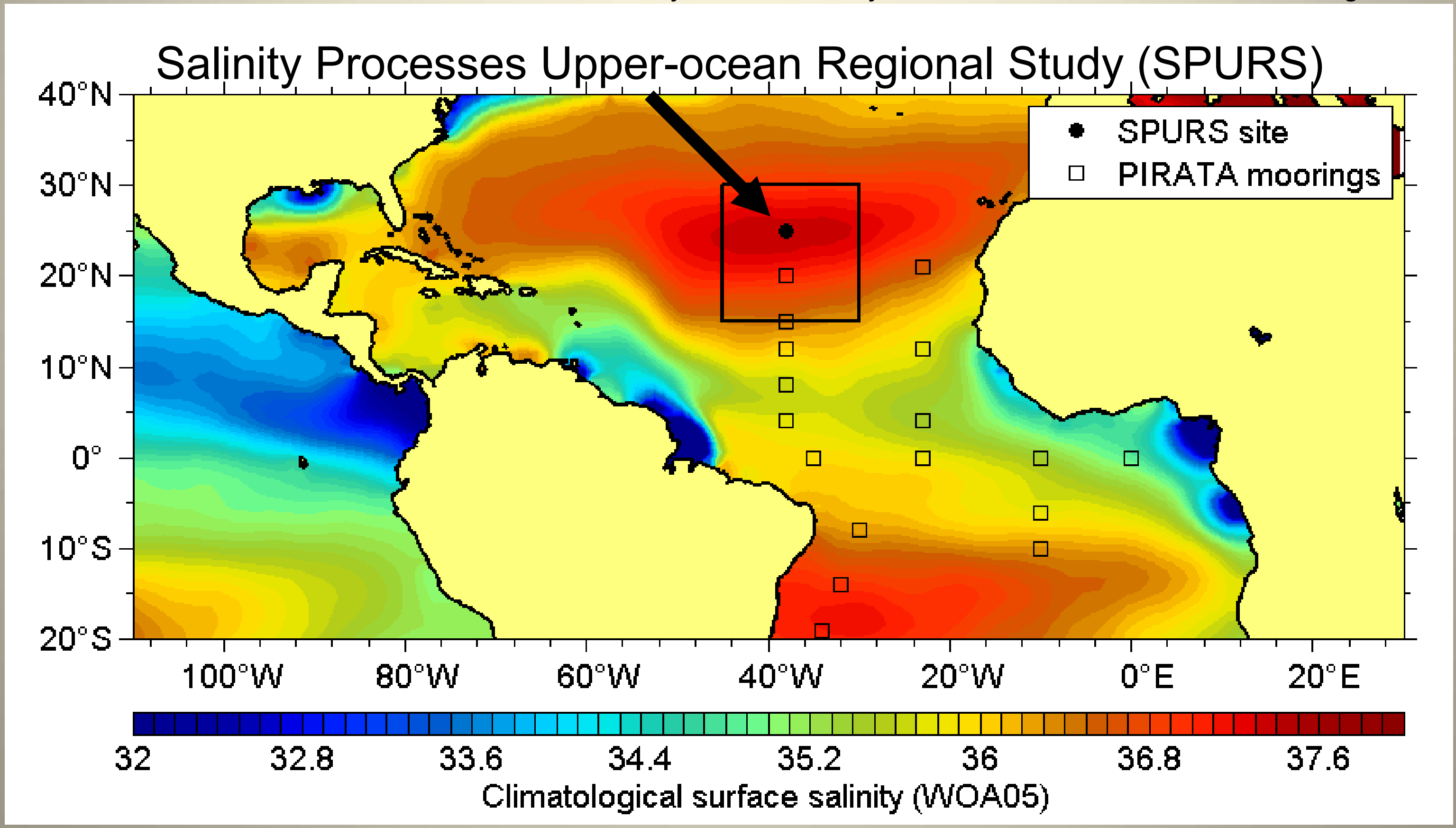
Salinity and temperature balances (and imbalances) at the SPURS central mooring

Tom Farrar[1], Luc Rainville[2], Al Plueddemann[1], Billy Kessler[3], Craig Lee[2], Ben Hodges[1], Ray Schmitt[1], Steve Riser[2], Jim Edson[4], Charles Eriksen[2], David Fratantoni[5]

1: Woods Hole Oceanographic Institution, 2: Univ. of Washington/Applied Physics Laboratory, 3: NOAA Pacific Marine Environmental Laboratory, 4: University of Connecticut, 5:Remote Sensing Solutions, Inc.

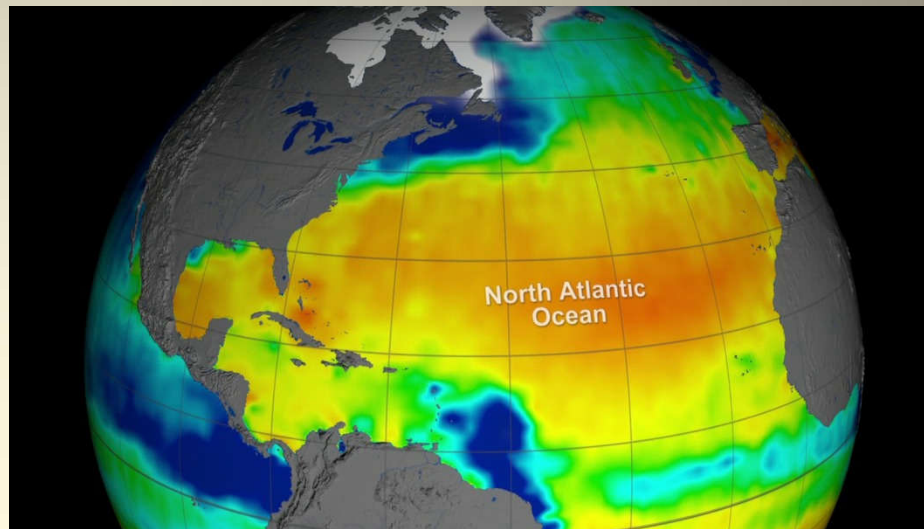


Global Ocean Salinity and the Water Cycle Workshop, May 24, 2017

SPURS-1

What are the physical processes responsible for the location, magnitude, and maintenance of the subtropical Atlantic sea surface and subsurface
salinity maximum?

SPURS-1 involved coordinated field work, numerical models, and remote-sensing.



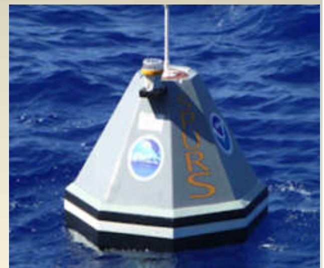
NASA's Goddard Space Flight Center Scientific Visualization Studio

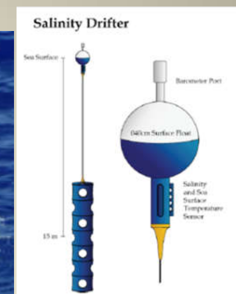
SPURS

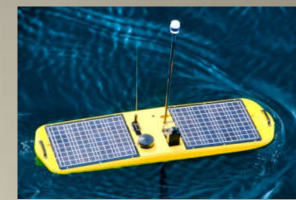
Salinity Processes in the Upper Ocean Regional Study

SPURS-1

What are the physical processes responsible for the location, magnitude, and maintenance of the subtropical Atlantic sea surface and subsurface
salinity maximum?







SPURS-1 central mooring

An organizing goal of the field campaign was to measure the terms in the equation for mixed-layer salinity:

$$\frac{\partial \overline{S}}{\partial t} = -\overline{\vec{u}} \cdot \overline{\nabla S} + \frac{\hat{S}_{-h}}{h}\left(\frac{\partial h}{\partial t}\right) - \frac{F_{-h}}{h} + \frac{(E-P)S_o}{h} - \overline{\hat{\vec{u}} \cdot \hat{\nabla} \hat{S}} - \overline{w\frac{\partial S}{\partial z}}$$

