Internal Boundary Layer Studies During CASPER

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Internal Boundary Layer Challenges?

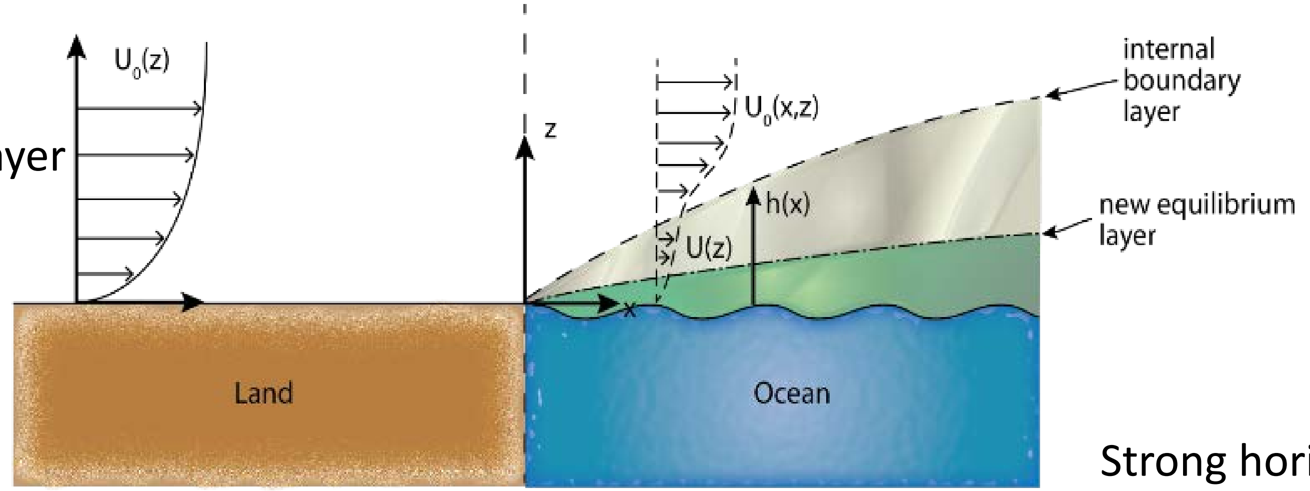
(i) **What are the scales of temporal and spatial heterogeneities in lower MBL**; to what extent they affect MOST, duct height and models for Surface based duct heights?

(ii) **What is the growth rate of internal boundary layer height and how can it be parameterized?** - effect on Surface based duct heights

(iii) **What are the parametrizations for vertical gradient of fluxes, $\boldsymbol{T}$ and $\boldsymbol{U}$, and how are they dependent on meteorological regimes?** Theoretical ideas in the data analysis and interpretation amidst heterogeneities

Internal Boundary Layer
– Vorticity production at a discontinuity

Boundary layer



Strong horizontal inhomogeneity

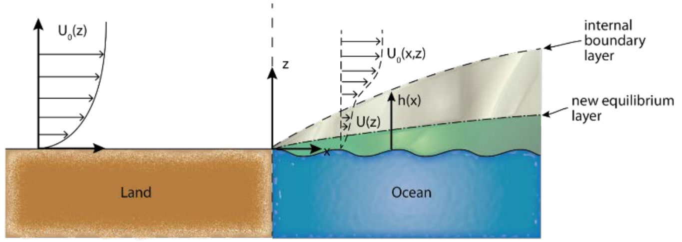
$$\frac{D\left(\underset{\sim}{\omega}\right)}{Dt} = \underbrace{\left(\underset{\sim}{\omega}\cdot\right)\bullet\nabla\underset{\sim}{u}}_{I} - \underbrace{\left(\underset{\sim}{\omega}\cdot\right)\nabla\bullet\underset{\sim}{u}}_{II} + \underbrace{\nabla p\times\nabla\frac{1}{\rho}}_{III} + \underbrace{\nu\nabla^2\underset{\sim}{\omega}}_{IV}$$

$$\frac{1}{\rho}\frac{\partial^2\tau_{xz}}{\partial x^2}\hat{j}$$

Flow jets through
upon finding
a low resistence media

Warm to cold –
Increase the speed

A Simple Formulation



$$U\frac{\partial U}{\partial x} = -\frac{\partial \overline{uw}}{\partial z}$$

$$U\frac{\partial T}{\partial x} = -\frac{a\overline{wT}}{\partial z}$$

$$U\frac{\partial q}{\partial x} = -\frac{\partial \overline{wq}}{\partial z}.$$

$$\frac{U}{U_0} = f\left(\frac{z}{h(x)}\right) = f(\eta)\,, \qquad \frac{\Delta T}{\Delta T_0} = g\left(\frac{z}{h(x)}\right)\,,$$

$$\eta = \frac{z}{h(x)} \qquad \Delta T = \left(\frac{T - T_0}{T_a - T_0}\right)$$

$$\mho = U_0\left(\frac{\partial h}{\partial x}\right)^{1/2}$$

$$\Gamma = \Delta T_0\left(\frac{\partial h}{\partial x}\right)$$

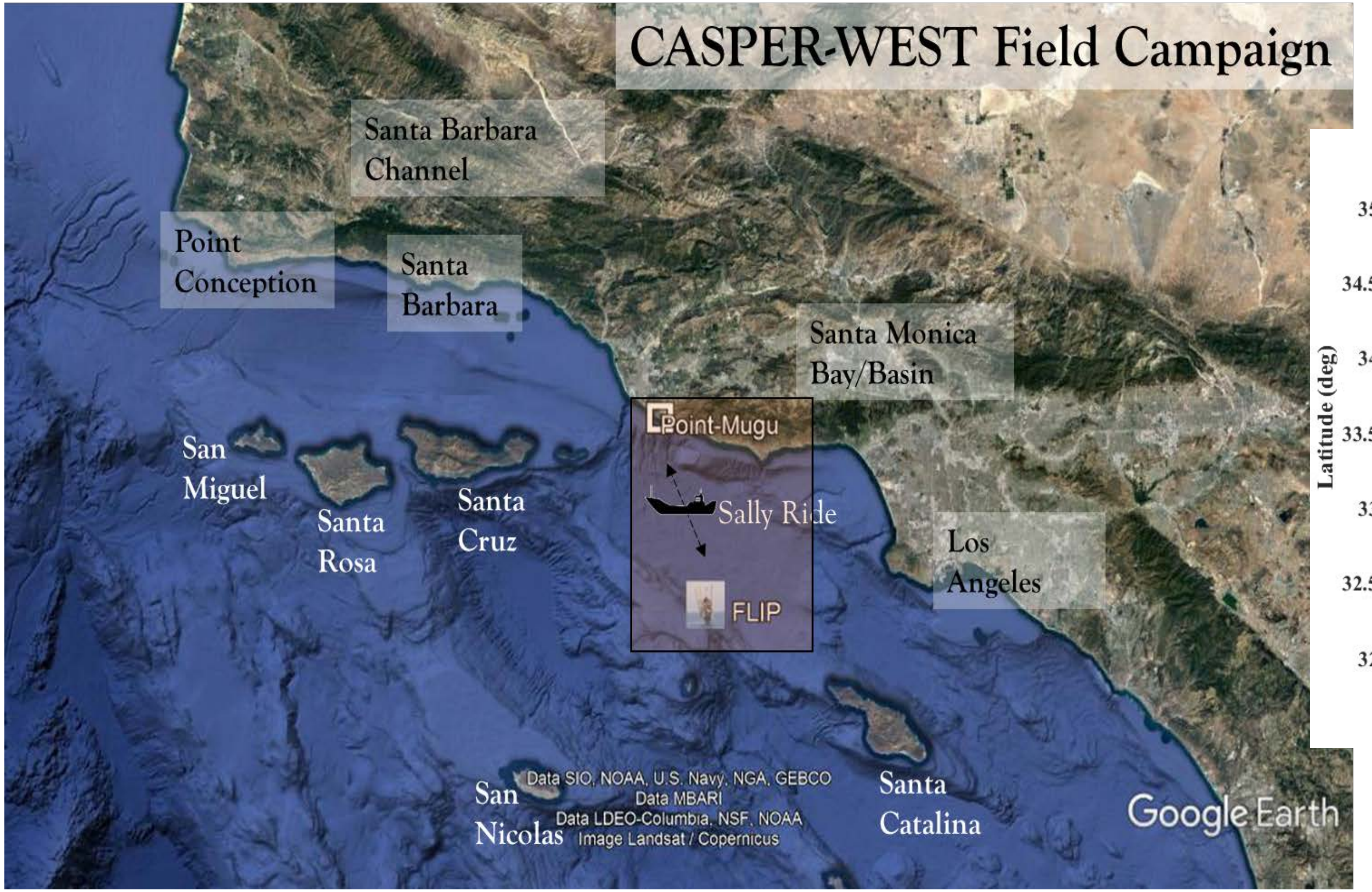
$$l = \frac{U_0^2}{g \propto \Delta T_0}\left(\frac{\partial h}{\partial x}\right)^{1/2}$$

