NEROGRAV

New Refined Observations of Climate Change from Spaceborne Gravity Missions

International Spring School
Neustadt an der Weinstraße, Germany, March 10-14, 2025

Background Modelling for Satellite Gravimetry

Linus Shihora (GFZ Helmholtz Centre for Geosciences)

TU berlin
Freie Universität Berlin
Technische Universität München TUM
GFZ Helmholtz Centre for Geosciences
UNIVERSITÄT BONN
hcu HafenCity Universität Hamburg

GRACE Monthly Solutions

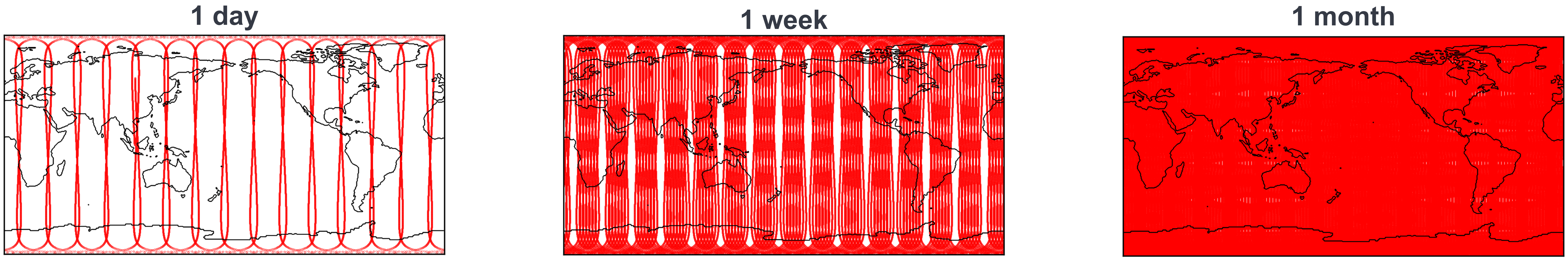
[1] Dahle, Christoph; Murböck, Michael (2019): Post-processed GRACE/GRACE-FO Geopotential GSM Coefficients GFZ RL06 (Level-2B Product). V. 0002. GFZ Data Services. https://doi.org/10.5880/GFZ.GRAVIS_06_L2B

GRACE Groundtrack Coverage

Main Objective: Measuring global mass redistributions

- Data is usually accumulated for 1 month to compute global gravity solution

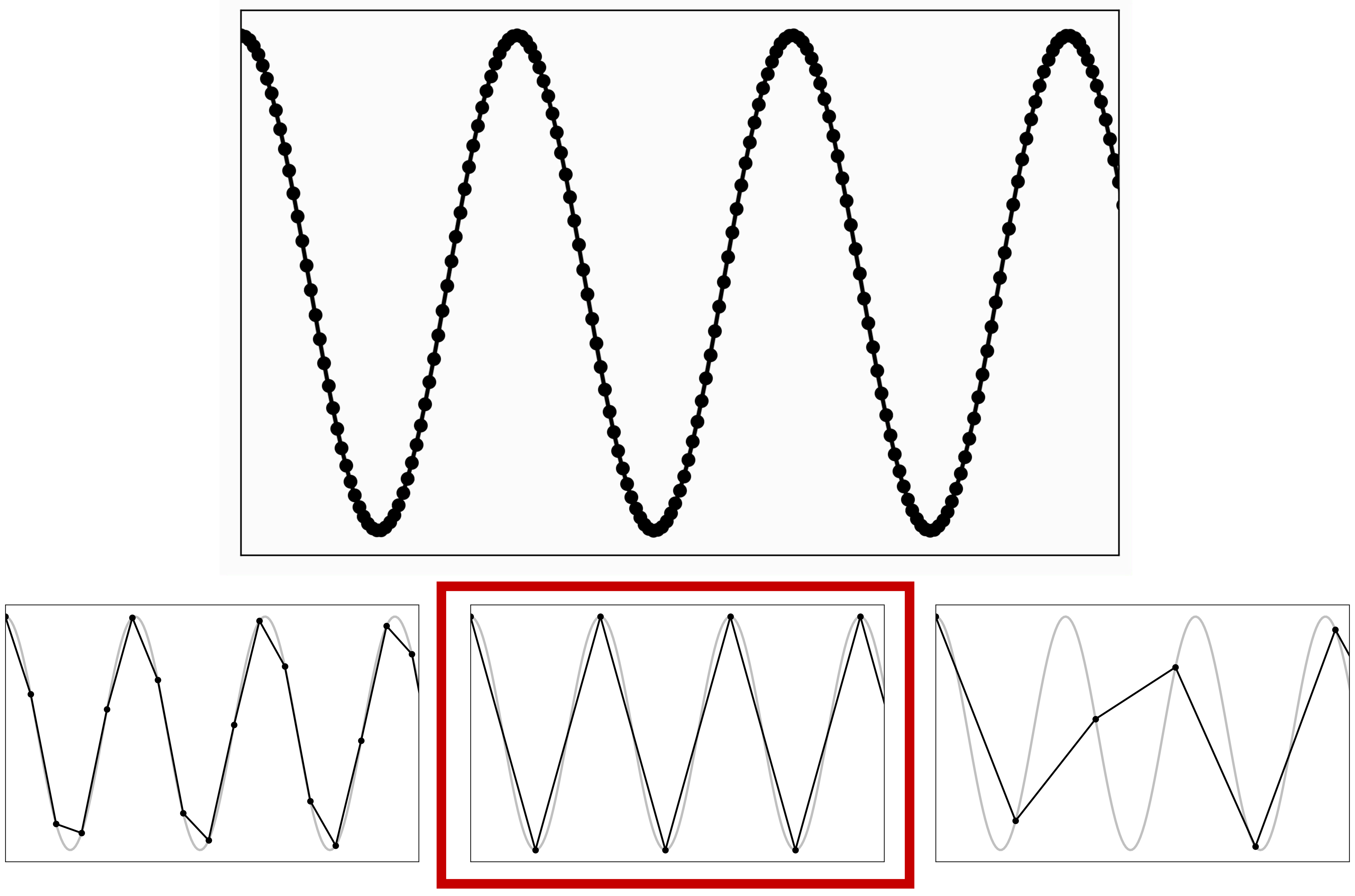
Example groundtrack after:



Temporal Aliasing

- Grace orbital period: ~90 min
- For final gravity solutions data is accumulated for ~30 days
- Signals with periods below twice the accumulation period can induce spurious signals
- Even with along-track data high frequency signals can not be resolved
- **Example**: sampling of sine-wave

Example: Sampling a Sine Wave



resolvable

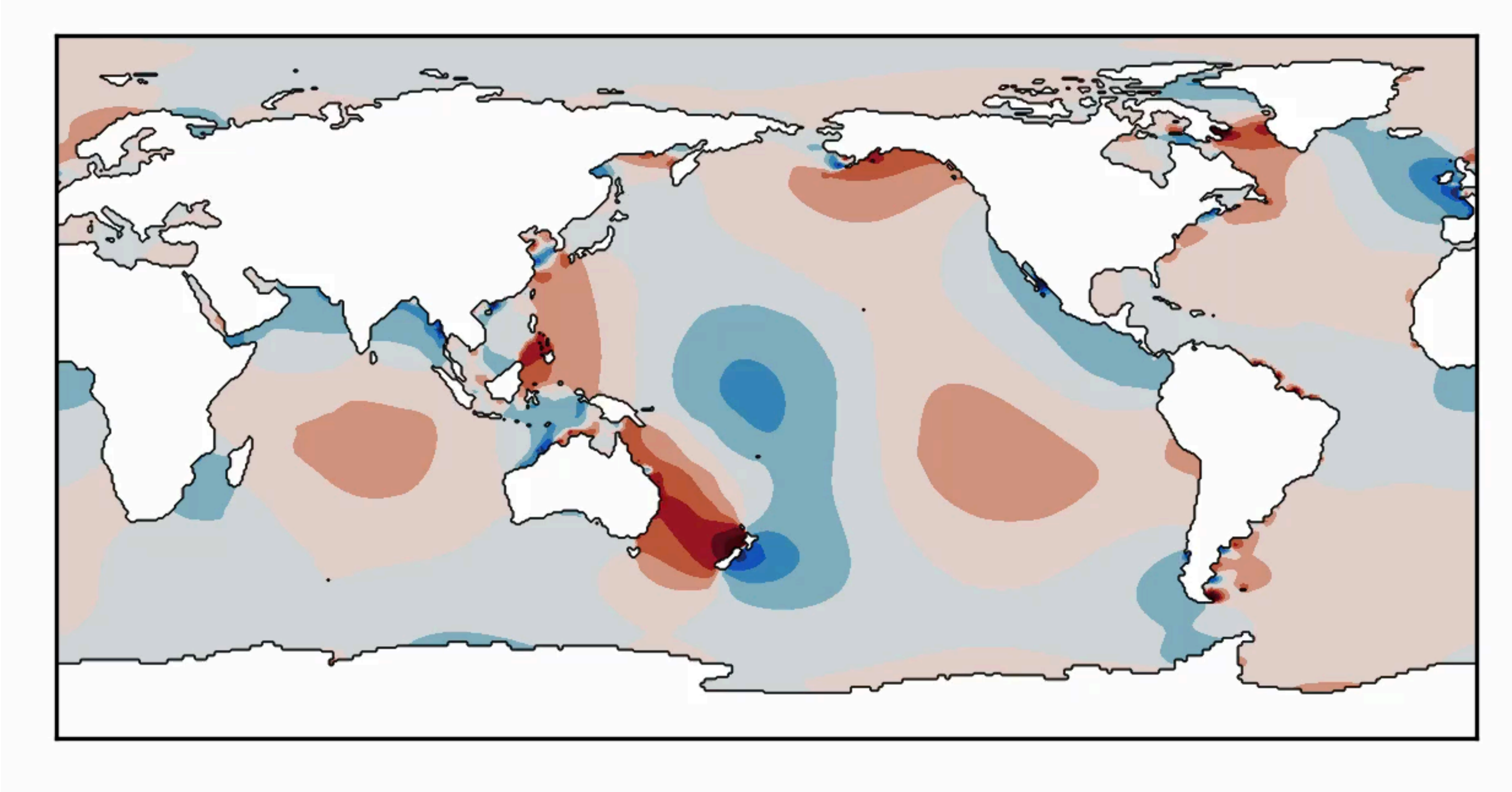
$\Delta t = T/2$

not resolvable

Temporal Aliasing

Example: M2 Tide & GRACE Groundtracks

M2 Tidal Signal



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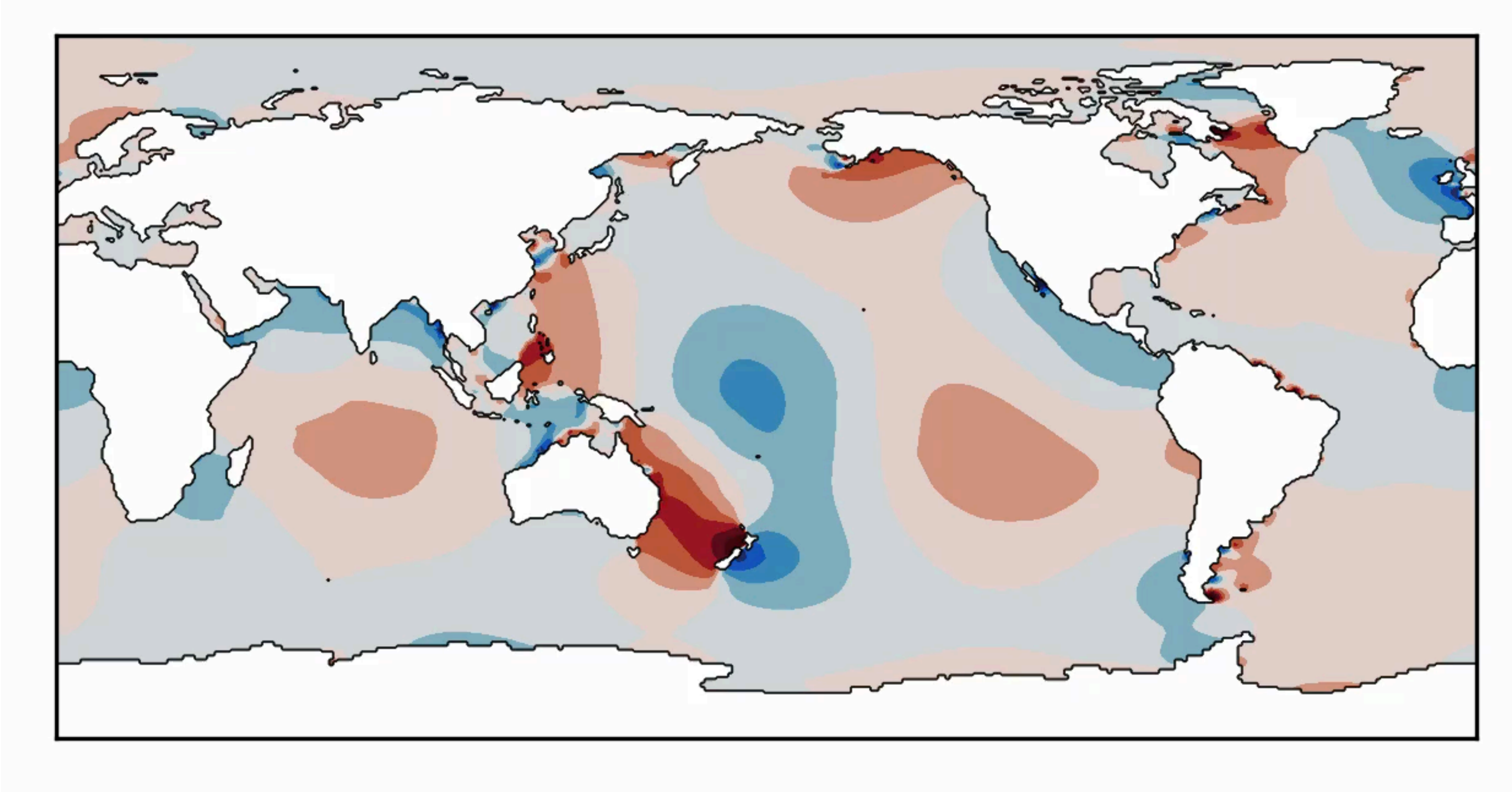
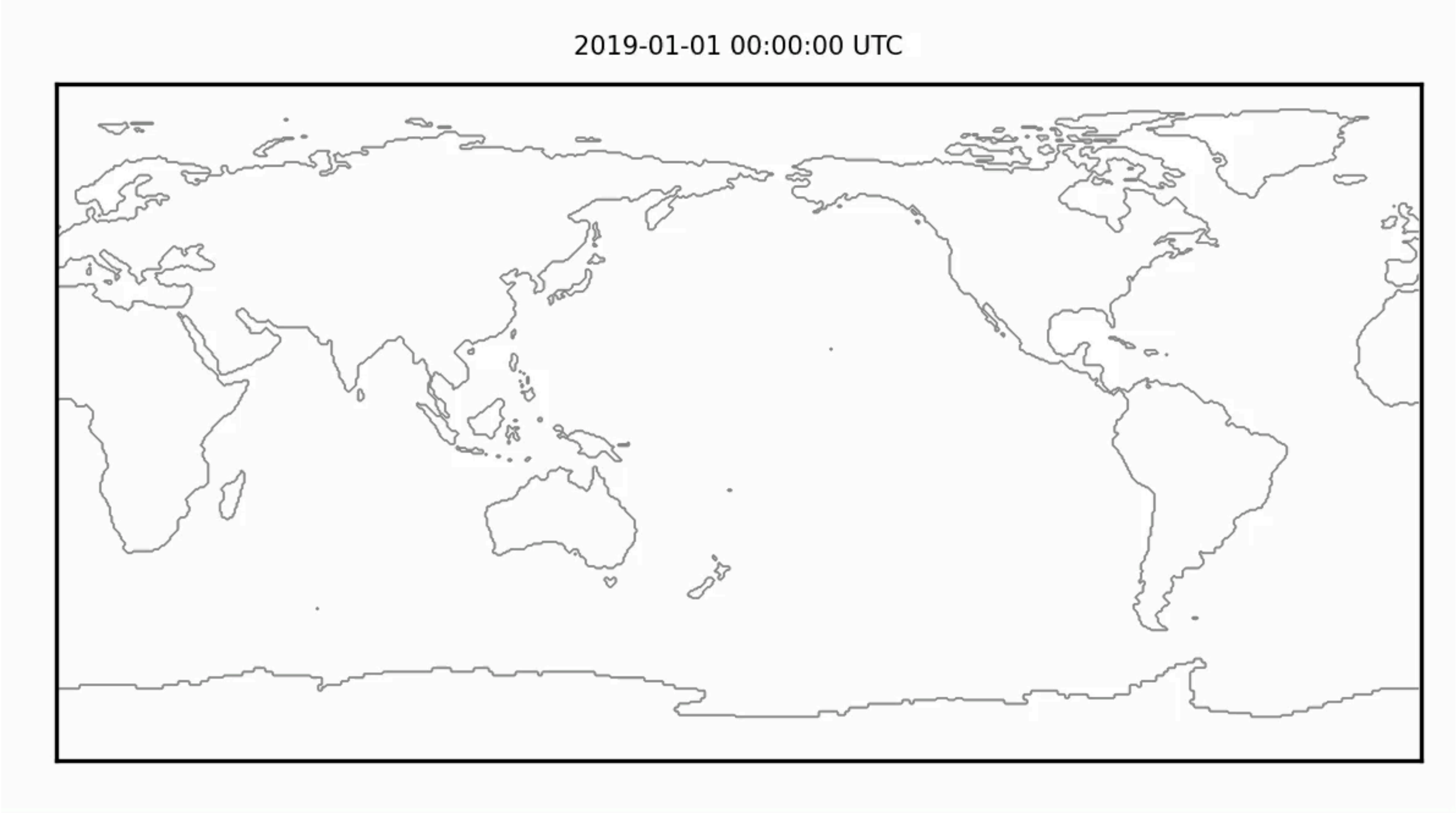


+

GRACE-FO Groundtrack



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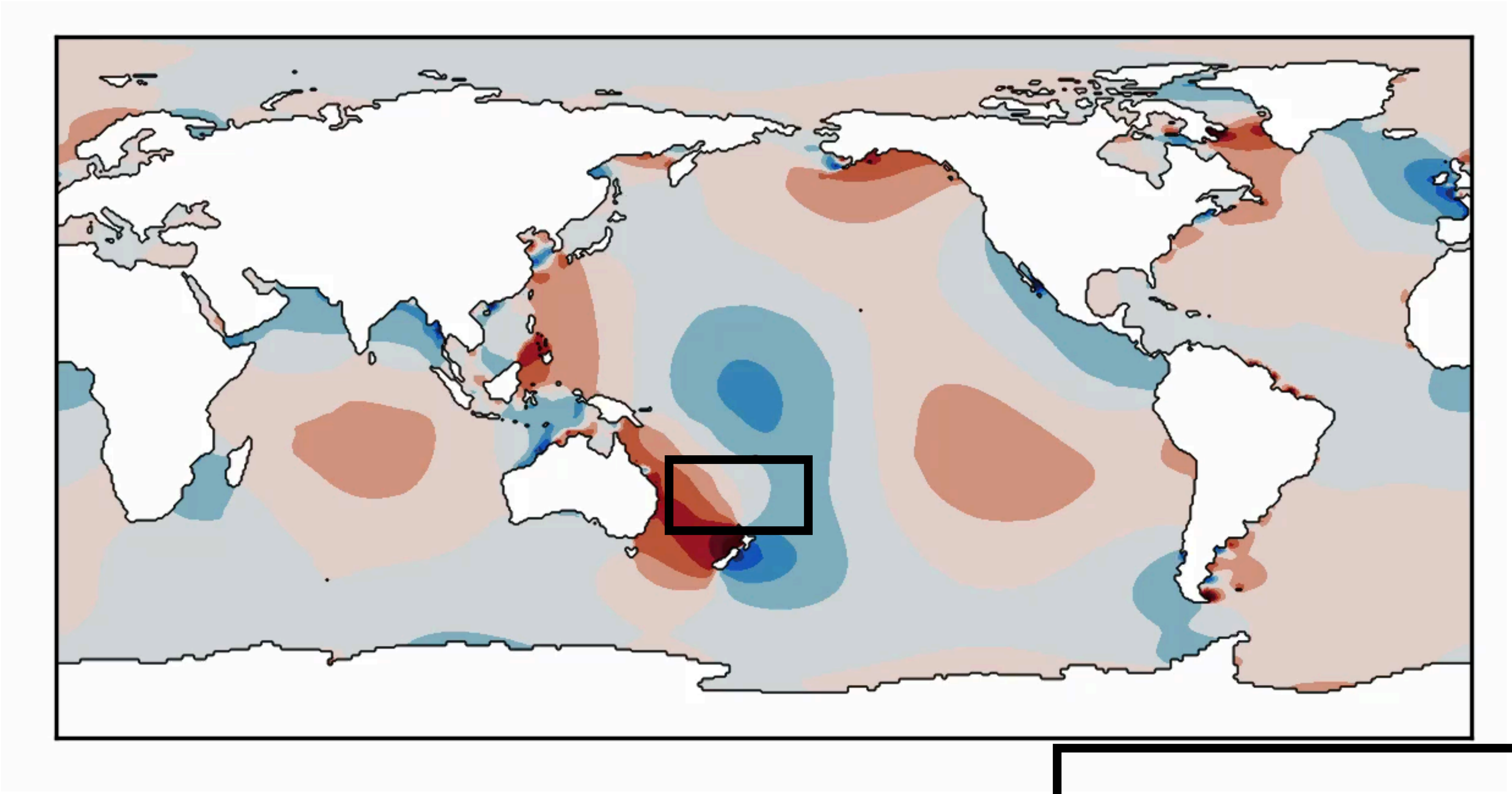

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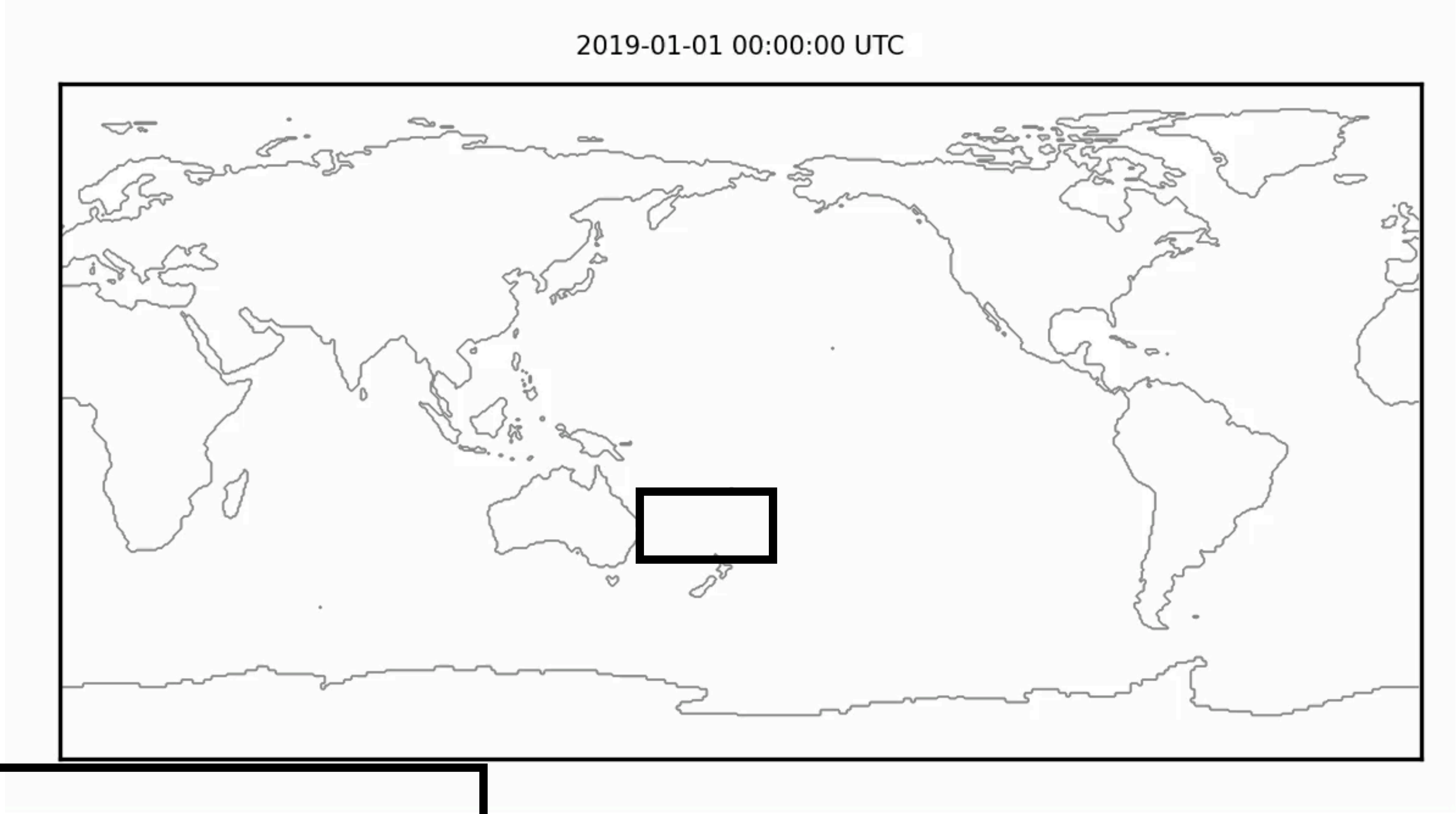

