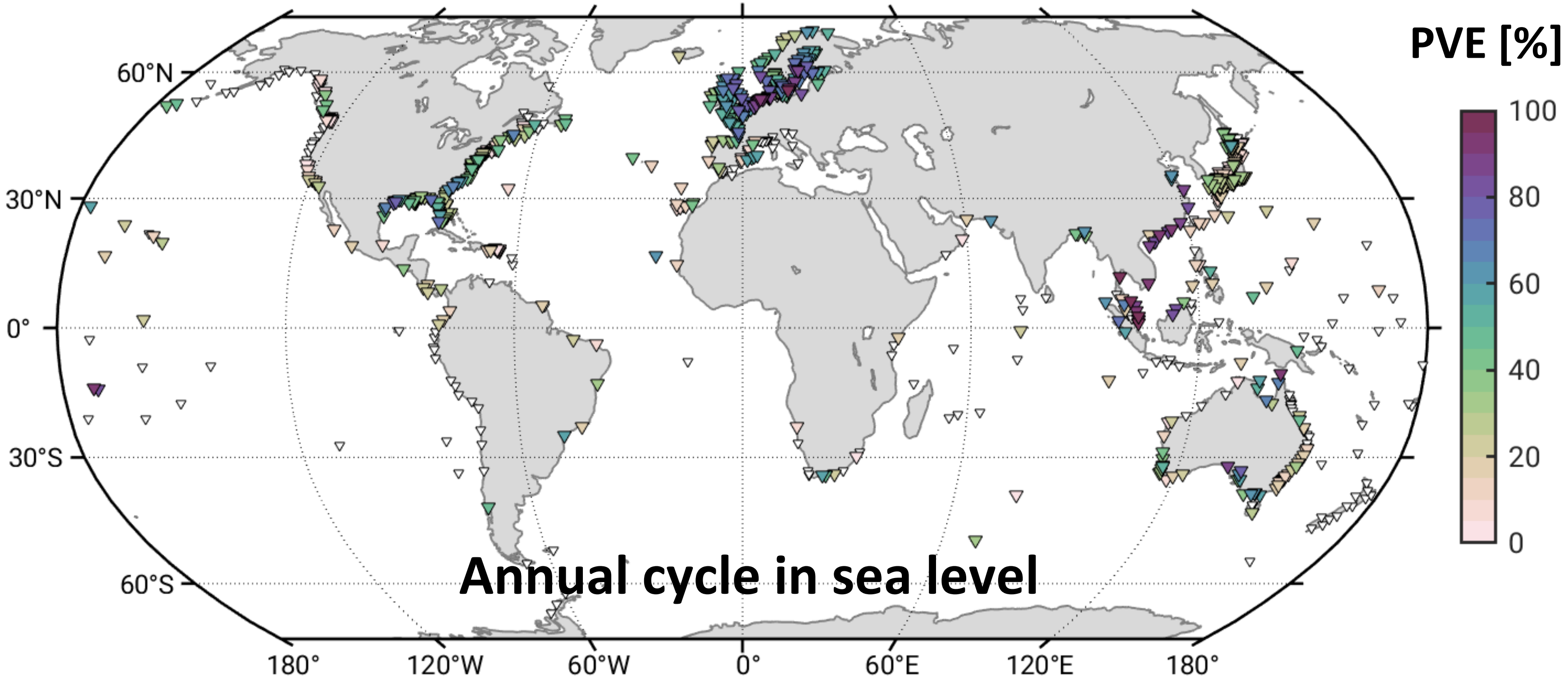


Ocean Bottom Pressure

GRACE/-FO & ocean applications (I):

- ζ_m explains how much variance in coastal sea level?

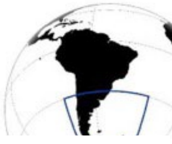
Ponte & Schindelegger (2024, Earth Space Sci.)