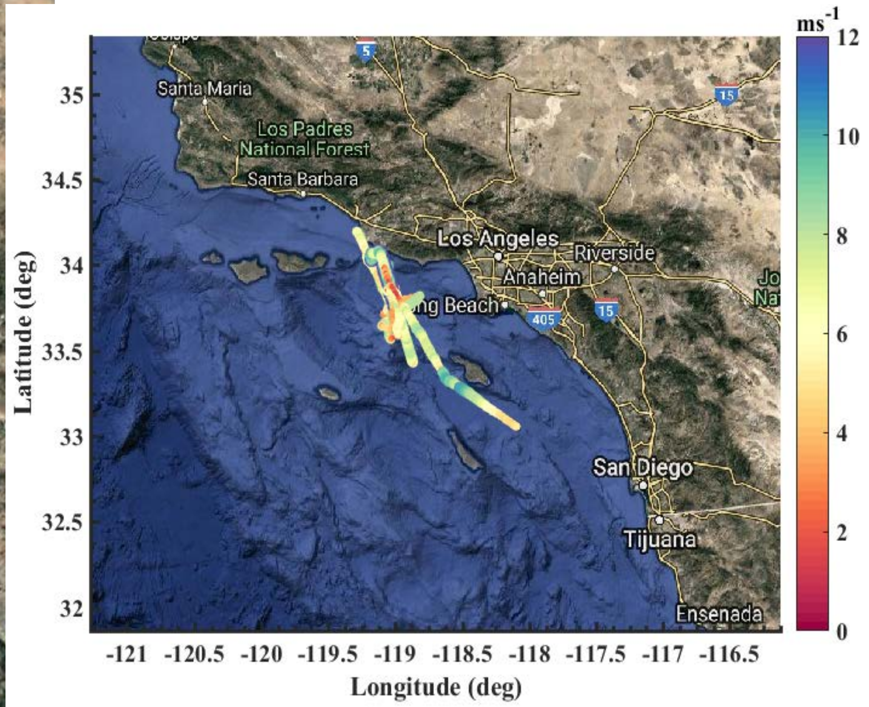
$$-(\overline{uw})_0 = C_u U_0^2 \frac{\partial h}{\partial x},\;\; C_u = \int_0^1 \eta f(\eta)\, f'(\eta) d\eta$$

$$-\overline{(wT)_0} = C_T U_0 \Delta T_0 \frac{\partial h}{\partial x},\;\; C_T = \int_0^1 \eta f(\eta) g(\eta) d\eta$$

$$\frac{\partial U(z)}{\partial z} = \frac{\mho}{\ell}\Psi\left(\frac{z}{\ell}\right), \quad \frac{\partial q(z)}{\partial z} = \frac{\mathbb{Q}}{\ell}\emptyset\left(\frac{z}{\ell}\right), \quad \frac{\partial T(z)}{\partial z} = \frac{\Gamma}{\ell}\Xi\left(\frac{z}{\ell}\right)$$

CASPER-West Field Campaign





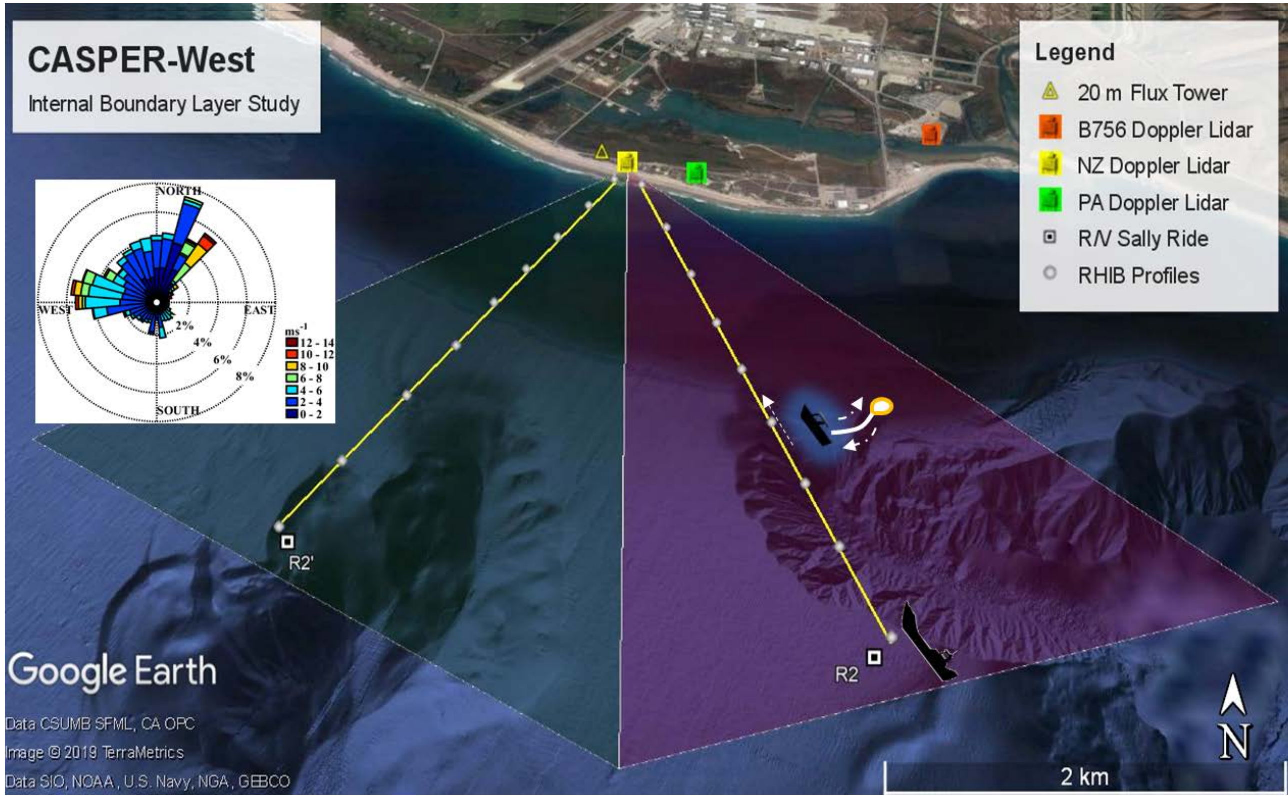
R/V Sally Ride Ship Track during CASPER-West and surface wind speeds

