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

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Questions

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

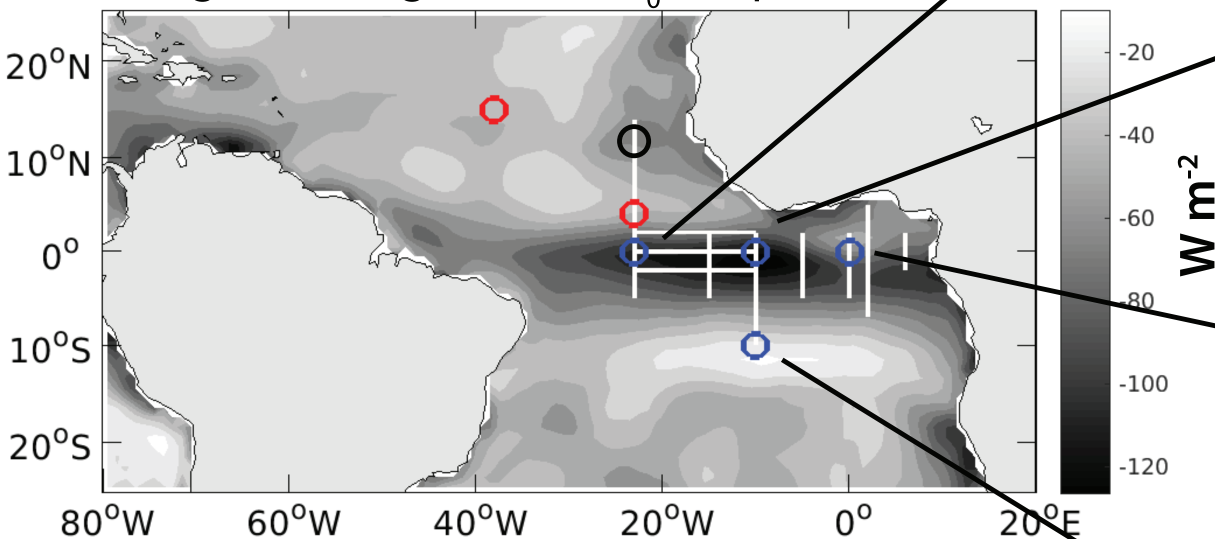
In the absence of strong mean shear, what drives mixing and cooling off the equator?

Approach

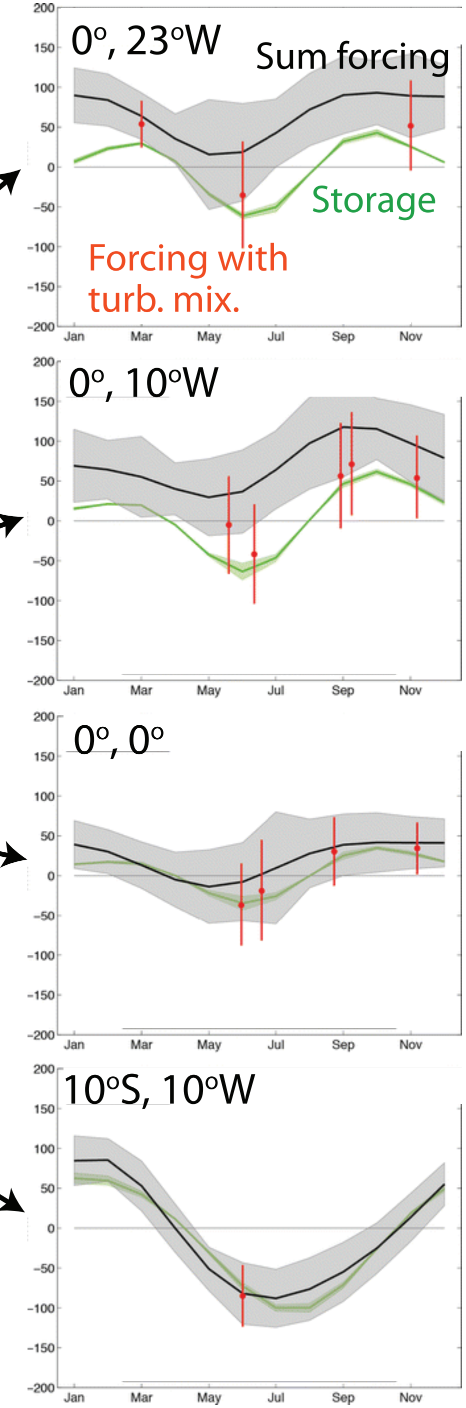
Hourly measurements from PIRATA moorings and one-dimensional models (KPP, PWP).

Previous measurements and estimates of turbulent cooling

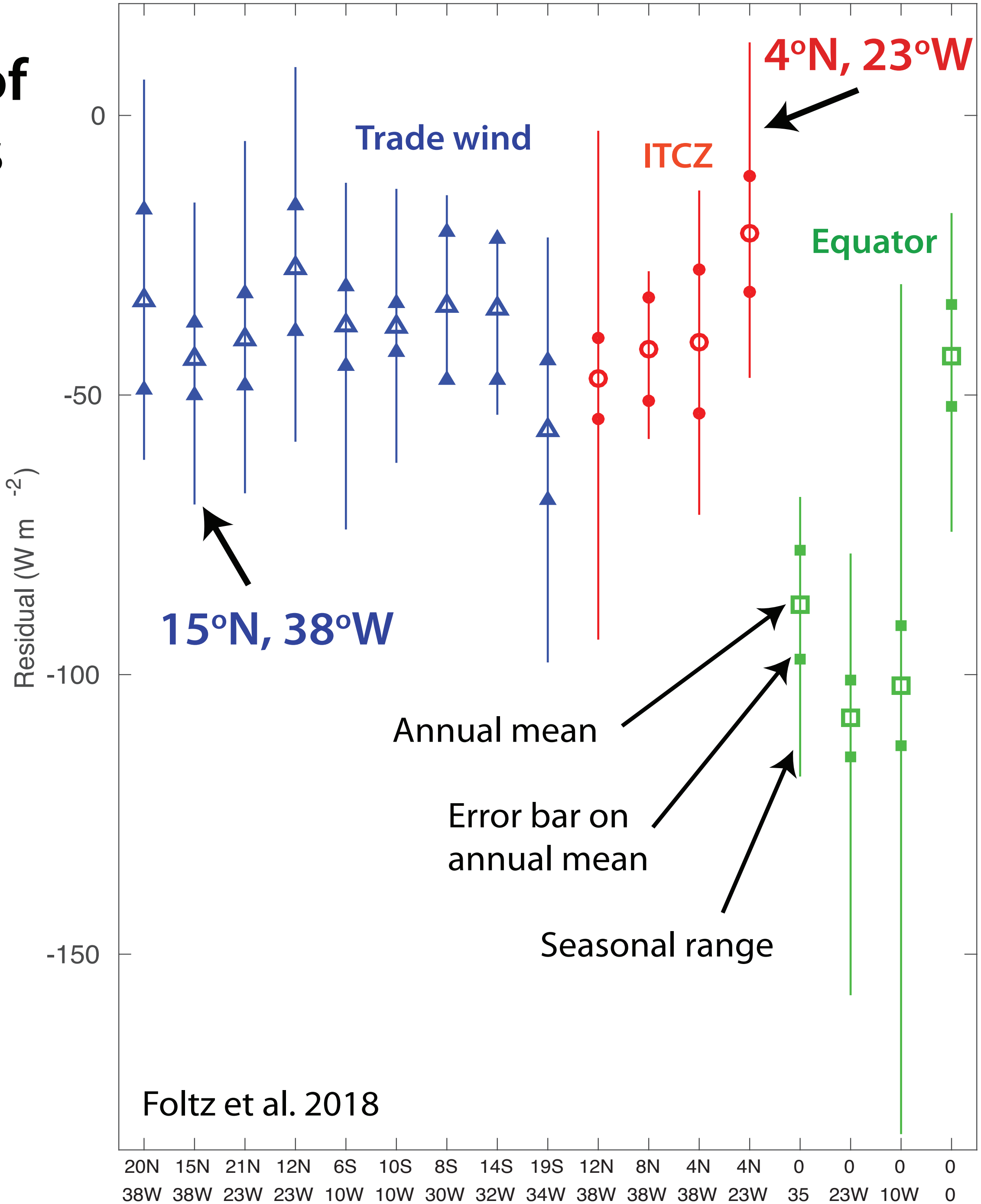
Shading: annual mean heat budget residual: Storage rate (Argo) minus Q_0 (TropFlux)