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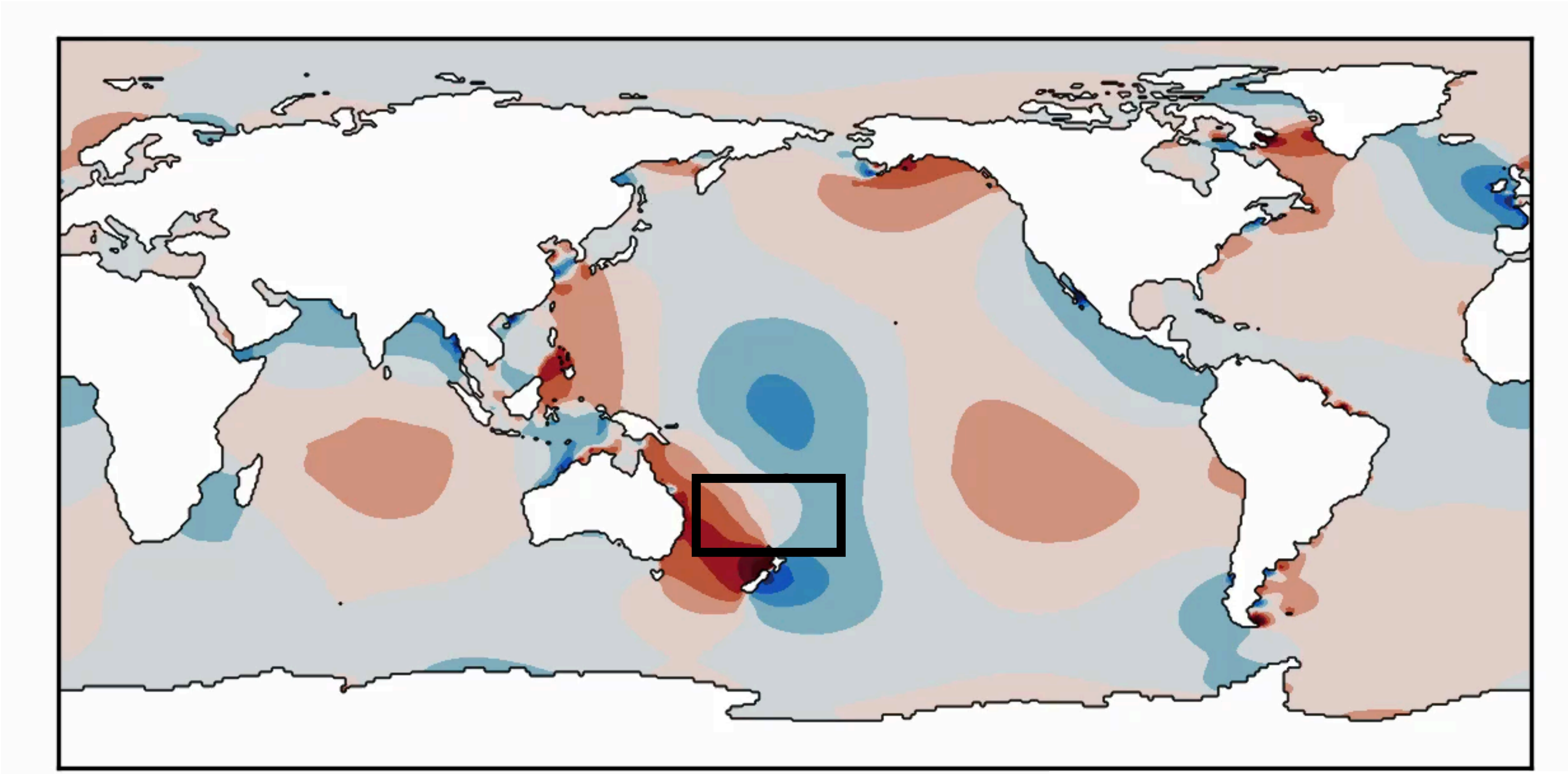

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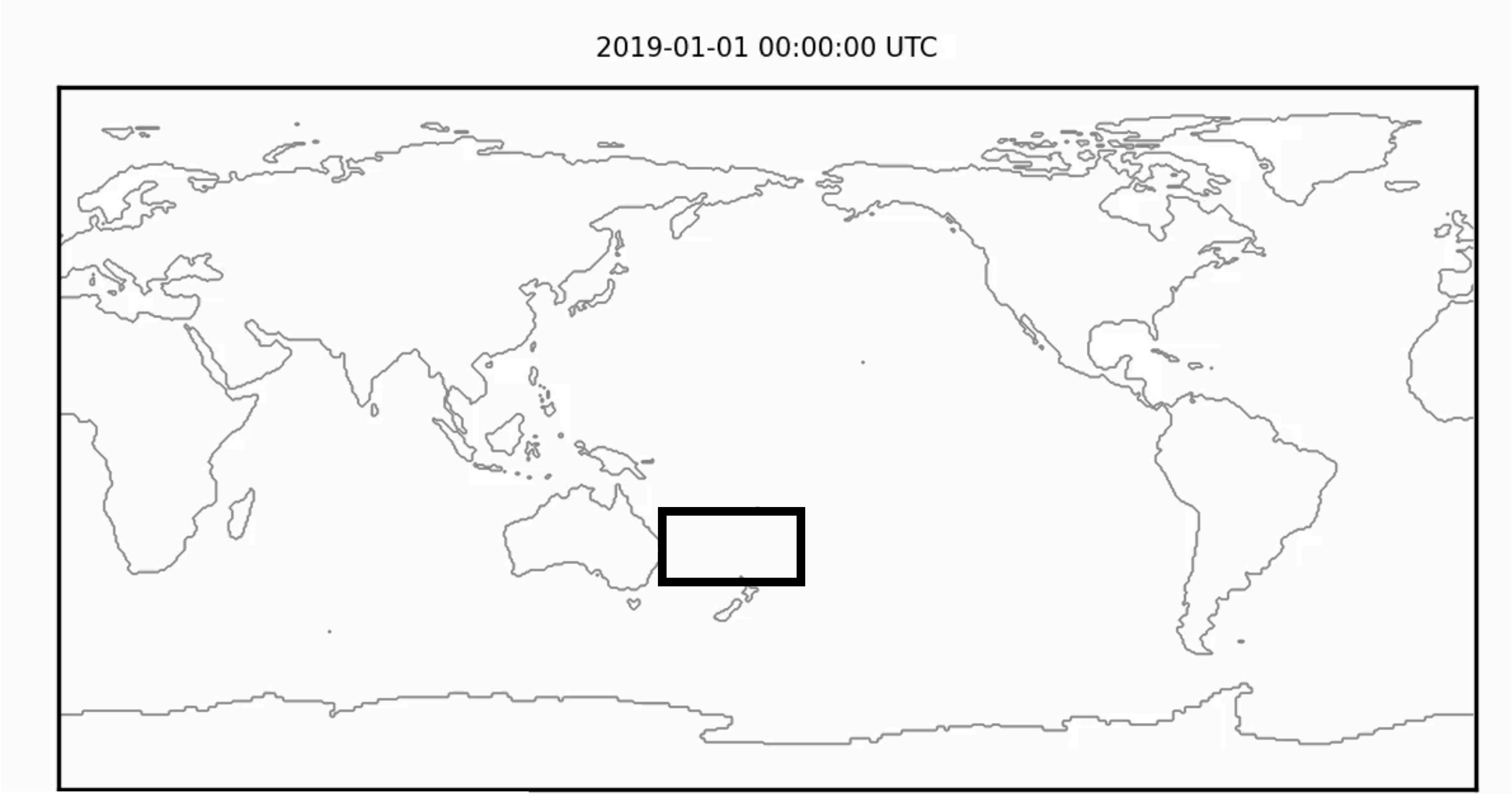
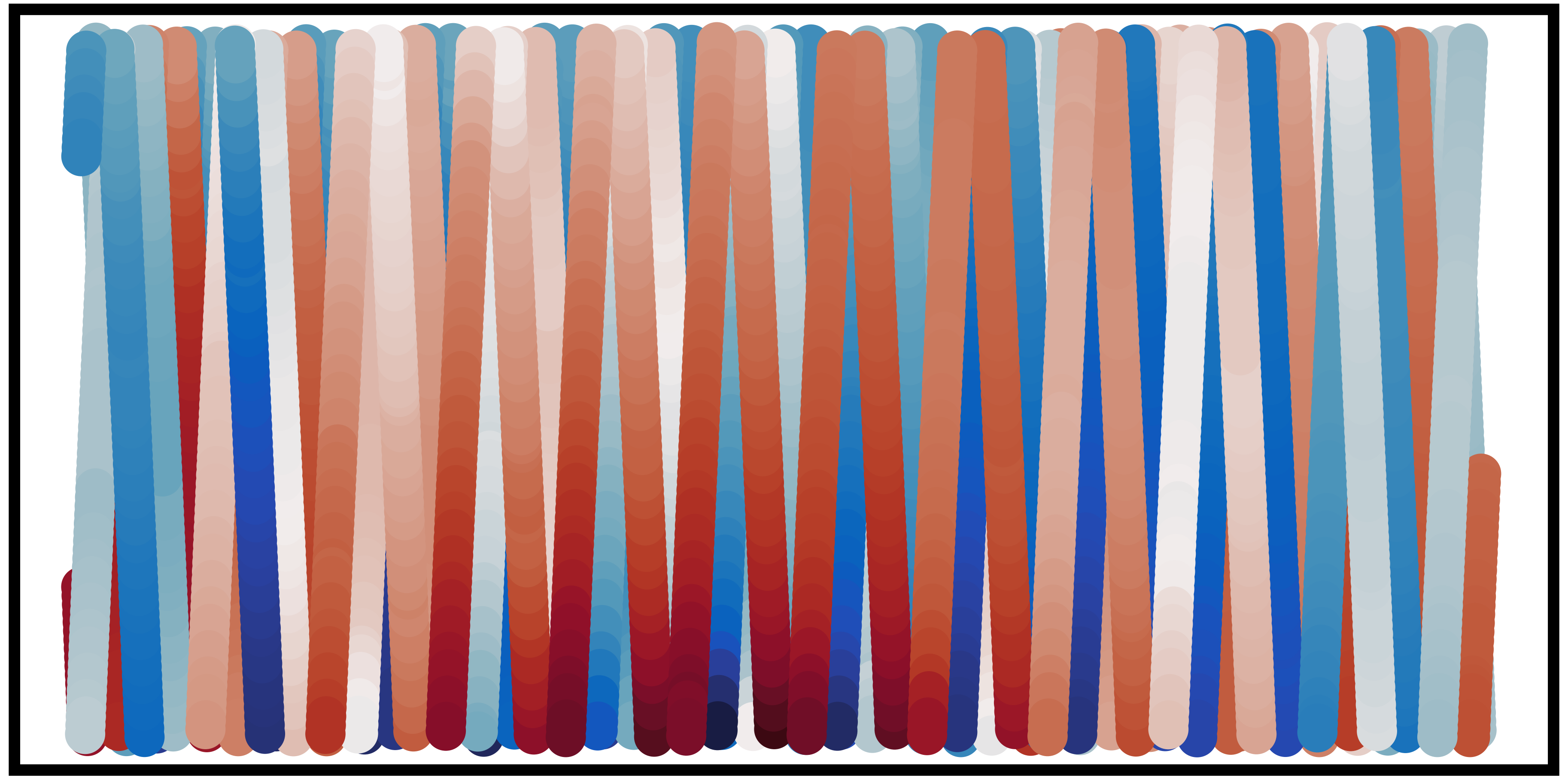




Temporal Aliasing

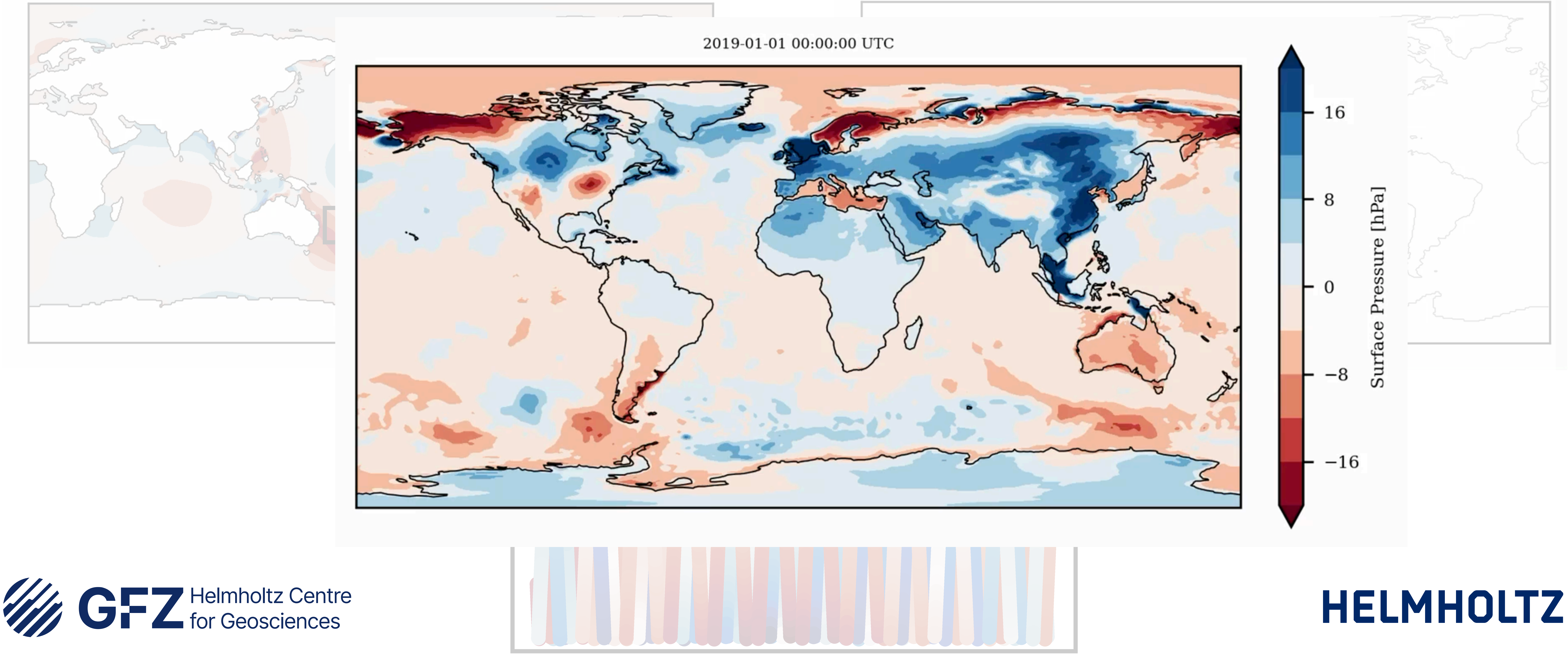
Example: M2 Tide & GRACE Groundtracks

M2 Tidal Signal

GRACE-FO Groundtrack

2019-01-01 00:00:00 UTC

Non-Tidal AO Variability



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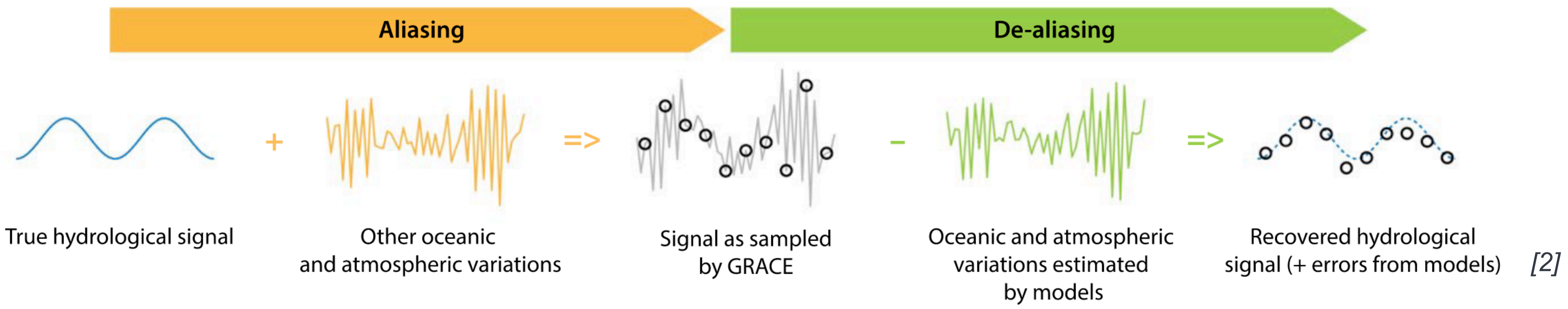
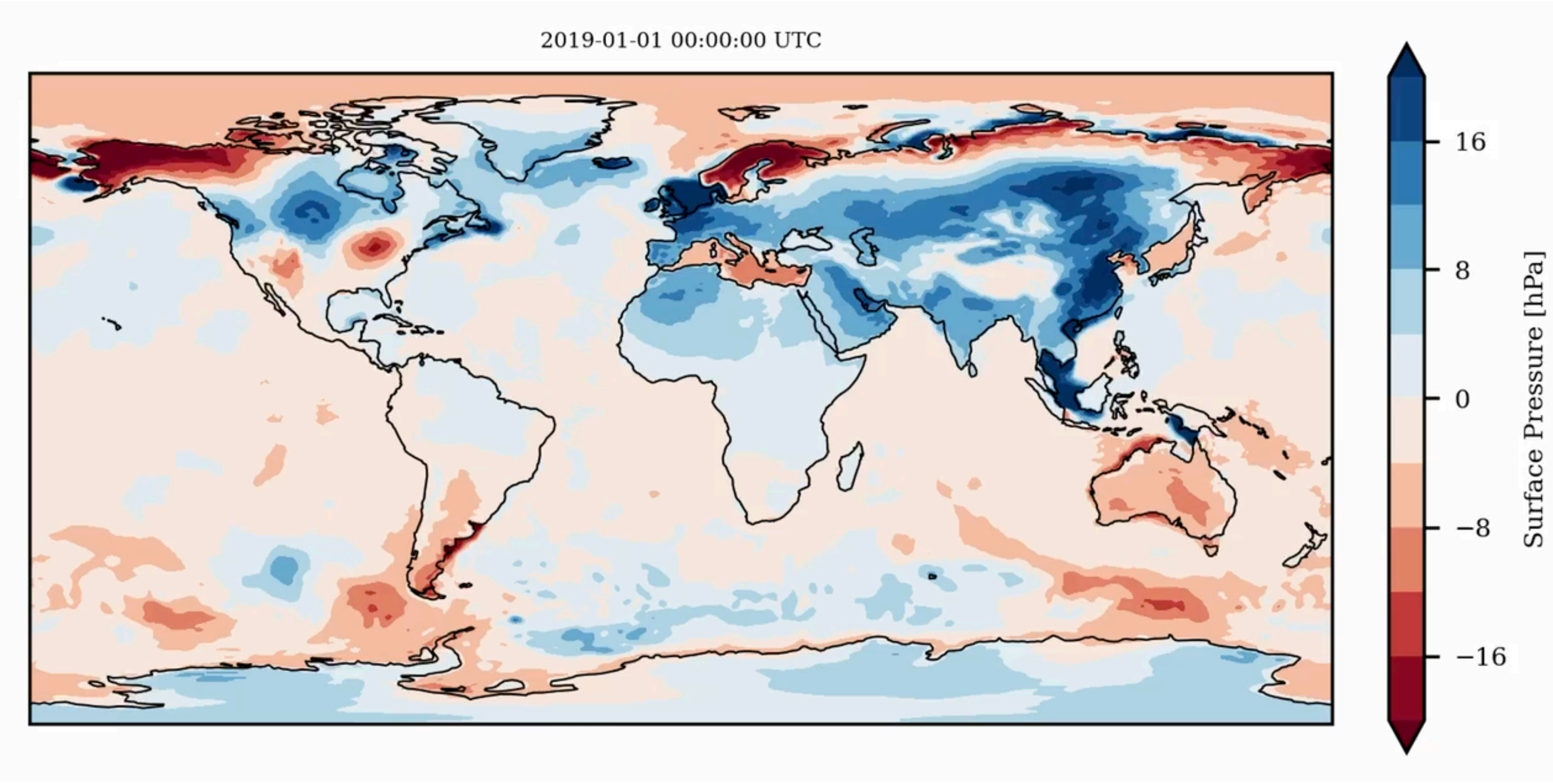

Aliasing

De-aliasing

True hydrological signal + Other oceanic and atmospheric variations => Signal as sampled by GRACE – Oceanic and atmospheric variations estimated by models => Recovered hydrological signal (+ errors from models) [2]

- High-frequency mass variations are modelled and supplied as background data products
- Subtracted in GRACE gravity field processing -> **de-aliasing**
- Non-tidal component provided by the Atmosphere and Ocean De-Aliasing Level-1B (**AOD1B**) data product
- Provides Stokes coefficients based on atmospheric and oceanic simulated mass variations

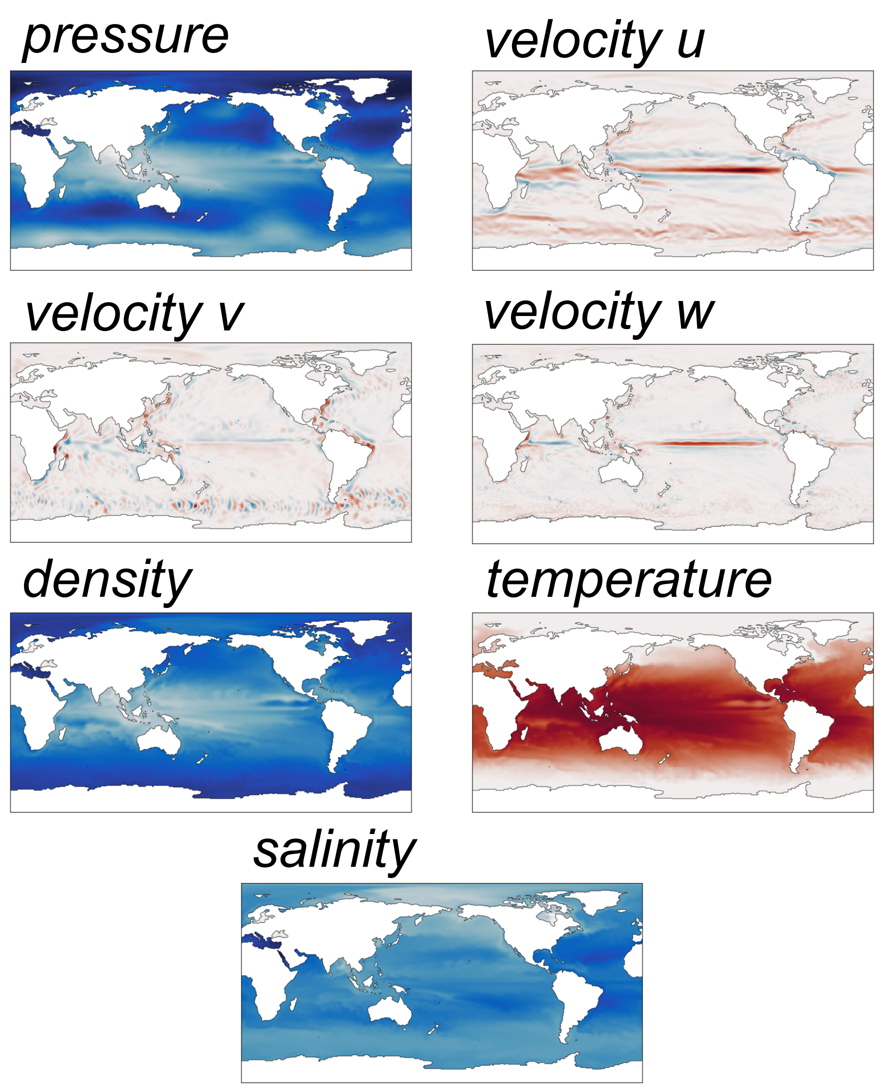


[2] Humphrey et al. (2023) Using Satellite-Based Terrestrial Water Storage Data: A Review, Surveys in Geophysics, 44:1489-1517

How do we model the atmosphere / ocean ?

