Potential for Remote Monitoring of Ocean Heat Content

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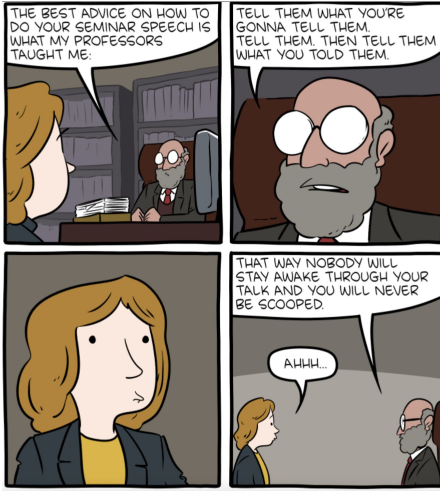
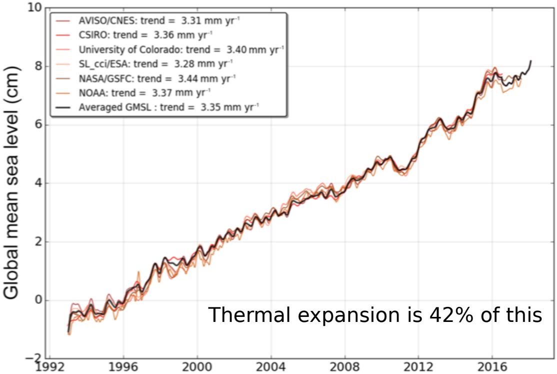
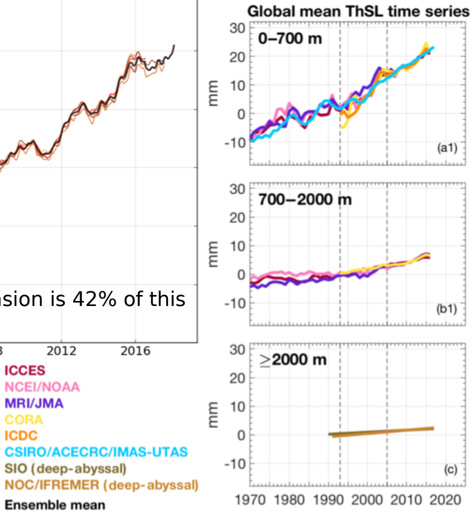
Outline


THE BEST ADVICE ON HOW TO DO YOUR SEMINAR SPEECH IS WHAT MY PROFESSORS TAUGHT ME:
TELL THEM WHAT YOU'RE GONNA TELL THEM. TELL THEM. THEN TELL THEM WHAT YOU TOLD THEM.
THAT WAY NOBODY WILL STAY AWAKE THROUGH YOUR TALK AND YOU WILL NEVER BE SCOOPED.
AHHH...

Ocean warming has contributed 42% of total observed sea level change, but this contribution has gone down to about a third of recently observed sea level change



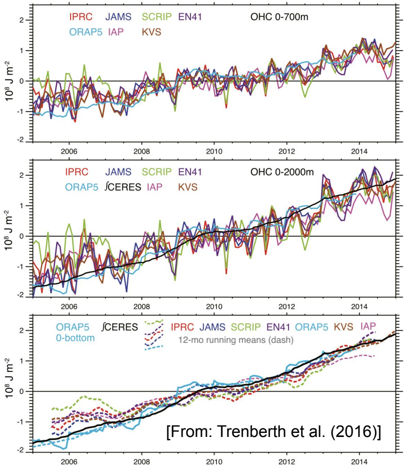


[From: WCRP Global Sea Level Budget Group (2018)]

Methods to monitor ocean heat content

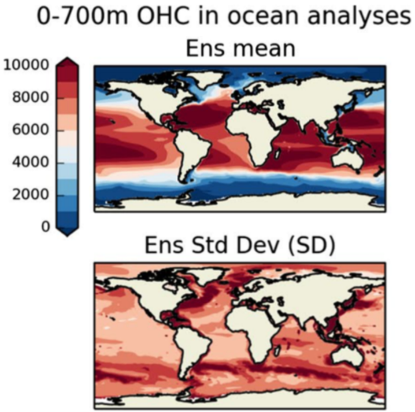
- Calculate from in situ observations and/or remotely sensed top-of-atmosphere net radiation
- Infer from residual of total sea level and all other contributors
- Reanalysis products from models that assimilate in situ and remotely sensed observations
- Proxy-based methods and machine learning algorithms

