Vertical turbulent cooling of the mixed layer in the tropical Atlantic ITCZ and trade wind regions

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Outline

- Motivation
- Enhanced PIRATA dataset
- Turbulent cooling at 15°N, 38°W
- Turbulent cooling at 4°N, 23°W
- Conclusions

Questions

- Is there significant turbulent cooling at off-equatorial locations? Does it vary seasonally?

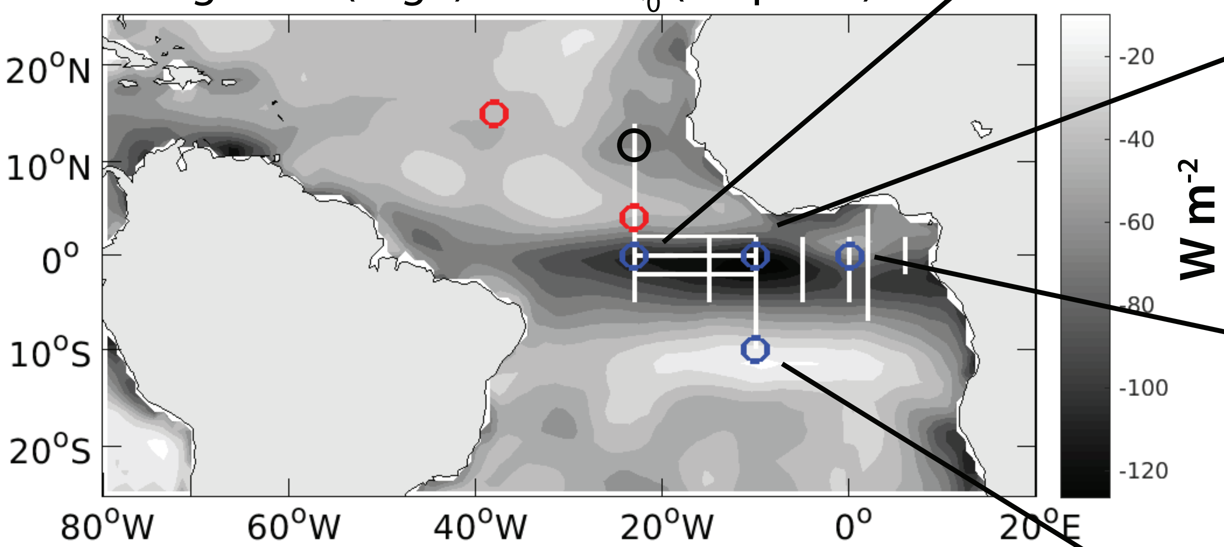
- In the absence of strong mean shear, what drives mixing and cooling off the equator?

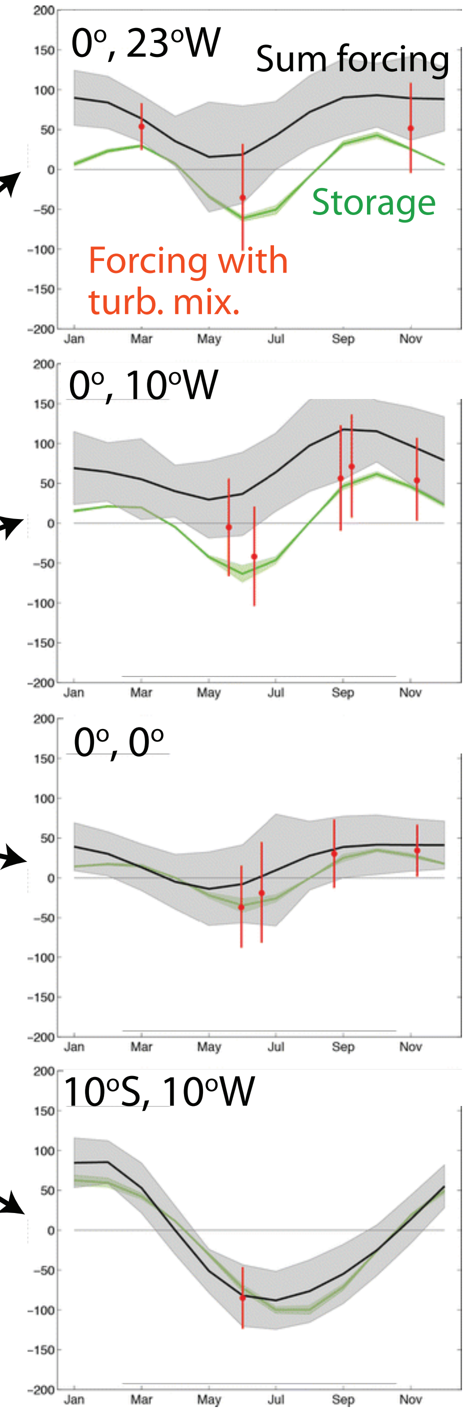
Approach

- Heat budget residuals, hourly measurements from PIRATA moorings and one-dimensional models (KPP, PWP).

Previous measurements and estimates of turbulent cooling

Shading: annual mean heat budget residual: Storage rate (Argo) minus Q_0 (TropFlux)





White lines: microstructure measurements

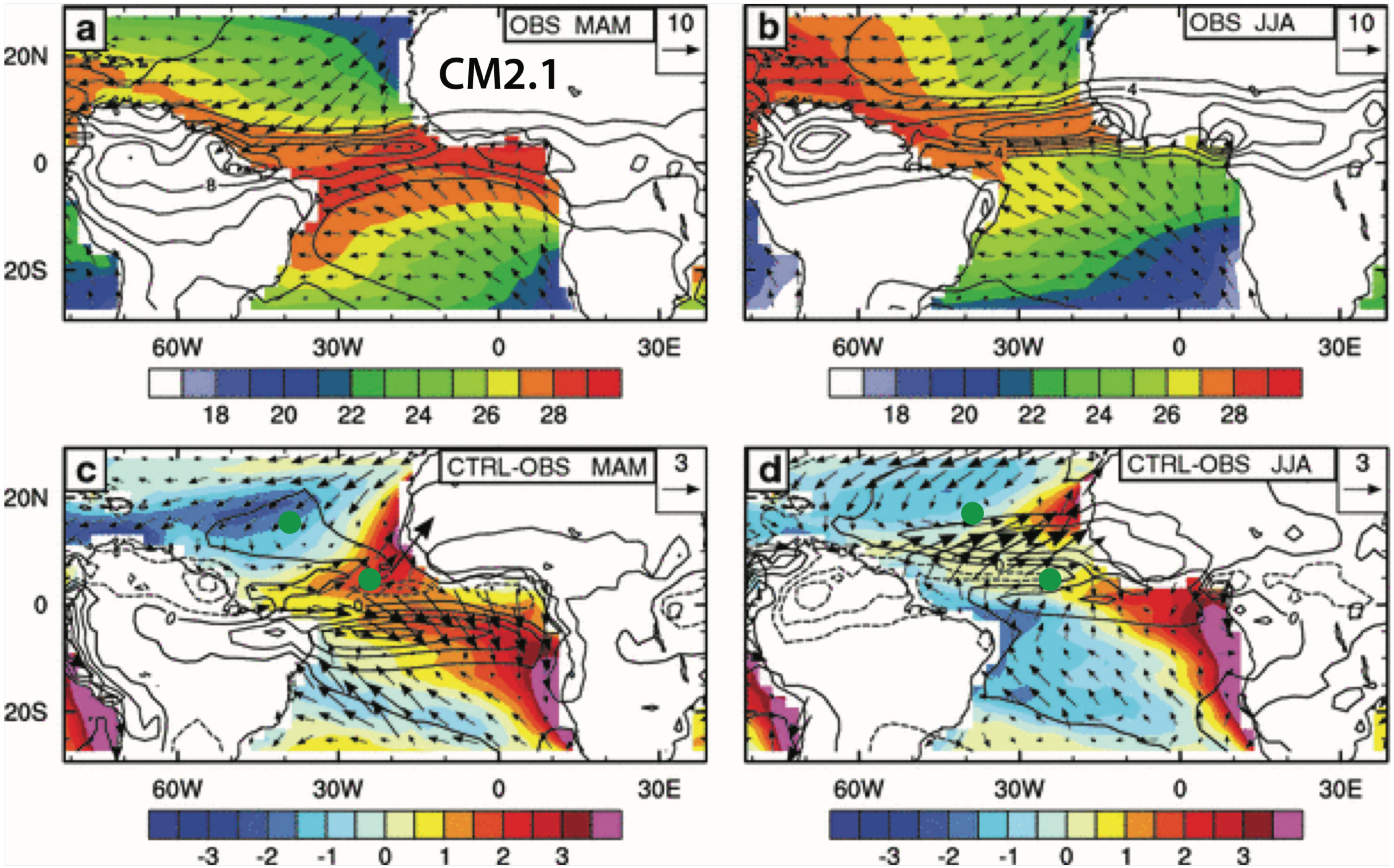
Blue circles: Hummels et al. (2014)

Black circle: Hummels et al. (2018)

Red circles: this study

Coupled model biases

March-April-May **June-July-August**



Richter et al. 2012

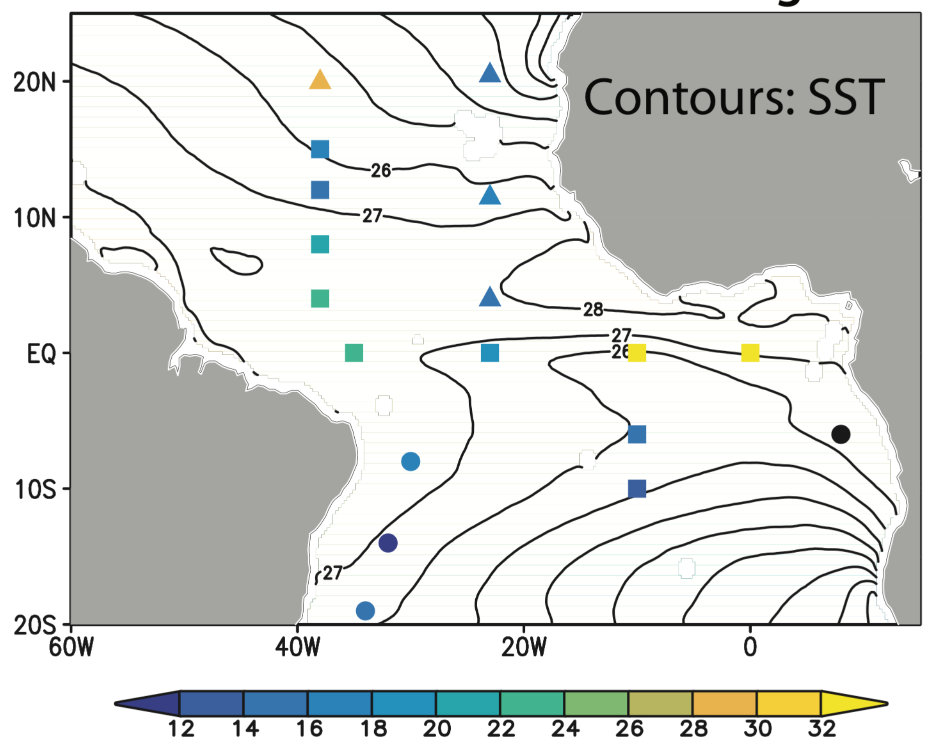
Prediction and Research Moored Array in the Tropical Atlantic (PIRATA)

- Daily air temp., rel. humid., winds, solar and longwave radiation (some), rain, ocean temperature, salinity, velocity at 10 m (some).
  12-21 years of data.

- Vert. resolution of T, S is typically 10-20 m.

