STRONGLY COUPLED OCEAN-ATMOSPHERE DATA ASSIMILATION

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Acknowledgements: Eugenia Kalnay, Steve Penny, Takemasa Miyoshi

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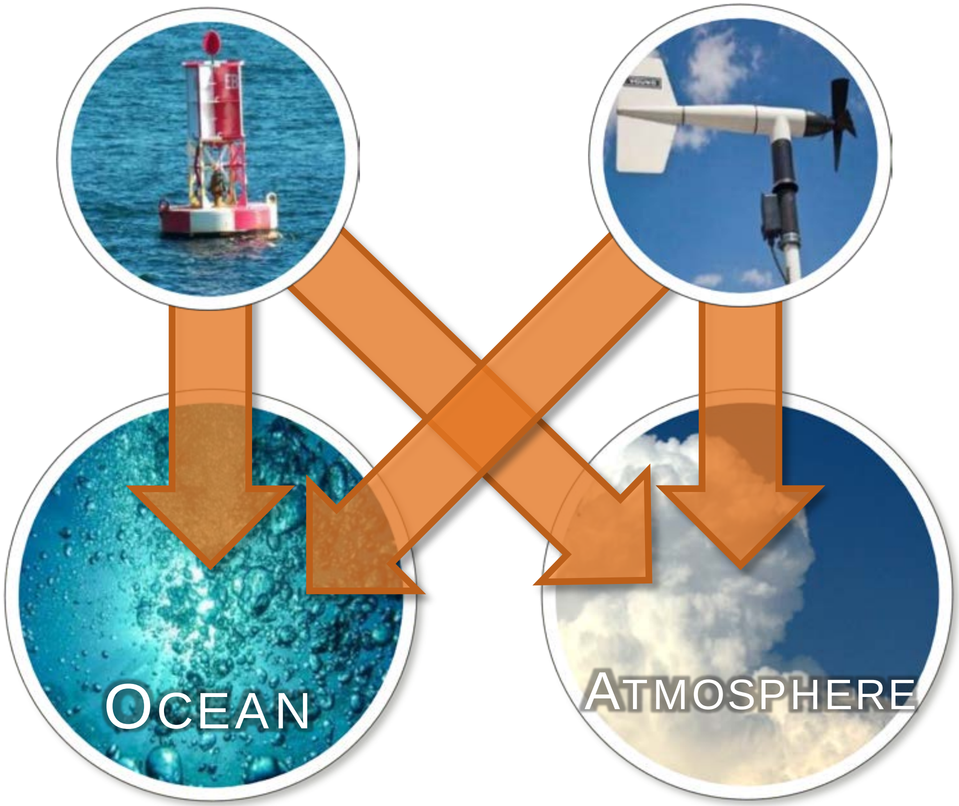
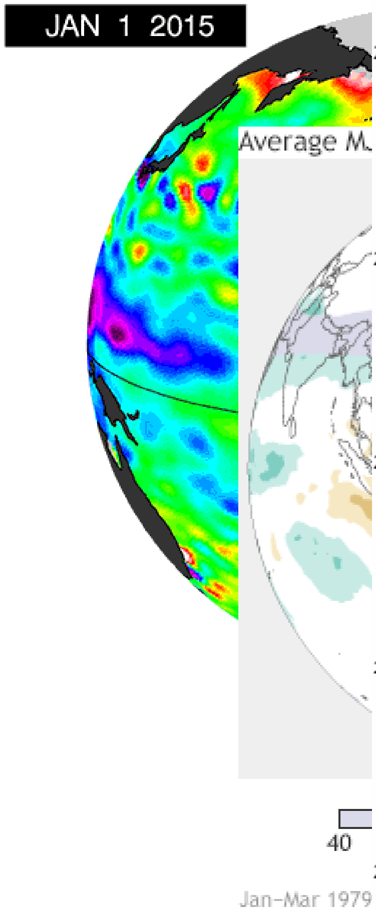
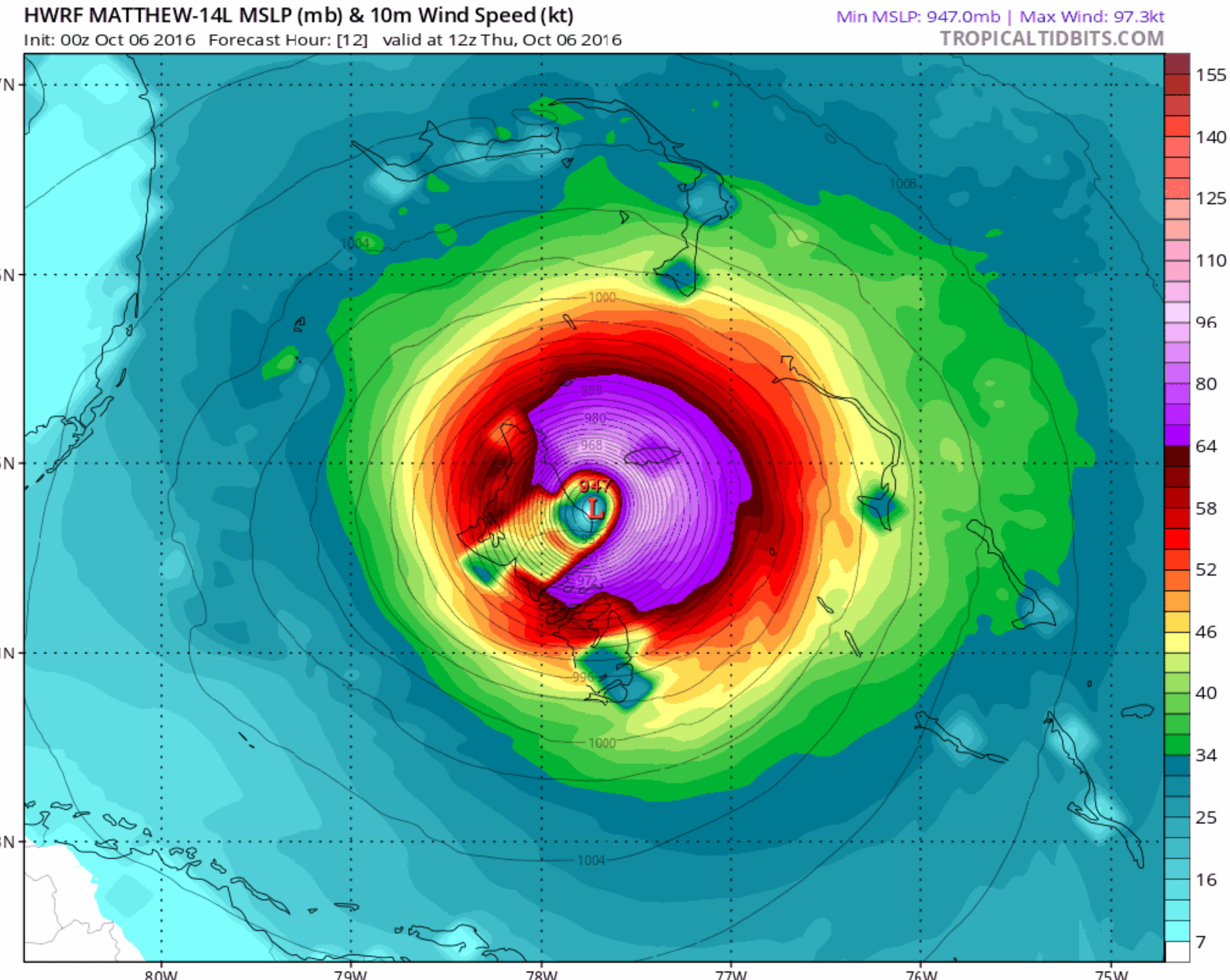
UNIVERSITY OF MARYLAND

- **Can an ocean buoy tell me something about the atmosphere?**
- **Can a weather balloon tell me something about the ocean?**