White lines: microstructure measurements
Blue circles: Hummels et al. (2014)
Black circle: Hummels et al. (2018)
Red circles: this study

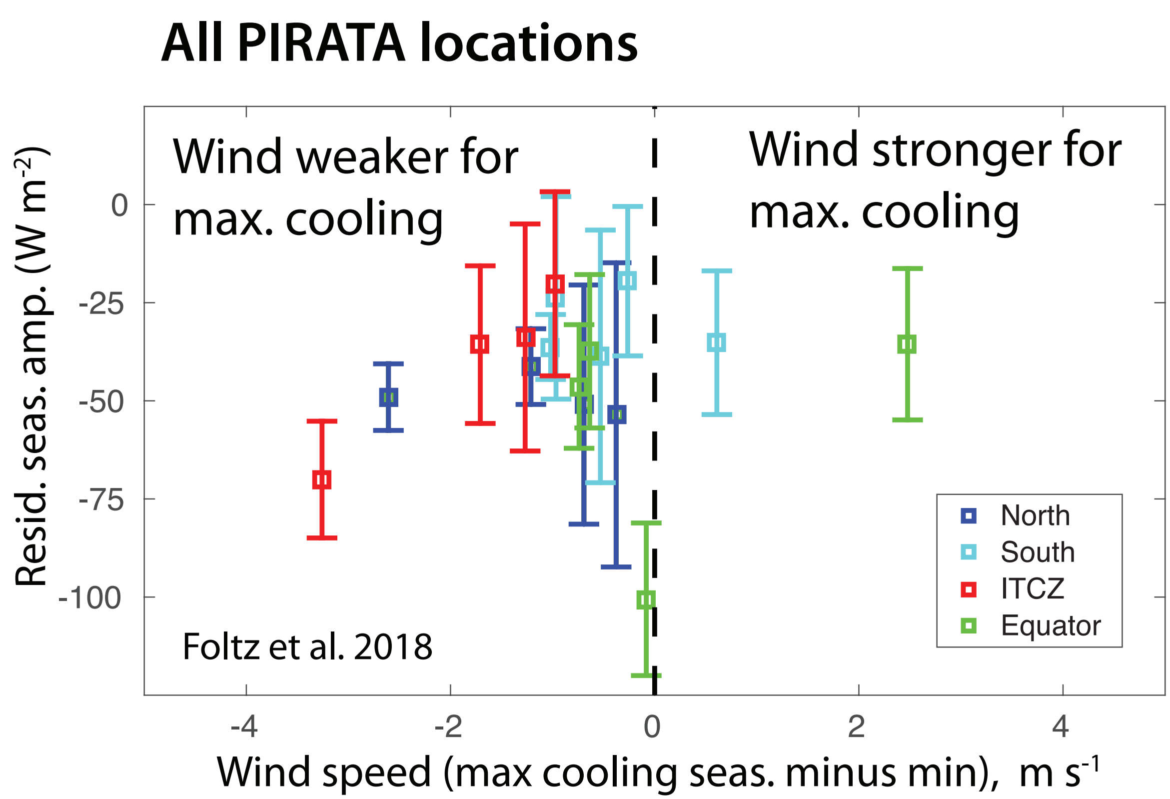


Strong seasonalities of heat budget residuals



Relationship between residual and wind speed

- Seasonally, more cooling occurs when wind is weak



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 (Large et al. 1994).

15°N, 38°W

- Daily ePIRATA **temp., salin**. (Foltz et al. 2018)
  Hourly PIRATA **air temp., rel. humidity, winds, shortwave, rain**

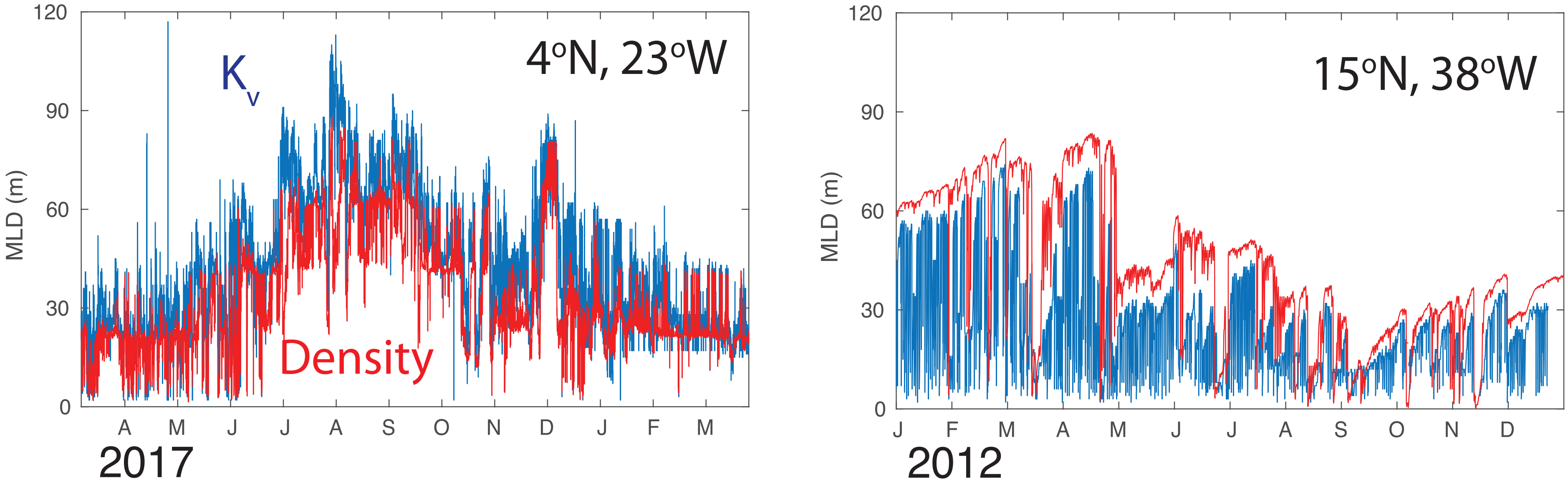
- Initialize **PWP model** (Price et al. 1986) at beginning of each month with ePIRATA T(z), S(z) then force with hourly winds, fluxes (2001, 2002, 2003, 2004, 2006, 2007, 2012). **84 monthly model runs**.

- Calculate K_v using KPP model: mooring sfc. forcing, PWP T(z), S(z), v(z).

