1d, 2d, & 3d Simulations of Hurricane Wake Restratification

Baylor Fox-Kemper

APL-UW, Seattle, Mon. 11/17/08, 13:15-13:40

Based on MITgcm simulations created with R. Ferrari

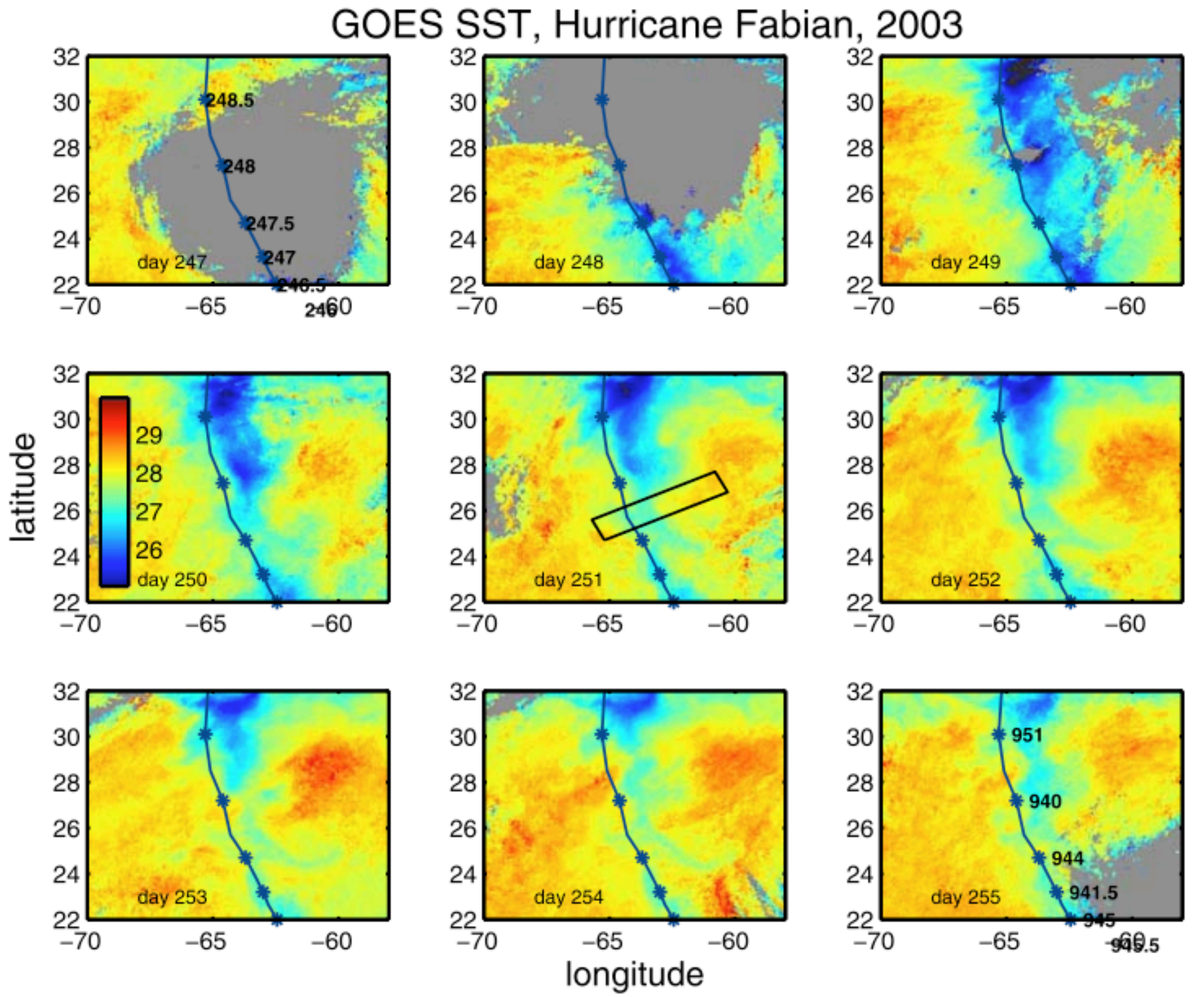


Figure 2. GOES SST images at daily intervals showing the passage of Hurricane Fabian through the central Sargasso Sea. The year day is shown in the lower left of each image. Hurricane Fabian is in the center of the image field on day 247, 4 September 2003. Bermuda is just above the northern edge of the region shown here and directly beneath the track of Fabian, whose track is the thin black line running roughly south to north. The eye location at half-day intervals is noted by the asterisks labeled with the year day (upper left) and central pressure (mbar) is noted on the lower right (track data are from the Johns Hopkins University online archive). Clouds are the uniform gray mass and SST is color-coded by the scale at left middle. The CBLAST region that is sampled for SST is shown as the rectangle in the center (more on this in section 3.2). Hurricane Isabel was just entering the southeast corner of the image field on the last day shown, 255, and continued almost due westward. Isabel caused enhanced wind speeds in the CBLAST region starting from day 255, when, notice, the SST cooling in the wake of Fabian reappeared.

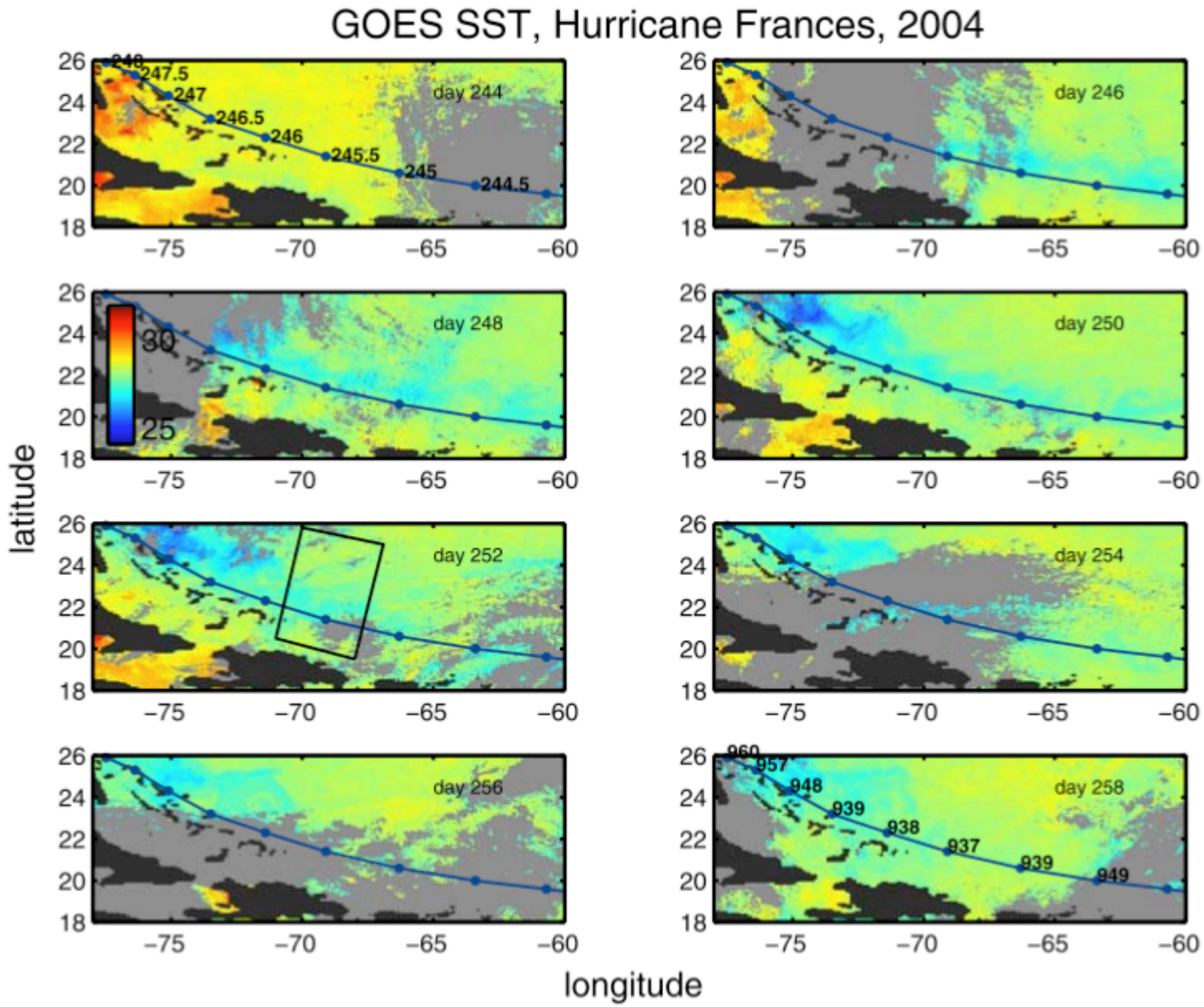
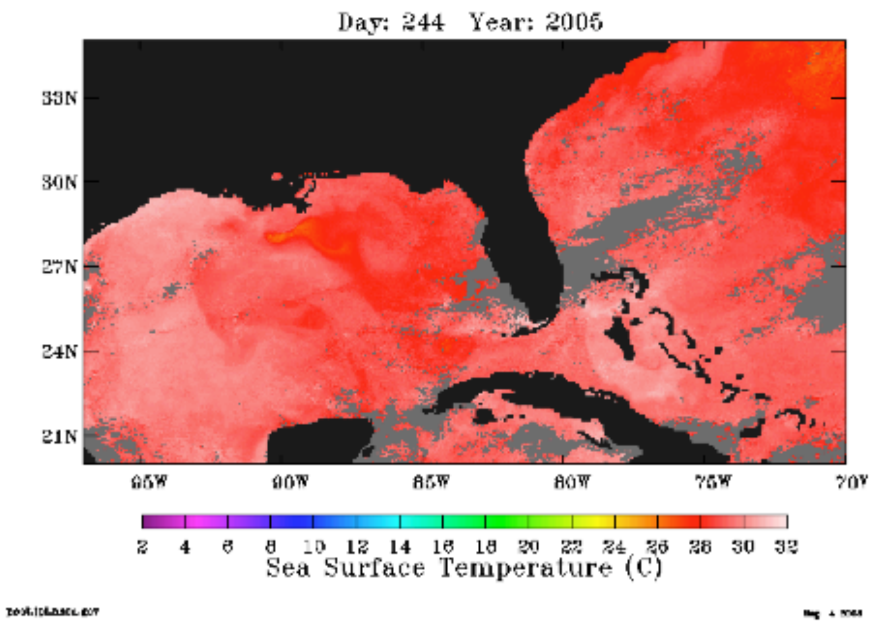


