ATMOSPHERE-OCEAN COUPLED DATA ASSIMILATION USING NASA-GEOS:
ESTIMATION OF AIR-SEA INTERFACE STATE VARIABLES

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Coupled Data Assimilation (1)

State Vector: \( x = [X_A, X_I, X_O]^T \)

- \( X_A \): Prior (background) cost:
  \[
  J_b = \frac{1}{2} (x^b - x)^T B^{-1} (x^b - x)
  \]

- \( X_I \): Likelihood (observational) cost:
  \[
  J_{obs} = \frac{1}{2} (y - H[x])^T R^{-1} (y - H[x])
  \]

- \( X_O \)

\( X_a = \min_x J_b + J_{obs} \)

Strongly Coupled Analysis
Strongly Coupled Analysis seems simple and straightforward to implement!

Why?
1. Dimension of (3-D atm, ocn + 2-D int) $X$
2. Covariance model for $B$
3. Sparsity of observations (ocn, int: surface) $Y$

Alternatively (or iteratively), solve for:
- Component states (atmosphere, ocean, …) separately
- Use already existing analyses
  - Different flavors of weakly (not strong!) coupled analysis
  - Which component is solved 1st? Atmosphere $X_A$ or Ocean $X_O$?
  - How is the interface state $X_I$ handled?
  - How realistic are the cross-correlations: $B_{AO}, B_{AI}, B_{OI}$; $H[\cdot]$
At the GMAO, we acknowledge the (future potential/need for) Strongly Coupled Analysis…

- As a first step, our first Coupled Analysis will be (weakly) coupled via interface state variables:
  - Sea Surface Temperature (Skin SST) $T_s$
  - Sea Surface Salinity (Skin Salinity) $S_s$
  - Sea Ice, etc

- All developments will naturally carry over to the future work
Air-sea Interface

Interface is complicated!

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CURRENT STATUS

OSTIA SST

http://ghrsst-pp.metoffice.com/

AQUARIUS SSS

NSIDC

https://aquarius.umaine.edu/cgi/gal_salinity.htm
But there are NO sensors to observe at these resolutions!

- How *real* are these data products?
- Do they capture all the scales of motion at which they are released (OSTIA SST “resolution” 0.05 deg)
- These are daily (weekly-SSS) products, but surface moves FAST!
- They are **NOT** observations!
SST OBSERVATIONS (2)

Spaceborne

In-Situ

Satellites DO NOT measure SST!

http://images.remss.com/amss/amss2_data_daily.html

JCOMMOPS
SST OBSERVATIONS

- Satellites measure radiance
- Which relates to physical variables via radiative transfer in the atmosphere H[.]

**Diagram Details:**
- IR, MW radiometer
- Skin Layer
- Ocean
- Depth
- Night-time, strong winds (well mixed)
- Daytime, light winds
- Cool skin layer:
  - dTc
- Warm layer:
  - dTw
- T - Tb
- Ts = air-sea interface (approx)
- Tb = skin-layer base temp

**Graphical Elements:**
- Atmosphere
- Skin Layer
- Ocean

**Notes:**
- ~15 micron
- ~1 mm
- ~2 m
- Cool skin layer: dTc
- Warm layer: dTw
Surface temperatures greater than 3.0 K, referenced to subsurface temperatures below the extent of surface heating, are not uncommon and may persist for hours [Kawai and Wada, 2007; Minnett, 2003; Yokoyama et al., 1995].

Even larger amplitude of diurnal warming (up to 4–6 K) have been reported in several studies [Flament et al., 1994; Merchant et al., 2008; Stramma et al., 1986; Ward, 2006]. Failing to account for diurnal cycle in SSTs leads to errors in determining surface fluxes for numerical weather prediction (NWP) and climate models [Webster et al., 1996; Woods et al., 1984].

Tropical atmospheric circulation is sensitive to relatively small changes in SSTs [Palmer and Mansfield, 1984; Shukla, 1998] affecting local atmospheric convection [Chen and Houze, 1997] and SST variability in this region is important to understanding climate change.

There is increasing interest in including satellite-based retrievals of SSTs in the historical record for climate applications. Satellite data can provide much needed measurements in remote or data-sparse regions and often lead to a more realistic representation of the spatial and temporal structure of seasonal and interannual variability and an improved reconstruction of global SST. NWP, climate, and mesoscale oceanography require remotely sensed SSTs with an accuracy of 0.1–0.3 K [GOOS Implementation Advisory Group (IAG), 1999].

Since diurnal warming of the ocean surface can reach amplitudes of 3.0 K or more, an improved understanding of diurnal warming is necessary to meet these temperature accuracy requirements. Blending SST retrievals made at different depths and different times of the day also requires a model of diurnal variability [Donlon et al., 2007]. Additionally, since diurnal warming affects the temperature of the ocean surface which is in direct contact with the atmosphere, improved estimates of diurnal warming will lead to better estimates of air-sea heat and gas fluxes.