How do we model the atmosphere / ocean ?

State at t_i



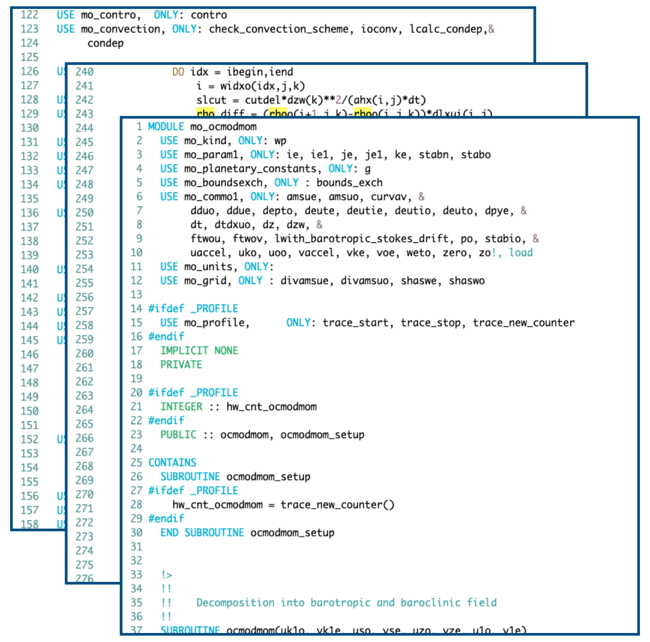
boundary conditions (e.g. atmospheric forcing)

numerical model

$$\frac{D\rho}{Dt} + \rho\nabla \cdot \vec{v} = 0 \qquad \rho\left[\frac{D\vec{v}}{Dt} + 2\vec{\Omega} \times \vec{v}\right] = -\nabla p + \rho\nabla\phi + \vec{F}$$

$$\frac{DS}{Dt} = \kappa_S \nabla^2 S + \dot{S}' \qquad \rho = \rho_0\left[1 - \alpha(T - T_0) + \beta(S - S_0)\right]$$

$$C_v \frac{DT}{Dt} = \left[\frac{k}{\rho}\nabla^2 T + Q'\right] - \left[p\frac{D}{Dt}\frac{1}{\rho}\right]$$