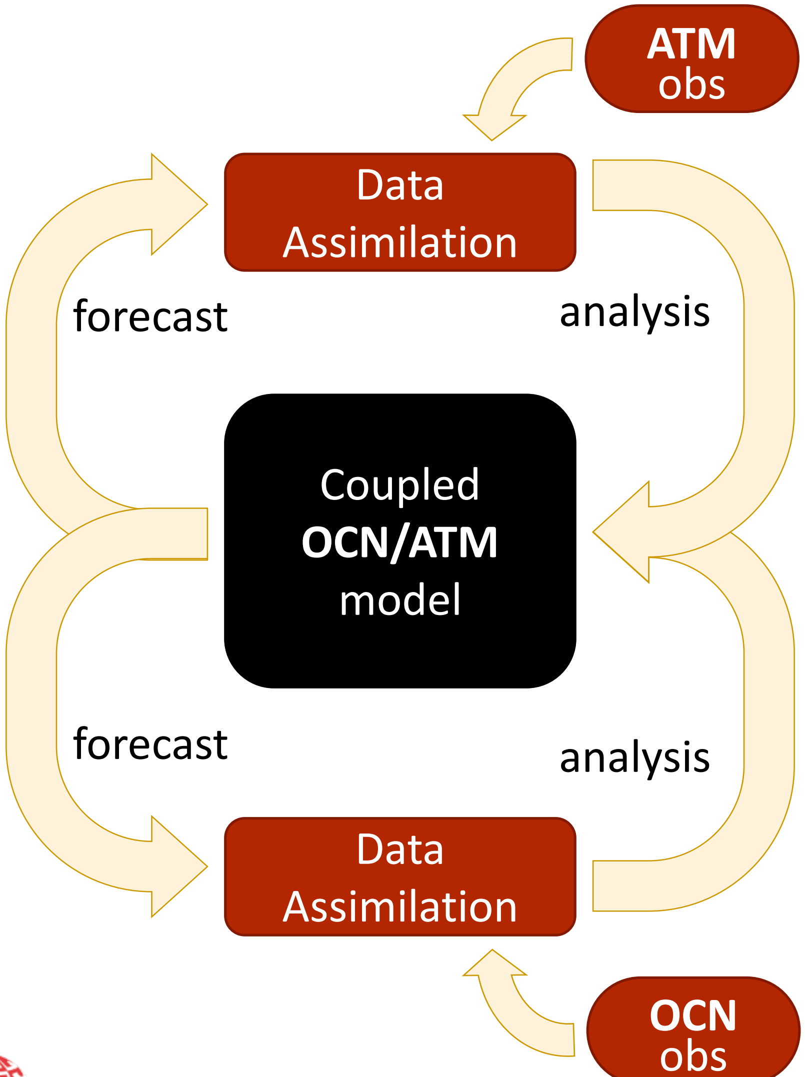
Ocean-atmosphere coupled systems





Hurricanes

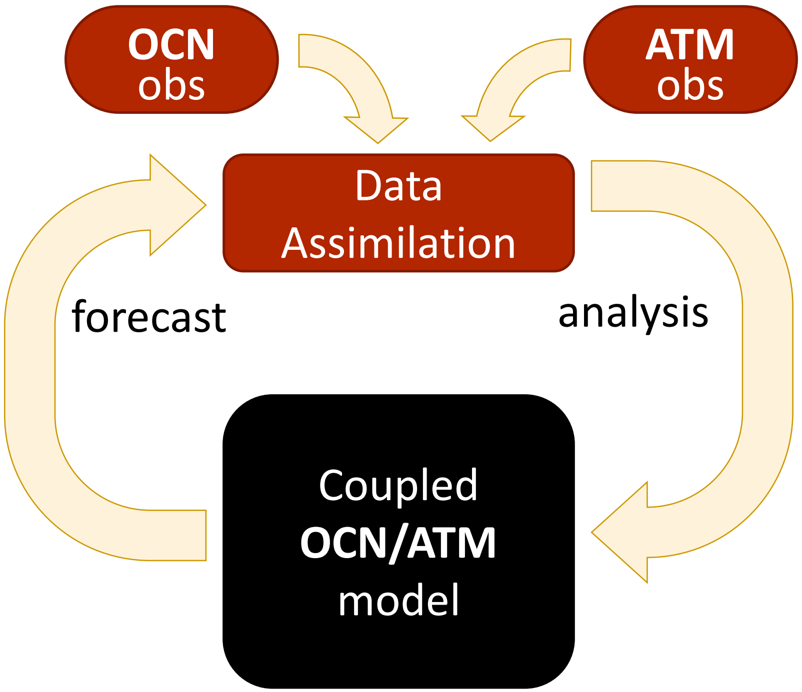
Weakly Coupled DA



A **single** coupled model generates background for **separate** DA systems. Already operational or planned at many centers.

- **EnKF**
  GFDL CDA
  (Zhang et al. 2007)
- **3D/4DVAR**
  CDAS, Met Office, ECMWF
  (Saha, 2010 Laloyaux et al., 2015; Lea et al. 2015)

Strongly Coupled DA



Studied w/ simple models:

- **EnKF**
  (Lu et al., 2015; Liu et al., 2013; Han et al., 2013; Luo & Hoteit, 2014; Tardif et al., 2013)
- **4DVAR**
  (Smith et al., 2015)

Studied w/ realistic models:

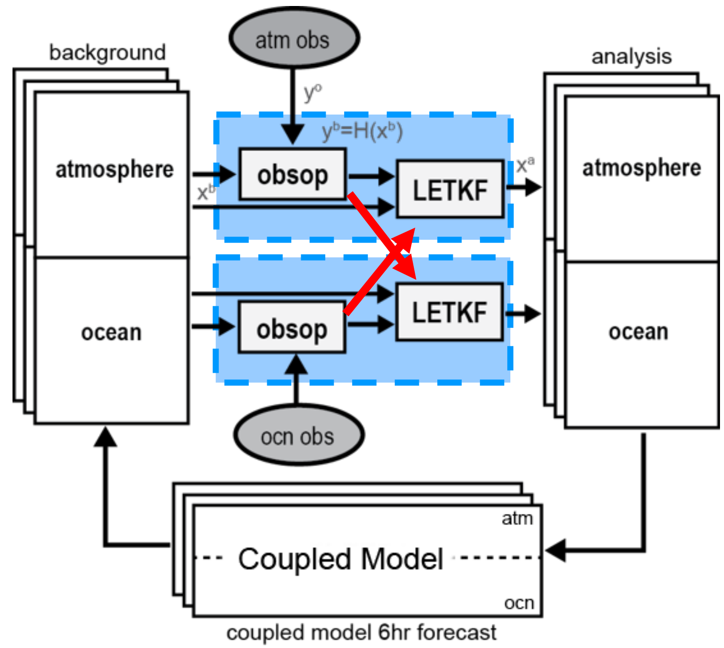
- **EnKF**
  (Lu et al., 2015)
- **4DVar**
  (Sugiura et al., 2008)
- **3D En-var**
  (Frolov, 2016)

Coupled LETKF

- Separate **local ensemble transform Kalman filter** (LETKF) for each domain helps keep implementation simpler. **Ocean LETKF and Atmosphere LETKF can be developed independently.**
- Sharing of observational departures allows system to act as single **strongly coupled** system.

EnKF has several benefits

- Don't need to develop coupled TL/adjoint
- Cross domain covariance generated automatically by the ensemble
- Assimilation can be performed at the shorter window of the atmosphere (Singleton, 2011)



Data assimilation systems, normally separate
"weakly coupled DA"

Addition of cross-domain observational departures
"strongly coupled DA"

Local Ensemble Transform Kalman Filter

Observation operator

$$\mathbf{y}^{b(i)} = H\mathbf{x}^{b(i)}$$

analysis mean

$$\tilde{\mathbf{P}}^a = \left[(k-1)\,\mathbf{I} + \left(\mathbf{Y}^b\right)^T \mathbf{R}^{-1}\mathbf{Y}^b \right]^{-1}$$

$$\bar{\mathbf{w}}^a = \tilde{\mathbf{P}}^a \left(\mathbf{Y}^b\right)^T \mathbf{R}^{-1}\left(\mathbf{y}^o - \bar{\mathbf{y}}^b\right)$$

$$\bar{\mathbf{x}}^a = \bar{\mathbf{x}}^b + \mathbf{X}^b\bar{\mathbf{w}}^a$$

analysis ensemble perturbations

$$\mathbf{W}^a = \left[(k-1)\,\tilde{\mathbf{P}}^a \right]^{\frac{1}{2}}$$

$$\mathbf{X}^a = \mathbf{X}^b\mathbf{W}^a$$

LETKF calculates analysis for each grid point in **parallel** using subset of obs around it. For **weakly coupled** DA, $\mathbf{y}$ contains only obs from its own domain. For **strongly coupled** DA, $\mathbf{y}$ contains obs from all domains.

