Hurricane Wake Restratification Mechanisms

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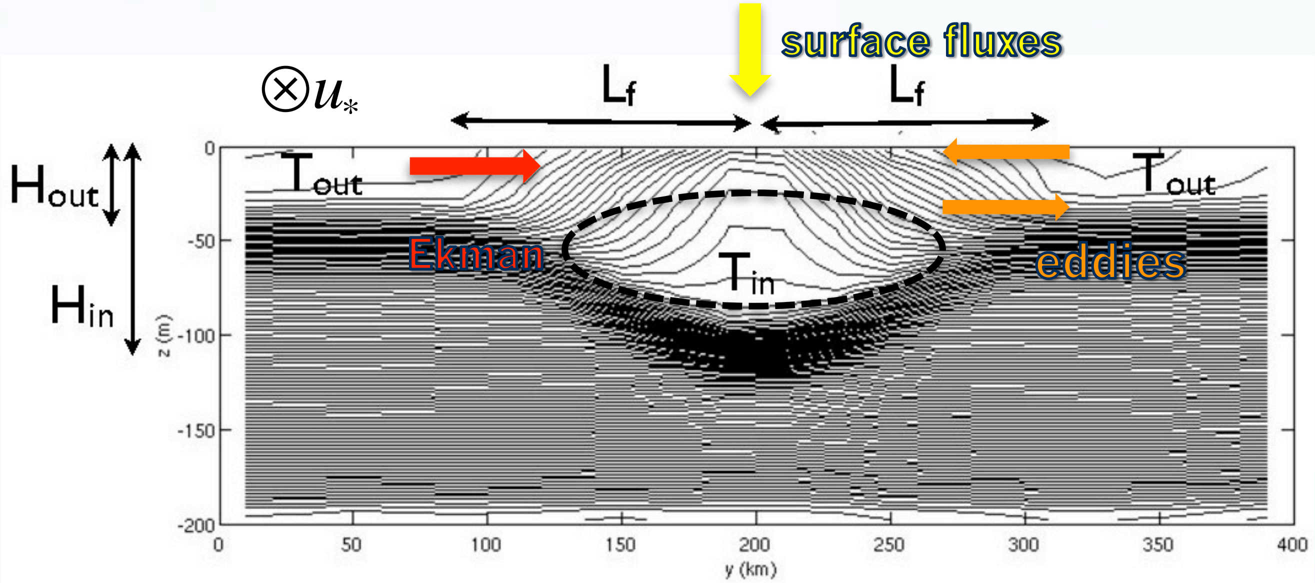
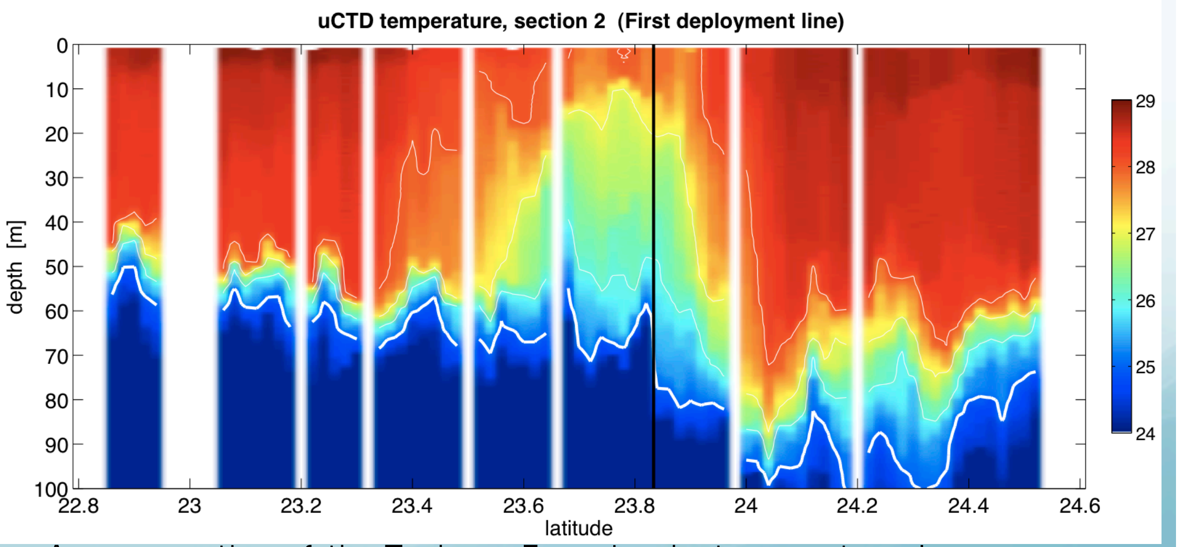
How does a wake warm back up?