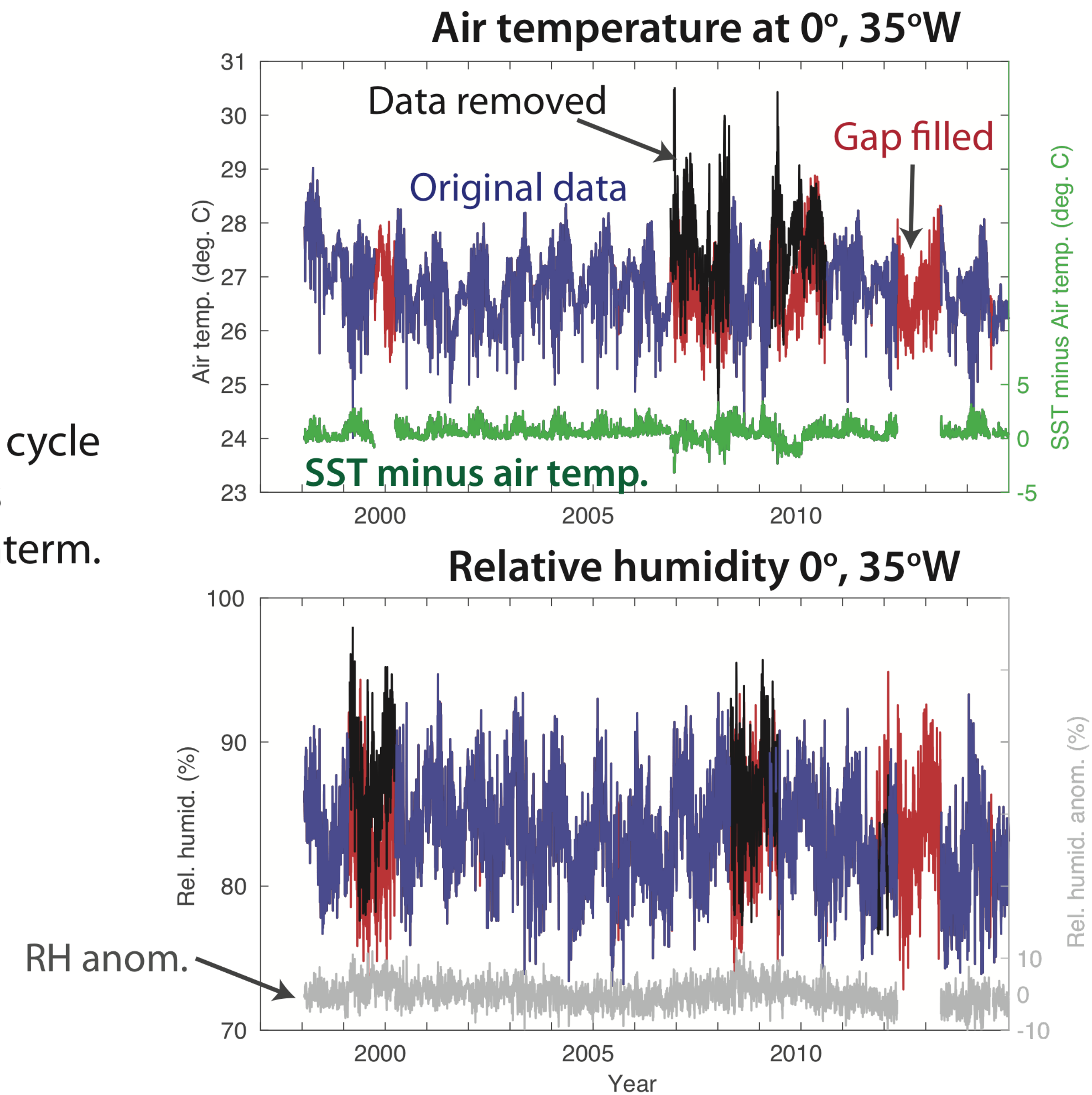
- Biases in S, air temp., rel. humid., solar rad.

Percent missing data



Biases in air temp., rel. humidity

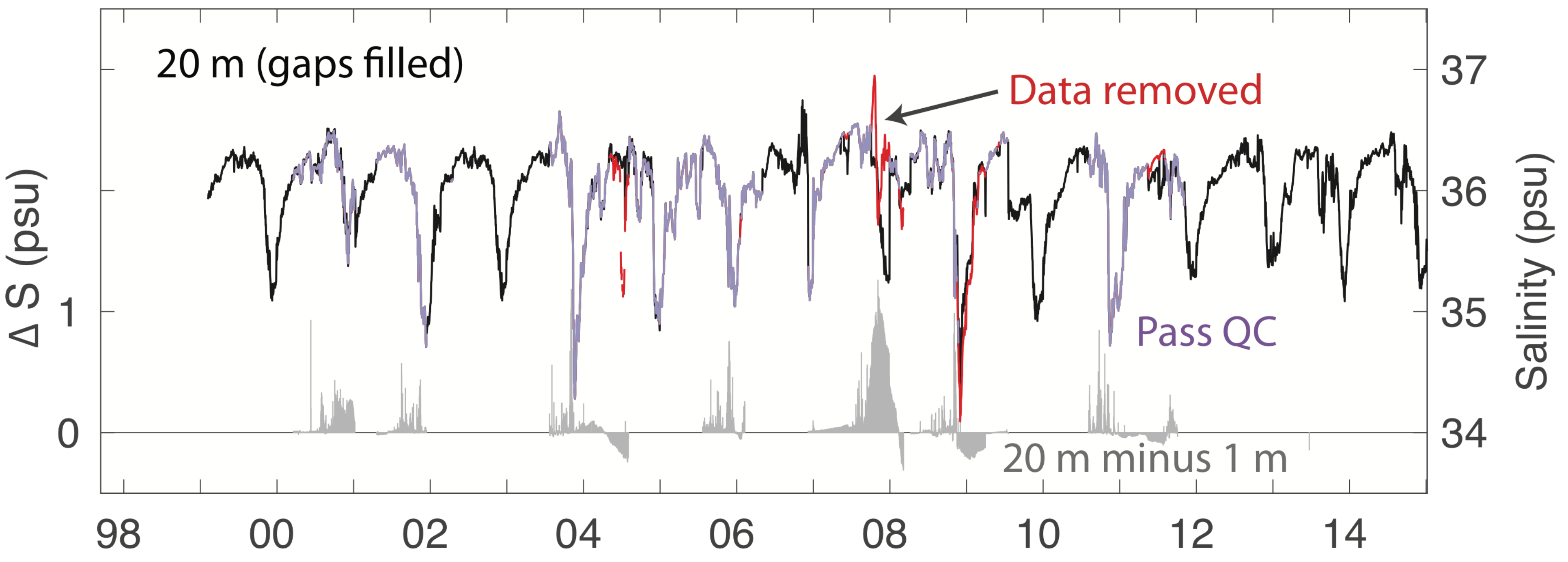
- Fill gaps with seas. cycle from mooring plus anom. from ERA-interm.



Biases in salinity

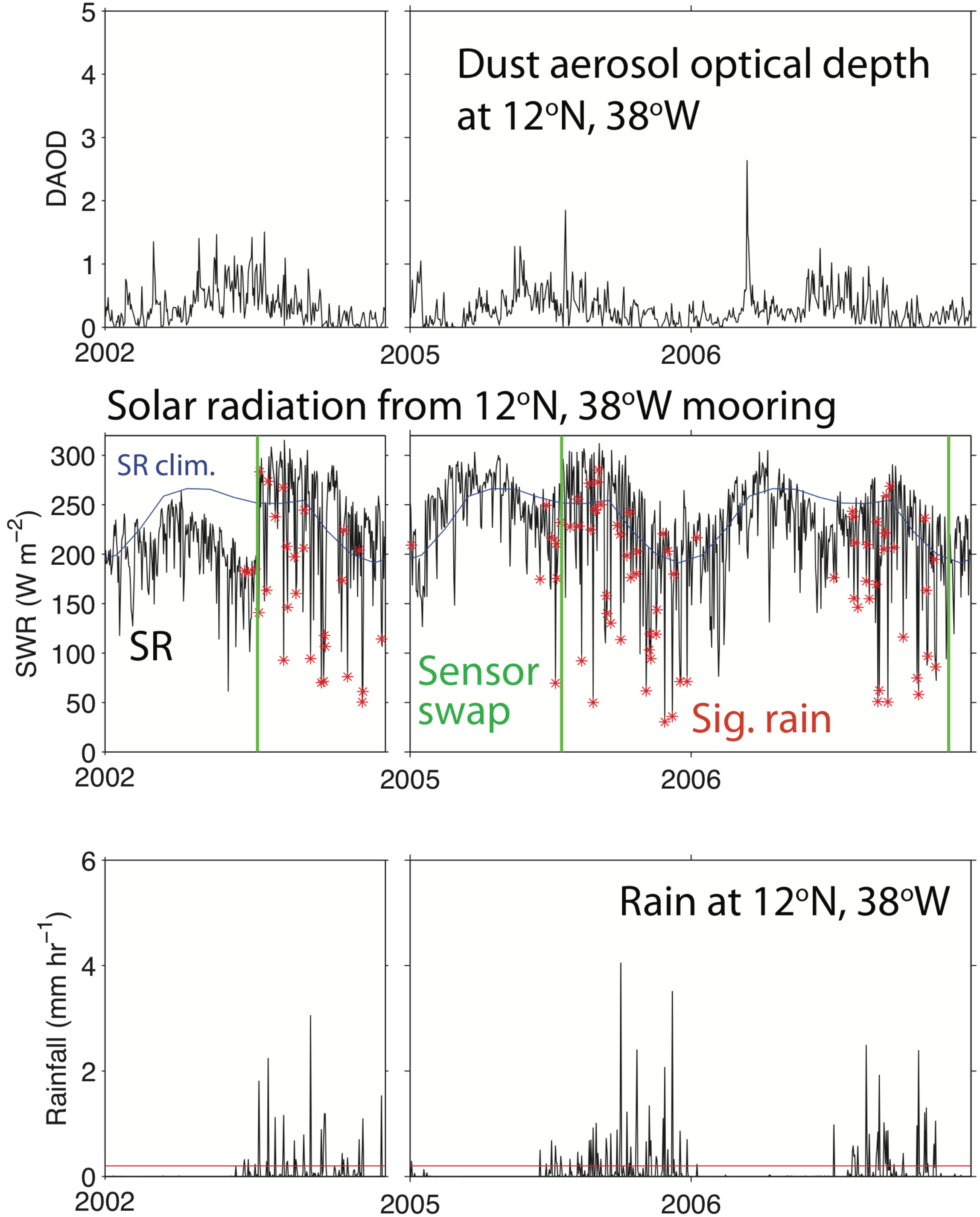
- Fill gaps with data from closest sensor or with Argo opt. interpolation if all data are missing.