There are problems with all of these methods

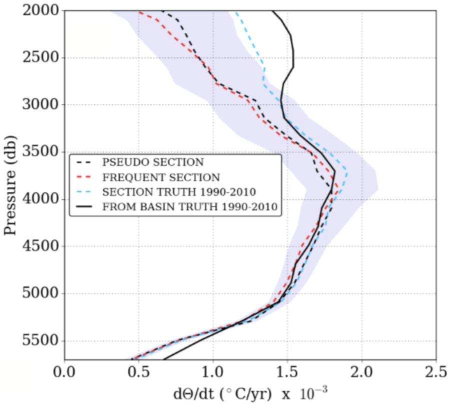


[From: Trenberth et al. (2016)]

There are biases in how we sample ocean heat content below 2000 meters depth and disagreement across reanalysis products

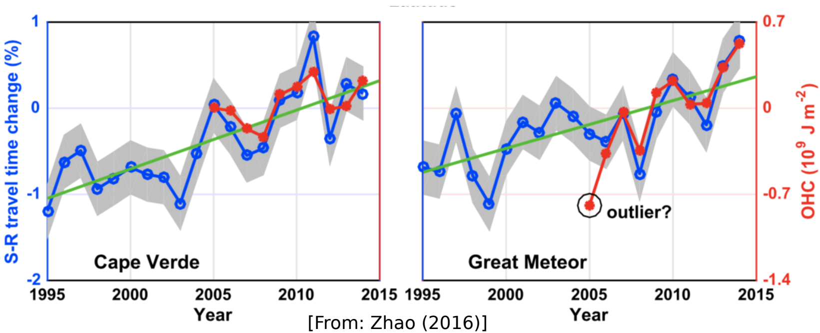


[From: Palmer et al. (2017)]



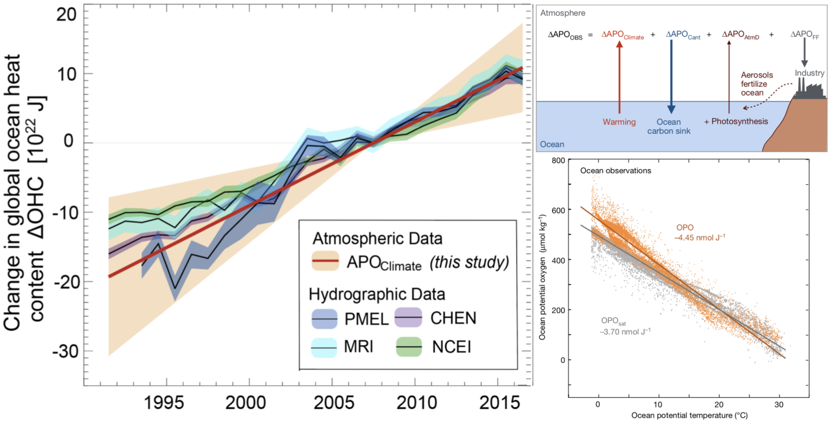
[From: Garry et al. (2019)]

Changes in stratification is related to changes in phase speed of tides, which has been proposed as a way to monitor thermal expansion of seawater



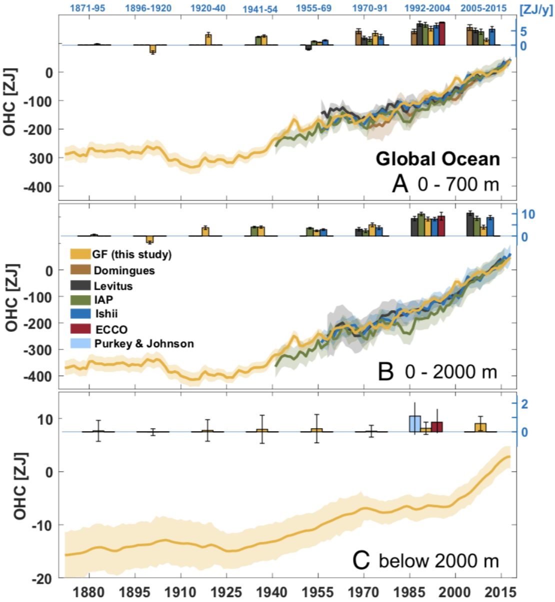
[From: Zhao (2016)]