2. Background

Stommel [1969] and Stommel and Woodcock [1951] took some of the earliest measurements of diurnal warming in the ocean. Profiles of upper ocean temperature were taken with a bathythermograph in the Gulf of Mexico, in April 1942, revealing wave-like variations in the upper ocean heat content. In March 1968, the R/V Chain deployed a number of Salinity-Temperature-Depth (STD) profilers with the goal of examining diurnal warming. The cruise took place in the southwest North Atlantic Ocean. Insolation was measured with an Eppley Laboratory pyrheliometer. By 9:30 Local-Mean-Time (LMT), a diurnal warm layer was observed; it continued to grow to 0.9 K by 14:15 LMT and then began to decay. The depth of the diurnally heated layer extended to 12 m. Stommel reported classical cooling from the surface where isotherms relaxed toward vertical and the warm layer deepened until all evidence of the warm layer was erased. Using the 1-D heat equation, he was able to roughly balance the radiative forcing with observed heating in the warm layer. Several other early measurements of diurnal warming were also focused on calculating the heat content [Delnore, 1972; Halpern and Reed, 1976; Kaiser, 1978].

Measurements have shown that the vertical profile of diurnal warming in the upper ocean is highly variable [Minnett and Ward, 2000; Ward, 2006] and therefore models developed from in situ measurements at depth may not fully describe the variability at the ocean surface skin layer. The validity of both the theoretical and empirical models in the skin layer has been explored by a limited number of studies.
Model the variation of Skin SST = OSTIA SST + ΔT_w - ΔT_c

- thermally stratification due to diurnal warming (ΔT_w)
- a thin cool-skin layer (ΔT_c)

Direct radiance assimilation for Skin SST $H[\cdot]$ 

- additional Infrared (AVHRR) satellite observations
- using radiative transfer model

Operational since 01/2017

Background error details follow…
Skin SST in GEOS DAS (2)
Improved forecast skill in SH; diminishes with height

S Hem- 500 mb geopotential height

Neutral in NH

S Hem- 1000 mb temperature

Improved forecast skill in SH; diminishes with height
Assimilation for skin SST in the NASA GEOS atmospheric data assimilation system
Current Work
**BACKGROUND ERROR FOR $T_s$**

Hybrid Analysis for $T_s$ using:

- **Deterministic (central):**
  - *Persistent, large-scale errors*

- **Probabilistic (ensembles):**
  - *Flow dependent, small-scale errors*

**Without** the $T_s$ model:

- For all ensemble members, $T_s = \text{OSTIA SST}$
- Ensemble generated covariance $B_e(T_s) \approx 0$

\[
B = \begin{bmatrix}
B_{AA} & 0 \\
0 & B_{II}
\end{bmatrix}
\]
**BACKGROUND ERROR FOR $T_s$**

**Improved Global Sea Surface Temperature Analyses Using Optimum Interpolation**

RICHARD W. REYNOLDS AND THOMAS M. SMITH

National Meteorological Center, NWS, NOAA, Washington, D.C.

Manuscript received 10 November 1992, in final form 29 August 1993

Derived ~1994 using a very-sparse SST observation network

- Long correlation length-scales (400-950Km)
- Over-confident $\sigma_b : 0.25 - 0.6^\circ C$
Hybrid analysis for $T_s$

Monthly mean of increment (ANA-BKG) 12UTC (December, 2017)

Increments:
- Very smooth
- Long correlations

Currently we use the deterministic analysis increment only, because…
HYBRID ANALYSIS FOR $T_s$

BKG
mean/sdev

ANA
mean/sdev

ANA-BKG
mean/sdev

Ensemble
(2018/01/31 06UTC)
HYBRID ANALYSIS FOR $T_s$

- Ensembles won’t fix this issue!
- An ensemble of analyzed ocean states (ocean model and analysis)
  - if **well** constructed and affordable (eddy-resolving)
  - could solve the problem!
- Climatological B is **needed**
  - NMC Method?
  - or, some other way…?
Hybrid Analysis for $T_s$

- High-variability (strong currents) is captured
- Diurnal variability is represented

NMC Method
01/2018 (mon mean)

48-hour forecasts not available for 06, 18 UTC
HYBRID ANALYSIS FOR $T_s$

OSTIA SST OI error
01/2018 (mon mean)

Jan, 2018
SUMMARY

- Coupled Data Assimilation
  - many challenges
  - and many possibilities (strong/weak; iterations, cross-correlations, …)
- Interface states (skin SST, Salinity, sea ice)
  - retrievals (of SST, Salinity, …) do not fully represent coupled processes
  - need internal self-consistency
  - must be part of coupled analysis
- Updates to the GEOS DAS
  - includes analysis for skin SST along with upper-air
  - the skin SST background error
Questions, Feedback, Suggestions
Thank You!