Evaluating Monin-Obukhov Scaling for the Turbulent Ocean Surface Layer

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Abstract

Turbulent flow in surface layer, the top few meters in the ocean, tends to exhibit consistent and repeatable characteristics, and useful empirical laws can be formed to shed light on turbulence parameterization. Here, Monin-Obukhov similarity theory (MOST), developed for the atmospheric surface layer, is examined for the ocean surface layer. Using data collected from several moored surface flux buoys, we consider the relationship between surface fluxes and subsurface temperature gradients under a wide range of stability conditions. Large deviations from MOST predictions are found in our analysis, with smaller observed temperature gradients under both stable and unstable forcing. We hypothesize that these are attributed to the presence of Langmuir structures through interaction of Eulerian current with Stokes drift, which is not included in traditional Monin-Obukhov formulation. We examine the ability of recent Langmuir turbulence closure models to predict the observed differences.

Does the Monin-Obukhov Similarity Theory work in the Oceanic Surface Layer?

- probably "not"

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Introduction

Monin-Obukhov Similarity Theory

- rigid-wall boundary layer
- horizontal homogeneity & stationarity
- simple eddy viscosity and diffusivity
- turbulence controlled by surface stress and buoyancy flux
- turbulence length scale ~ $\kappa|z|$

$$K_m = \frac{u_*\kappa|z|}{\phi_m(|z|/L)}, \quad K_h = \frac{u_*\kappa|z|}{\phi_h(|z|/L)}, \quad \phi_m = \frac{\partial U/\partial z}{u_*/\kappa|z|}, \quad \phi_h = \frac{\partial \Theta/\partial z}{\theta_*/\kappa|z|},$$

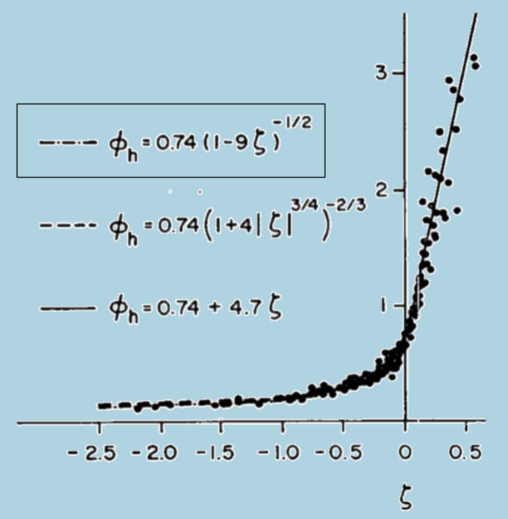
The stability functions ϕ depend on parameter $\zeta = |z|/L$, the distance from boundary normalized by the Obukhov length $L = u_*^3/\kappa B_o$. Note the Obukhov length is where the buoyancy flux contributes equally to the turbulence kinetic energy as the shear production.

Langmuir Turbulence Closure Model - Harcourt 2015

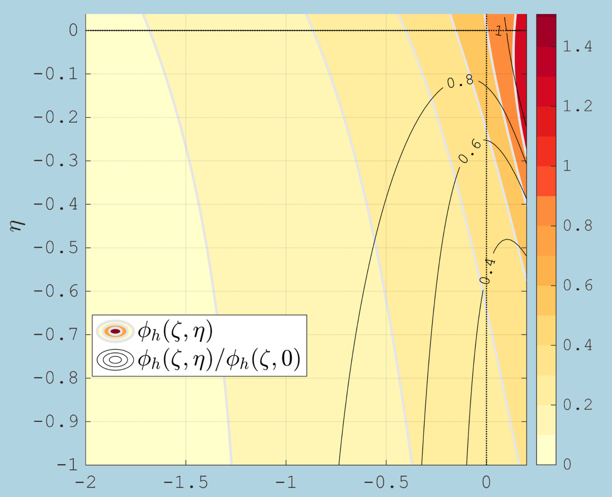
- wavy boundary layer
- horizontal homogeneity
- super-equilibrium limit of the model equations has predictions for surface layer stability functions ϕ
- tuned to neutral LES solutions
- turbulence in surface layer controlled by surface stress, buoyancy flux, Stokes drift shear, and surface proximity function f_z^S

$$\eta = -\hat{\tau}_w \cdot \frac{\partial \mathbf{u}^s/\partial z}{u_*/\kappa z}, \quad f_z^S = 1 + \tanh(\frac{z}{4Ls})$$

Kansas curve of ϕ_h



ϕ_h in Harcourt 2015 ($f_z^S = 0$)



Conclusions

- The classic **Monin-Obukhov** scaling **doesn't capture** the enhanced mixing observed in oceanic surface layer, consistent with the expectations from previous studies.
- The **Harcourt 2015 model marginally improves** the prediction of of surface layer temperature gradient.
- The behavior of near-surface temperature gradient in non-neutral LES solutions needs to be examined.

