An Ocean Heat Budget for the Florida Reef Tract

Sea temperature variability, air-sea flux, and the *thermal siphon*

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http://ecoforecast.coral.noaa.gov

Significance of reef sea temperature

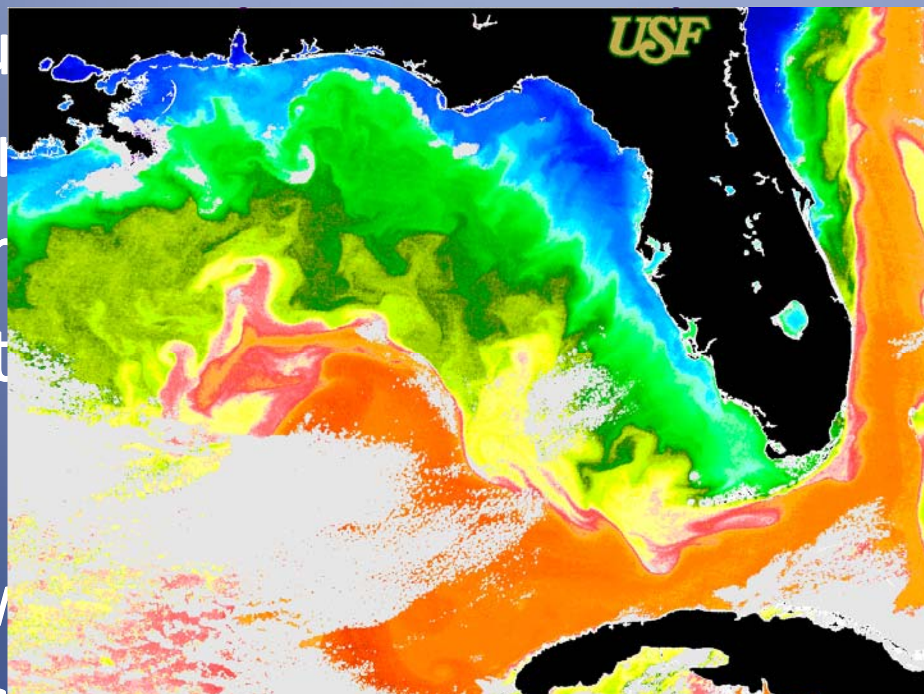
- Thermal environment
  - Sea temperature is a control on growth rate of reef-building corals (e.g., Cantin et al. 2010)
  - Extremes can cause bleaching and mortality
  - Can play a role in spawning & settlement success
- As a proxy for studying nutrient fluxes
  - Upwelling (T/N,P relationships below thermocline, e.g., Leichter et al. 2003, Hitchcock et al. 2005)
  - Cross-shore flows (land sources)

Reef Sea Temperature and Climate

- Our current understanding of the global air-sea climate system comes from coupled numerical models at regional scales, using satellite data at kilometer scales and greater.

- To downscale long-term forecasts to coral reef ecosystem impacts means accounting for physical processes at all scales – from global systems to *individual coral communities*.

Reef Sea Temperature and Climate



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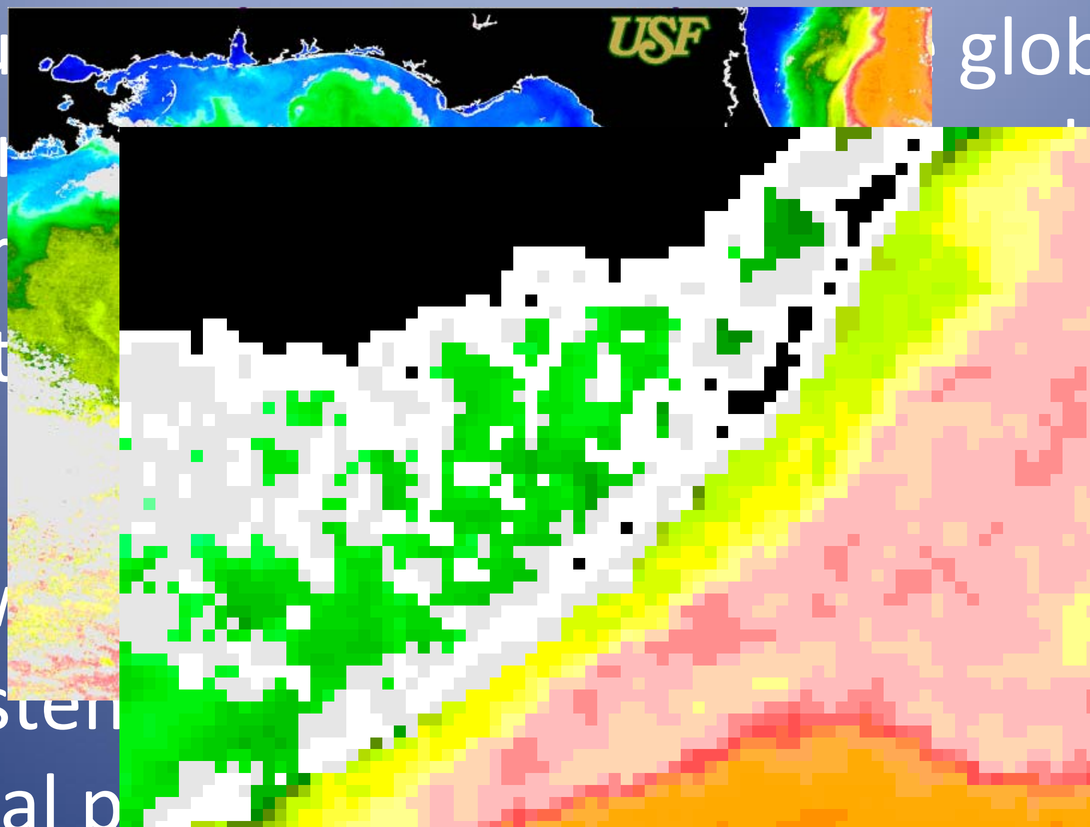

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Reef Sea Temperature and Climate

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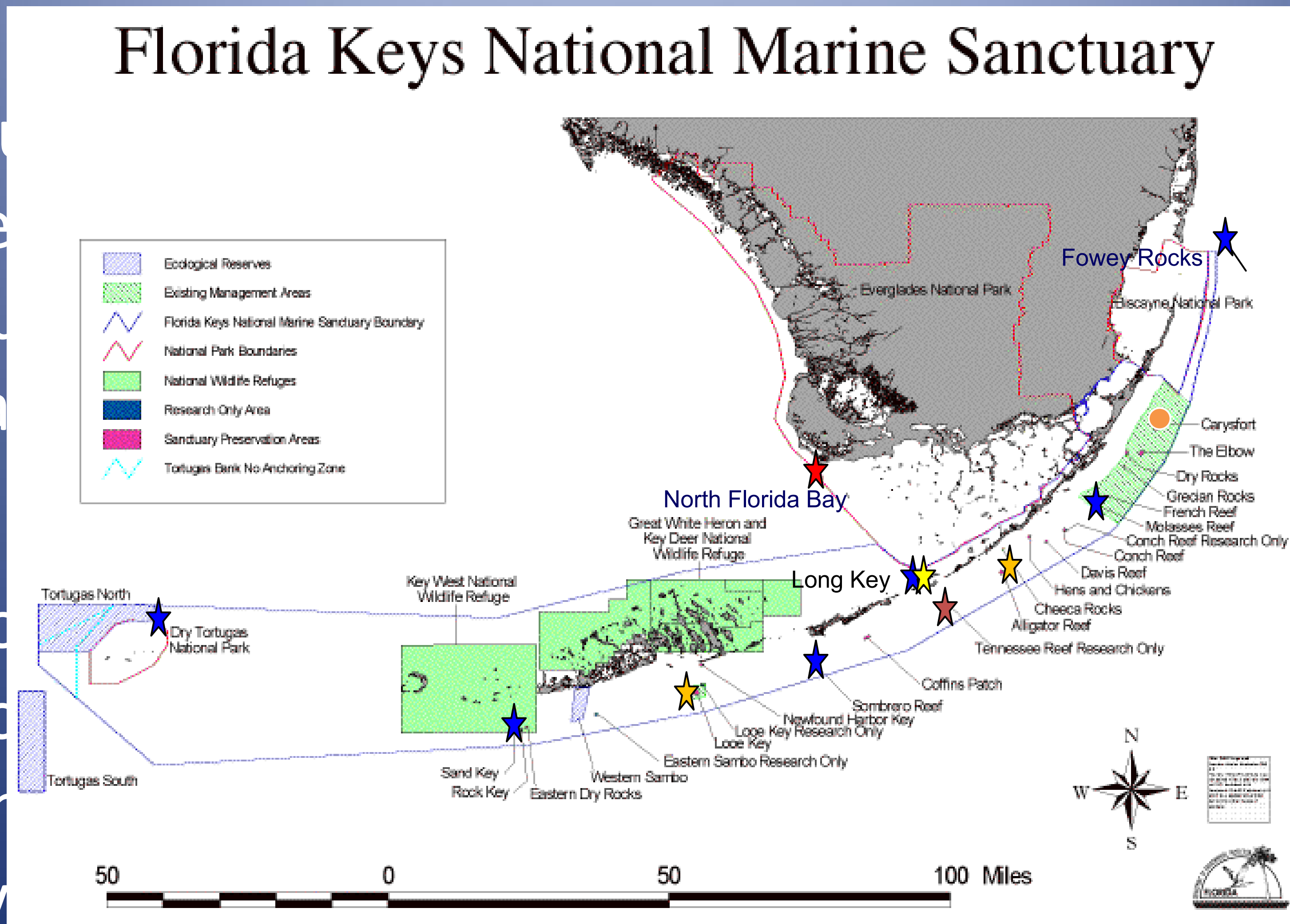