Salinity at 12°N, 38°W



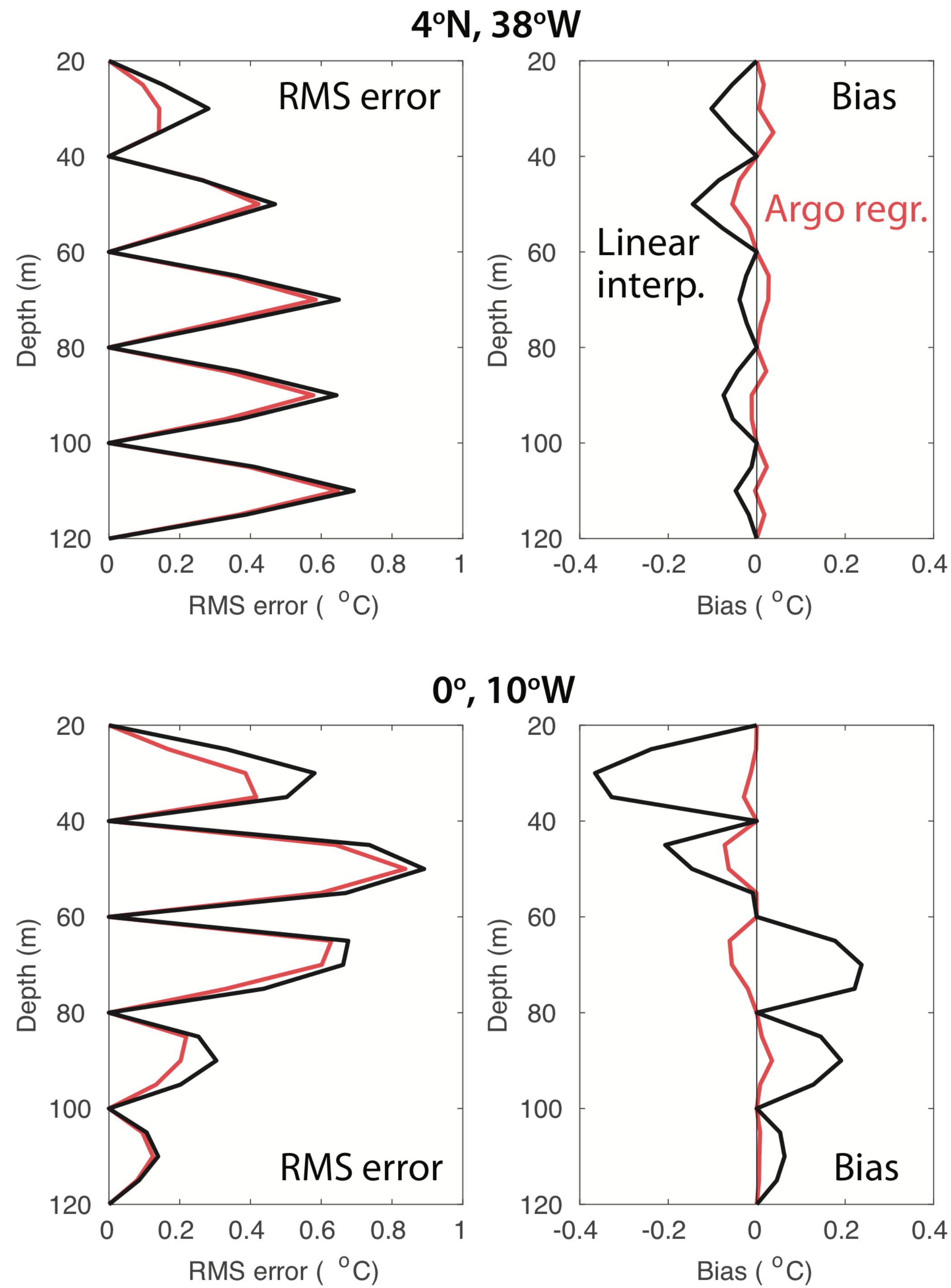
Biases in solar radiation

- Correct using "clear-sky" technique (Foltz et al. 2013). Fill gaps with ISCCP-FD seas. cycle plus anoms. from OLR regression.

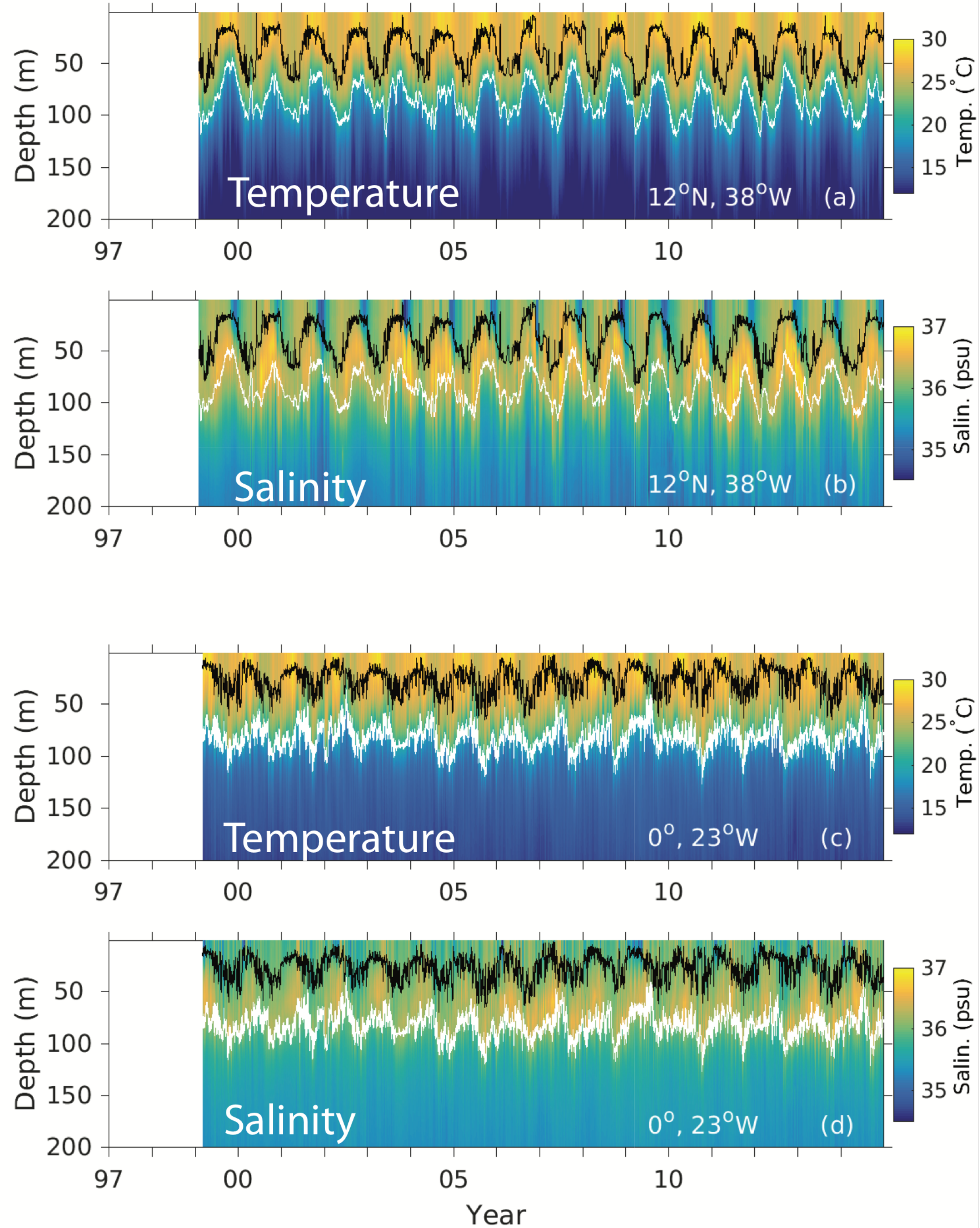


Biases in ocean temperature

- **Regrid original mooring T(z) to 5 m resolution using historical Argo profiles near mooring.** Separate linear regression model for each day at each mooring, based on depths where data is available.
- Similar results for salinity

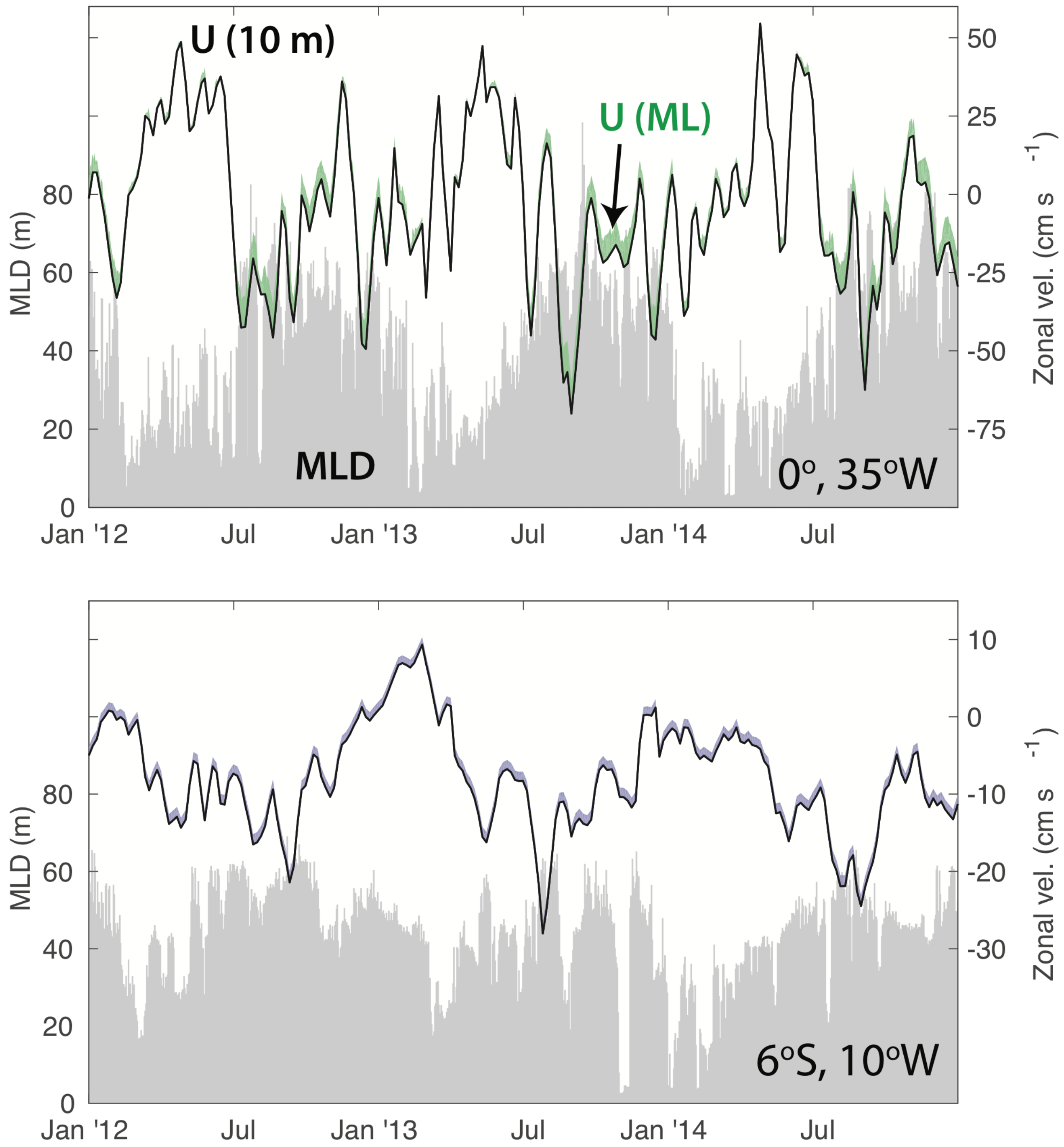


ePIRATA T(z), S(z)



Mixed layer velocity

Adjust 10 m mooring vel. to ML vel. using ORAS4. Fill gaps with Drifter-alt.-wind synthesis and OSCAR.



Mixed layer heat budget

Mixed layer heat storage rate

Sfc. heat flux (LHF + Abs. SWR + LWR + SHF)