Figure 3. GOES images at 2 day intervals showing the passage of Hurricane Frances along a path just north of the Leeward Islands. The year day is shown at upper left; day 244 was 31 August 2004. Central pressure (mbar) is at lower right. The color scale for SST is shown on day 248, and the CBLAST region is shown as the black rectangle. Notice that there was fairly extensive cloud cover on many days; the clouds on day 254 are associated with Hurricane Ivan, which passed through the central Caribbean Sea on day 255, and the clouds on day 258 were a precursor of Hurricane Jeanne, which passed through the CBLAST region on 16 September, just after the last image shown here.

Mixing Depth of Hurricane Ophelia Deduced by Comparison of GOES SST and World Ocean Atlas 2005 Data

J. Rudolph

Department of Atmospheric and Oceanic Sciences, University of Colorado at Boulder, Boulder, Colorado, USA



preOphelia crop.pdf

Figure 3. Satellite SST Before Arrival of Ophelia: September 1, 2005 (POET)

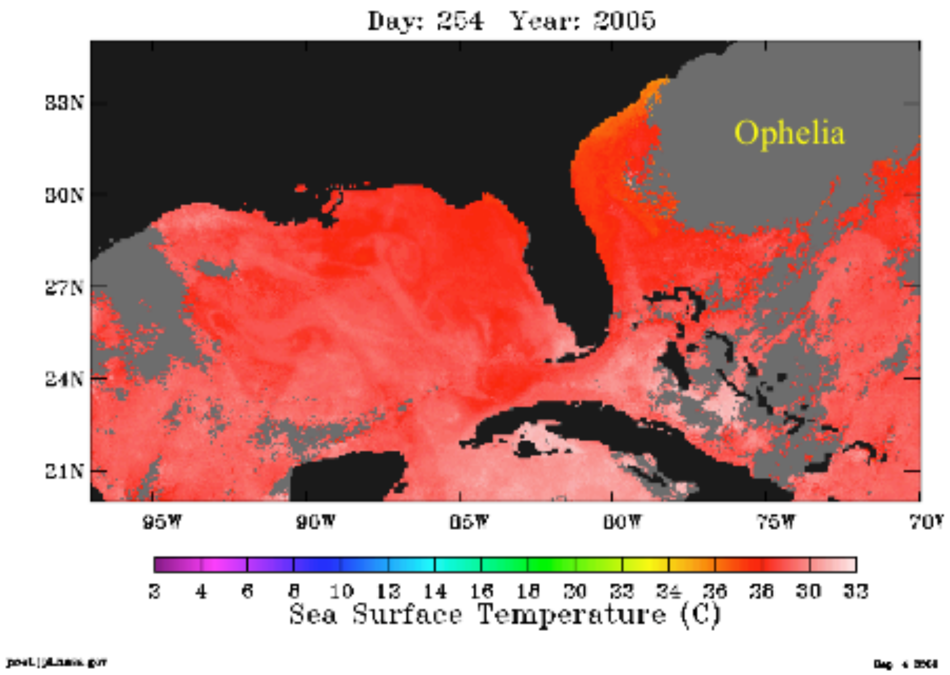
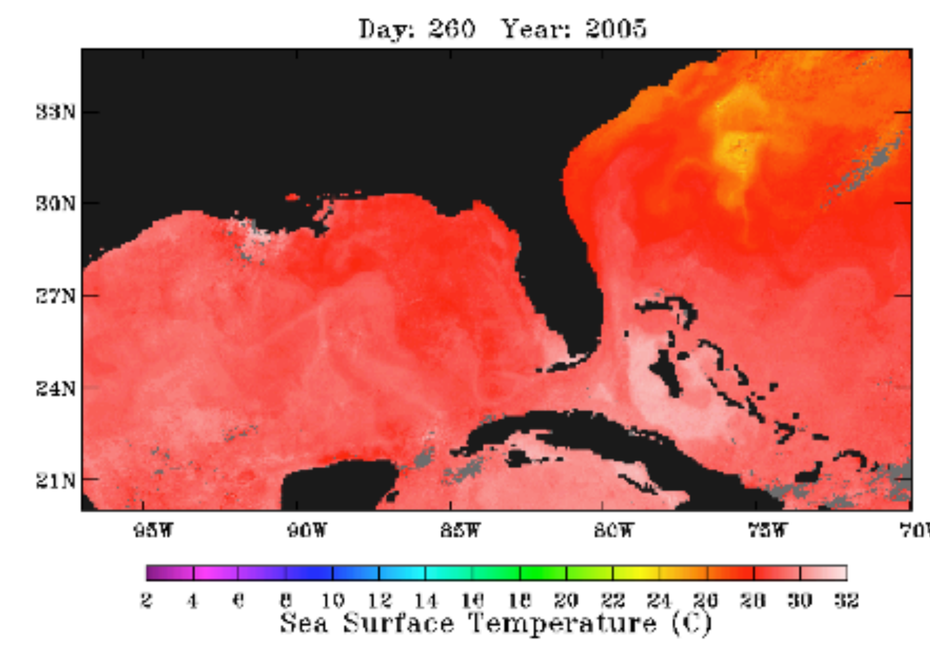


Figure 4. Satellite SST with Ophelia Visible: September 11, 2005 (POET)

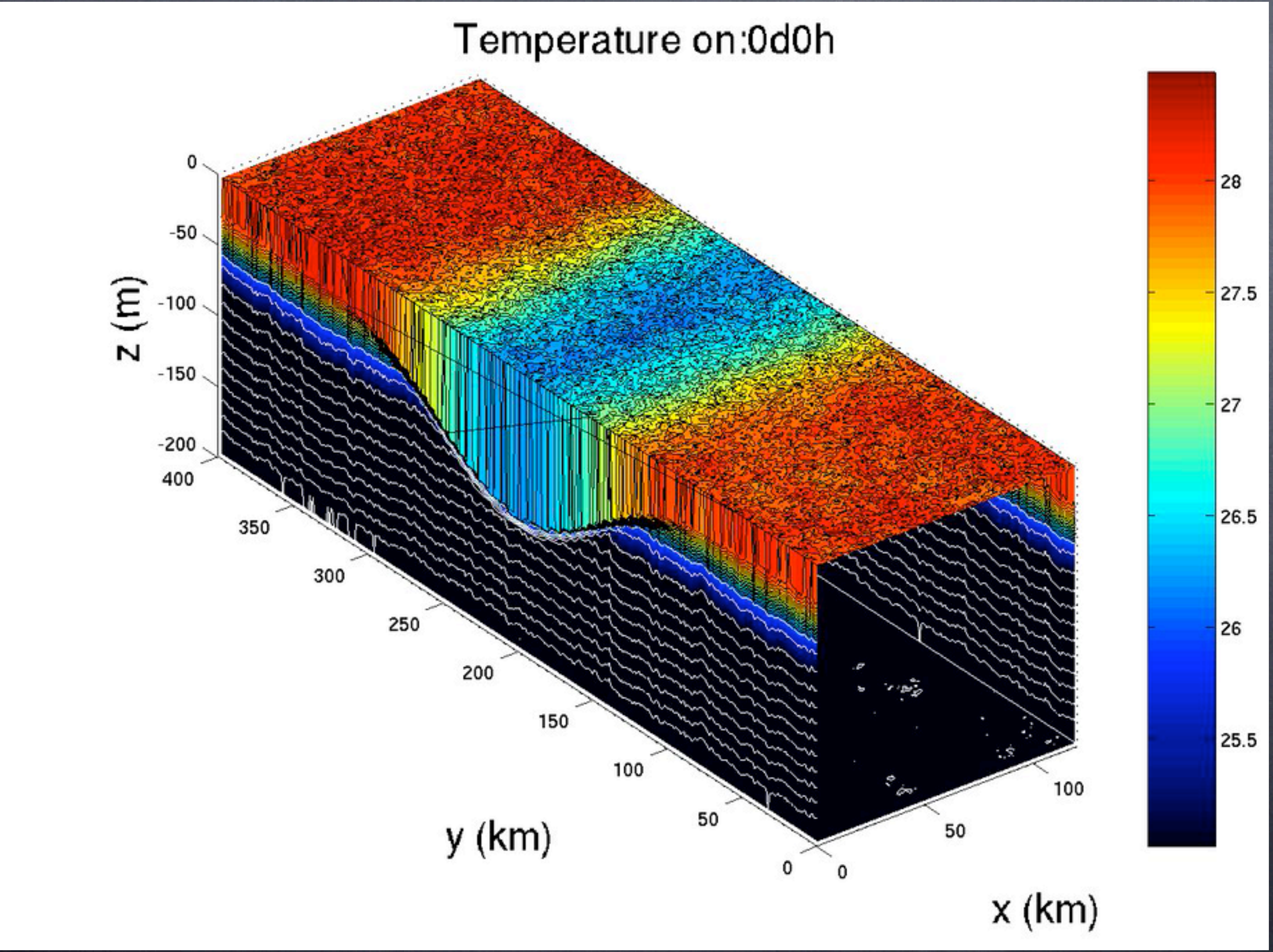
Mixes to ~320m! From a paper by one of my Intro. to Oceanography students!