Experimental Setup

Sally Ride
Stabilized Halo Doppler Lidar
Ceilometer CL31
Microwave Radiometer
MP3000

meto

Triple Doppler Lidars at Point-Mugu + Flux Tower



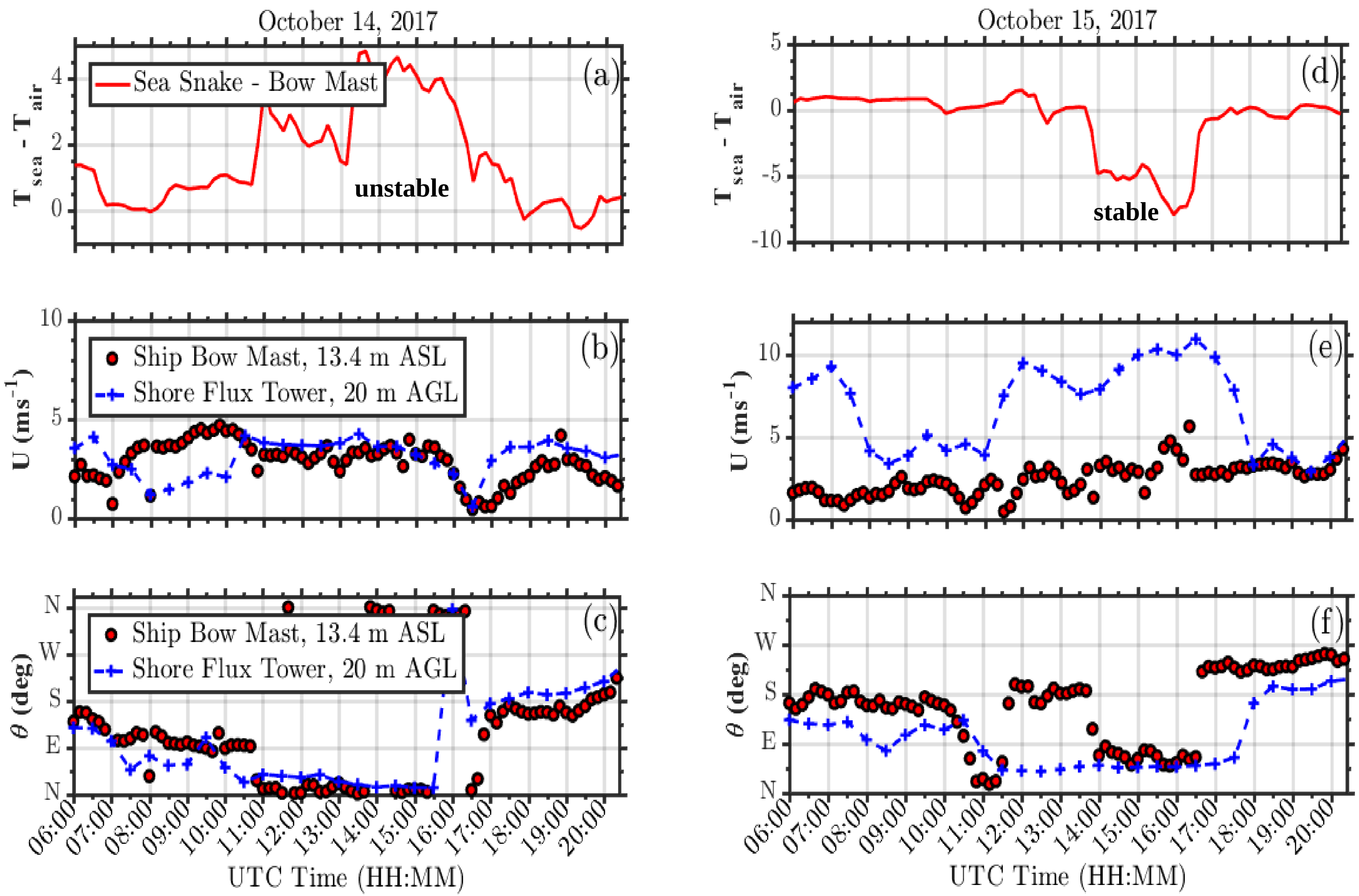
Rigid Hull Inflatable Boat (RHIB) operations

