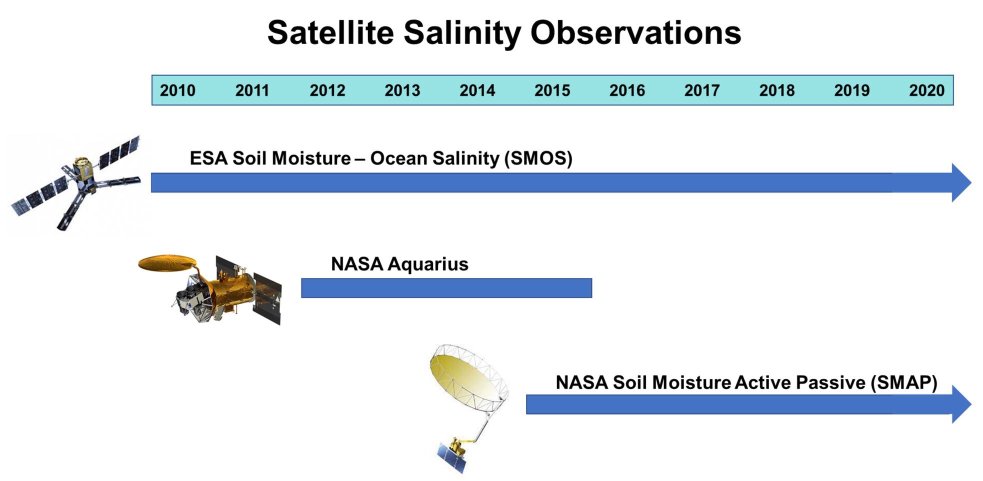

Satellite Sea-surface Density

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ABSTRACT: Density drives the global ocean's thermohaline circulation, governed by the three principle components of ocean density: temperature, salinity, and pressure. Sparse *in situ* observations have limited observations of ocean density. Exploiting satellite observations of the ocean surface for temperature and salinity, where pressure is a negligible factor, allows for unprecedented global spatial and temporal coverage and resolution. Satellite sea-surface salinity (SSS), in conjunction with satellite sea-surface temperature (SST), produces the ocean skin density, with satellite SSS observations measuring approximately the top centimeter and satellite SST observations measuring approximately the top-10 micrometers. Using concurrent satellite SSS and SST observations provides consistency when computing sea-surface density (SSD). With a decade of satellite SSS observations, this study explores SSD variability and trends, as well as the temperature and salinity contributions to the observed density changes. Examining the ocean's density and spiciness in the context of thermal expansion (alpha) and salinity contraction (beta) helps highlight the significance of satellite SSS observations for ocean modeling, along with regional sensitivities. Mapping where SSS changes dominate SSD changes can guide where future *in situ* salinity measurements are most needed for enhancing ocean prediction.

BACKGROUND:

- **Density (ρ) = f(Salinity, Temperature, Pressure)**
  - Ref: *Thermodynamic Equation of Seawater – 2010 (TEOS-10)*
    - Manuals & Guides #56, Intergovernmental Oceanographic Commission

- **Satellite-only sea-surface density (SSD)**
  - Sea-surface salinity (SSS): skin depth ~ 1 cm
  - Sea-surface temperature (SST): skin depth ~ 10-20 µm
  - SSD ~ < 1 cm depth: approximate P = 0
  - ** Absolute Salinity (S_A) was used for calculations (TEOS-10)
  - ** Plots depict Practical Salinity (S_P)

- **Density Components** (at surface, pressure = 0)
  - Temperature contribution
    - Thermal expansion (@ P = 0) → ($\alpha\Delta T$)ρ
  - Salinity contribution
    - Haline contraction (@ P = 0) → ($\beta\Delta S$)ρ

- **Spiciness (τ):**
  - Salinity & temperature balance along a surface of constant density (isopycnal)
    - For a constant density: cool-fresh (minty) ← → warm-salty (spicy)
  - McDougall & Krzysik (2015) employing TEOS-10:
    - Using potential density (τ) and Conservative Temperature (Θ), computed corresponding S_A
    - Spiciness (S_A, Θ) plane: S_A (0 → 42 g/kg); Θ (-2C → 45C)
    - **Along Θ = constant, changes in spiciness (τ) exactly = changes in potential density**
    - τ(S_A =35.16504, Θ=0C) → 0; where S_A(35.16504) ≡ 35 pss