cold tr crop.pdf

Figure 5. Ophelia's Cold Trail Visible in Satellite SST: September 17, 2005 (POET)

3d



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-100
-150
-200
z (m)
400
350
300
250
200
150
100
50
0
y (km)
0
50
100
x (km)
28
27.5
27
26.5
26
25.5

Goals

- Discuss physics of 1d modeled restratification
- Discuss physics of 2d modeled restratification
- Discuss physics of 3d modeled restratification
- Scaling 3d restratification.
- Time & Length Scales of modeled restratification

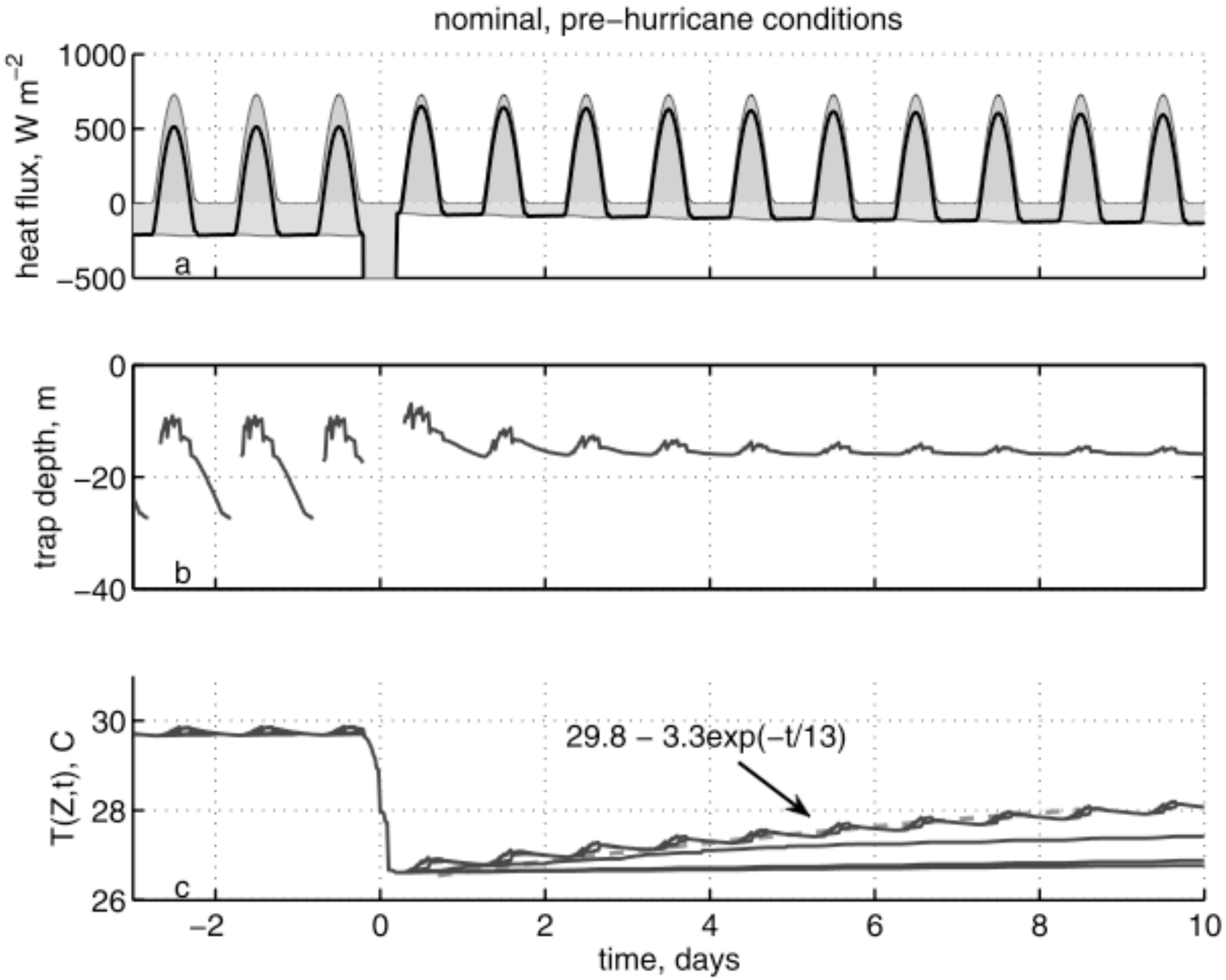
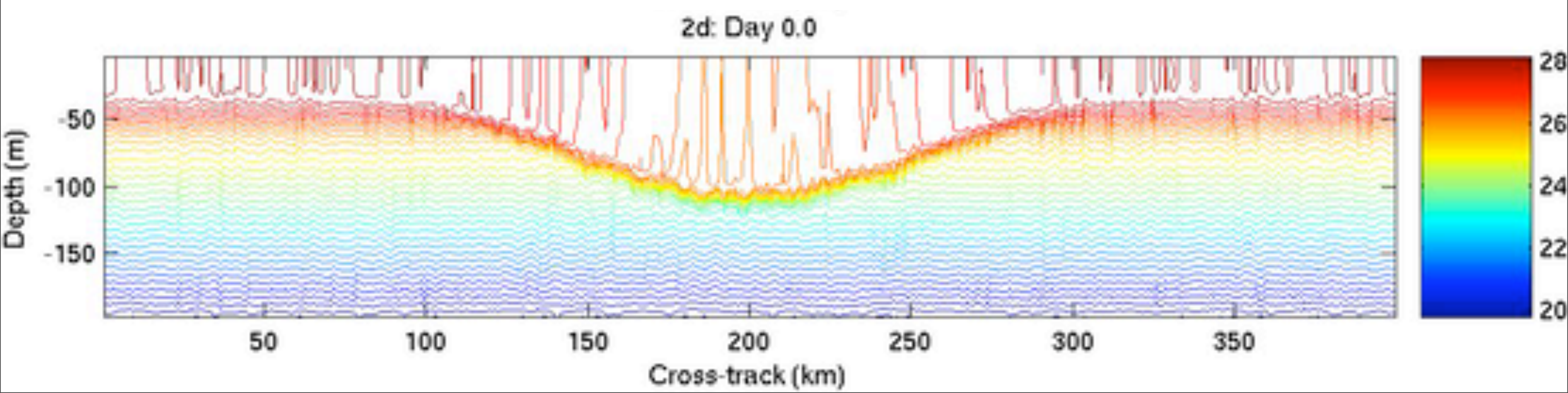