Winds at the shore and R/V Sally Ride

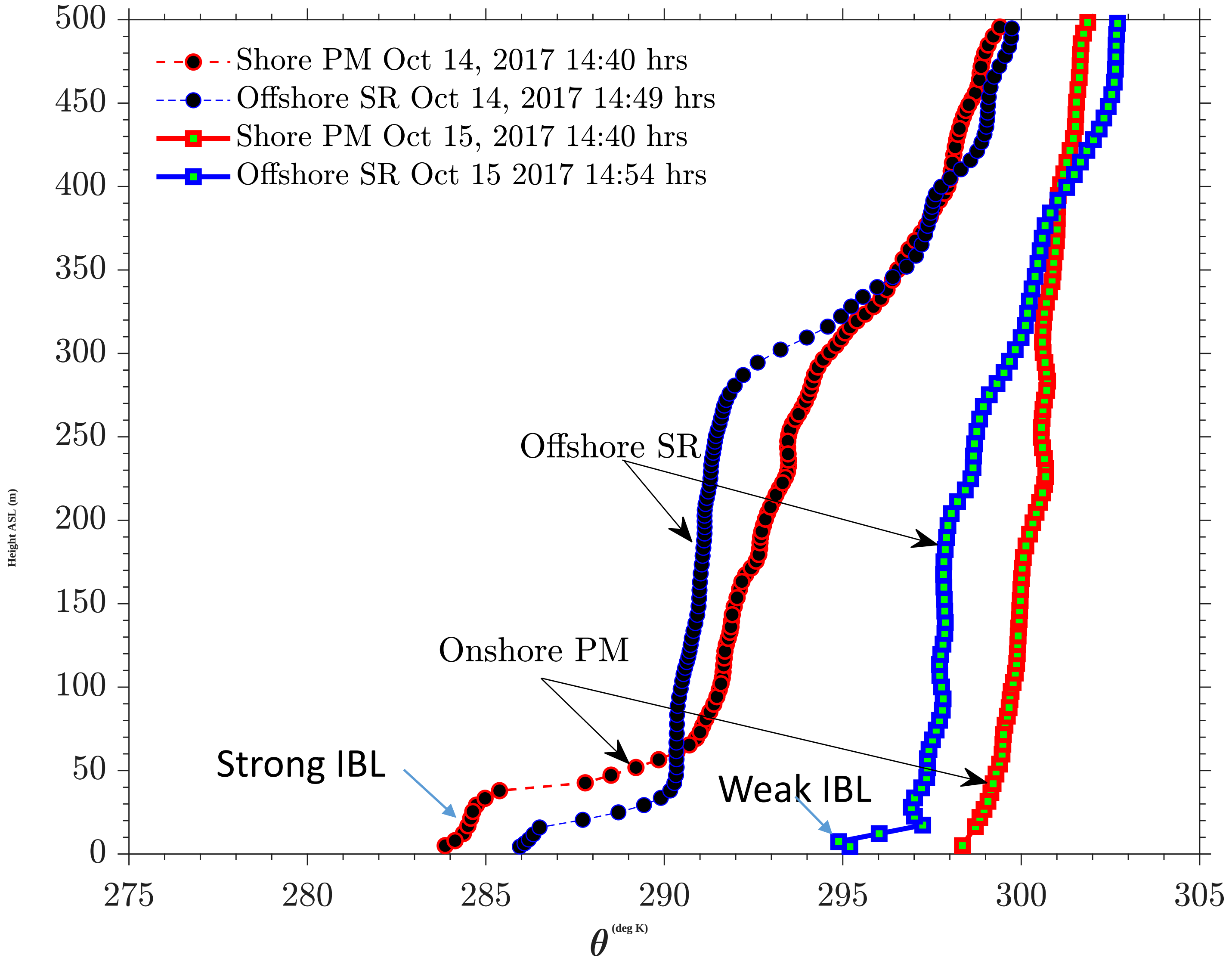
SST-Air

speed

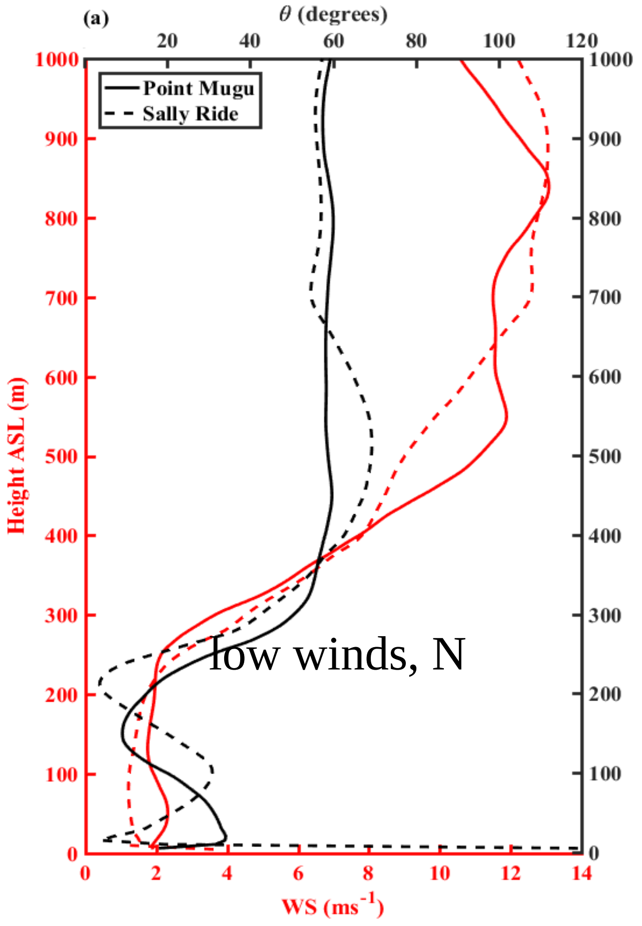
direction



Potential Temperature profiles from Point Mugu and Sally Ride Radiosondes

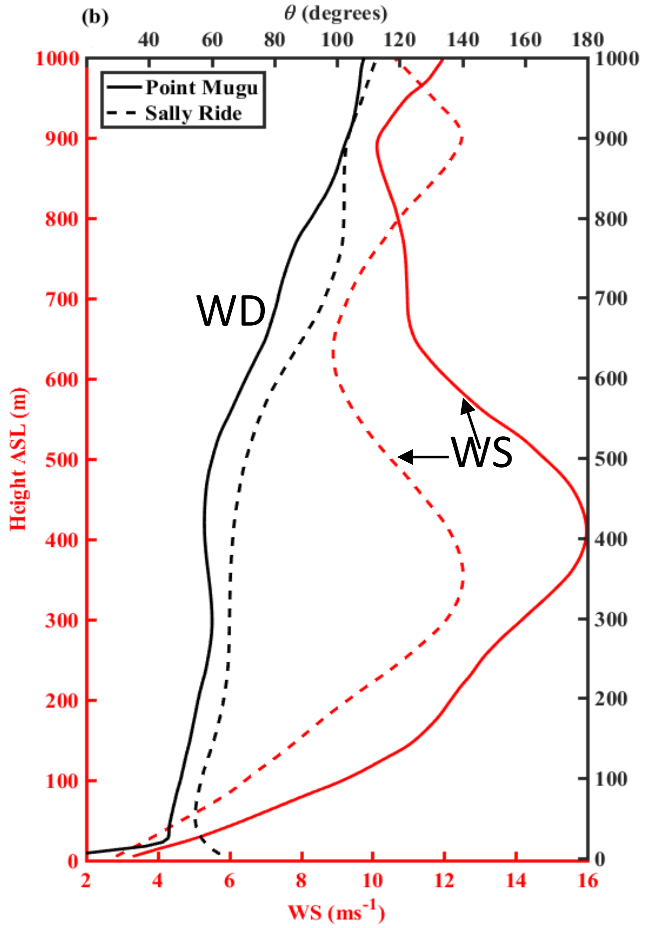


Wind speed and direction profiles from Point Mugu and Sally Ride Radiosondes



October 14

Unstable



October 15

Stable

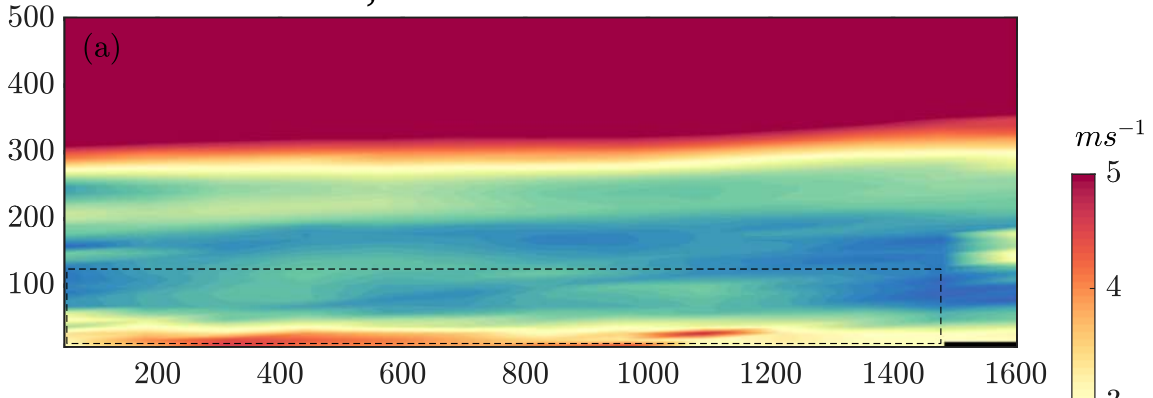
1430 hours UTC.