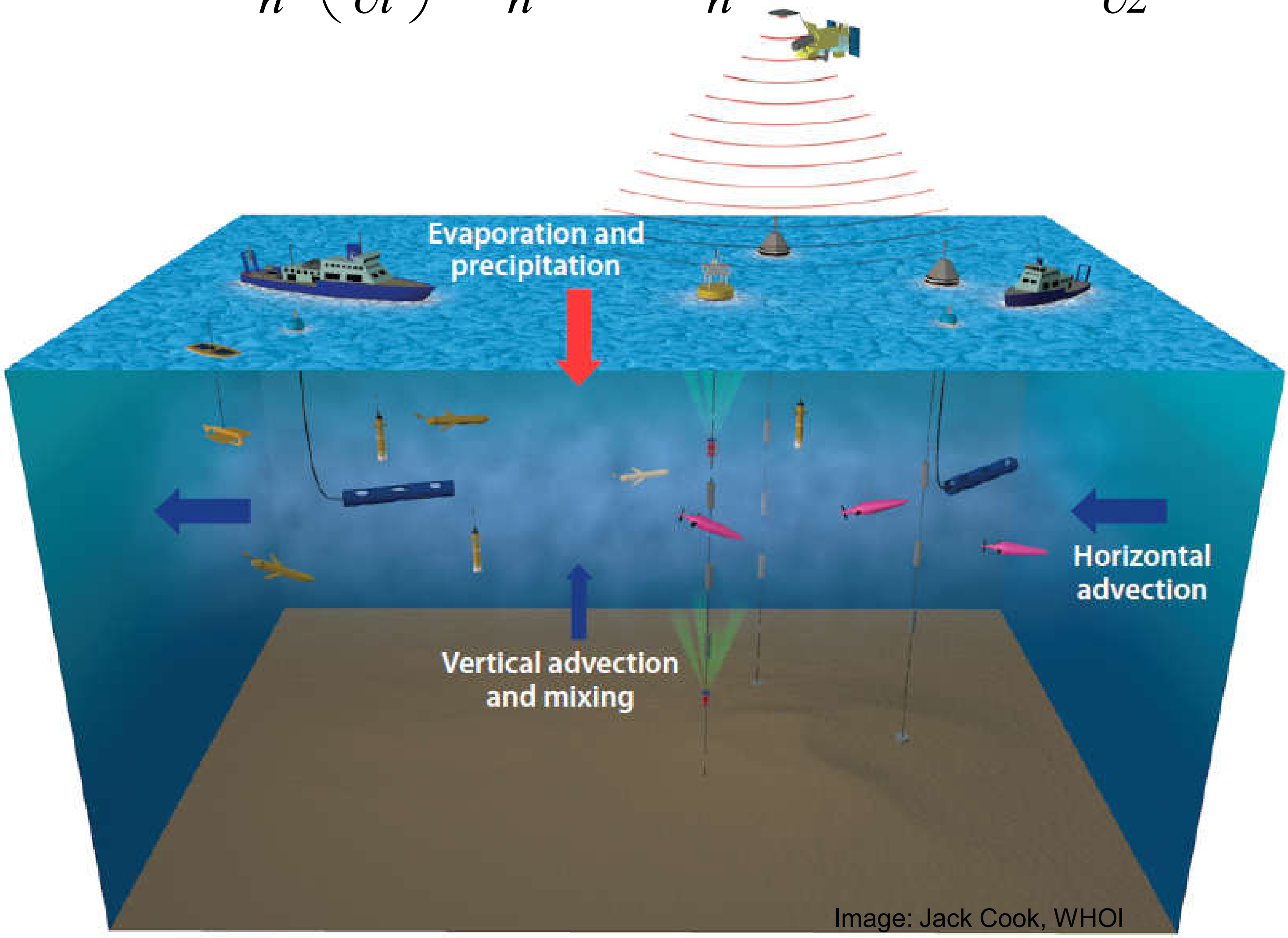
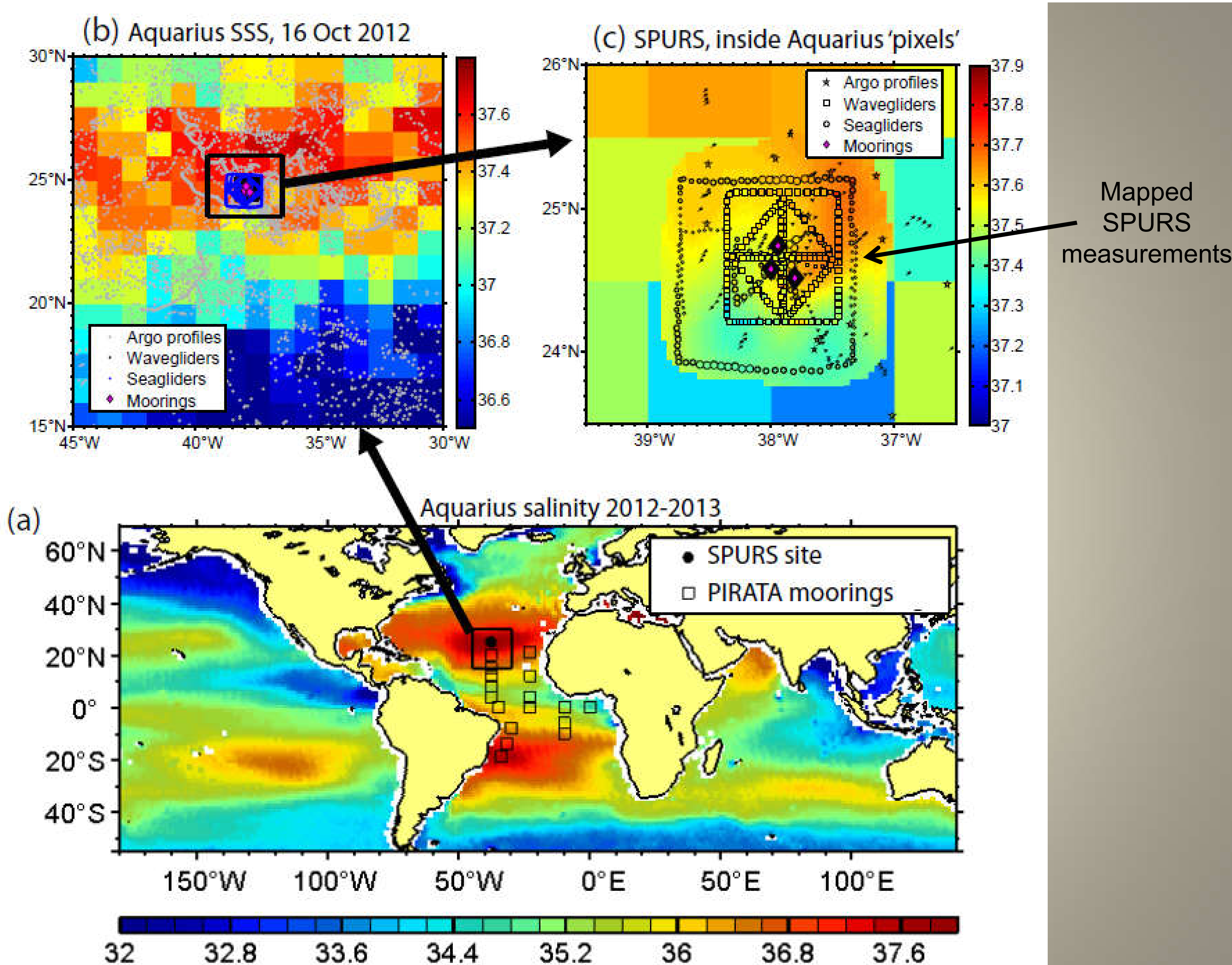


Image: Jack Cook, WHOI

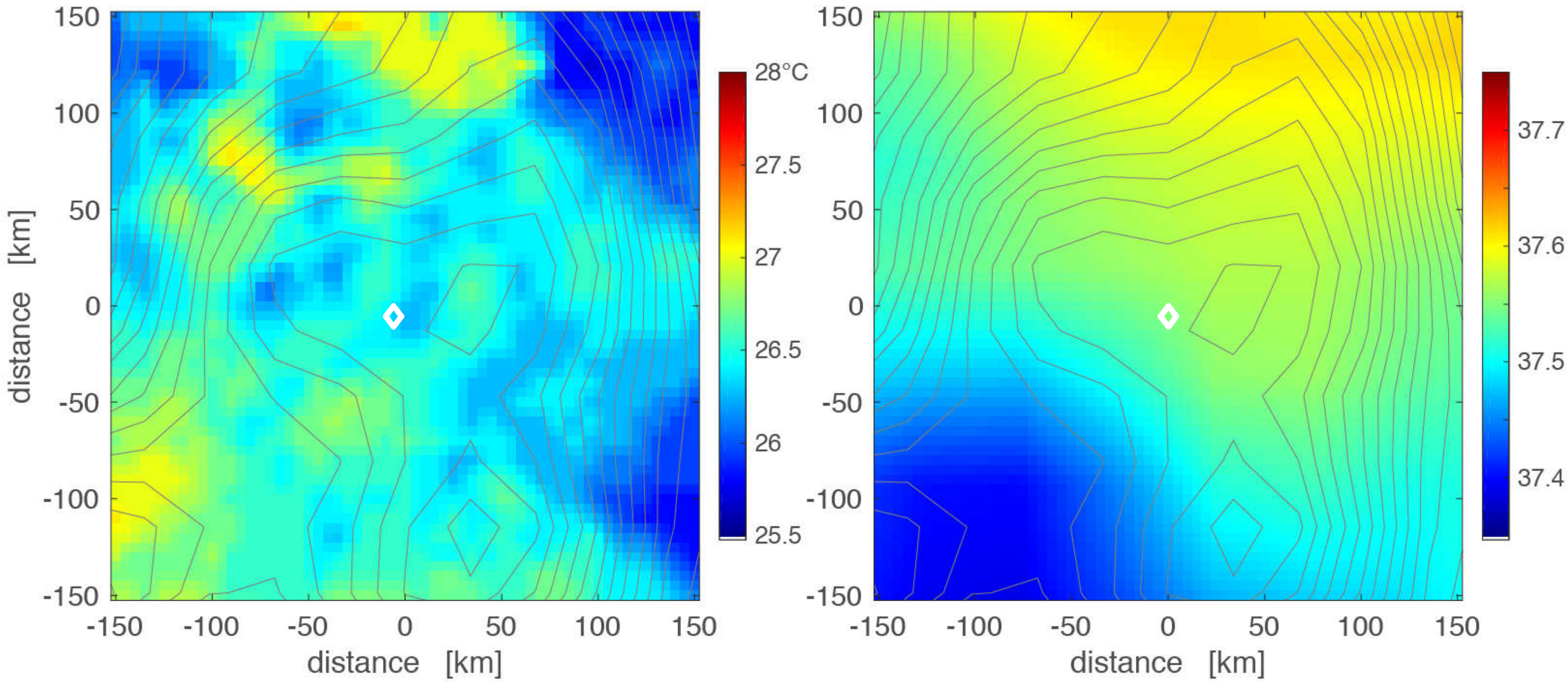


Farrar et al., 2015

SPURS
Salinity Processes in the Upper Ocean Regional Study

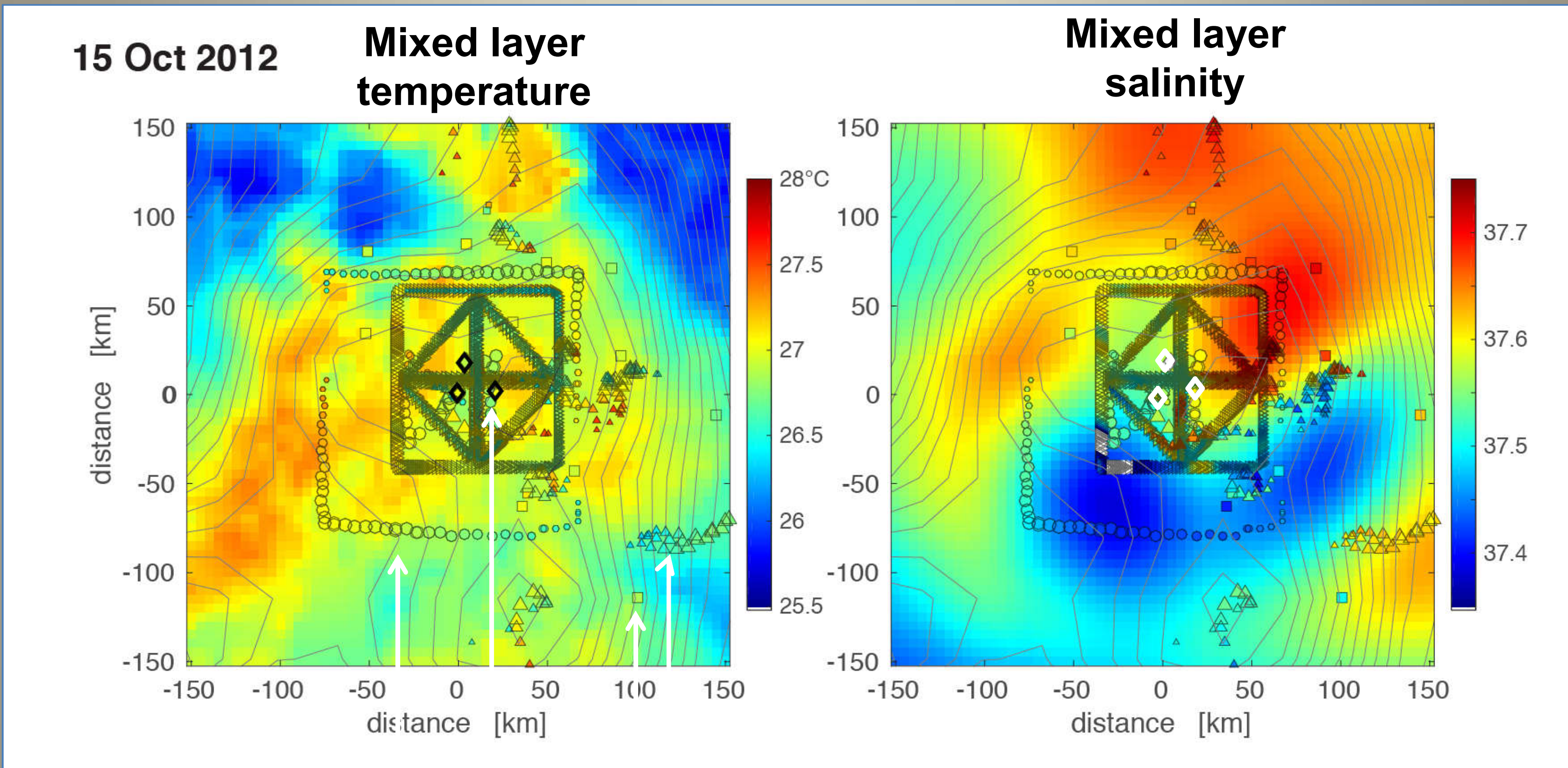
15 Oct 2012

Surface temperature | **Surface salinity**



microwave (MW) and infrared (IR) SST
Optimal Interpolation
(Remote Sensing Systems)

Aquarius SSS
Optimal Interpolation
(Melnichenko et al.)