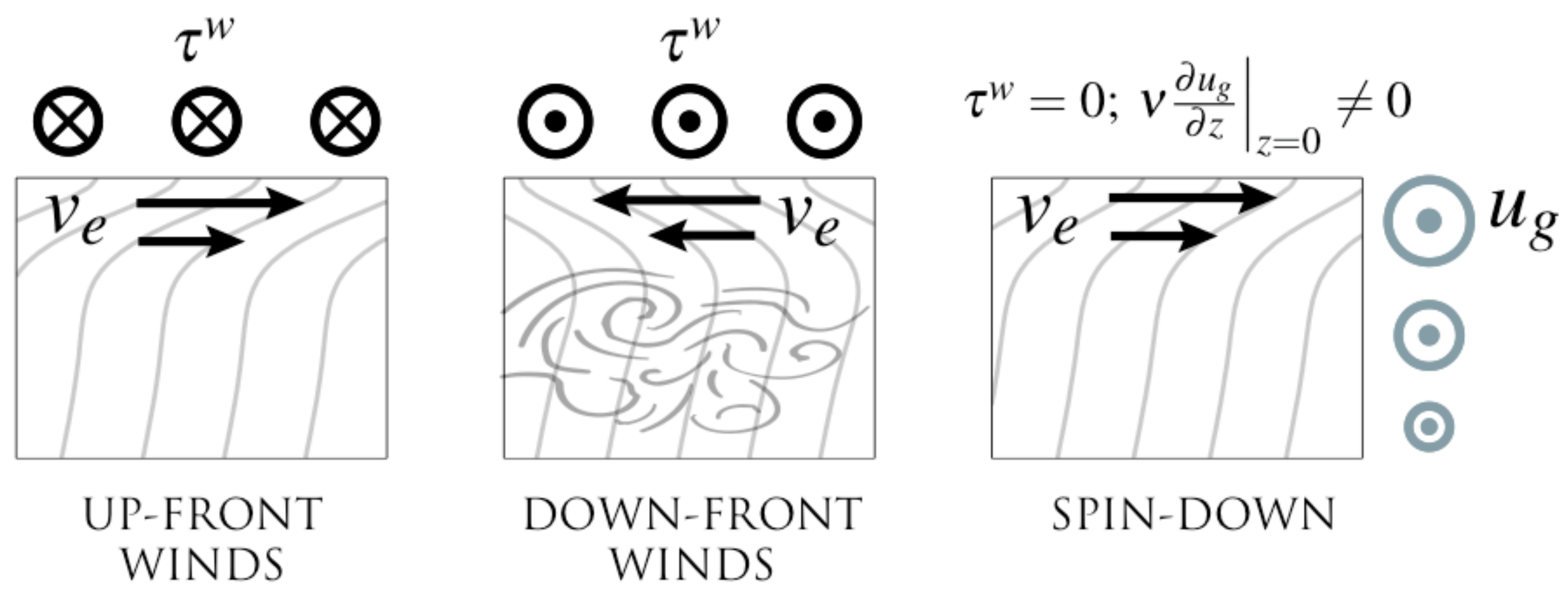
Figure 13. A simulation by a one-dimensional upper ocean model showing a trade wind regime with cloud cover and wind speed taken from prehurricane conditions and perturbed by a strong, transient wind event around time = 0. (a) The surface heat fluxes: solar insolation (light grey), heat loss (dark grey) and the net heat flux (black line). (b) The trapping depth, *D*, of the surface layer defined by (1). (c) Ocean temperature at depths of 0 (SST), 5, . . .25 m. Note that the wind event caused SST to cool by about 3°C. After the wind event, the SST and near-surface layer then began to warm back toward the equilibrium SST, about 29.8°C. The postwind event cooling can be characterized as a decaying exponential with an e-folding time of about 13 days (the dashed line). The gradual warming at depths of 20 m and below was due to penetrating solar radiation.

Comparison to 2d.

Penetrating Solar & Mixing of Latent/ Sensible as in Price et al 1d case.



Frontogenesis & Overturning via downfront winds; upfront winds -> restratifiation



From Thomas & Ferrari 08

Figure 1: Schematic illustrating frictional re/destratification at a baroclinic current in the upper ocean. Up-front winds (left) blowing against a baroclinic geostrophic flow, u_g, will drive an Ekman flow, v_e, that flattens isopycnals (gray) and hence restratifies the fluid via differential horizontal advection of buoyancy. When the wind is oriented down-front (middle), Ekman advection of buoyancy destabilizes the water column, driving convective mixing and a reduction of the stratification. With no wind-forcing (right), the frictional spin-down of a baroclinic current arising from the mismatch of the geostrophic shear and the zero stress boundary condition induces a restratifying Ekman flow.

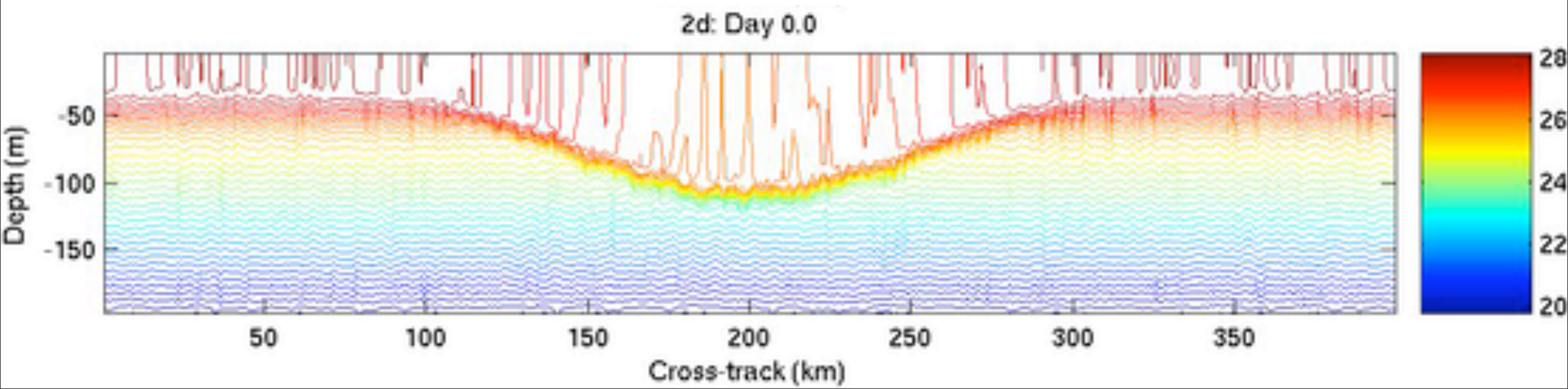
Thomas & Lee 05 note:

Repetition of these steps leads to frontogenesis. The most frontogenetic ASCs have cross-front widths $L_o = 4H\sqrt{-q_{\mathrm{ml}}}/f^2$ and do not translate with the Ekman transport.

Comparison to 2d.

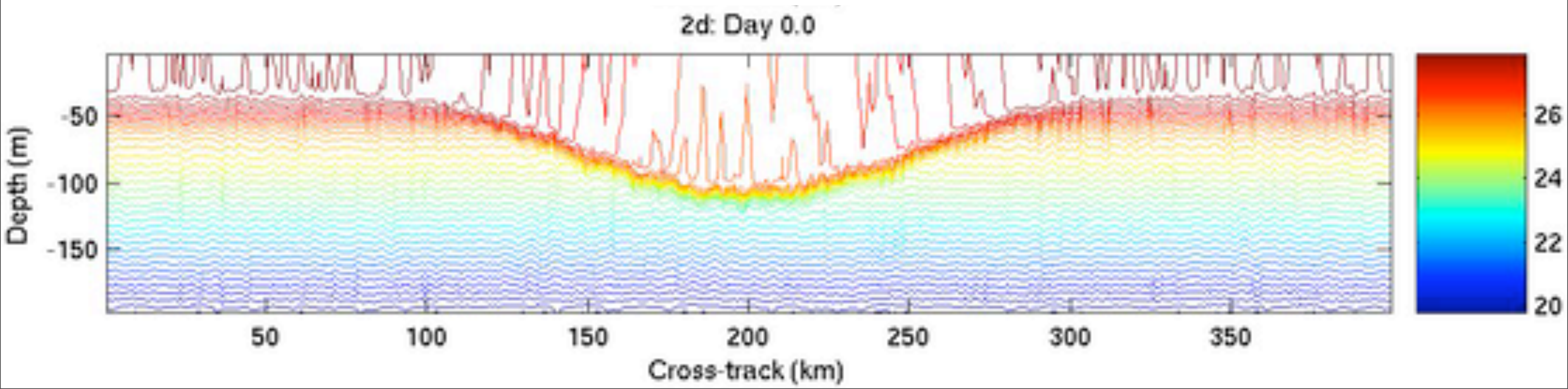
Frontogenesis via downfront winds; upfront winds -> restratifiation

Penetrating Solar & Mixing of Latent/ Sensible as in Price et al 1d case.