A combination of oxygen, nitrogen, and carbon dioxide concentrations in the atmosphere can be used to get estimates of ocean heat content



[From: Resplandy et al. (2018, corrected version)]

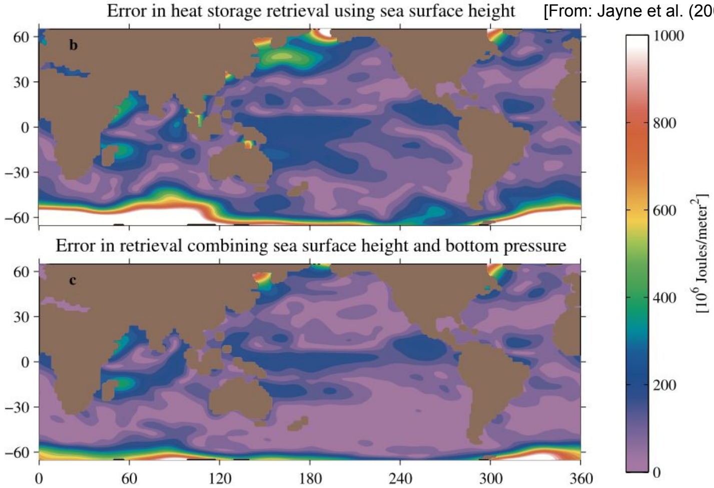
Models can be used to derive Green's functions, which can be used to calculate heat content (with many assumptions)



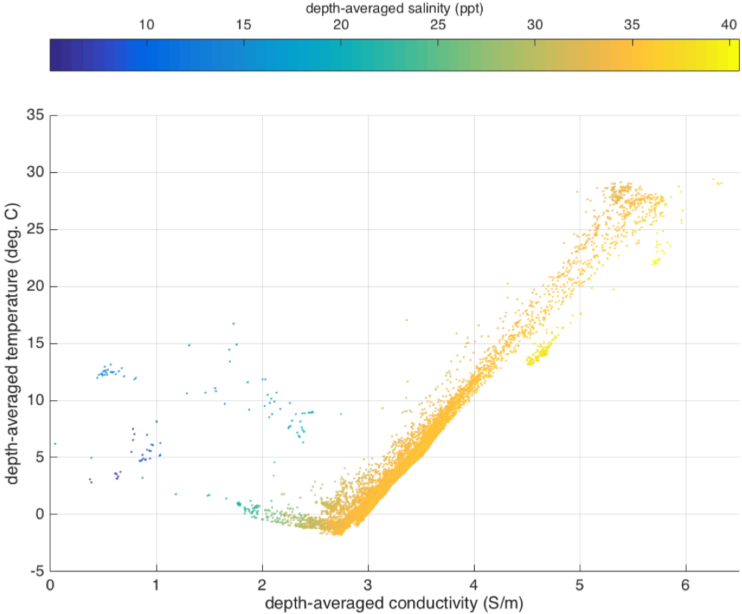
[From: Zanna et al. (2019)]

Ocean heat content can be accurately predicted using a combination of sea surface heights and bottom pressures (but not so well in high latitude regions)

[From: Jayne et al. (2003)]



Observed depth-averaged conductivity and temperature of the ocean are strongly correlated

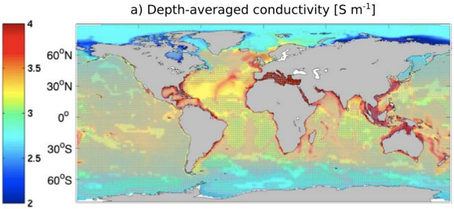


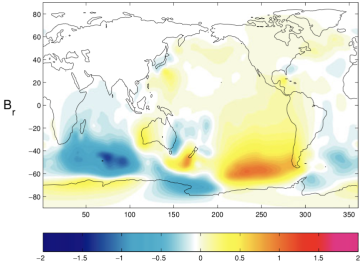
Our research question regarding satellite magnetometry and the ocean's electrical conductivity

Question:

Is there climate-relevant information in ocean conductivity?