- Moorings
- Drifters
- Seagliders
- Argo floats
- UCTD

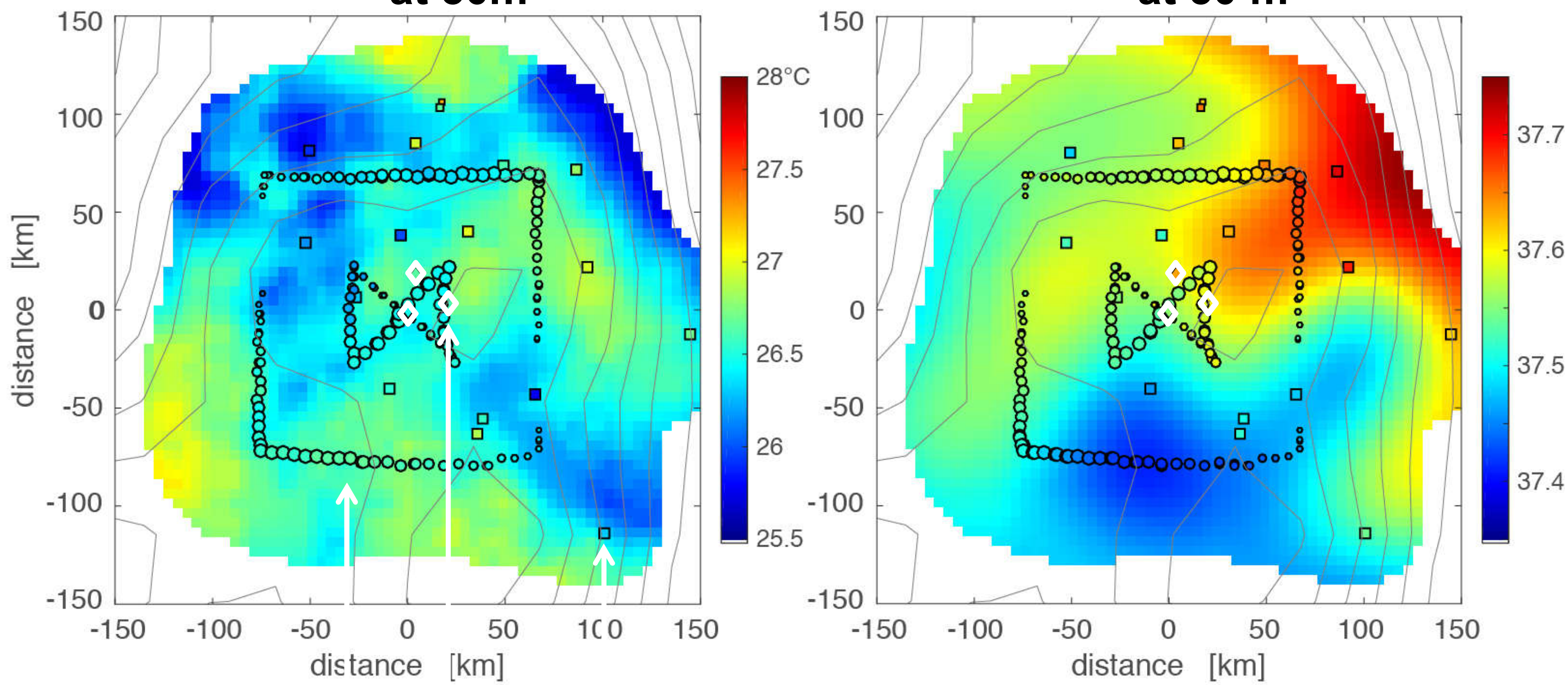
Decorrelation scales: 75 km and 5 days mapped as perturbations from remote sensing

Note: Size of data marker is scaled by when it was collected relative to the map time.

SPURS

Salinity Processes in the Upper Ocean Regional Study

15 Oct 2012



Moorings

Seagliders

Argo floats

UCTD

Decorrelation scales: 75 km and 5 days mapped as perturbations from previous depth

Note: Size of data marker is scaled by when it was collected relative to the map time.

Buoy/mooring measurements:

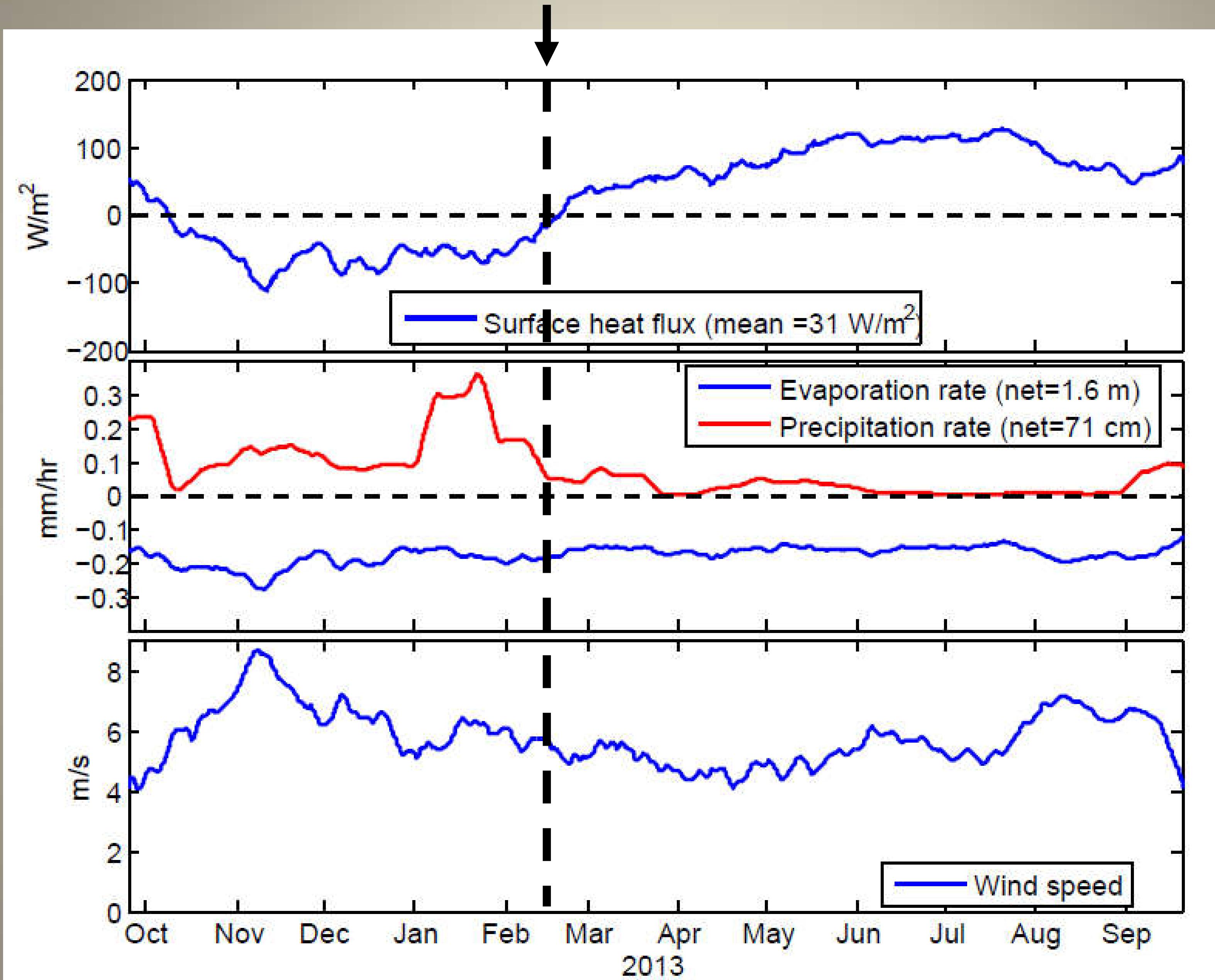
(1) Measurements of surface meteorology and radiation for air-sea fluxes

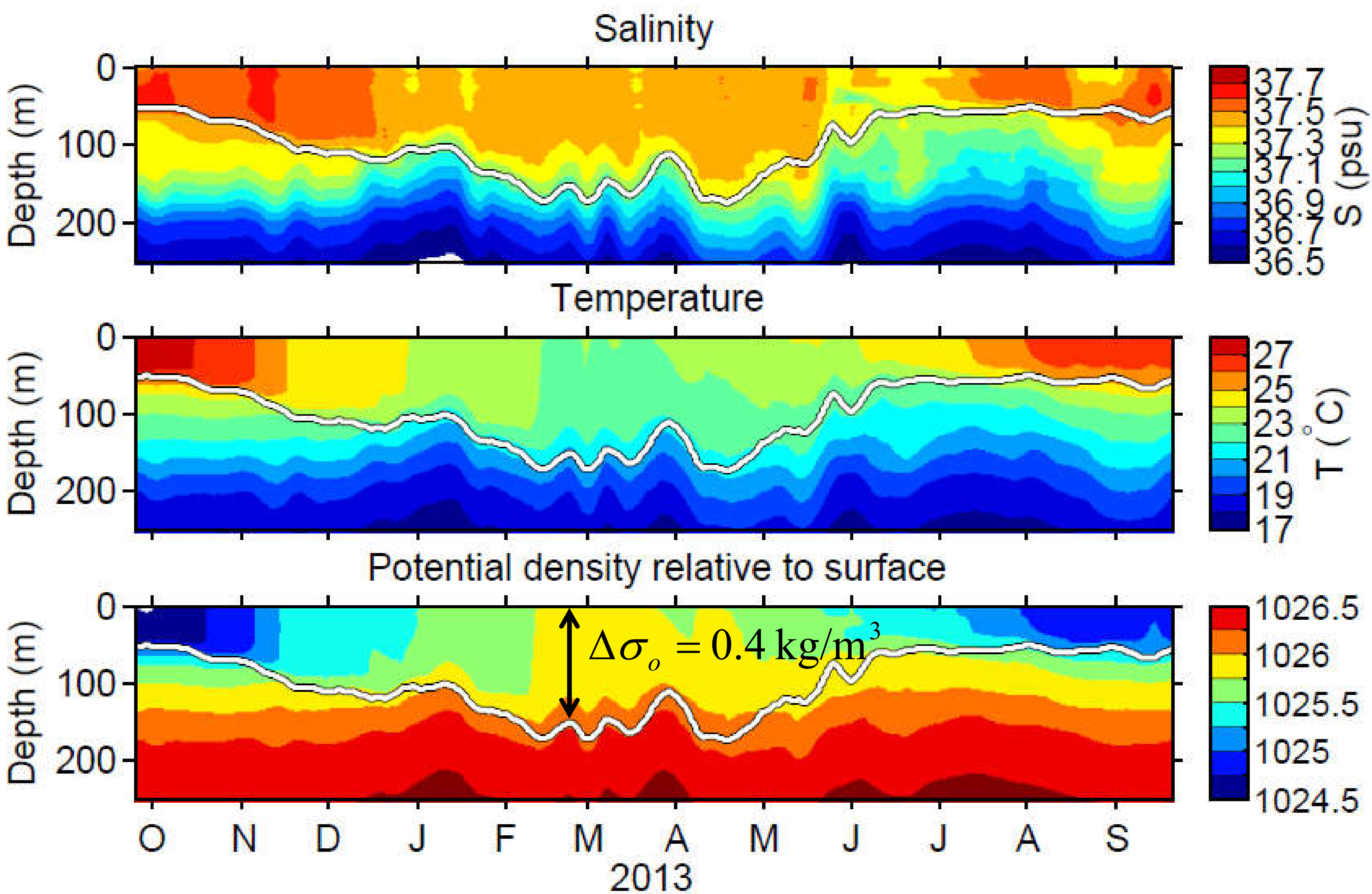
(2) Direct turbulent flux measurements (wind stress, latent heat flux/evap, sensible heat flux)