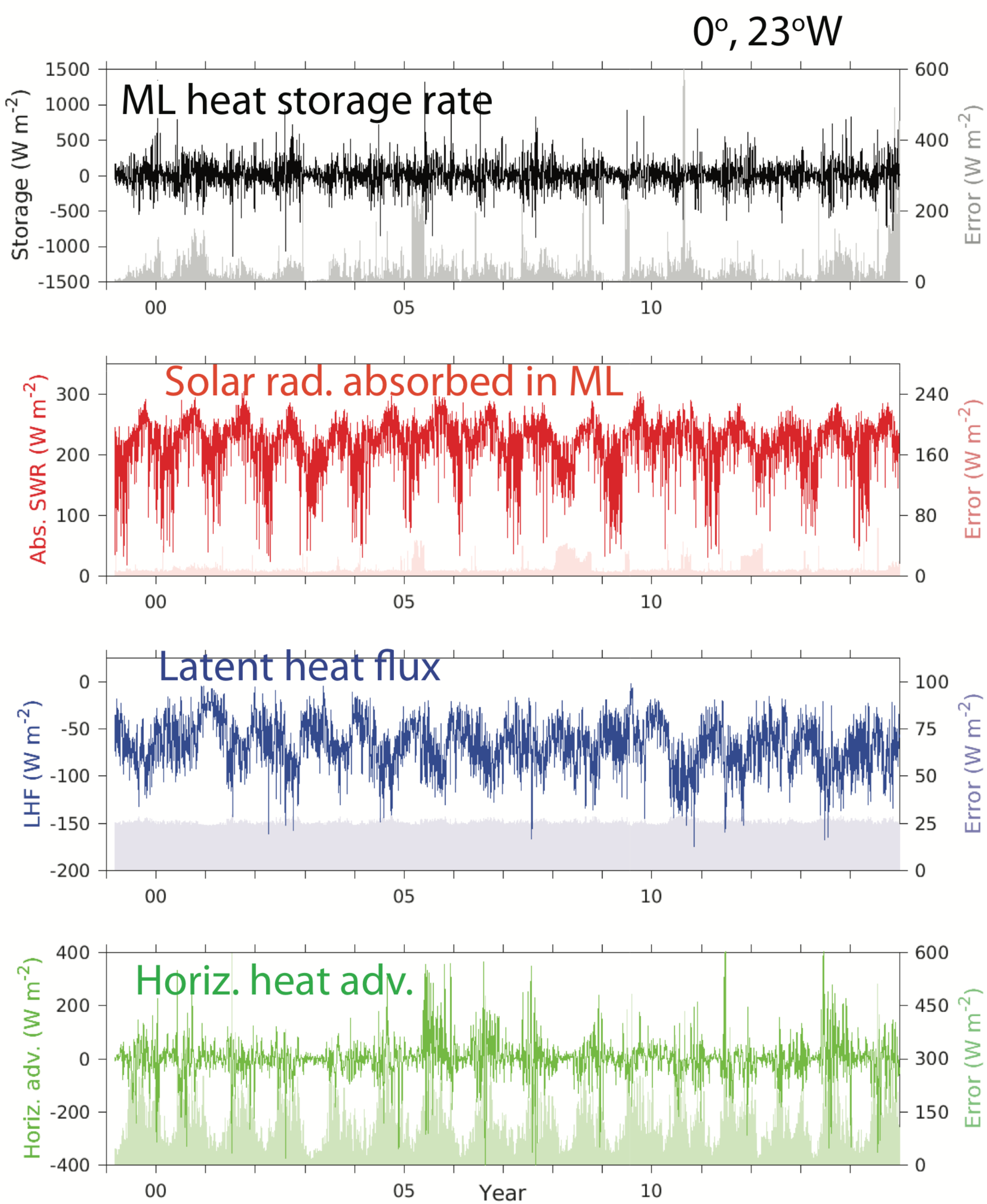
Horiz. advection

$$\rho c_p h \frac{\partial T}{\partial t} = q_0 - \rho c_p h \mathbf{v} \cdot \nabla T + q_{-h}$$

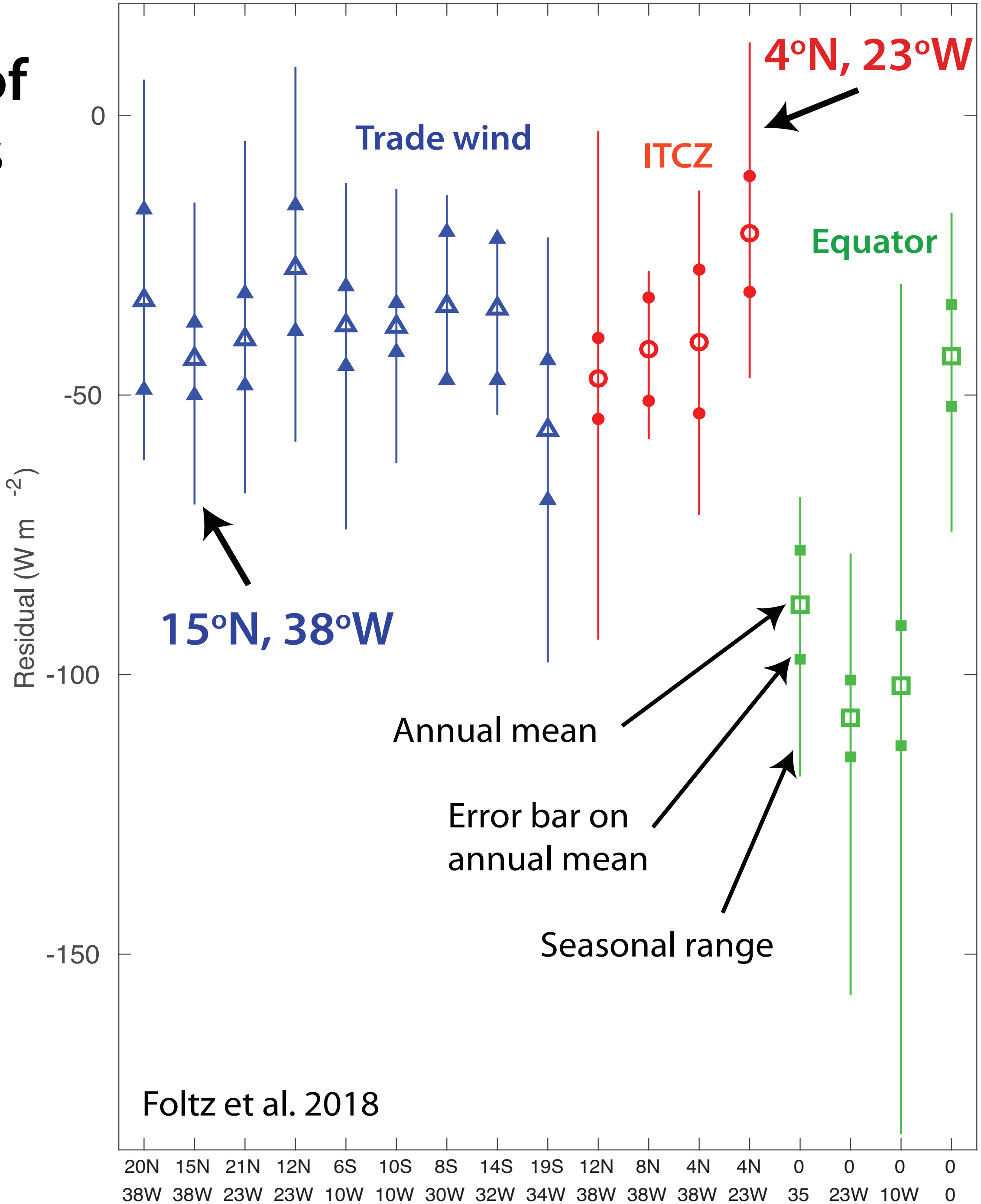
Vert. turb. mixing + errors

- **h**: 0.12 kg m^{-3} density increase from 1 m
- **∇T**: daily microwave SST
- **q_{-h}**: residual