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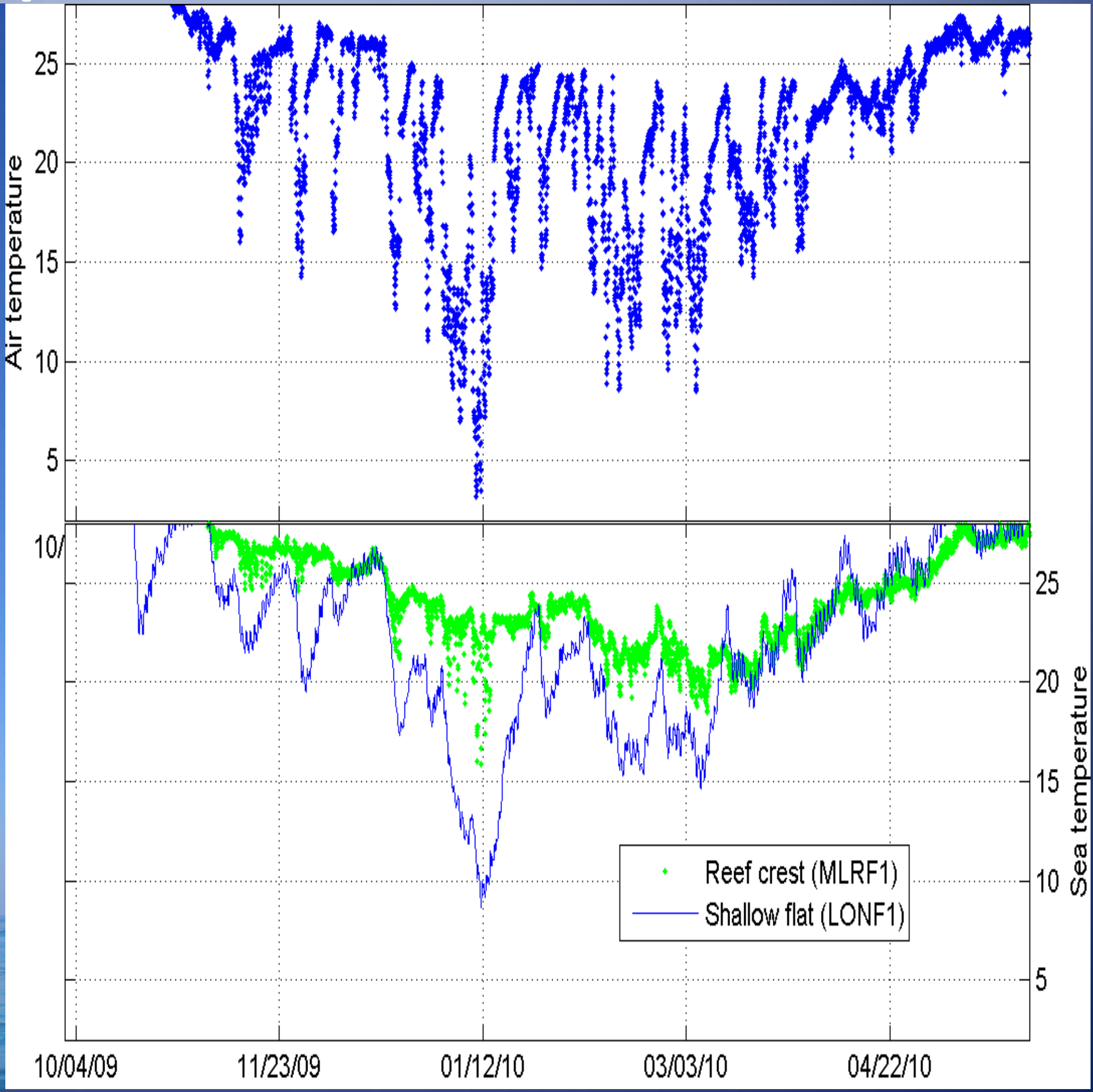
Reef Sea Temperature and Climate



Reef Sea Temperature Variability

- Rapid cooling events in summer can often be identified with storm-induced surface waves and storm surge (Manzello et al. 2007)
- Higher than normal variability can also be coincident with passage of eddies offshore (Gramer et al. 2009), and with shoaling of internal waves (e.g., Davis et al. 2008).
- To characterize these events in the record, we must account for all sources of ocean heating.

Heat budget

$$T_t = -\vec{u}_{km} \bullet \nabla_h T_{km} - \vec{u}_{qe} \bullet \nabla_h T_{sfc} - \vec{u}_{hc} \bullet \nabla_h T_{hc}(Q_0, h, \beta) + \frac{Q_0}{\rho C_p h}$$

- Air-sea fluxes:
  - Turbulent – TOGA-COARE 3.0a (Fairall et al. 2003)
  - Radiative – NCEP NARR (32km reanalysis, Mesinger et al. 2006)
- Kilometer-scale advection: sources of estimates
  - Gulf of Mexico HYCOM (4km res., 2003-2010)
  - Florida Keys HYCOM (~900m res., 2008)
- Sub-kilometer scale advection

  (Only parameterized in kilometer-scale ocean models)
  - Wind- and swell-driven surface transport? (Ardhuin et al. 2009)

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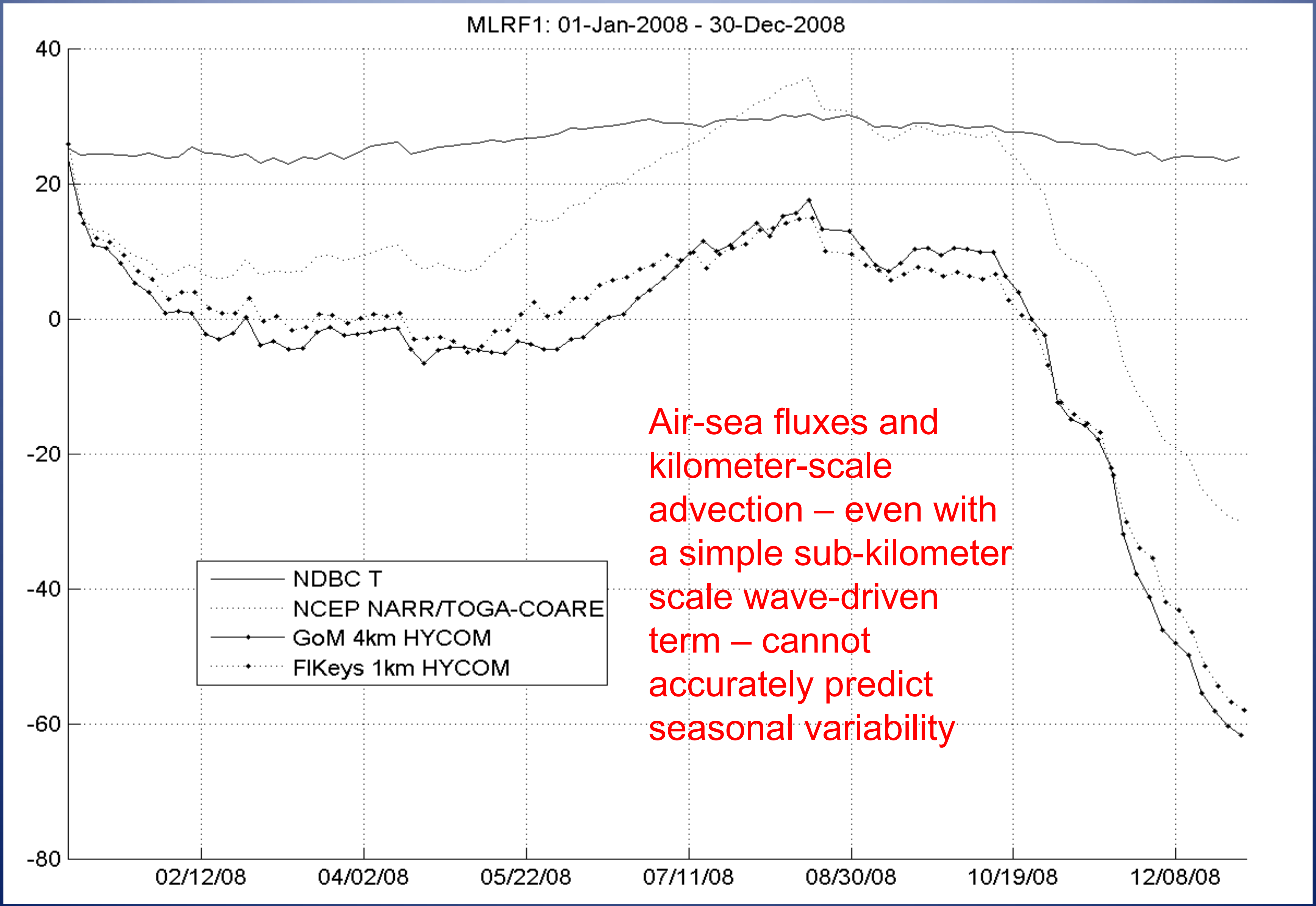
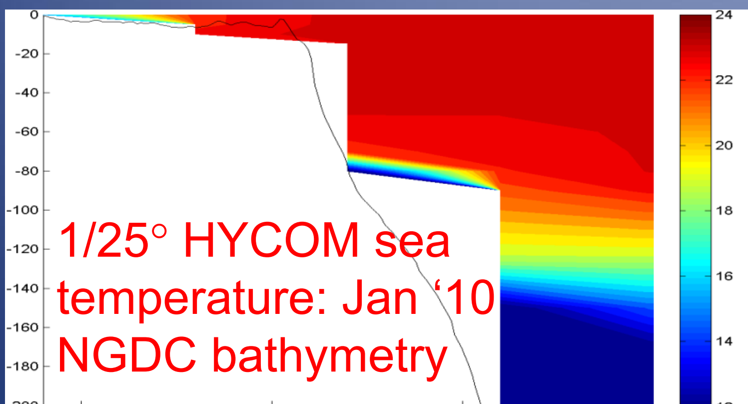
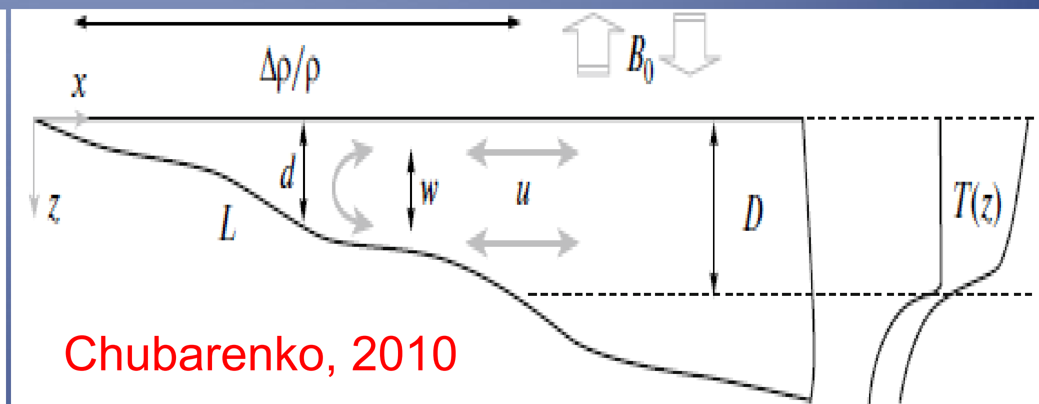
Results – air-sea and km-scale only



Horizontal Convection – *thermal siphon*

- Air-sea flux and km-scale heat advection alone do not model variability well: is there also a smaller-scale oceanographic process at work?