(3) Measurements of T, S, and currents with good vertical and temporal resolution (<5m in upper 90 m)

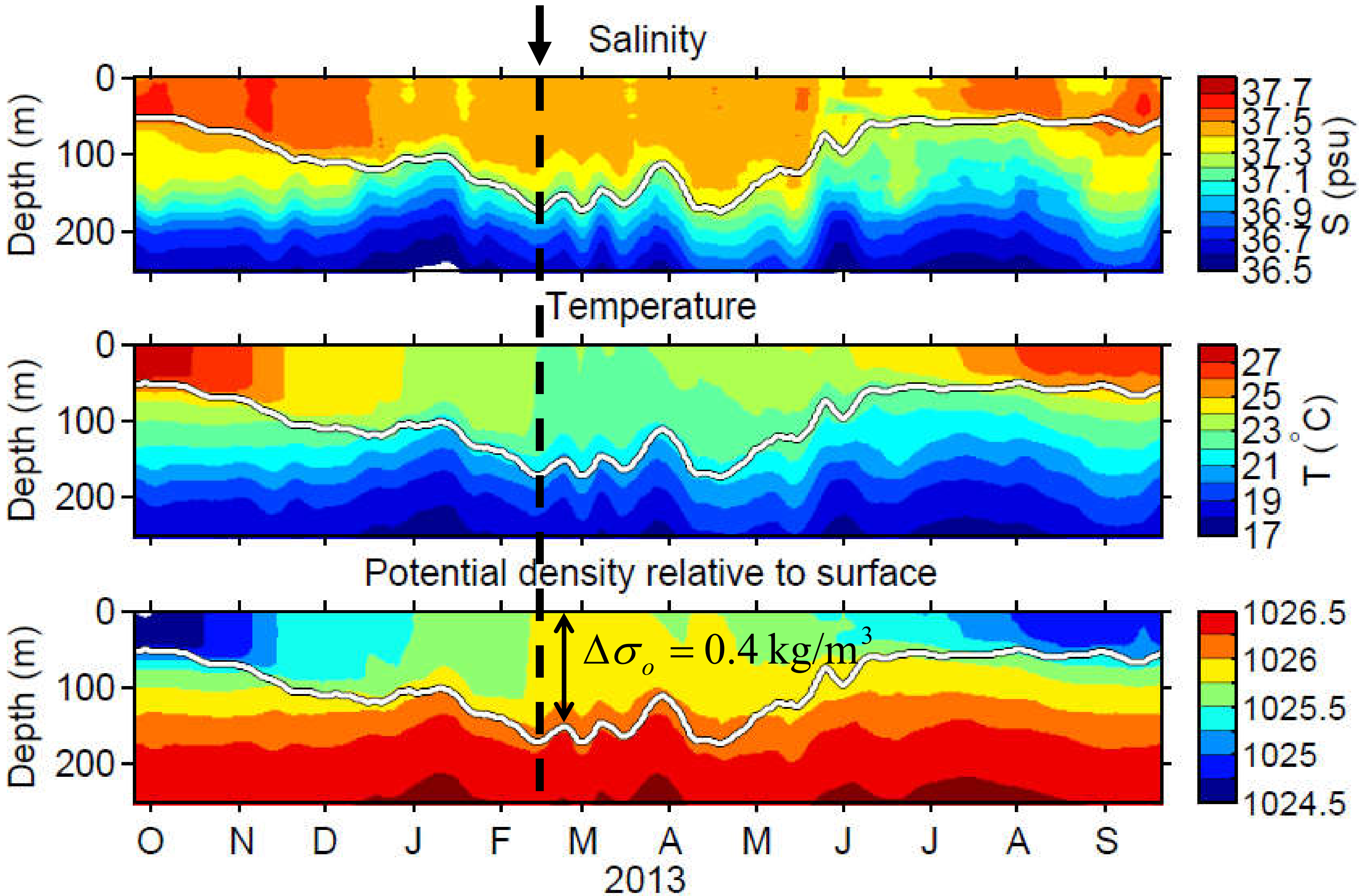
SPURS central mooring

Surface forcing at the SPURS buoy: (3-week running averages)



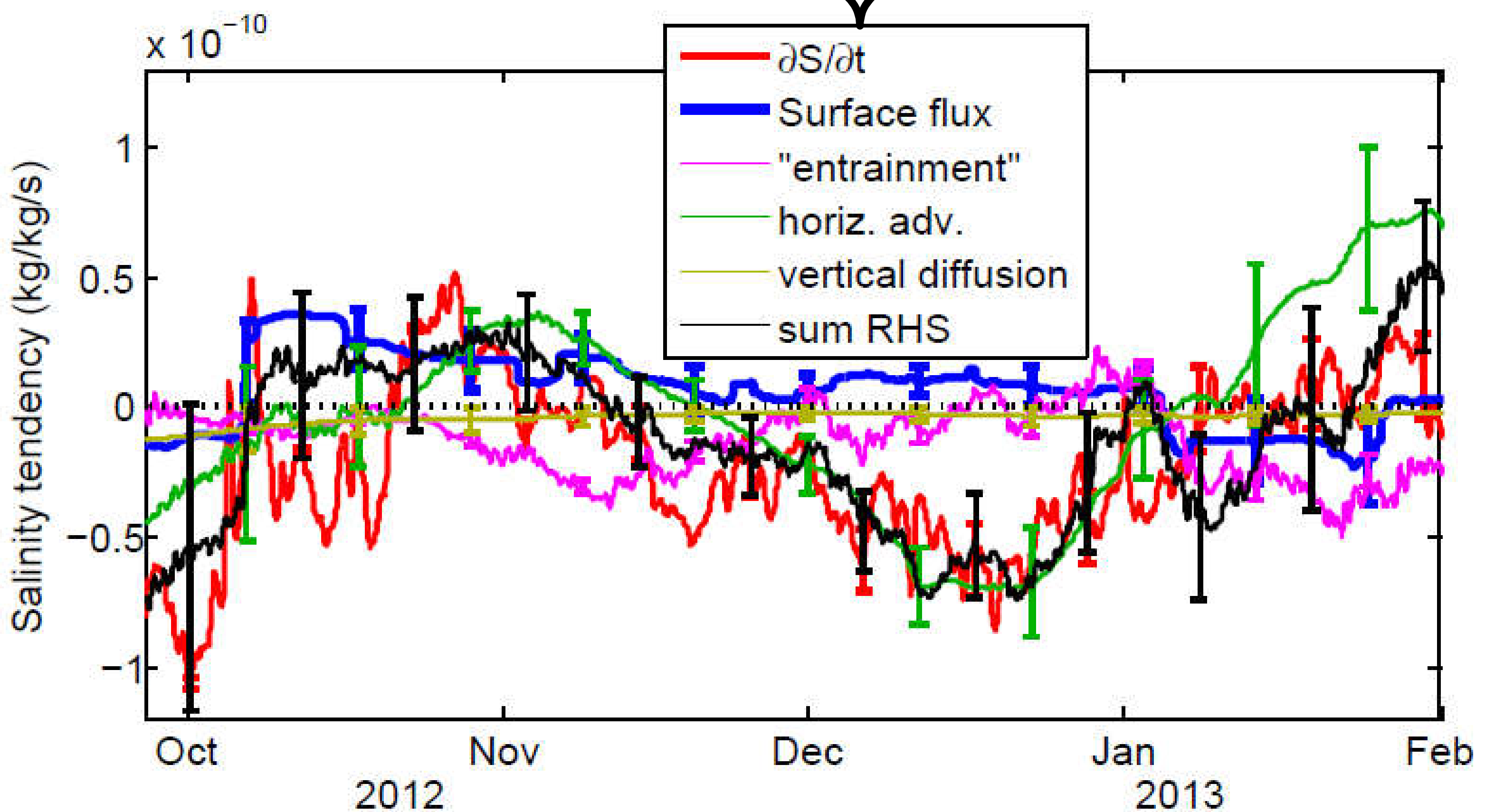


Salinity
Temperature
Potential density relative to surface
Depth (m)
0
100
200
S (psu)
37.7
37.5
37.3
37.1
36.9
36.7
36.5
T (°C)
27
25
23
21
19
17
1026.5
1026
1025.5
1025
1024.5
$\Delta\sigma_o = 0.4$ kg/m^3
O N D J F M A M J J A S
2013


Salinity
Temperature
Potential density relative to surface
Depth (m)
0
100
200
S (psu)
37.7
37.5
37.3
37.1
36.9
36.7
36.5
T (°C)
27
25
23
21
19
17
1026.5
1026
1025.5
1025
1024.5
$\Delta\sigma_o = 0.4$ kg/m^3
O
N
D
J
F
M
A
M
J
J
A
S
2013

The surface-layer salinity balance during the cooling season (fall and winter):

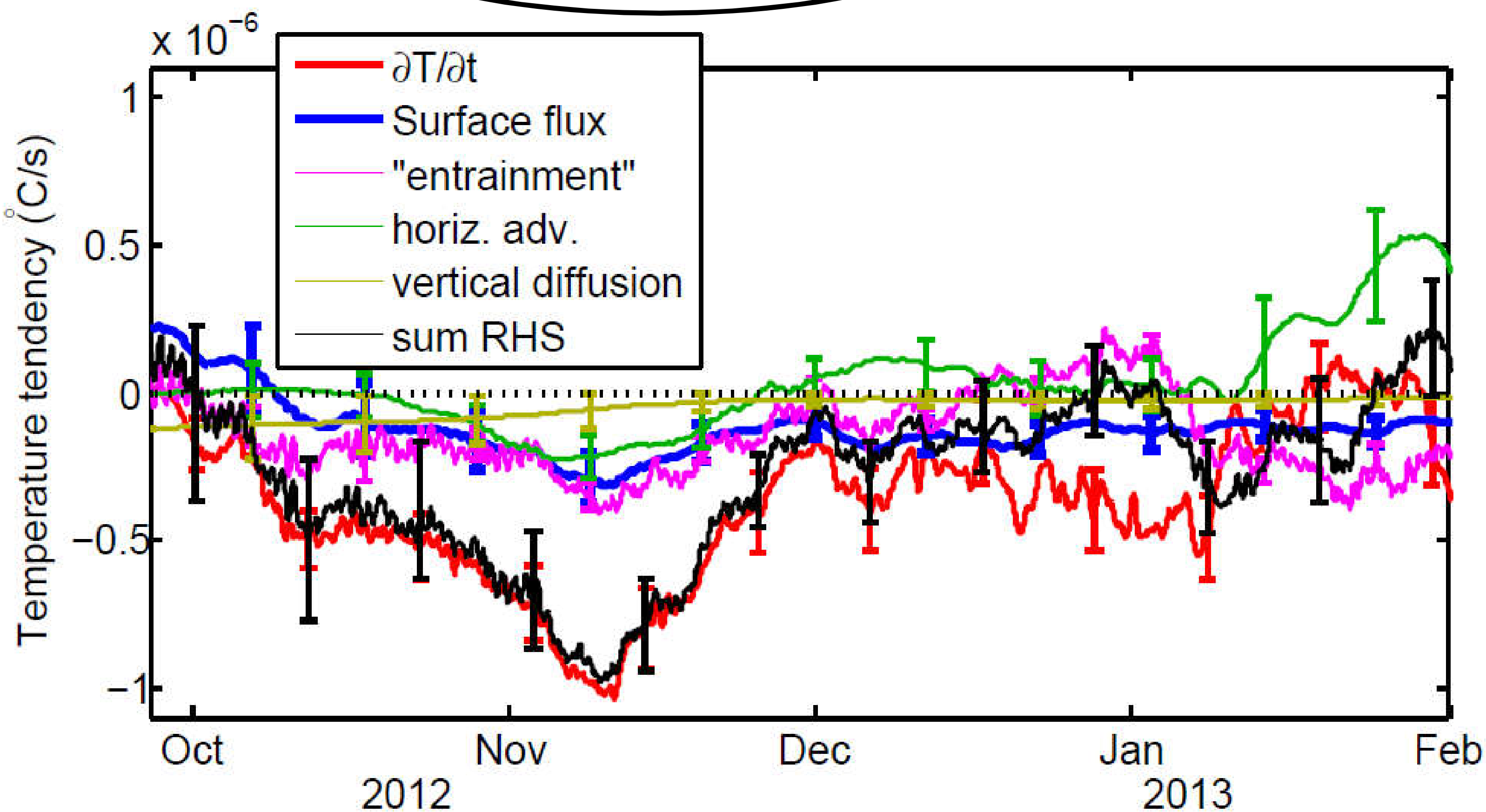
$$\frac{\partial \overline{S}}{\partial t} = \underbrace{-\overline{\vec{u}} \cdot \overline{\nabla S} + \frac{\hat{S}_{-h}}{h}\left(\frac{\partial h}{\partial t}\right) - \frac{F_{-h}}{h} + \frac{(E-P)S_o}{h} - \overline{\hat{\vec{u}} \cdot \hat{\nabla} \hat{S}} - \overline{w\frac{\partial S}{\partial z}}}$$