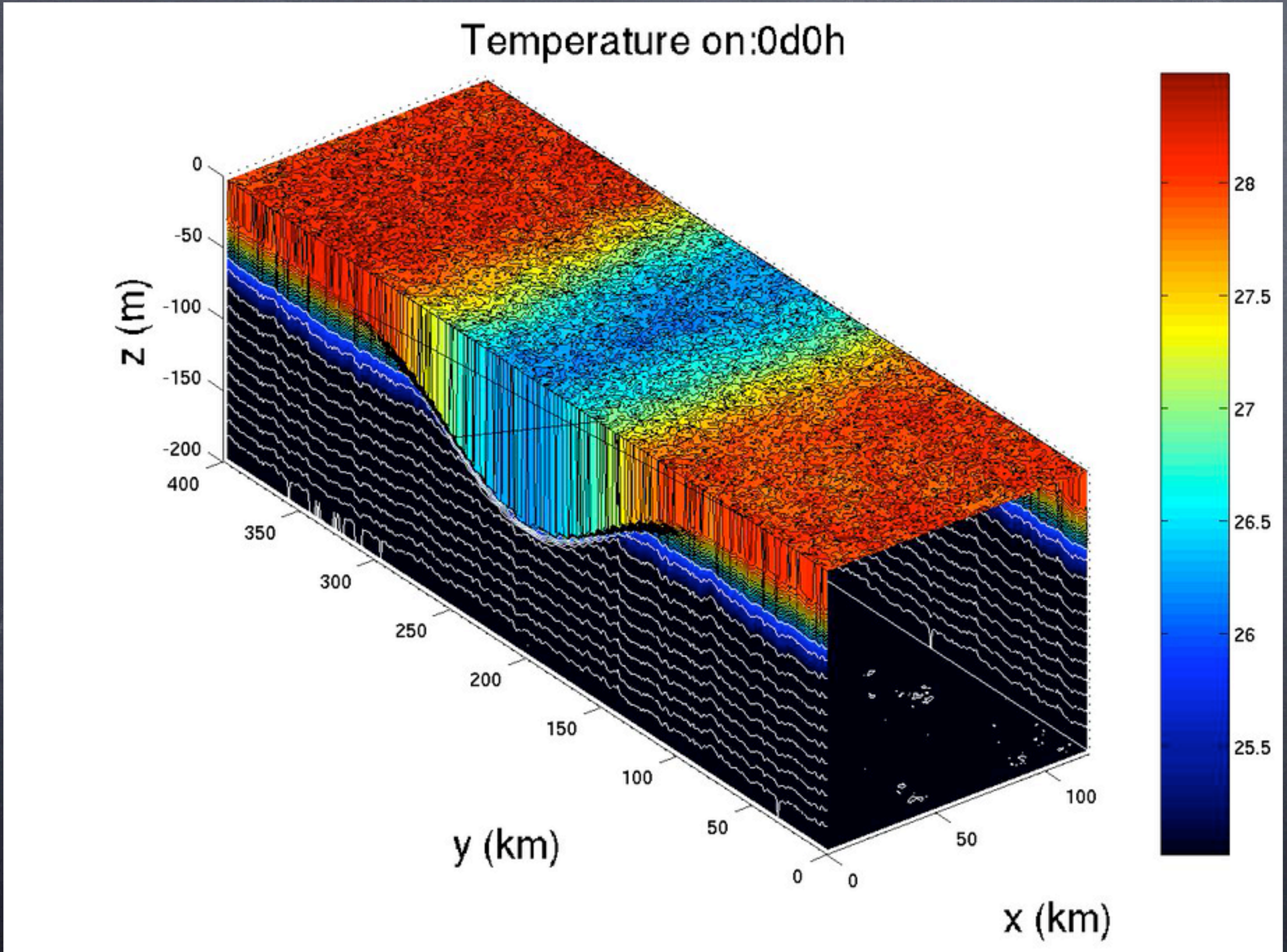


Turn off solar & Atmos. forcing and winds...

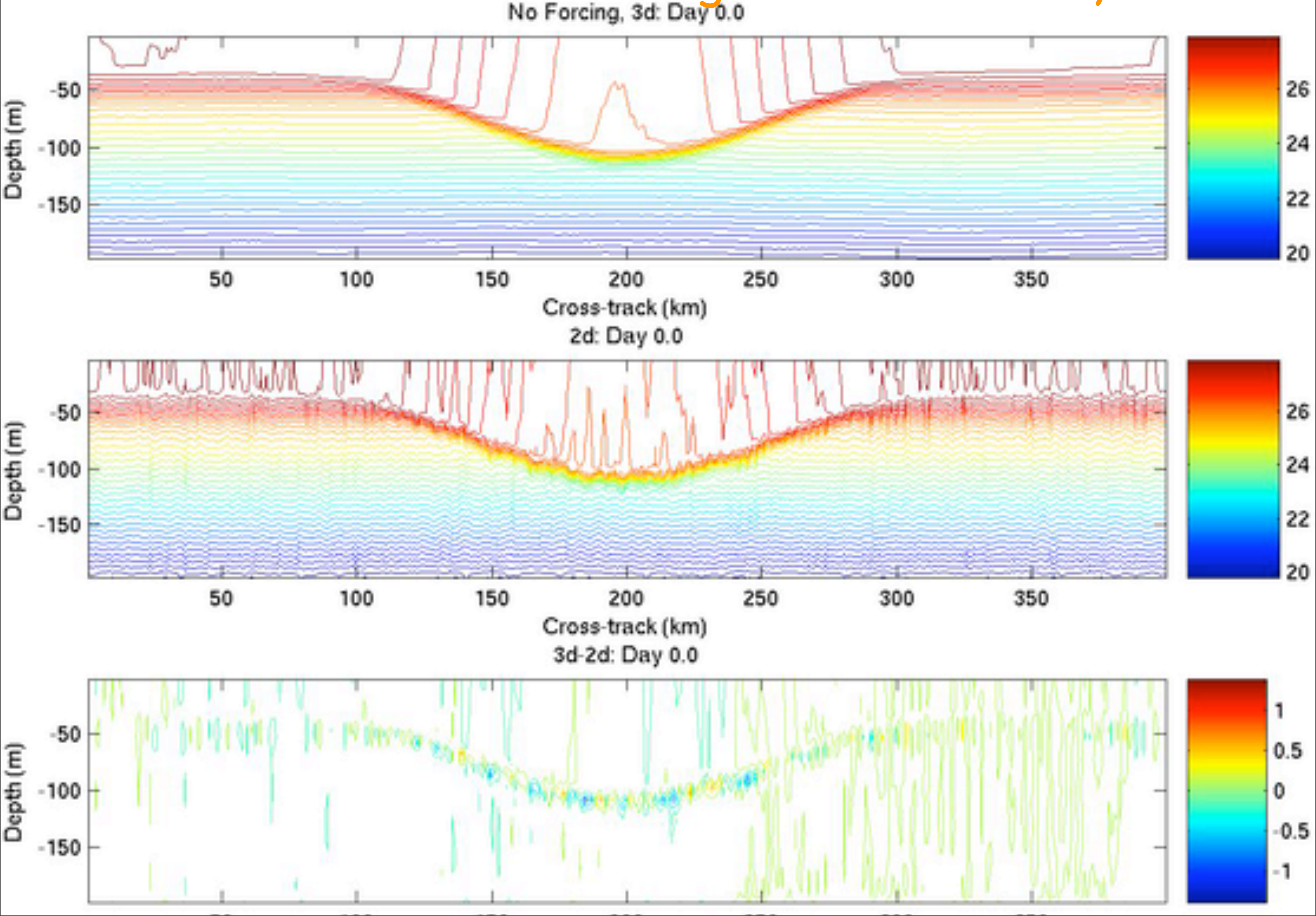
Inertial Oscillations about Geostrophic Adjustment & little bit of diffusion left.