- The ocean's general circulation generates a magnetic field of ± 5 nT (± 0.5 nT in interannual variability), compared to Earth's $\sim 50,000$ nT
- Remote magnetic field observations can be used to infer ocean's depth-integrated electrical conductivity
- There may be large uncertainties in this inversion of conductivity from magnetic field observations



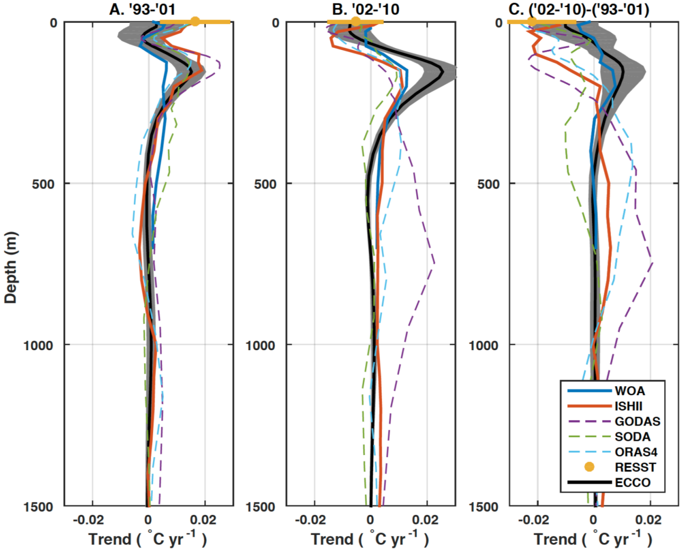


Ocean state estimate: ECCO

ECCO version 4 release 3, or ECCO.v4r3 (*Fukumori et al.*, 2017): https://ecco.jpl.nasa.gov

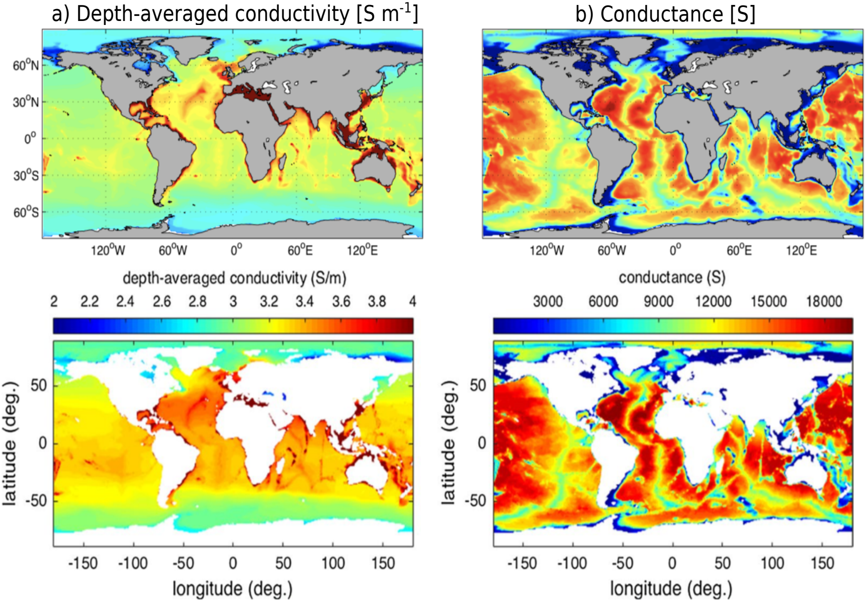
- MITgcm: global nominally 1^o grid with 50 z-levels
- Time period: 1992-2015
- Assimilated observations: GRACE-derived ocean bottom pressure, Aquarius SSS, SSH from various satellites, Argo/CTD/SEaOS/ITP temperature profiles, Argo/CTD/SEaOS salinity profiles, AVHRR/AMSR-E SST, TAO array and other moorings, sea ice concentration from various satellites, WOA for climatology, DTU13 mean dynamic topography
- Objective: minimize cost function, J (weighted sum of model-data misfits and sum of penalties on control parameters)
- Adjoint capabilities: gradient of cost function is used to modify control variables (initial conditions, surface forcing, and mixing parameters)

ECCO performs better relative to an observational climatology than other reanalyses