Farrar et al., 2015

The surface-layer temperature balance during the cooling season (fall and winter):

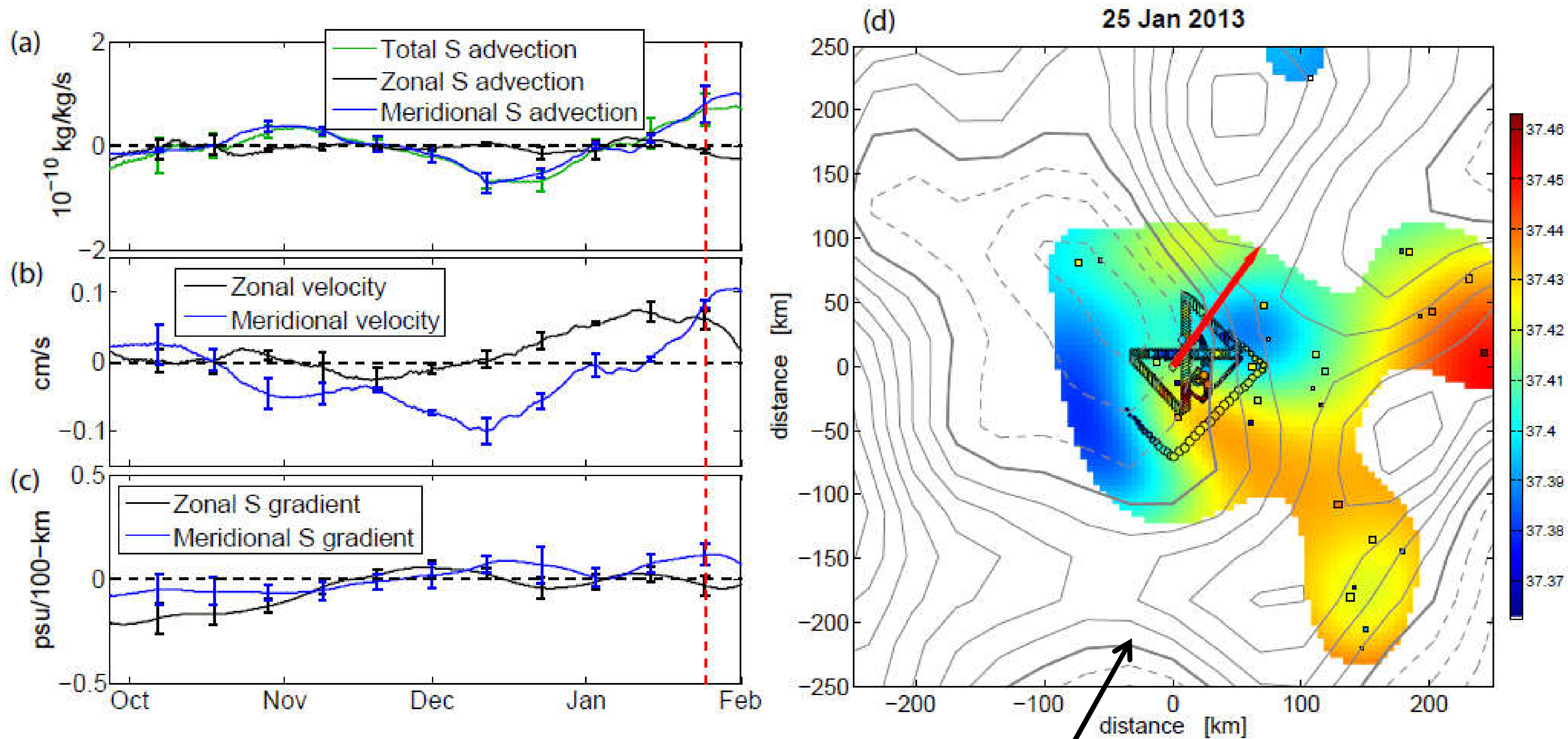
$$\frac{\partial \overline{T}}{\partial t} = -\overline{\vec{u}} \cdot \overline{\nabla T} + \frac{\hat{T}_{-h}}{h}\left(\frac{\partial h}{\partial t}\right) - \frac{Q_{-h}}{\rho c_p h} + \frac{Q_o}{\rho c_p h} - \overline{\hat{\vec{u}} \cdot \hat{\nabla} \hat{T}} - \overline{w \frac{\partial T}{\partial z}}$$



Farrar et al., 2015

The budget allows insight into the importance of physical processes on different time/space scales:

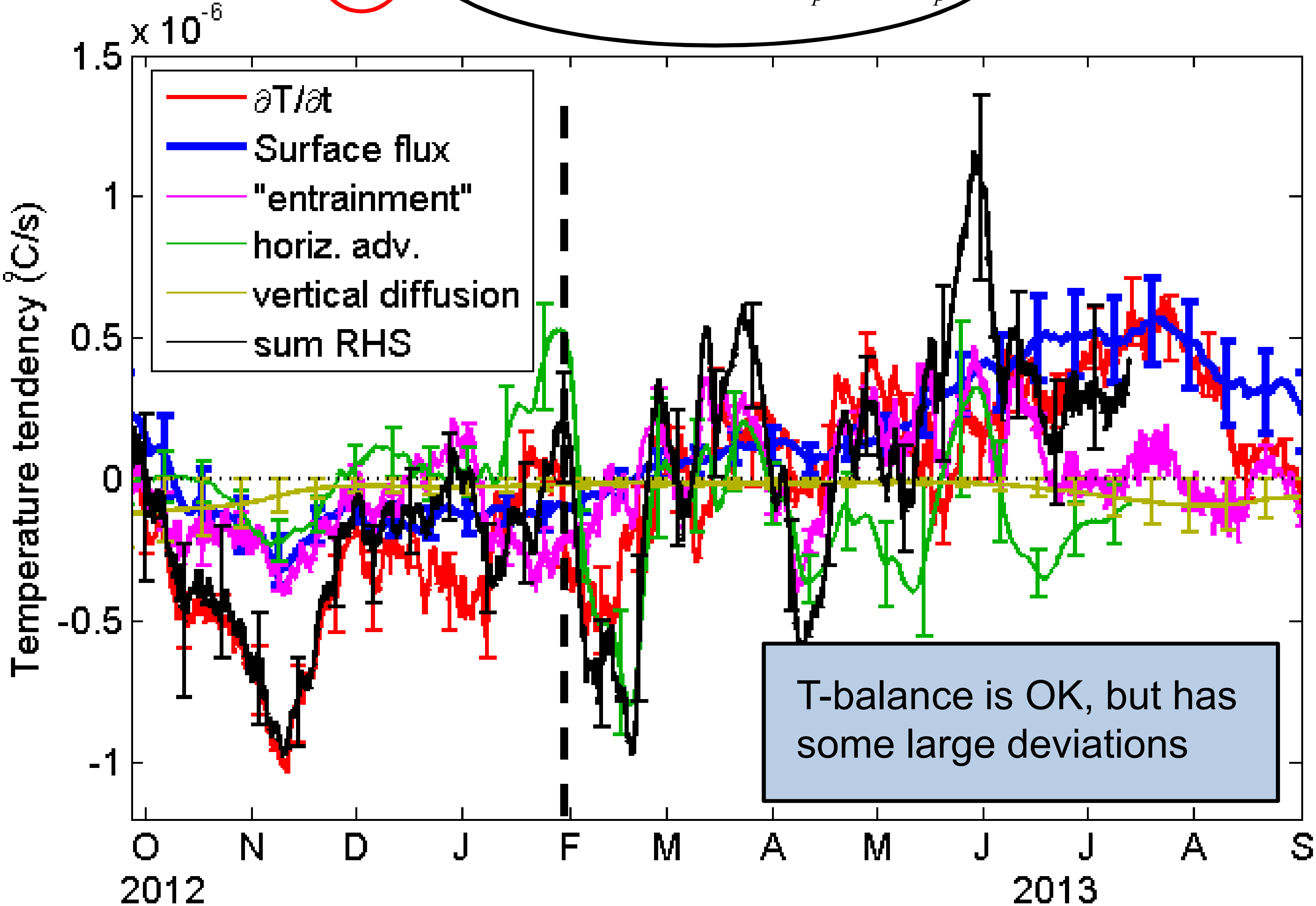
For example: the local 1-3 month SSS variability seen here is dominated by mesoscale advection on a spatial scale marginally resolved by Aquarius