Monismith et al., 2006

TABLE 1. Possible scalings for ΔV.

Balance	Unsteady inertia	Stress divergence	Advective inertia
Steady temperature	$V_{US} \sim (u_f^3 T/D)^{1/2}$	$V_{VS} \sim (u_f^{3/2}/q^{1/2})$	$V_{NS} \sim \beta^{-1/3} u_f$
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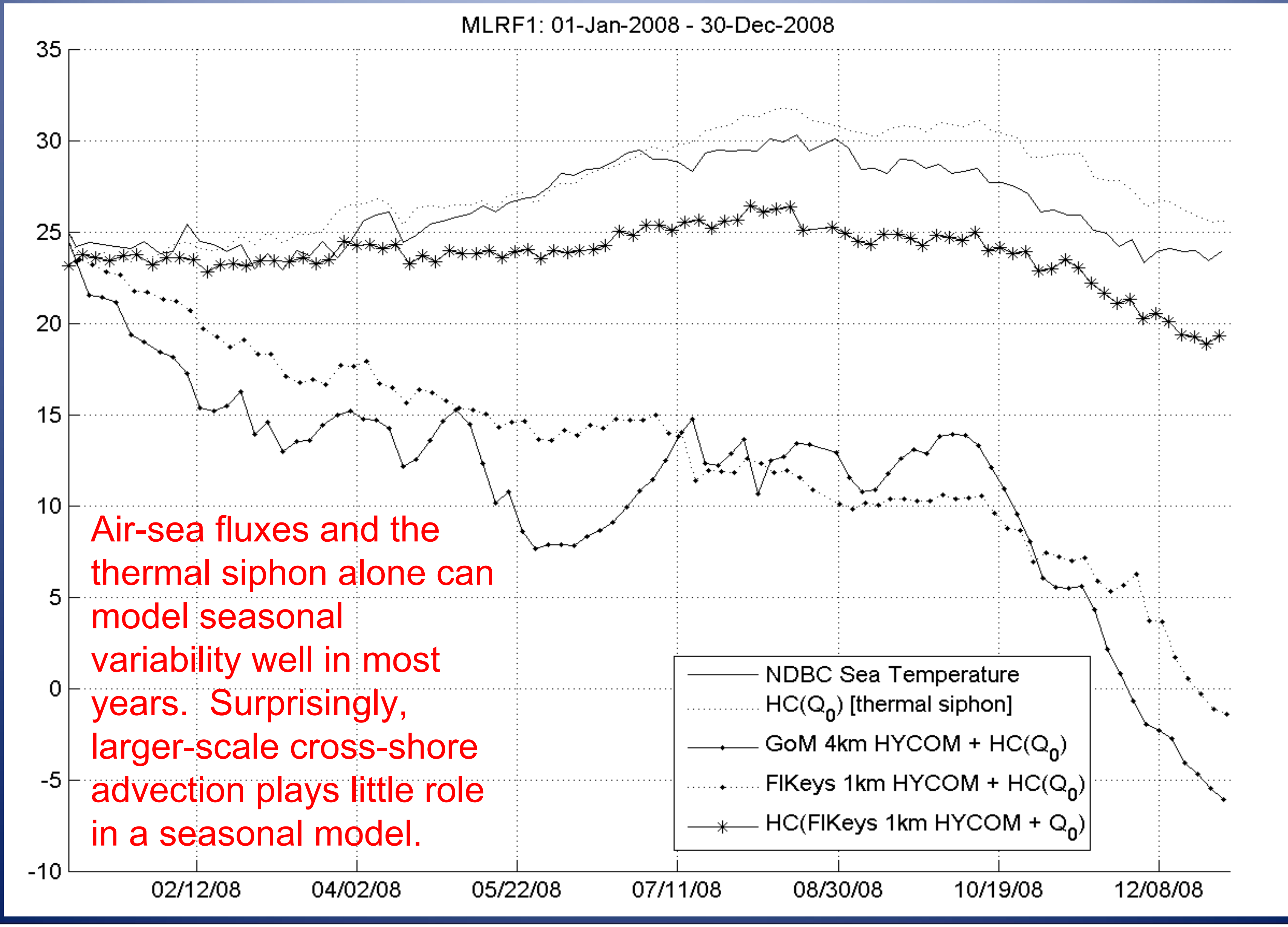
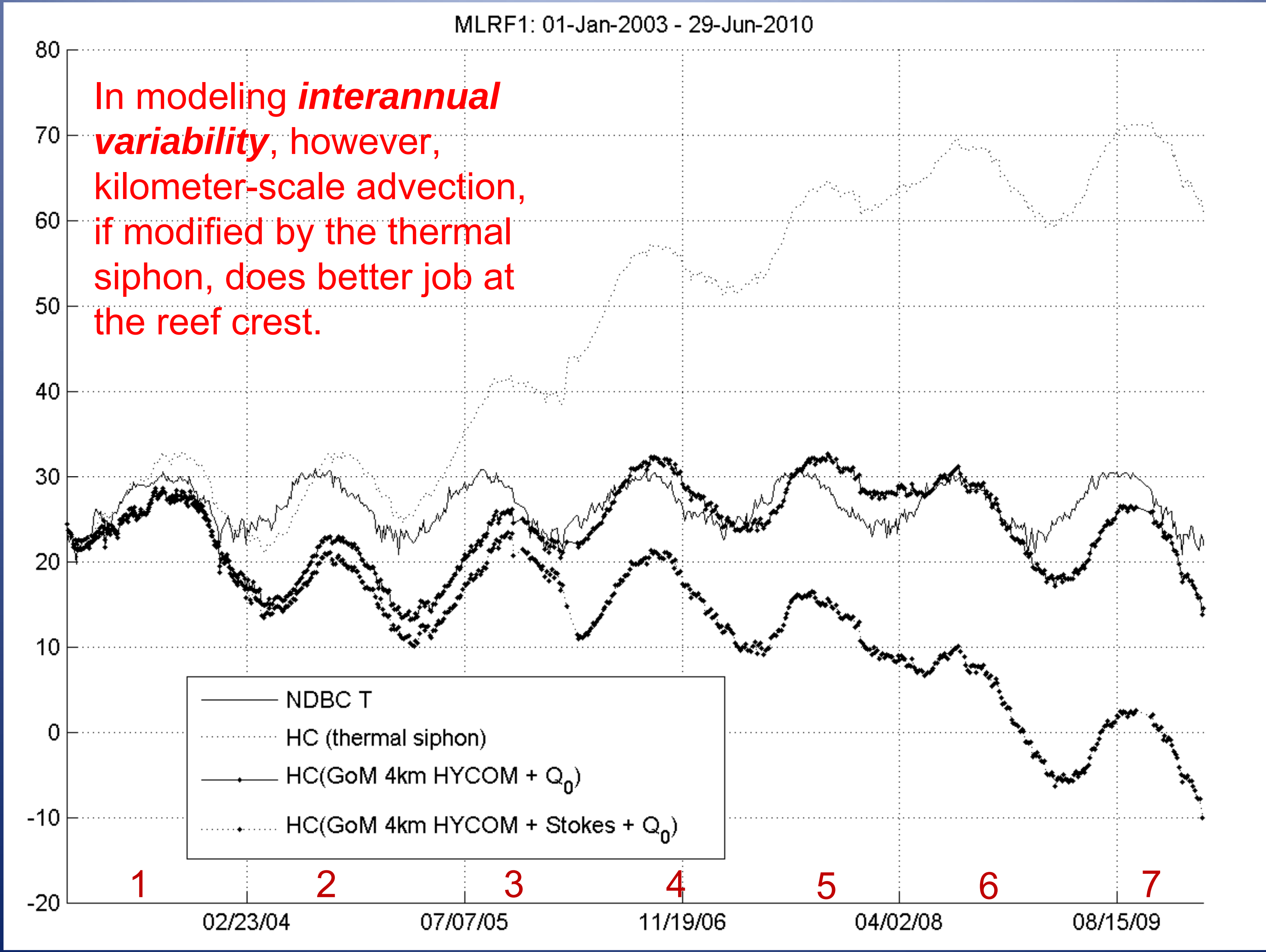
Results (various models, with and without siphon)