- **Goal:** make simple scalings for 1D, 2D, and 3D processes that restratify cold hurricane wakes.

- Scalings depend on readily available observations from satellites, profiling floats, and reanalysis data.

- Scalings for both the thin surface layer and for the sub-surface bolus are derived.





A cross section of the Typhoon Fanapi wake temperature. Image courtesy of Dr. Steve Jayne and the ITOP Group.

Surface Scalings

$$\tau_{Ekman} = K_1 \frac{f H_{out} L_f}{u_*^2}$$

$K_1 = 2$

Ekman buoyancy fluxes
(Thomas & Ferrari, 2008)

$$\tau_{SF} = K_2 H_{out}$$

$K_2 = \frac{\rho C_p}{\lambda} \sim 1\left(\frac{days}{m}\right)$

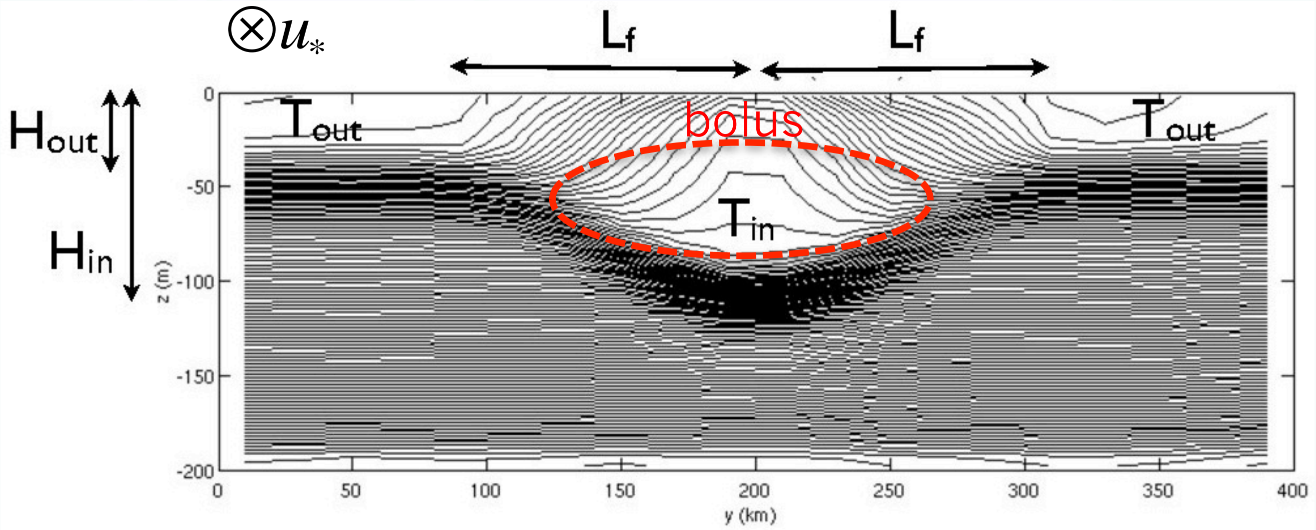
surface, and penetrating solar buoyancy fluxes
(Price et al., 2008, Kraus & Turner, 1967)

$$\tau_{eddy} = K_3 \frac{L_f^2 \left| f \right|}{H_{out} \Delta T}$$

$K_3 = \frac{0.2 C_e}{g\alpha} \sim 6\left(\frac{s^2 K}{m}\right)$

eddy buoyancy fluxes
(Fox-Kemper & Ferrari, 2008)