Local Ensemble Transform Kalman Filter

Observation operator

$$\mathbf{y}^{b(i)} = H\mathbf{x}^{b(i)}$$

analysis mean

$$\tilde{\mathbf{P}}^a = \left[(k-1)\,\mathbf{I} + \left(\mathbf{Y}^b\right)^T \mathbf{R}^{-1}\mathbf{Y}^b\right]^{-1}$$

$$\boxed{\bar{\mathbf{w}}^a} = \tilde{\mathbf{P}}^a \left(\mathbf{Y}^b\right)^T \mathbf{R}^{-1}\left(\mathbf{y}^o - \bar{\mathbf{y}}^b\right)$$

$$\bar{\mathbf{x}}^a = \bar{\mathbf{x}}^b + \mathbf{X}^b\bar{\mathbf{w}}^a$$

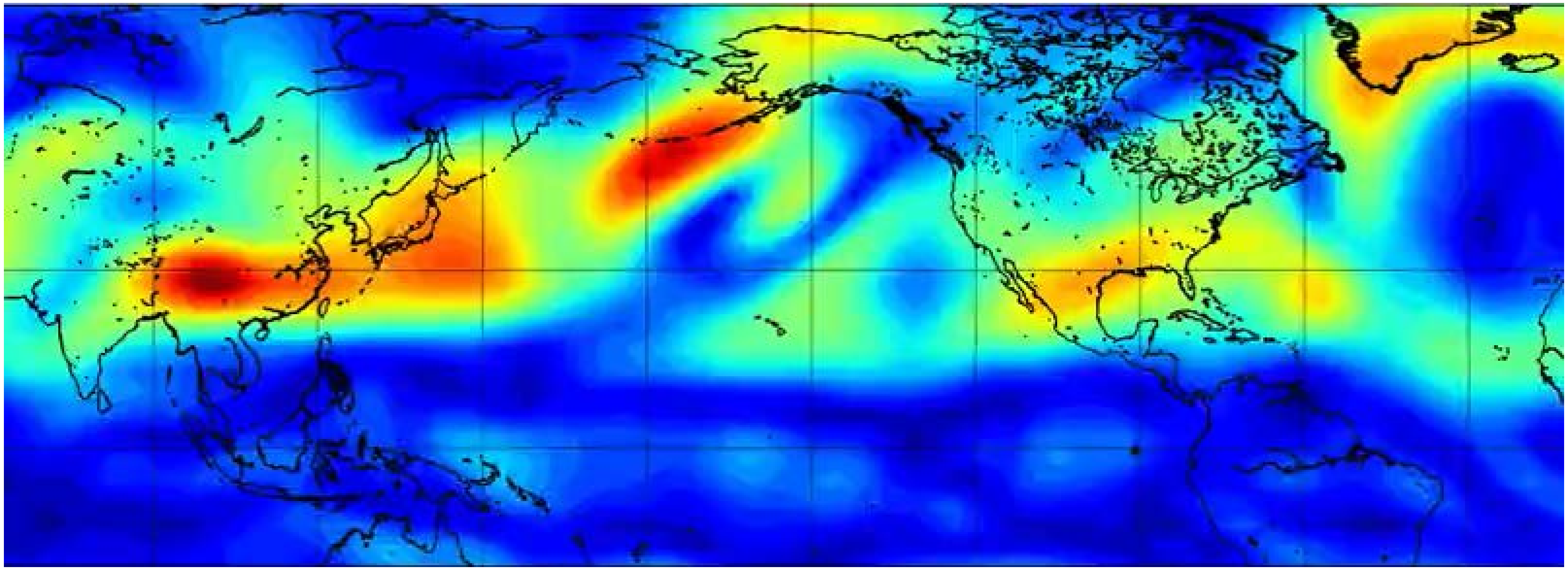
- Cross-domain observation impacts **analysis mean**

analysis ensemble perturbations

$$\boxed{\mathbf{W}^a} = \left[(k-1)\,\tilde{\mathbf{P}}^a\right]^{\frac{1}{2}}$$

$$\mathbf{X}^a = \mathbf{X}^b\mathbf{W}^a$$

- **W** varies smoothly across domain interface, allows individual ensemble members to stay “matched” together, allowing for **better balance of ensemble members**



SPEEDYNEMO nature run – **Jet Stream Winds**

SPEEDYNEMO-LETKF

Strongly coupled DA with an intermediate complexity CGCM

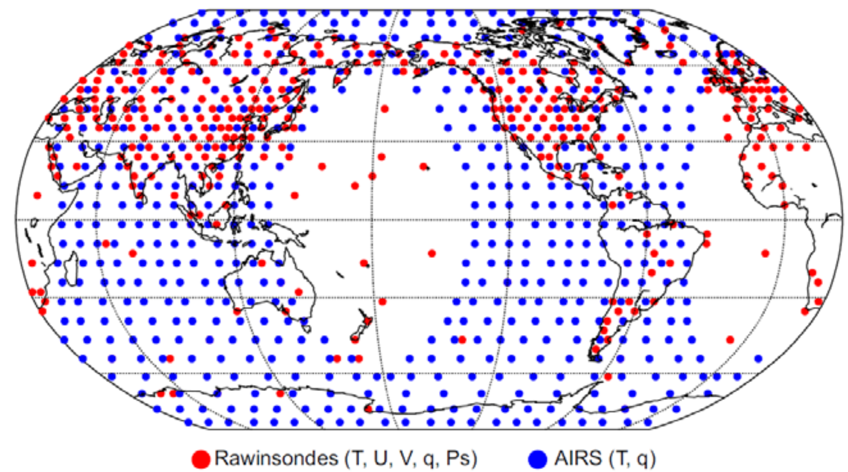
Sluka, T. C., Penny, S. G., Kalnay, E. & Miyoshi, T. Assimilating atmospheric observations into the ocean using strongly coupled ensemble data assimilation. *Geophys. Res. Lett.* **43,** 752–759 (2016).

SPEEDY-NEMO OSSE

Using the fast SPEEDY-NEMO (one year run takes only 12 hours on 1 core)

- Perfect model OSSE conducted first using **only atmospheric observations**

6 hr ATM observations



SPEEDY-NEMO

- T30 atmosphere
- 2 degree ocean
- Coupling every 6 hours

Experiment parameters

- 40 ensemble members
- Localization: 1000km Hz
- Relaxation to prior spread: 90% for OCN, 60% for ATM

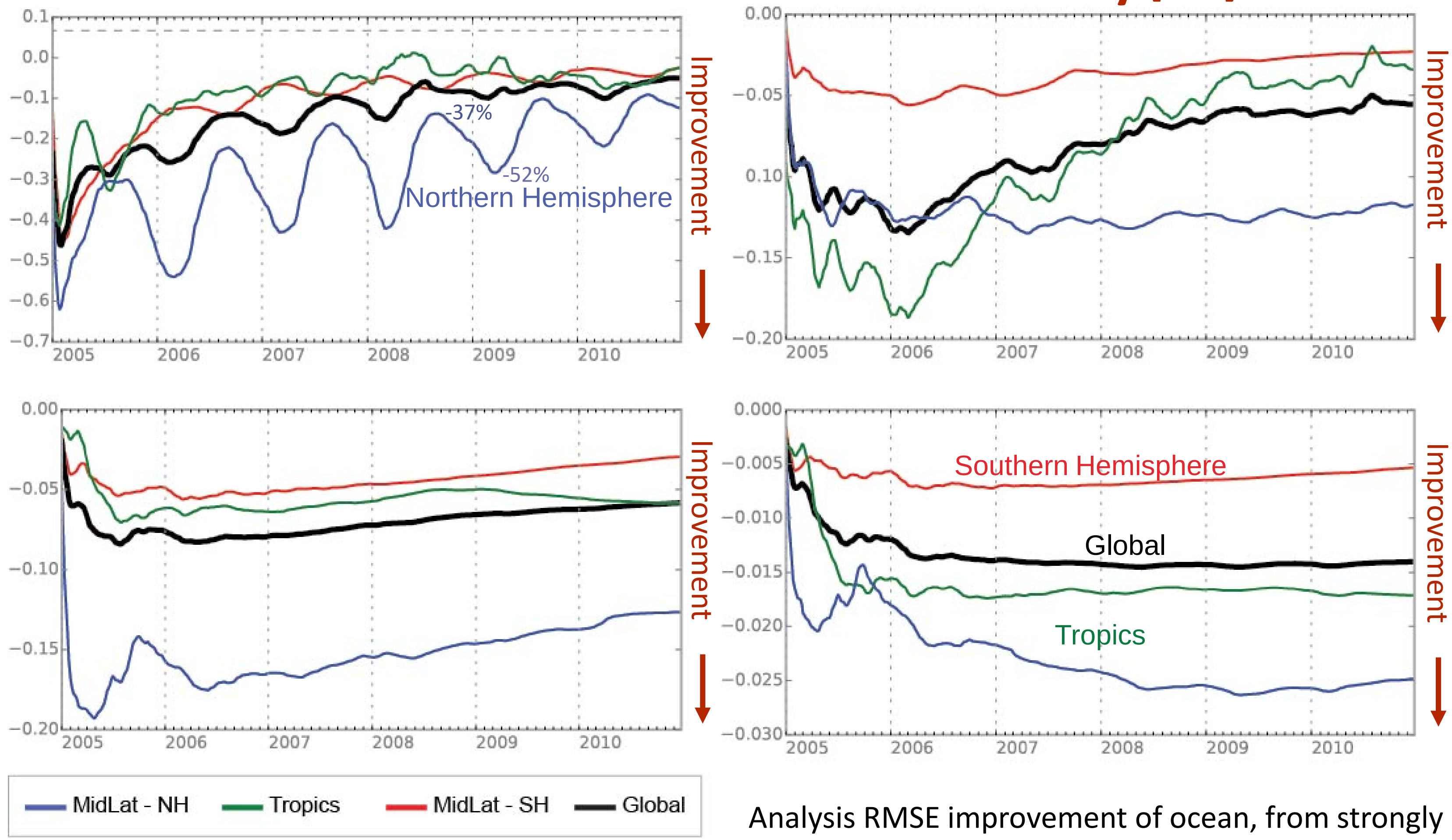
SPEEDY-NEMO Strongly Coupled DA

STRONG-WEAK analysis RMSE

Temperature [C] | Salinity [PSU]