Methods

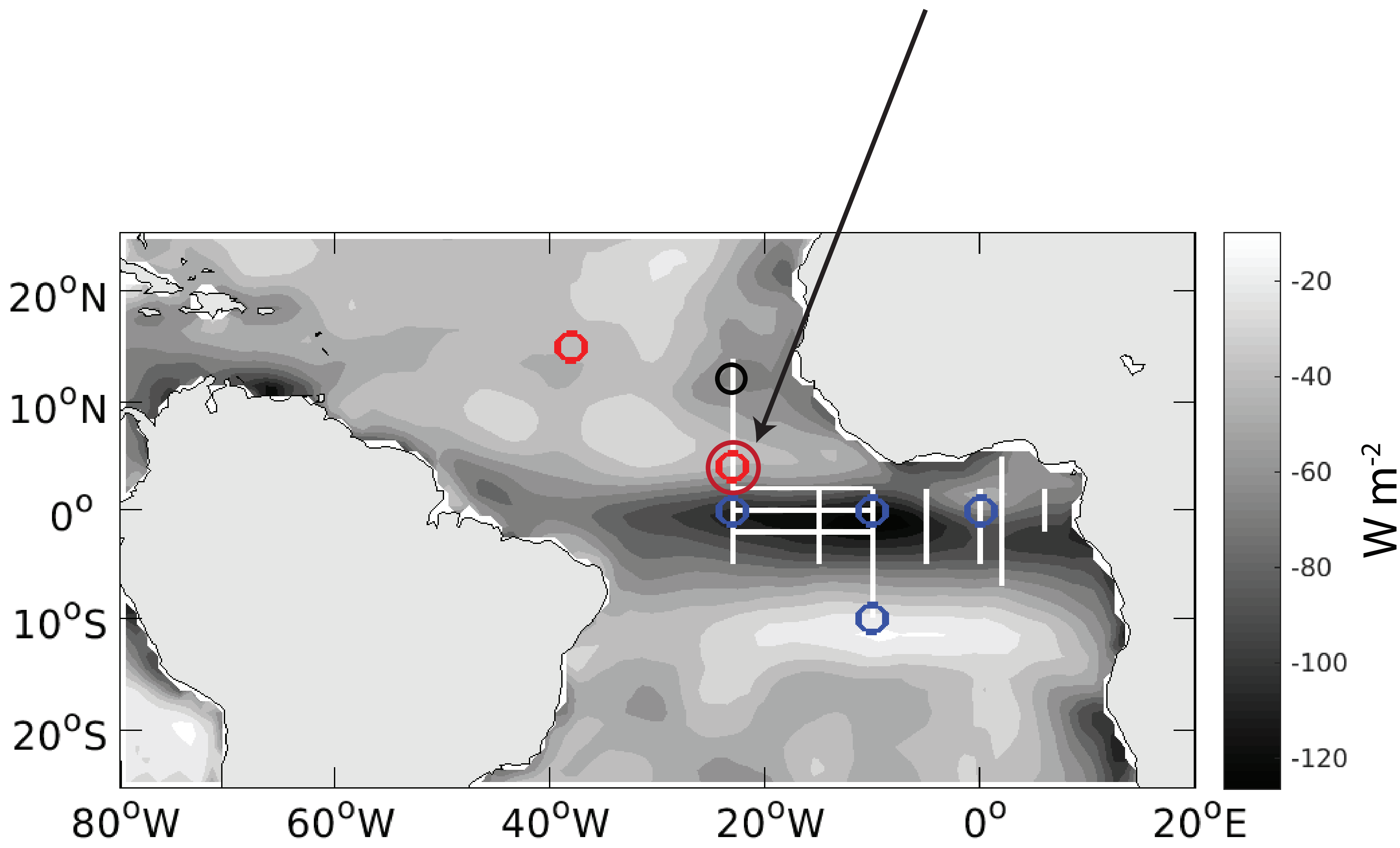
MLD: shallowest depth where K_v is less than 0.001 $m^2\ s^{-1}$

Comparison of K_v-based and density-based MLD

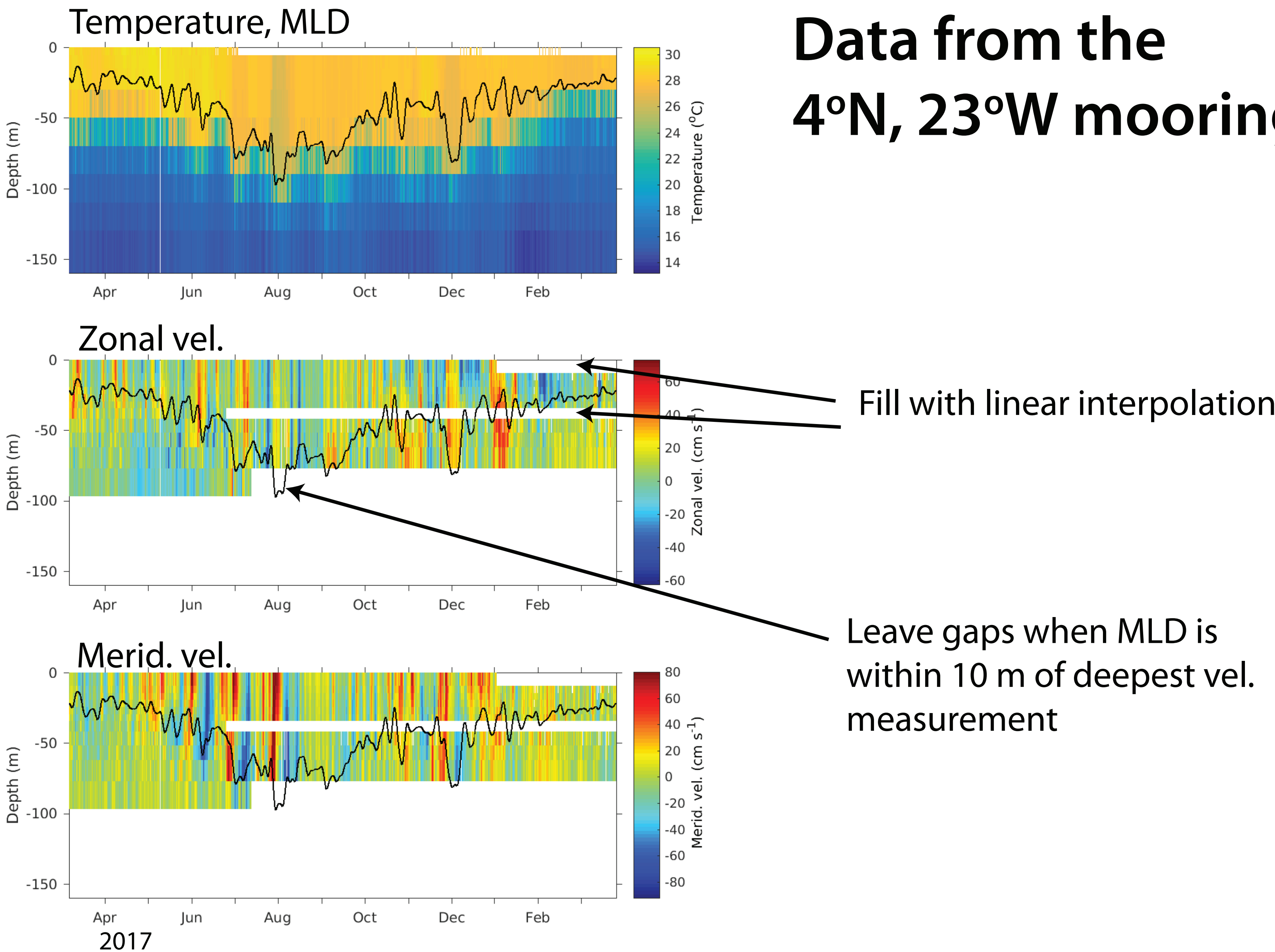


Vert. turb. cooling of ML: K_v at MLD+10 m and dT/dz calculated between MLD and MLD+10 m: **dens*c_p*K_v*dT/dz**