Sub-Surface Bolus Scalings



$$\tau_{sb} = K_4 \frac{(H_{in} - H_{out})\Delta T}{\int_{-H_{in}}^{-H_{out}} \left(I_1 e^{k_1 z} + I_2 e^{k_2 z}\right) dz}$$

$$K_4 = \frac{\rho C_p}{S_0}$$

solar in the sub-surface bolus

$$\tau_{eb} = K_5 \frac{L_f^2 \left|f\right|}{\Delta T \left(H_{in} - H'\right)}$$

$$K_5 = \frac{1}{7.11 C_e g \alpha}$$

eddies in the sub-surface bolus

Ekman buoyancy fluxes are fastest

Surface Timescales

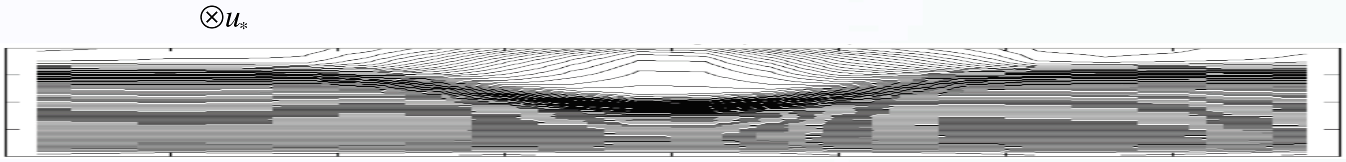
Cyclone	τ_{Ekman} (days)	τ_{SF} (days)	τ_{eddy} (days)
Frances	6	30	525
Igor	2	26	287
Katrina	2	15	163

Sub-Surface Bolus Timescales

Cyclone	τ_{eb} (days)	τ_{sb} (days)
Frances	122	435,000
Igor	39	325,000
Katrina	23	1,650

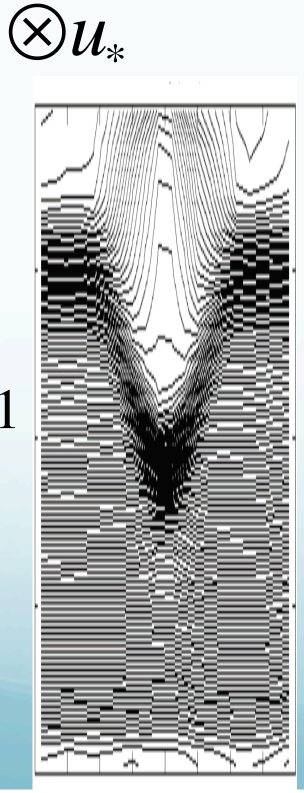
Who Wins Under What Conditions?

surface fluxes beat wind



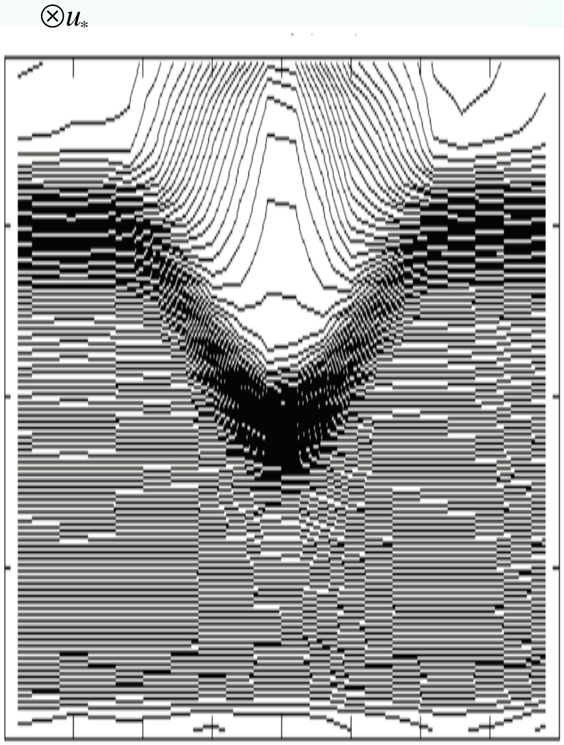
$$\frac{\tau_{Ekman}}{\tau_{SF}} = \frac{K_1}{K_2}\frac{fL_f}{u_*^2} > 1$$

eddies beat surface fluxes



$$\frac{\tau_{SF}}{\tau_{eddy}} = \frac{K_2}{K_3}\frac{H^2\Delta T}{L_f^2 f} > 1$$

eddies beat wind



$$\frac{\tau_{Ekman}}{\tau_{eddy}} = \frac{K_1}{K_3}\frac{H^2\Delta T}{L_f u_*^2} > 1$$