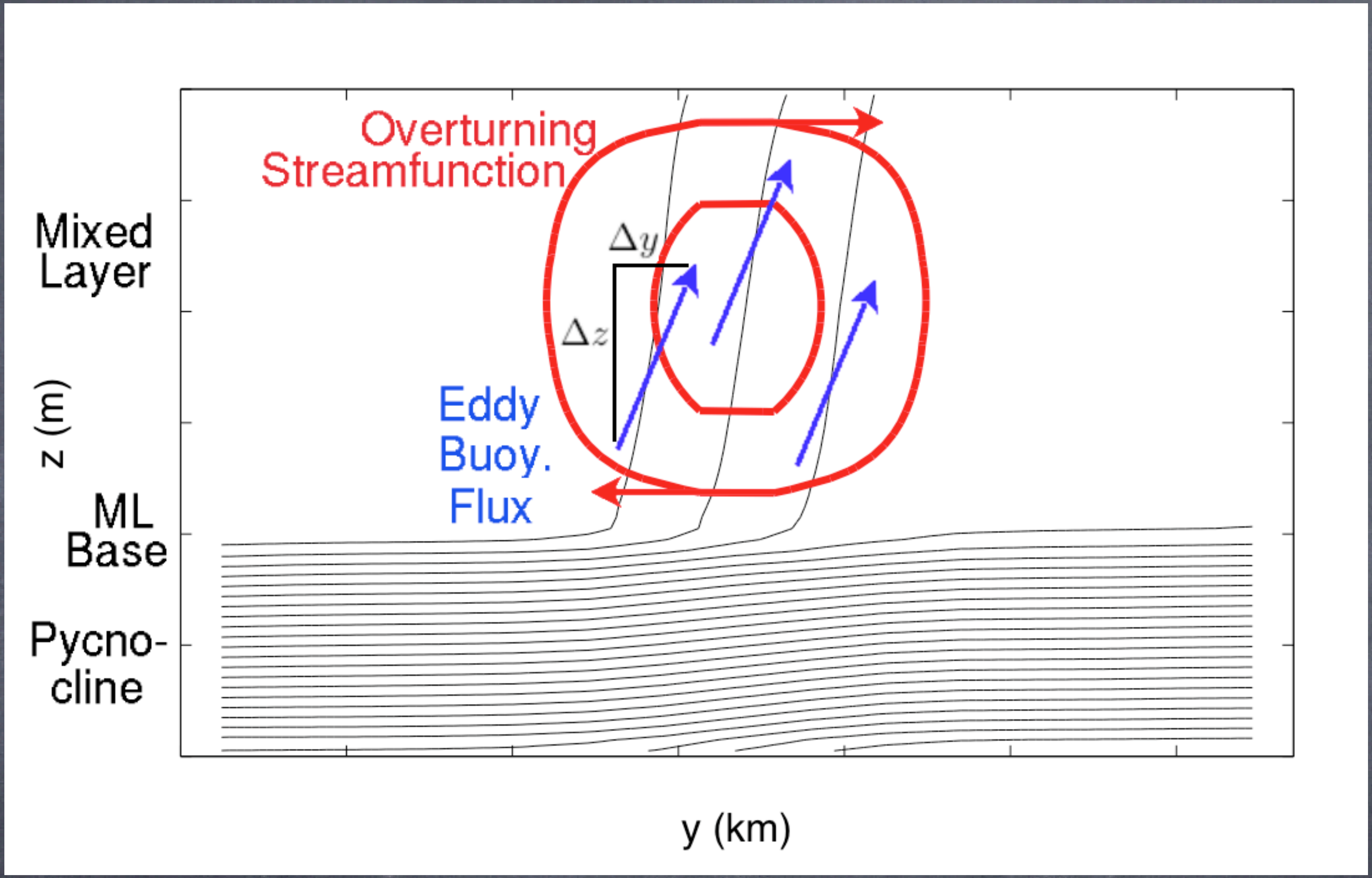
3d


Temperature on:0d0h
z (m)
0
-50
-100
-150
-200
400
350
300
250
200
150
100
50
0
y (km)
0
50
100
x (km)
28
27.5
27
26.5
26
25.5

Turn off solar & Atmos. forcing and winds...Eddy Restrat.



Baroclinic Eddy Restratification



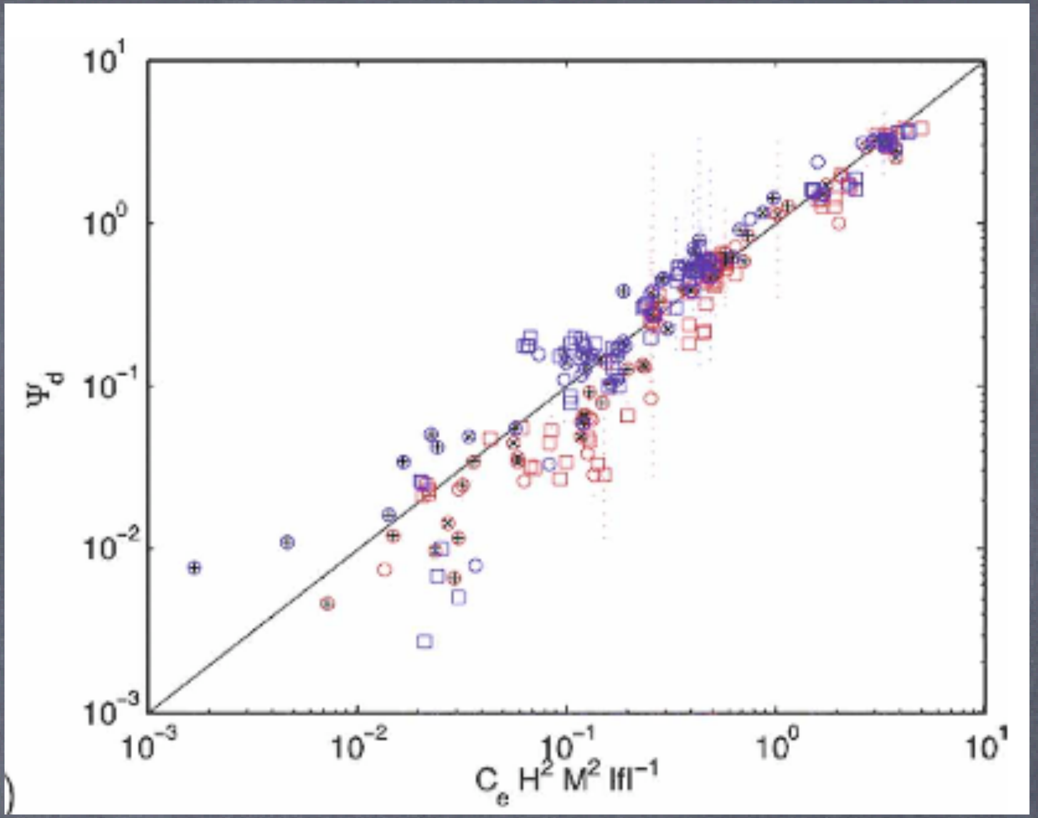
- Mixed Layer Instabilities (Boccaletti et al 07)
- Parameterization (Fox-Kemper et al. 08a,b,c)

The Scaling of Eddy Restratification:

$$\Psi = \frac{C_e H^2 \mu(z)}{|f|} \nabla \bar{b} \times \hat{\mathbf{z}}$$

$$\mu(z) = \left[1 - \left(\frac{2z}{H} + 1\right)^2\right]\left[1 + \frac{5}{21}\left(\frac{2z}{H} + 1\right)^2\right]$$

$$C_e \approx 0.06 \rightarrow 0.08$$



- The horizontal fluxes are downgradient:

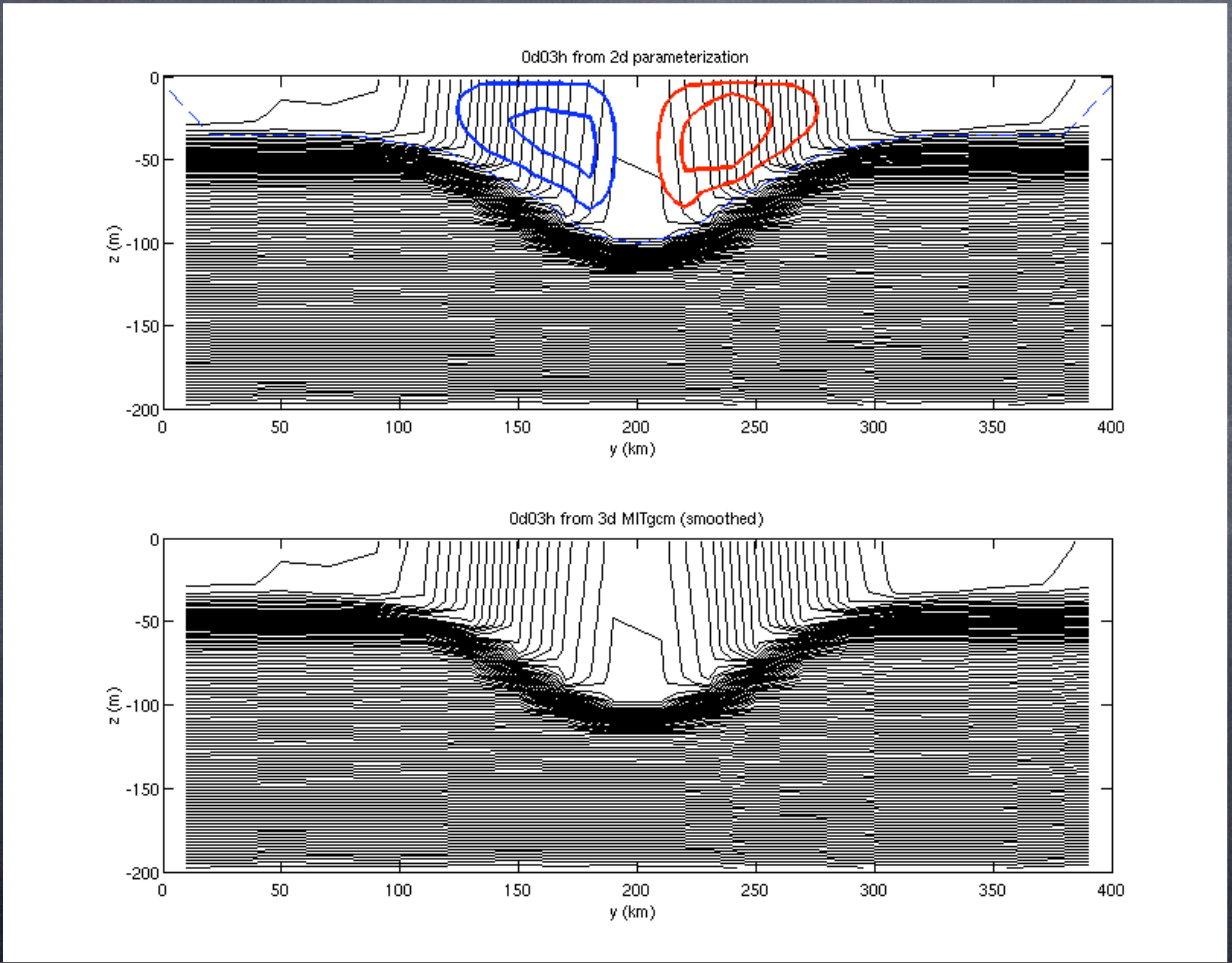
$$\overline{\mathbf{u}'_{\mathbf{H}} b'} = -\frac{C_e H^2 \mu(z) \frac{\partial \bar{b}}{\partial z}}{|f|} \nabla_H \bar{b}$$

- Vertical fluxes always upward to restratify with correct extraction rate of potential energy:

$$\overline{w' b'} = \frac{C_e H^2 \mu(z)}{|f|} |\nabla \bar{b}|^2$$

- Can be thought of as overturning streamfunction or along-isopycnal bolus flux--mathematically equivalent.