Surface

Deeper Ocean (500m-2km)



Analysis RMSE improvement of ocean, from strongly coupled DA of simulated **atmospheric observations**

SPEEDY-NEMO Strongly Coupled DA

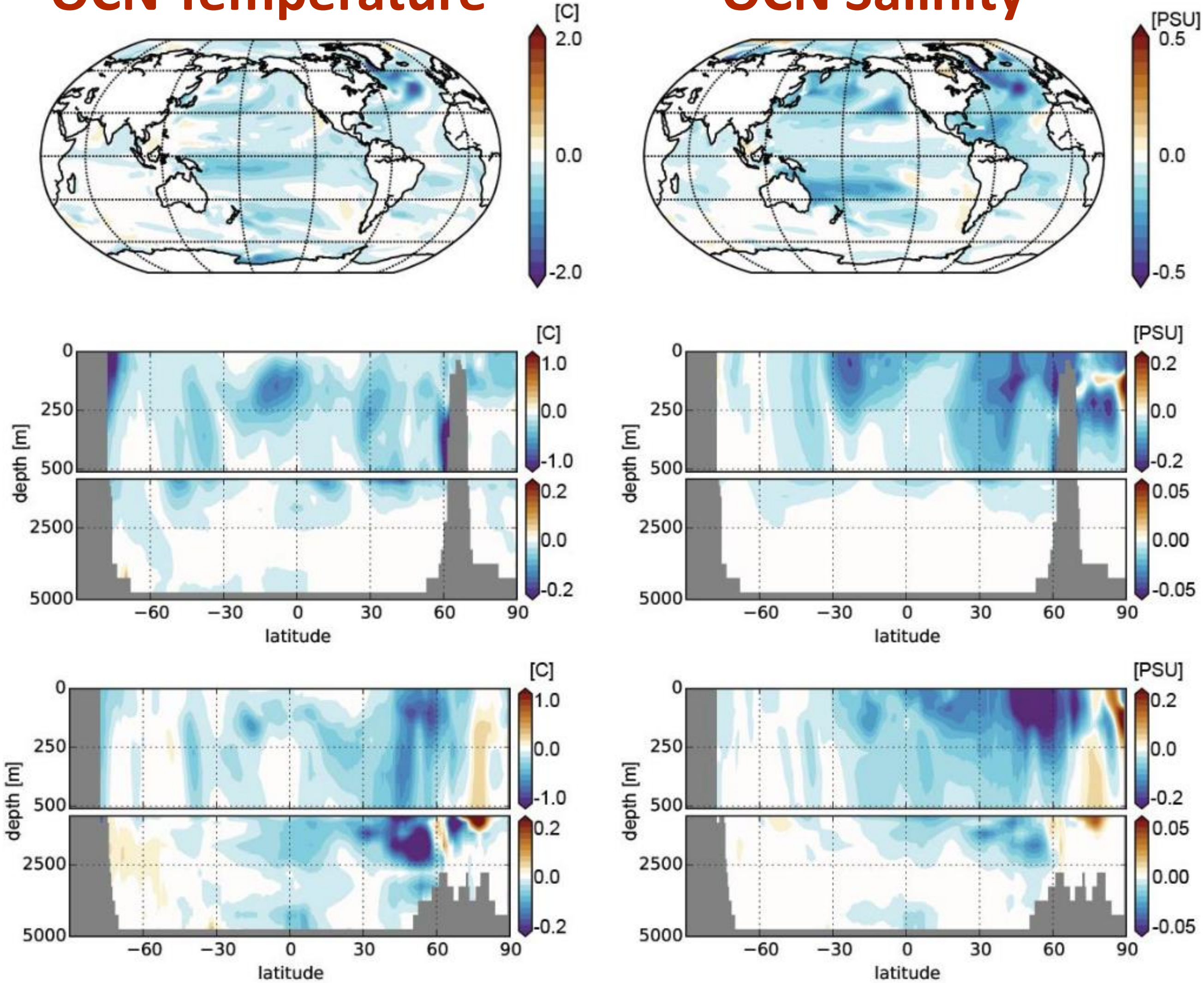
STRONG-WEAK analysis RMSE

OCN Temperature | **OCN Salinity**

Upper 500m

Pacific

Atlantic



SPEEDY-NEMO Strongly Coupled DA

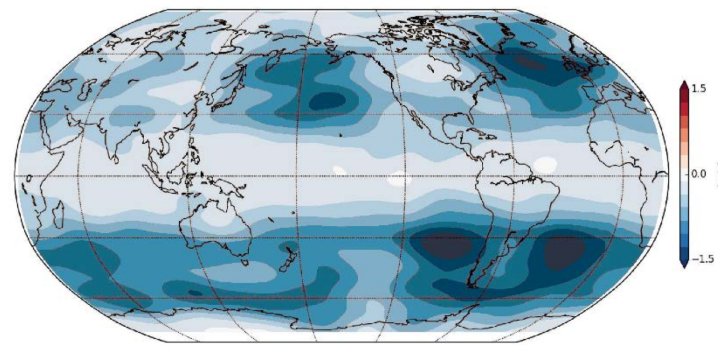
STRONG-WEAK analysis RMSE

- The opposite experiment (assimilating OCN obs into the atmosphere) shows improvement as well
- A possible latitudinal dependence on cross domain impact?

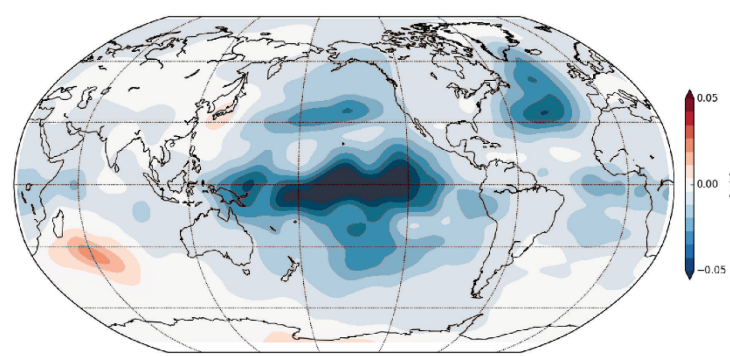
STRONG-WEAK, (blue is good)