Conclusions

- Restratification by Ekman buoyancy fluxes is the fastest mechanism in the thin surface layer for the wakes considered
- Restratification by eddy buoyancy fluxes is the fastest in the subsurface bolus.
- In the subsurface bolus restratification is generally slower, so temperature anomalies will persist
- Who wins may easily change if L_f, H, ΔT, u_*, f change
- Eddies are particularly sensitive to H and L_f.

References

- Fox-Kemper, B., R Ferrari (2008), Parameterization of mixed layer eddies. part II: prognosis and impact, J. Phys. Oceanography, 38, 1166-1179.
- Kraus, E. B., and J. S. Turner (1967), A one-dimensional model of the seasonal thermocline. II: The general theory and its consequences. Tellus, 19, 98–105.
- Price, J. F., J. Morzel, and P. P. Niiler (2008), Warming of SST in the cool wake of a moving hurricane, J. Geophys. Res., 113, C07010, doi:10.1029/2007JC004393.
- Thomas, L., R. Ferrari (2008), Friction, frontogenesis, and the stratification of the surface mixed layer, J. Phys. Oceanography, 38, 2501-2518.

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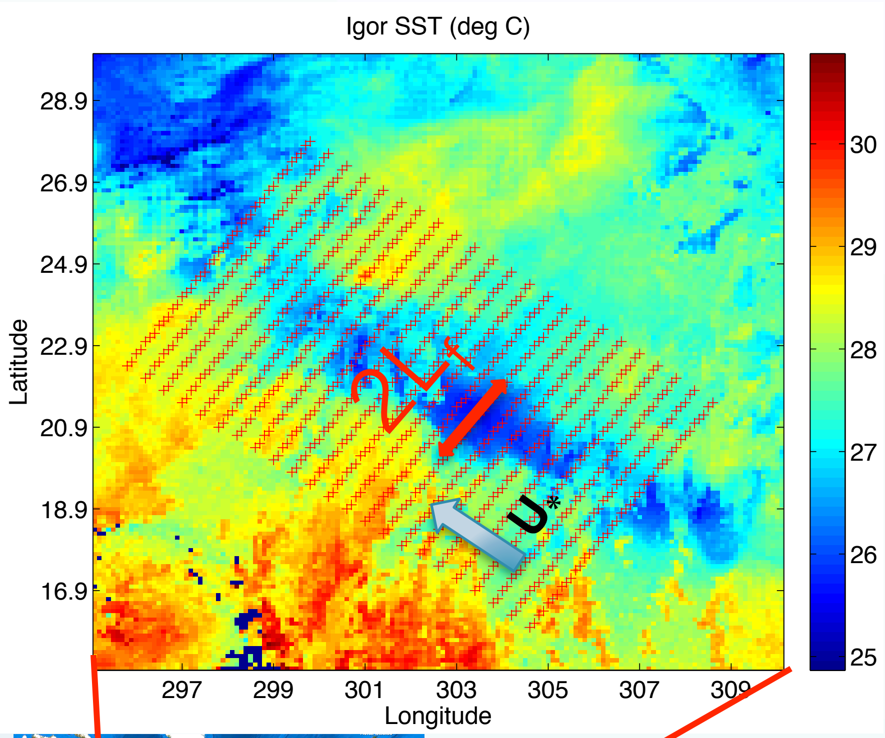
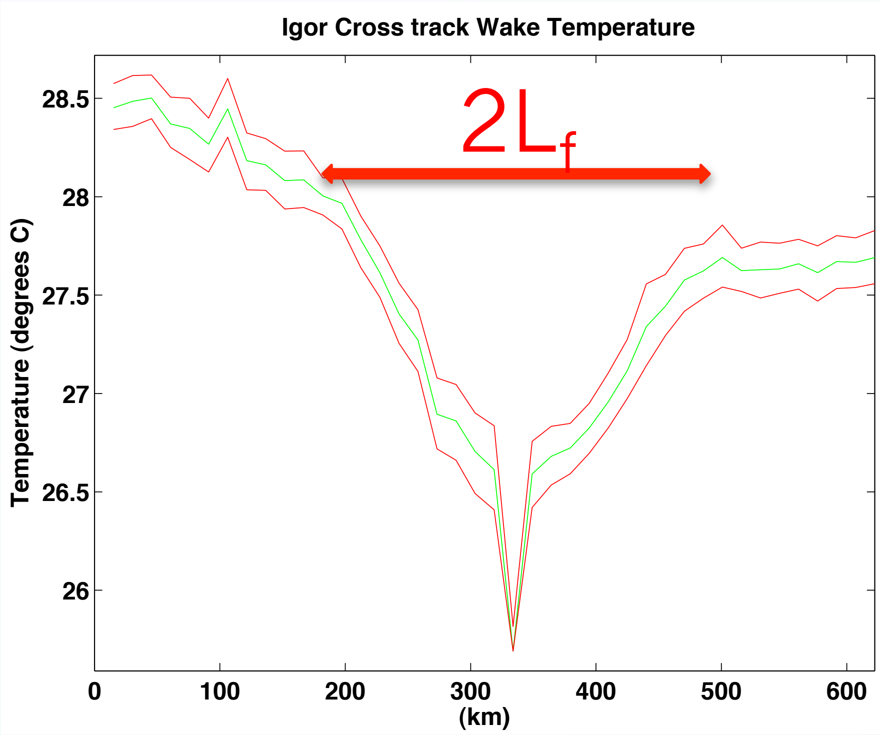
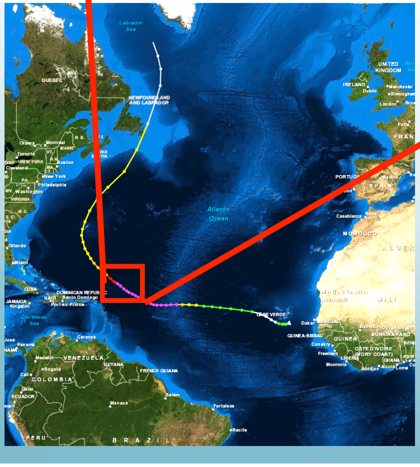
Modeling