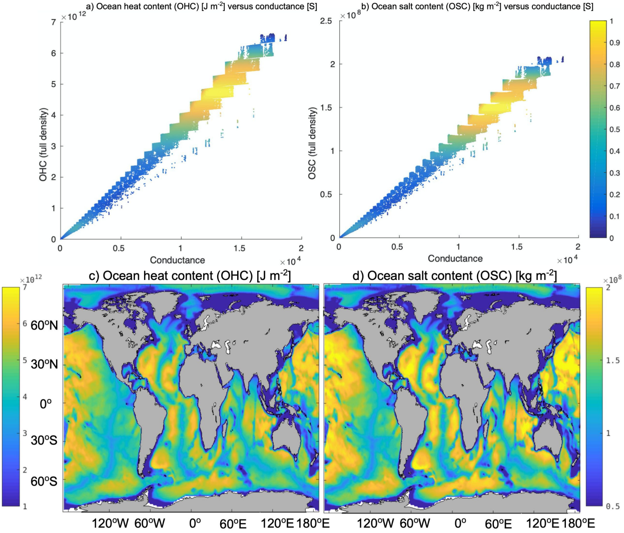


[From: Heimbach et al. (2019)]

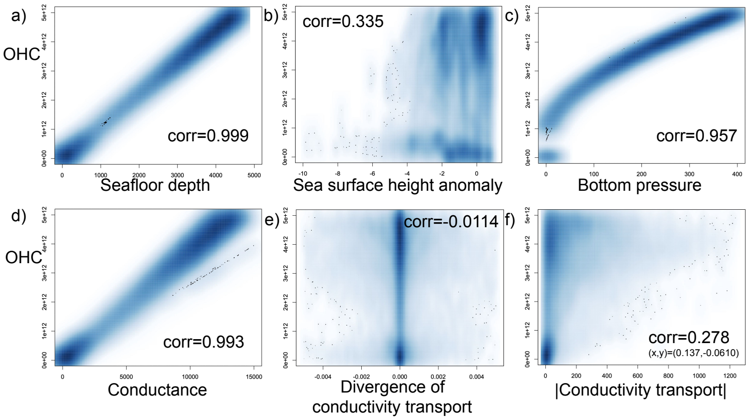
Depth-integrated/-averaged conductivity also look a lot like those from observations



Depth-integrated conductivity and ocean heat(/salt) content are strongly correlated



Ocean heat content is highly correlated with many variables that are remotely monitored on a global scale



$OHC = f_0 + f_1(\Sigma) + f_2(H) + f_3(p_b) + f_4(\eta') + g(\Sigma, H, p_b, \eta')$ If $g(\Sigma, H, p_b, \eta') = g(\Sigma, p_b, \eta')$, then $f_0' = f_0 + f_2(H)$ for OHC'

Ocean heat content can be accurately predicted, with vanishing returns when adding observable variables to the statistical model

terms included in GAM: OHC= f_0+...	percent RMSE in OHC
$f_1(\mathrm{SSH})$	43.6%
$f_1(p_b)$	5.51%
$f_1(\Sigma)$	5.92%
$f_1(H)$	0.60%
$f_1(\lvert\mathbf{T}_\sigma\rvert)$	41.4%
$f_1(\mathrm{SSH}) + f_2(p_b)$	6.12%
$f_1(\mathrm{SSH}) + f_2(p_b) + g(\mathrm{SSH}, p_b)$	6.10%
$f_1(\mathrm{SSH}) + f_2(p_b) + f_3(\Sigma)$	1.92%
$f_1(\mathrm{SSH}) + f_2(p_b) + f_3(\Sigma) + g(\mathrm{SSH}, p_b, \Sigma)$	0.93%
$f_1(\mathrm{SSH}) + f_2(p_b) + f_3(\Sigma) + f_4(H)$	0.21%
$f_1(\mathrm{SSH}) + f_2(p_b) + f_3(\Sigma) + f_4(H) + g(\mathrm{SSH}, p_b, \Sigma, H)$	0.15%
$f_1(\mathrm{SSH}) + f_2(p_b) + f_3(\Sigma) + f_4(H) + f_5(\lvert\mathbf{T}_\sigma\rvert)$	0.21%
$f_1(\mathrm{SSH}) + f_2(p_b) + f_3(\Sigma) + f_4(H) + f_5(\lvert\mathbf{T}_\sigma\rvert) + g(\mathrm{SSH}, p_b, \Sigma, H, \lvert\mathbf{T}_\sigma\rvert)$	0.15%