ePIRATA mixed layer heat budget

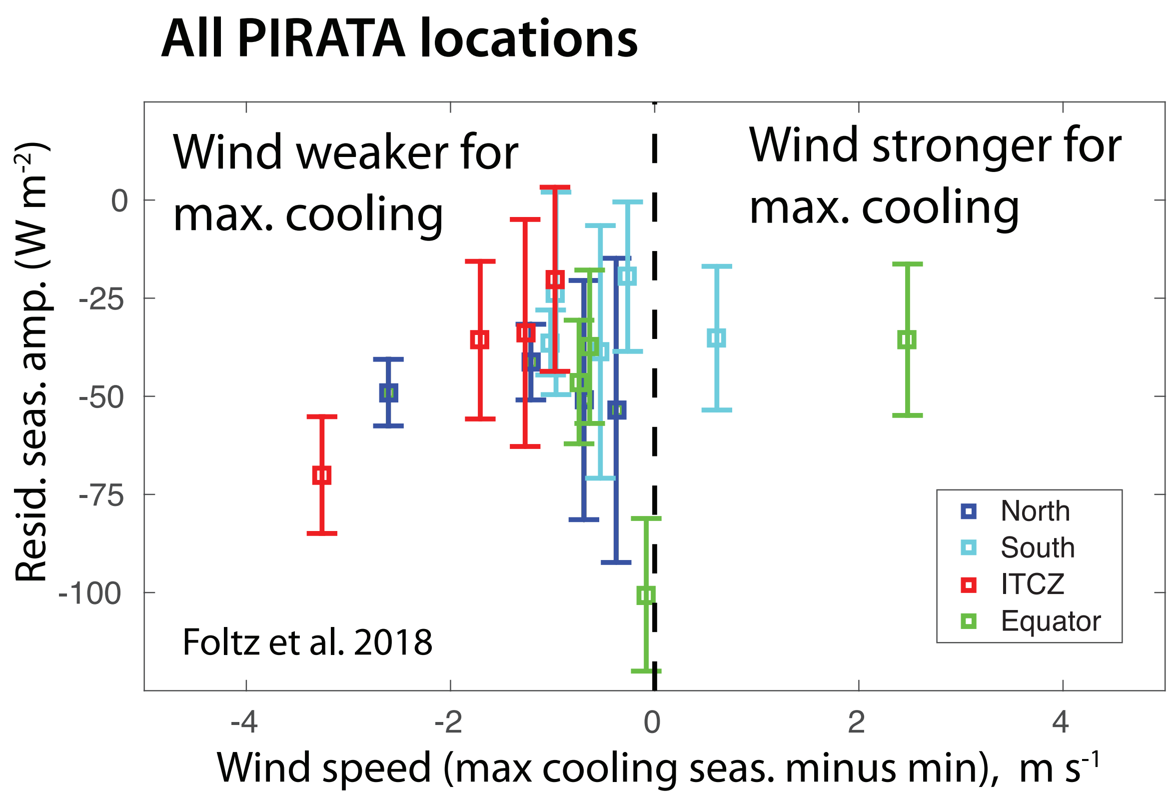


Strong seasonalities of heat budget residuals



Relationship between residual and wind speed

- Seasonally, more cooling occurs when wind is weak



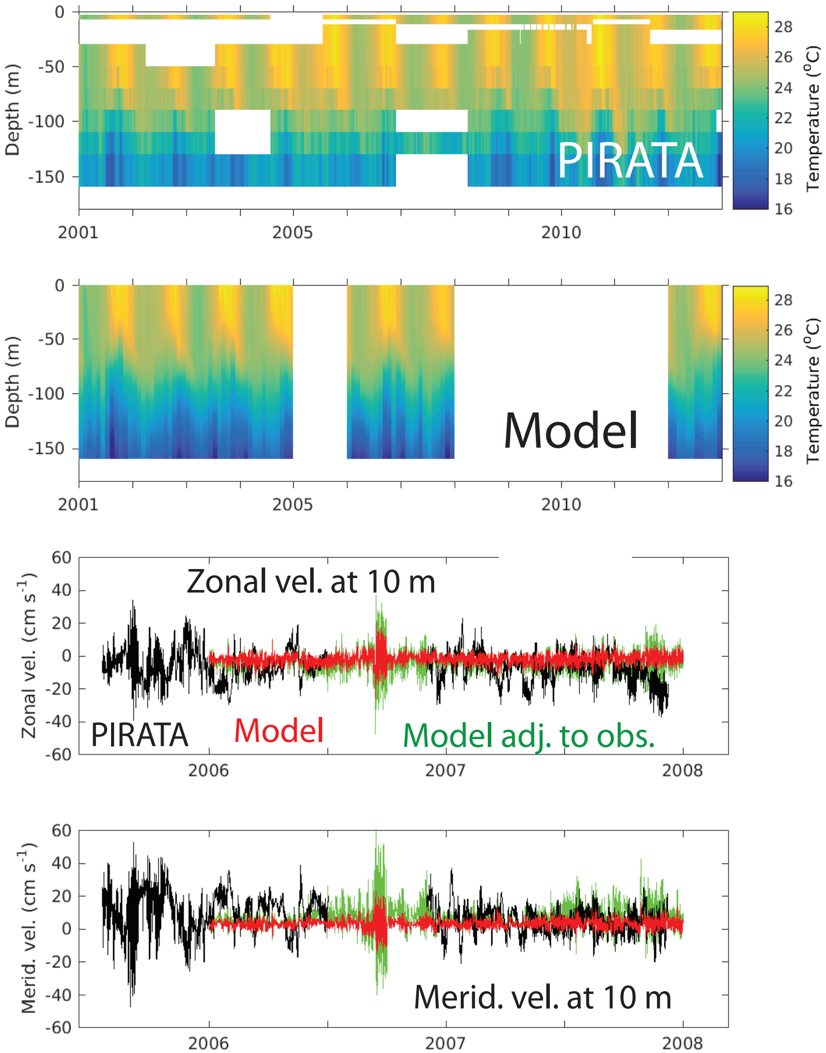
Data and methods

15°N, 38°W

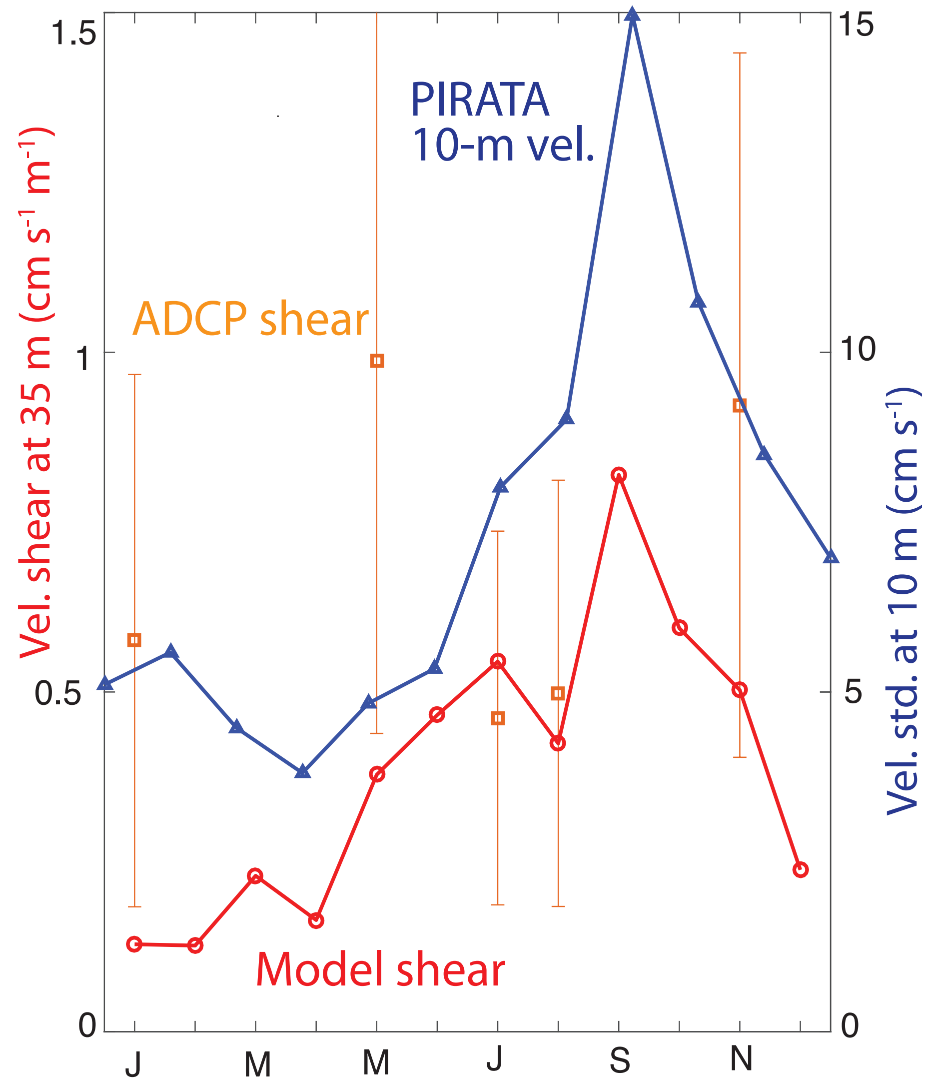
- Daily ePIRATA **temp., salin**. (Foltz et al. 2018)
  Hourly PIRATA **air temp., rel. humidity, winds, shortwave, rain**
- Initialize **PWP model** (Price et al. 1986) at beginning of each month with ePIRATA T(z), S(z) then force with hourly winds, fluxes (2001, 2002, 2003, 2004, 2006, 2007, 2012).
  84 monthly model runs.
- Calculate K_v using **KPP model** (Large et al. 1994):
  mooring sfc. forcing, PWP T(z), S(z), v(z).

Validation of PWP model at 15°N, 38°W

T(z), velocity at 10 m



Stand. devs. of 10-m vel. and 35-m shear



Data and methods

4°N, 23°W

- Hourly PIRATA **temp.** (1, 10, 20, 40, 60, 80, 100, 120, 140, 180 m)
  salin. (1, 10, 20, 40, 60, 120 m)
  vel. (7, 12, 17, 22, 27, 32, 37, 47, 57, 67, 87 m)
  air temp., rel. humidity, winds, shortwave, rain

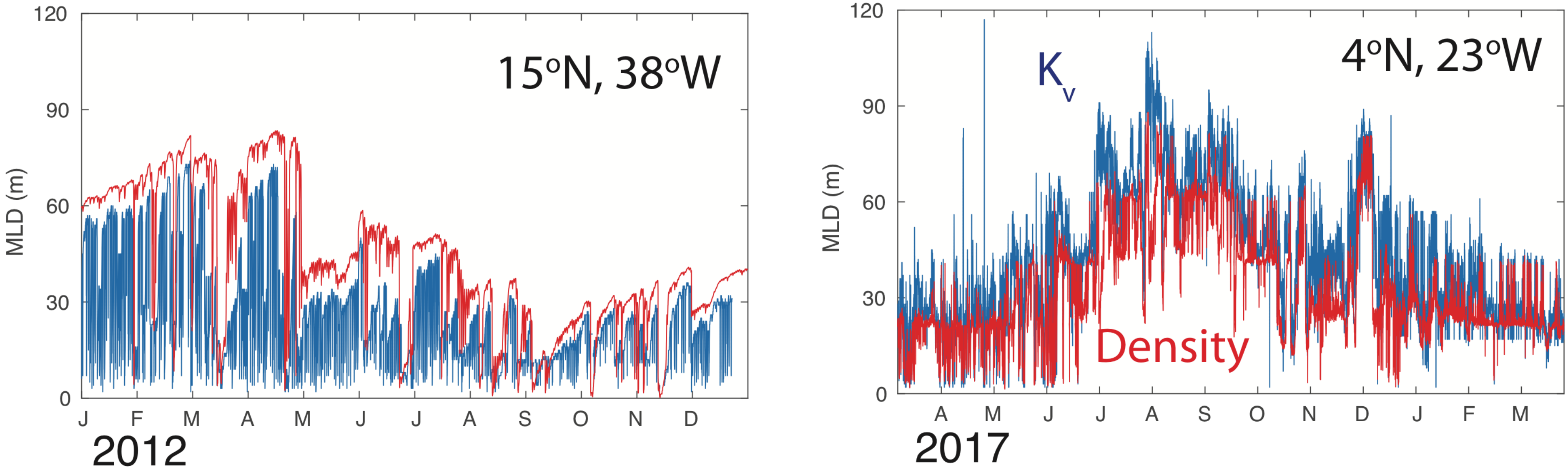
- March 2017 - March 2018

- Calculate vertical diffusivity (K_v) using KPP model.

Methods

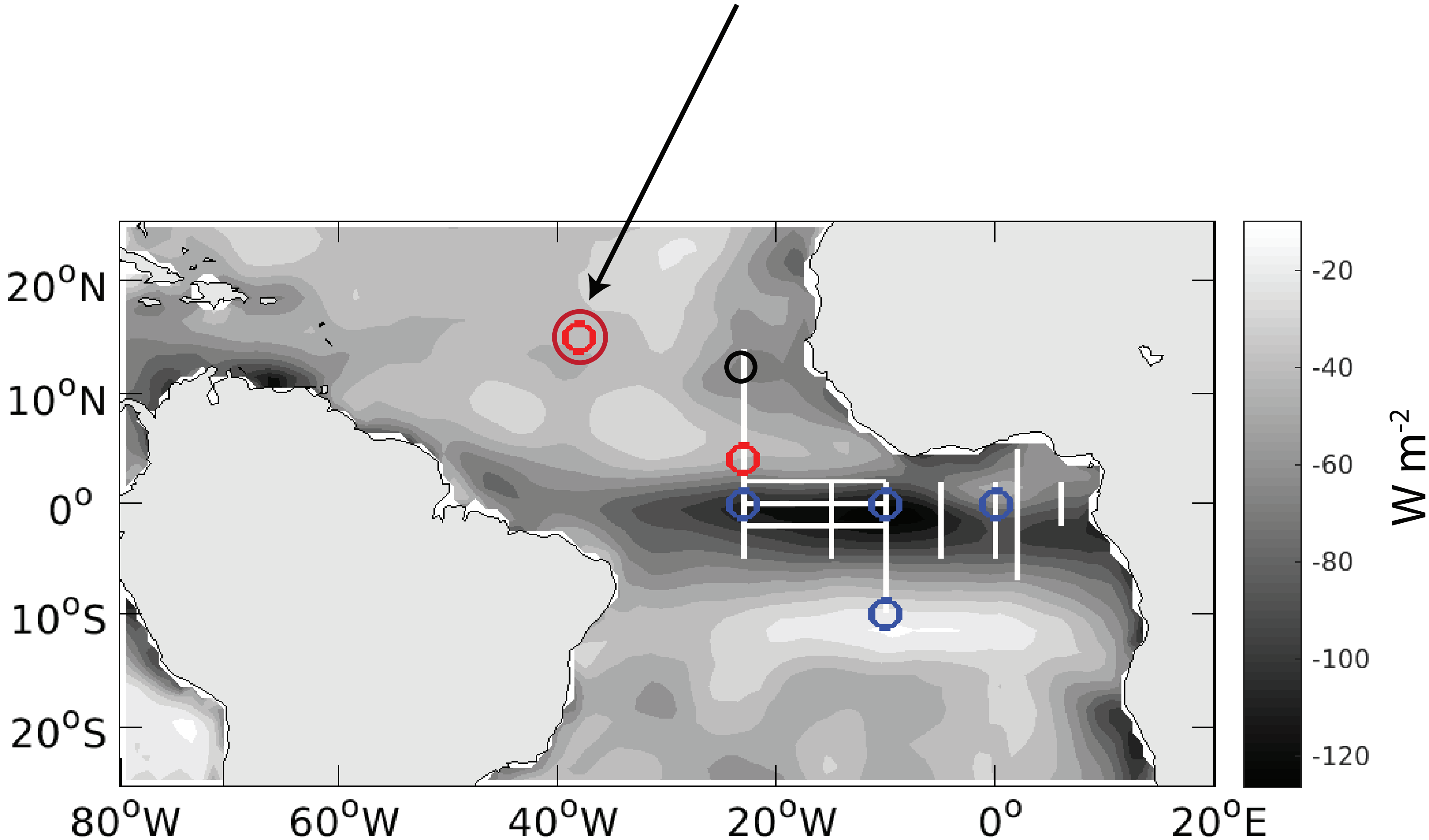
MLD: shallowest depth where K_v is less than $0.001 m^2 s^{-1}$

Comparison of K_v-based and density-based MLD



Vert. turb. cooling of ML: K_v at MLD+10 m and dT/dz calculated between MLD and MLD+10 m: **$dens*c_p*K_v*dT/dz$**