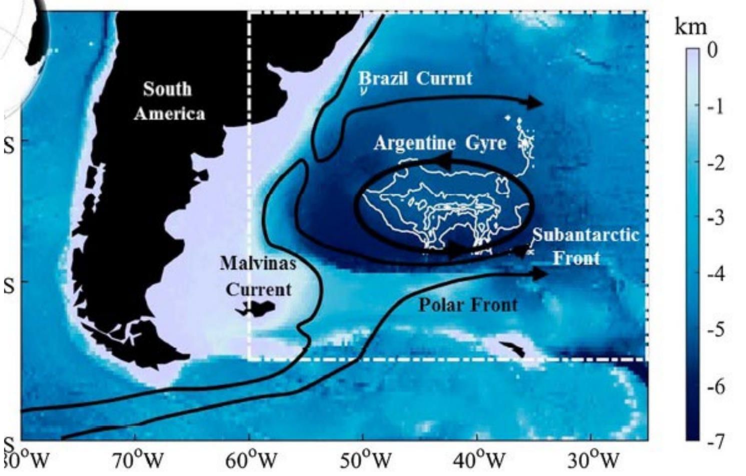


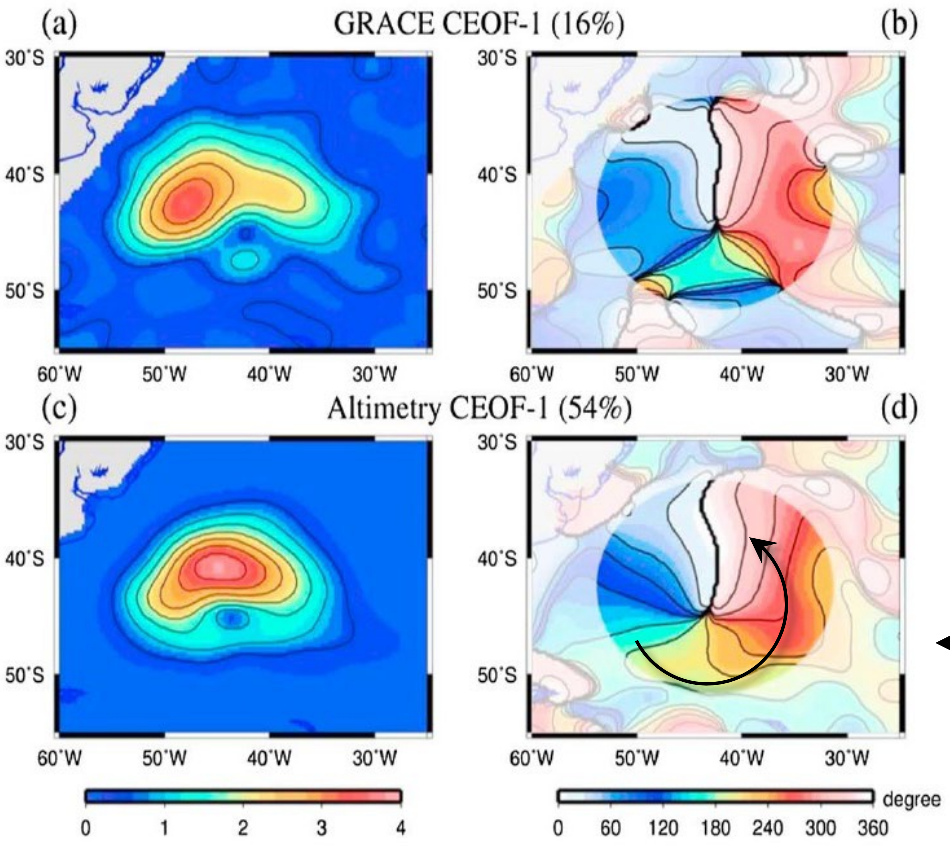
Ocean Bottom Pressure

GRACE/-FO & ocean applications (II):

- Modes of variability







Amplitude [-] and **phase** of first mode (period ~25 days)

Yu et al. (2018, JGR Oceans)

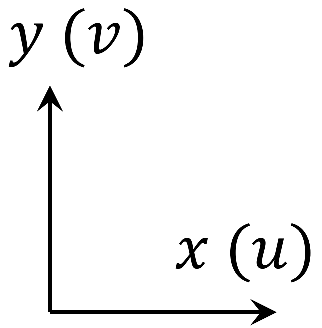
Ocean Bottom Pressure

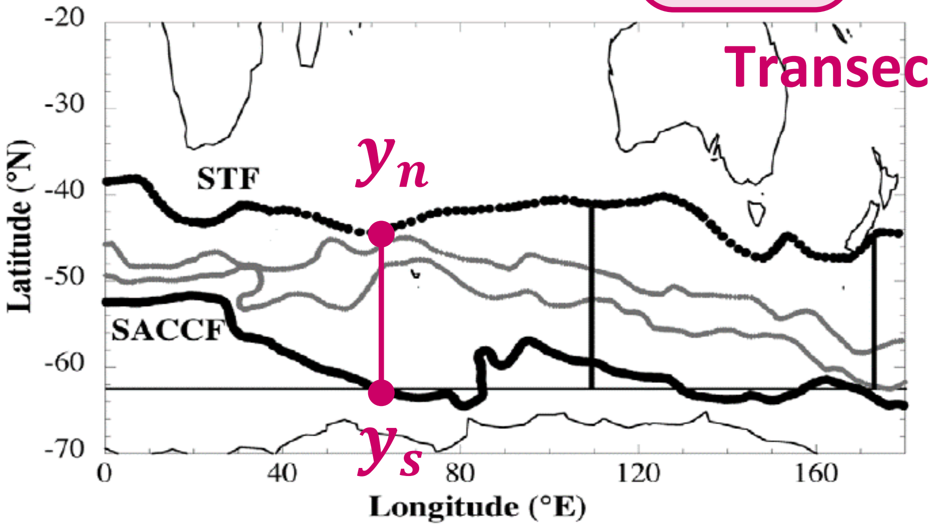
GRACE/-FO & ocean applications (III):