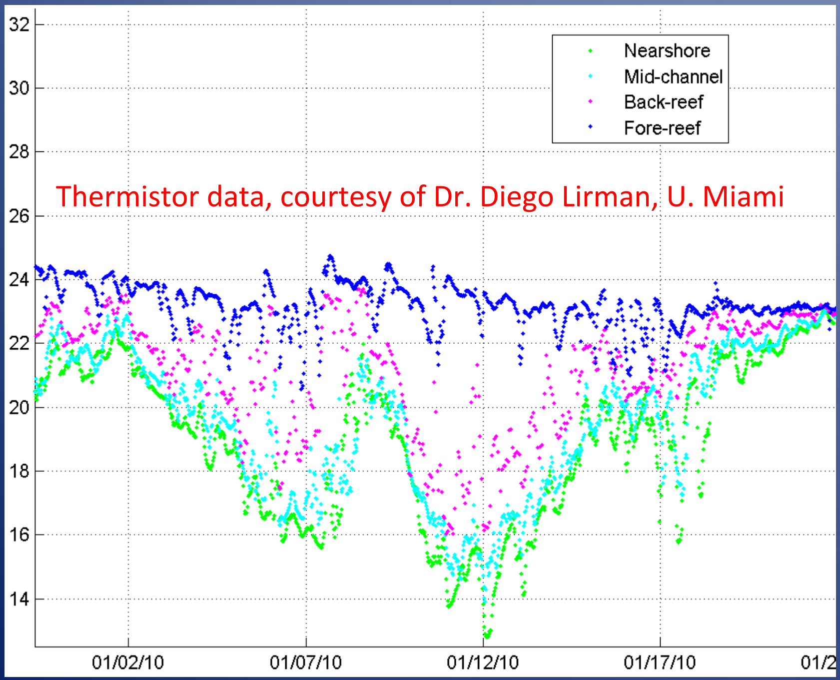


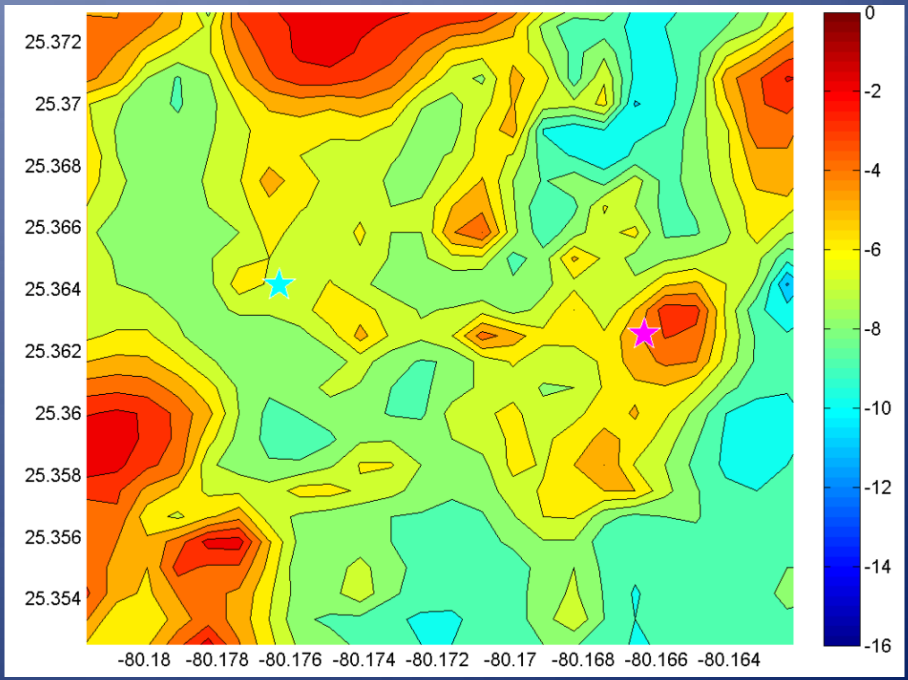
Results – reef crest sites



Results – low-relief areas

- Two Upper Keys thermistor sites at similar depths of 4-5m, one on a mid-Channel flat, the other a back-reef promontory (magenta and cyan stars in bathymetry map below): in the cold snap of 2010, the same air-sea forcing brought very different responses between the two sites – the thermal siphon only being able to moderate sea temperature variability effectively at the higher-relief site (magenta).





Future Work

- Apply heat budget to analyze higher-frequency (***weekly to diurnal period***) variability.
- Model extreme events (e.g., ***upwelling***) not well explained by the current heat budget
- Adapt the heat budget as a ***management tool***, recognizing patterns in physical data likely to impact effective management of reef ecology.

Acknowledgements, References

In situ data from NOAA NDBC and FIO, and Dr. Diego Lirman, UM RSMAS; insightful comments by Drs. Derek Manzello and Kevin Helmle, NOAA AOML

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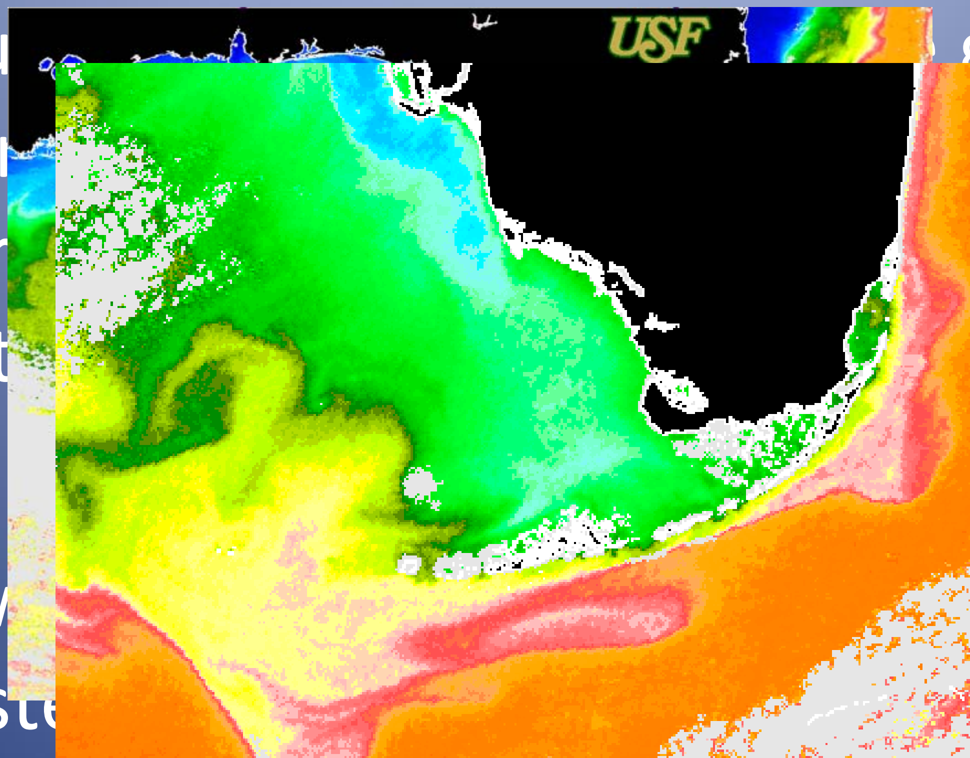
Photo © J. E. N. Veron, Corals of the World, 2000
Large *Porites astreoides* (“mustard hill coral”)

Additional Slides

Background - SEAKEYS

- C-MAN / SEAKEYS monitoring stations
  - At sites on the reef crest (8km offshore) and near shore
  - Continuous long-term hourly records (>20 years)
  - Sea temperature, meteorology, and in some cases salinity, tide depth, surface and sub-surface light, and other variables
  - Quality control procedures applied to most variables
- Hourly sea temperature record
  - Energetic variability at multiple periodicities: 6- and 8-hour, M_2 tidal, diurnal, inertial (28h), seasonal, *interannual trends*
  - Strong mean squared coherence with air temperature at diurnal, seasonal, 4-, 12-, and 80-day periodicities
  - Occasional periods of very low diurnal coherence

Reef Sea Temperature and Climate



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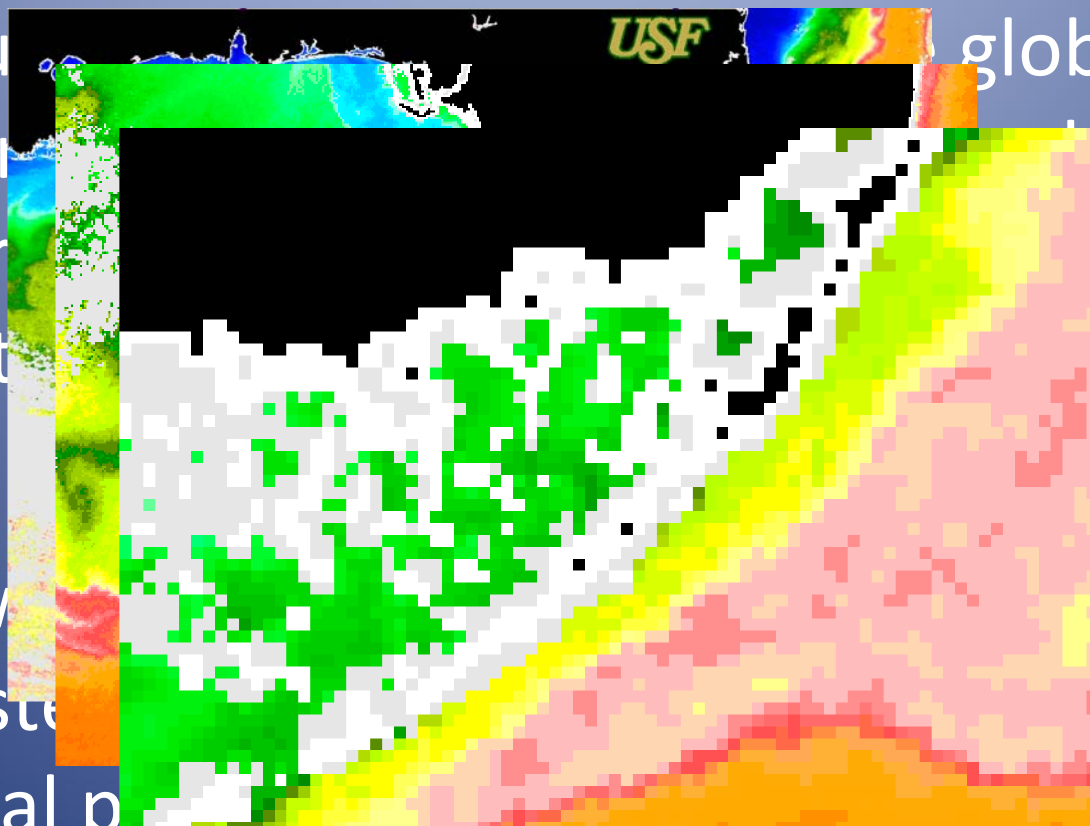