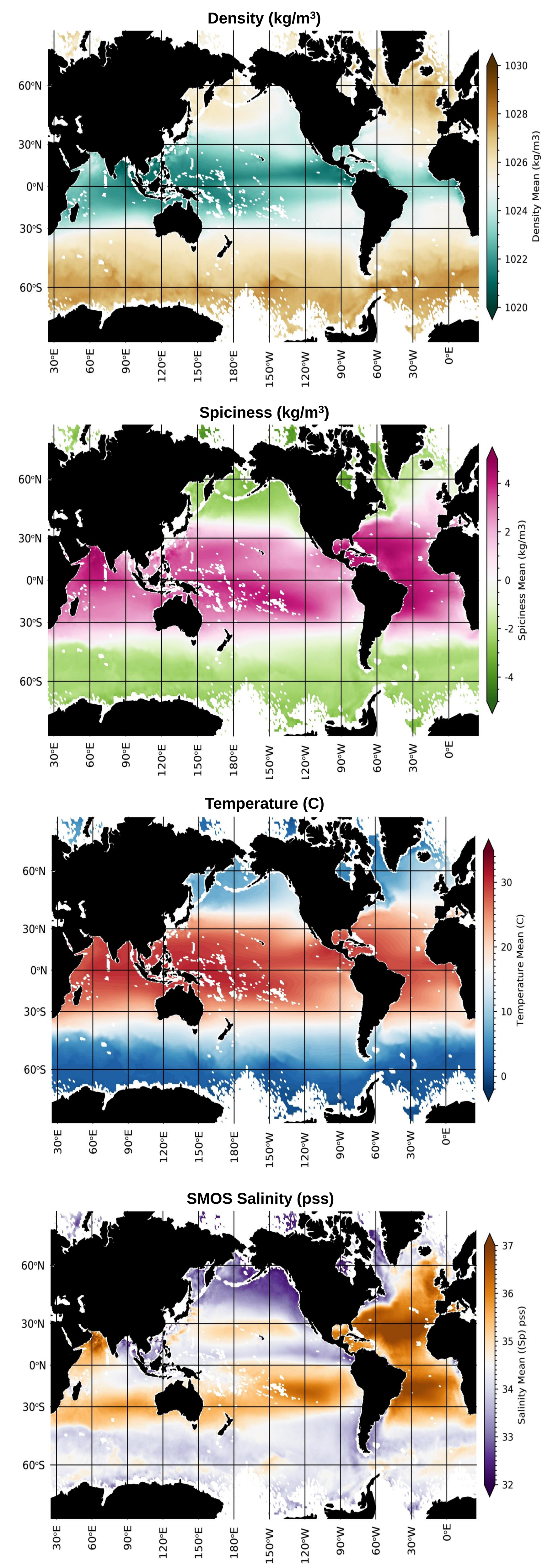
DATA:

- **Sea-surface Salinity (SSS) Sources**
  - **Soil Moisture and Ocean Salinity (SMOS)**
    - Level-3 CoastWatch SMOS SSS
      - Generated from ESA MIRAS SMOS Level-2 data
    - ¼-degree resolution
    - **Period: 6/1/2010 – present**
  - **Soil Moisture Active Passive (SMAP)**
    - Level-3 CoastWatch SMAP SSS
      - Generated from NASA JPL SMAP Level-2B data
    - ¼-degree resolution
    - **Period: 4/1/2015 – present**
- **Sea-surface Temperature (SST) Source**
  - **Geo-Polar Blended Sea Surface Temperature (GOES/POES SST)**
    - Level-4 Nightly GOES/POES Blended SST
    - 1/20th-degree resolution
    - **Period: 9/1/2002 – present**

