SST Analysis in NCEP GFS

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General Picture

--- SST Improvement

Better SST Analysis Product

Extract SST information from satellite data more effectively
From Empirical retrieval to Physical retrieval to Direct assimilation of radiances

Resolve the vertical structure from surface to diurnal warming depth
Enable to use depth dependent observations consistently
Require to solve new, related issues
Assimilation scheme

• SST is analyzed with the atmospheric data assimilation system (GSI) in NCEP GFS
  – Add a new analysis variable (SST or equivalent) to GSI
    • Single cost function with more elements in the state vector
  – Add observation data related to SST
  – Error variance and correlation length for the new analysis variable

• Problems
  – SST prediction
  – Observation operators ($H$) for the new analysis variable ($x$) are not available, if the observations ($y$) are depth dependent.
  – Jacobii of the new observation operators need to be derived
  – Different lower temperature condition required for atmospheric model ($Ts$) and radiative transfer model ($Tr$).
Observations for SST analysis

<table>
<thead>
<tr>
<th>Satellite: IR &amp; MW</th>
<th>In situ: Buoys, Ships</th>
</tr>
</thead>
<tbody>
<tr>
<td>The radiances emitted from the sea water at skin depths (0.01mm – 1 mm)</td>
<td>The sea water temperature at the depths (0.01 mm – 15+ m)</td>
</tr>
</tbody>
</table>

SST is not observed directly

1. A various depths instead of surface (z = 0) only
2. Radiance instead of temperature

Questions

Is it necessary to resolve the vertical structure near surface? How?
How to assimilate the indirectly observed data?
Representative temperatures near sea surface and analysis variable

(a) Night or Day without diurnal warming

(b) Day with strong diurnal warming

\[ T_s \]: Surface Temperature, \( z=0 \)
\[ T_{ir} \]: Skin temperature, \( z \sim 0.01 \) mm. Detected by shortest IR (80000 GHz, CH-2 of AVHRR)
\[ T_{mw} \]: Sub-skin temperature, \( z \sim 1.0 \) mm. Detected by longest MW (6.7 GHz, CH-1 of AMSRE)
\[ T_r \]: Skin temperature, \( z \sim 0.01 \) mm - 1.0 mm. Between \( T_{ir} \) and \( T_{mw} \)
\[ T_d \]: Depth Temperatures, \( z \sim 0.17m \sim 15m \). Detected by buoys and ships
\[ T_f \]: Foundation temperature, \( z = D_T \sim 0.5 m – 10 m \)

**Analysis variable: Foundation temperature** \( T_f \)

\[ T_s = f_s(T_f) = T_f + \Delta T_w(0) - \Delta T_c(0) \]
\[ T_r(\delta_r) = f_r(T_f) = T_f + \Delta T_w(\delta_r) - \Delta T_c(\delta_r) \]
\[ T_{mw}(\delta_c) = f_{mw}(T_f) = T_f + \Delta T_w(\delta_c) \]
\[ T_d(d) = f_d(T_f) = T_f + \Delta T_w(d) \]
Sub-layer and diurnal warming layer

Sub-layer cooling model (Fairall et al, 1996):

\[-Q = R_{nl} - H_s - H_i\]

\[\delta_c = \frac{\lambda v}{(\rho_a / \rho)^{1/2} u_{*a}} = 6 \left\{ 1 + \frac{16 Q_b g a \rho c_p v^3}{u_{*a}^4 (\rho_a / \rho)^2 \kappa^2} \right\}^{3/4} \}

\[Q_b = Q + \left( \frac{S \beta c_p}{\alpha L_c} \right) H_i\]

\[\Delta T_c = \frac{H \delta_c}{\kappa} = \frac{6v (\delta S_w - Q)}{\kappa (\rho_a / \rho)^{1/2} u_{*a}} \left\{ 1 + \frac{16 g a \rho c_p v^3}{u_{*a}^4 (\rho_a / \rho)^2 \kappa^2} \right\}^{3/4} \}

Diurnal warming model (Fairall et al, 1996):

The model assumes linear anomaly profiles of temperature and current in the diurnal warming layer. Once the solar heating exceeds the combined cooling of sensible, Latent and long wave radiation, integrate temperature equation and current equations (rotation effect omitted) along time \( t_0 \to t \) and depth \( 0 \to D_T \):

\[\Delta T_w = \frac{I_h}{\rho c_p (D_T / 2)}; \quad \Delta \rho = \rho \Delta T_w; \quad \delta v = \frac{2I_v}{D_T}; \quad I_h = \int_{t_0}^{t} (\delta S_w - Q) dt; I_v = \int_{t_0}^{t} u_{*a}^2 dt\]