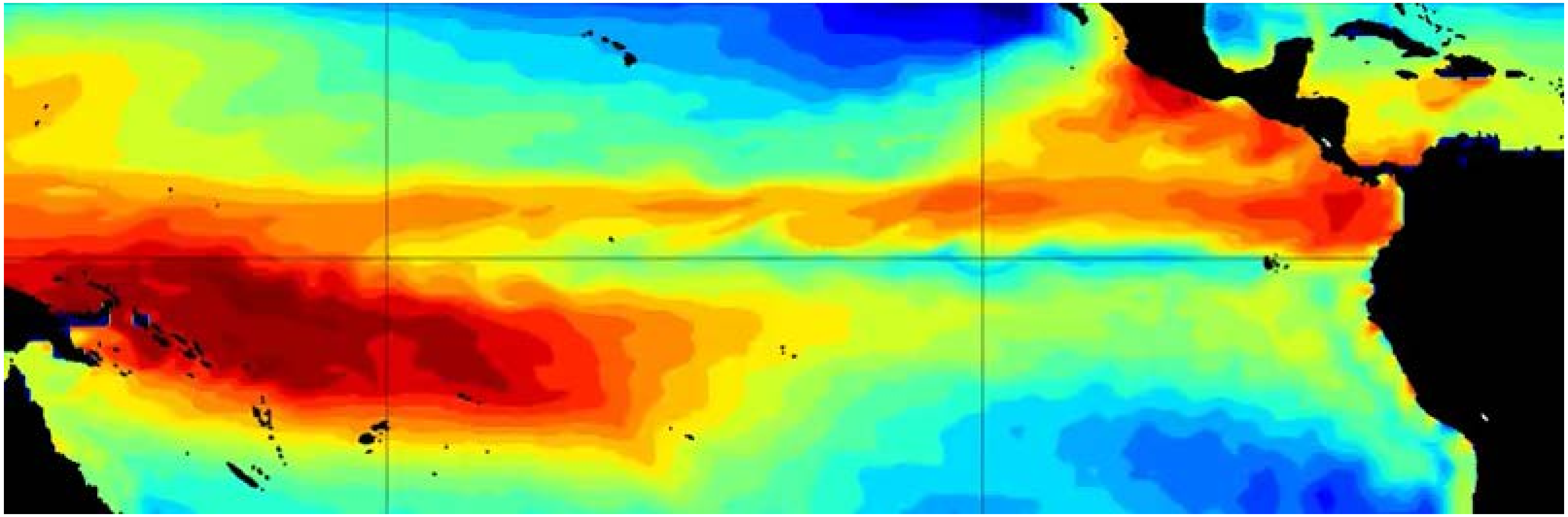
atm U

Ocean Observations



Atmosphere Observations





CFSv2 - **SST**

CFSv2-LETKF

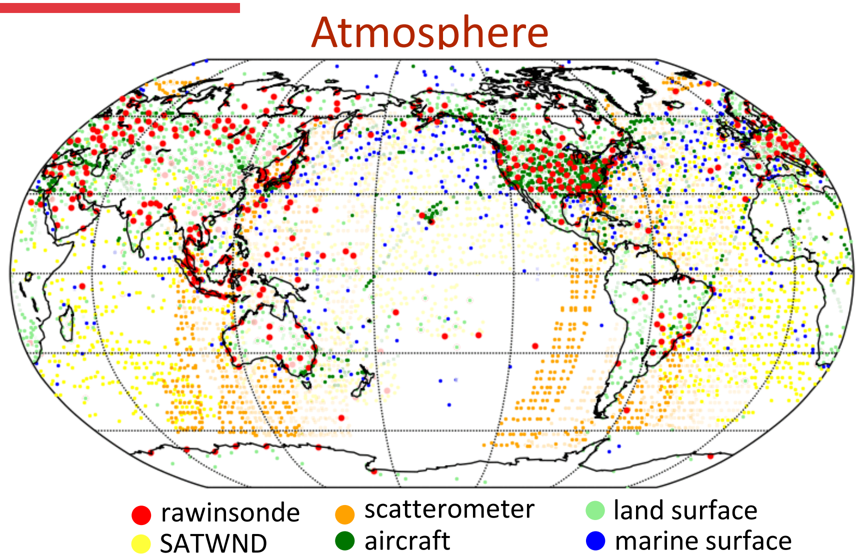
Strongly coupled data assimilation with the Climate Forecasting System v2, using real observations

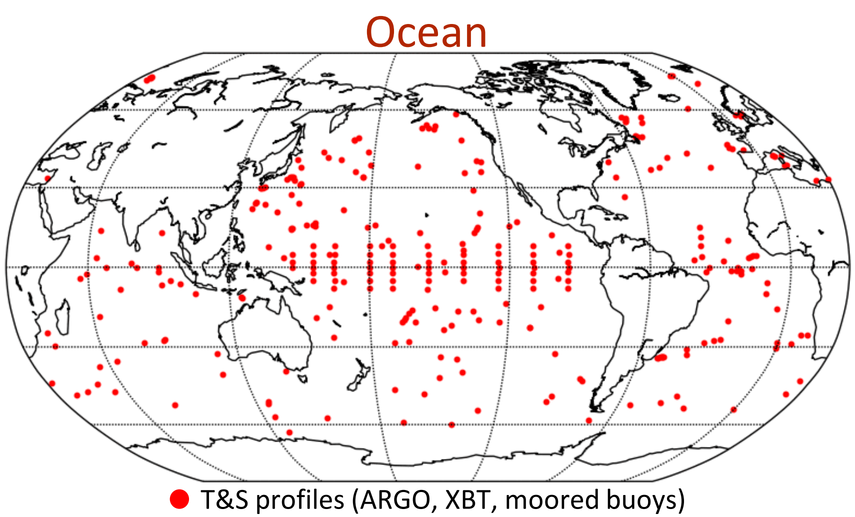
CFSv2-LETKF

- Combined **existing** GFS-LETKF (Lien, 2013) and MOM-LETKF (Penny, 2013)

- T62/L64 atm 0.5deg ocn (reduced resolution ATM)
- 50 member ensemble (initialized from CFSR, run freely for 6 months to develop sufficient spread)

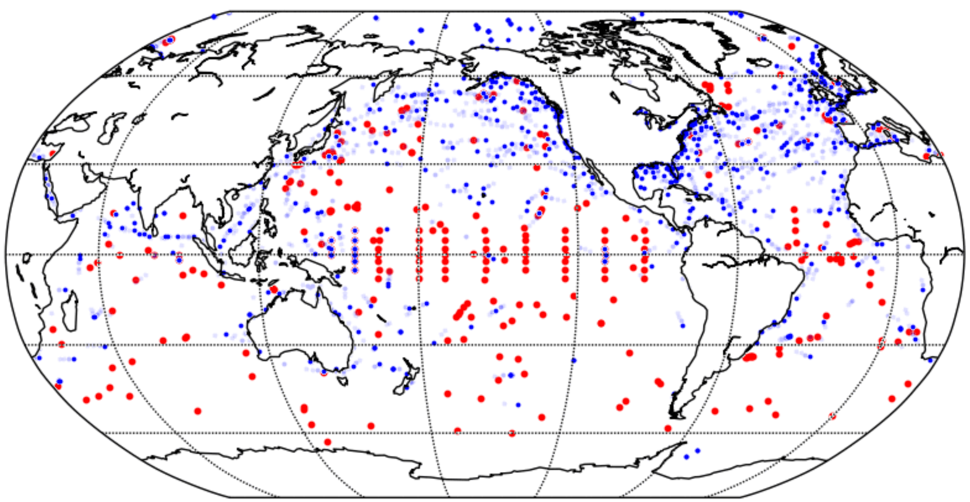
- observations from operational ATM PREPBUFR and OCN profiles used by GODAS





Strongly coupled DA

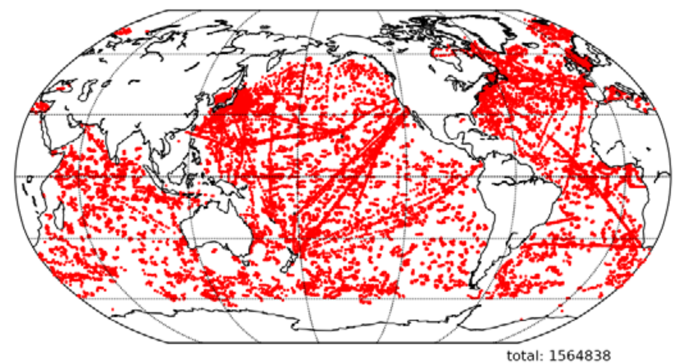
- 1 way strongly coupled DA
- Strongest cross correlations are between OCN_T and ATM_T/ATM_q, so…
- OCN assimilates surface marine T and q as well, given by the **SFCSHP** section of the PREPBUFR



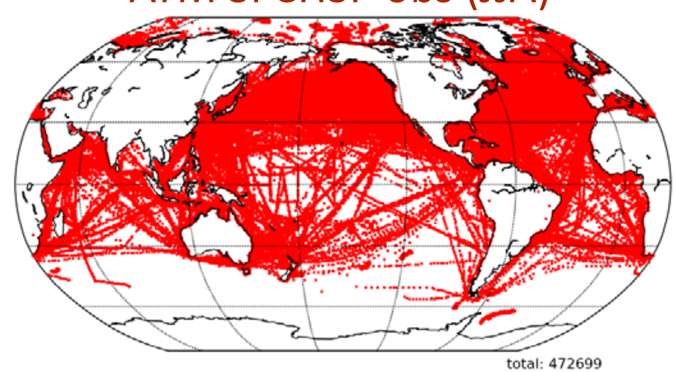
ocn profiles (argo, XBT,…)

ATM SFCSHP T&q

OCN obs (JJA)