Results at 4°N, 23°W



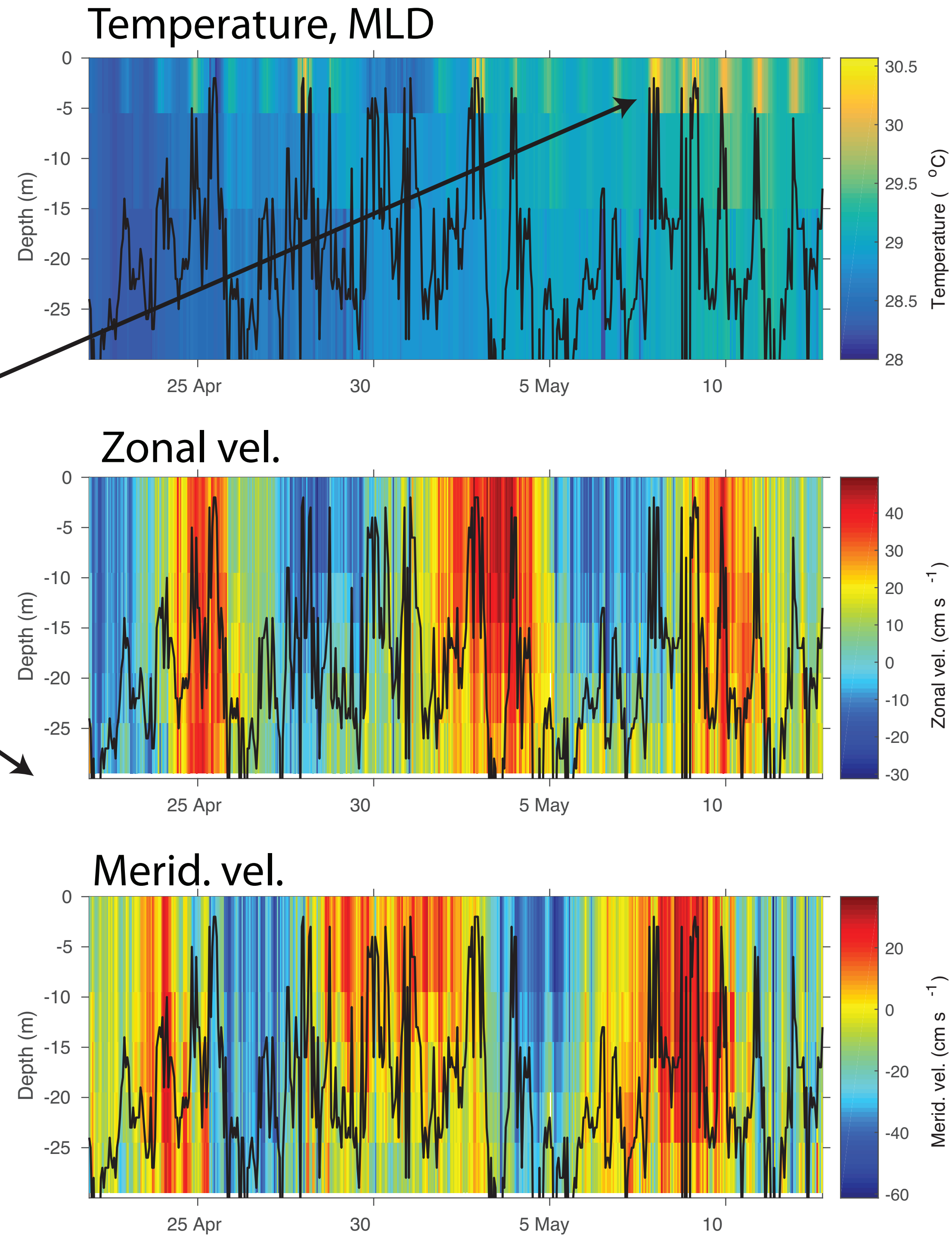
Data from the 4°N, 23°W mooring

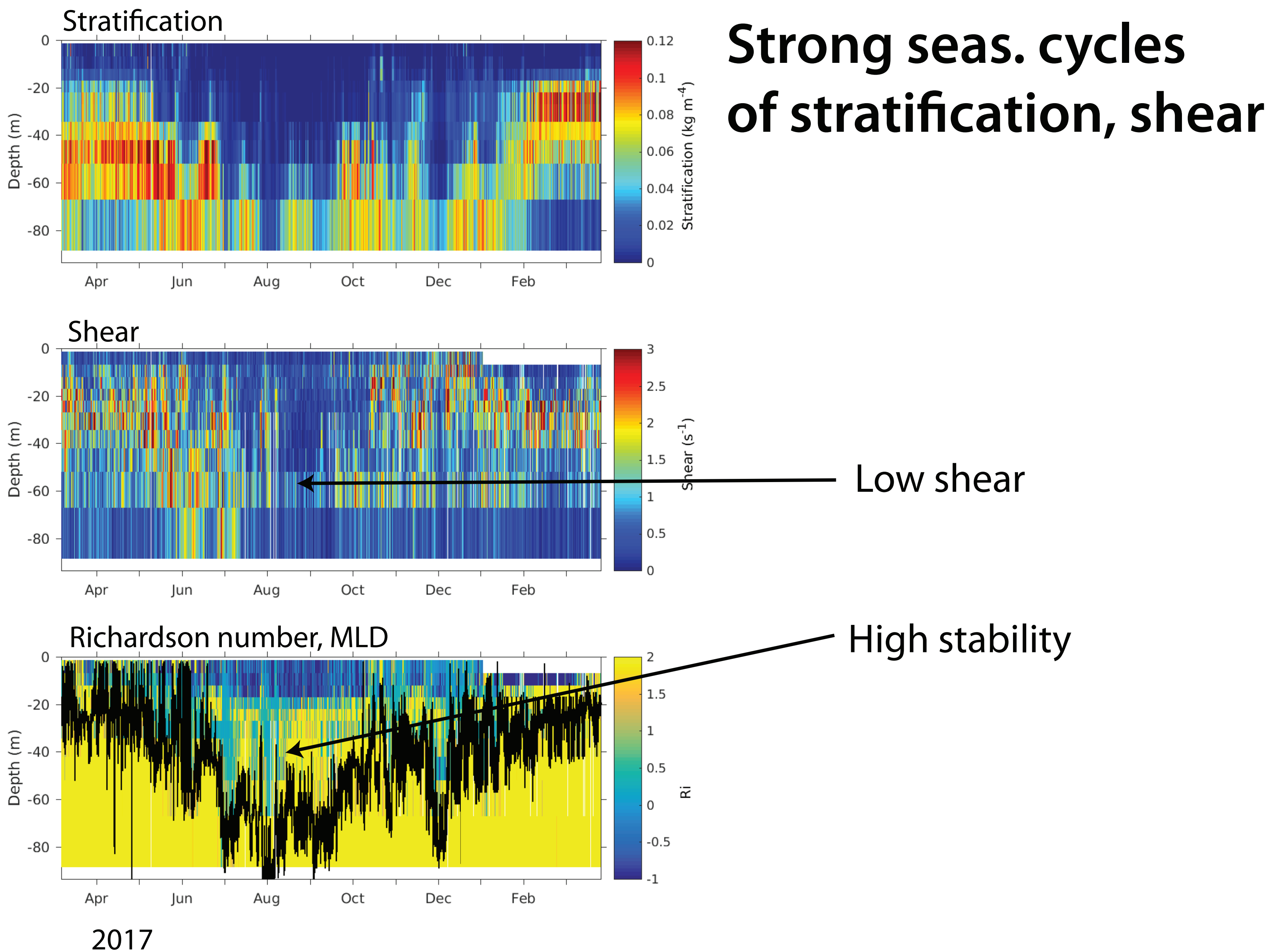


Temp., vel. during April-May

Diurnal temp.