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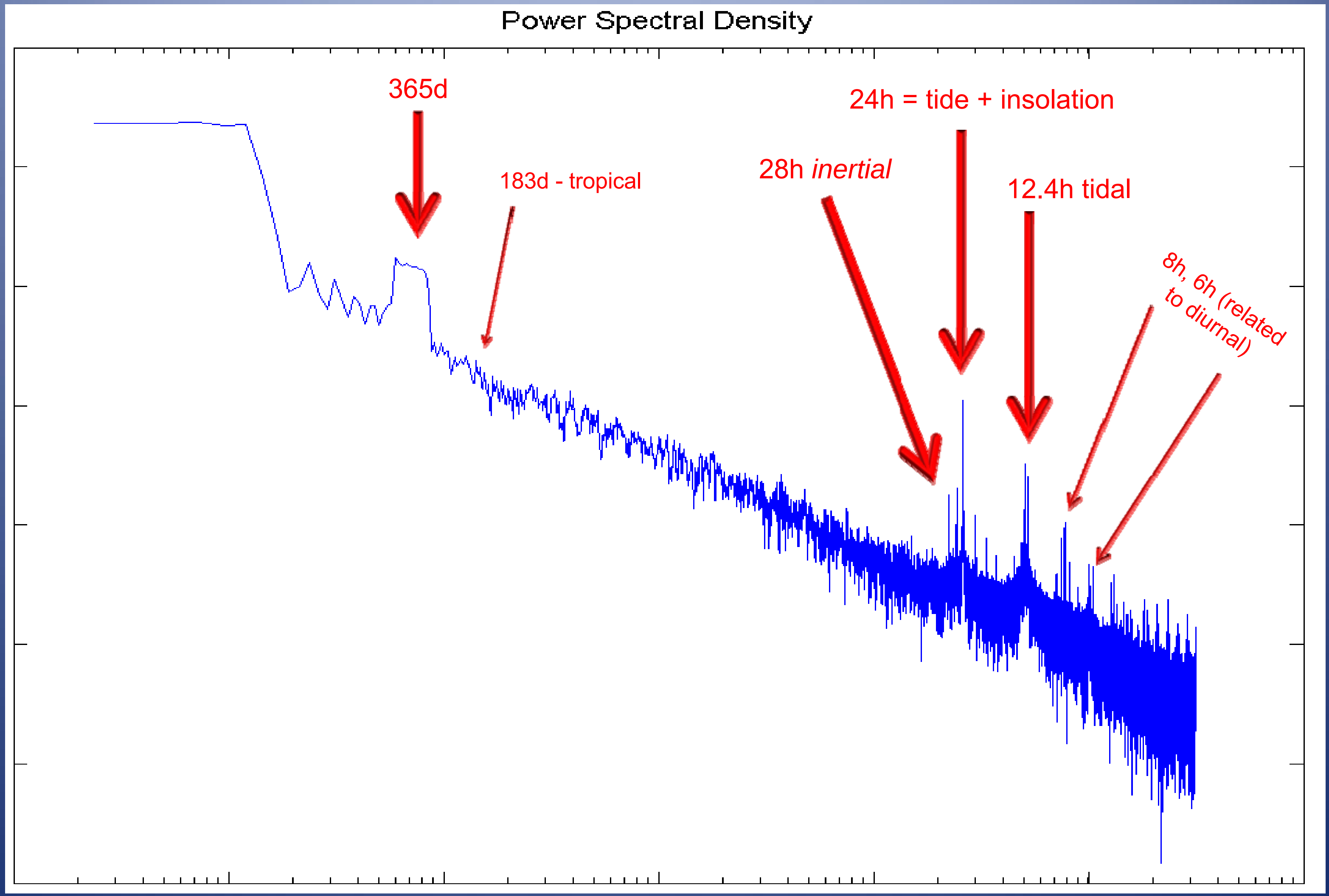
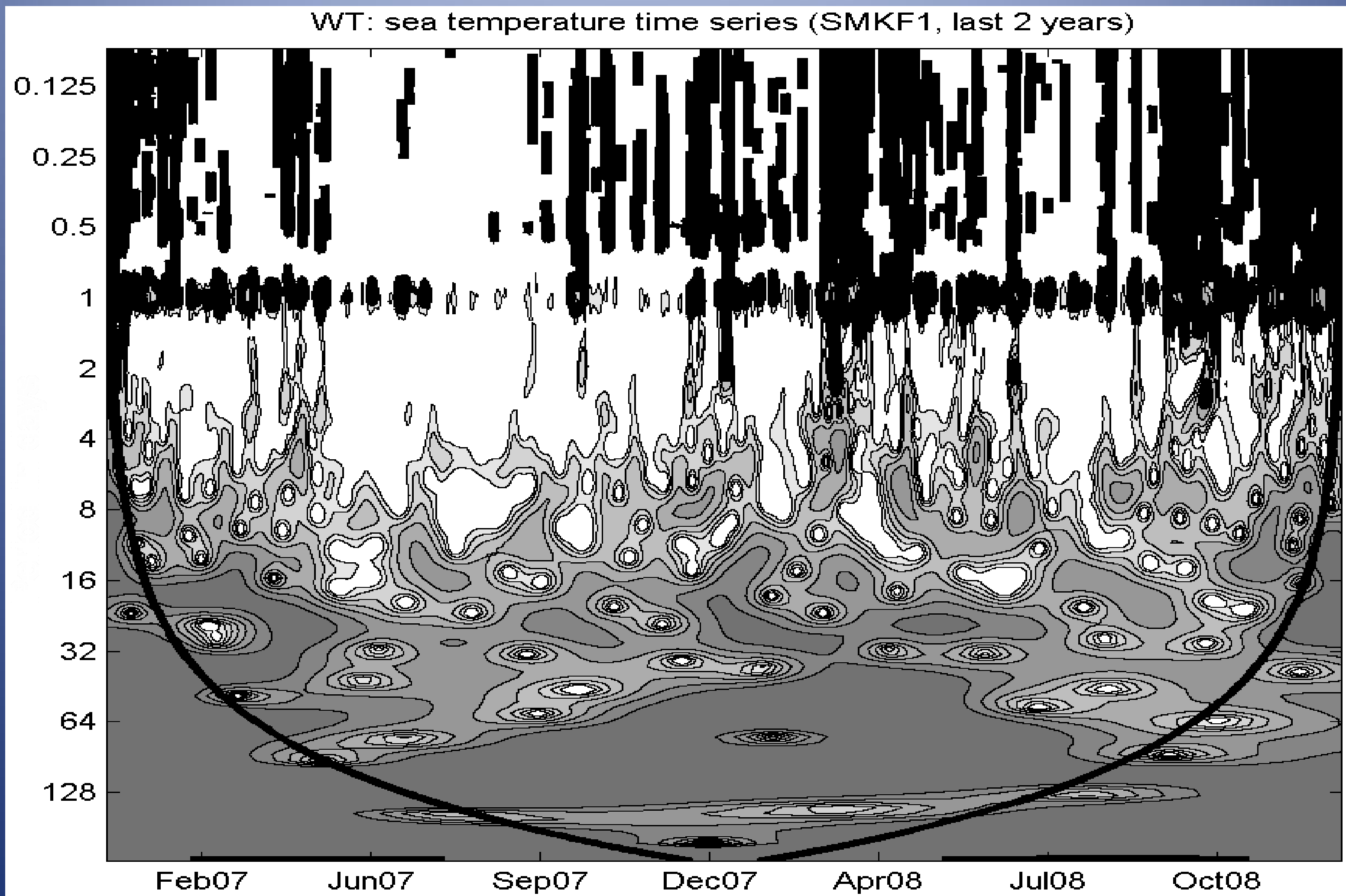
Sea temperature spectrum



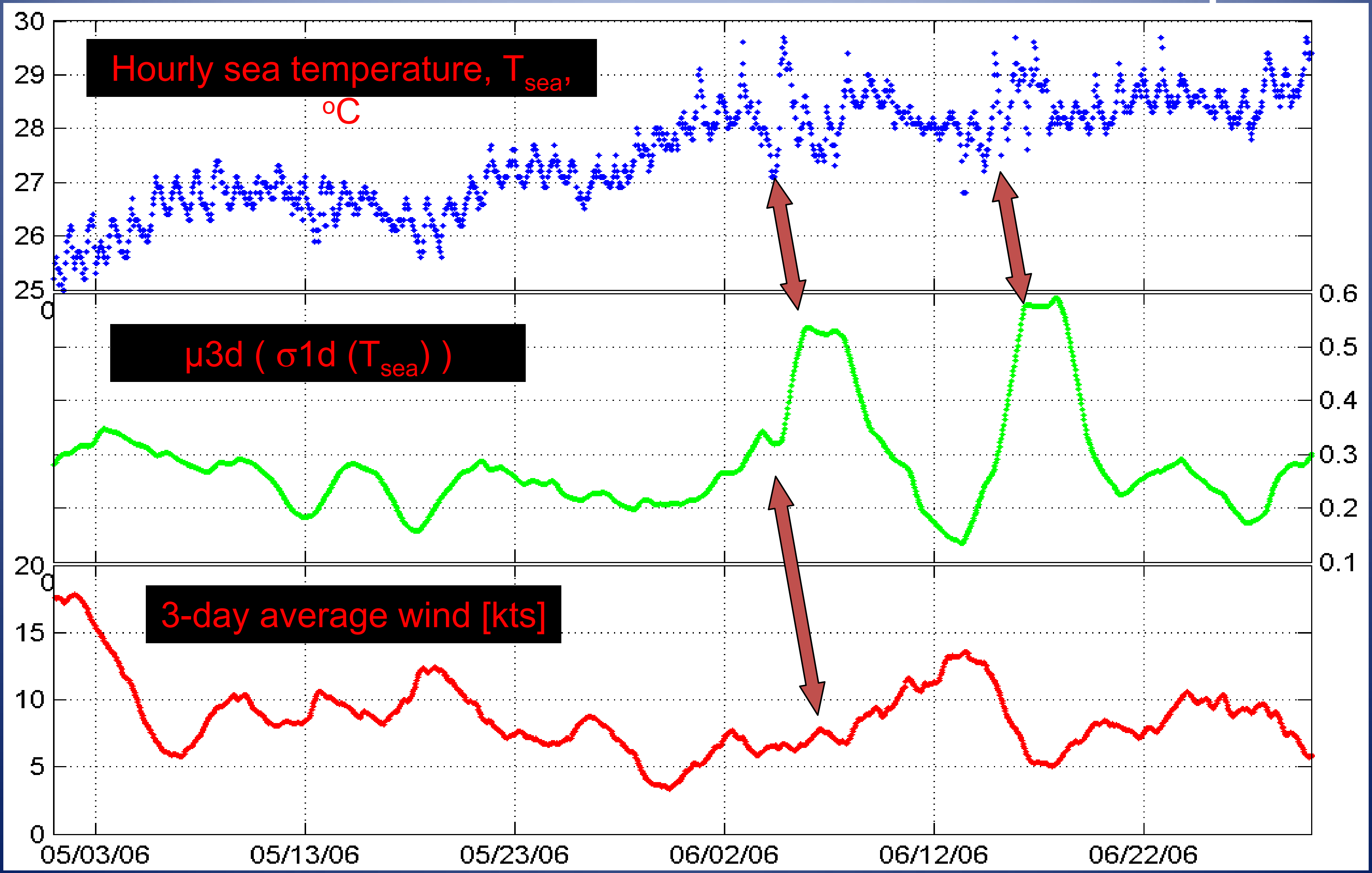
Oceanographic and air-sea processes at a range of time/space scale