low-level jet, NE

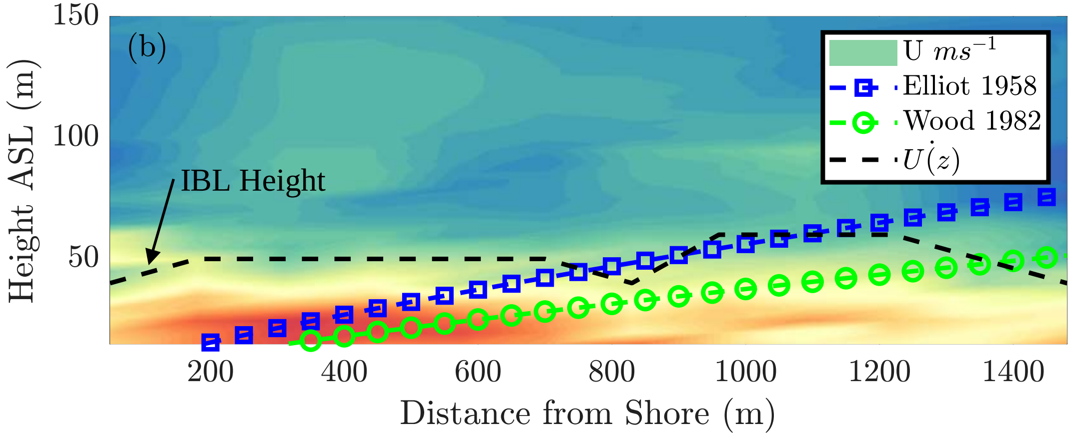
Lidar

Triple Doppler Lidar Winds

October 14th, 2017 at 1500 hours UTC



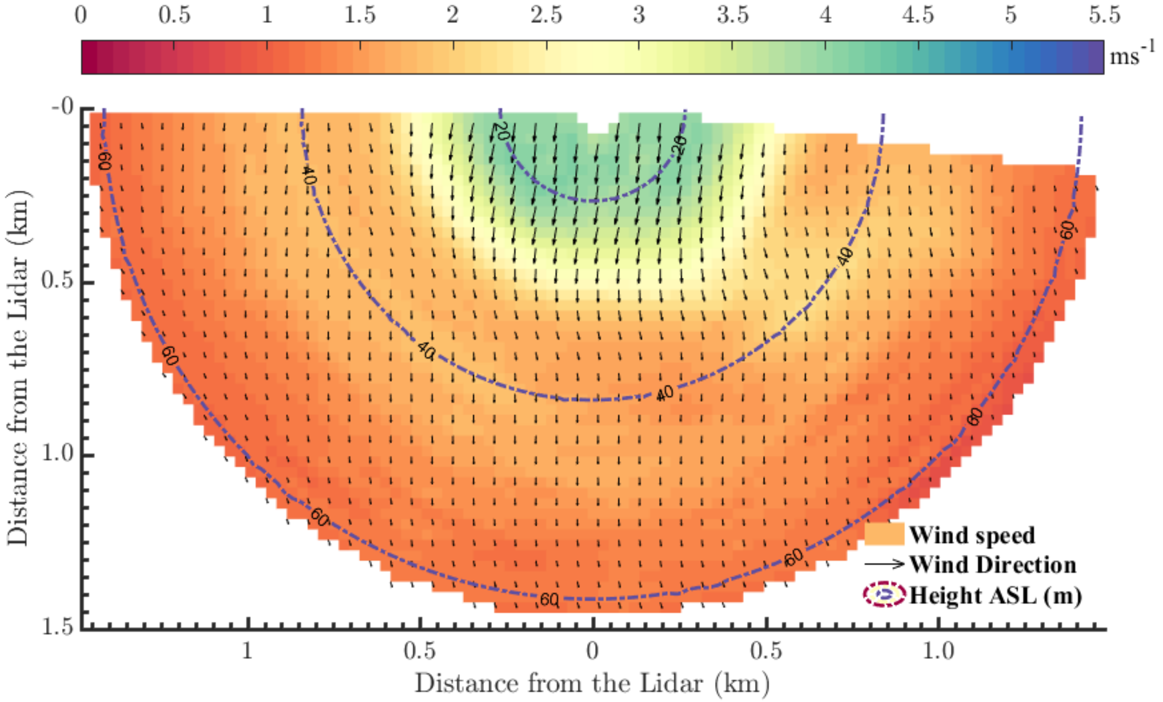
lowest 150 m ASL



Velocity "kink" determines the IBL height

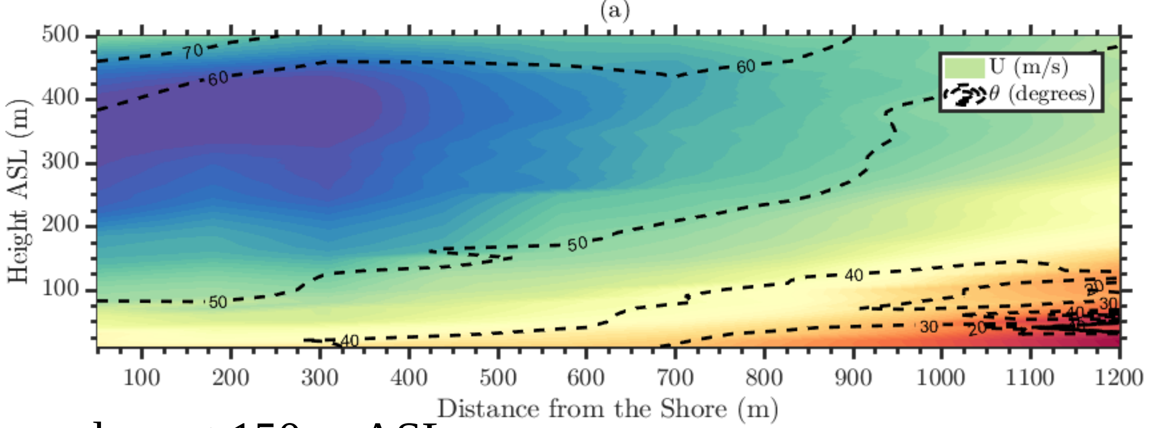
Elliot 1958 and Wood 1982 IBL models are shown

Single Doppler Lidar wind retrieval of speed and direction using 2D Variational Scheme on a 2-degree elevation, PPI



Triple Doppler Lidar Winds

October 15th, 2017 at 1500 hours UTC



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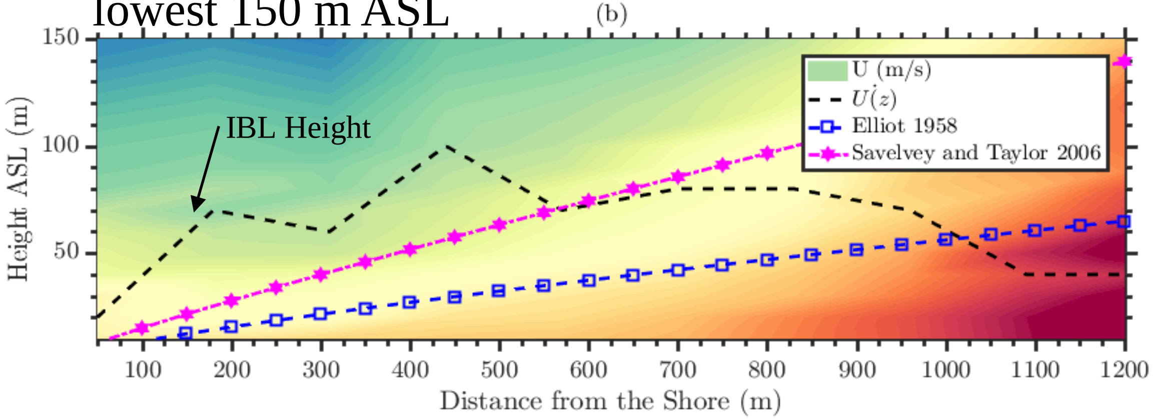
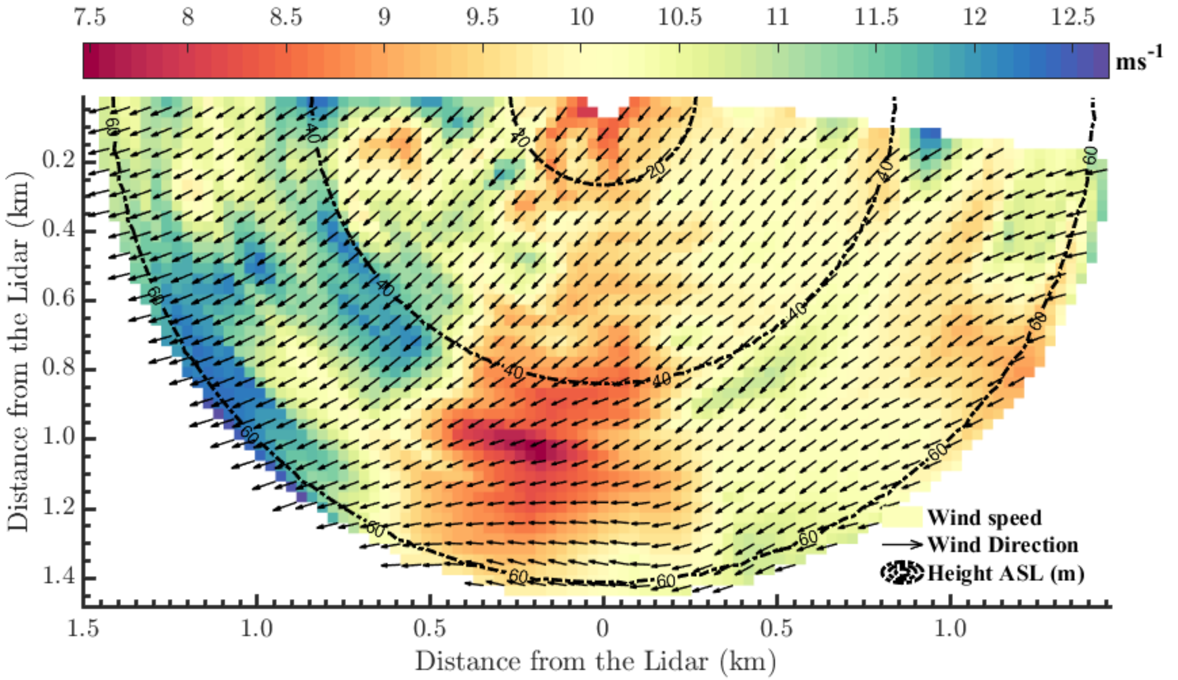