- Transport variability ΔT from geostrophy

$$\overset{\text{Bottom current}}{fu} = -\frac{1}{\rho}\overset{\text{OBP anomaly}}{\frac{\partial p}{\partial y}} \Longrightarrow \Delta T(x) = -\boxed{\int_{y_s}^{y_n}\int_{-H}^{0}}\frac{1}{f\rho}\frac{\partial p}{\partial y}\,\underline{dzdy}$$

Transect integral





Ocean Bottom Pressure

GRACE/-FO & ocean applications (III):

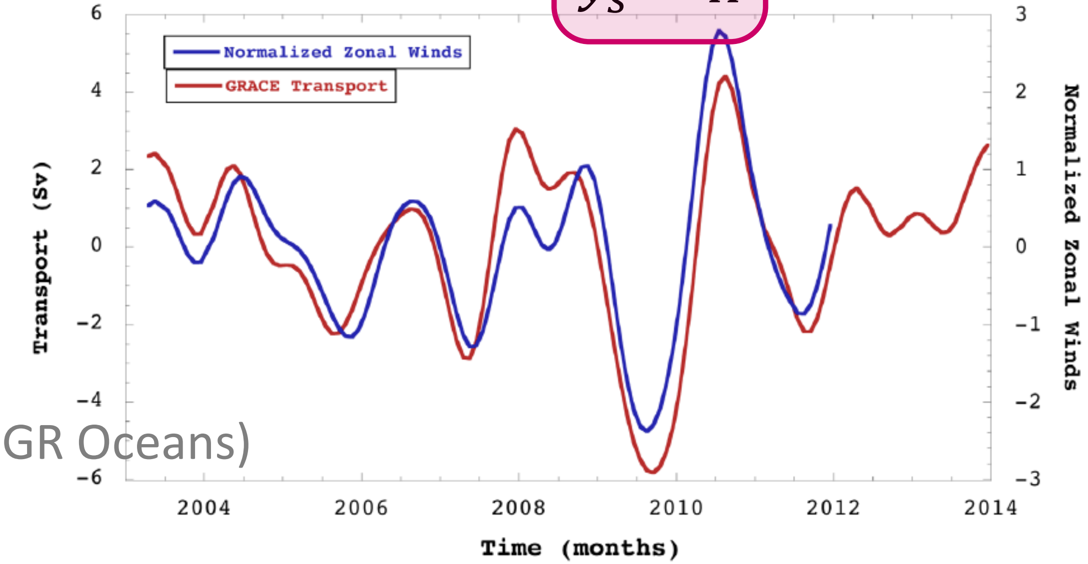
- Transport variability ΔT from geostrophy

Bottom current

OBP anomaly

$$fu = -\frac{1}{\rho}\frac{\partial p}{\partial y} \implies \Delta T(x) = -\boxed{\int_{y_s}^{y_n}\int_{-H}^{0}}\frac{1}{f\rho}\frac{\partial p}{\partial y}\,\underline{dzdy}$$

ACC transport variability at 60°E

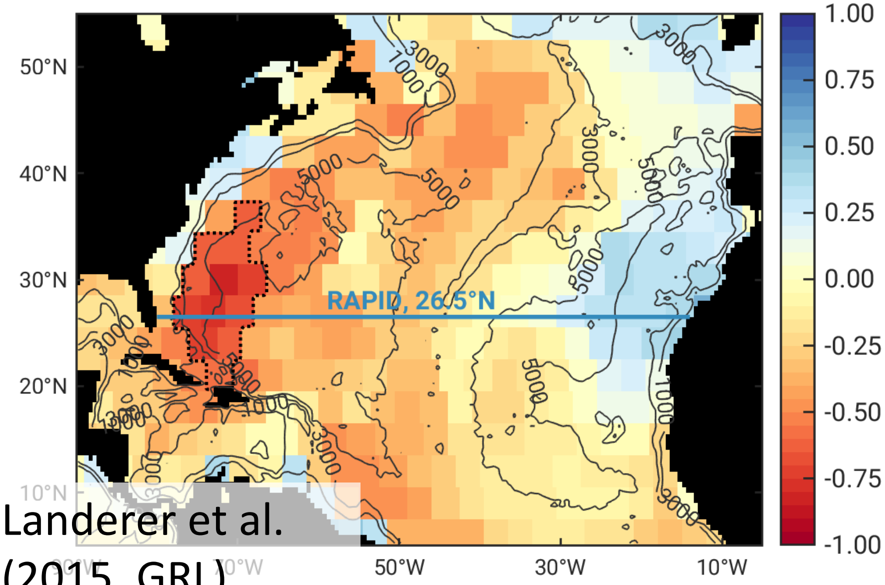


Makowski et al. (2015, JGR Oceans)