Results at 15°N, 38°W

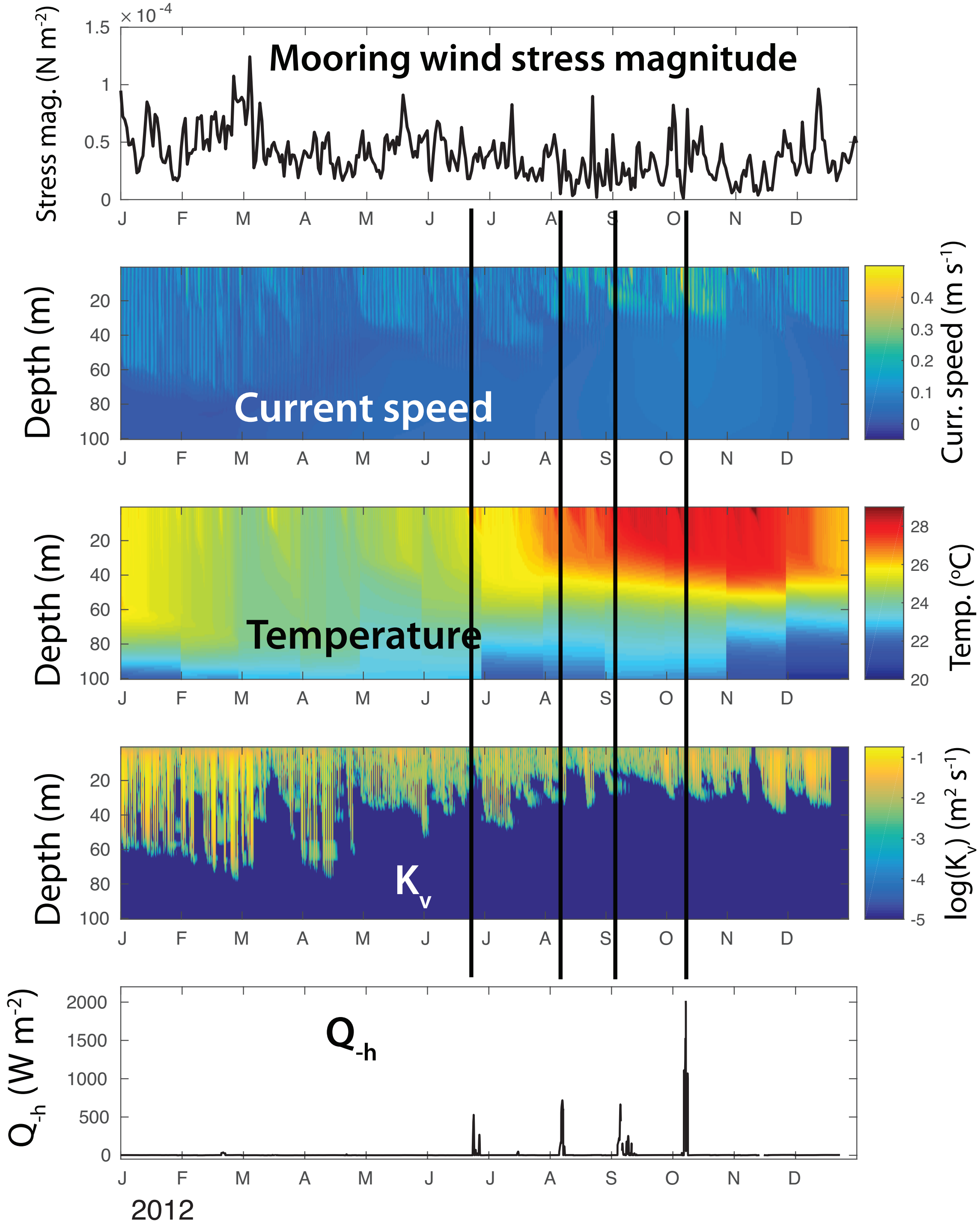


Results from 2012 (PWP, KPP)

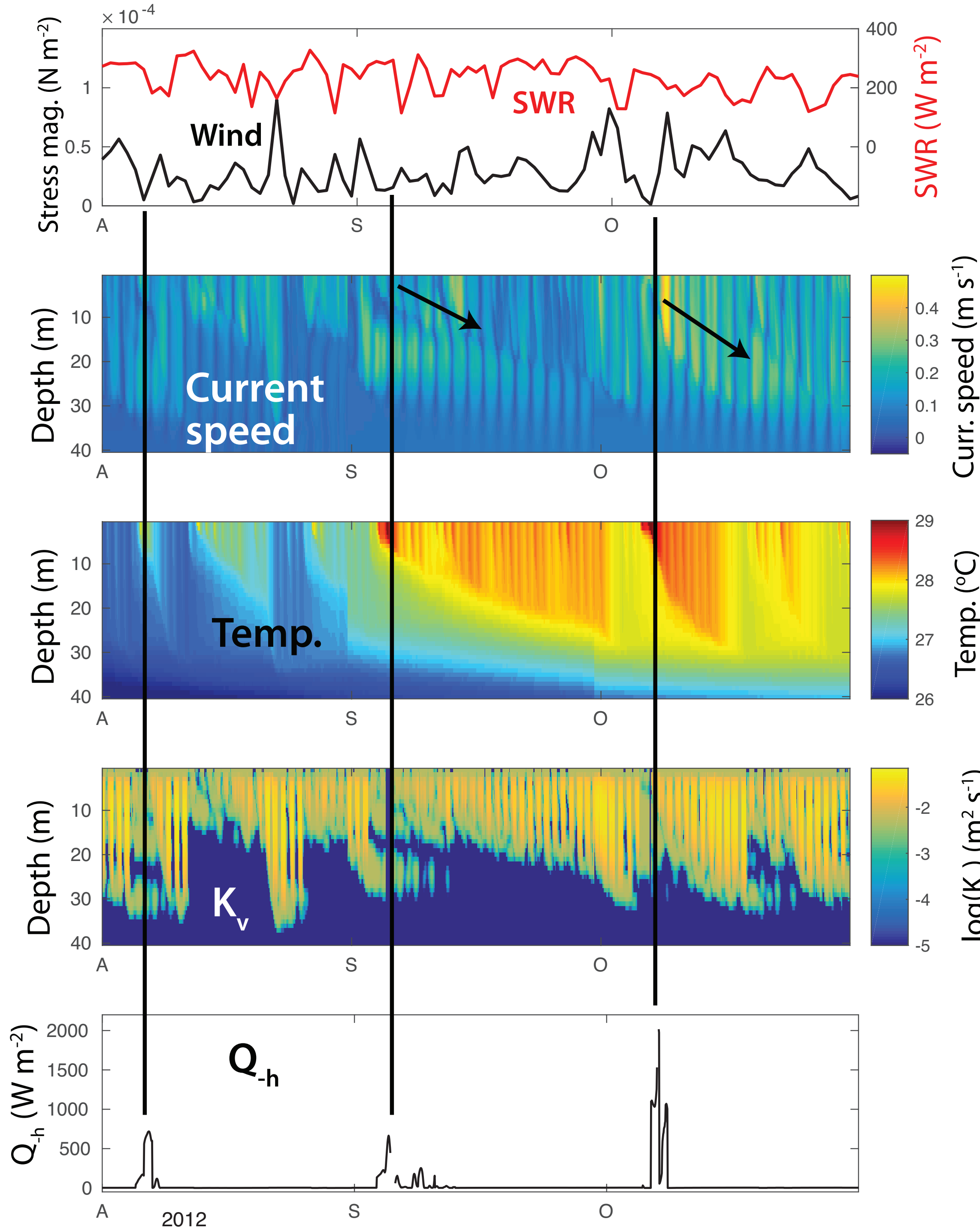
Strongest cooling occurs during summer-fall:

First: weak wind, surface warming,

Then: stronger wind, temp. and currents mixed downward, episodic ML cooling

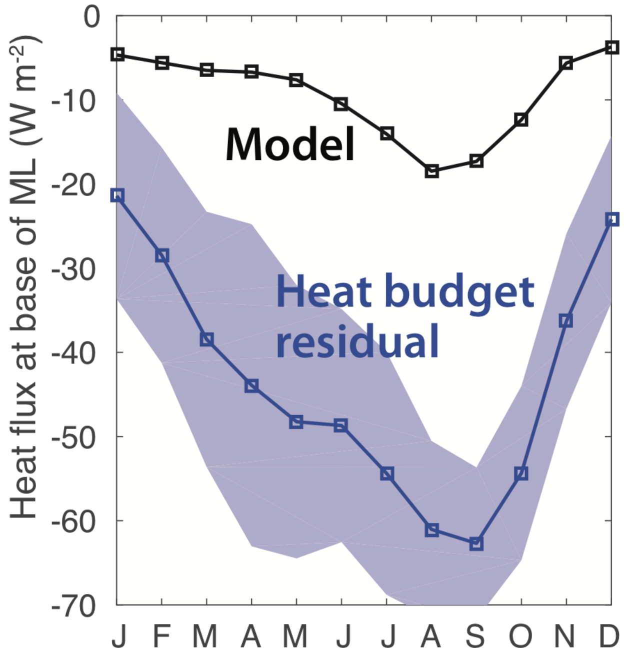


Aug-Oct 2012

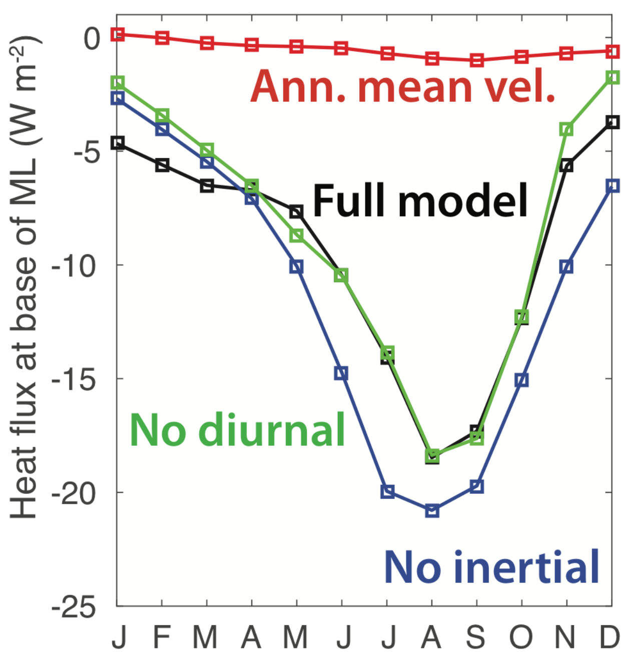


× 10^-4
Stress mag. (N m^-2)
SWR (W m^-2)
Wind
SWR
Current speed
Curr. speed (m s^-1)
Temp.
Temp. (°C)
K_v
log(K_v) (m^2 s^-1)
Q_-h
Q_-h (W m^-2)
Depth (m)
A
S
O
2012

Means seas. cycle (7 years, 2001-2012)

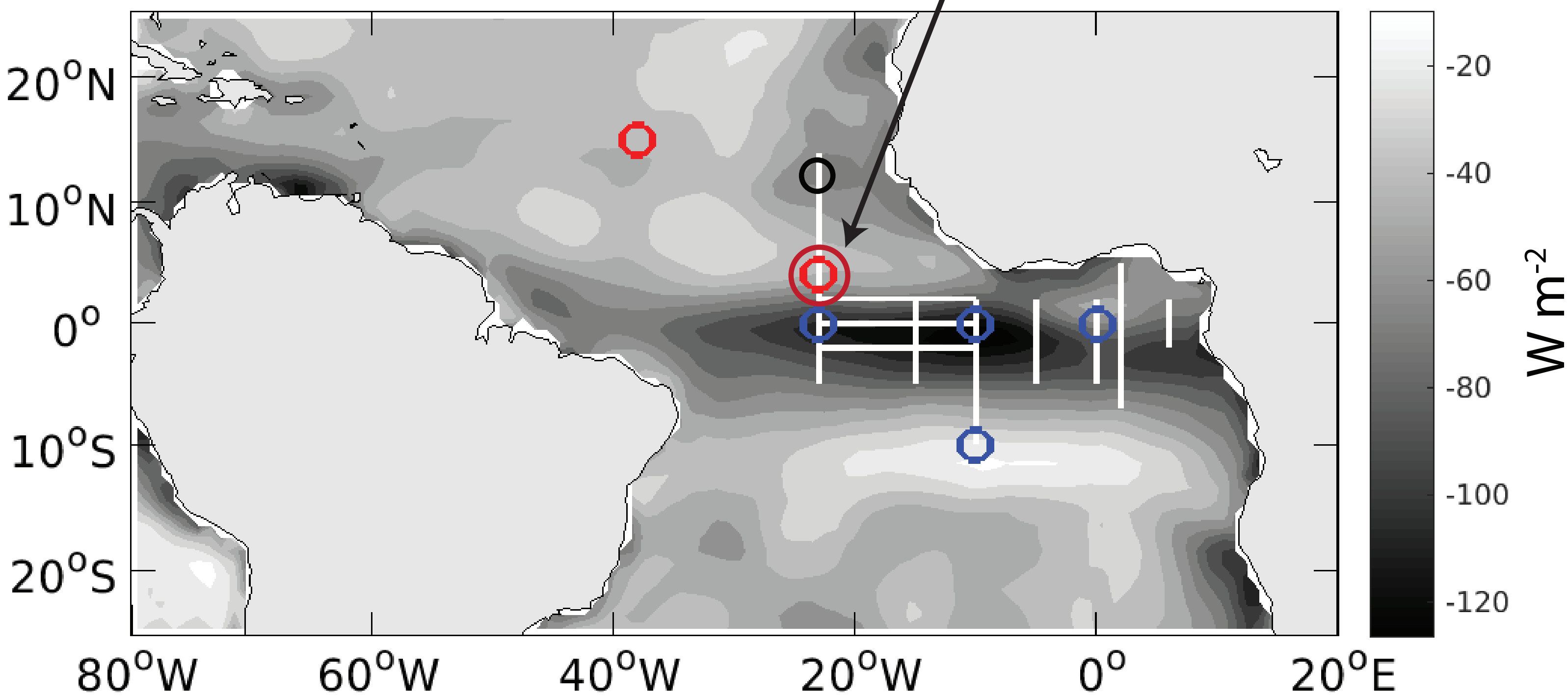


Phases of seas. cycles are similar, but **model underestimates cooling**, likely because high-freq. shear is missing.