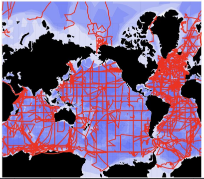
Three experimental designs

Knowledge of each variable everywhere from satellites, but:

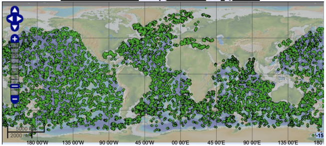
- Ocean heat content throughout the full water column everywhere in the ocean
- Ocean heat content only in the upper 2000 meters
- Ocean heat content (throughout the full water column) only along ship-based hydrographic transects

Repeat these experiments for ocean heat content *anomalies*

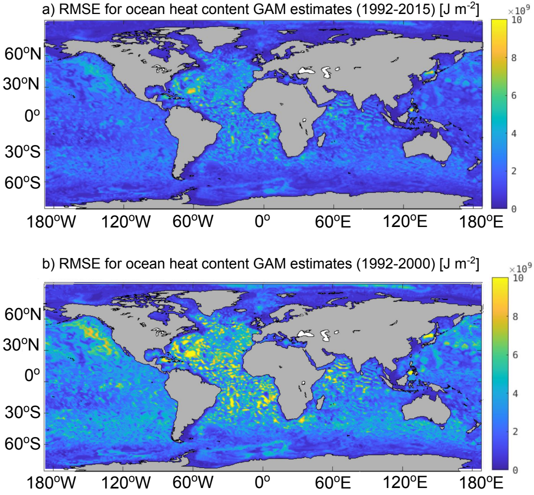
Ship-based hydrographic transects (WOCE/CLIVAR,...)



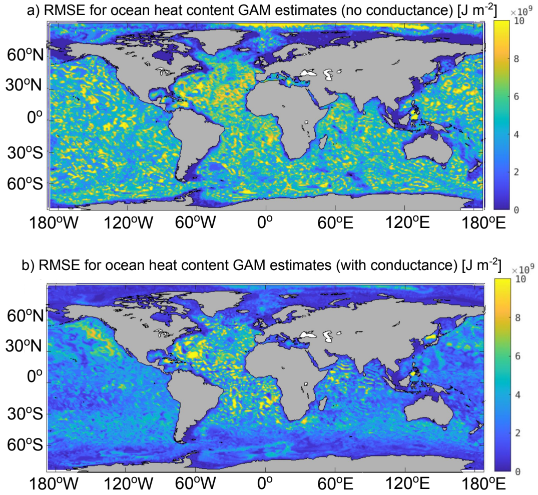
(P)ALACE/Argo



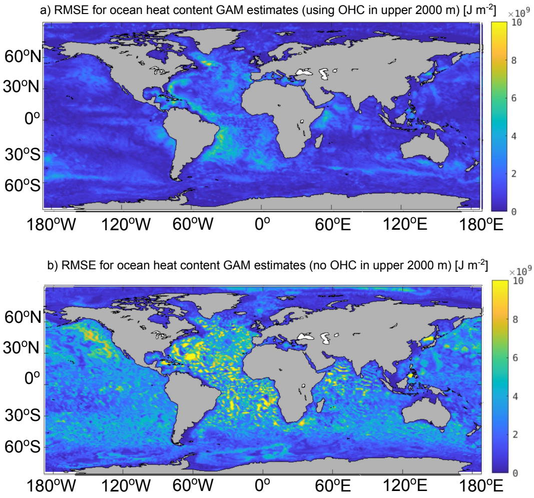
Ocean heat content can be accurately predicted (to within 0.1% on 24-year average) using a combination of quantifies that can be remotely sensed; the first 9 years are less accurately predicted



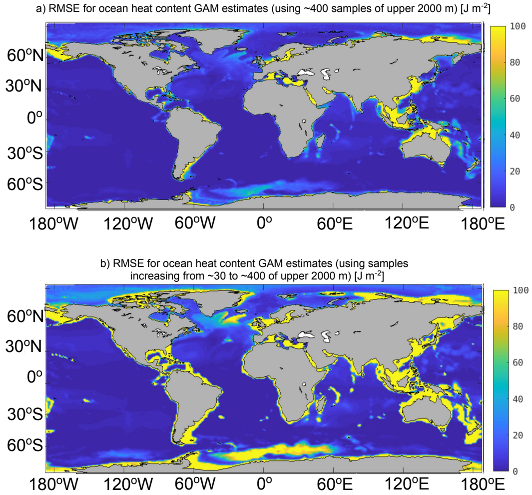
Ocean heat content is less accurately predicted without depth-integrated conductivity