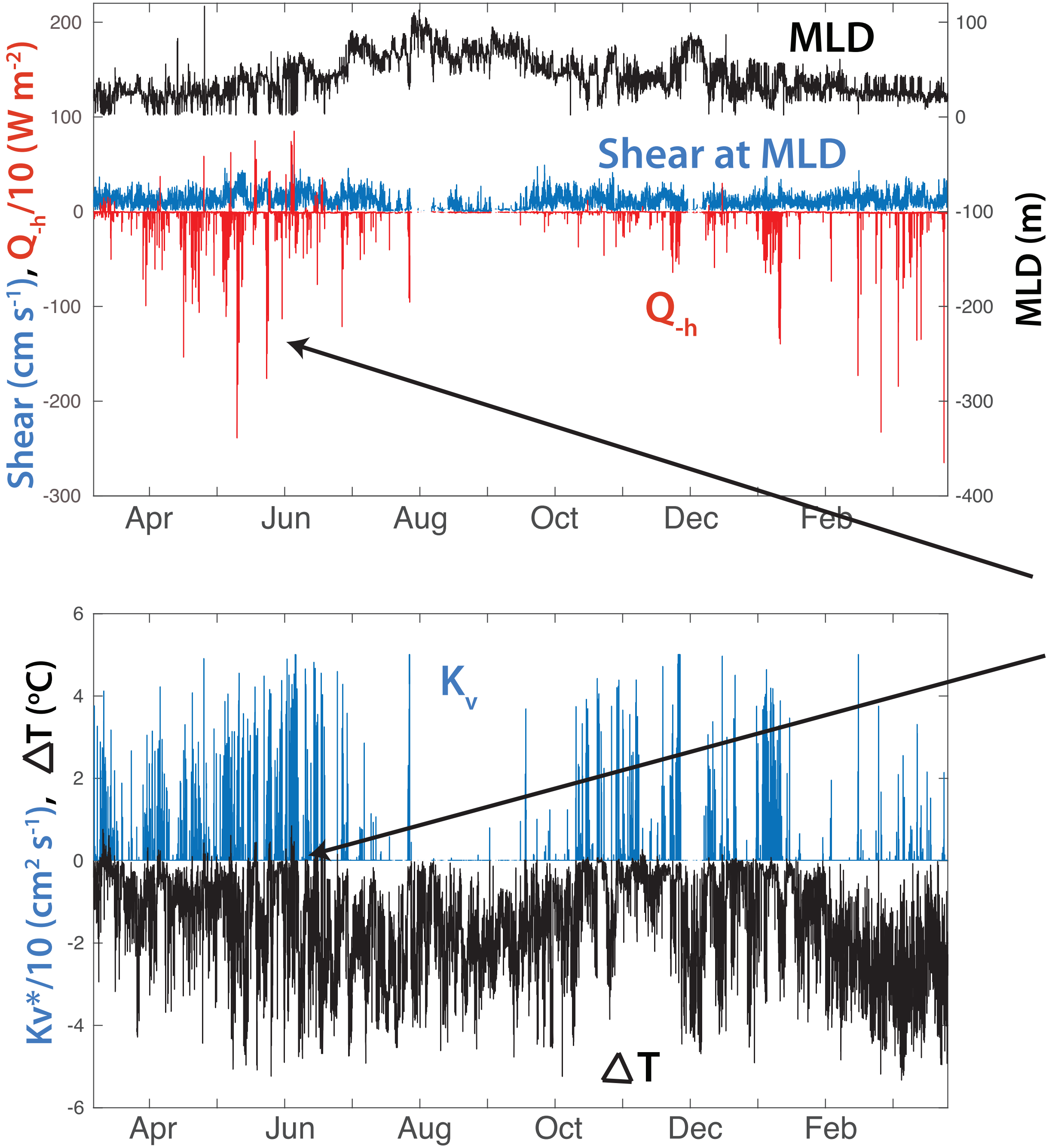
Near-inertial waves, semidiurnal velocity





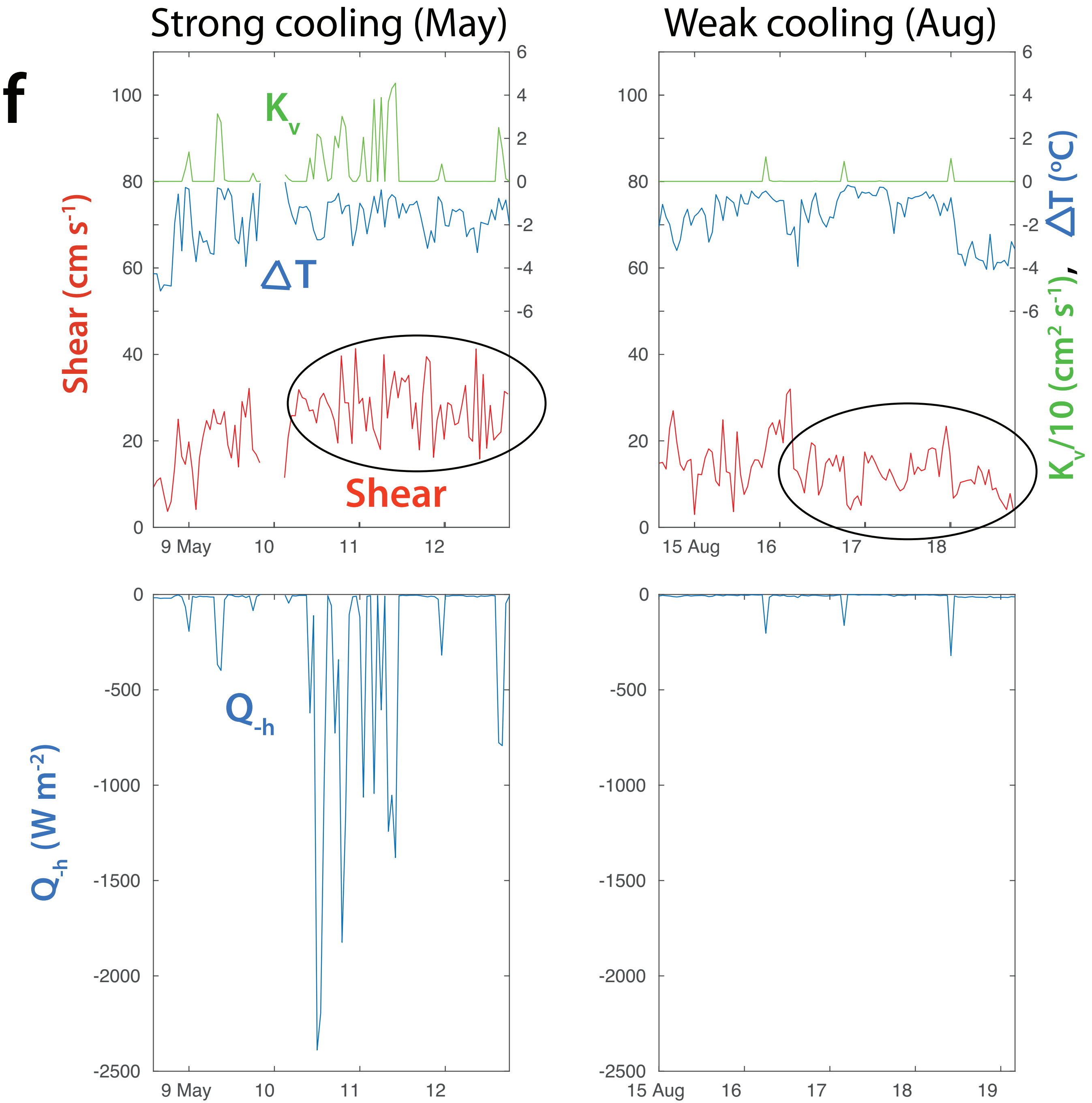
Strong seas. cycles of stratification, shear
Stratification
Shear
Richardson number, MLD
Depth (m)
0
-20
-40
-60
-80
Apr
Jun
Aug
Oct
Dec
Feb
Stratification (kg m-4)
0.12
0.1
0.08
0.06
0.04
0.02
Shear (s-1)
3
2.5
2
1.5
1
0.5
Ri
-0.5
-1
Low shear
High stability
2017