Time-dependent spectrum

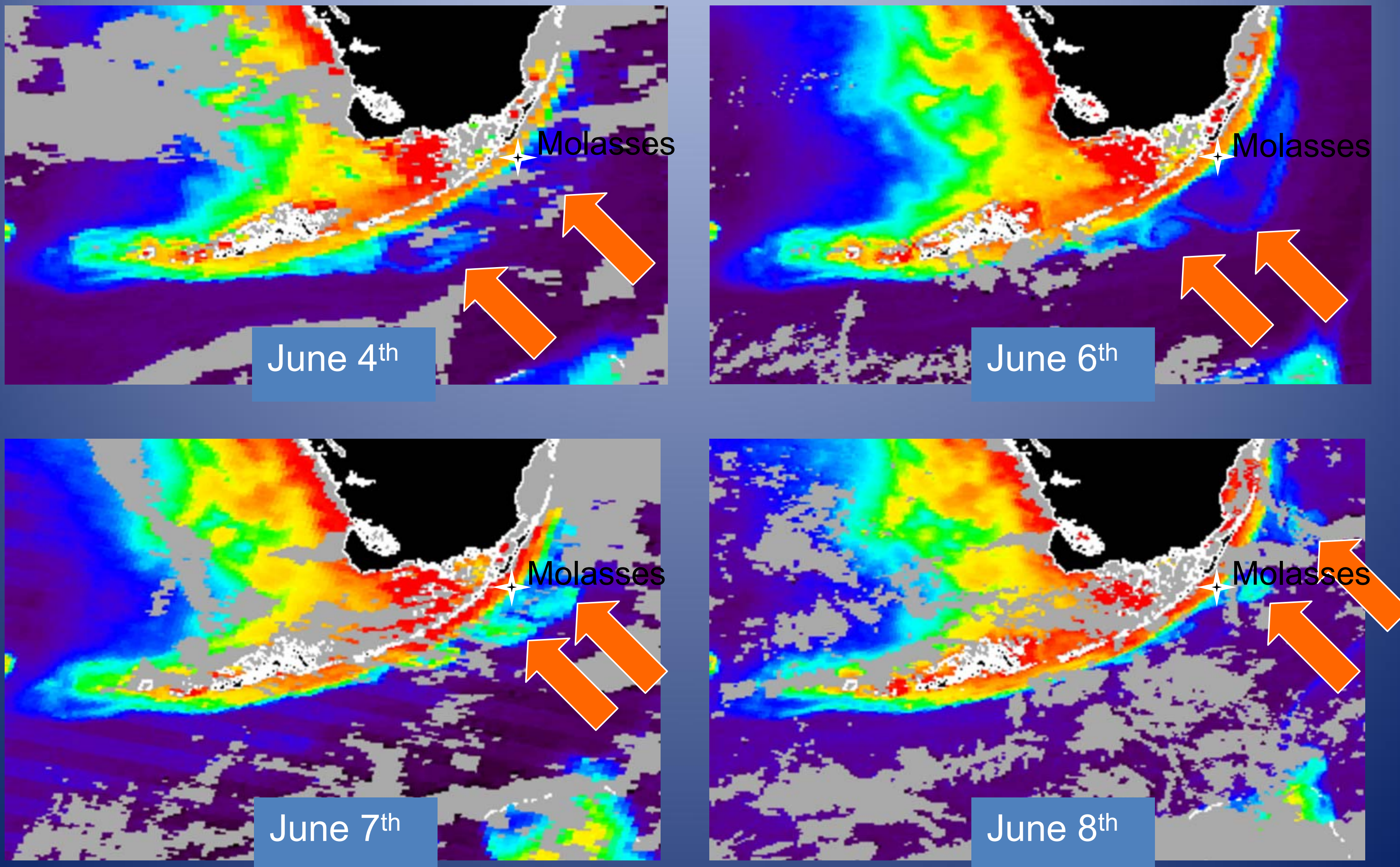


Energy in reef processes ***bleeds between*** time scales!

Initial Motivation – June 2006 example



June 2006 – *cyclonic* chlorophyll features



Heat budget

- Sea temperature variability
  - How much is forced by direct air-sea flux? Horizontal mixing and advection? Vertical mixing and upwelling (winds, eddies, internal waves)?

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$$Q_0 = \gamma Q_{SW} + Q_{LW} + Q_{SH} + Q_{LH} + Q_{RH}$$

$$\gamma = 1 - A_b \cdot \tau_{PAR} \cdot (1 - \tau_{PAR}), \ \tau_{PAR} = \exp(-K_d^{PAR} \cdot h \cdot \sec(\theta))$$

$$|\vec{u}_{qe}| \cong 5.0\times10^{-4}[1.25 - 0.25(\frac{0.5}{f_c})^{1.3}]\left|U_{10} \times \min\{U_{10}, 14.5\}\right| + 0.025(H_S - 0.4)$$

$$Q^V{}_{hc} = C \cdot \beta \cdot u_f{}^3 \cdot T_f{}^2 / h^2$$

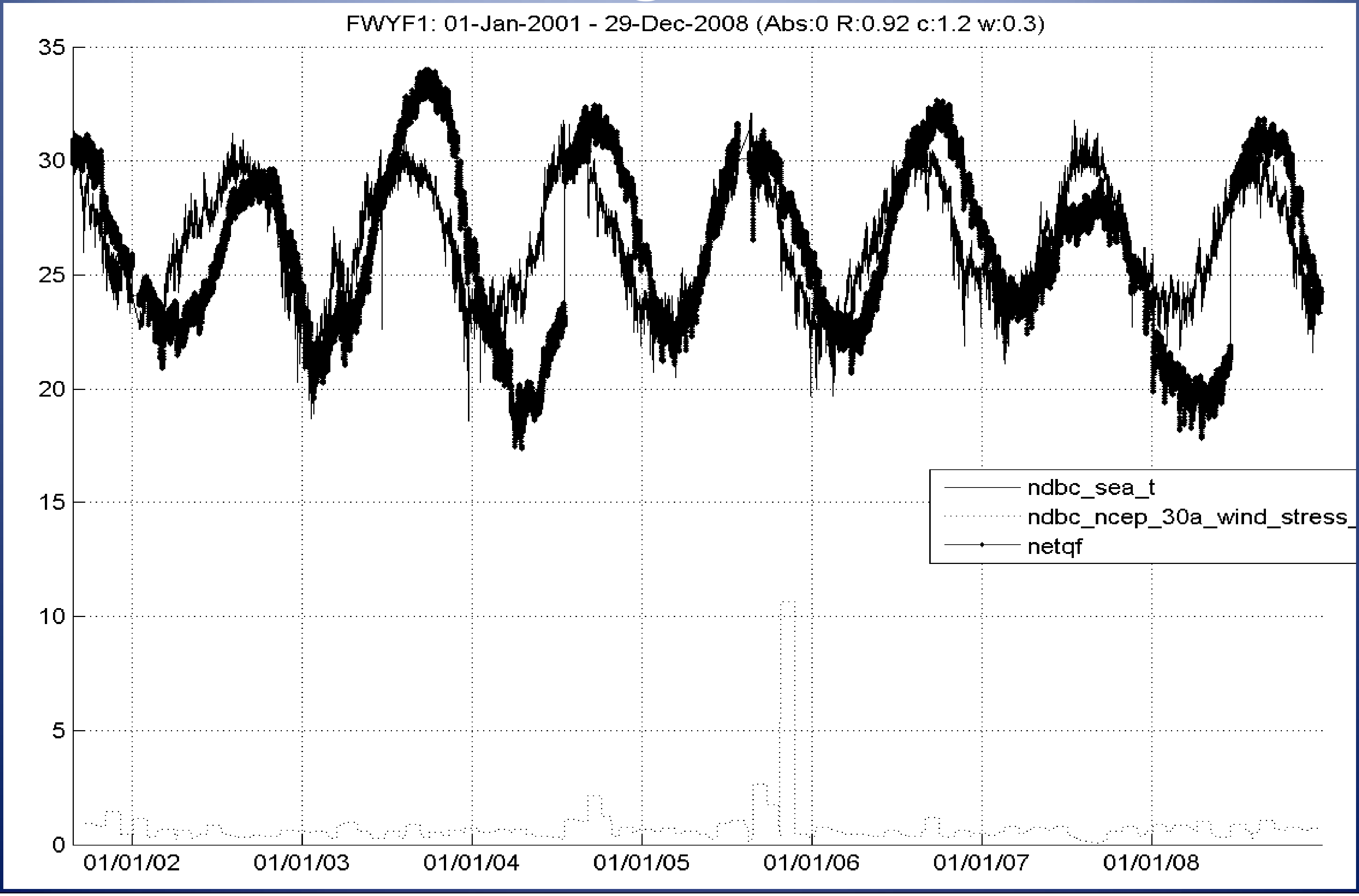
$u_f = (\alpha \cdot g \cdot h \cdot H_0)^{1/3}$,

$H_0 = Q_{24hSMA}/\rho C_p$.

$$\vec{u}_{hc} = \frac{Q^V{}_{hc}}{h};$$

$$|\nabla_h T_{hc}| = \frac{H_0}{\rho C_p}\left(\frac{1}{h} - \frac{1}{(h + \beta\ell)}\right)$$

Heat Budget - Results



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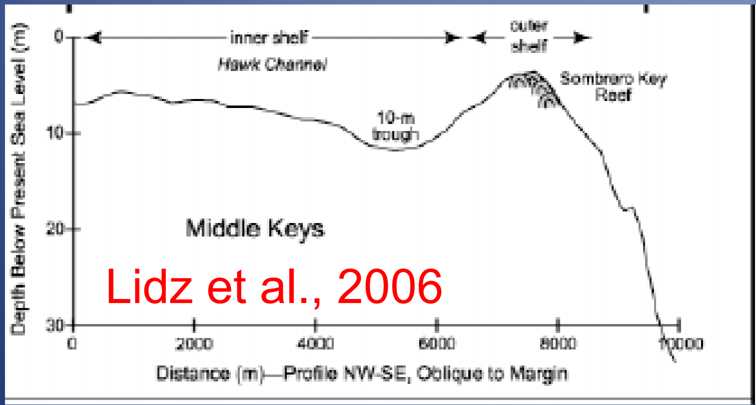