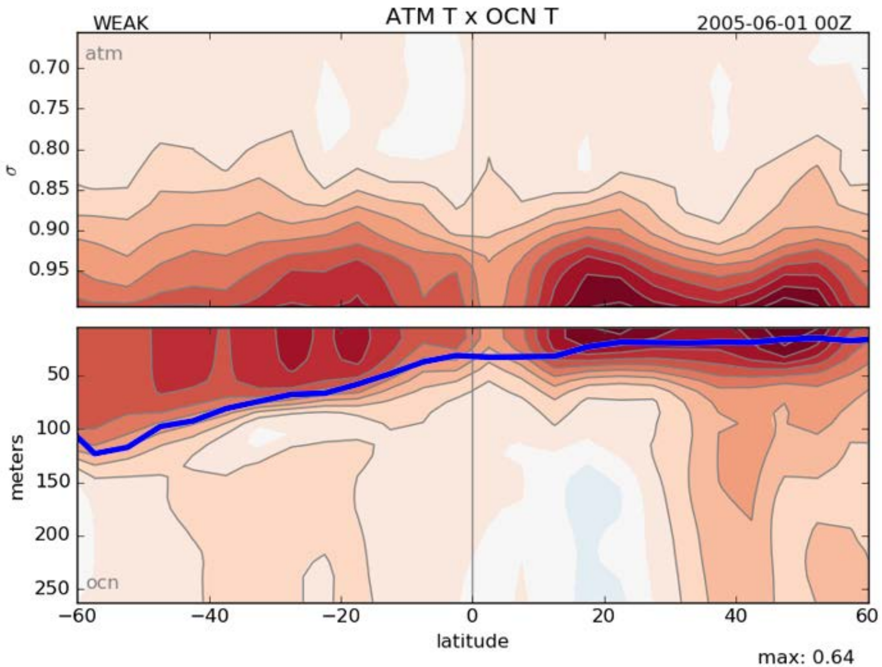
ATM SFCHSP obs (JJA)



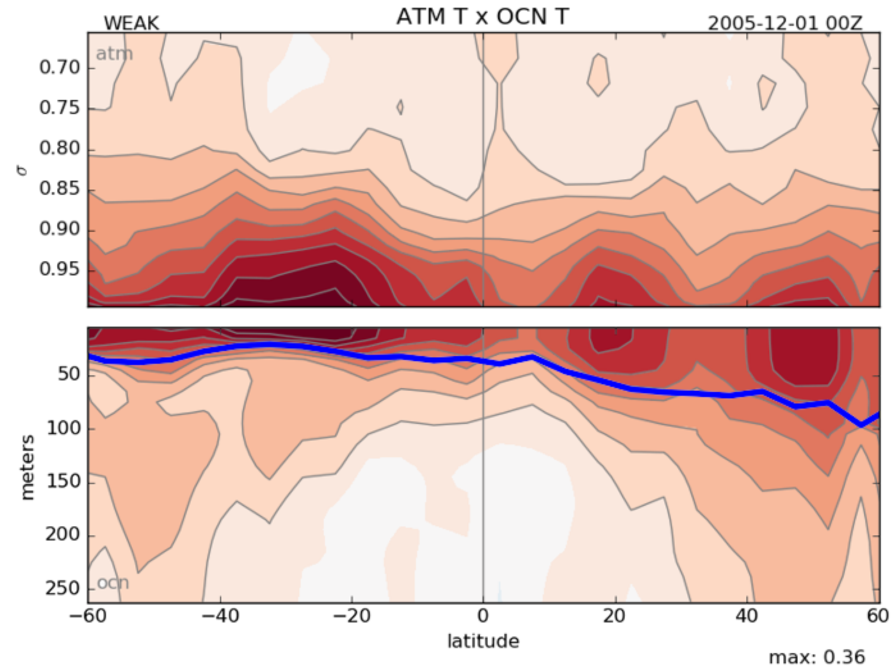
Weakly Coupled DA – cross covariances

- Cross correlations given by the ensemble for a single date
- ATM and OCN temperature max correlation of 0.36, highest values in that hemisphere's summer, below 850mb and above top of thermocline
- June values likely artificially large do to insufficient spin up time for the ocean

June



December



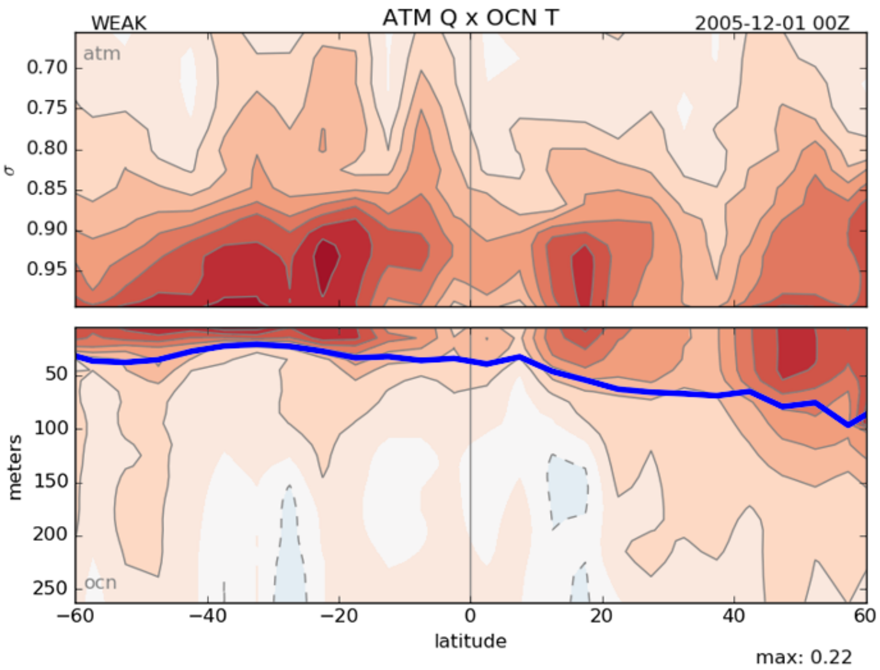
Mixed Layer depth (depth of $T_{10m} \pm 0.2$°C)

Weakly Coupled DA – cross covariances

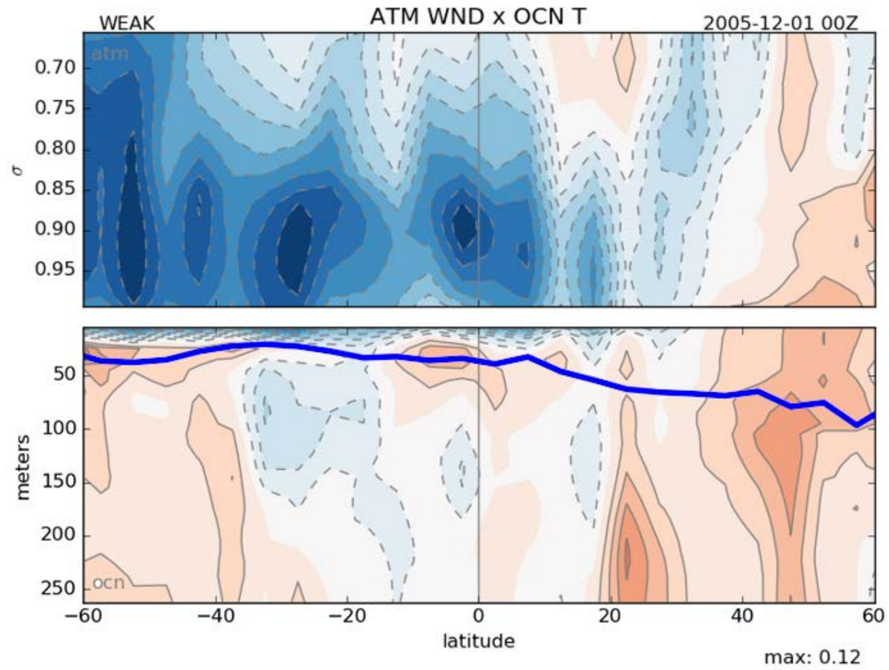
- ATM_Q x OCN_T correlations weaker, though same pattern as ATM_T x OCN_T
- Increase in windspeed correlated with decrease in surface temperature