Vertical mixing and cooling



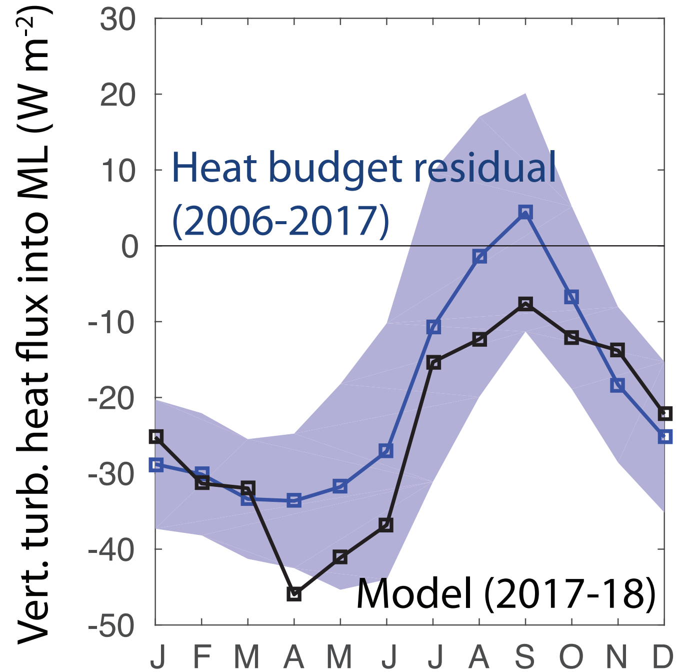
Largest K_v, strongest cooling when shear is strong, stratification (ΔT) is weak

Importance of shear and stratification

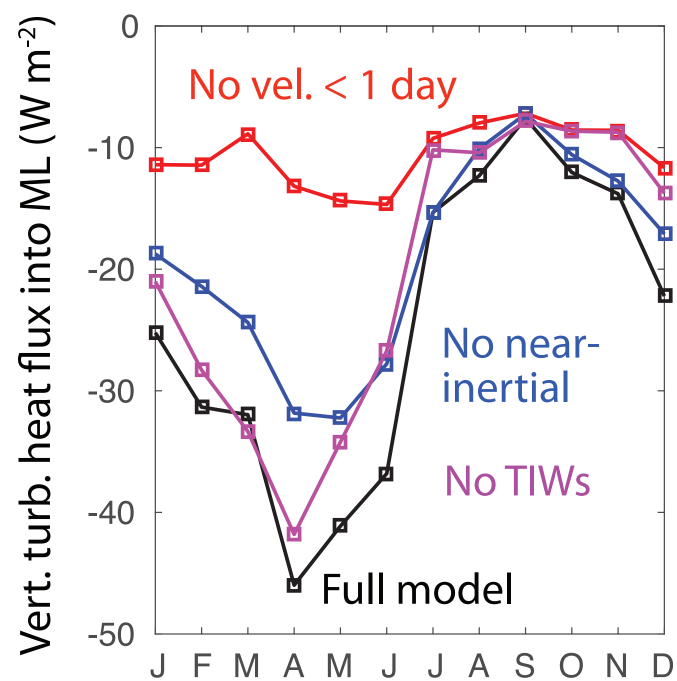


Validation and diagnosis

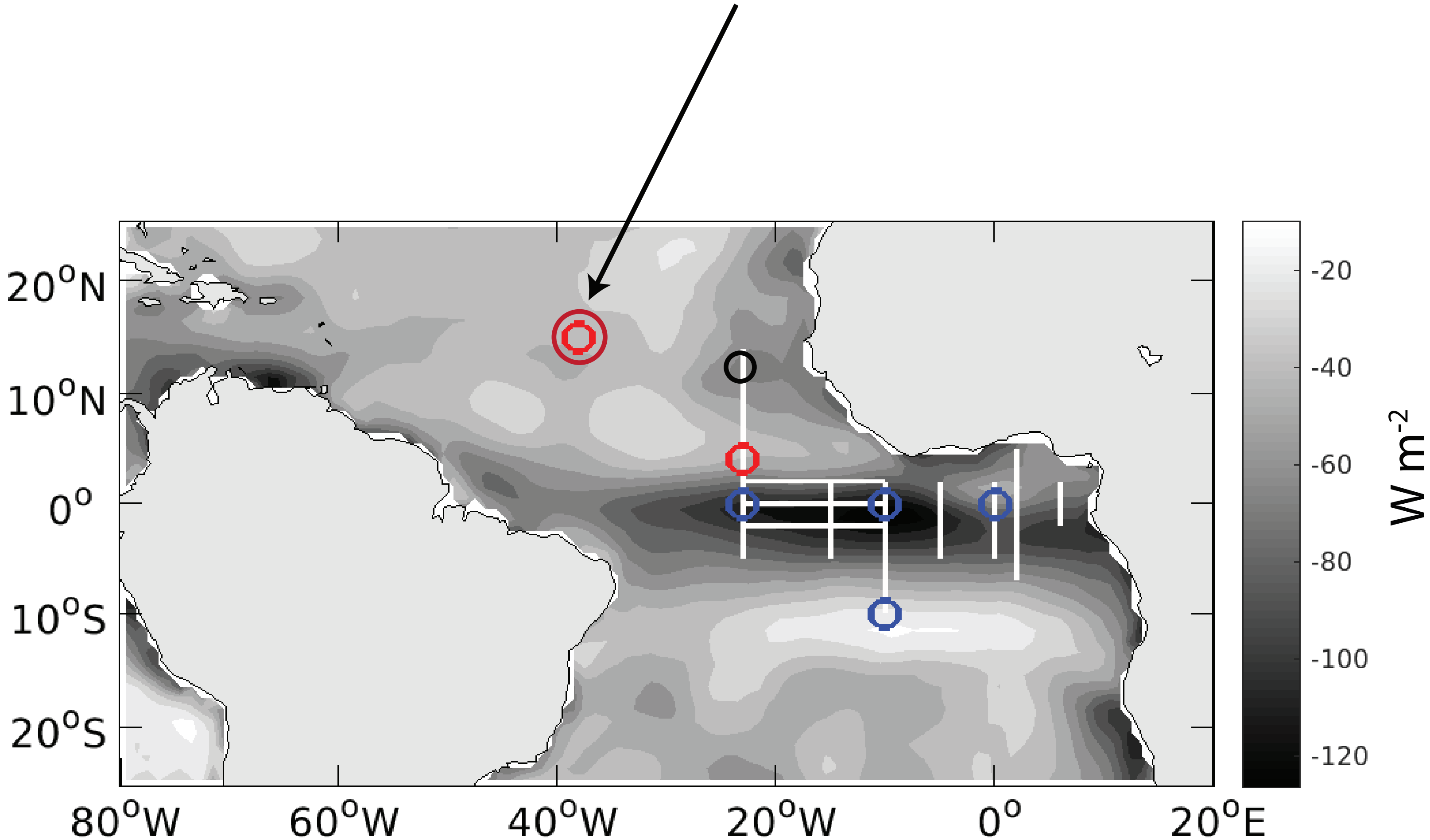
Seasonal cycle from model agrees well with that of heat budget resid.