Assume the density and current anomalies, which mean the departures from the early morning oceanic state, and length scale satisfy Richardson number criterion:

\[
\frac{gh \delta \rho}{\rho_o (\delta v)^2} \geq R_{ic} = 0.65 \implies D_T(t) = \sqrt{\frac{2R_{ic}}{\rho_o (\delta \rho) I_v}} \cdot \frac{I_h}{\sqrt{(ag / \rho c_p)}}
\]
Observation operators from $T_f$ to $T_d$ and $T_r$:

**Conventional data:**

$T_d(d) = f_d(T_f) = T_f + \Delta T_w(d)$

$H_c(T_f) \Rightarrow T_f$

$H_c[f_d(T_f)] \Rightarrow T_d$

**Satellite data:**

$T_r(\delta_r) = f_r(T_f) = T_f + \Delta T_w(\delta_r) - \Delta T_c(\delta_r)$

$H_r(T_r) \Rightarrow T_r$

$H_r[f_r(T_f)] \Rightarrow T_r$

**Conversion between SST ($T_s$) and $T_r$:**

$T_s = f_s(T_f) = T_f + \Delta T_w(0) - \Delta T_c(0)$  \quad $H_c(T_f) \Rightarrow T_f$; $H_c[f_s(T_f)] \Rightarrow T_s$

**Sensitivities of the representative temperatures to $T_f$:**

**Conventional data** $\frac{\partial T_d}{\partial T_f}$:

$T_d(d) = f_d(T_f) = T_f + \Delta T_w(d) \Rightarrow F_d[T_d, T_f, \Delta T_w[D_T(I_h(D_T, T_s))] = 0$

$F_d[T_d, T_f, \Delta T_w(T_s)] = 0 \Rightarrow \frac{\partial T_d}{\partial T_f} = P_d(\frac{\partial \Delta T_w}{\partial T_s}, \frac{\partial T_s}{\partial T_{mw}}, \frac{\partial T_{mw}}{\partial T_d})$

**Satellite data** $\frac{\partial T_r}{\partial T_f}$:

$T_r(\delta_r) = f_r(T_f) = T_f + \Delta T_w(\delta_r) - \Delta T_c(\delta_r)$

$\Rightarrow F_r[T_r, T_f, \Delta T_w(T_s) - \Delta T_c(T_s)] = 0$

$\Rightarrow \frac{\partial T_r}{\partial T_f} = P_r(\frac{\partial \Delta T_w}{\partial T_s}, \frac{\partial T_s}{\partial T_r})$

**Observation operator:** To transform analysis variable to corresponding partner in observation space.

$H_c$ : available, interpolation operator

$H_r$ : available, radiative transfer model

$F_d$ : Implicit compound function to relate $T_d(z = d)$ and $T_f$ through heat fluxes and therefore $T_s$. 
Diurnal warming model run with 3-hourly GFS fluxes
Simulation of ocean sub-layer cooling with 3-hour mean fluxes.
09Z, 02/08/2008
Sub-layer cooling correction (K) $\Delta T_c(z = 0)$
Wind Stress ($\text{N/m}^2$)

Sub-layer thickness (mm) $\delta_c$
Net heat flux across sub-layer ($\text{W/m}^2$)

Sub-layer model run with 3-hourly GFS fluxes
Sensitivity of representative temperatures to foundation temperature
Simulation of ocean diurnal warming and sub-layer cooling.

00Z, 02/03/2008 (8-hour warming integration with 3-hour mean fluxes, from 00Z, 02/03/2008)

**Diurnal warming (K)**

\[ \Delta T_w(z = 0) \]

**Warming - Cooling (K)**

\[ \Delta T_w - \Delta T_c \]

**Sub-layer cooling (K)**

**Experiment:**
Use the SST currently used by GFS, \( T_{ctl} \) as the foundation temperature. Satellite instruments are divided into IR and MW:
For IR: \( T_{ir} = T_{ctl} + \Delta T_w(z = 0) - \Delta T_c(z = 0) \)
For MW: \( T_{mw} = T_{ctl} + \Delta T_w(z = 0) \)
Then, 7-day analysis is done with GSI, GFS forecast (03, 06, 09) used as the first guess; GFS fluxes used to get \( \Delta T_w \) and \( \Delta T_c \)

**Control Run:** \( T_{ir} = T_{mw} = T_{ctl} \)
Impacts of sea water diurnal warming and sub-layer cooling on AVHRR radiance simulation (Bias), based on the data used in both experiments.
Impacts of sea water diurnal warming and sub-layer cooling on the analysis of AVHRR data
Plan

- **Foundation temperature analysis in GSI**
  - $T_f$ error statistics based on a period of analysis sample
  - How often the fluxes and therefore the diurnal warming amount updated?
  - Parallel run
    - Consistency among SST, fluxes and atmosphere

- **Diurnal warming model improvement**
  - Theoretical analysis done: rotation effect, vanish wind handle, E-P effect, linear to exponent profile
  - Solar radiation penetration

- **One-dimensional oceanic model**
  - $T_f$ forecasting