- These are the correlations LETKF will be using…

Humidity



Windspeed



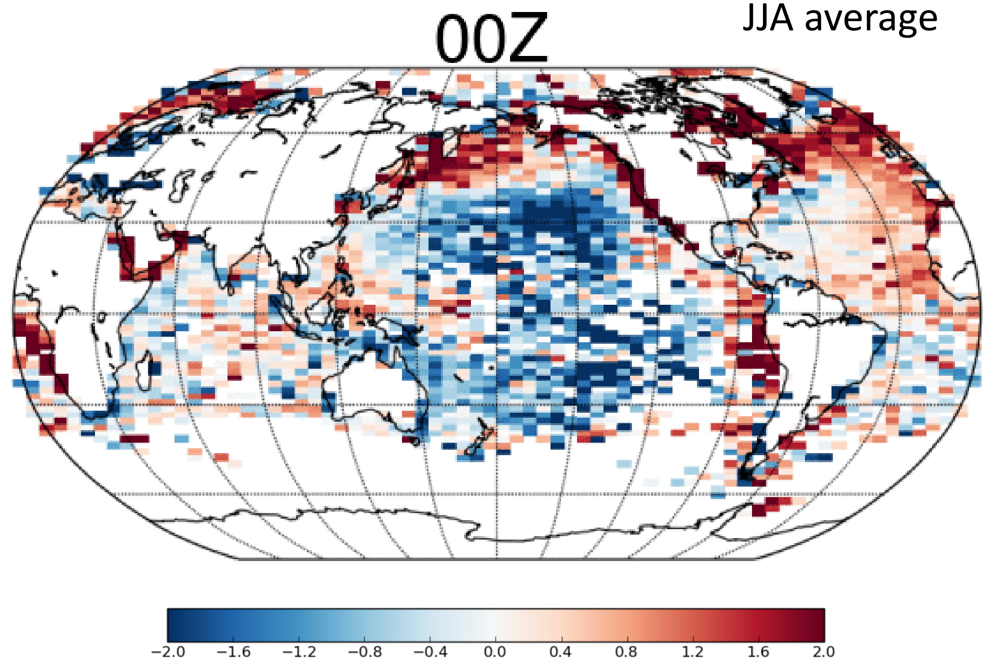
Mixed Layer depth (depth of $T_{10m} \pm 0.2$°C)

SFCSHP T bias

- Known diurnal bias in SFCSHP T, is a problem (sensors placed over warm deck of a ship, no NSST in model)
- also visible in MERRA2 reanalysis *(Carton, personal comm)*
- Still, there are areas of persistent bias of same sign, caused by SST bias in our weakly coupled run, which strongly coupled DA should improve upon

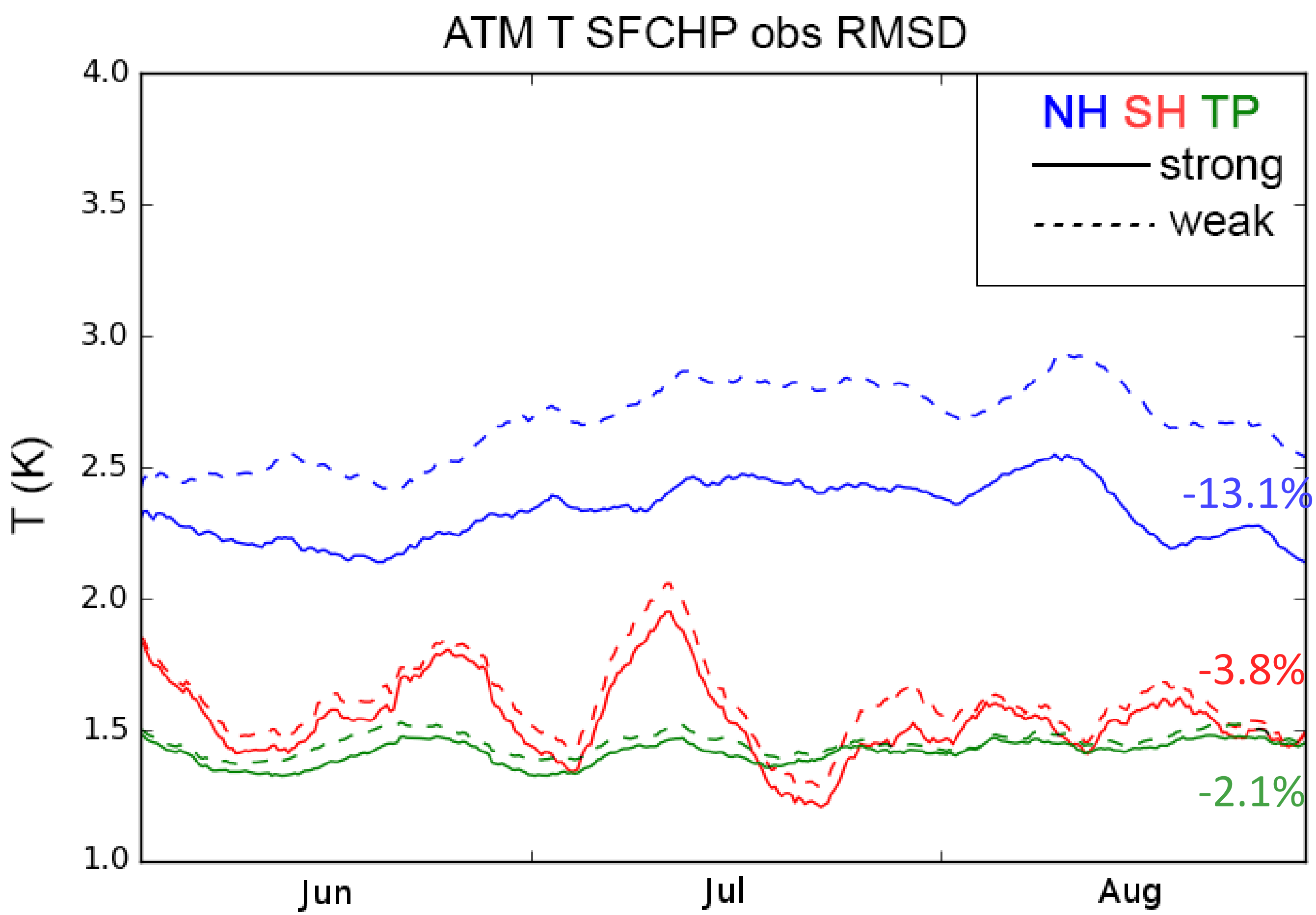
B-O using SFCSHP T

JJA average



Strongly Coupled CFS - results

- Errors in 6 hour background for ATM T are greatly reduced in the NH

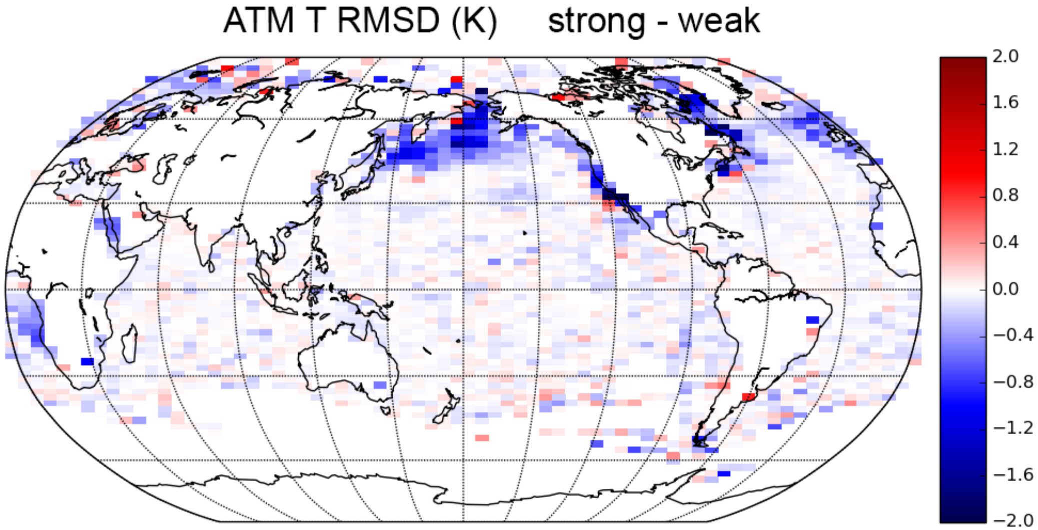


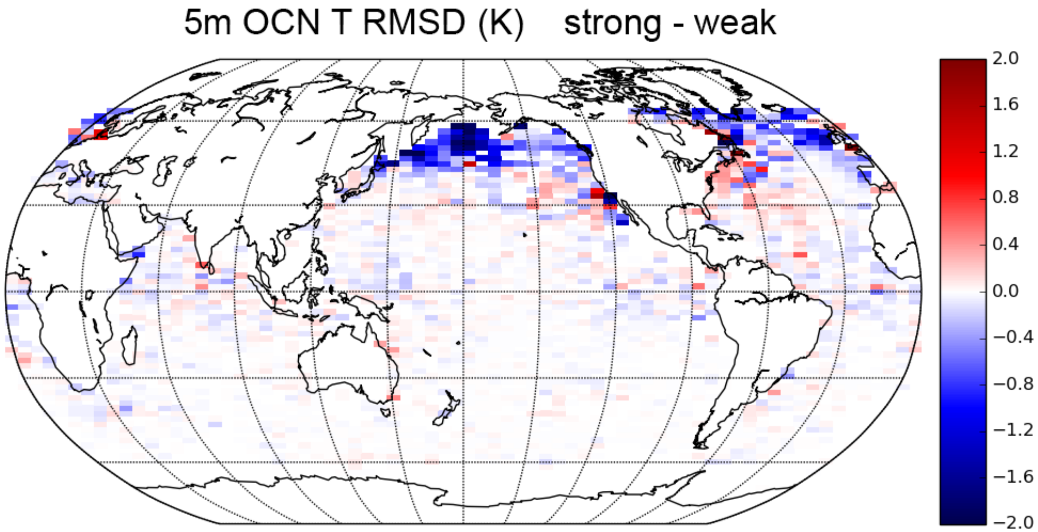
Strongly Coupled CFS - results

- Strong improvement in both ATM and OCN in NH
- Some problems immediately near coast of NA