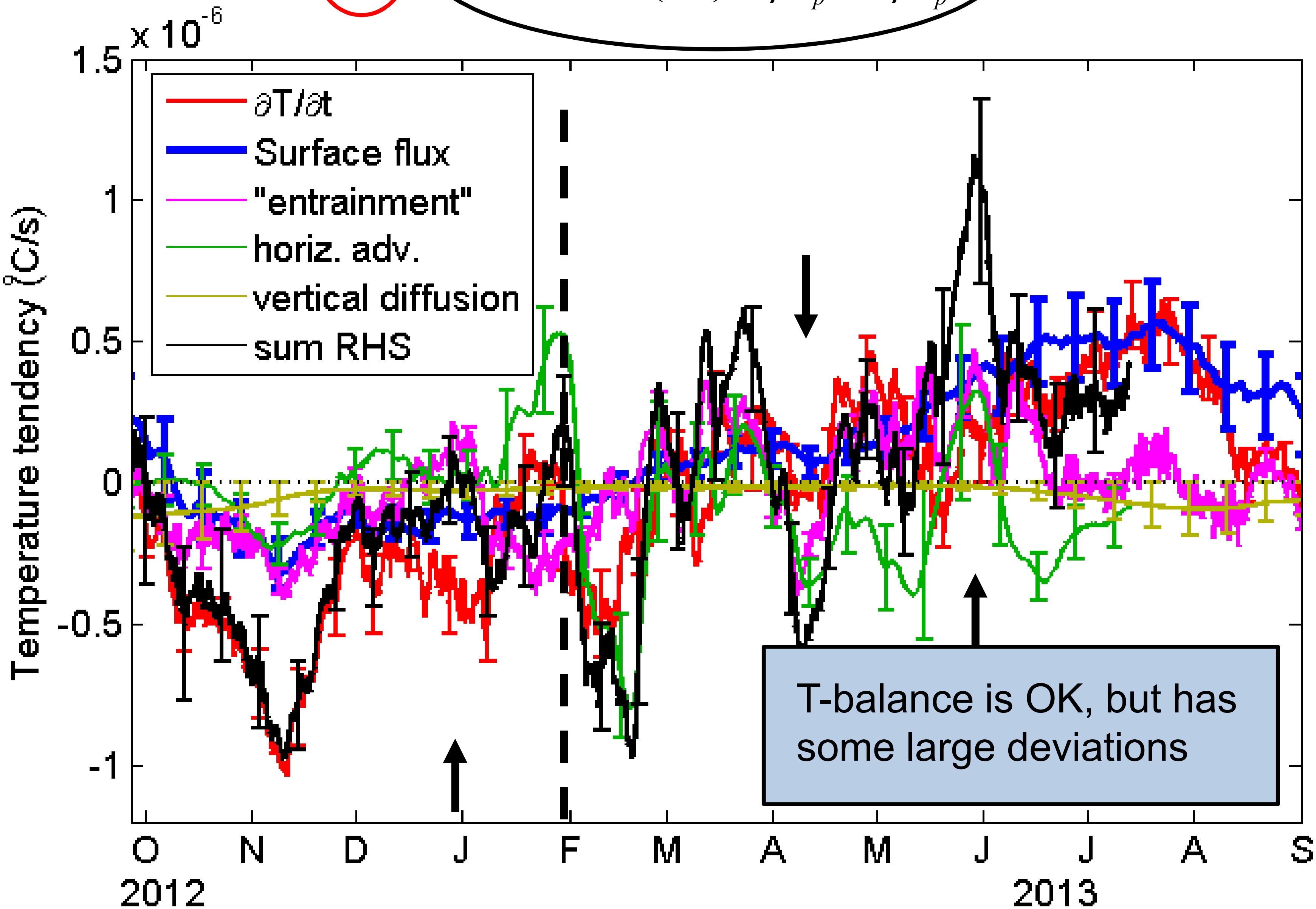
Farrar et al., 2015

OK, so what about the rest of the record (spring and summer)?

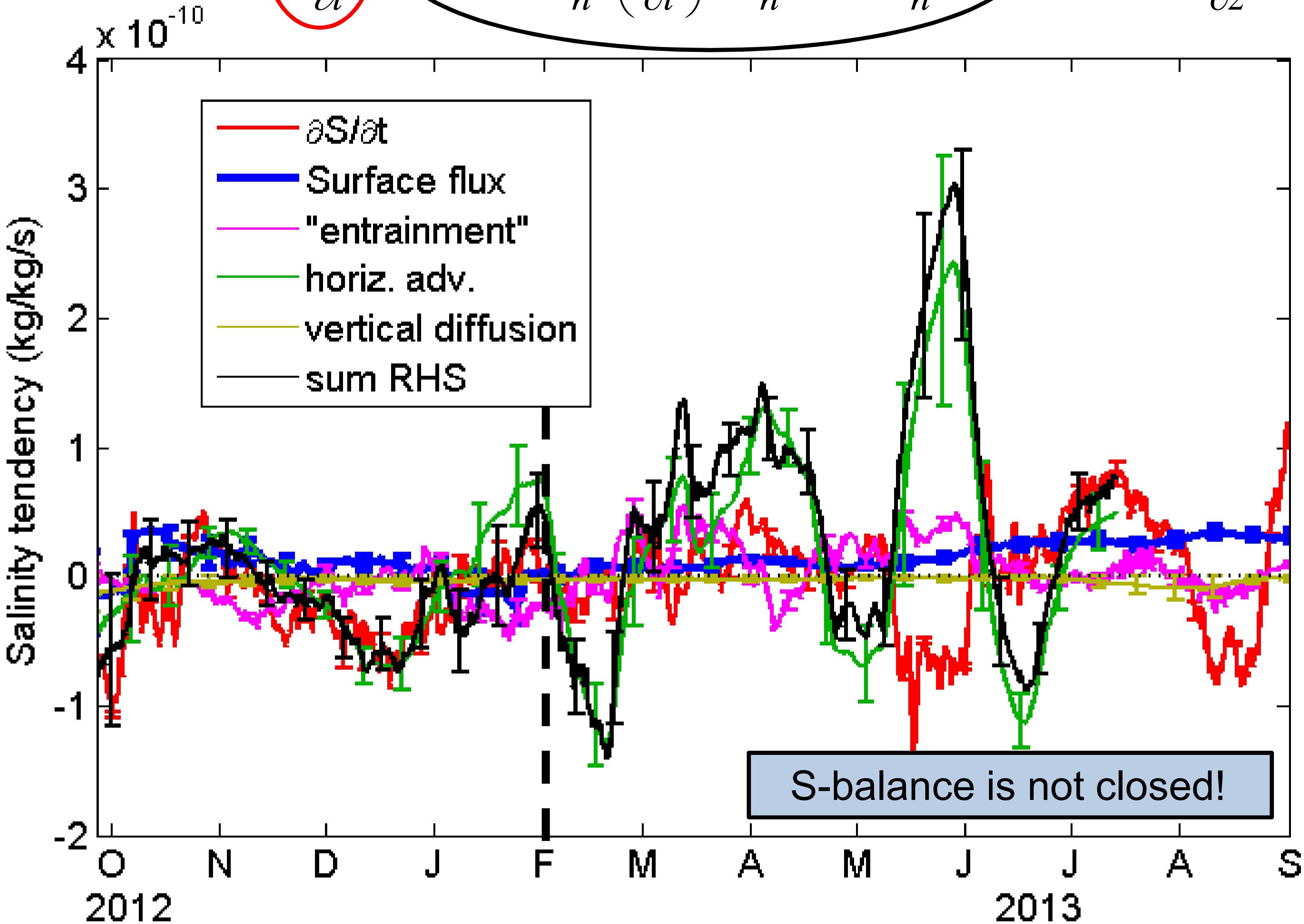
$$\frac{\partial \overline{T}}{\partial t} = -\overline{\vec{u}}\cdot\overline{\nabla T} + \frac{\hat{T}_{-h}}{h}\left(\frac{\partial h}{\partial t}\right) - \frac{Q_{-h}}{\rho c_p h} + \frac{Q_o}{\rho c_p h} - \overline{\hat{\vec{u}}\cdot\hat{\nabla}\hat{T}} - \overline{w\frac{\partial T}{\partial z}}$$



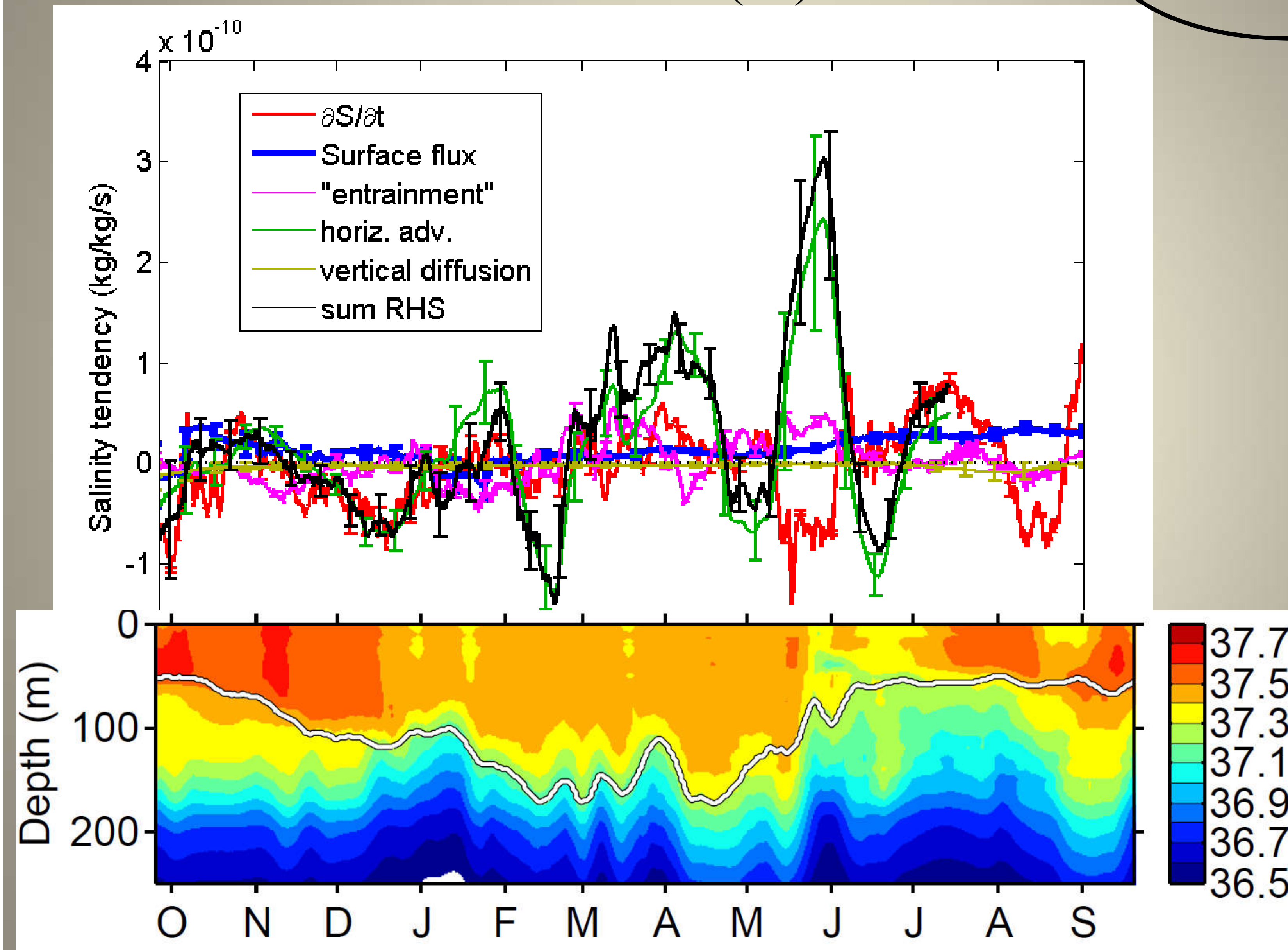
$$\frac{\partial \overline{T}}{\partial t} = -\overline{\vec{u}} \cdot \overline{\nabla T} + \frac{\hat{T}_{-h}}{h}\left(\frac{\partial h}{\partial t}\right) - \frac{Q_{-h}}{\rho c_p h} + \frac{Q_o}{\rho c_p h} - \overline{\hat{\vec{u}} \cdot \hat{\nabla} \hat{T}} - \overline{w \frac{\partial T}{\partial z}}$$



$$\frac{\partial \bar{S}}{\partial t} = -\overline{\vec{u}} \cdot \overline{\nabla S} + \frac{\hat{S}_{-h}}{h}\left(\frac{\partial h}{\partial t}\right) - \frac{F_{-h}}{h} + \frac{(E-P)S_o}{h} - \overline{\hat{\vec{u}} \cdot \hat{\nabla} \hat{S}} - \overline{w\frac{\partial S}{\partial z}}$$



$$\frac{\partial \overline{S}}{\partial t} = -\overline{\vec{u}} \cdot \overline{\nabla S} + \frac{\hat{S}_{-h}}{h}\left(\frac{\partial h}{\partial t}\right) - \frac{F_{-h}}{h} + \frac{(E-P)S_0}{h} - \overline{\hat{\vec{u}} \cdot \hat{\nabla} \hat{S}} - \overline{w \frac{\partial S}{\partial z}}$$



$$\frac{\partial \bar{S}}{\partial t} = -\bar{\vec{u}} \cdot \overline{\nabla S} + \frac{\hat{S}_{-h}}{h}\left(\frac{\partial h}{\partial t}\right) - \frac{F_{-h}}{h} + \frac{(E-P)S_o}{h} - \overline{\hat{\vec{u}} \cdot \hat{\nabla} \hat{S}} - \overline{w\frac{\partial S}{\partial z}}$$