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USE mo_convection, ONLY: check_convection_scheme, ioconv, lcalc_condep,&
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```

```
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```
MODULE mo_ocmodmom
  USE mo_kind, ONLY: wp
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  USE mo_planetary_constants, ONLY: g
  USE mo_boundsexch, ONLY : bounds_exch
  USE mo_commo1, ONLY: amsue, amsuo, curvav, &
       dduo, ddue, depto, deute, deutie, deutio, deuto, dpye, &
       dt, dtdxuo, dz, dzw, &
       ftwou, ftwov, lwith_barotropic_stokes_drift, po, stabio, &
       uaccel, uko, uoo, vaccel, vke, voe, weto, zero, zo!, load
  USE mo_units, ONLY:
  USE mo_grid, ONLY : divamsue, divamsuo, shaswe, shaswo

#ifdef _PROFILE
  USE mo_profile,      ONLY: trace_start, trace_stop, trace_new_counter
#endif
  IMPLICIT NONE
  PRIVATE

#ifdef _PROFILE
  INTEGER :: hw_cnt_ocmodmom
#endif
  PUBLIC :: ocmodmom, ocmodmom_setup

CONTAINS
  SUBROUTINE ocmodmom_setup
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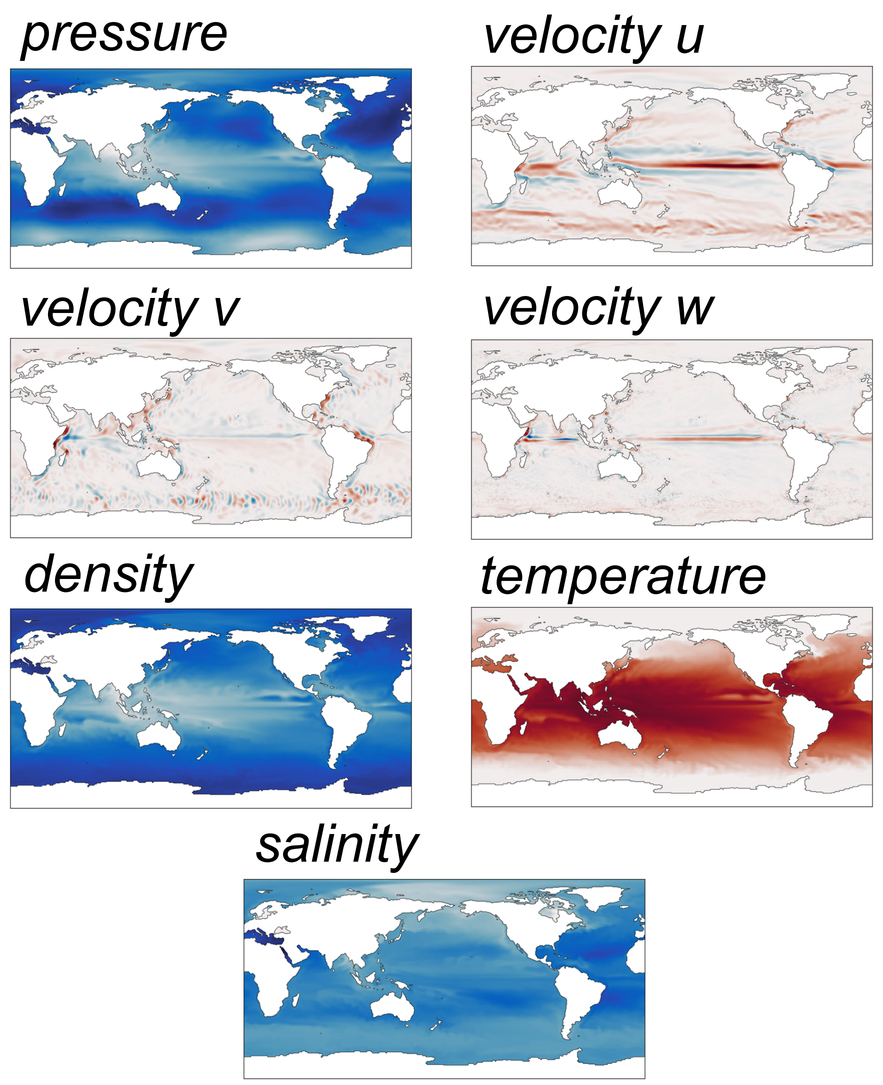
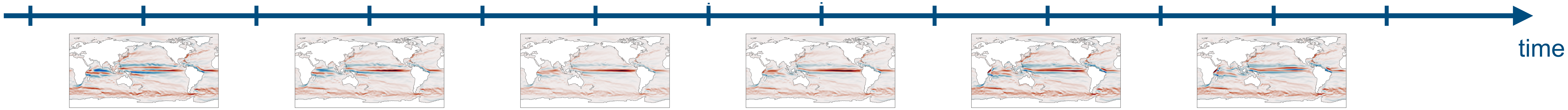
State at t_{i+1}





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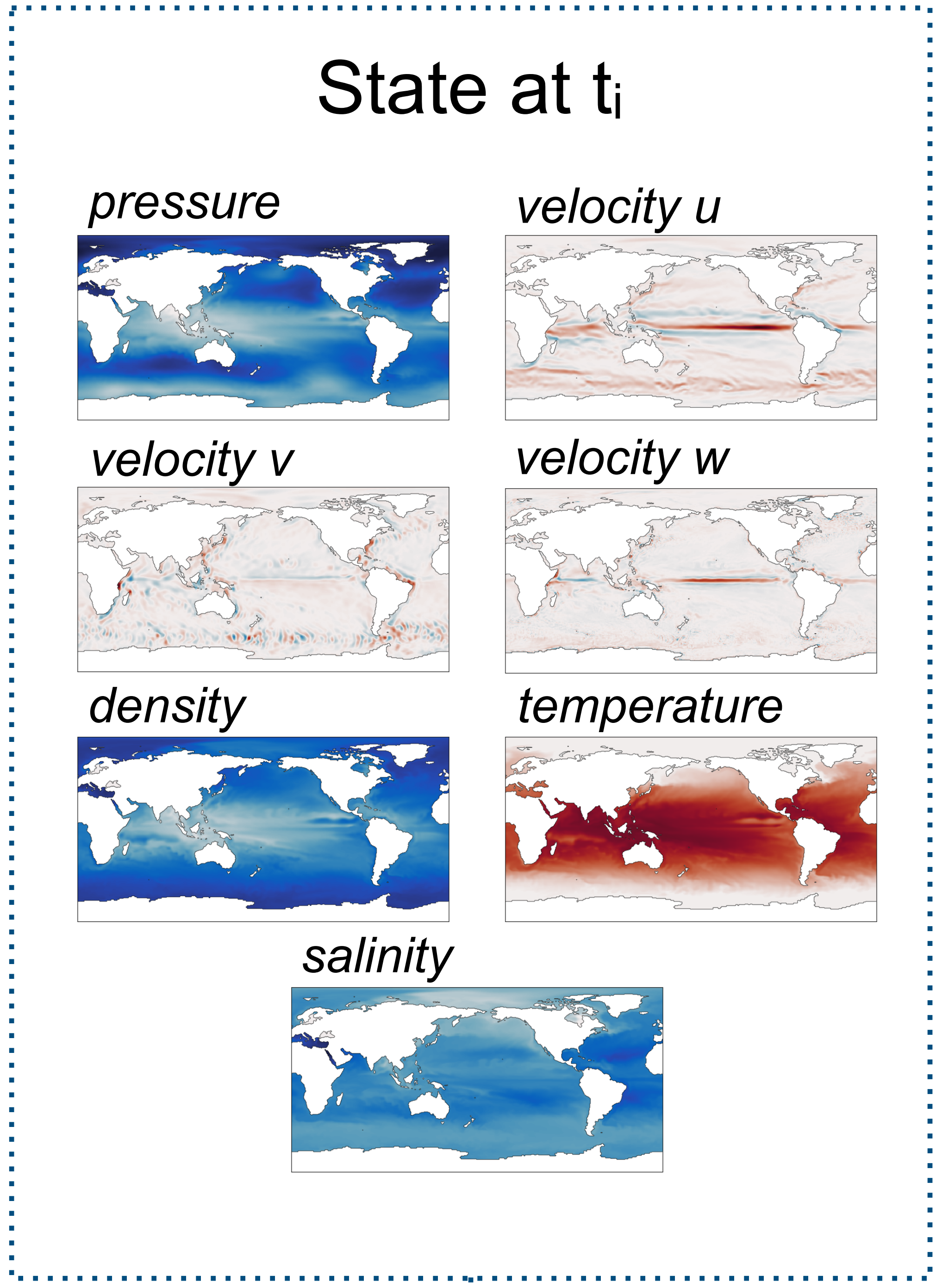

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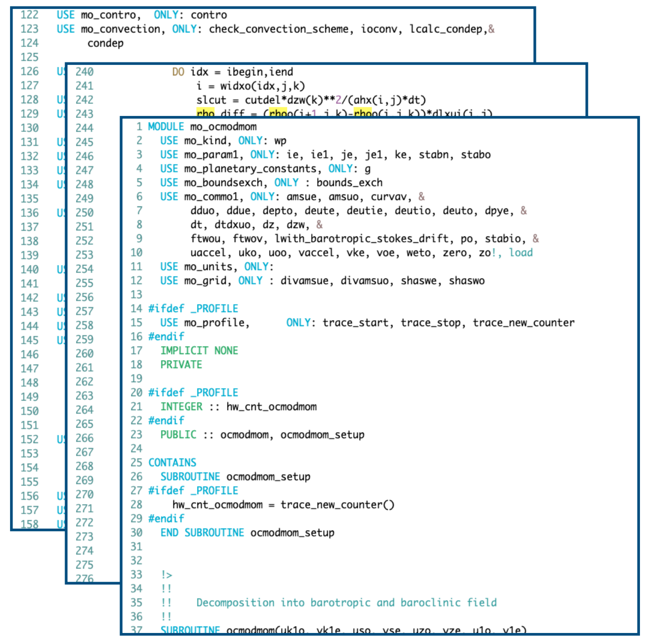

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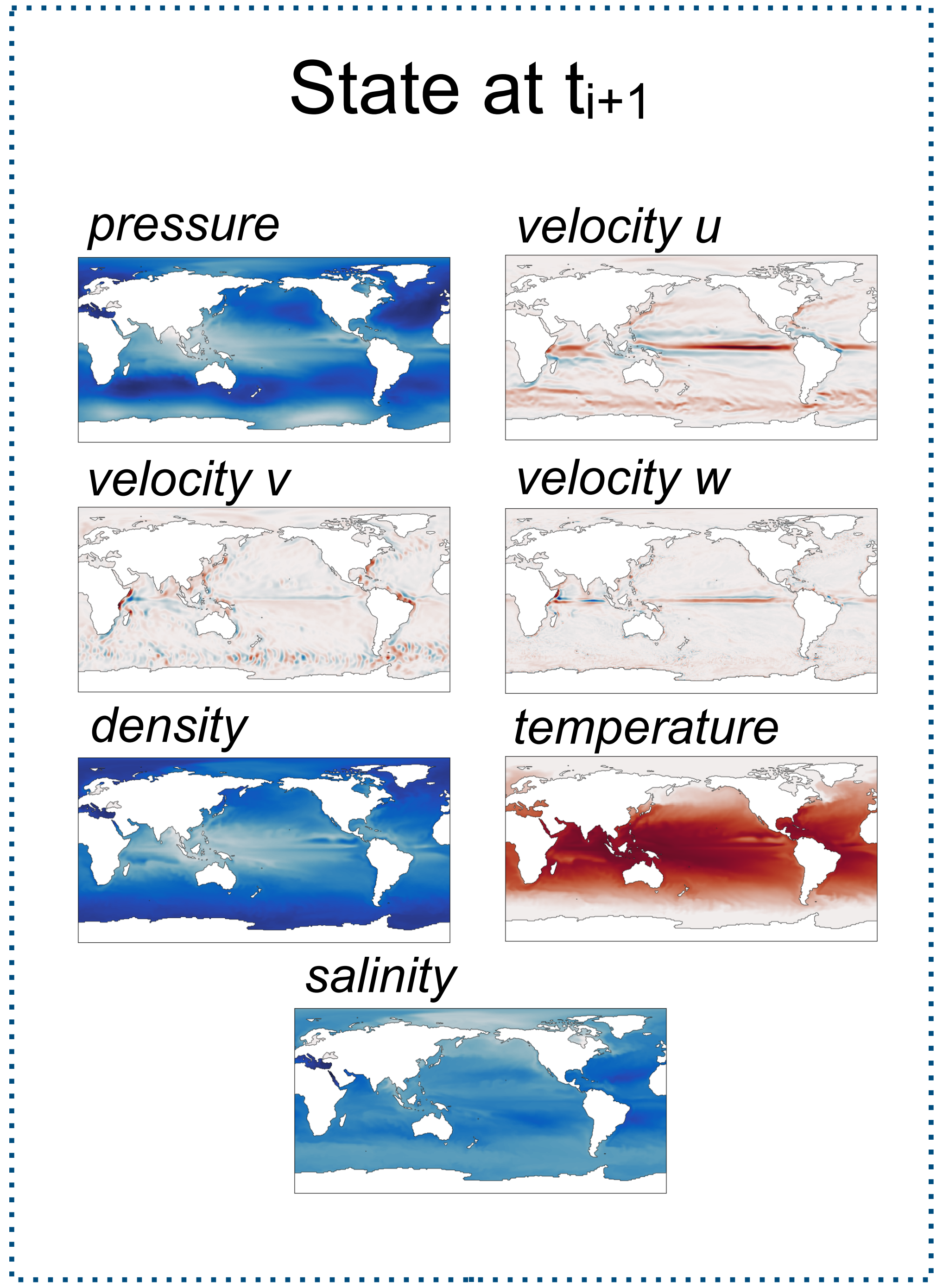
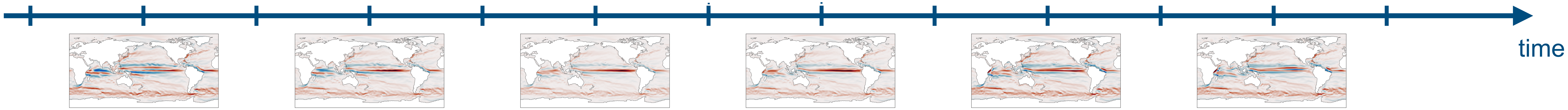


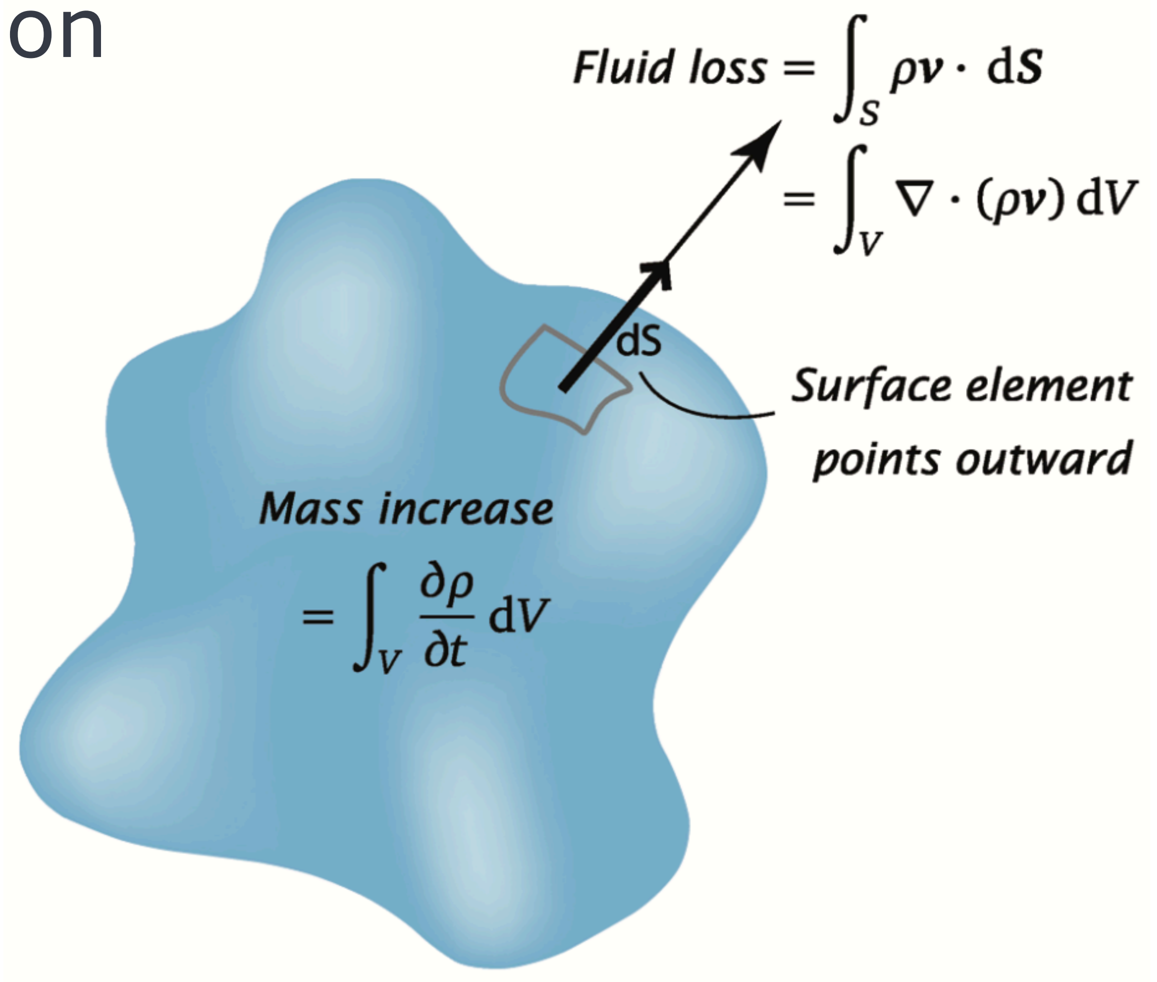


Fundamental Equations for Geophysical Flows

I. Continuity:

- In classical mechanics mass conservation is usually not *explicitly* considered
- For a fluid: density can change and mass conservation is one of the equations of motion

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{v} = 0$$



[3]

[3] 1. Vallis GK. Atmospheric and Oceanic Fluid Dynamics: Fundamentals and Large-Scale Circulation. 2nd ed. Cambridge University Press; 2017.

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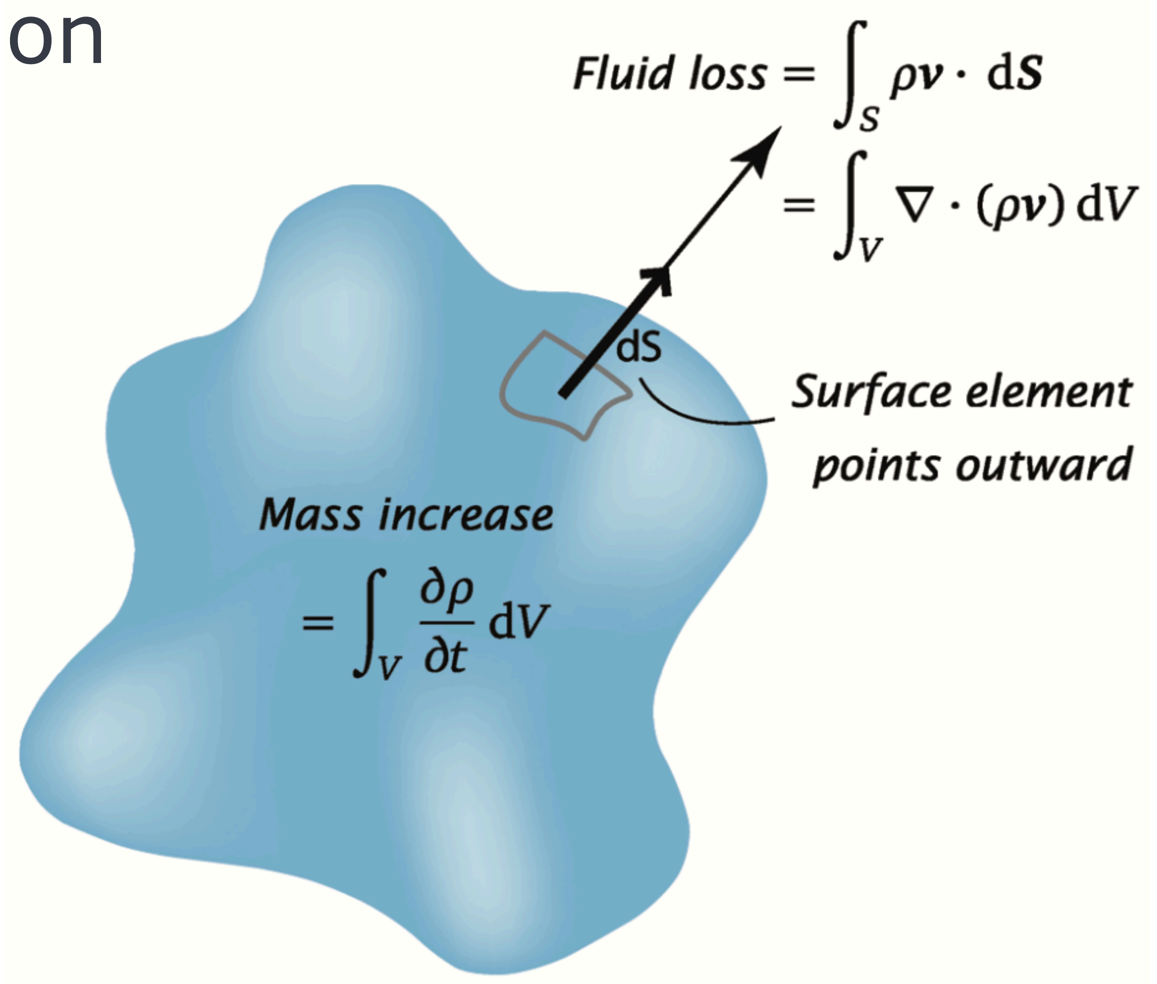

[3]

Side-note: material derivative

- We often use the *material derivative* which describes changes of a property of a fluid parcel as it moves with the flow
- Combines local time-derivative and change due to movement (advection) $$\frac{D\rho}{Dt} = \frac{\partial \rho}{\partial t} + \left(\vec{v}\,\nabla\right)\rho$$
- The continuity equation can thus be written: $$\frac{D\rho}{Dt} + \rho \nabla \cdot \vec{v} = 0$$

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Fundamental Equations for Geophysical Flows

II. Momentum:

pressure-gradient force

$$\rho \frac{\mathrm{D}\vec{v}}{\mathrm{D}t} = - \nabla p + \rho \nabla \phi + \overrightarrow{F}$$

e.g. friction

conservative forces,
e.g. gravity

- How to account for friction on larger scales can be very difficult

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- How to account for friction on larger scales can be very difficult

- We observe the atmosphere / ocean from the Earth and thus a rotating reference frame

$$\Rightarrow \quad \rho \left[\frac{\mathrm{D}\vec{v}}{\mathrm{D}t} + 2\overrightarrow{\Omega} \times \vec{v} \right] = - \nabla p + \rho \nabla \phi + \overrightarrow{F}$$

- Rotational effects play a crucial role in GFD (see lecture on *Mass Change of the Oceans* tomorrow)

Fundamental Equations for Geophysical Flows

III. Equation of State:

- So far: 4 equations and 5 unknowns $(\vec{v}, p, \rho)$
- So far no distinction between atmosphere and ocean. Consider now the nature of the fluid
- How does density change with pressure, temperature, etc.

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- How does density change with pressure, temperature, etc.

Atmosphere:

- For an ideal (dry) gas: $\rho = \frac{p}{RT}$
- While the composition of dry air is fairly uniform, water vapour can vary

$$\rho = \frac{p}{RT(1 + 0.608q)}$$

Ocean:

- Seawater varies mostly with temperature & salinity
- There is no equivalent to the ideal gas law
- Empirical (linear & simplified) equation of state:

$$\rho = \rho_0 \left[1 - \alpha(T - T_0) + \beta(S - S_0)\right]$$

Fundamental Equations for Geophysical Flows

IV. Energy Budget:

- The equation of state determines the relationship between pressure and density but it introduces new variables (temperature and salinity / humidity)

- Additional consideration: changes in the internal energy of the fluid $\dot{e}$

$$\frac{\mathrm{D}e}{\mathrm{D}t} = \overset{\text{rate of heat gain}}{Q} - \overset{\text{rate of work done}}{W}$$

$$C_v \frac{\mathrm{D}T}{\mathrm{D}t} = \left[\underbrace{\frac{k}{\rho} \nabla^2 T}_{\text{Heat gain through diffusion, i.e. neighboring parcels}} + \overbrace{Q'}^{\text{internal heat sources}} \right] - \left[p \frac{\mathrm{D}}{\mathrm{D}t} \frac{1}{\rho} \right]$$

- Internal heat sources (Q’) not important for ocean but for atmosphere through evaporation and condensation

Fundamental Equations for Geophysical Flows

V. Salt & Moisture Budgets:

- **Ocean:** density varies with salinity
- **Atmosphere:** density varies with humidity

diffusion of salinity

$$\frac{\mathrm{D}S}{\mathrm{D}t} = \kappa_S \nabla^2 S + \dot{S}'$$

sources / sinks
e.g. air-sea water
exchange, river
runoff, ice formation

- On a high level, both budgets are similar
- Sources and sinks of salinity mainly confined to boundaries
- In the atmosphere, phase changes need to be considered which depend heavily on temperature
- Variability of water content in the atmosphere considerably higher

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IV. Energy budget:

$$C_v\frac{\mathrm{D}T}{\mathrm{D}t} = \left[\frac{k}{\rho}\nabla^2 T + Q'\right] - \left[p\frac{\mathrm{D}}{\mathrm{D}t}\frac{1}{\rho}\right]$$

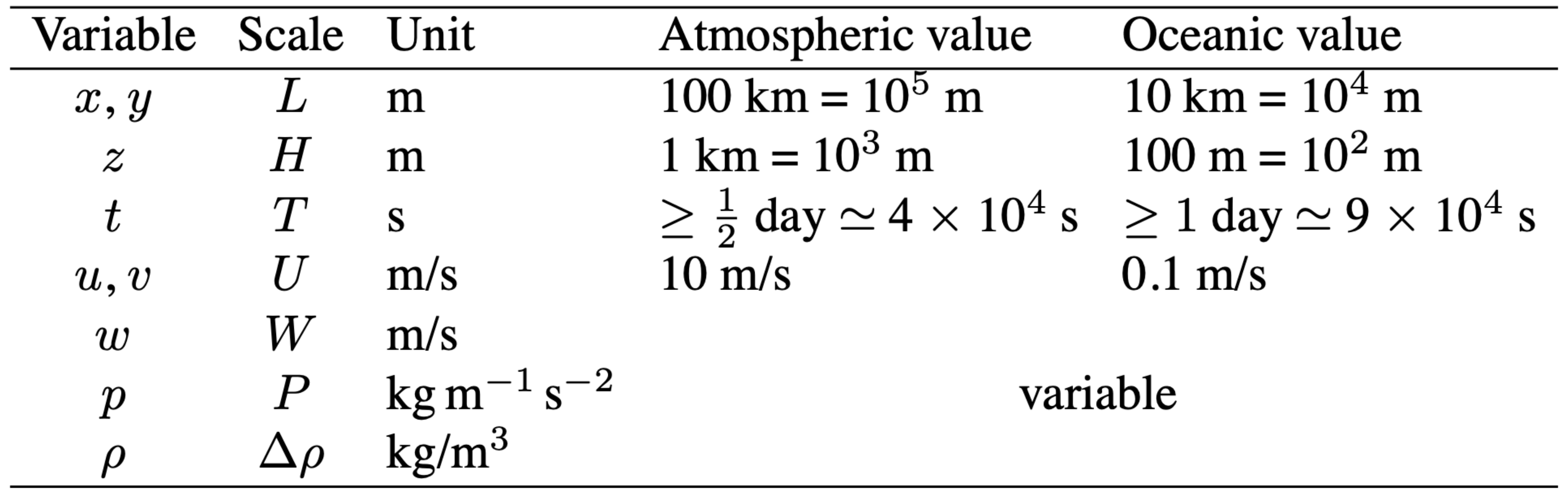
V. Salt & moisture:

$$\frac{\mathrm{D}S}{\mathrm{D}t} = \kappa_S\nabla^2 S + \dot{S}'$$

Common Approximations

- The equations are rarely used without approximations to reduce complexity
- These can be quite different for the atmosphere and oceans

Typical Scales of Atmospheric and Oceanic Flows



Variable	Scale	Unit	Atmospheric value	Oceanic value
x, y	L	m	100 km = 10^5 m	10 km = 10^4 m
z	H	m	1 km = 10^3 m	100 m = 10^2 m
t	T	s	$\geq \frac{1}{2}$ day $\simeq 4 \times 10^4$ s	≥ 1 day $\simeq 9 \times 10^4$ s
u, v	U	m/s	10 m/s	0.1 m/s
w	W	m/s	variable	
p	P	$\mathrm{kg\,m^{-1}\,s^{-2}}$		
ρ	$\Delta\rho$	$\mathrm{kg/m^3}$		

[4]

1. Hydrostatic Approximation:

- Horizontal scales much larger than vertical scales
- Vertical pressure gradient balanced by weight of fluid

$$\rho\left[\frac{D\vec{v}}{Dt} + 2\vec{\Omega} \times \vec{v}\right] = -\nabla p + \rho\nabla\phi + \vec{F} \quad \xrightarrow{\text{z-component}} \quad \frac{\partial p}{\partial z} = -\rho g$$

2. Shallow-Fluid Approximation:

- Vertical dimension of ocean & atmosphere small compared to Earth radius

[4] B. Cushman-Roisin and J.-M. Beckers, Introduction to Geophysical Fluid Dynamics: Physical and Numerical Aspects, Academic Press, 2011,

Common Approximations

3. Boussinesq Approximation:

- Mainly used in ocean general circulation models
- Assumes variations in density are small compared to mean density

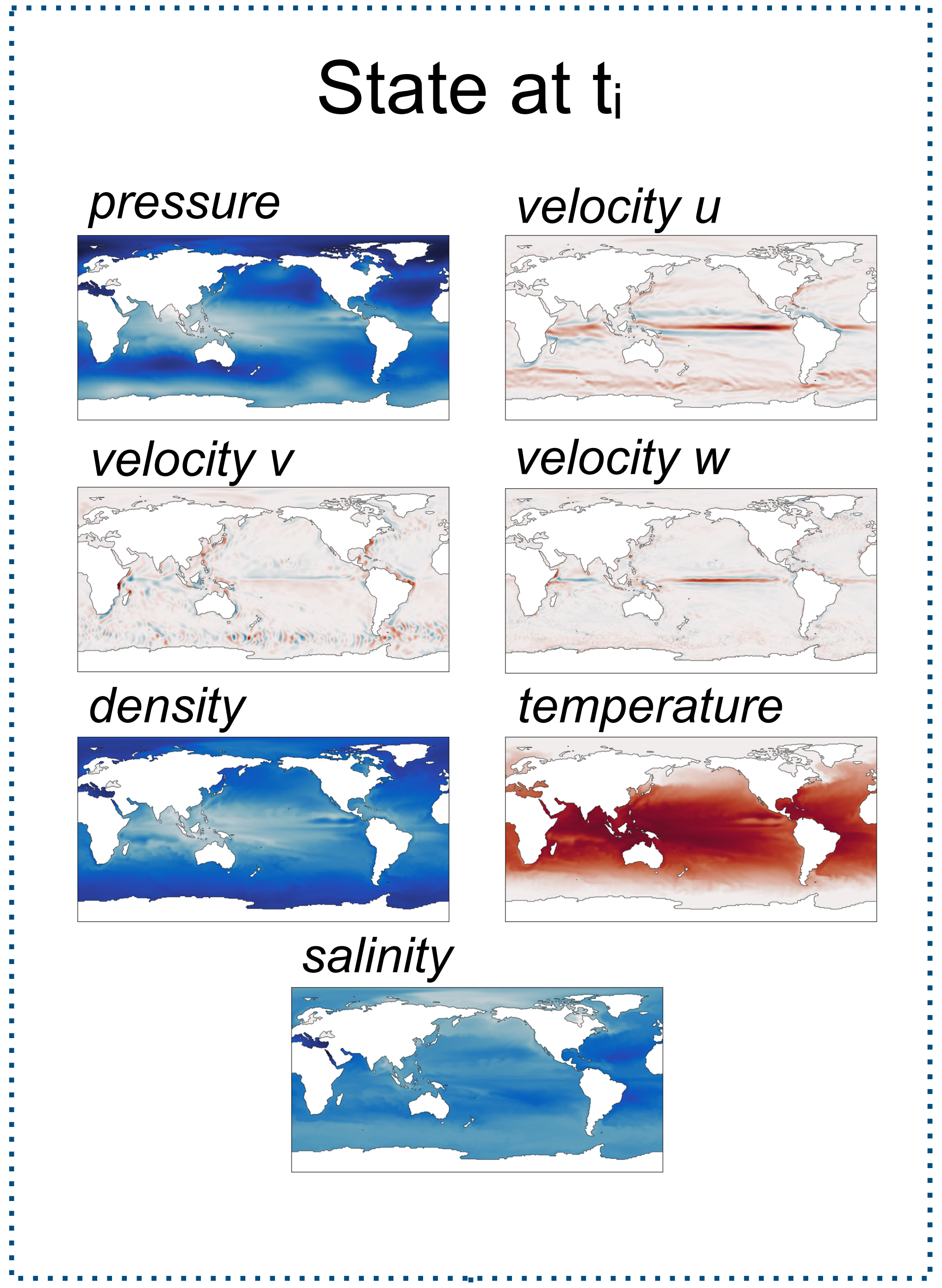
$$\rho = \rho_0 + \rho' \qquad |\rho'| \ll \rho_0$$

- Simplifies equations in several ways, but most importantly the continuity eq.:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{v} = 0 \qquad \rightarrow \qquad \nabla \cdot \vec{v} = 0$$

- Conservation of mass becomes conservation of volume!
- In applications where ocean mass is relevant (i.e. GRACE contexts), Boussinesq ocean model data often needs to be corrected!

How do we model the atmosphere / ocean ?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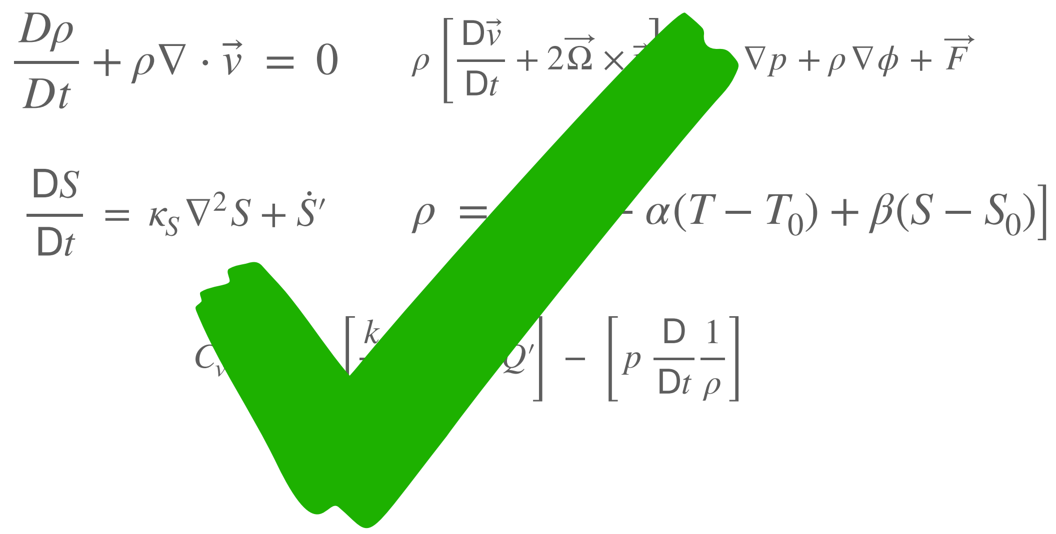
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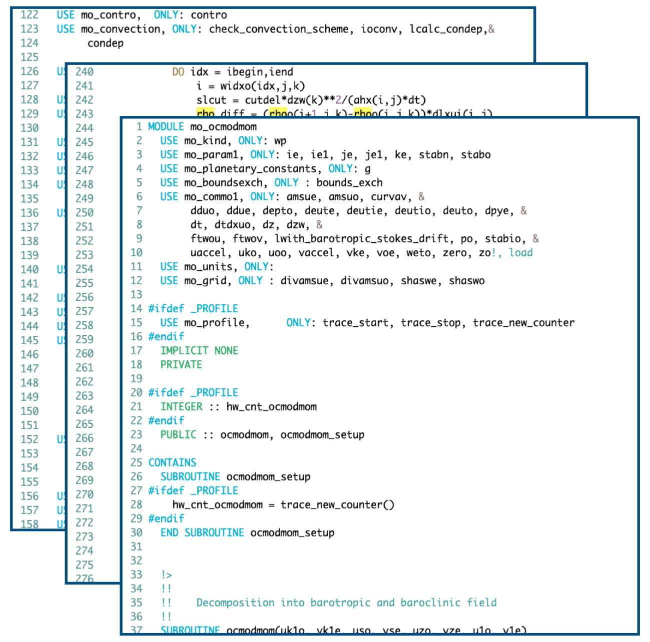