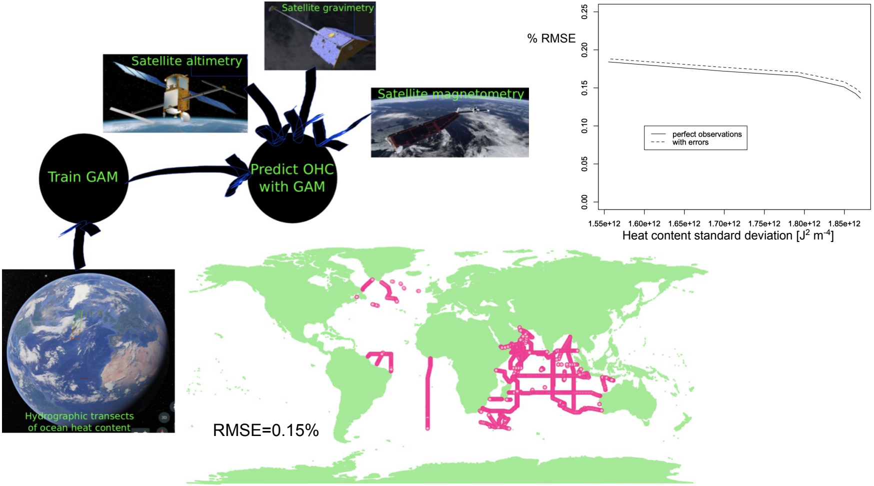
Ocean heat content can be more accurately predicted (to within 0.1% over 1992-2000) using the same predictors, but also with a function of ocean heat content in the upper 2000 meters



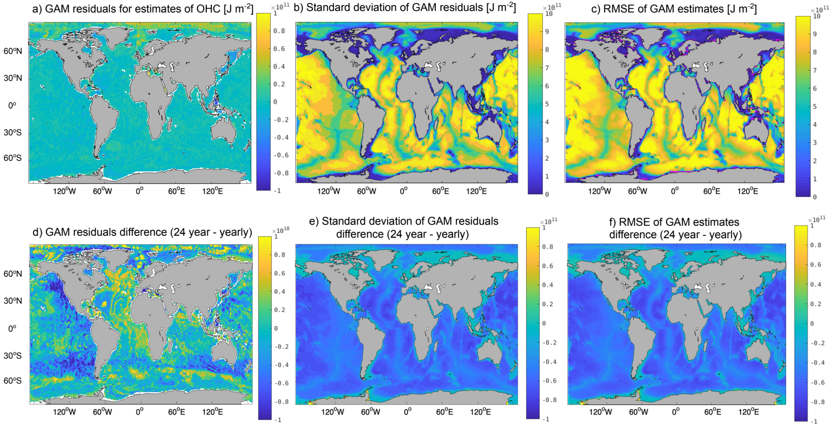
Ocean heat content is more accurately predicted using the same predictors when trained on a greater number of randomly sampled deep Argo-like floats (3% RMSE with ∼ 400 instead of increasing over time)



Ocean heat content can be accurately monitored remotely (to within 0.15% on bidecadal time scales)



Ocean heat content is still difficult to accurately monitor in many regions; training hydrographic data set needs strategic planning