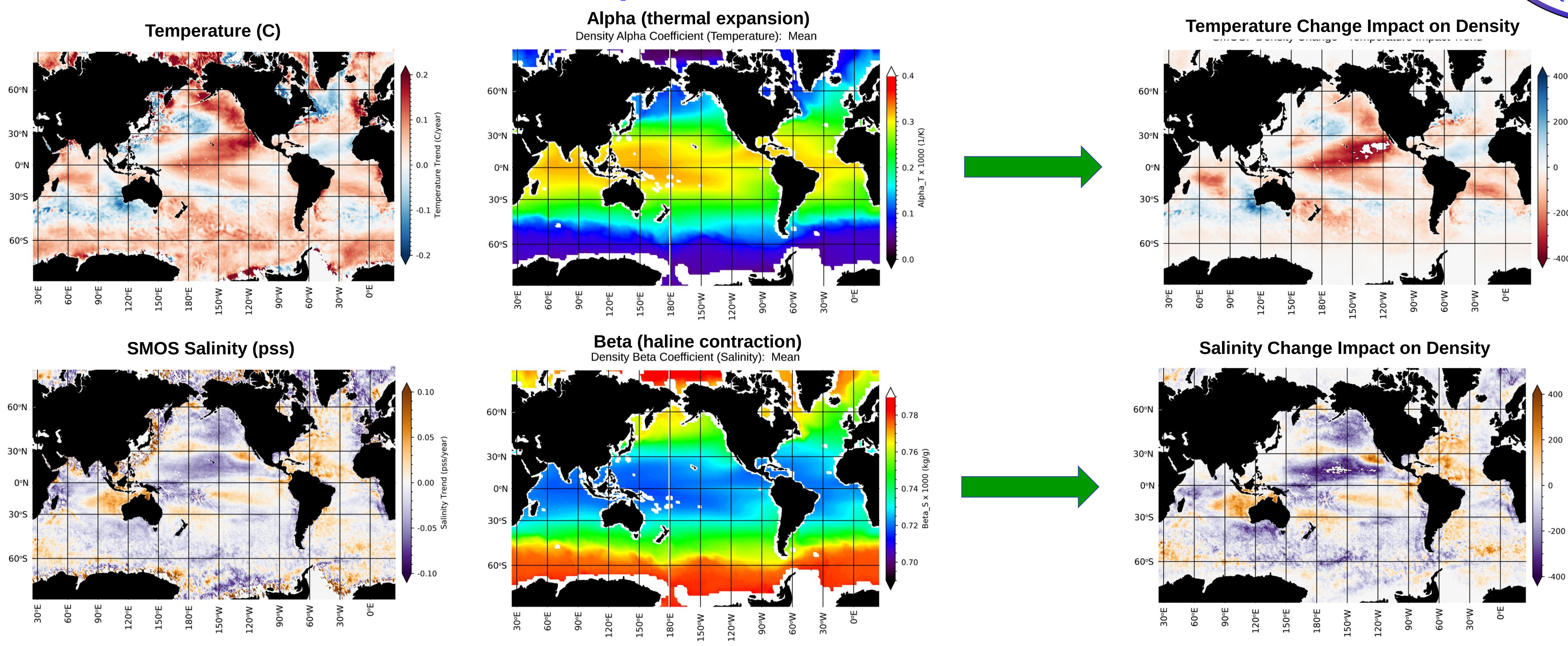
METHODOLOGY

1. Regridded high-resolution GOES/POES SST to match lower-resolution SSS products using bilinear interpolation
2. Matched daily SST with daily SSS
3. Computed sea-surface density, spiciness, alpha, and beta terms
   - Python implementation of the Gibbs SeaWater (GSW) Oceanographic Toolbox of the Thermodynamic Equation of Seawater – 2010 (TEOS-10)
   - https://teos-10.github.io/GSW-Python/
4. Data outputted into single daily netCDF files for all variables
   - Conservative temperature and absolute salinity were used in the calculations of density
   - Converted using the TEOS-10 GSW toolbox.
5. Daily data files were then averaged into weekly, monthly, seasonal, and annual compositing periods and disseminated as aggregated netCDF files
6. Aquarius SSS 1-degree data were scaled down to ¼-degree resolution via bilinear interpolation to allow for comparison with both SMAP- and SMOS-derived SSD