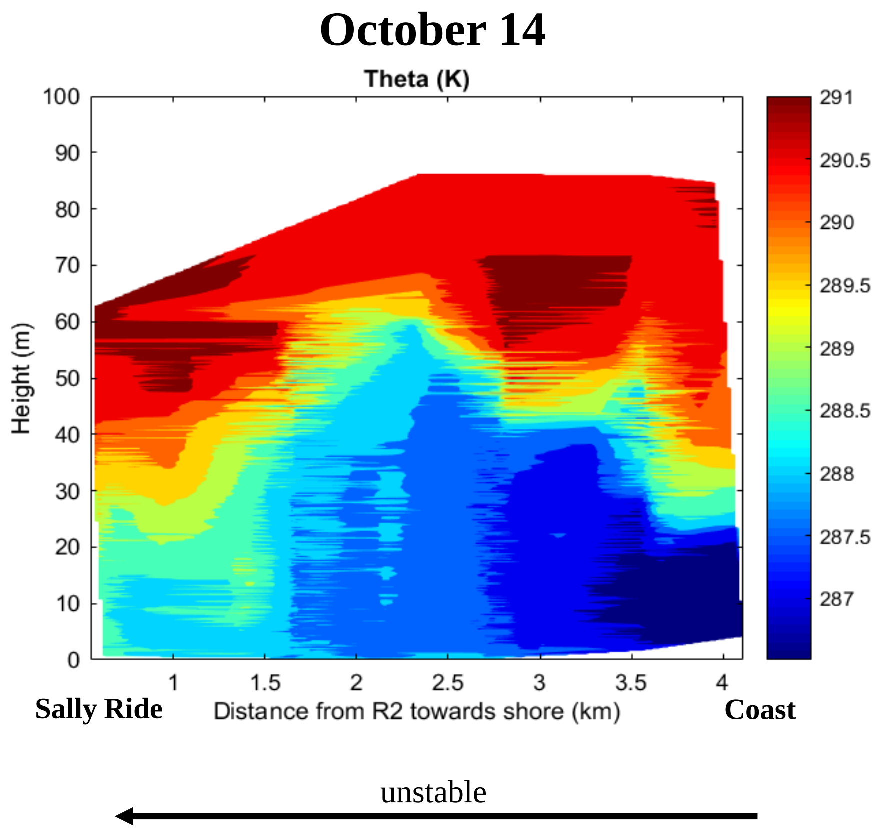
Velocity "kink" determines the IBL height

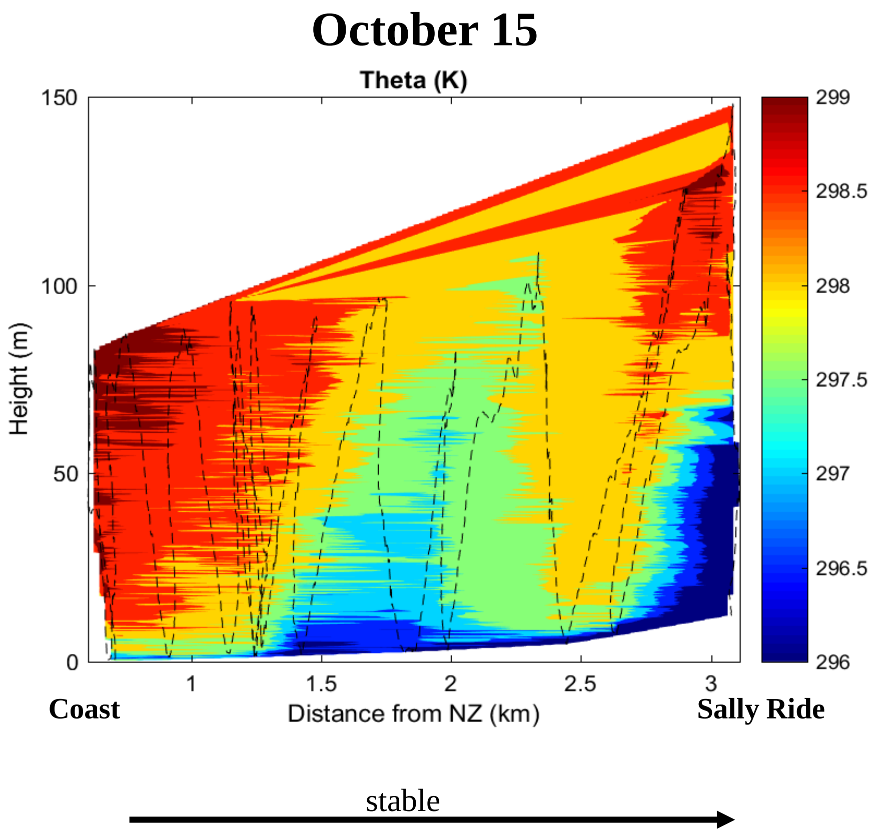
Elliot 1958 and Savelvey & Taylor 2006 IBL models are shown

Single Doppler Lidar wind retrieval of speed and direction using 2D Variational Scheme on a 2-degree elevation, PPI