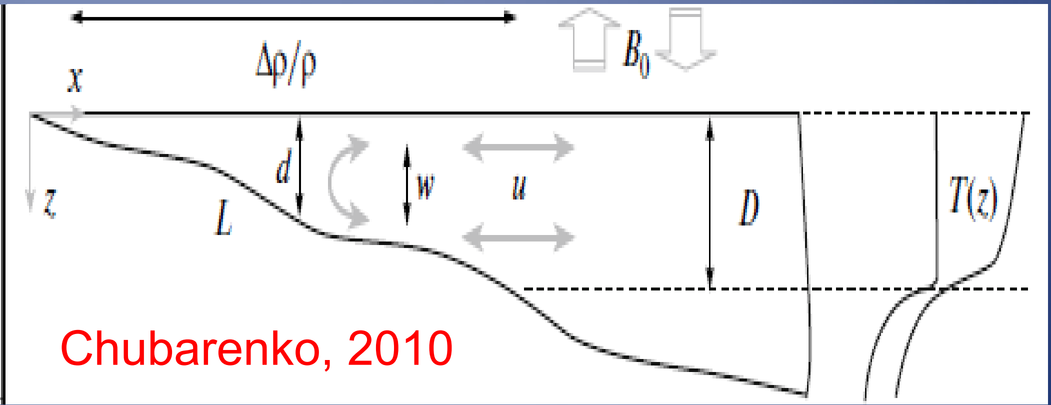

Monismith et al., 2006

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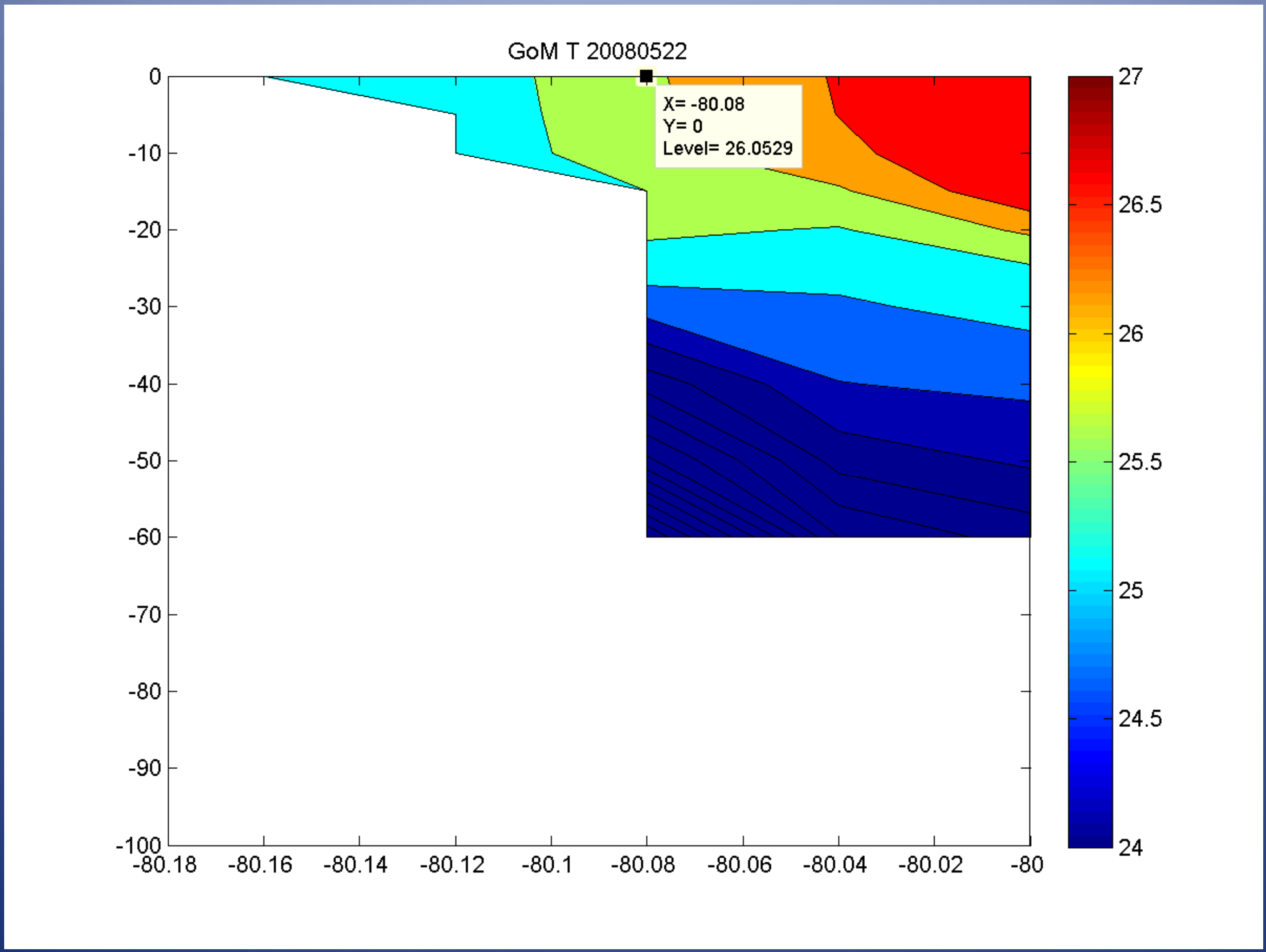
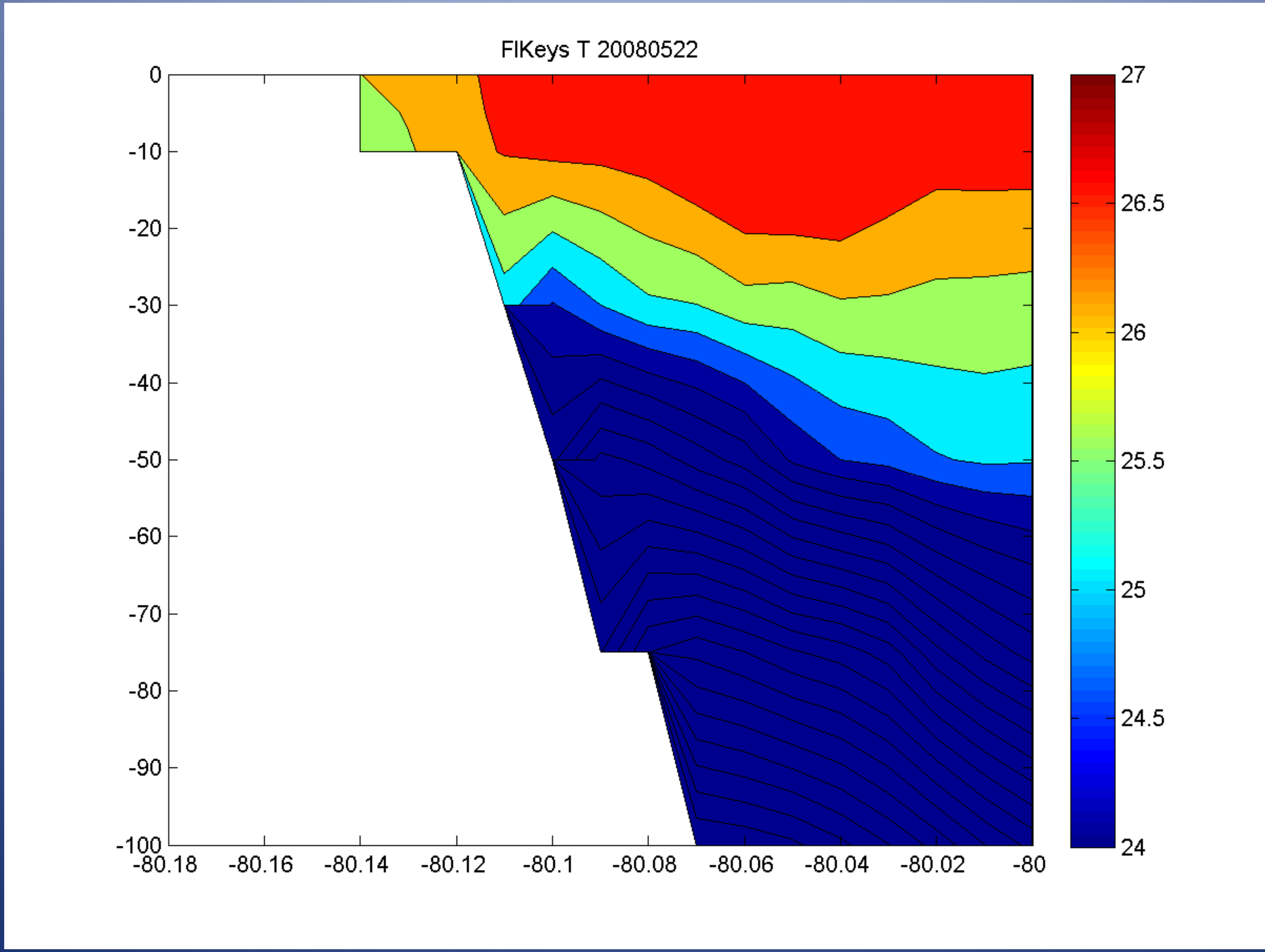
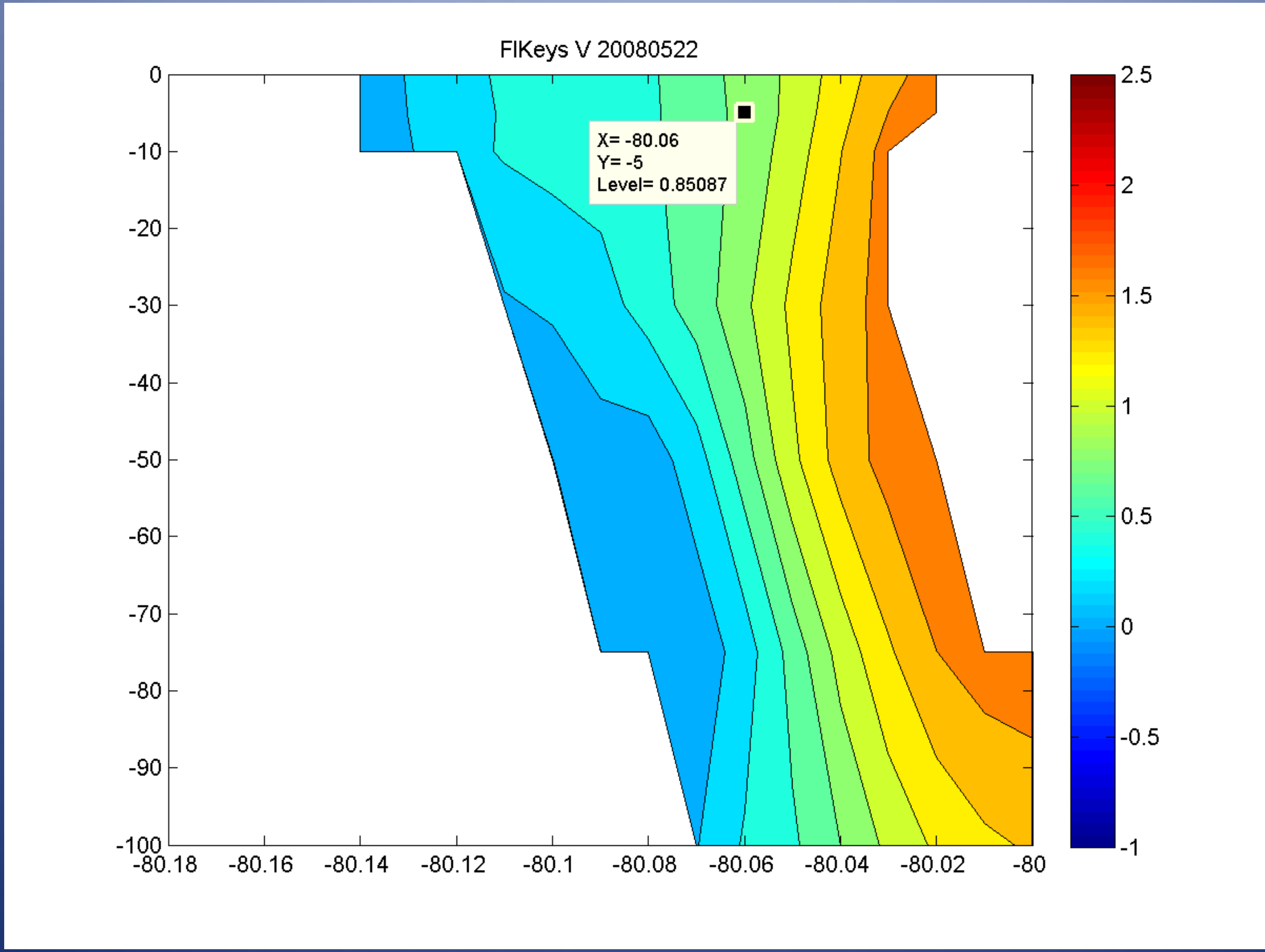
Cross-shore temperature profile – Gulf of Mexico HYCOM (May 2008)