Stratified, sheared advection
(e.g., “frontal slumping” or
intrusions)

Vertical
advection

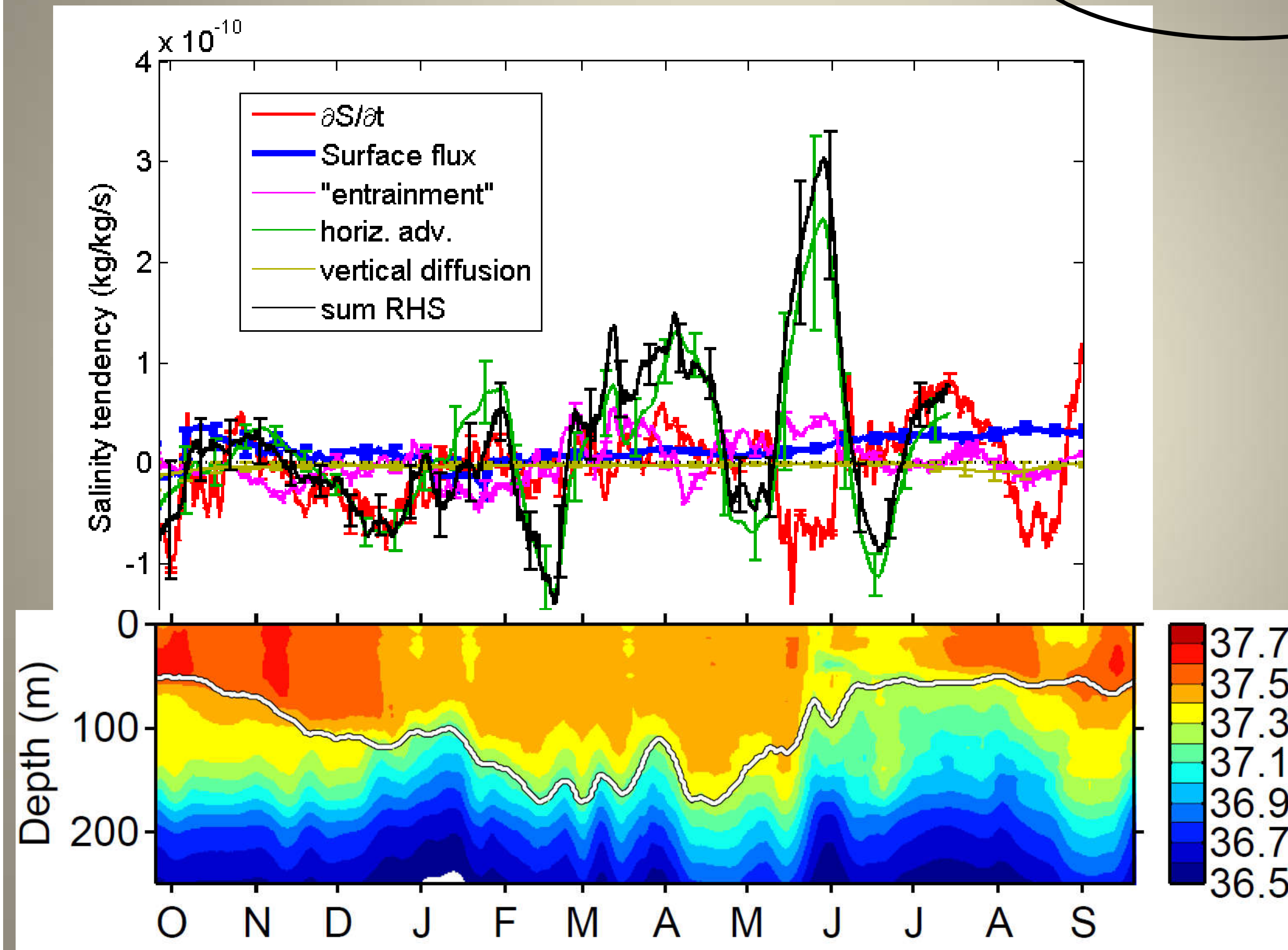
$$\frac{\partial \bar{S}}{\partial t} = -\vec{\bar{u}} \cdot \overline{\nabla S} + \frac{\hat{S}_{-h}}{h}\left(\frac{\partial h}{\partial t}\right) - \frac{F_{-h}}{h} + \frac{(E-P)S_o}{h} - \overline{\hat{\vec{u}} \cdot \hat{\nabla} \hat{S}} - \overline{w \frac{\partial S}{\partial z}} - \overline{\vec{u} \cdot (\nabla S)'}$$

Stratified, sheared advection (e.g., “frontal slumping” or intrusions)

Vertical advection

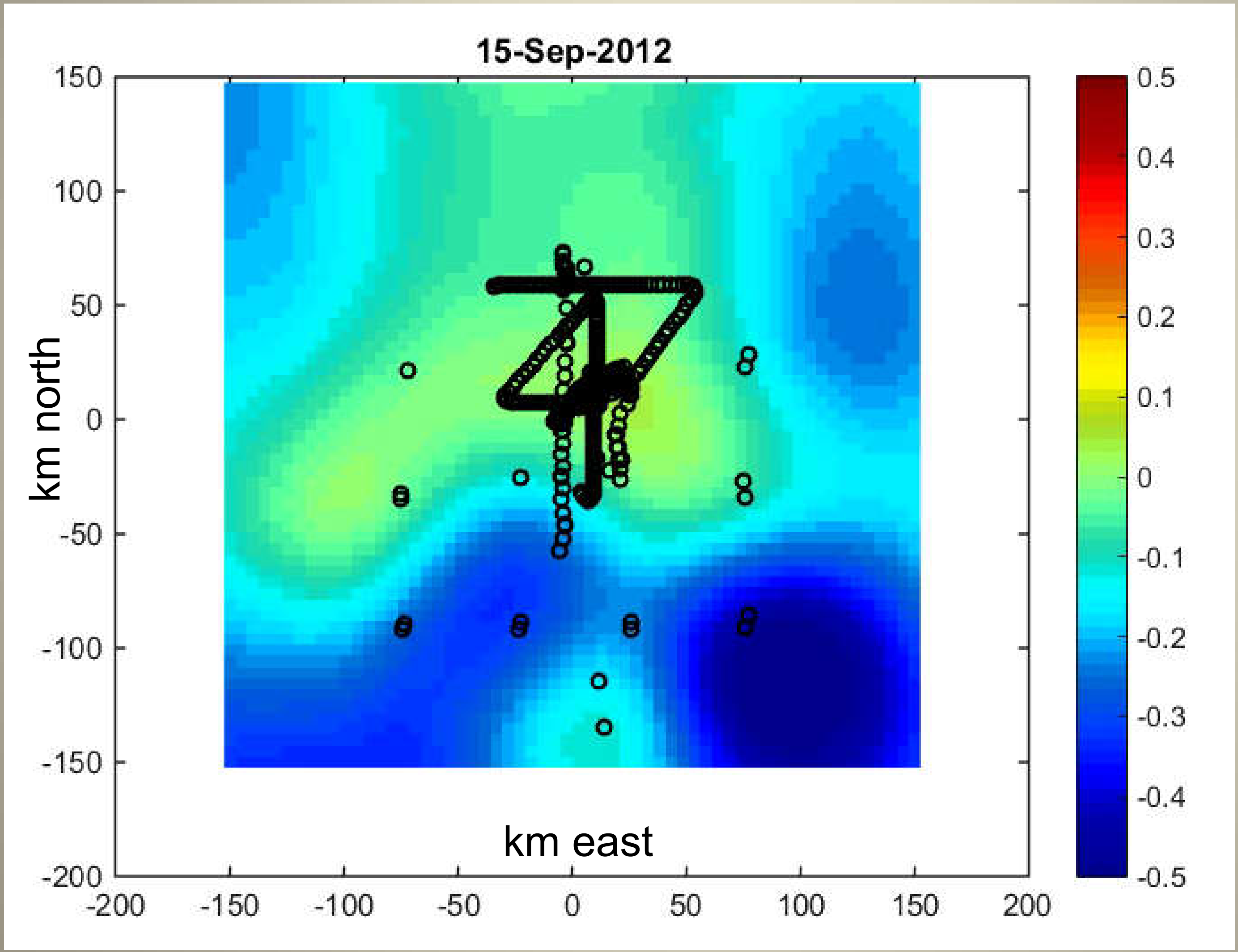
Unresolved salinity gradients and gradient estimation errors

$$\frac{\partial \bar{S}}{\partial t} = -\bar{\vec{u}} \cdot \overline{\nabla S} + \frac{\hat{S}_{-h}}{h}\left(\frac{\partial h}{\partial t}\right) - \frac{F_{-h}}{h} + \frac{(E-P)S_o}{h} - \overline{\hat{\vec{u}} \cdot \hat{\nabla} \hat{S}} - \overline{w \frac{\partial S}{\partial z}} - \overline{\vec{u} \cdot (\nabla S)'}$$



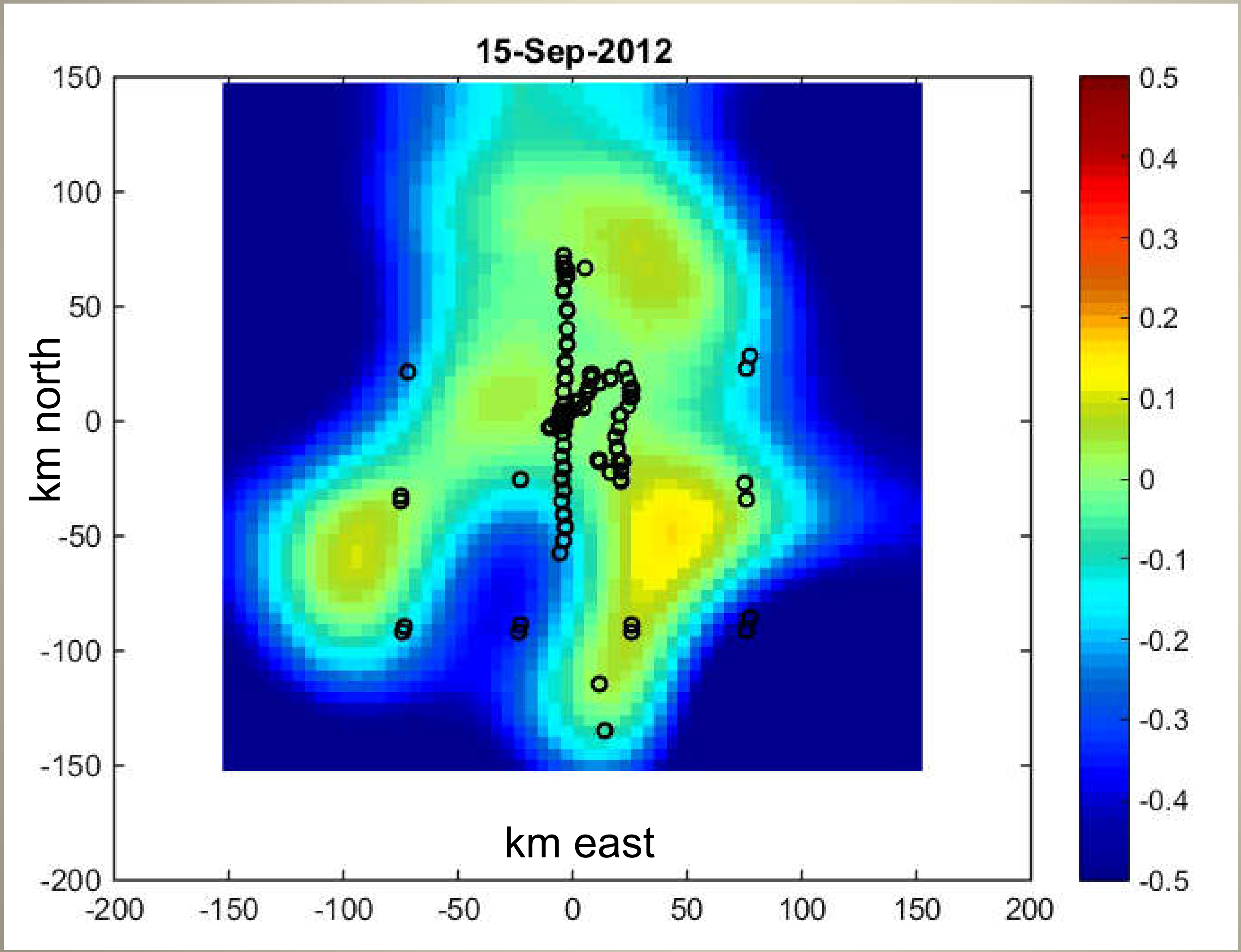
Loss of some instruments/platforms caused some trouble, especially at depths>10m