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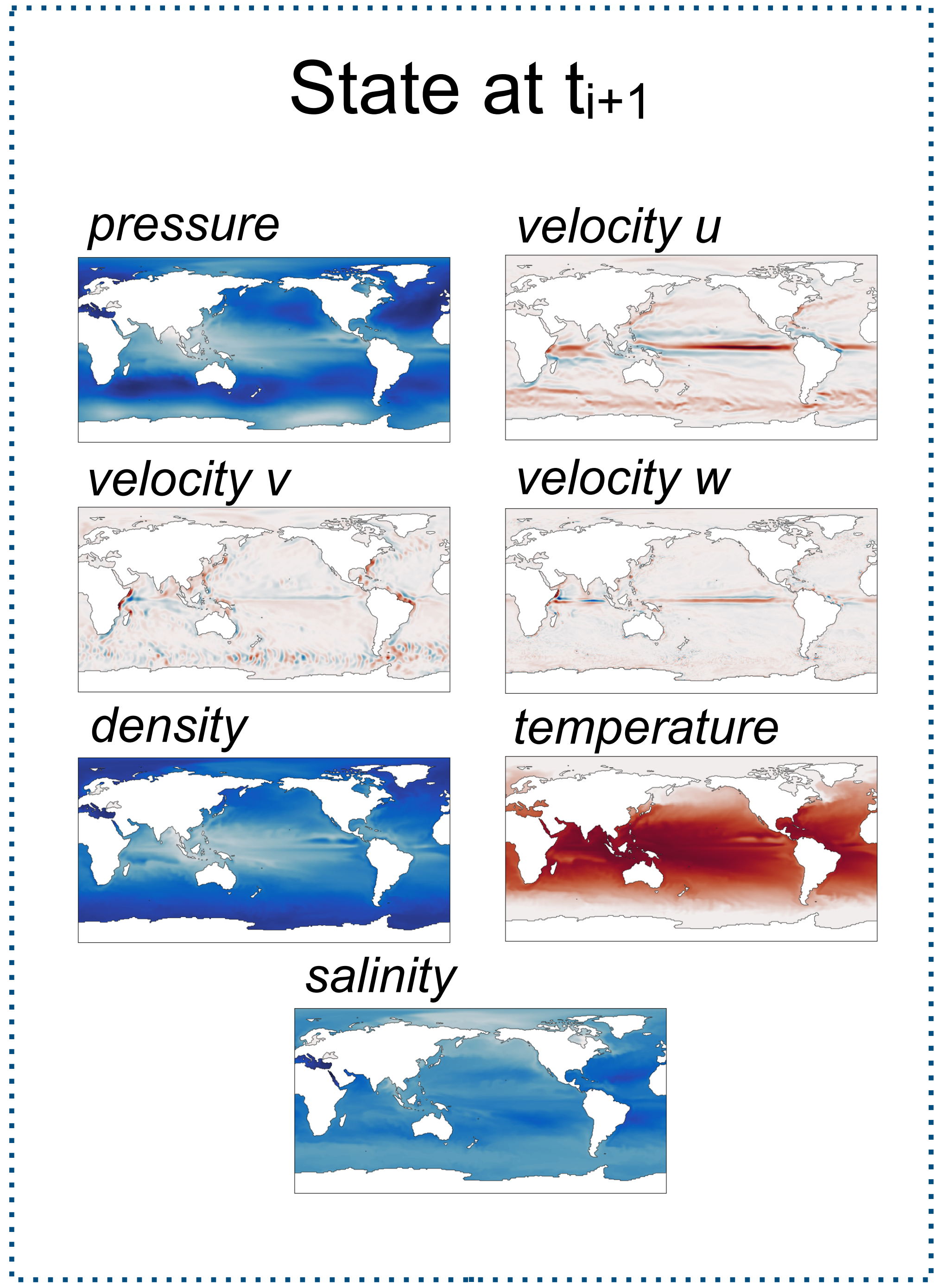
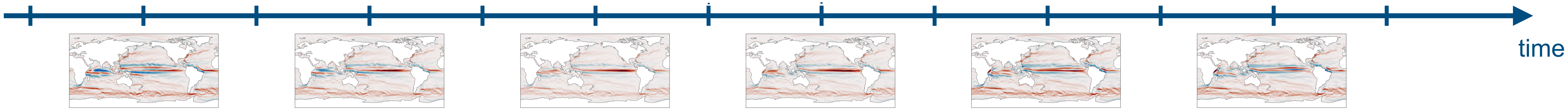
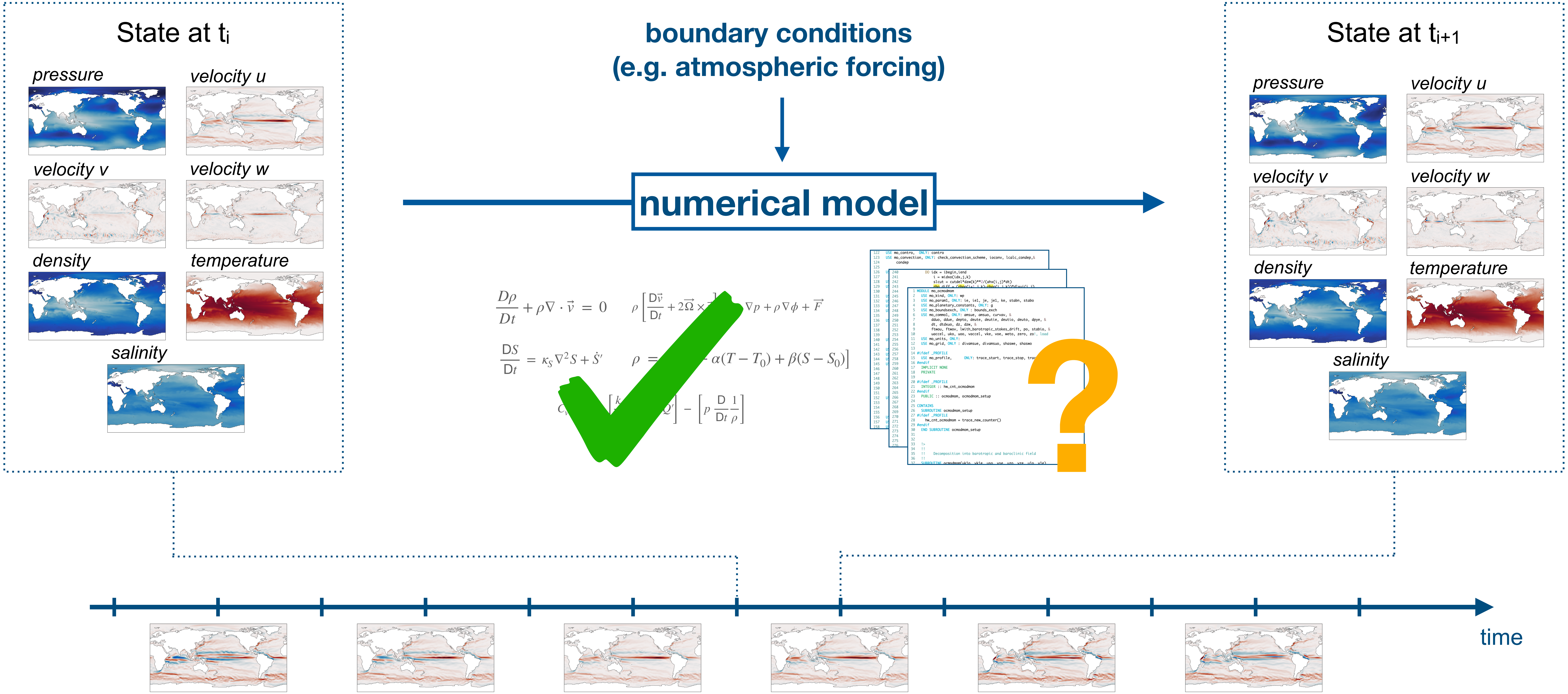

State at t_{i+1}



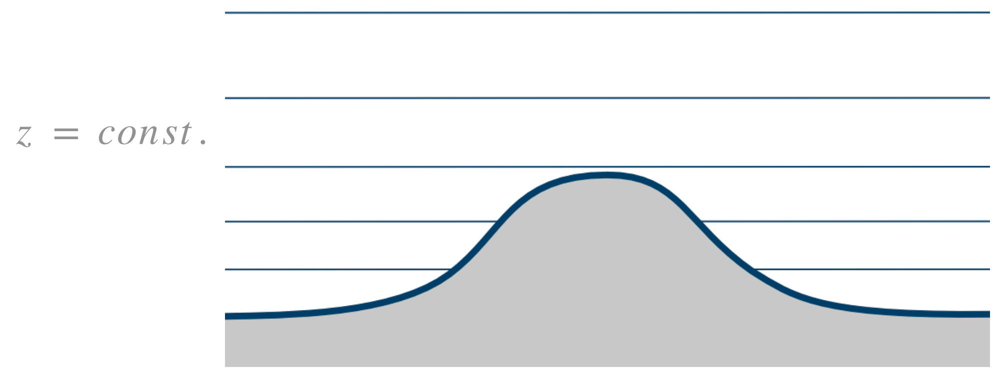
How do we model the atmosphere / ocean ?

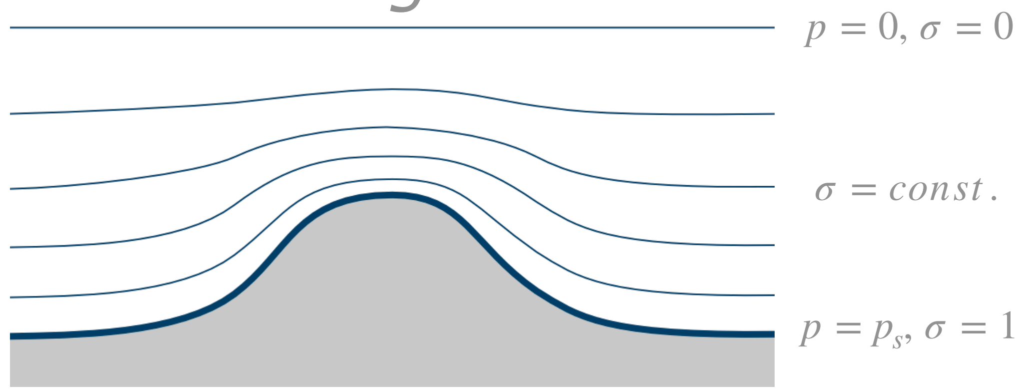


A Few Points on Numerical Implementations:

- How the geophysical equations are implemented plays a huge role in the applicability of the model
- These are just a few examples of many:

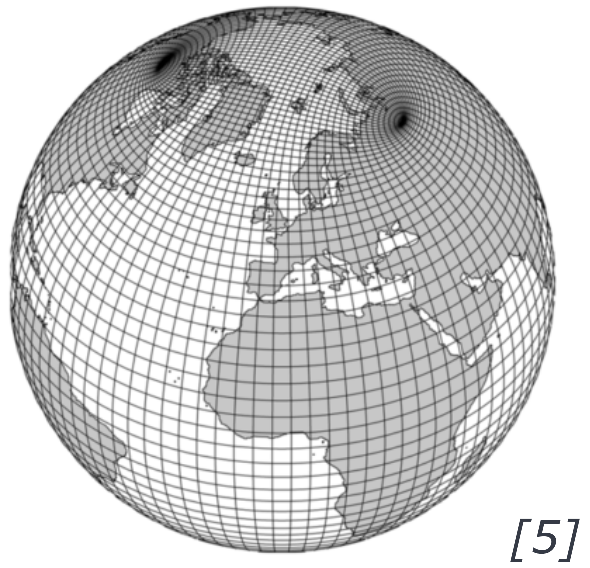
Vertical Coordinates:


z-coordinates

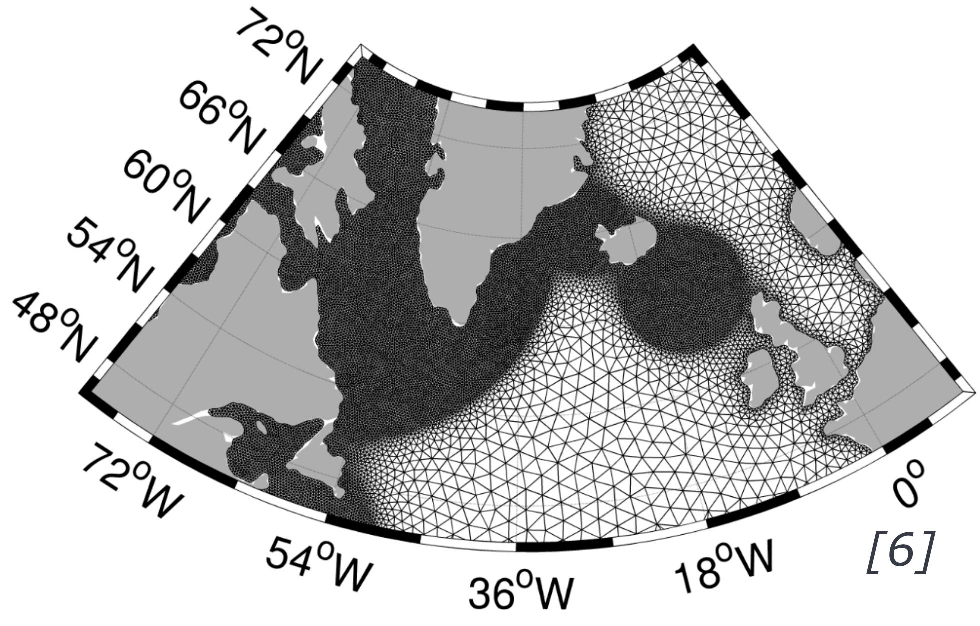

terrain-following σ-coordinates

Horizontal Grids:


regular grid


curvilinear grid

[5]


unstructured meshes

[6]

Subgrid processes:

- Many processes occur on scales that are not resolvable by the model but are important for accurate representation of the dynamics
- Impact included through parametrization that describe their net effect on the flow
- Examples: turbulent friction, boundary interactions, cloud microphysics, …

---

[5] Mats Bentsen, https://expearth.uib.no/?page_id=28
[6] Ocean modeling on unstructured meshes, S. Danilov (2013), J. Ocean Mod., 10.1016/j.ocemod.2013.05.005

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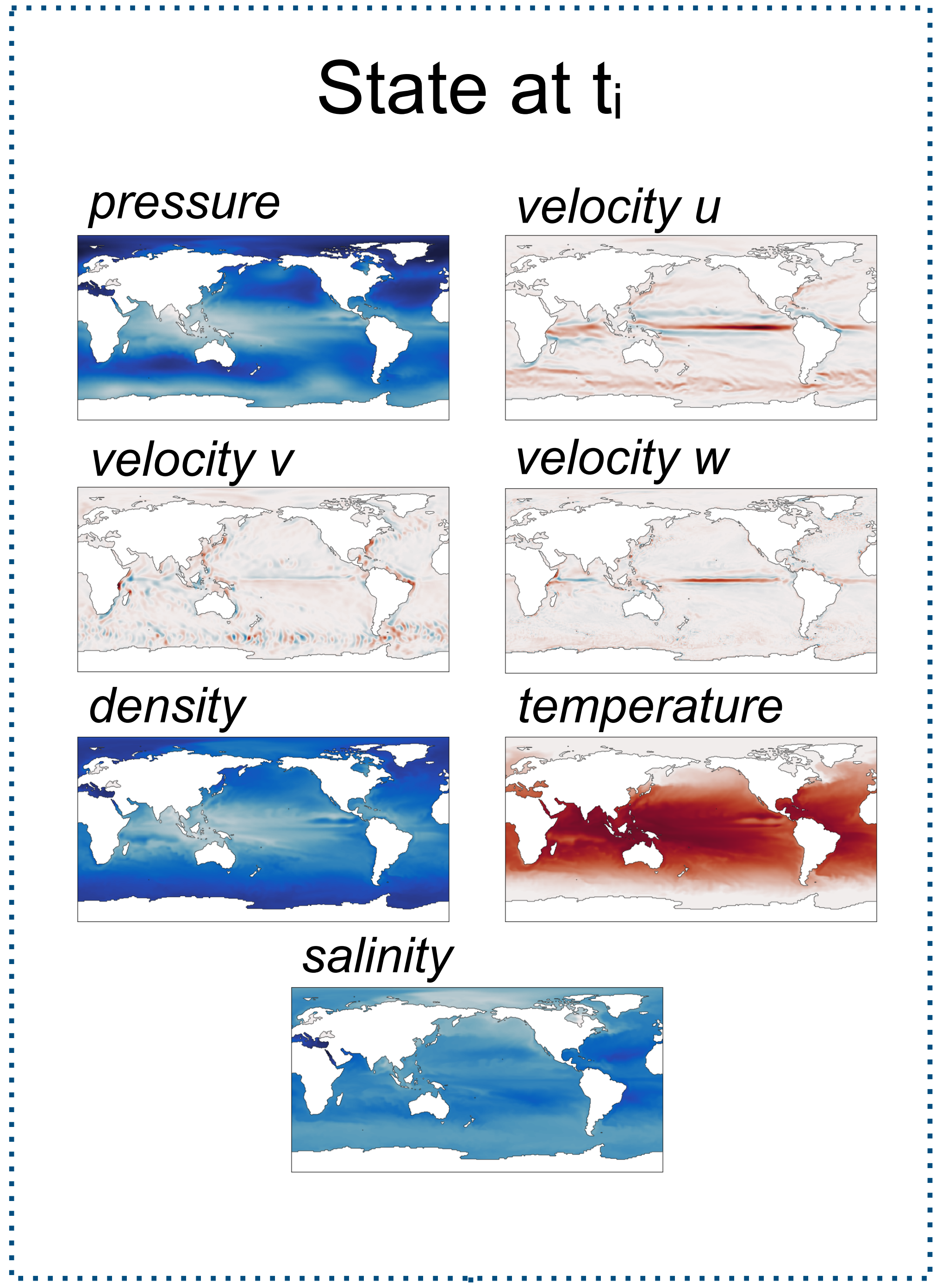

State at t_i

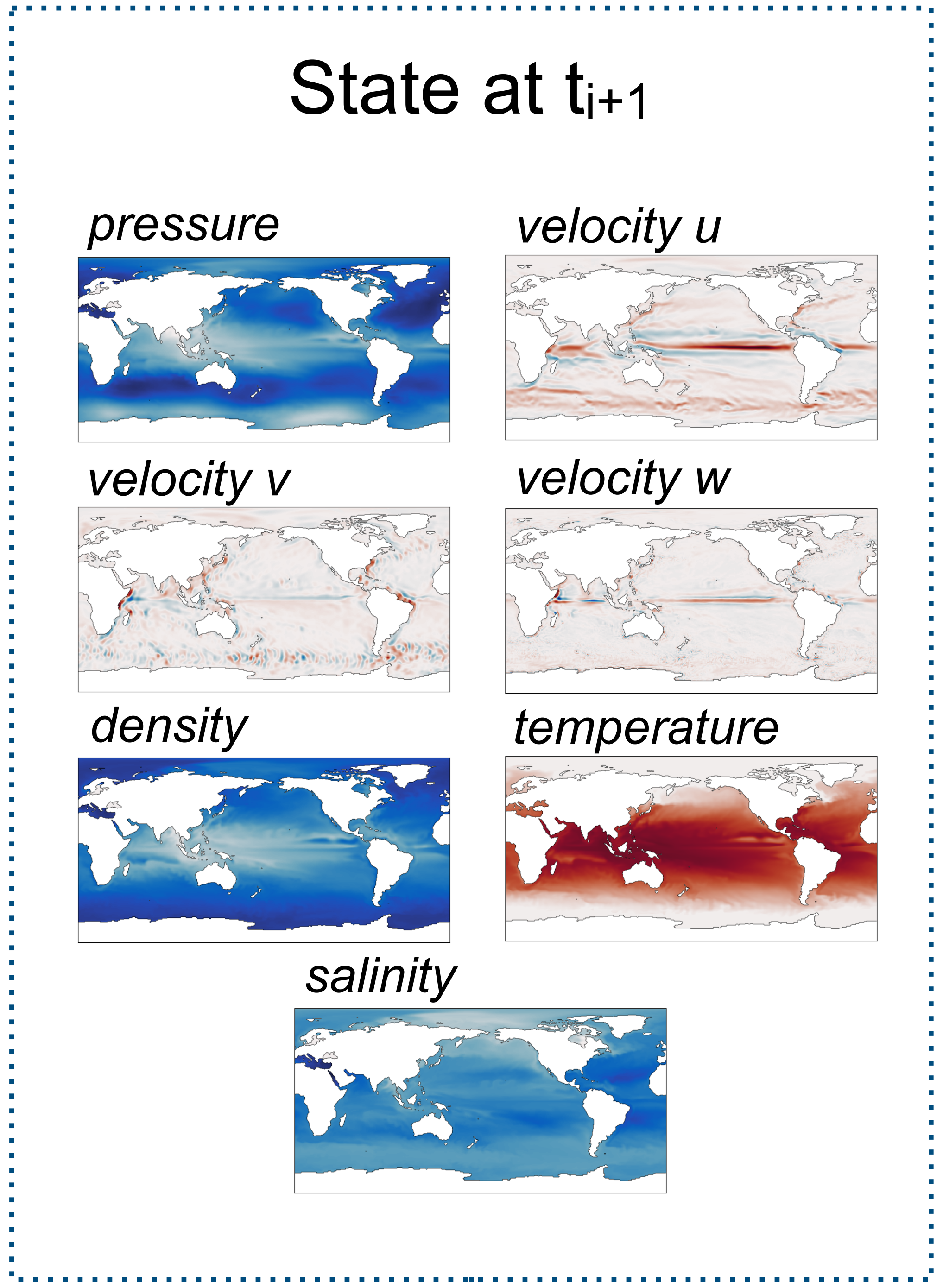
boundary conditions (e.g. atmospheric forcing)

numerical model

$$\frac{D\rho}{Dt} + \rho\nabla\cdot\vec{v} = 0 \qquad \rho\left[\frac{\mathrm{D}\vec{v}}{\mathrm{D}t} + 2\vec{\Omega}\times\vec{v}\right] = -\nabla p + \rho\nabla\phi + \vec{F}$$

$$\frac{\mathrm{D}S}{\mathrm{D}t} = \kappa_S\nabla^2 S + \dot{S}' \qquad \rho = \rho_0\left[1 - \alpha(T - T_0) + \beta(S - S_0)\right]$$

$$C_v\frac{\mathrm{D}T}{\mathrm{D}t} = \left[\frac{k}{\rho}\nabla^2 T + Q'\right] - \left[p\,\frac{\mathrm{D}}{\mathrm{D}t}\frac{1}{\rho}\right]$$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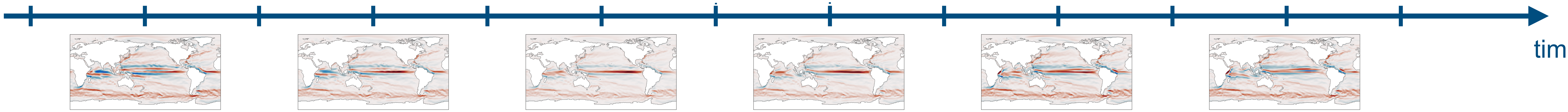
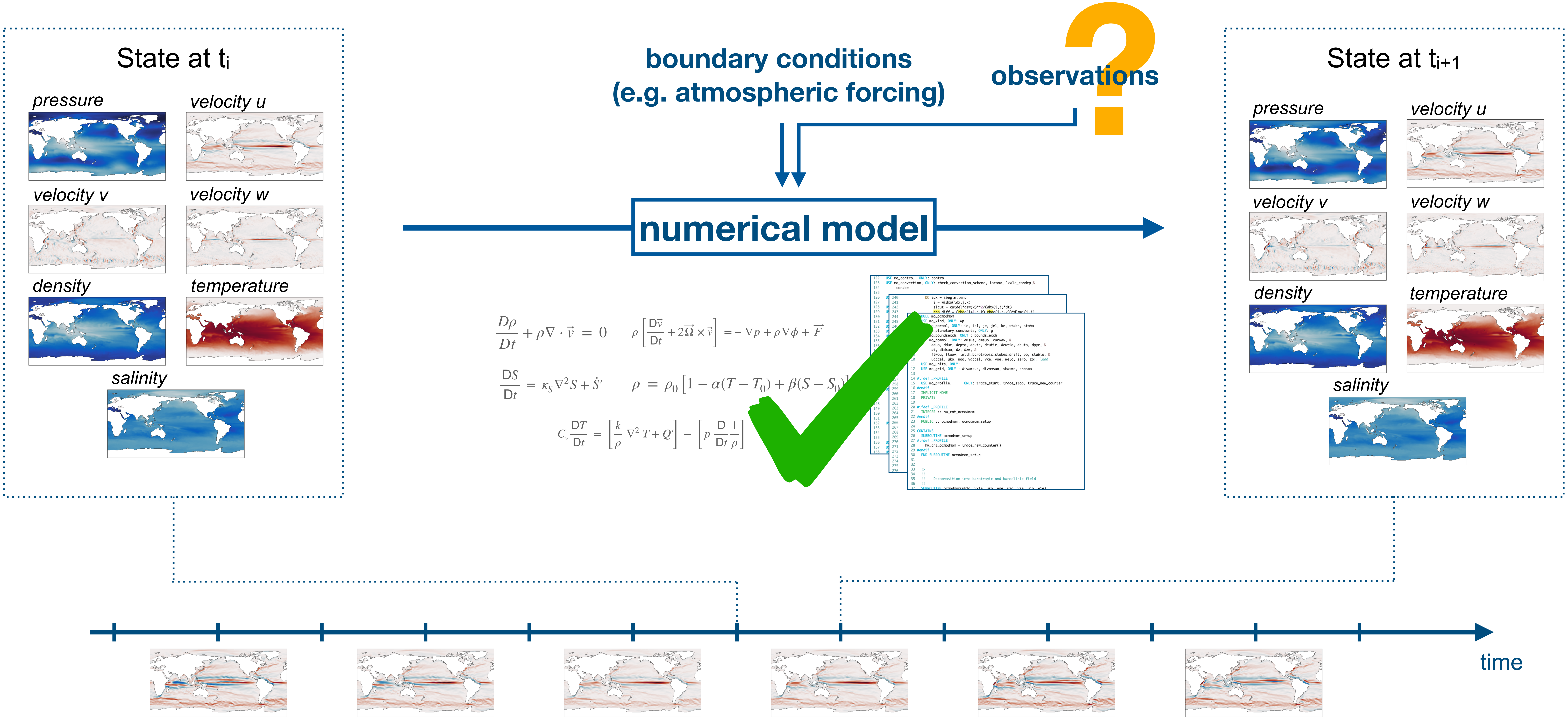


How do we model the atmosphere / ocean ?



State at t_i

pressure

velocity u

velocity v

velocity w

density

temperature

salinity

boundary conditions (e.g. atmospheric forcing)

observations

?

numerical model

$$\frac{D\rho}{Dt} + \rho\nabla \cdot \vec{v} = 0 \qquad \rho\left[\frac{\mathrm{D}\vec{v}}{\mathrm{D}t} + 2\vec{\Omega}\times\vec{v}\right] = -\nabla p + \rho\nabla\phi + \vec{F}$$

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State at t_{i+1}

pressure

velocity u

velocity v

velocity w

density

temperature

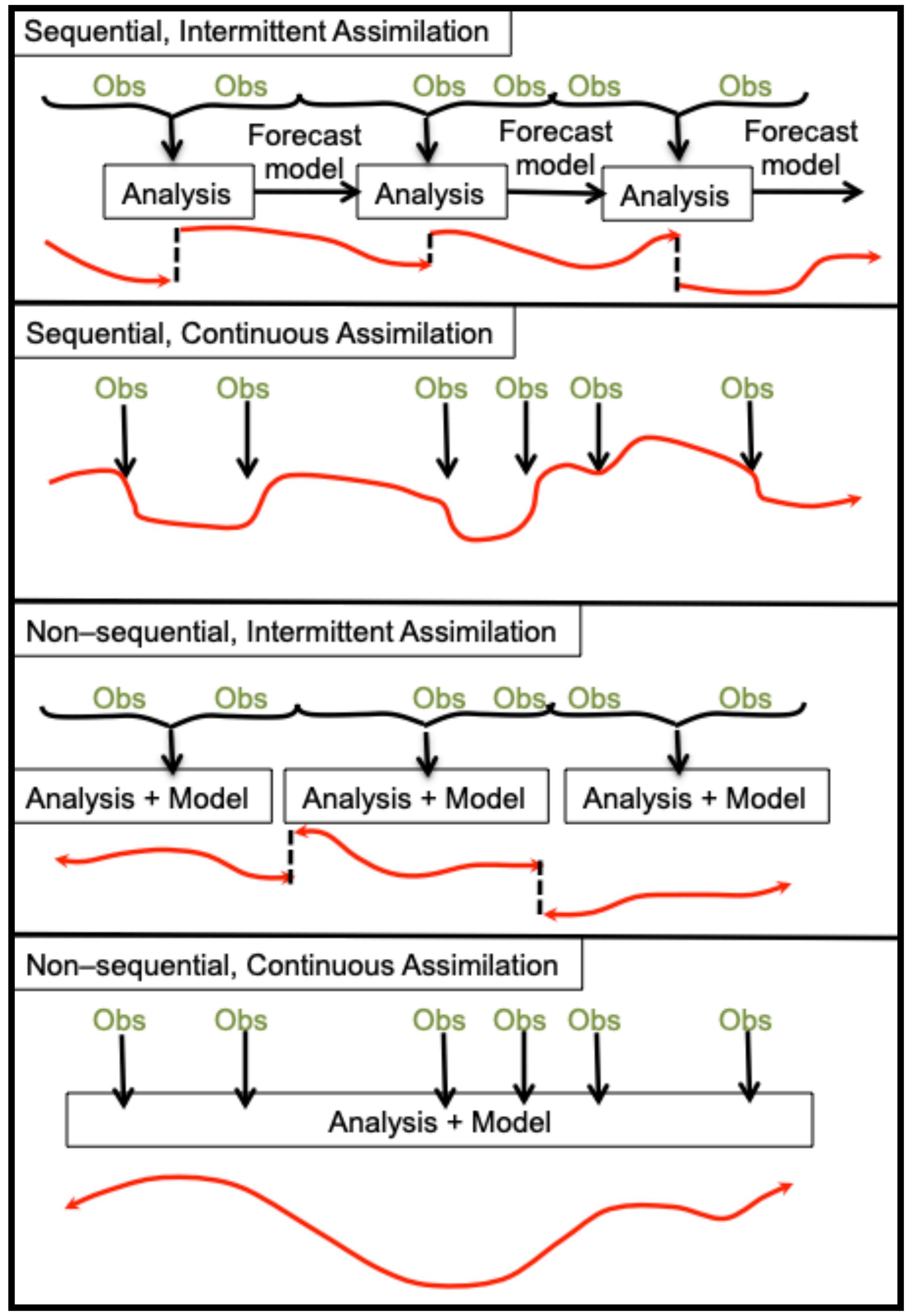
salinity

time

Including observational data / data assimilation

- Measurement data can be introduced into models through data assimilation to create the best estimate of the atmospheric / oceanic state

Approaches to data assimilation:



[7]

Sequential assimilation:
only considers observation made in the past until the time of analysis

Non-sequential:
considers observations made before and after the nominal time of the analysis (e.g. 4D–var)

Retrospective assimilation:
observation from the future can be used (e.g reanalysis)

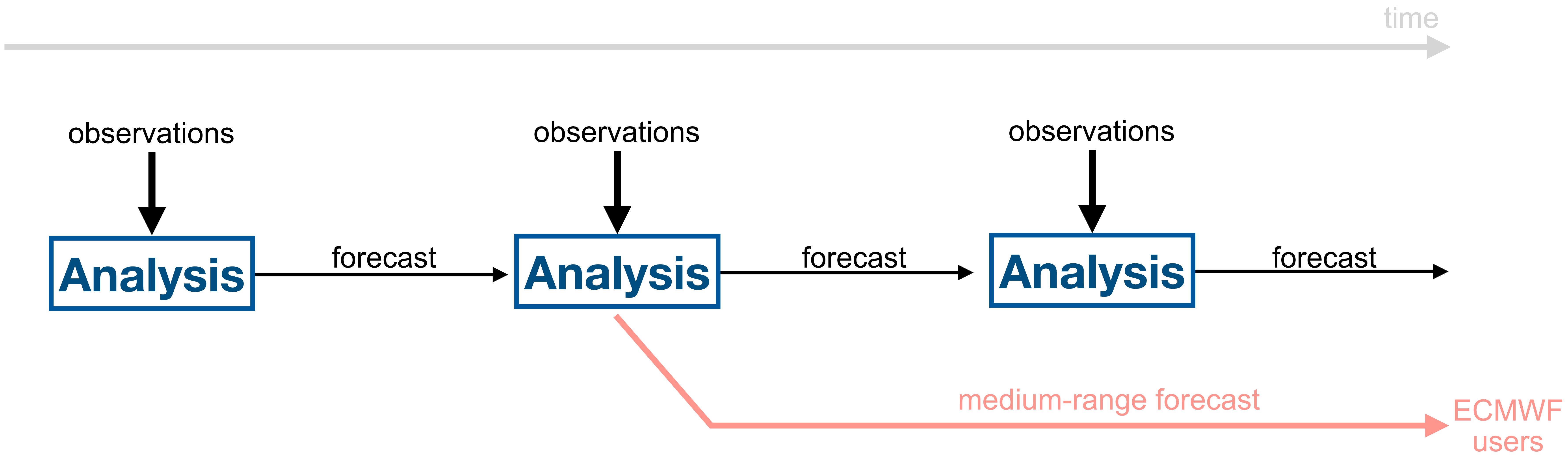
Intermittent:
observations can be processed in small batches - often leads to abrupt changes

Continuous:
observation batches over longer periods are considered

[7] R. Owens, T. Hewson, ECMWF Forecast User Guide, Section 2.5, 10.21957/m1cs7h

Example: ECMWFs 4D-Var

- Goal: produce the ‘optimal’ initial conditions (analysis) for numerical forecasts



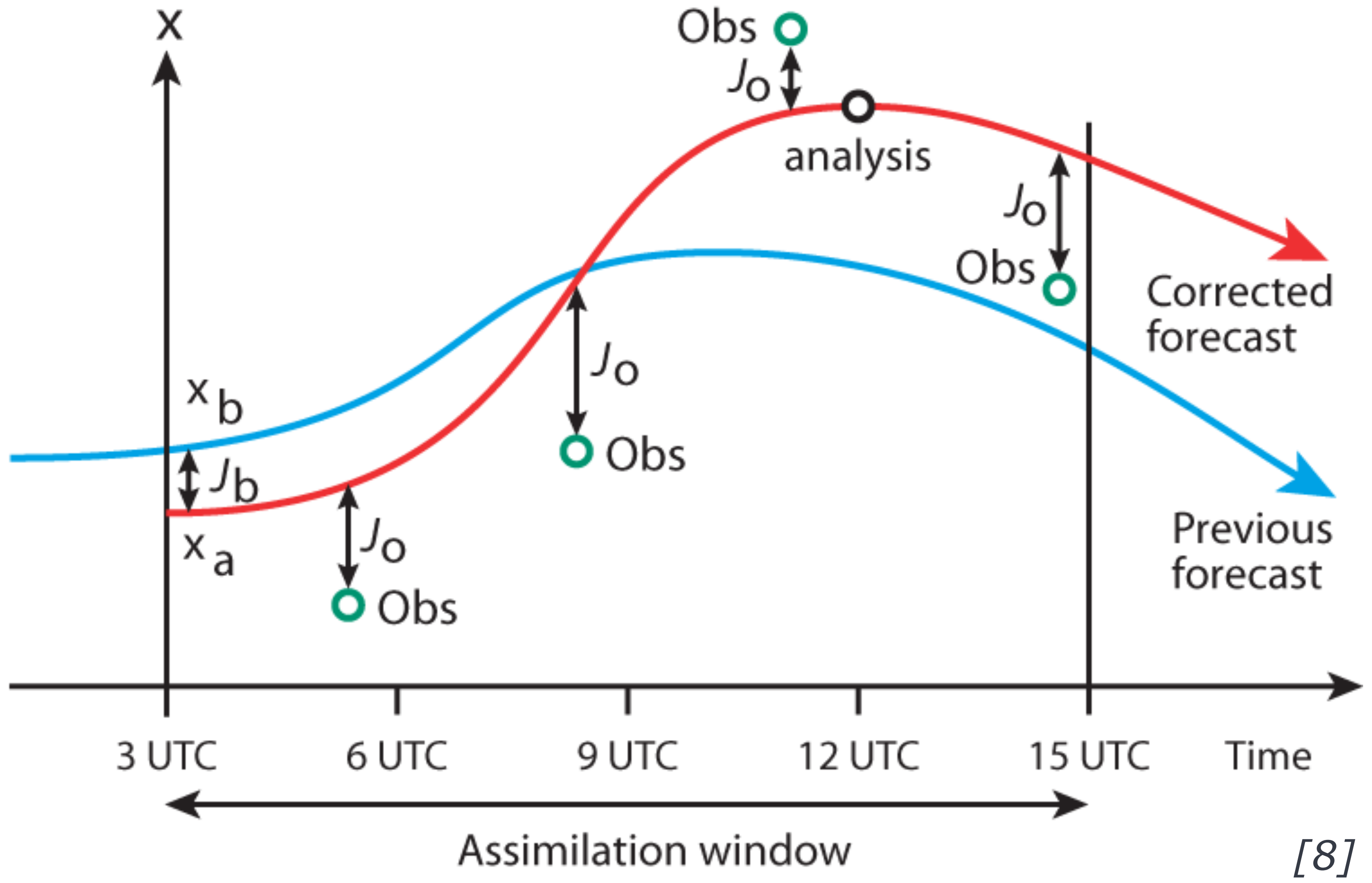
- Based on an analysis (i.e. initial conditions) a short forecast is made
- Observations are used to correct the forecast and produce a new analysis
- From an analysis, longer forecasts are produced and disseminated to users

Example: ECMWFs 4D-Var

- Short-range forecast (12 hours) produced from previous analysis