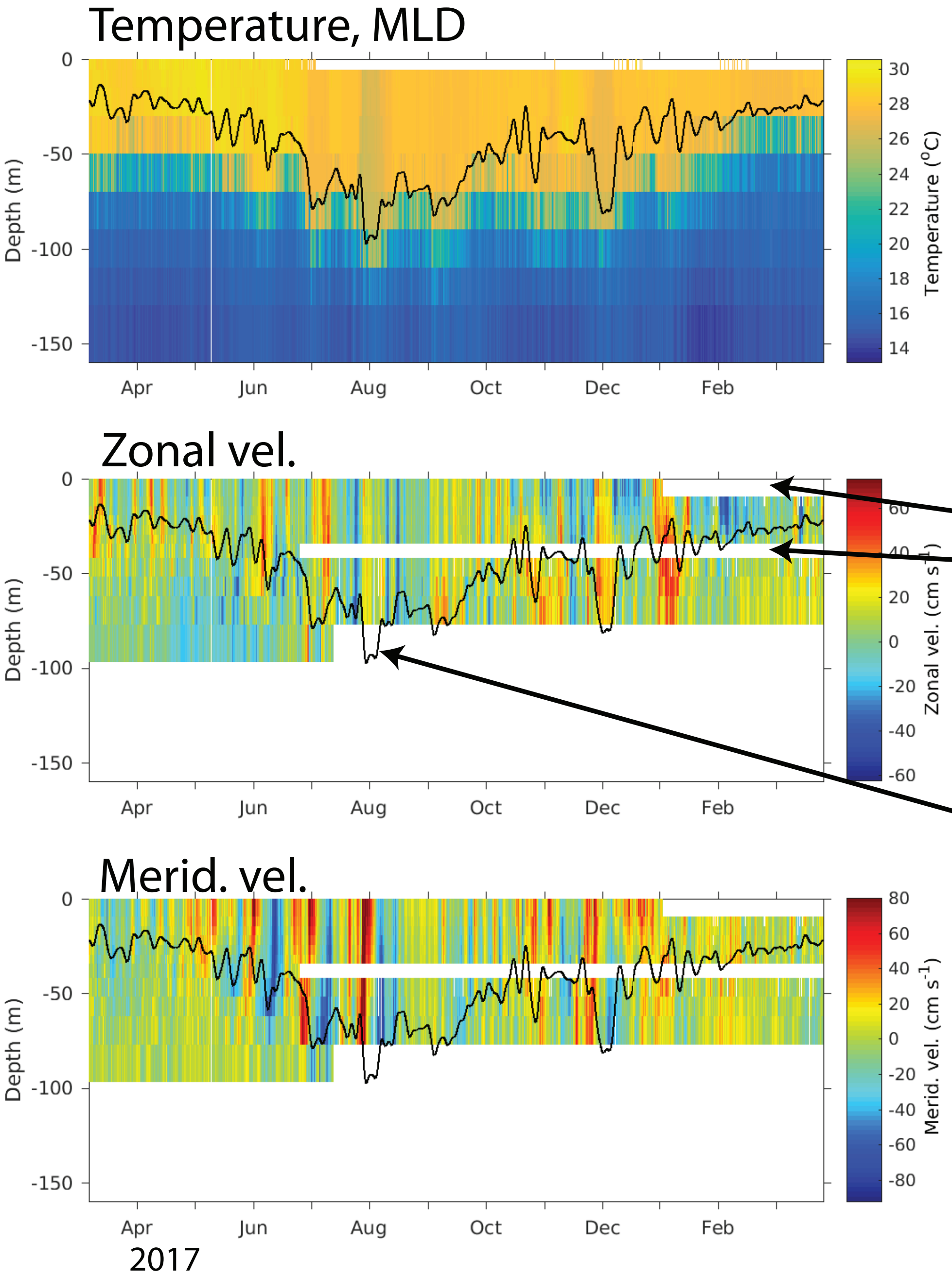


Turbulent mixing in model is driven mainly by episodic shear. Weak influence from diurnal cycle and near-inertial waves.

Results at 4°N, 23°W



Data from the 4°N, 23°W mooring



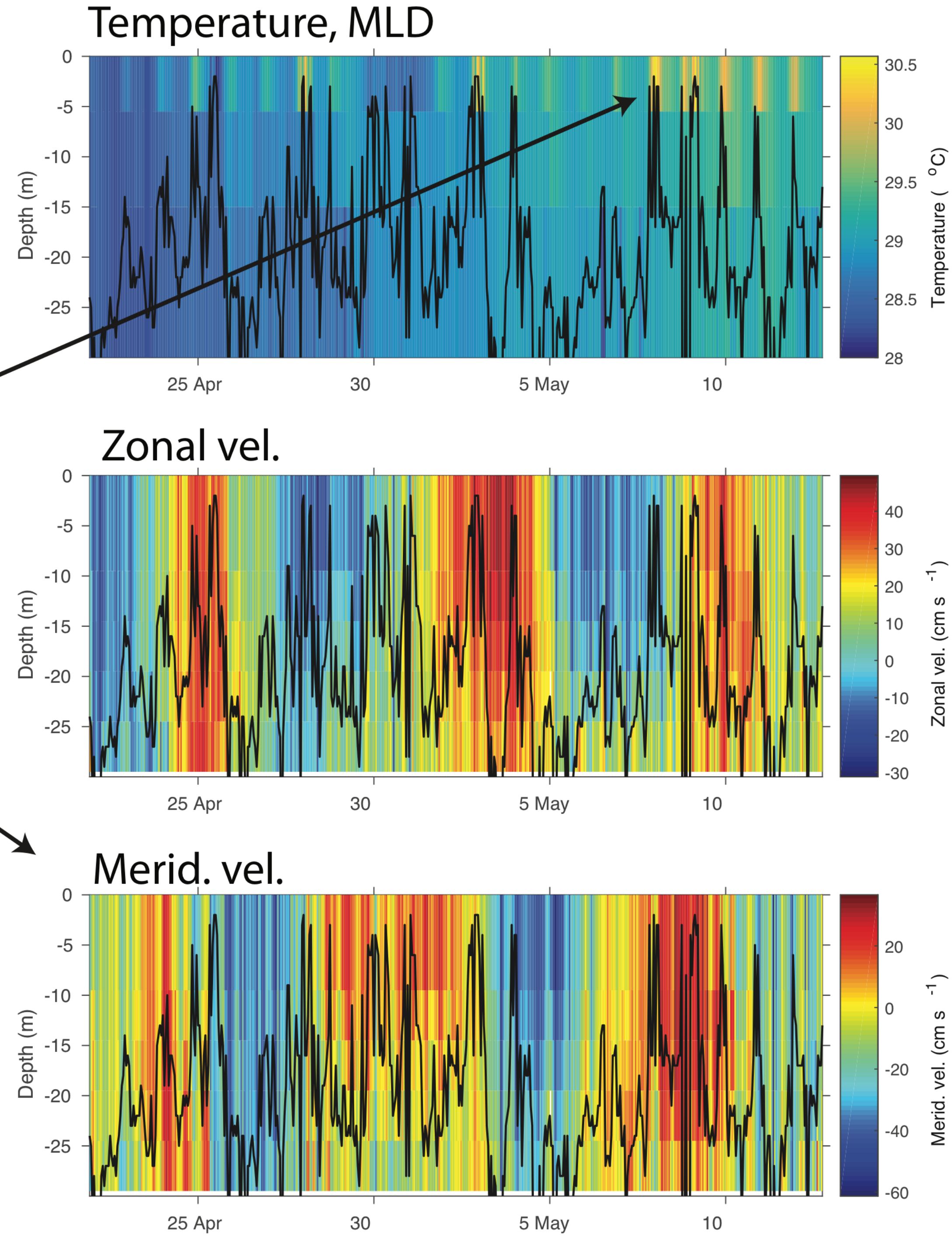
Fill with linear interpolation

Leave gaps when MLD is within 10 m of deepest vel. measurement

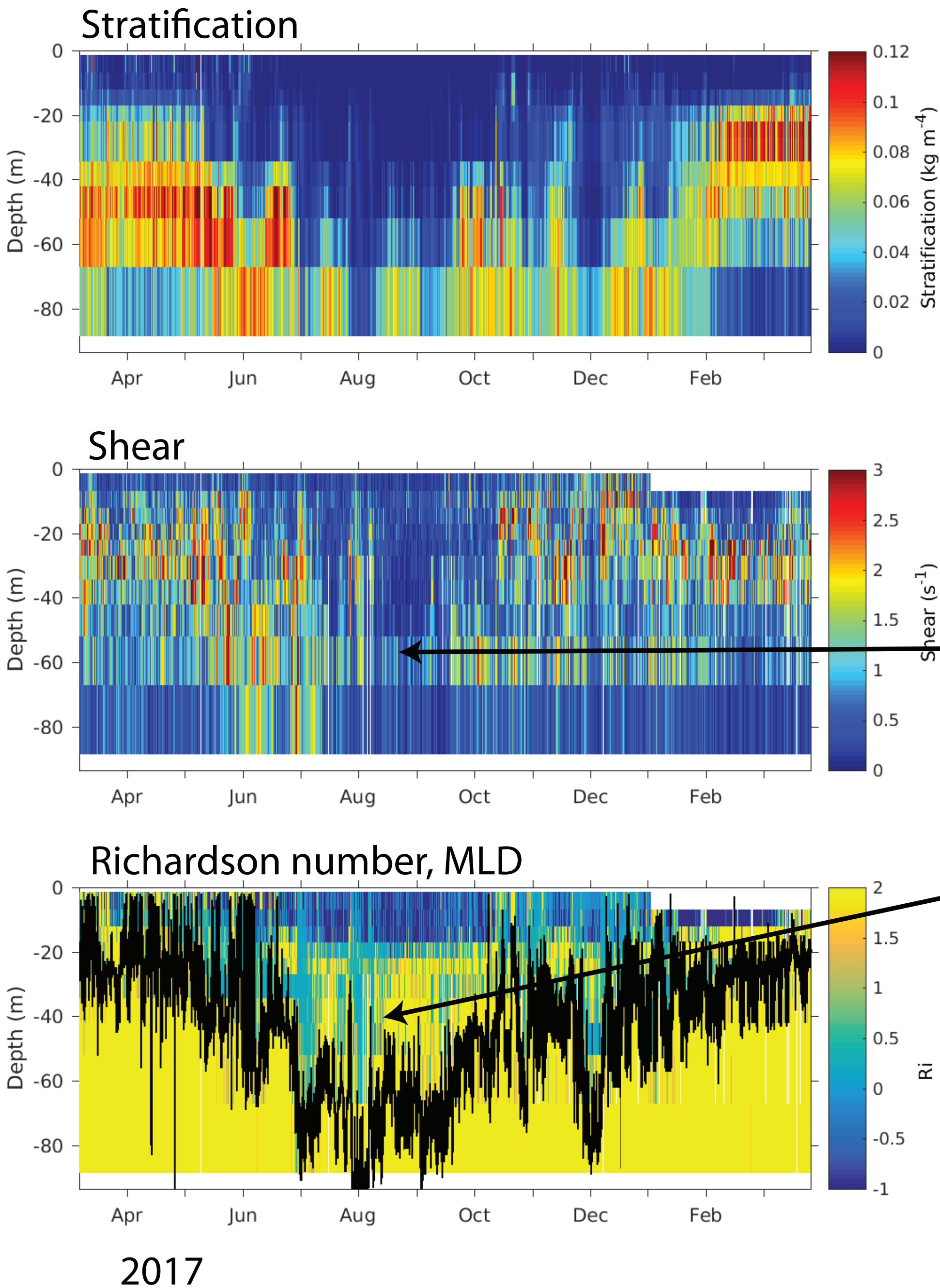
Temp., vel. during April-May

Diurnal temp.