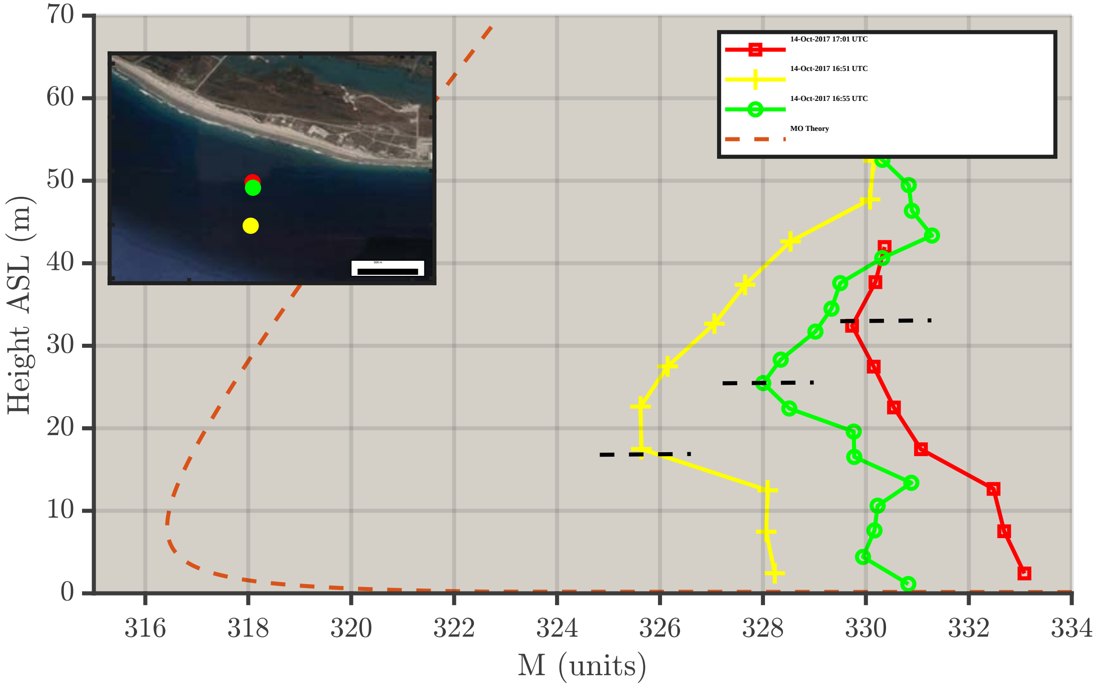


RHIB operations potential temperature profiles

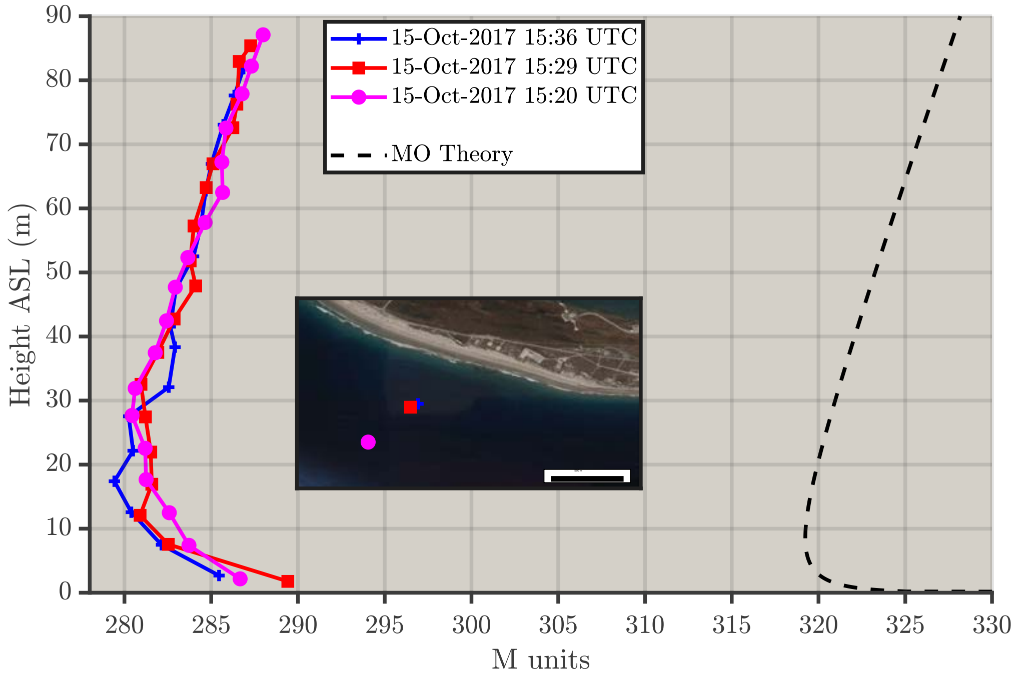




Modified refractive index (M) profiles



October 14th



October 15th

M Profile development, within 500 m from the coast from SBO and MO-theory. Surface based duct heights are shown with dotted lines. inset - location of measurements

$$N = 77.6 \, {}^{P}/_{T} + 3.73 \; x \; 10^{5} \, {}^{e}/_{T^2}$$

Internal Boundary Layer Parametrizations

IBL Growth Equations	Reference
$\frac{h(x)}{Z_{od}} = \left(0.75 - 0.03 \ln \frac{Z_{od}}{Z_{ou}}\right)\left(\frac{x}{Z_{od}}\right)^{0.8}$	Elliot (1958)
$1.73\,\kappa \frac{x}{Z_{od}} = \frac{h(x)}{Z_{od}}\left(\ln \frac{h(x)}{Z_{od}} - 1\right) - \frac{h(x)}{Z_{od}}\left(\ln \frac{h(x)}{Z_{od}} - 1\right)$	Miyake 1965
$\frac{h(x)}{Z_o} = 0.28\left(\frac{x}{Z_o}\right)^{0.8}$, Where $Z_o = \max\{Z_{od}, Z_{ou}\}$	Wood 1982
$\frac{h(x)}{Z_{od}} = 0.32\left(\frac{x}{Z_{od}}\right)^{0.8}$	Pendergrass and Foken 1984
$\frac{h(x)}{Z_{od}} = 10.56\left(\frac{x}{Z_{od}}\right)^{0.33}$	Cheng and Castro 2002
$\frac{dh}{dx} = \frac{\sigma_w}{u^*}\kappa\left(1 + \frac{h}{x}\Lambda\right)\left(\ln \frac{h}{Z_{ou}}\right)^{-1}$	Savelvey and Taylor 2001
$h\left(\ln \frac{h}{Z_{ou}} - 1 - \frac{\sigma_w}{u^*}\kappa \ln \frac{Z_{od}}{Z_{ou}}\right) = 2\frac{\sigma_w}{u^*}\kappa\, h\left(\ln \frac{h}{\sqrt{Z_{ou}Z_{od}}} - 1\right)$	Savelvey and Taylor 2006

$z_{ou} = upstream\ roughness\ height$

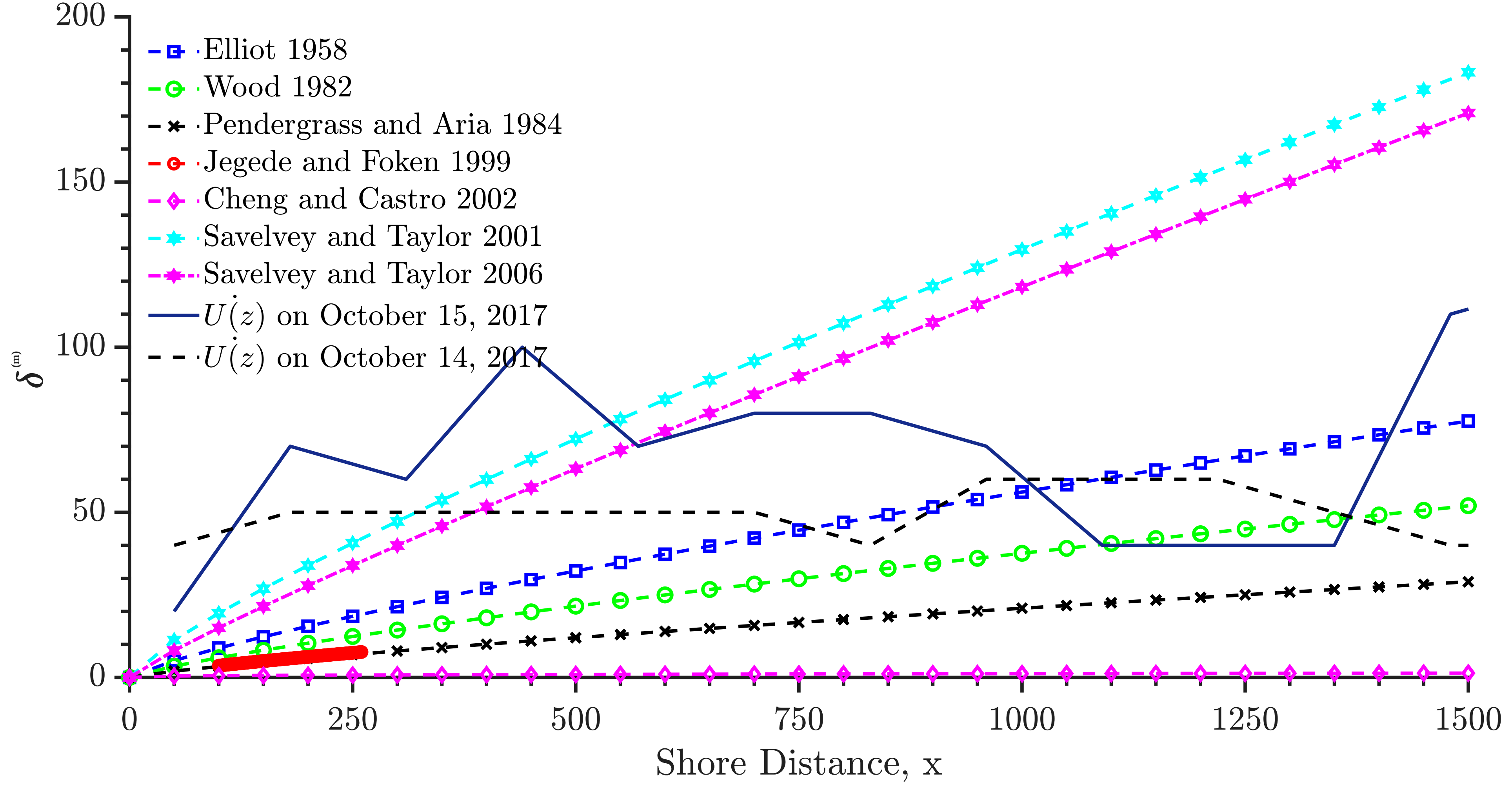
$z_{od} = downstream\ roughness\ height$