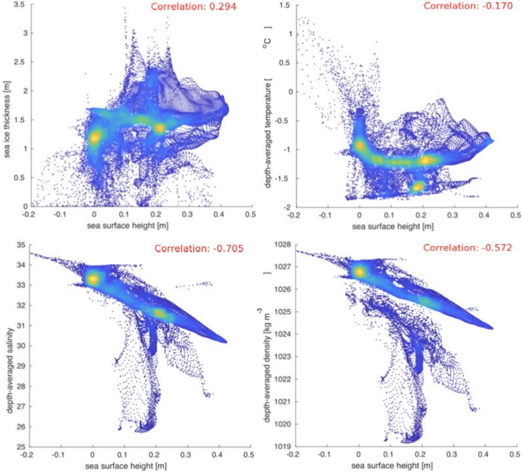
Summary

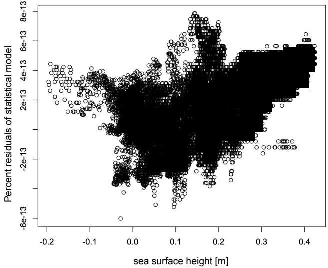
- Ocean heat content $\sim$ depth-integrated conductivity (inferred from satellite magnetometry), ocean bottom pressure (derived from satellite gravimetry), seafloor depths (inferred from various methods), and sea surface height anomalies (derived from satellite altimetry)
- Ocean heat content is more accurately predicted (even at high latitudes) by supplementing sea surface heights and bottom pressure with depth-integrated conductivity
- Ocean heat content in upper 2000 meters increases predictability of ocean heat content throughout water column, but there need to be lots of (P)ALACE/Argo floats to practically apply this
- A practical method to remotely monitor ocean heat content could use ship-based hydrographic transect (and potentially other in situ) data to train a statistical model, plugging in global satellite data

Future directions

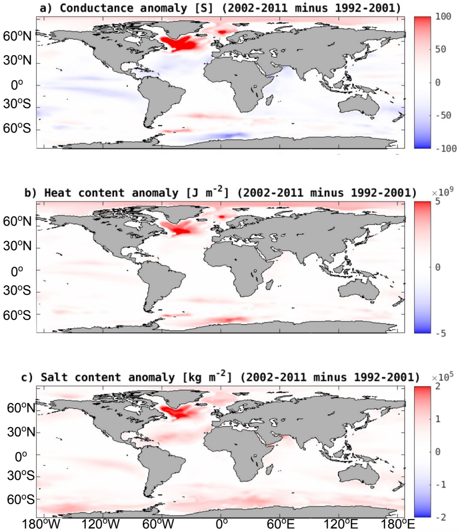
- Supplement ship-based hydrographic transect training data with deep Argo float data
- Account for errors associated with in situ and remotely sensed observations in RMSE of each estimate
- Apply the most accurate type of model to observations (trained on in situ ones and predicted using satellite ones) and compare with existing ocean heat content products
- Can this proposed remote monitoring method supplement other people's methods in particular regions where there aren't enough observations and/or insufficient resolution in reanalysis products?
- Everything shown here can be repeated for ocean heat content **anomalies**, but may be much less accurate, unless predictors' anomalies are known

One detail: what do we do about remotely monitoring sea surface heights in regions covered by sea ice?



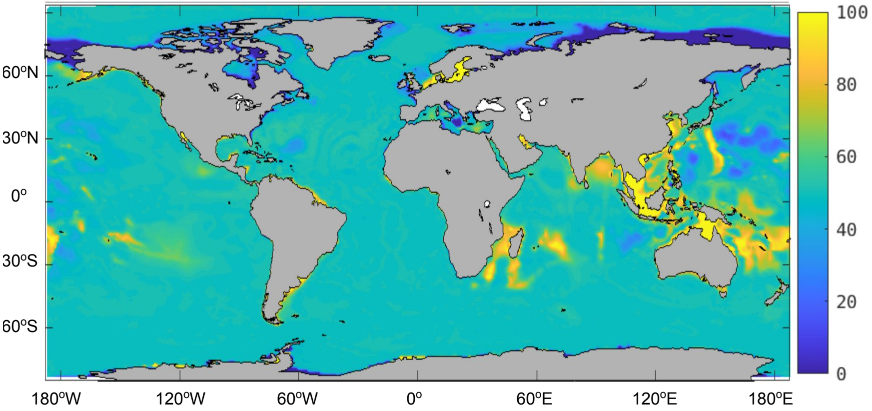


But ocean heat content anomalies are what we need to monitor for the Earth's energy imbalance



Ocean heat content anomaly is not so accurately predicted (about 30% for January of 1993) using the same predictors for ocean heat content, trained on 19 transects

Percent bias in ocean heat content anomaly based on GAM trained on deep Argo-like floats



Ocean heat content anomalies (in April of 2000 and in general) at are not as highly correlated with the same variables, with the exception of sea surface height anomalies