Ocean Bottom Pressure

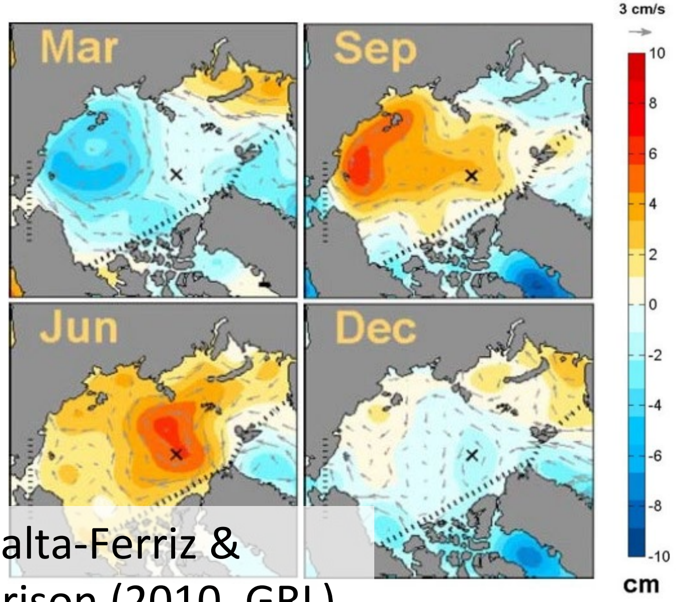
GRACE/-FO & ocean applications (III):

- ΔT or currents from geostrophy – other examples



Landerer et al. (2015, GRL)

Correlation OBP ↔ GRACE-derived transport at 26.5°N



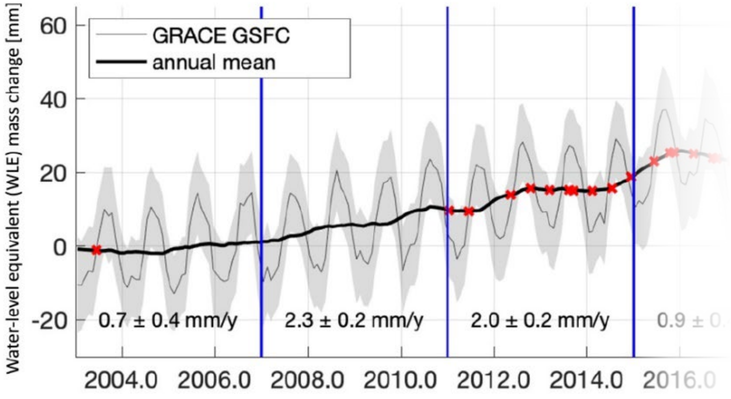
Peralta-Ferriz & Morison (2010, GRL)

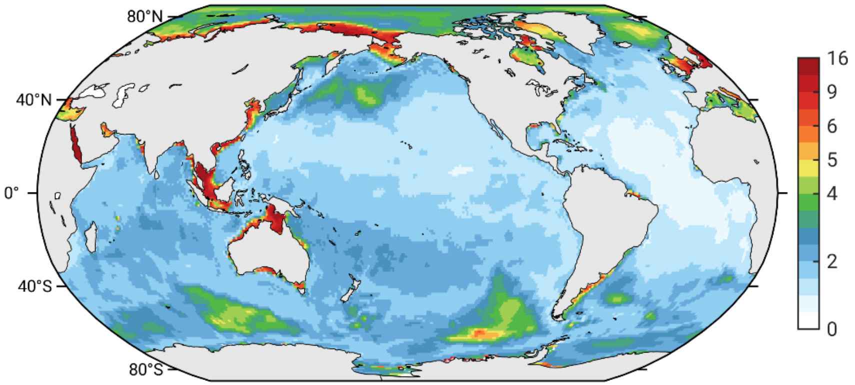
Arctic OBP (cm) and resulting geostrophic velocity (→)

Mass Change of the Oceans

Take-away messages:

- Mass change of the ocean is an interdisciplinary topic
- Multiple facets and spatiotemporal scales:
  - Global ocean mass → climate, gravity & deformation
  - Local to regional variability → dynamics
- Key insights from satellite gravimetry





Mass Change of the Oceans

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