$\sigma_w = rms\ vertical\ velocity$

$u_* = friction\ velocity$

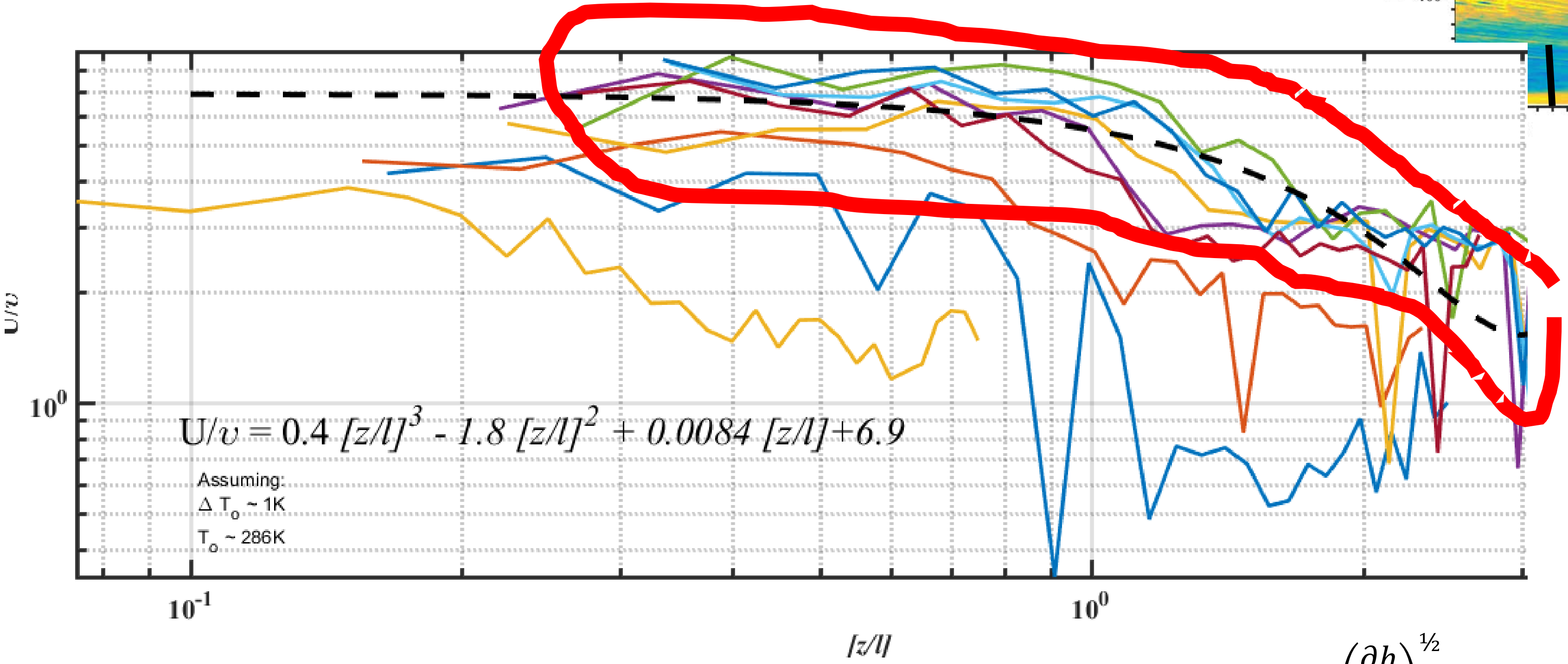
comparisons

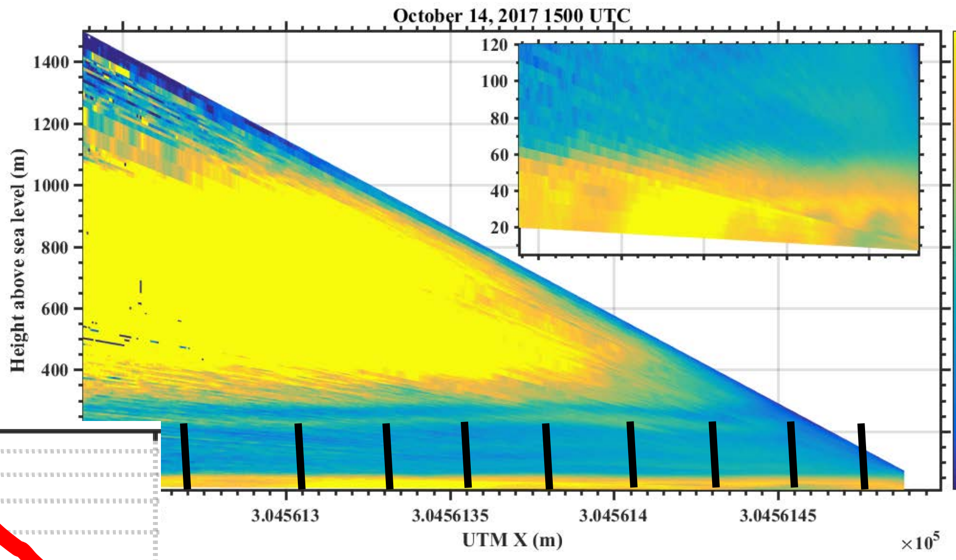
Comparison between IBL models and triple Doppler Lidar data

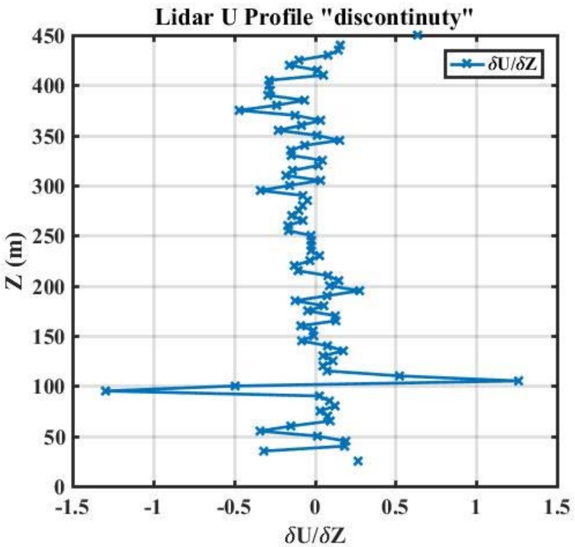


Calculations were made assuming land surface roughness (Z_{ou}) of 0.0436 and the downwind ocean surface roughness (Z_{od}) of 0.0012, based on Flux tower and ship Bow-mast datasets, respectively.

Scaling of Internal Boundary Layer Growth







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Thank You