- Calculate forecast-based ‘observation predictions’
  - For in-situ observation: interpolate the model variable to observation location
  - For remote sensing: calculate observed quantities from model variables

- Adjust forecast to find best compromise between initial prediction (J_b) and observations (J_o)

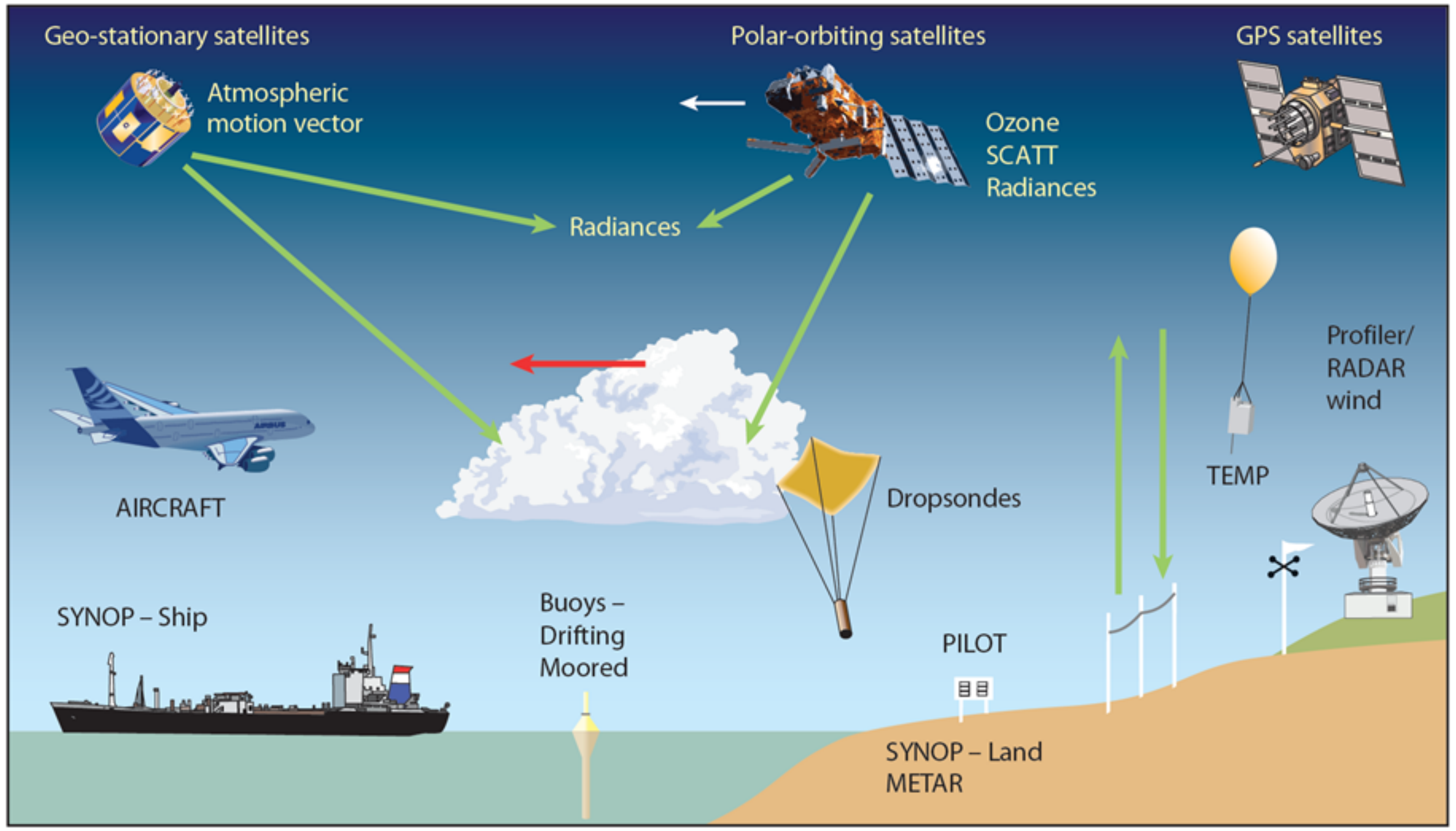


[8]

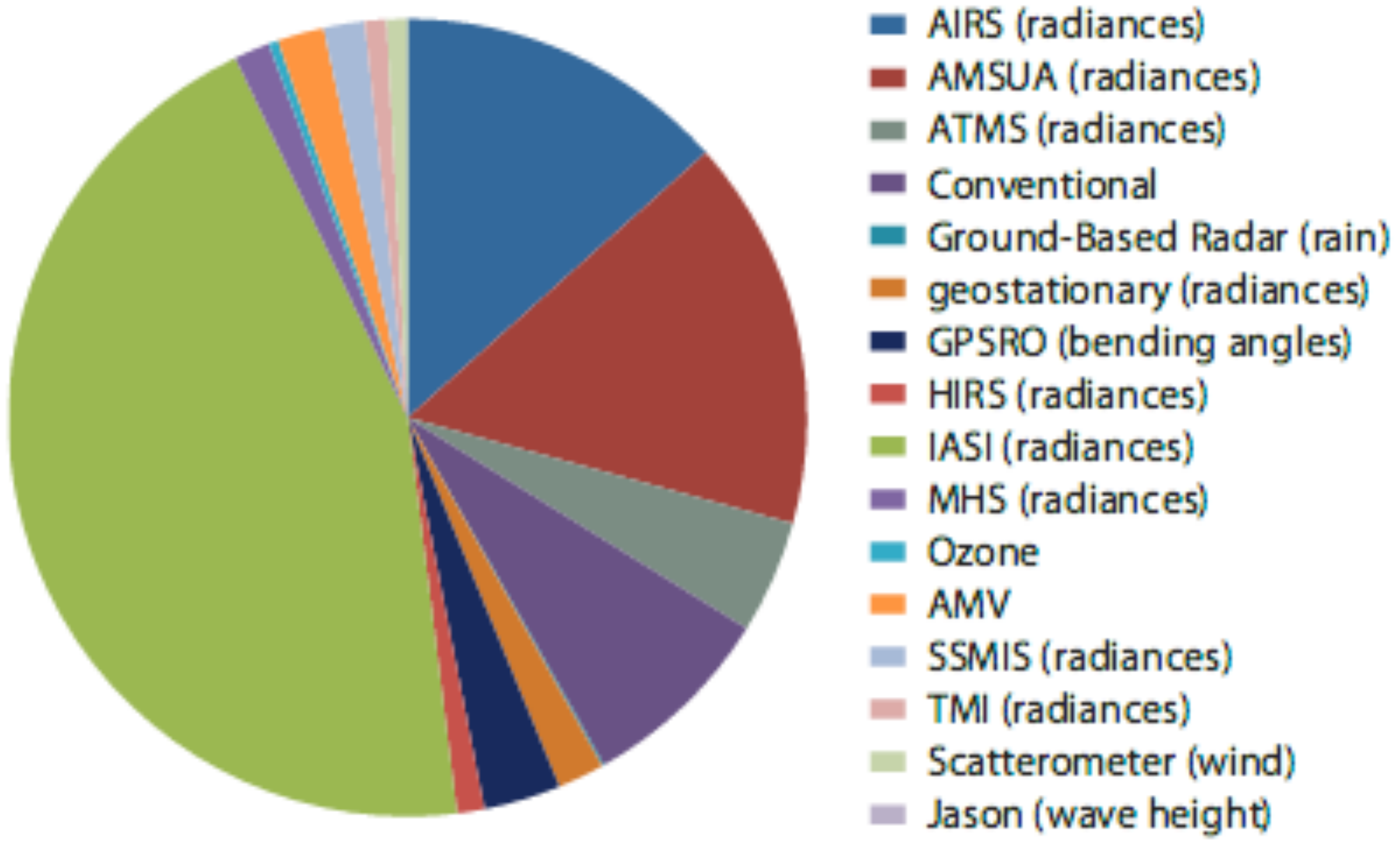
[8] https://www.ecmwf.int/sites/default/files/medialibrary/2017-11/Andersson-NL115-figure-1-box-754px.png

Example: ECMWFs 4D-Var

Observation sources



[9]

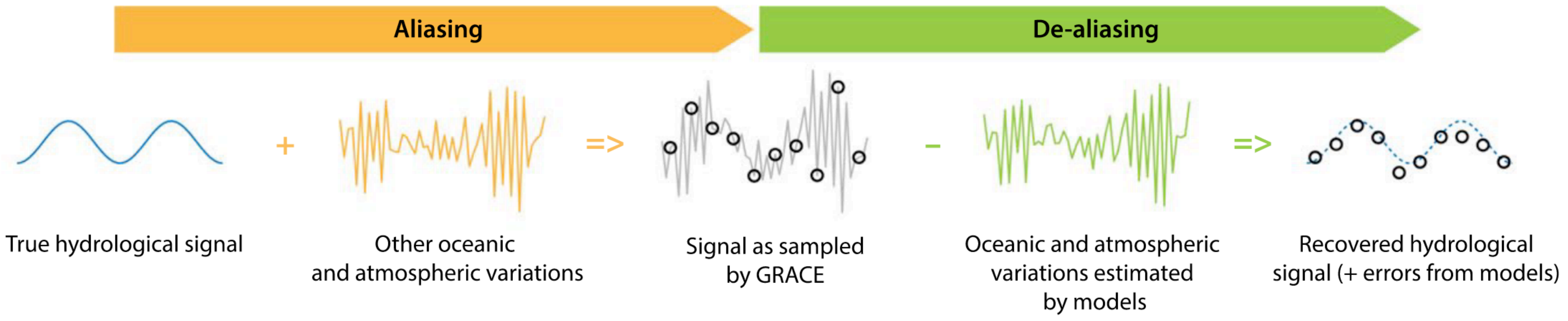


[10]

- Majority of observations are satellite based (largely radiances)
- ~ 60 million observations are available each day for assimilation

[9] https://www.ecmwf.int/sites/default/files/obs_inputs.png
[10] R. Owens, T. Hewson, ECMWF Forecast User Guide, Section 2.4, 10.21957/m1cs7h

Back to GRACE Background Modeling

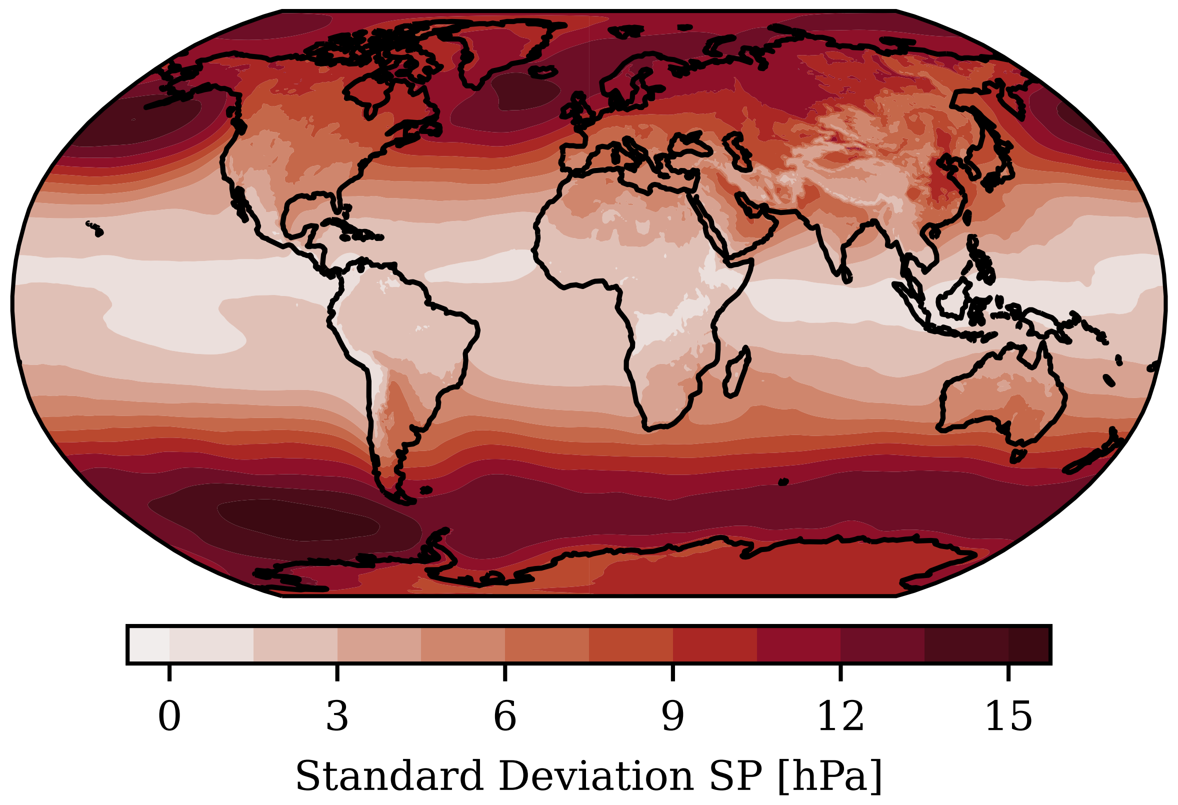


[2]

[2] Humphrey et al. (2023) Using Satellite-Based Terrestrial Water Storage Data: A Review, Surveys in Geophysics, 44:1489-1517

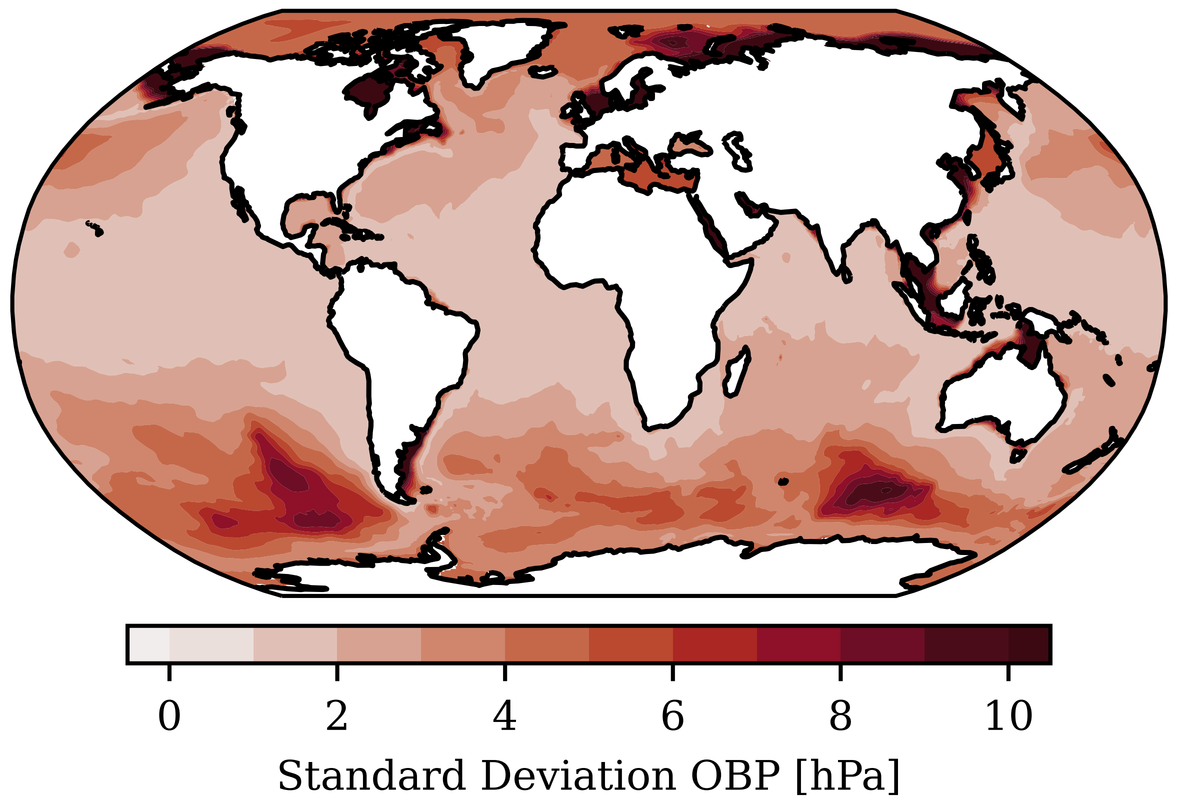
AOD1B Components

Atmospheric Surface Pressure:



+

Ocean Bottom Pressure:



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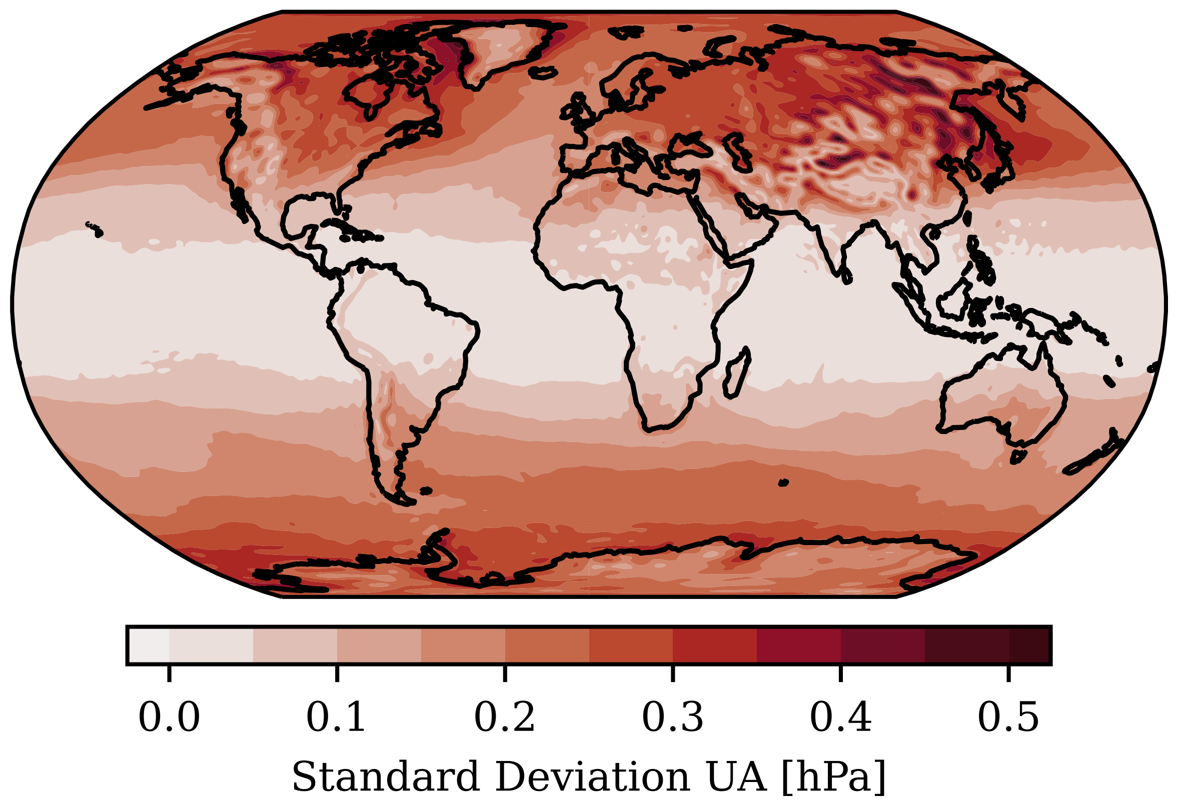
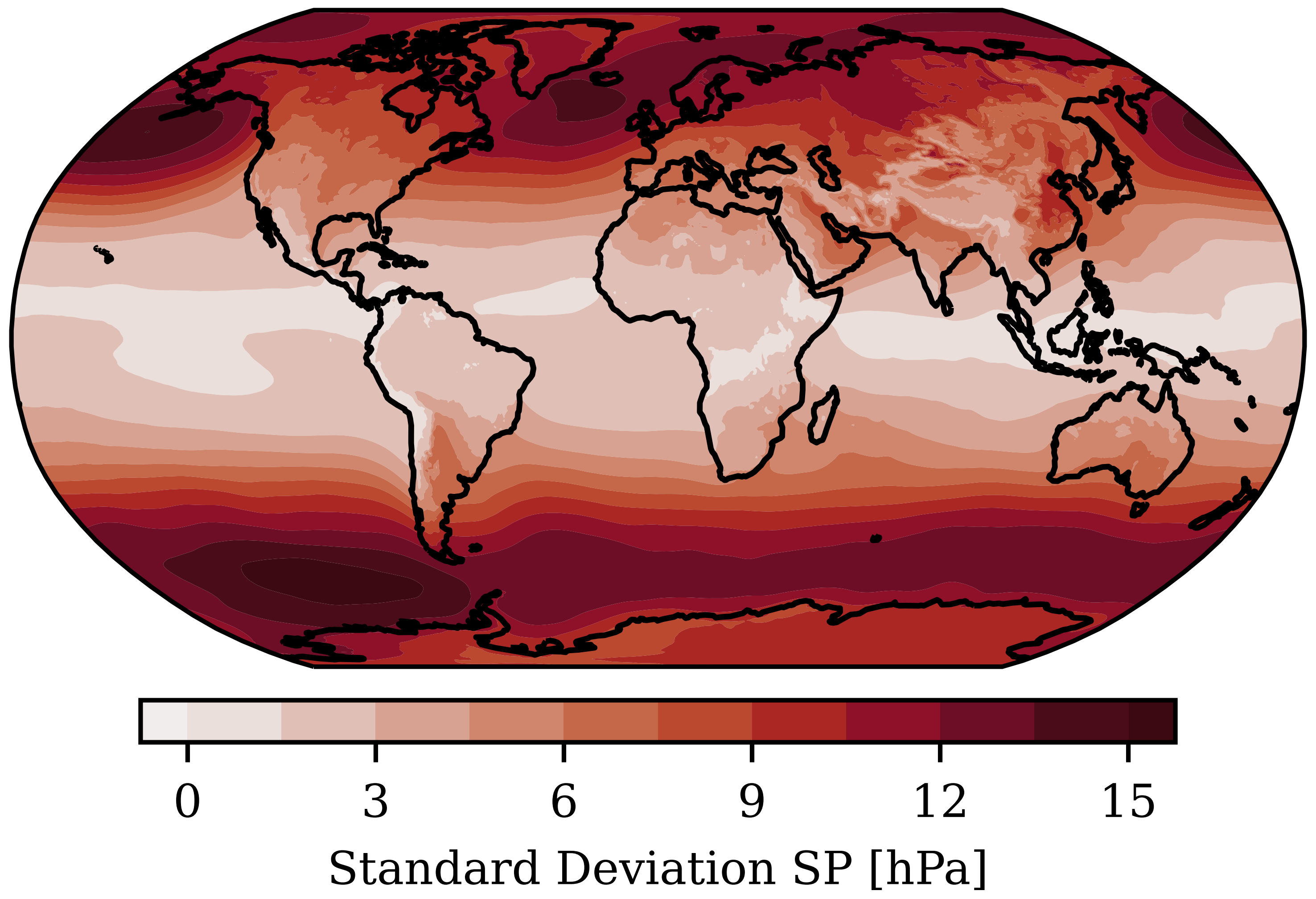
Upper Air Variations:

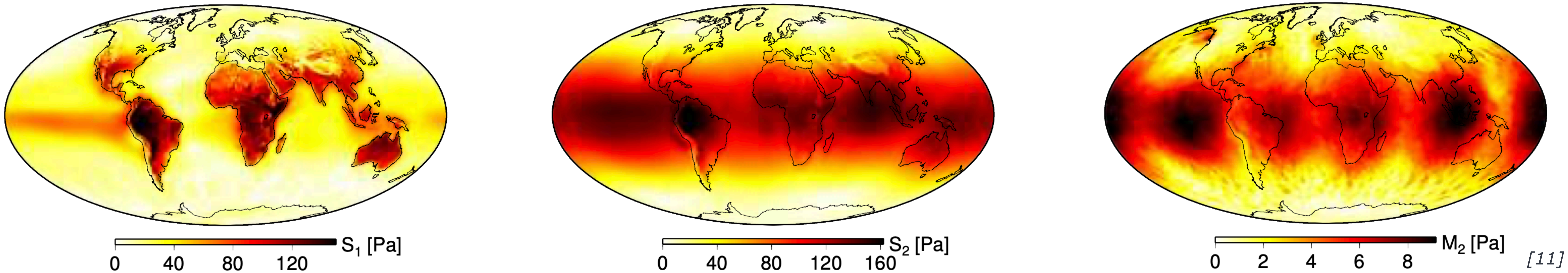


AOD1B Components: Surface Pressure

- Based on ECMWFs ERA5 reanalysis and ECMWF IFS data for operational processing
- Contains tidal signals driven by:
  - Solar radiation (S_1 & S_2)
  - Ocean tides (i.e. variations of the lower boundary, e.g. M_2)
- Tidal signals are estimated and removed
- Generally very good representation due to high weight of barometer data in ECMWFs DA



Example Amplitudes of Atmospheric Tides:



GFZ Helmholtz Centre for Geosciences

[11] Balidakis, K., Sulzbach, R., Shihora, L., Dahle, C., Dill, R., & Dobslaw, H. (2022). Atmospheric contributions to global ocean tides for satellite gravimetry. Journal of Advances in Modeling Earth Systems, 14, e2022MS003193. 10.1029/2022MS003193

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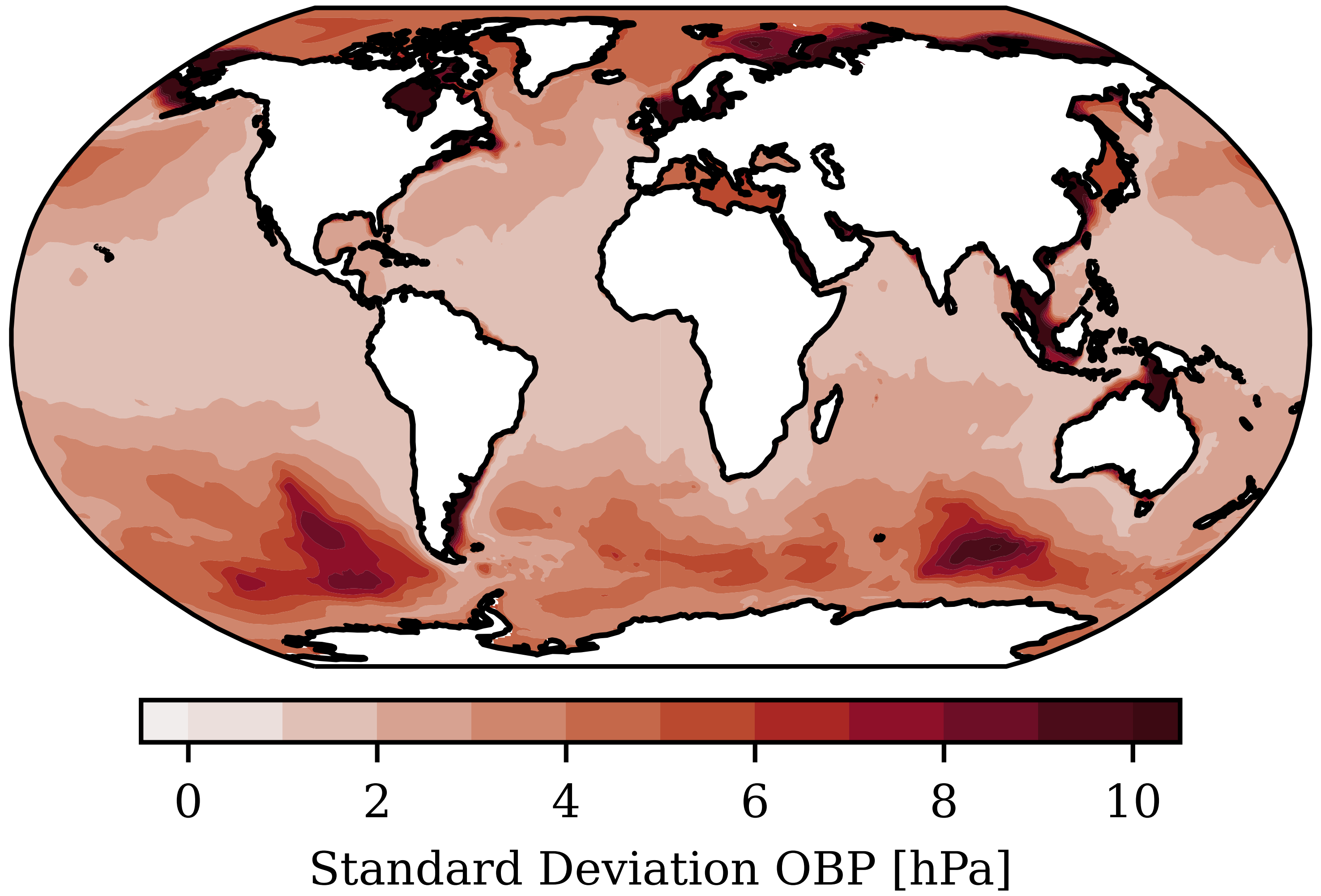
AOD1B Components: Ocean Bottom Pressure

- No ‘operational weather prediction’ for ocean bottom pressure (OBP)
- Perform dedicated simulations using ocean general circulation model MPIOM
- Focus on high-frequency variability driven by atmospheric winds and pressure
- MPIOM forced using atmospheric fields from ECMWFs ERA5 & IFS
- No luni-solar tidal forcing but atmospheric induced tides are removed

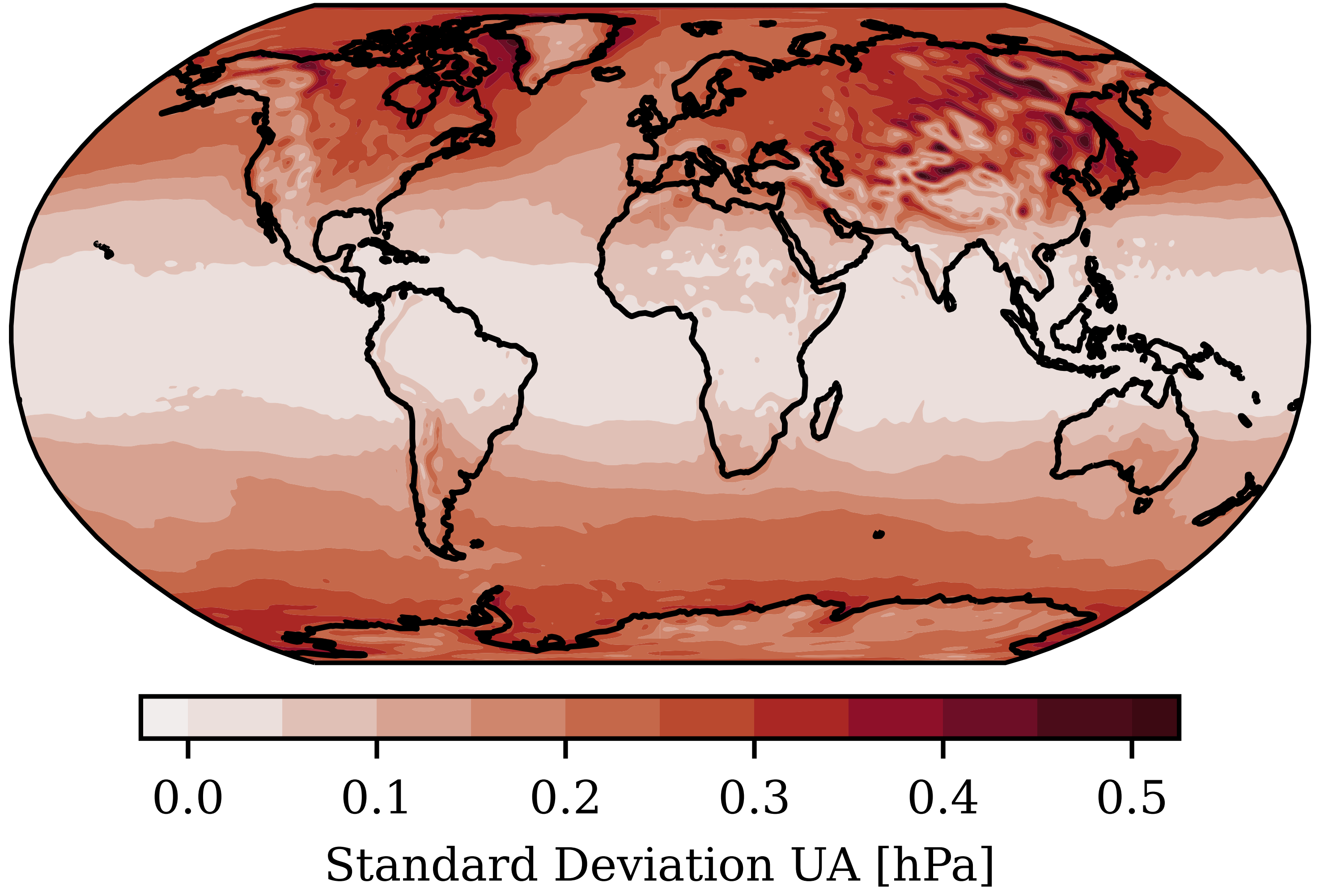


- No data assimilation
- Large-scale variability well represented
- Semi-enclosed seas and some coastal regions are harder to simulate

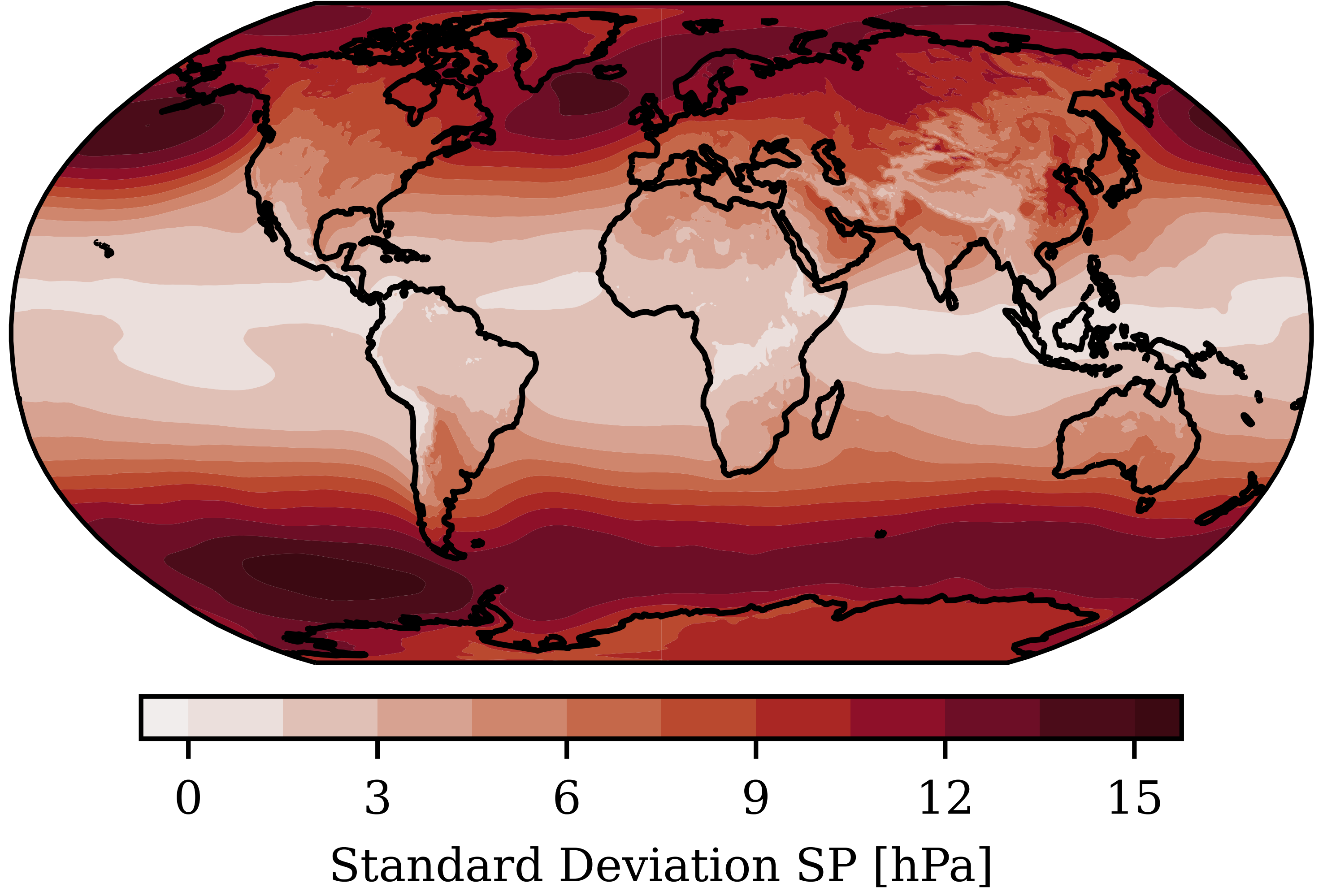
AOD1B Components: Upper Air Variations

- Additional atmospheric contribution: density anomalies in the upper atmosphere
- Common assumption: atmospheric effects confined to very thin layer
- Vertical structure *does* have a small effect
- Calculate contribution via a vertical integration considering temperature and humidity
- Variability small (<0.5 cm EWH) compared to surface pressure

Upper Air Variations:



Atmospheric Surface Pressure:



AOD1B Processing at GFZ

ECMWF

latest operational analysis data

surface pressure

wind

precipitation

evaporation

temperature

…

+ 3h forecasts

6-day forecasts

last day 3-hourly

forecast 3-hourly

atmospheric wind

atm. pressure

ocean forcing

hydrol. forcing

atmospheric wind

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Atmosphere

3-hourly, 0.5°x0.5° regular grid

Analysis and forecast data out of the operational high-resolution global numerical weather prediction model from the European Centre for Medium-Range Weather Forecasts (ECMWF).

OCEAN

3-hourly, 1.0°x1.0° tri-polar grid, 40 vertical layers