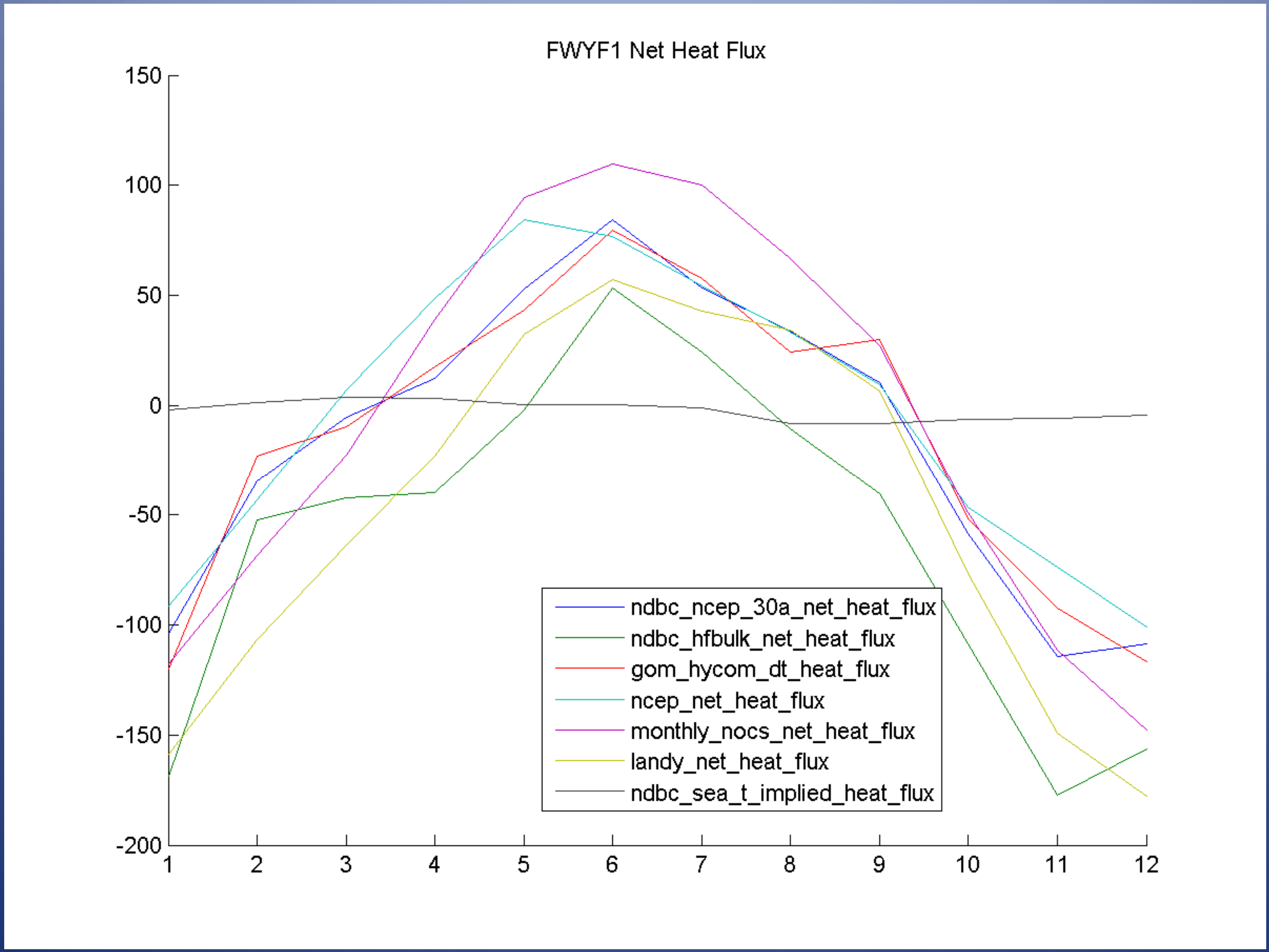
Cross-shore temperature profile – Florida Keys HYCOM (May 2008)



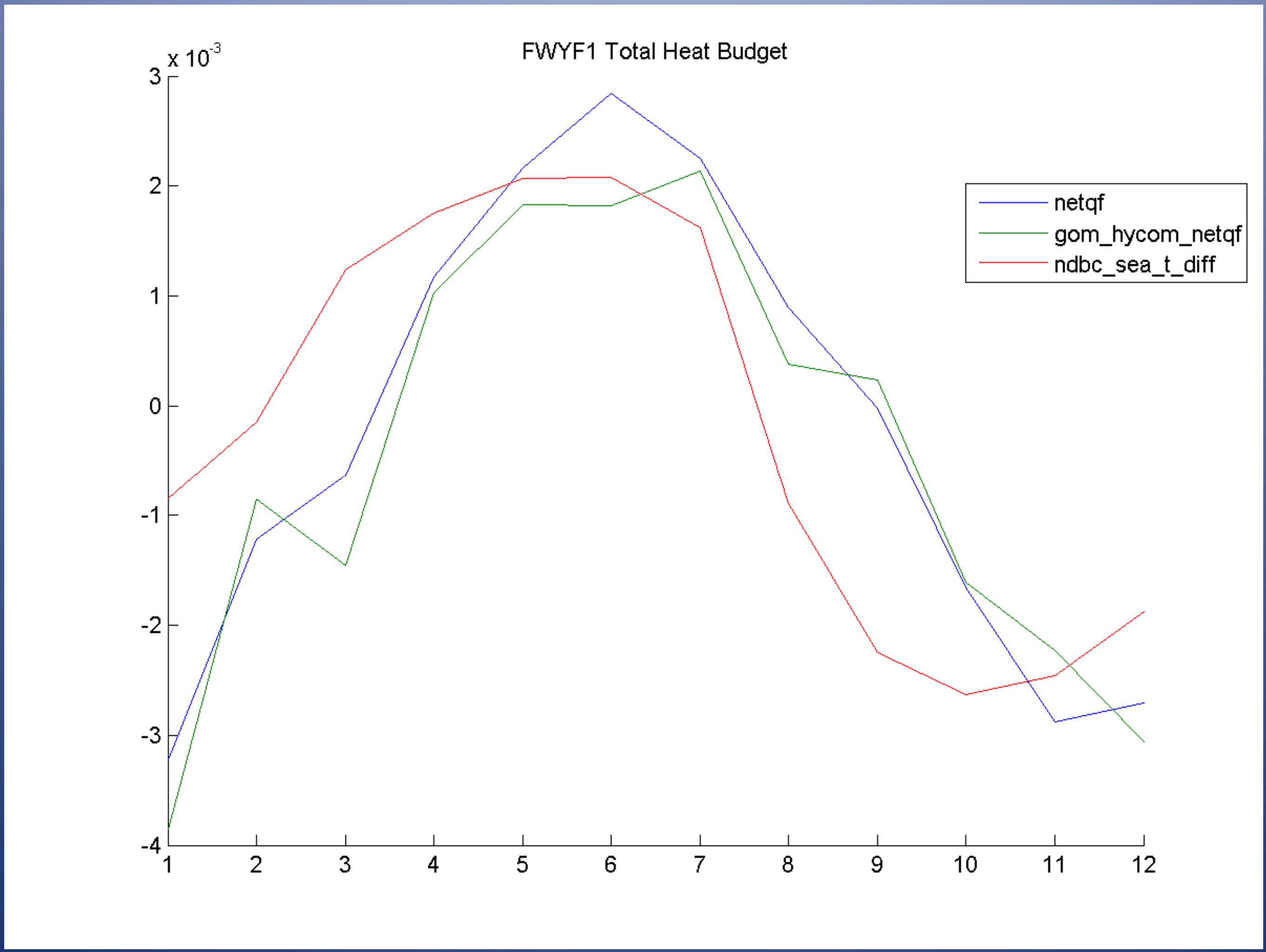
Cross-shore along-shore velocity – Florida Keys HYCOM (May 2008)



Monthly climatology from literature and current work – air-sea fluxes only



Monthly climatology – with thermal siphon



Weekly climatology – with thermal siphon