Short timescale variability of shear (periods < 1 day) is most important, likely due to tides and remotely-forced internal waves. **Near-inertial waves enhance cooling** during winter-spring.



Results at 15°N, 38°W

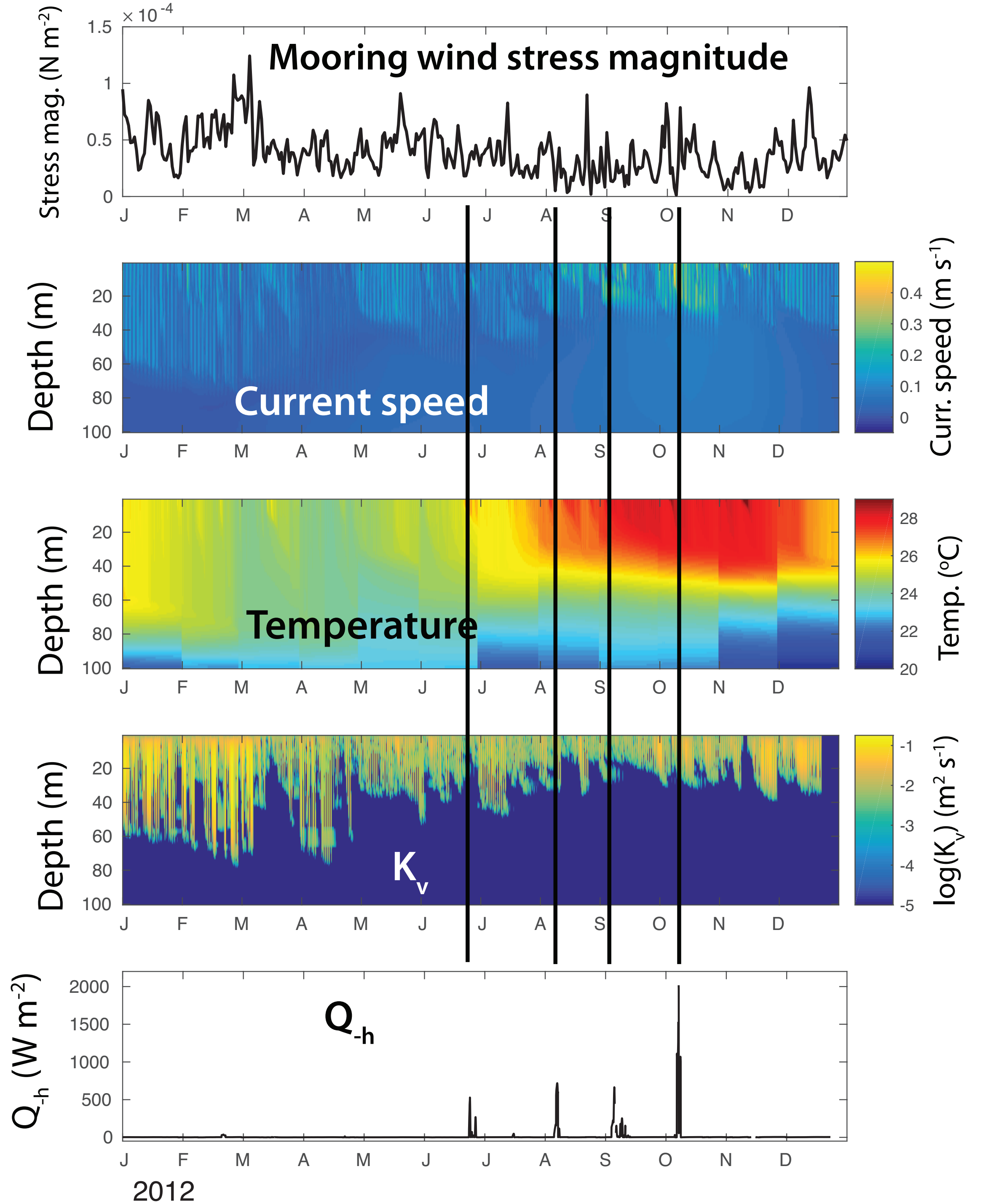


Results from 2012 (PWP, KPP)

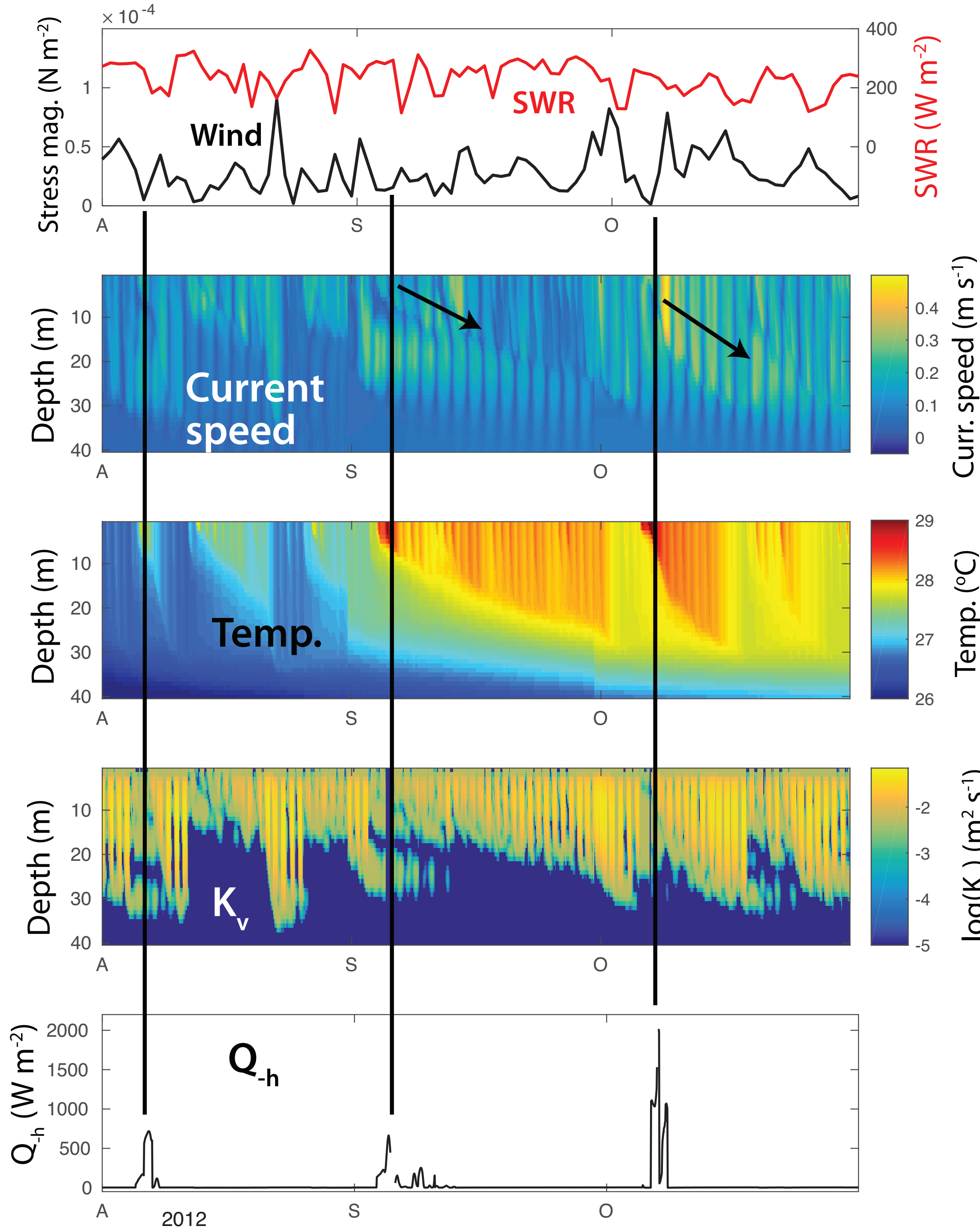
Strongest cooling occurs during summer-fall:

First: weak wind, surface warming,

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

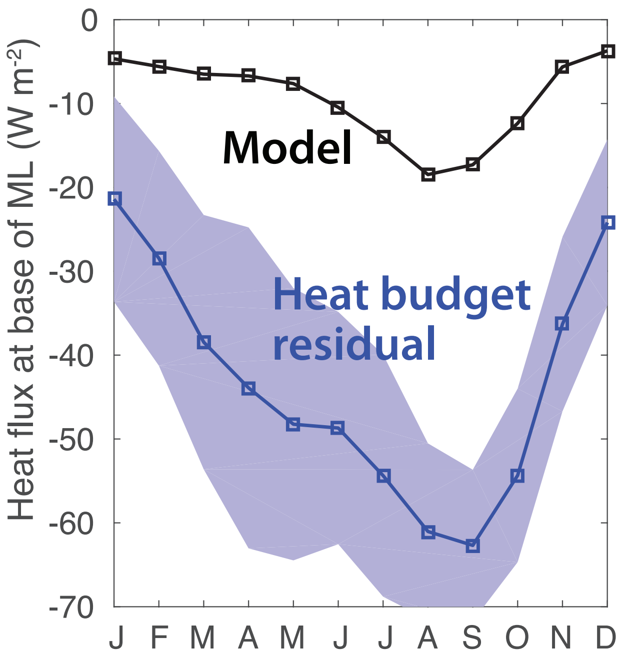


Aug-Oct 2012

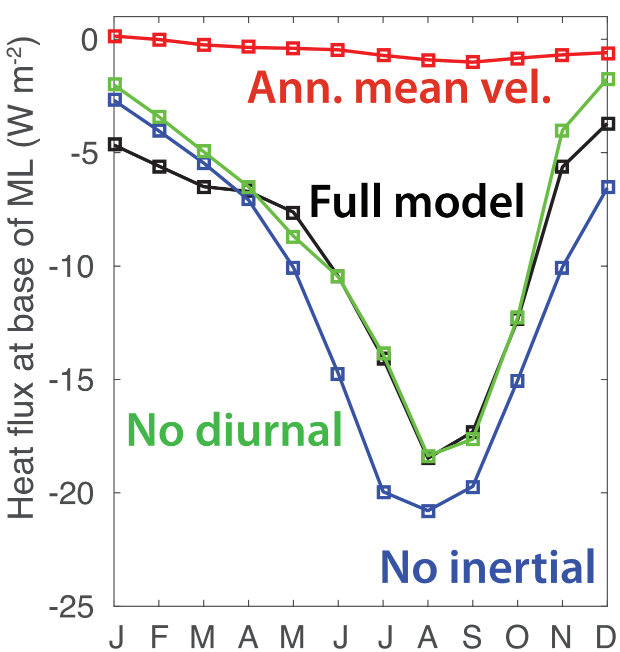


× 10^-4
Stress mag. (N m^-2)
SWR (W m^-2)
Wind
SWR
400
200
0
1
0.5
0
A
S
O
Depth (m)
Current speed
Curr. speed (m s^-1)
0.4
0.3
0.2
0.1
0
10
20
30
40
Temp.
Temp. (°C)
29
28
27
26
K_v
log(K_v) (m^2 s^-1)
-2
-3
-4
-5
Q_-h
Q_-h (W m^-2)
2000
1500
1000
500
2012

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



Phases of seas. cycles are similar, but model underestimates cooling, likely because tides and internal waves are missing.



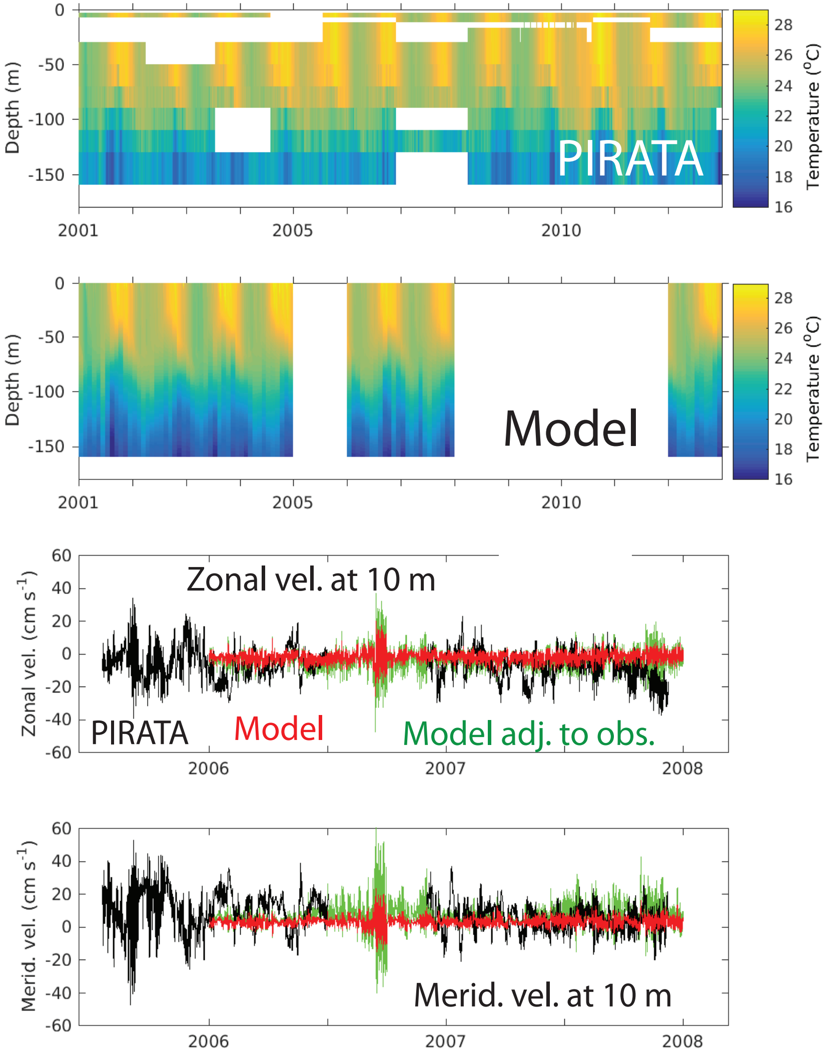
Turbulent mixing in model is driven mainly by episodic shear. Weak influence from diurnal cycle and near-inertial waves.

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, which appears to originate mainly from remotely-forced internal waves with periods < 1 day.
- Local wind- and buoyancy-forced mixing accounts for at most ~25% of the seasonal cycle of cooling.
- Many unanswered questions remain, including the sources of remotely-forced shear and turbulence.
- These results need verification from direct measurements of turbulence.

Validation of PWP model at 15ºN, 38ºW

T(z), velocity at 10 m



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