unconstrained simulation of the global ocean general circulation model MPIOM

HYDROLOGY

24h, 0.5°x0.5° regular grid

hydrological Land Surface Discharge Model LSDM remapping to a GIS-based 0.125° river map

Sealevel

Barystatic sealevel accounting for self-attraction and loading

wind

mass

current

mass

flow

mass

sealevel equation

mass

subtract tides

subtract tides

IB

SH analysis

Loading

subtract tides

subtract tides

IB

SH analysis

Loading

Loading

Loading

AAM motion

AAM mass

AOD1B ATM

NTAL

OAM motion

OAM mass

AOD1B OCN

NTOL

AOD1B OBA

HAM motion

HAM mass

HYDL

SLAM mass

SLEL

ESMDATA

ISDC

GFZ Helmholtz Centre for Geosciences

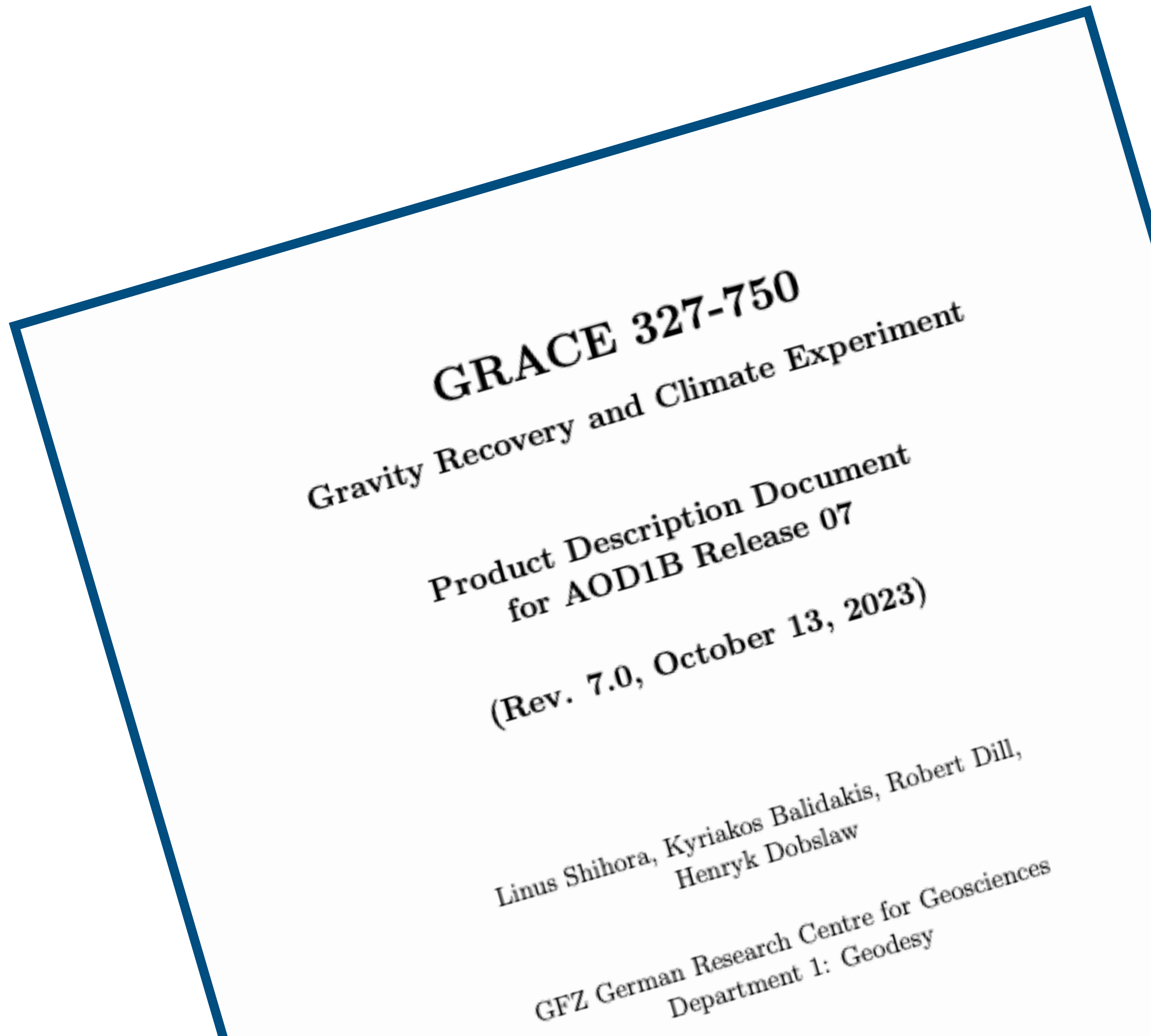
HELMHOLTZ

Some Technical Details

- AOD1B is provided as fully normalised Stokes coefficients up to d/o 180
- 3-hourly resolution
- Operationally updated daily
- 4 sets of coefficients:
  - ATM: surface pressure & upper air variability over continents
  - OCN: dynamic ocean bottom pressure
  - **GLO**: combination of ATM + OCN ← **used in GRACE processing**
  - OBA: same as GLO but without upper air contribution

- Monthly coefficients are available to be added back to the GSM fields for specific application (GAA, GAB, GAC, GAD)
  - Example: applications deriving OBP from GRACE data should restore GAD

- Details in Product Description Document in ISDC



GRACE 327-750

Gravity Recovery and Climate Experiment

Product Description Document
for AOD1B Release 07

(Rev. 7.0, October 13, 2023)

Linus Shihora, Kyriakos Balidakis, Robert Dill,
Henryk Dobslaw

GFZ German Research Centre for Geosciences
Department 1: Geodesy

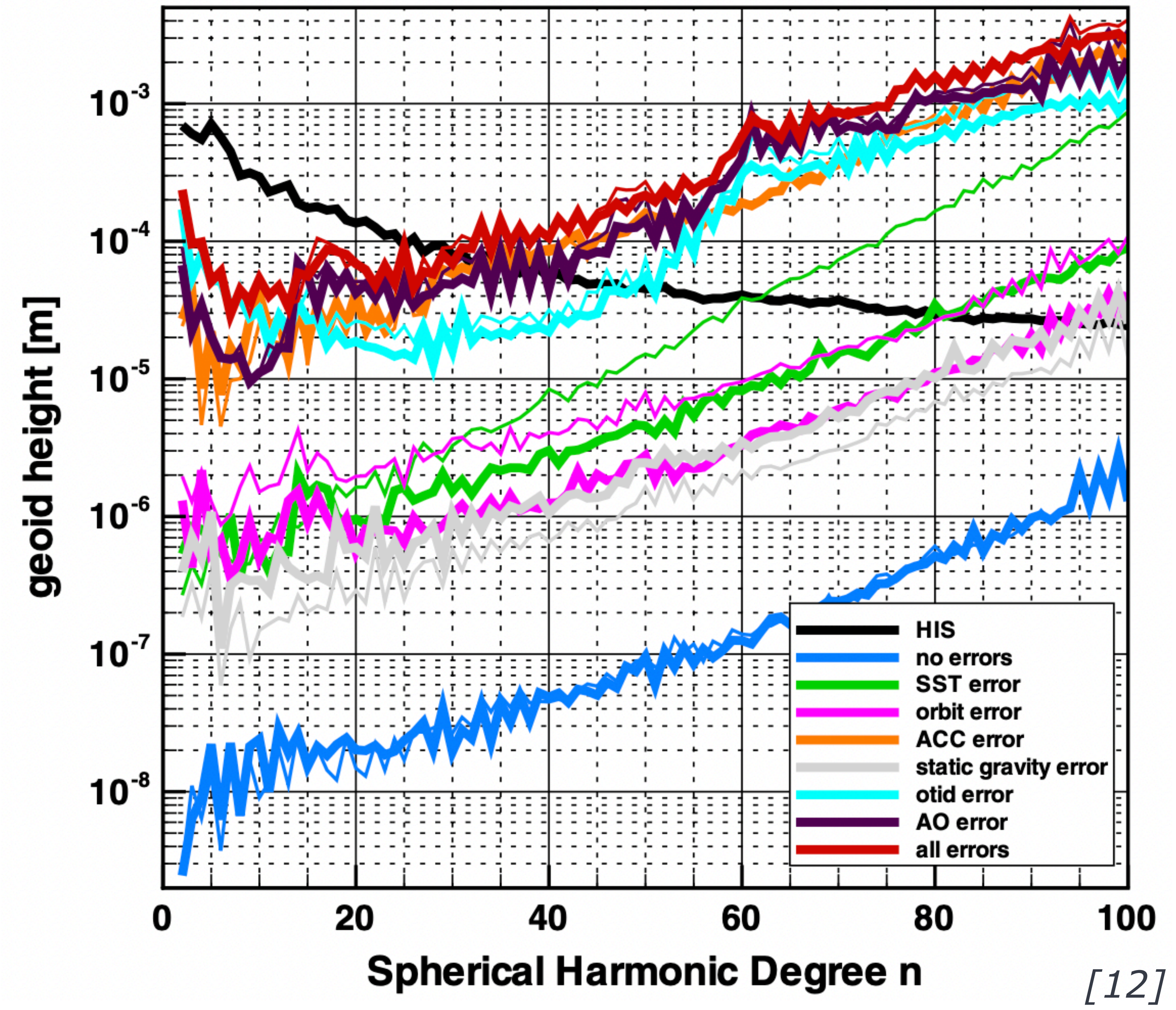
Residual Errors in Background Models

- Background models are inevitably imperfect
- Residual errors contribute to the overall error of monthly solutions
- Stochastic information on the residual error can help improve gravity fields

- AOe07: time-series of background model uncertainties
- Based on model differences using ERA5 and MERRA2 re-analyses and simulated OBP

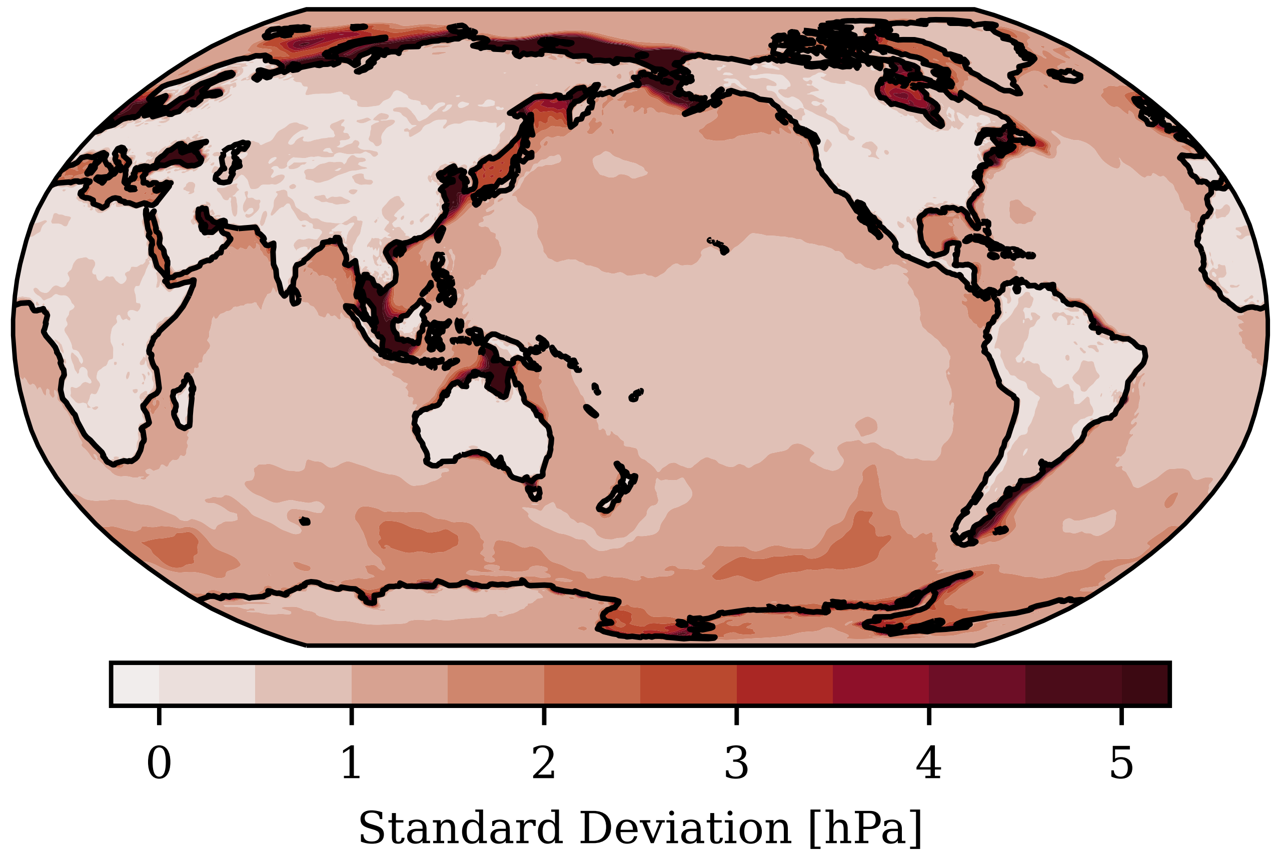
- Weighting observations based on background model accuracy can improve gravity fields up to O(30%)

Simulated GRACE-FO Error Contributions

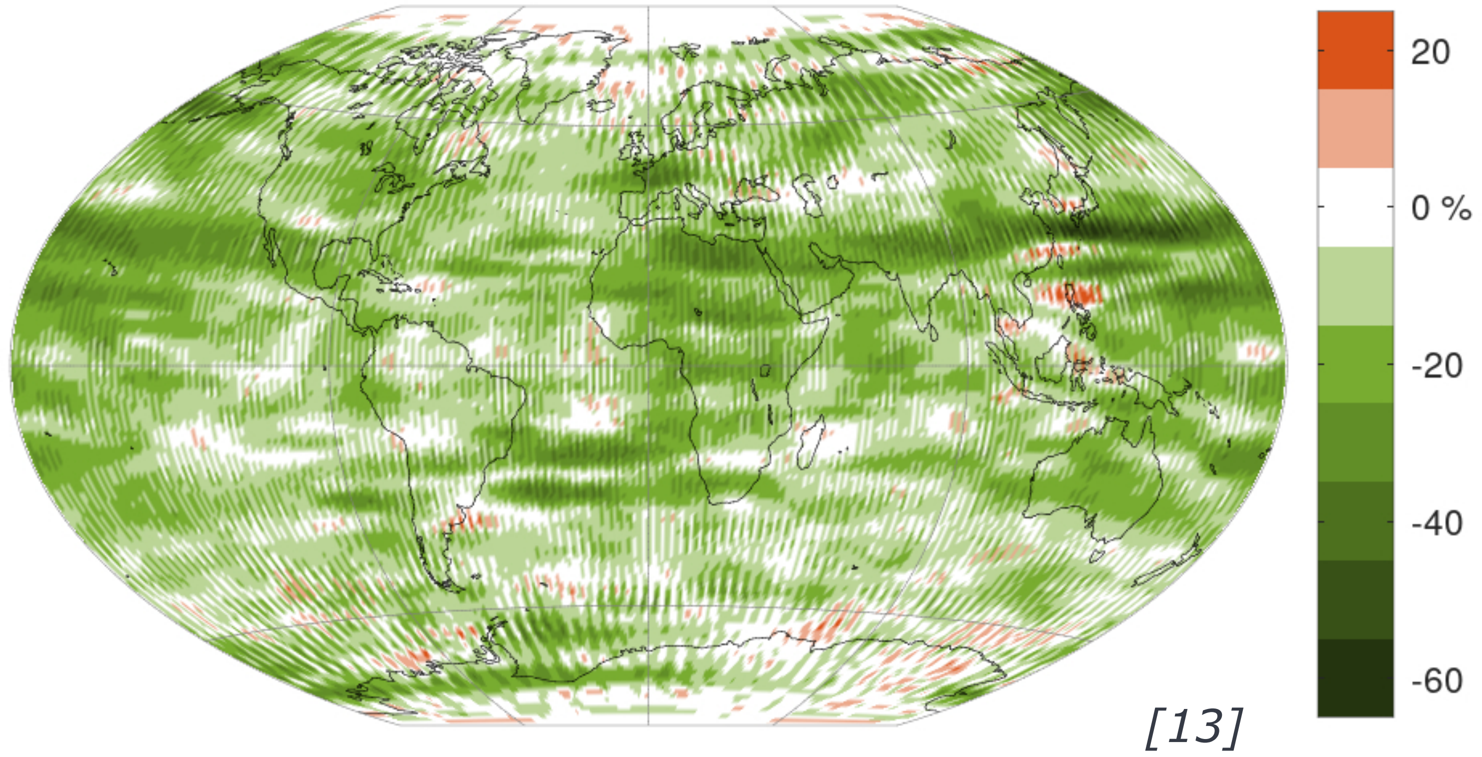


[12]

AOe07



Improvement in GFZ RL07prel due to stochastic modeling



[13]

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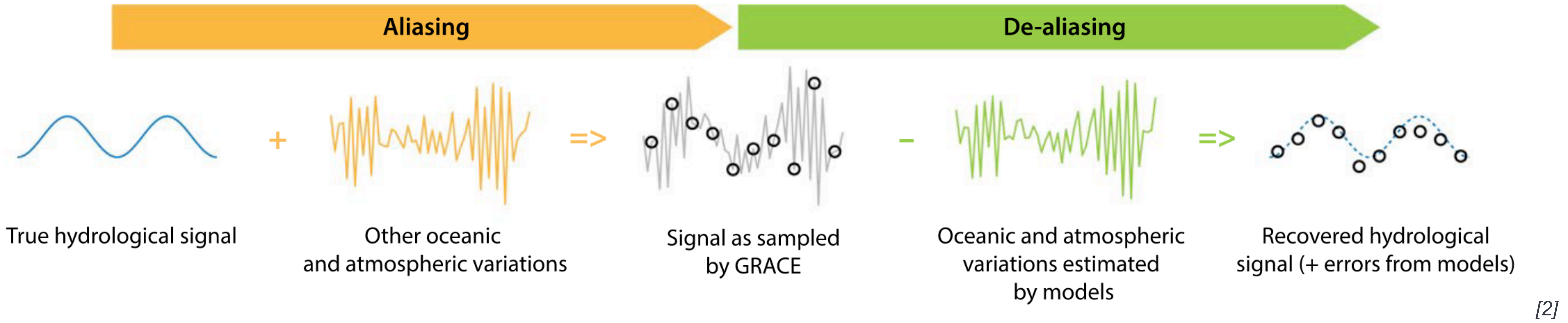
[12] *Flechtner et al. (2016) What Can be Expected from the GRACE-FO Laser Ranging Interferometer for Earth Science Applications ? Surv Geophys, 37, 453–470*

[13] *M. Murböck, personal communication*

Wrap-Up in Figures

Wrap-Up in Figures



True hydrological signal

Other oceanic
and atmospheric variations

Signal as sampled
by GRACE

Oceanic and atmospheric
variations estimated
by models

Recovered hydrological
signal (+ errors from models)

[2]

[2] Humphrey et al. (2023) Using Satellite-Based Terrestrial Water Storage Data: A Review, Surveys in Geophysics, 44:1489-1517

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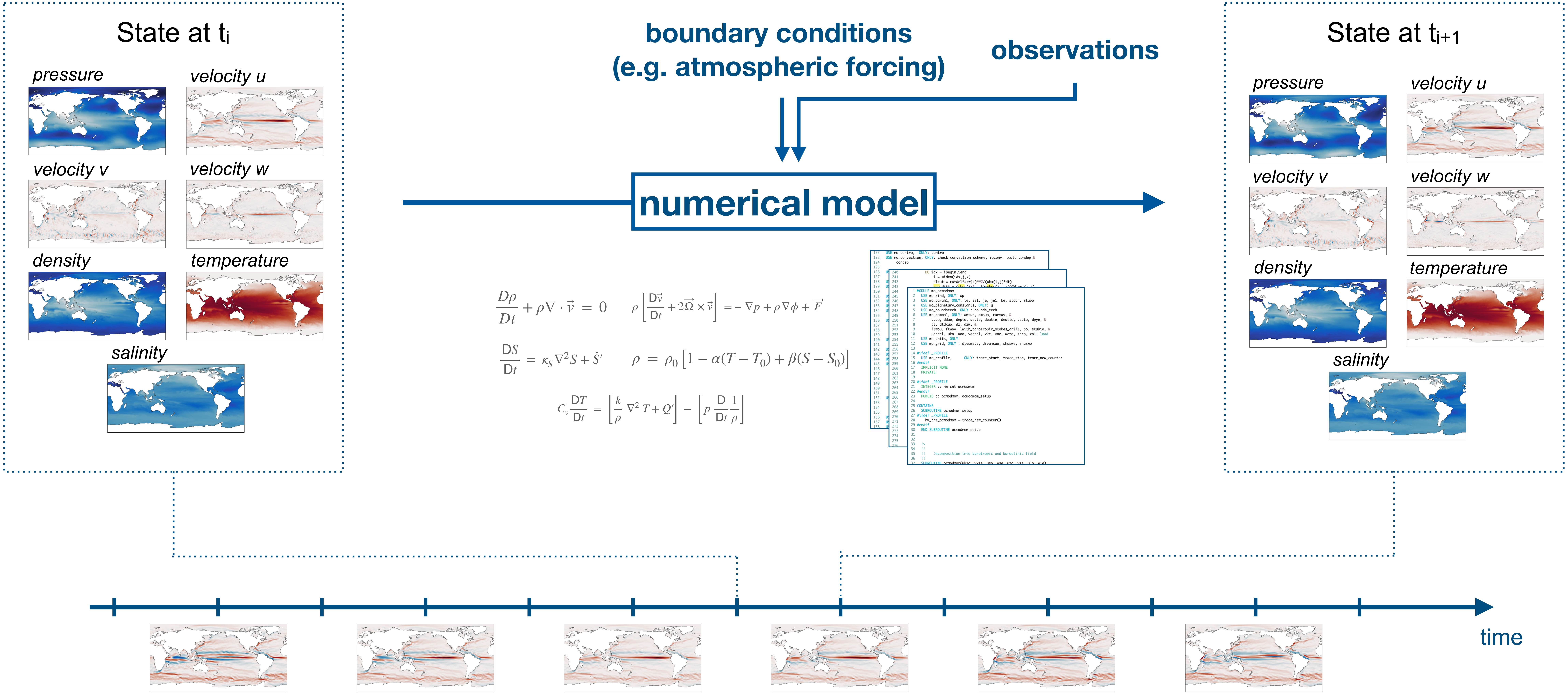

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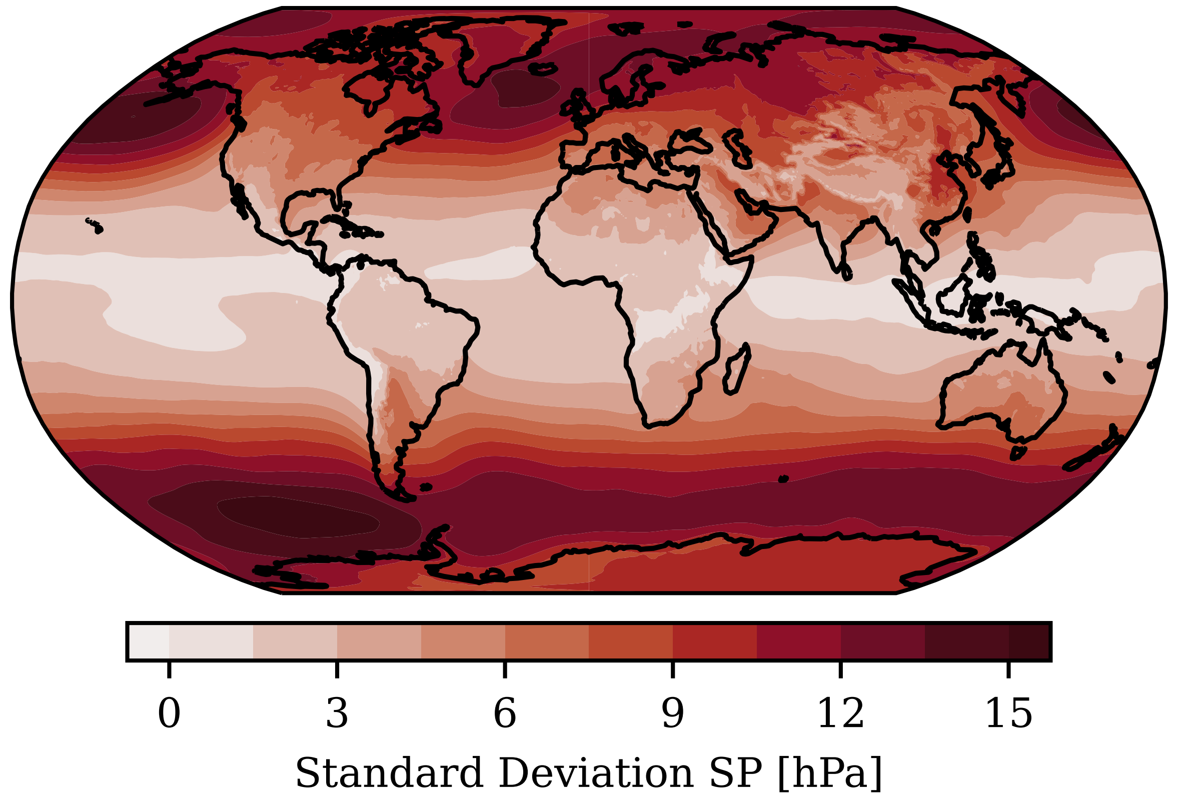

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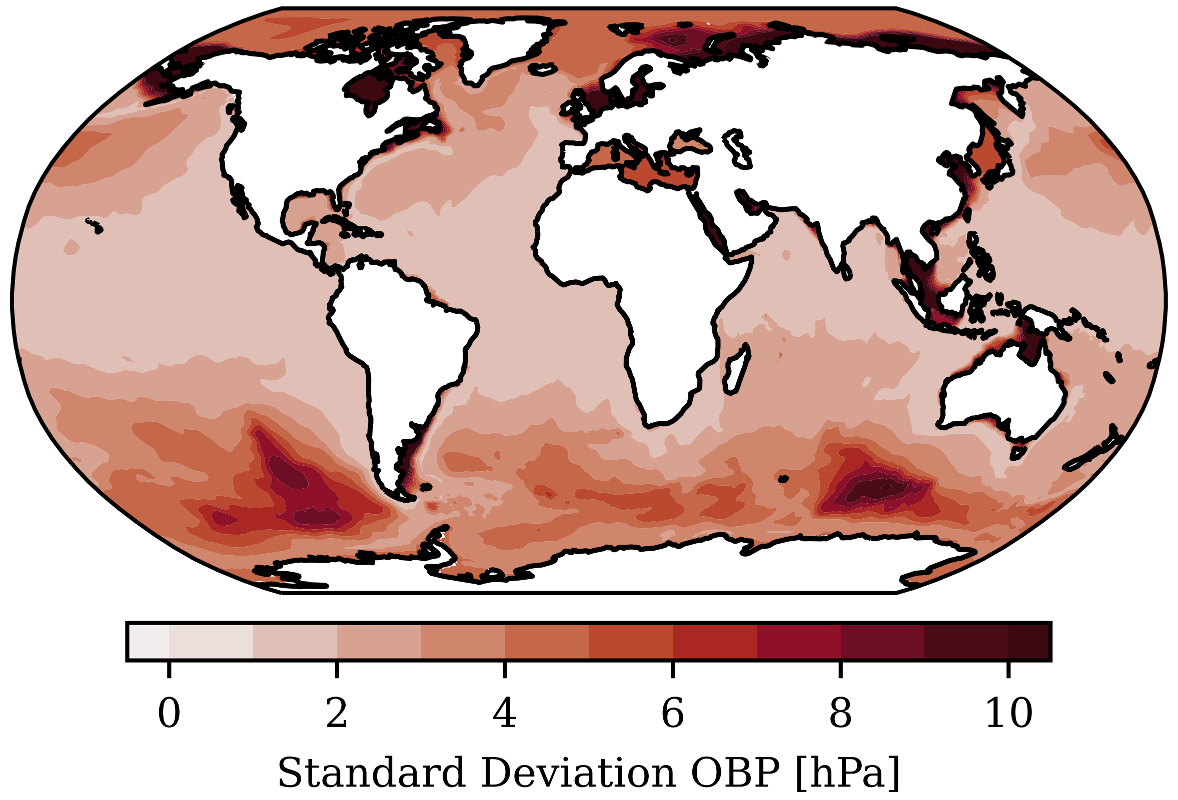

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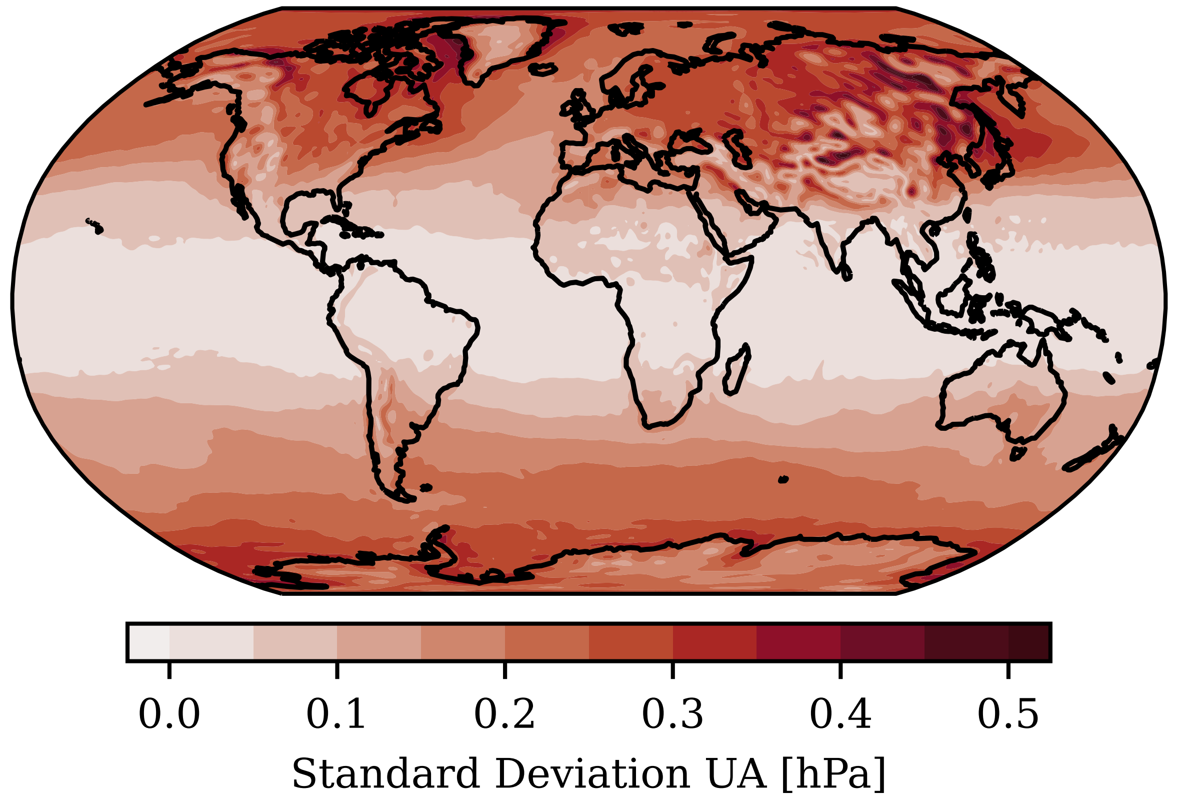

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+ 3h forecasts

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NEROGRAV

New Refined Observations of Climate Change from Spaceborne Gravity Missions

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Neustadt an der Weinstraße, Germany, March 10-14, 2025

Background Modelling for Satellite Gravimetry

Linus Shihora (GFZ Helmholtz Centre for Geosciences)

TU berlin
Freie Universität Berlin
Technische Universität München TUM
GFZ Helmholtz Centre for Geosciences
UNIVERSITÄT BONN
hcu HafenCity Universität Hamburg