5m salinity anomaly relative to WHOI mooring

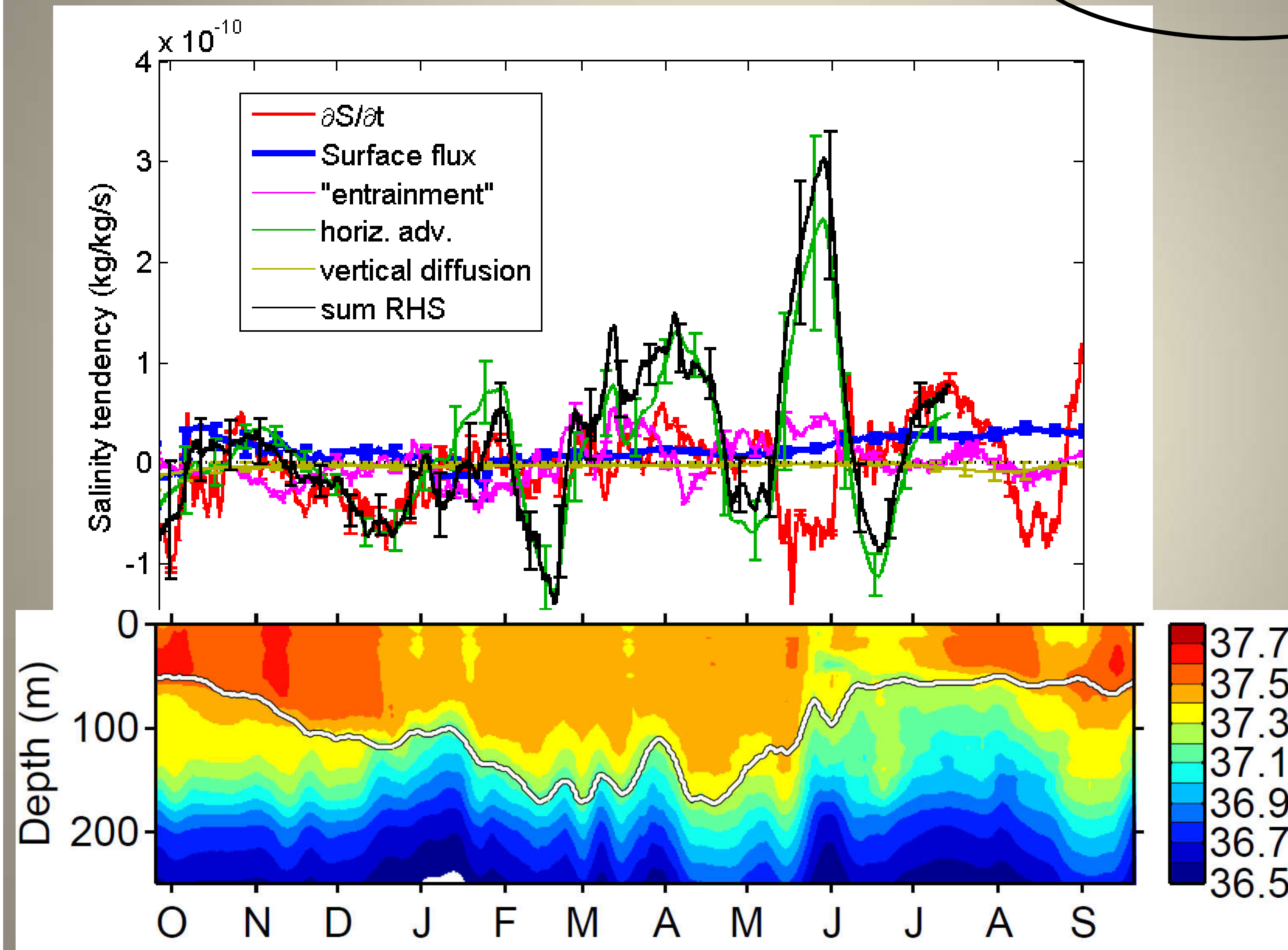


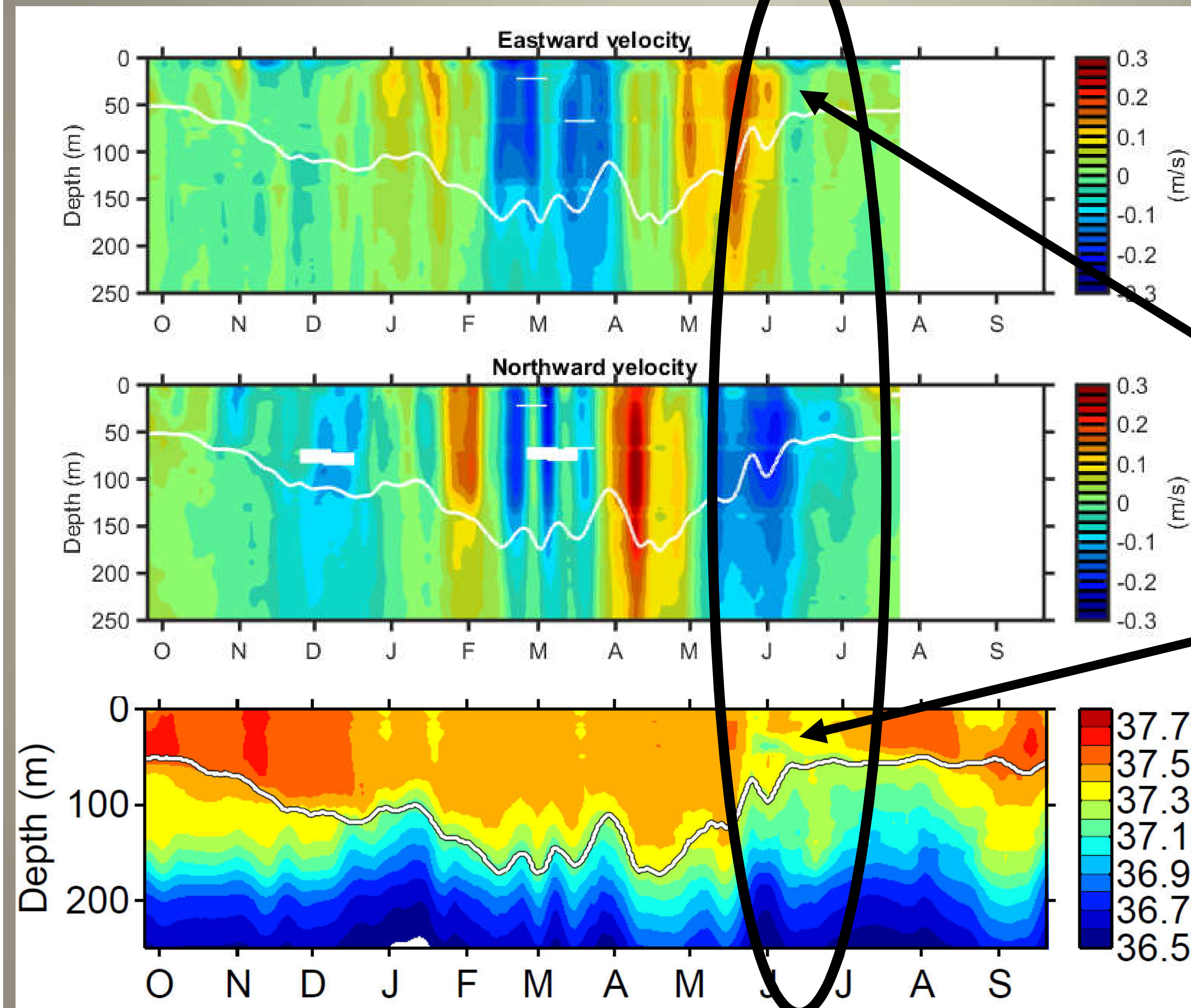
Loss of some instruments/platforms caused some trouble, especially at depths>10m

50m salinity anomaly relative to WHOI mooring



$$\frac{\partial\overline{S}}{\partial t} = -\overline{\vec{u}}\cdot\overline{\nabla S} + \frac{\hat{S}_{-h}}{h}\left(\frac{\partial h}{\partial t}\right) - \frac{F_{-h}}{h} + \frac{(E-P)S_o}{h} - \overline{\hat{\vec{u}}\cdot\hat{\nabla}\hat{S}} - \overline{w\frac{\partial S}{\partial z}} - \overline{\vec{u}\cdot(\nabla S)'}$$





In addition to estimation errors in the gradients, the stratified, sheared advection term (e.g., "frontal slumping" or intrusions) is probably important here

Conclusions and trajectory:

- During fall and winter, mixed-layer T and S balances are "closed" (i.e., balanced within error bars by terms we estimated).
  - For the 3-week averages considered here, the variability in salinity is mostly from mesoscale advection
- In spring and summer, the salinity balance is markedly different
  - The salinity balance has very large contributions from horizontal advection that do not covary with dS/dt. These 'unbalanced' advection terms may indicate important:
    - *Estimation errors* and unresolved gradients
    - The "stratified, sheared advection" term
    - Vertical advection

→ Next steps: (1) attempt to estimate missing terms, (2) consider 3D conservation equations (when array permits), (3) use budgets to home in on important physical processes

An organizing goal of the field campaign was to measure the terms in the equation for mixed-layer salinity:

$\overline{S} \equiv$ vertical average of S over depth h(t)

$\hat{S}(z) \equiv$ deviation of S from its vertical average in the mixed layer (h)

Version used here:

$$\frac{\partial \overline{S}}{\partial t} = -\overline{\vec{u}} \cdot \overline{\nabla S} + \frac{\hat{S}_{-h}}{h}\left(\frac{\partial h}{\partial t}\right) - \frac{F_{-h}}{h} + \frac{(E-P)S_o}{h} - \overline{\hat{\vec{u}} \cdot \hat{\nabla} \hat{S}} - \overline{w\frac{\partial S}{\partial z}}$$

Version more often used:

$$\frac{\partial \overline{S}}{\partial t} = -\overline{\vec{u}} \cdot \nabla \overline{S} + \frac{\hat{S}_{-h}}{h}\left(\frac{\partial h}{\partial t} + w_{-h} + \vec{u}_{-h} \cdot \nabla h\right) - \frac{F_{-h}}{h} + \frac{(E-P)S_o}{h} - \frac{1}{h}\nabla \cdot \int_{-h}^{0} \hat{\vec{u}}\hat{S}\,dz$$