Param vs. unforced model



The Scaling of MLIs

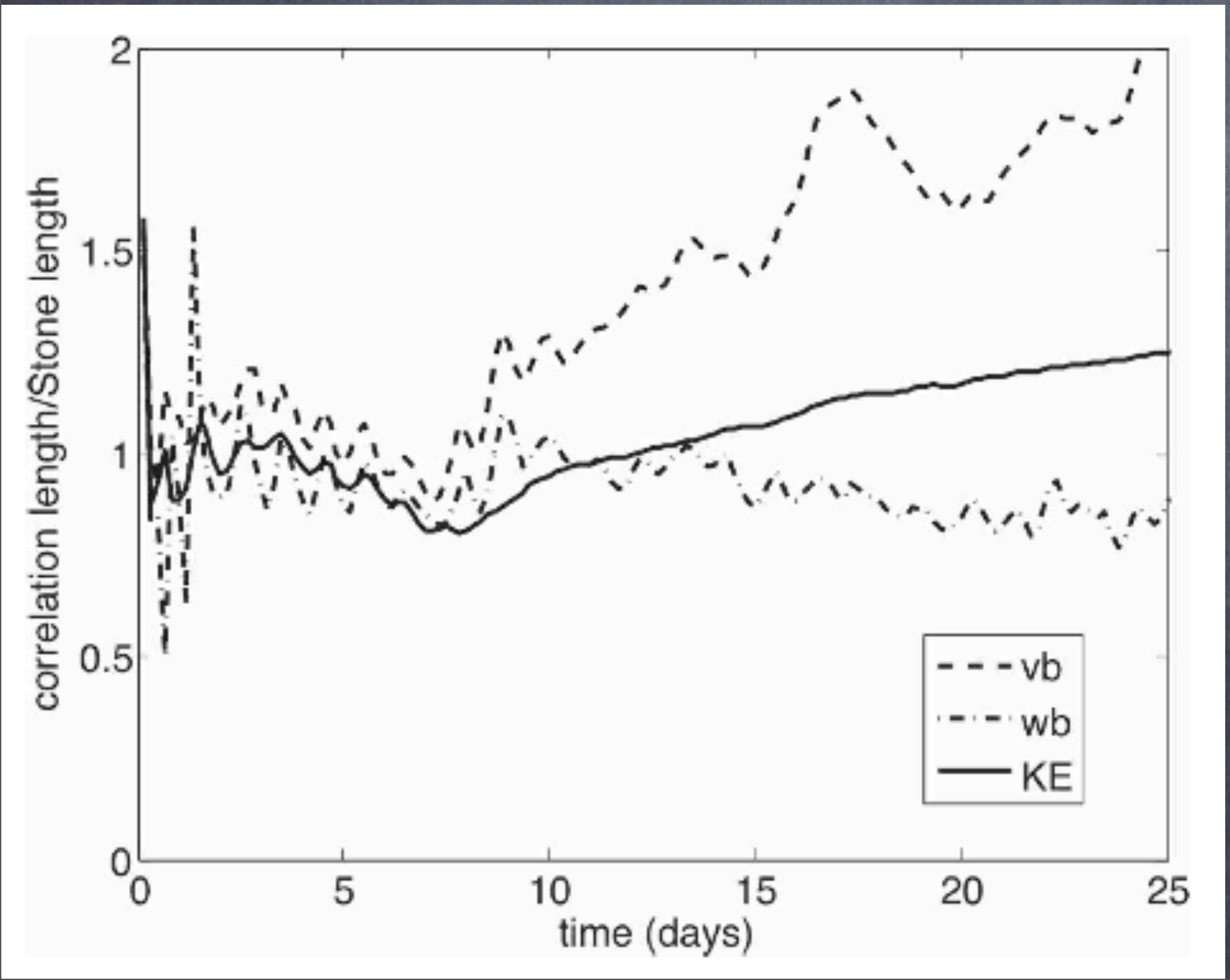
Mixed Layer Eddies (MLEs) begin as ageostrophic baroclinic instability of a front in the Mixed Layer: the Mixed Layer Instability (MLI)

MLI=infinitesimal
MLE=finite amplitude

$$L_s = \frac{2\pi U}{|f|}\sqrt{\frac{1+Ri}{5/2}} \approx 5.6\frac{NH}{|f|}$$

$$\tau_s = \sqrt{\frac{54}{5}}\frac{\sqrt{1+Ri}}{|f|} \approx \frac{4.6}{|f|}$$

(Fastest growing modes of Stone 66, 70, 72)



See Boccaletti et al 07, Fox-Kemper et al 08 & Hosegood et al 06

The Scaling of MLEs

MLEs form from MLIs, but scale differently due to an inverse cascade.

(i) the relevant time scale Δt is *advective:* the time it takes for an eddy to traverse the decorrelation length with typical eddy velocities, $\mathcal{V}$, is

$$\Delta t \propto \Delta y / \mathcal{V}; \tag{7}$$

(ii) the horizontal eddy velocity $\mathcal{V}$ scales as the mean thermal wind U (see Fig. 5):

$$\mathcal{V} \propto U = \frac{M^2 H}{f}; \tag{8}$$

(iii) the vertical decorrelation length scales with the ML depth (see Fig. 6):

$$\Delta z \propto H; \quad \text{and} \tag{9}$$

(iv) fluid exchange occurs along a shallower slope (i.e., PE extracting) and proportional to the mean isopycnal slope (see Fig. 7):

$$\frac{\Delta z}{\Delta y} = \frac{1}{C}\frac{M^2}{N^2}, \quad C > 1. \tag{10}$$

See Fox-Kemper et al 08

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MLI=infinitesimal

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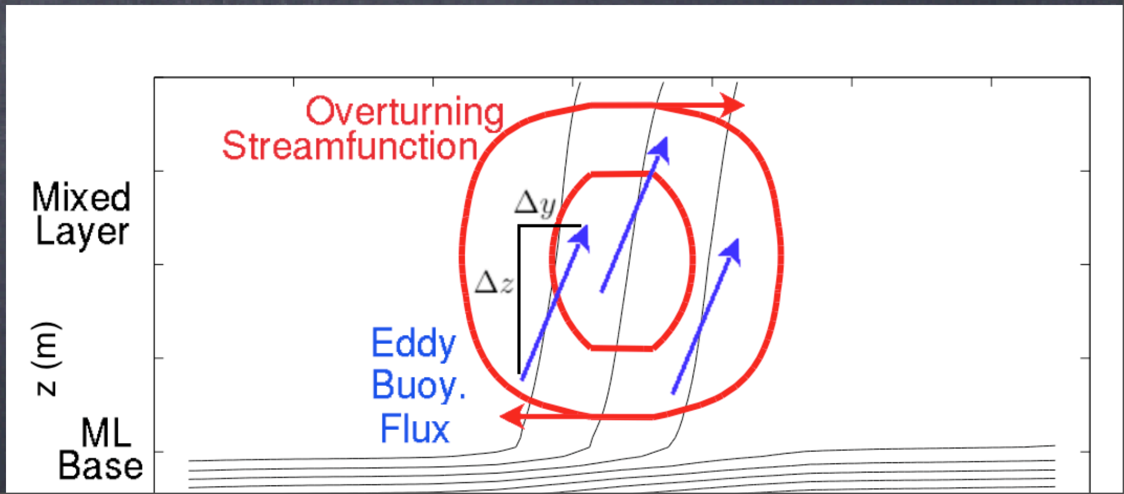
$$\tau_s = \sqrt{\frac{54}{5}}\frac{\sqrt{1+Ri}}{|f|} \approx \frac{4.6}{|f|}$$