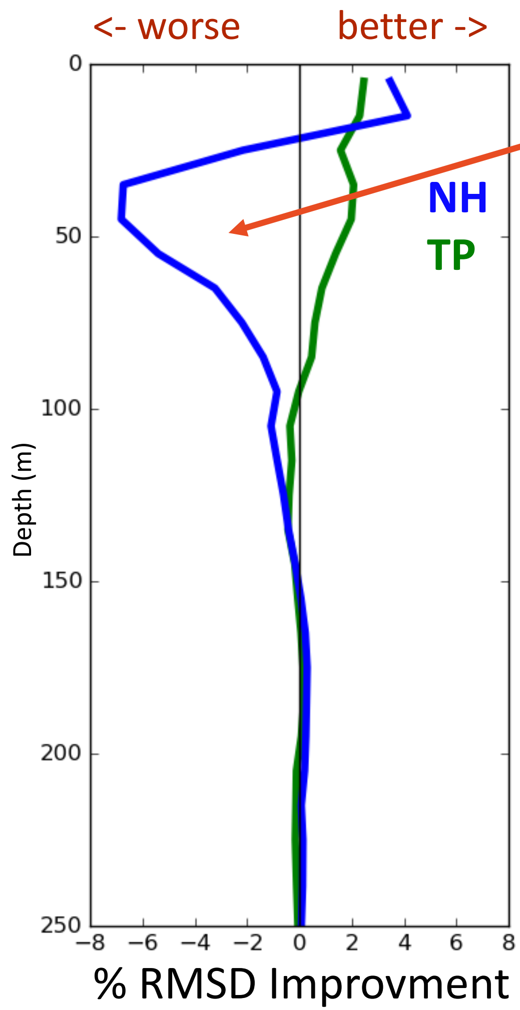
observations too close to land should probably be excluded

Low resolution of ATM likely causing problems near gulfstream

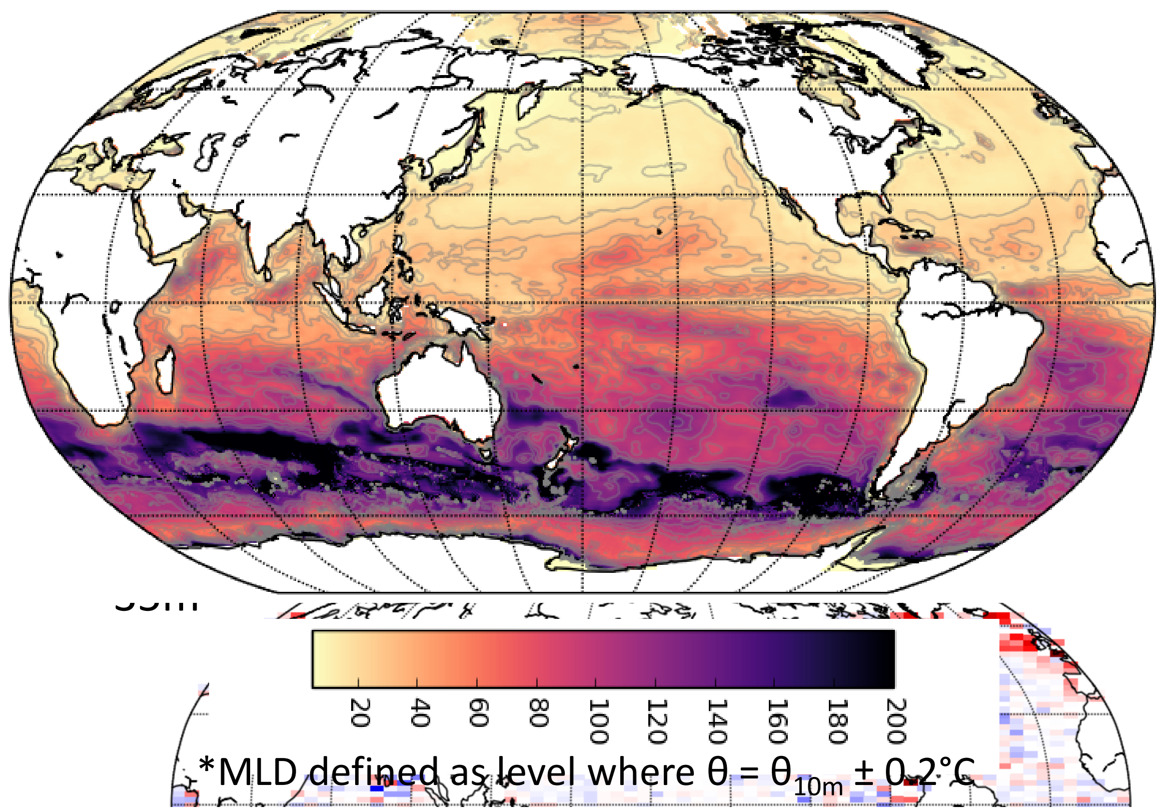




Strongly Coupled CFS - results



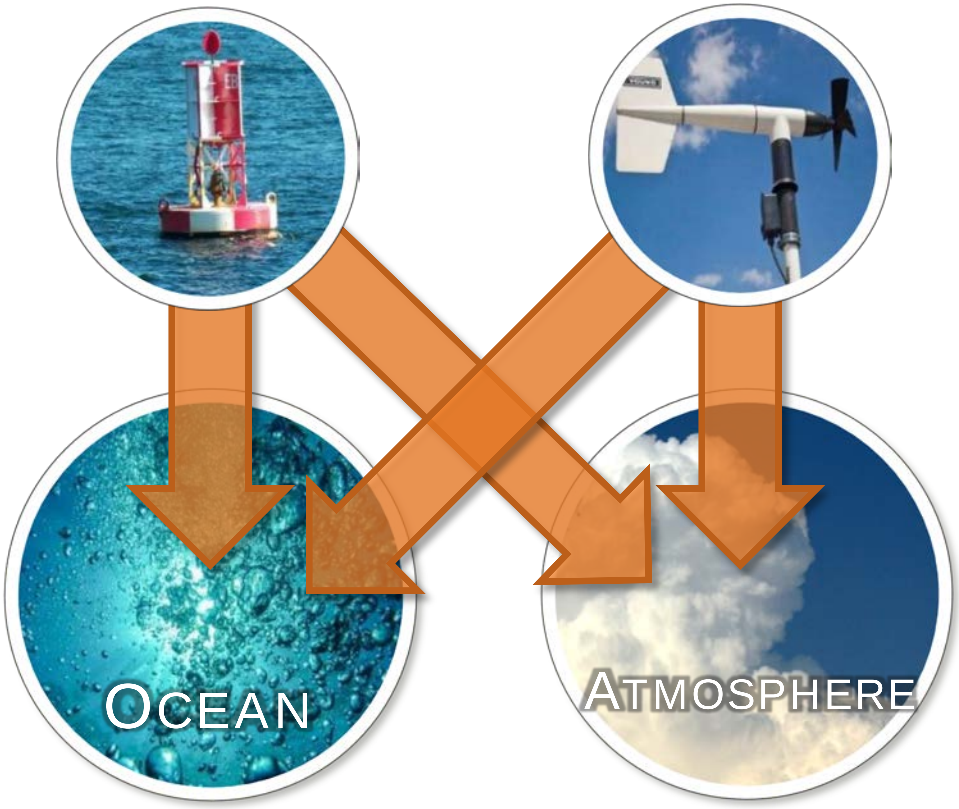
Caused by naïve fixed vertical localization of ATM observations into ocn (σ=50m), need to limit impact to mixed layer only



*MLD defined as level where $\theta = \theta_{10m} \pm 0.2°C$

- **Can an ocean buoy tell me something about the atmosphere?**
- **Can a weather balloon tell me something about the ocean?**

YES!



Ultimate Goal…

- At NCEP, developing Hybrid DA for ocean (LETKF + observation space 3DVar with static ensemble covariance) could enable SCDA for UGCS (next CFS)?
- Strongly coupled 20CR