Caveats: $L_f \sim 0.5L_f$ (Igor).
$T_{out} - T_{in} > T_{out} - T_{in}$ (Igor)

More Measured Parameters







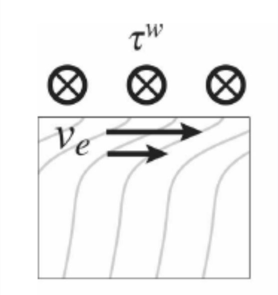
SST data from: NOAA OceanWatch http://las.pfeg.noaa.gov/oceanWatch Delayed, Science-Quality Satellite Data for the Sea Surface Temperature Multi-Satellite Blended Product (blending MODIS, AVHRR AMSR-E).

Parameters

Cyclone	L_f (km)	$T_{out} - T_{in}$ (°C)	H_{out} (m)	H_{in} (m)	u_* (m/s)	f (s^{-1}) x 10^{-5}
Frances	170	0.89	30	120	0.022	2.53 (20.4°N)
Igor	159	1.80	26	160	0.036	2.77 (22.4°N)
Katrina	55	0.78	15	89	0.016	3.23 (26.4°N)

A Starting Point for the Scalings

$$v_{ekman} = \frac{u_*^2}{fH}$$



Ekman buoyancy fluxes
(Thomas & Ferrari, 2008)

$$\rho C_p H \frac{\partial T}{\partial t} = \lambda\left(T_a - T_o\right) - S_0 \int_{-H}^{0} \left(I_1 e^{k_1 z} + I_2 e^{k_2 z}\right) dz$$

LW, latent,
sensible

SW

surface, and penetrating solar
buoyancy fluxes
(Price et al., 2008, Kraus & Turner, 1967)

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

eddy buoyancy fluxes
(Fox-Kemper & Ferrari, 2008)

$$\mu(z) = \max\left\{0, \left[1 - \left(\frac{2z}{H} + 1\right)^2\right]\left[1 + \frac{5}{21}\left(\frac{2z}{H} + 1\right)^2\right]\right\}$$