MLE=finite amplitude

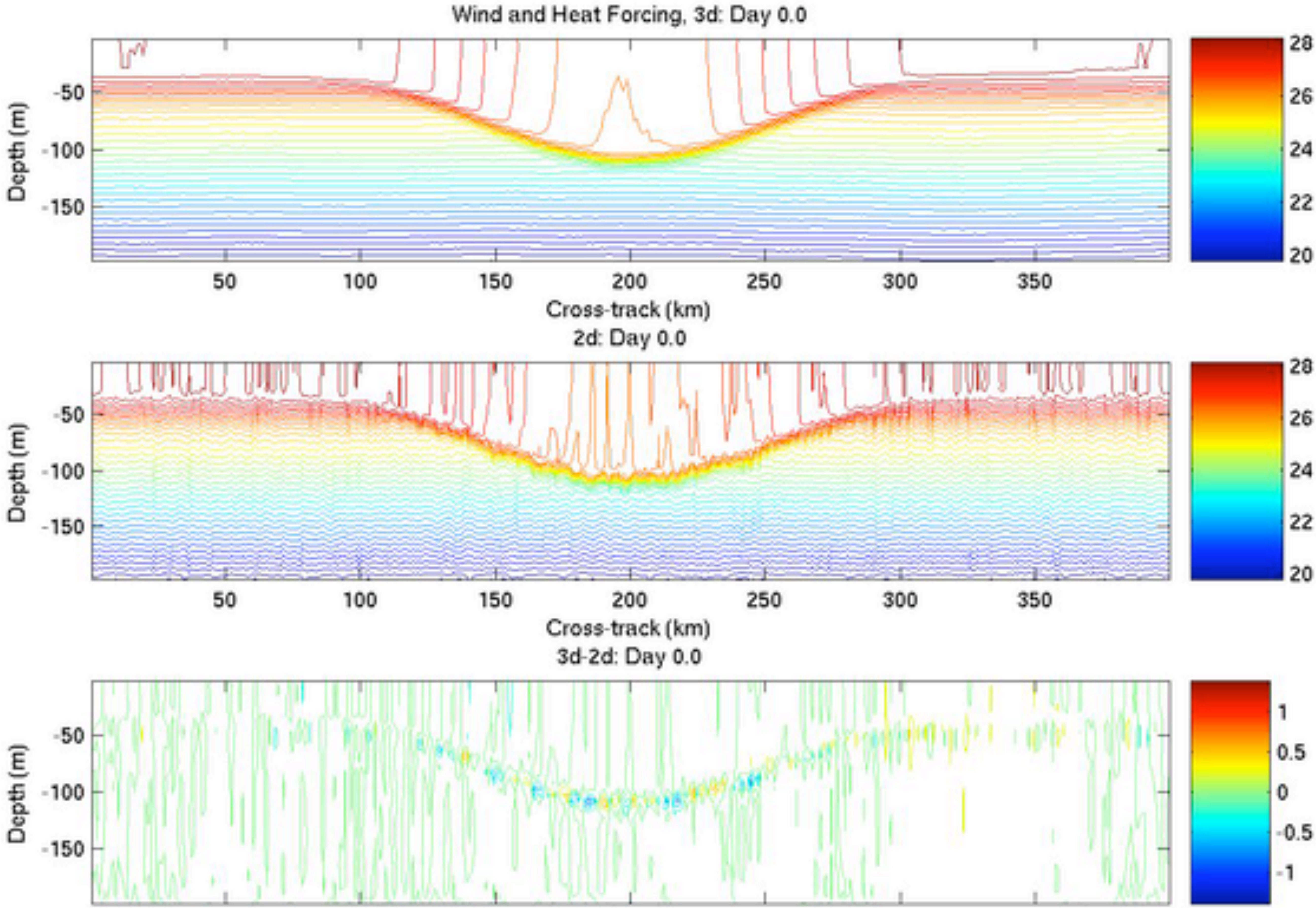
$$L_{mle} \propto H\frac{N^2}{M^2} = \frac{H}{\text{slope}}$$

$$T_{mle} \propto \frac{L_{mle}}{U_{mle}} \propto \frac{L_{mle}|f|}{M^2 H} \propto \frac{N^2|f|}{M^4} \propto \frac{|f|}{M^2 \cdot \text{slope}}$$

See Fox-Kemper et al 08



So what do eddies do?



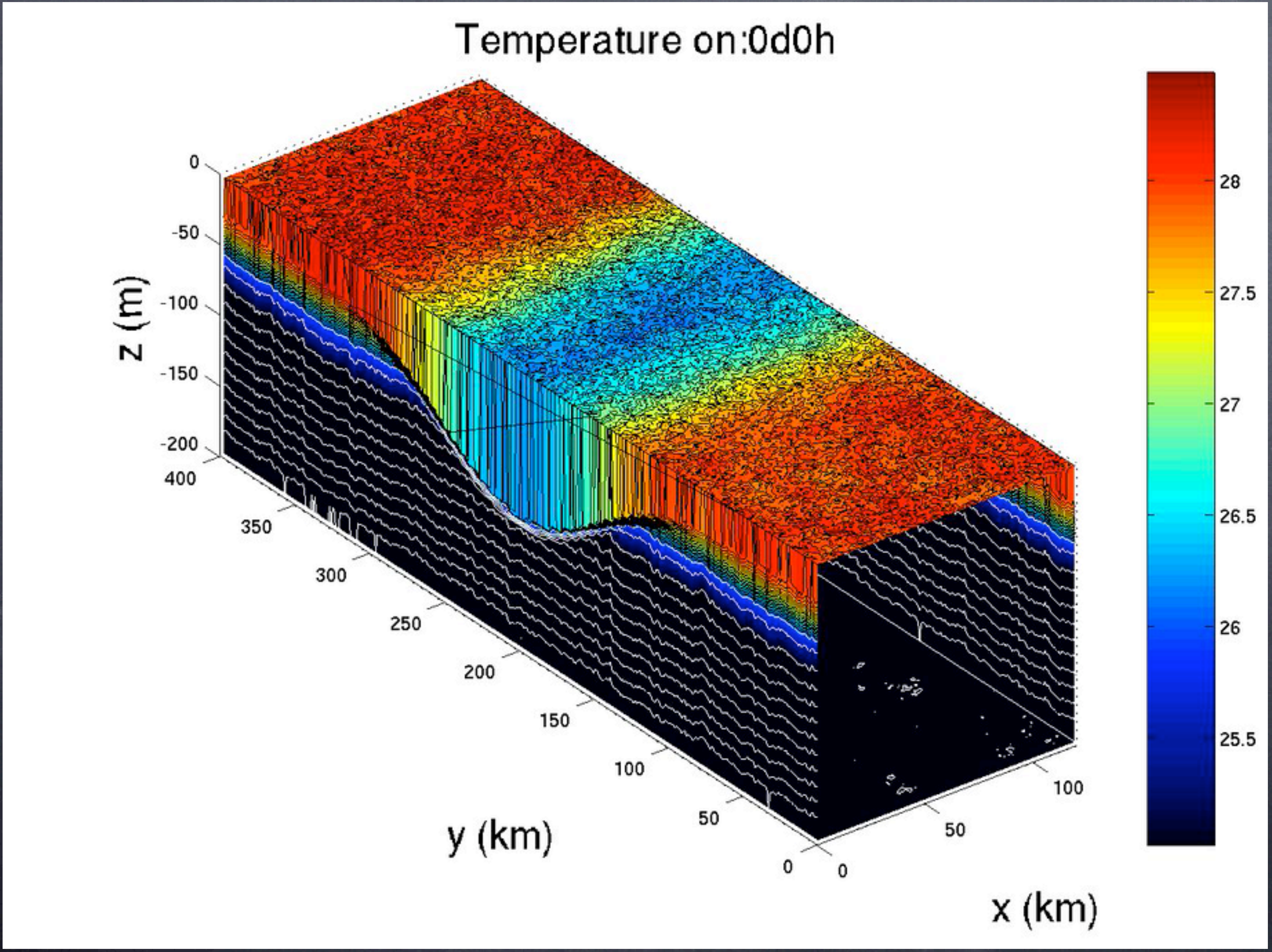
Summary

- In 1d, penetrating solar and surface+mixing restratifies
- In 2d, above plus Thomas & Lee and Geostrophic adjustment.
- In 3d, above plus eddies.
- Who wins? Subject to parameters of the specific event.
- However, scaling of <wb> from all known (in theory).
- Hosegood et al (JPO, in press) see a very different near-inertial restratification.

Observational Possibilities

- As in Price et al., Obs can be compared to PWP or KPP 1d.
- If edges of wake are observed, Thomas & Lee
- In 3d, eddies will compete with above, but will also eliminate Bolus trapped below other processes. Help theory here!
- For eddies, must observe τ_s, L_s to T_{mle}, L_{mle}

Thanks!



Temperature on:0d0h
z (m)
0
-50
-100
-150
-200
400
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50
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y (km)
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x (km)
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27
26.5
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