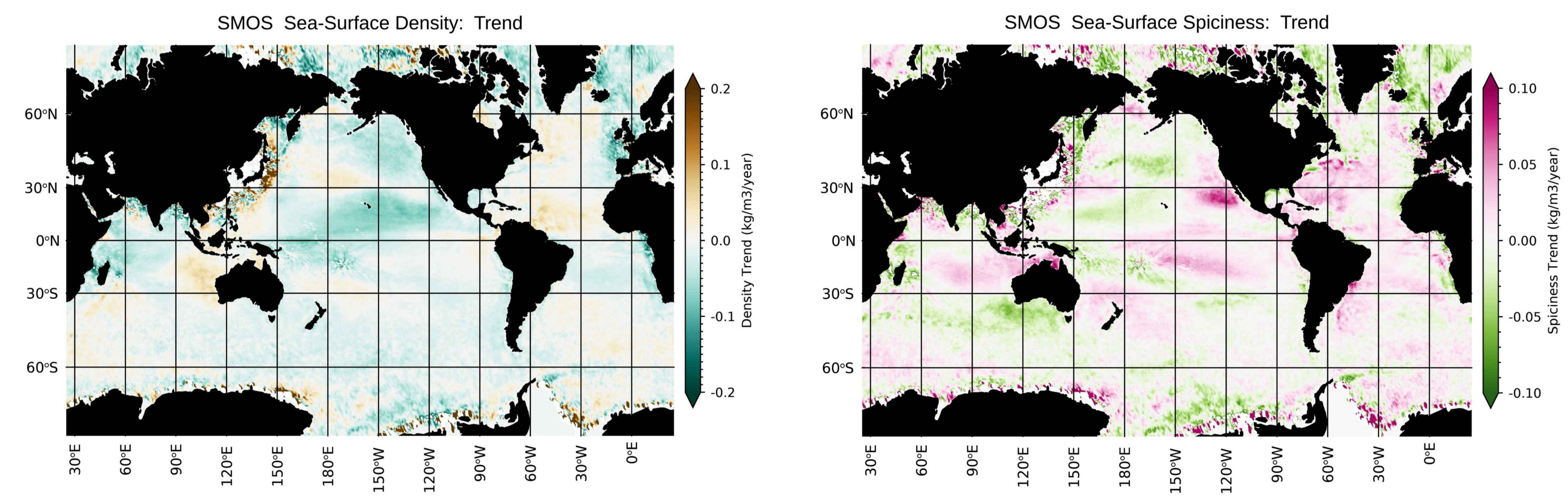
2010-2020 Mean



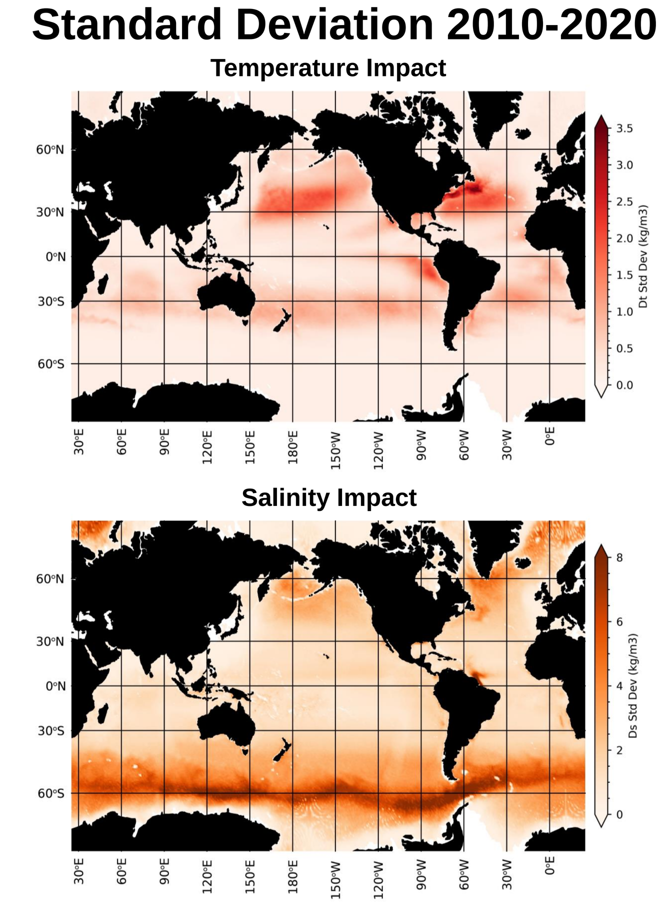
Component Trends 2010-2020



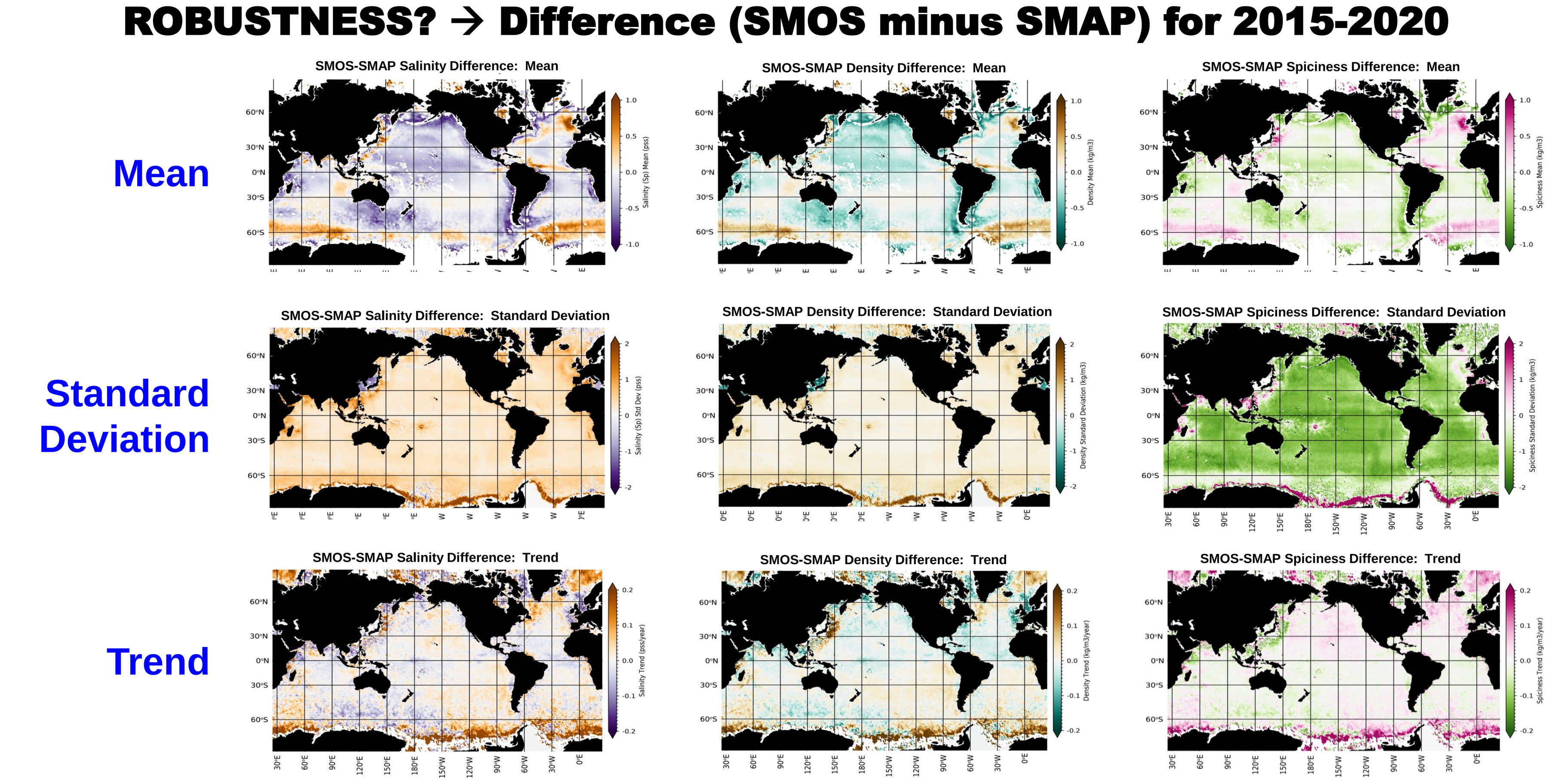
Resulting Trends 2010-2020



Component Change: Standard Deviation 2010-2020



ROBUSTNESS? → Difference (SMOS minus SMAP) for 2015-2020



FINDINGS:

- Satellite SSS observations now have a sufficiently long data record for insights into climatic-scale change and trends.
- The mean values for SSS and SST confirm expectations.
- The mean values for density and spiciness provide the first view of long-term values at high-temporal and high-spatial resolution.
- Spatial trends in spiciness largely reflect the SSS trends
- Comparison of SMOS and SMAP results for their overlapping period are largely consistent, with the most significant differences in regions of high variability and/or greater SSS uncertainty, such as in high-latitude areas.
- Satellite-only sea-surface density (SSD) provides global insight into global processes and drivers for the ocean thermohaline circulation.

Ocean Salinity Conference (6-9 June 2022), Columbia University, New York, NY