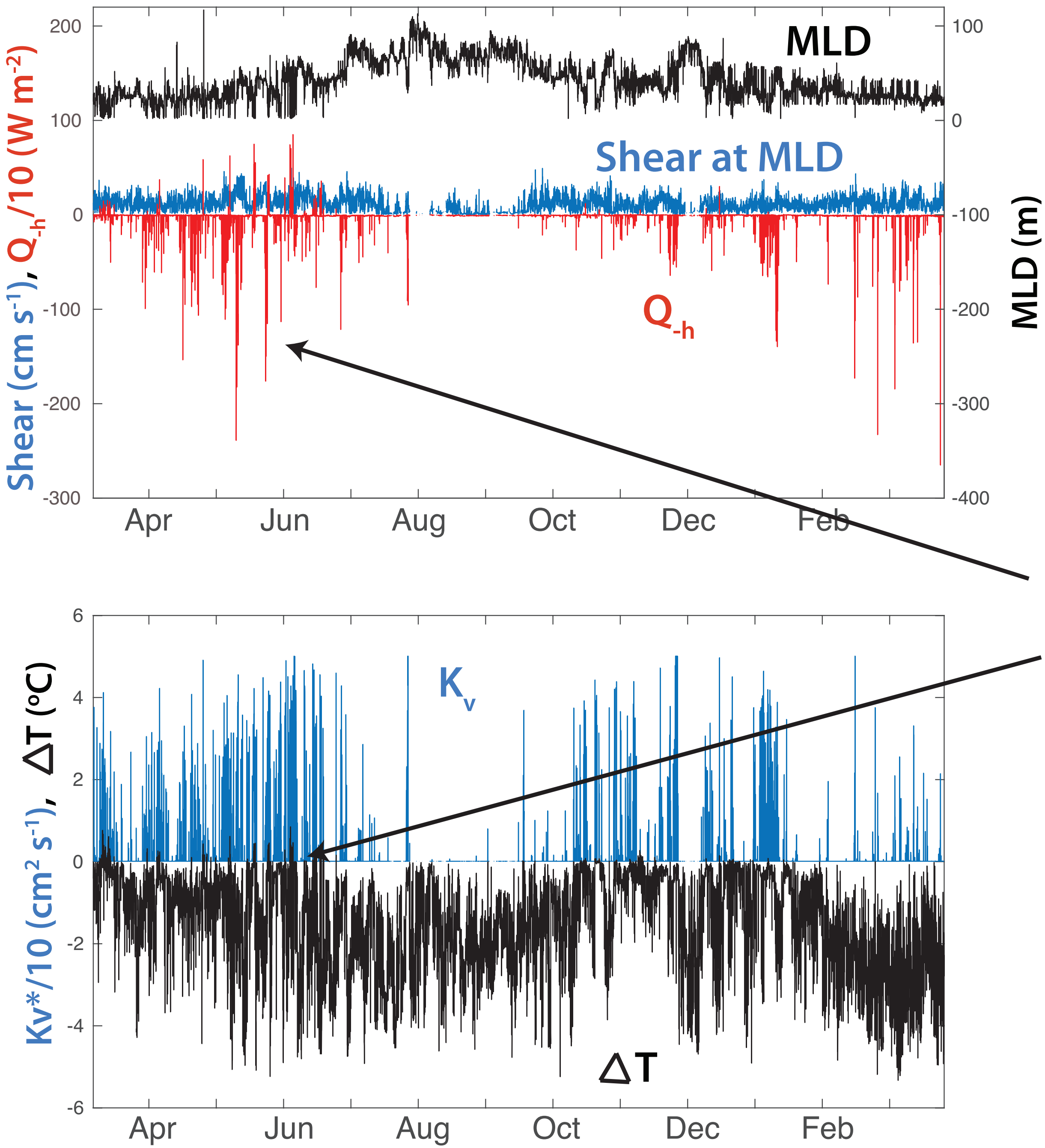
Near-inertial waves, high-freq. (<1 day) velocity



Strong seas. cycles of stratification, shear

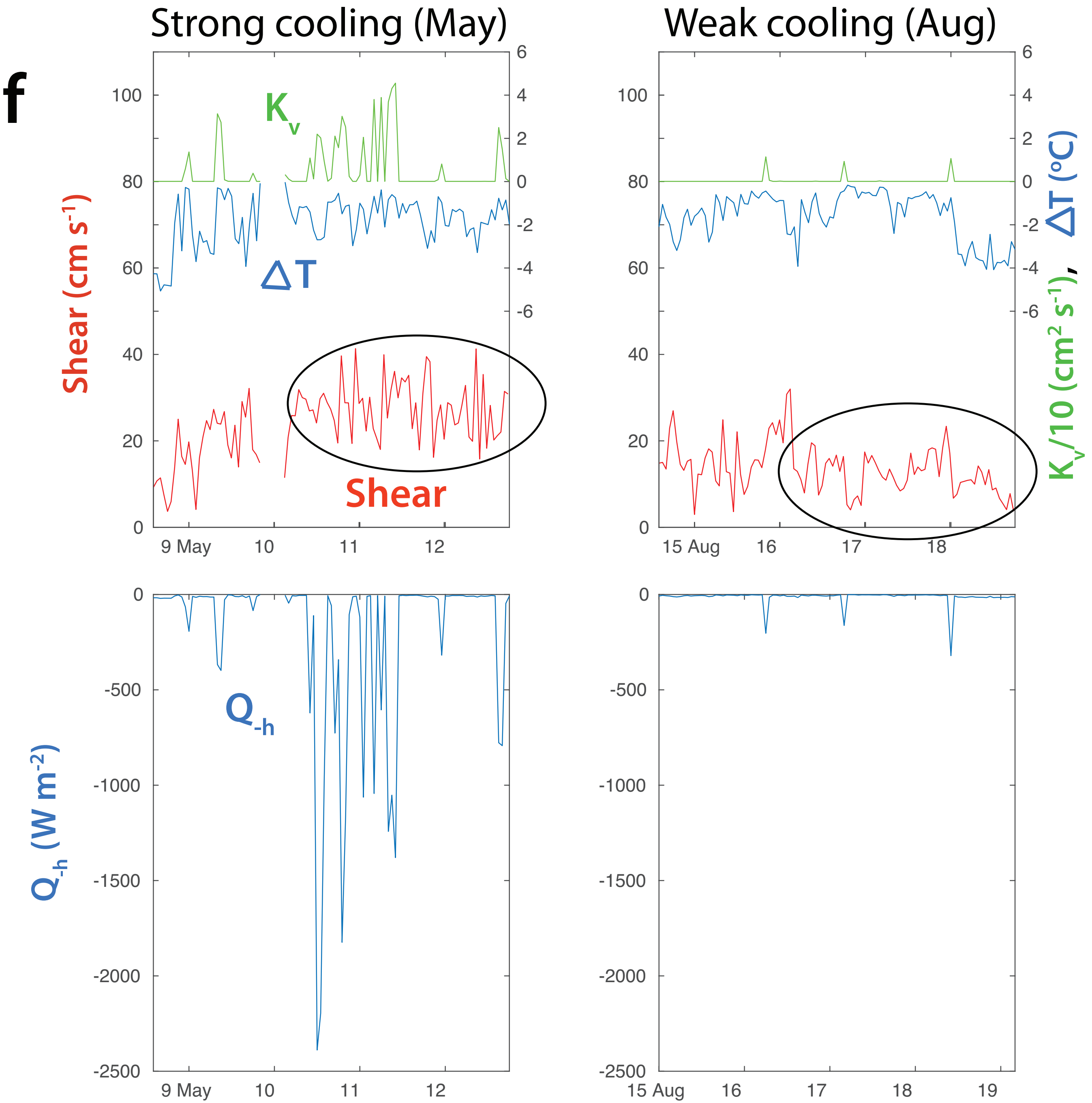


Vertical mixing and cooling



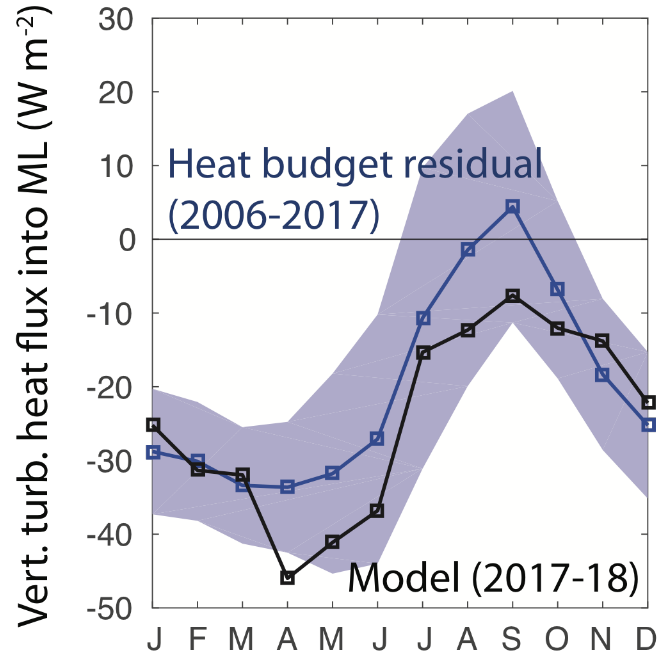
Largest K_v, strongest cooling when shear is strong, stratification (ΔT) is weak

Importance of shear and stratification

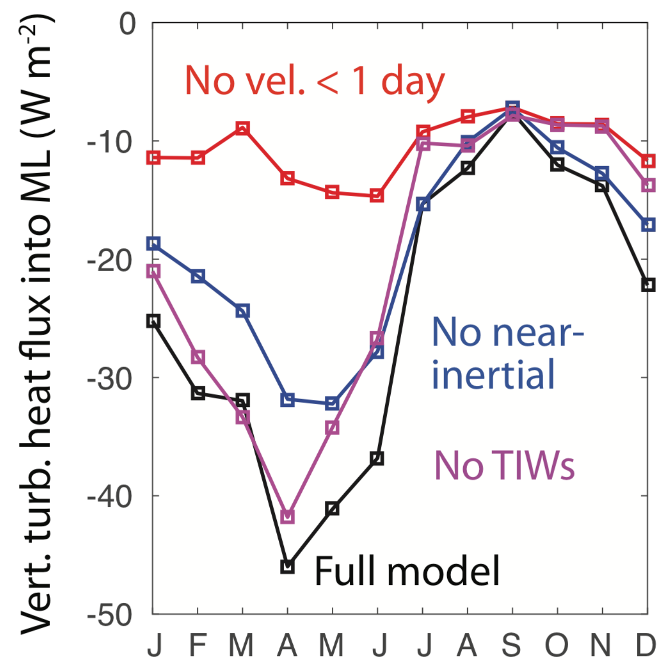


Validation and diagnosis

Seasonal cycle from model agrees well with that of heat budget resid.



Short timescale variability of shear (periods < 1 day) is most important. **Near-inertial waves enhance cooling** during winter-spring.



Summary and conclusions

- There are pronounced seasonal cycles of turbulent cooling at off-equatorial locations.

- Cooling tends to be strongest when winds are weakest and the mixed layer is thinnest. These conditions lead to enhanced shear at the base of the ML, especially with periods < 1 day.

- Local wind- and buoyancy-forced mixing (including near-inertial waves) accounts for at most ~25% of the seasonal cycle of cooling.

- These results need verification from direct measurements of turbulence.

Remaining questions

- What is the source of high-freq. (< 1 day) shear? Local wind is uncorrelated with shear on these timescales. Remotely-generated surface gravity waves, internal waves?

- Why is shear strongest in boreal winter-spring at 4°N, 23°W? Thinnest mixed layer?

- Do models reproduce the observed shear, its seasonality, and its vertical structure at 4°N, 23°W? Do they simulate the correct seasonal cycle of turbulent cooling?