Objectives

- To evaluate the validity of **classic Monin-Obukhov** similarity relationship in the **oceanic surface layer** by comparing observations of surface layer **temperature gradient** to the Monin-Obukhov predictions.
- To assess the ability of the **Langmuir closure model of Harcourt (2015)** in predicting near-surface temperature gradient.

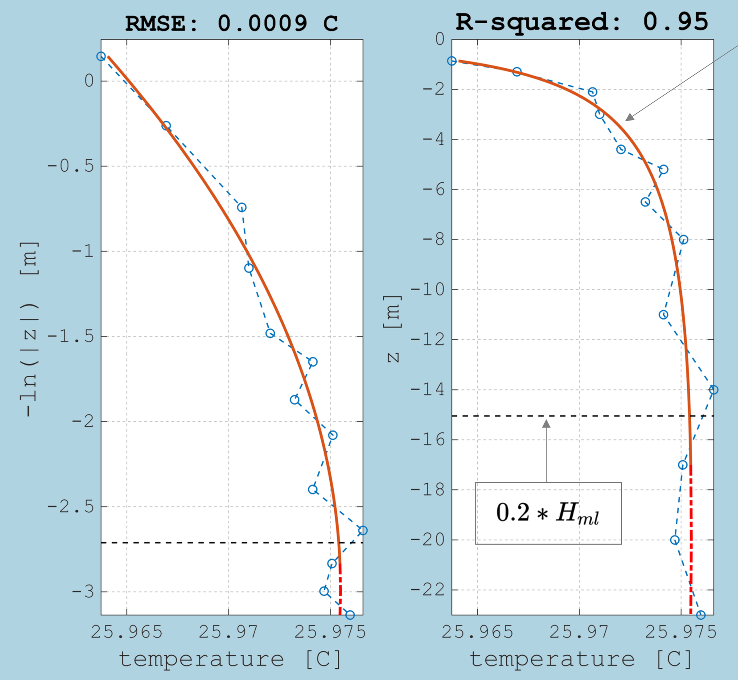
Methodology

As the canonical Monin-Obukhov scaling didn't include penetrative shortwave radiation, and the measurements were sparse when oceanic surface layer was shallow, we constrained our analysis on the unstable side only.

Observational Datasets

Info	OCS Papa	SPURS-I
location	Pacific (50N, 145W)	Atlantic (24.6N, 38W)
time	2010 - 2019, hourly	2012 - 2013, hourly
CTD sensor spacing	~4m	~1m

Polynomial Fit of Profile



$$\Theta(|z|) = p_0 + p_1 \ln|z| + p_2(\ln|z|)^2$$

Integrated Temperature Difference

Predictions of temperature difference between any two depths within the surface layer, computed by integrating the temperature gradient predictions from **Monin-Obukhov** (Kansas curve) or **Harcourt 2015 model**:

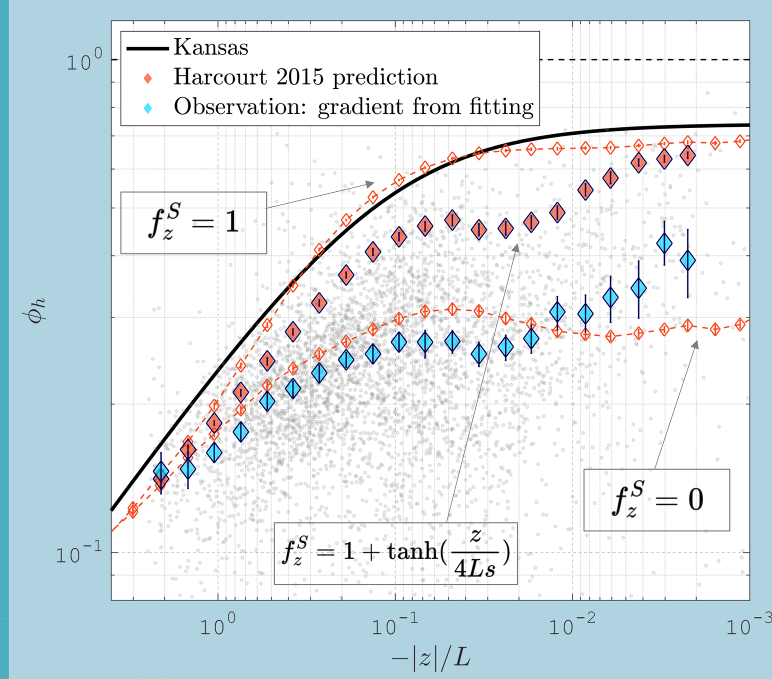
$$\Delta\Theta^{ij}_{prediction} = \int_{z_j}^{z_i} \frac{\theta_*}{\kappa|z|} \cdot \phi_h(\frac{|z|}{L})dz$$

are compared to the observed temperature differences

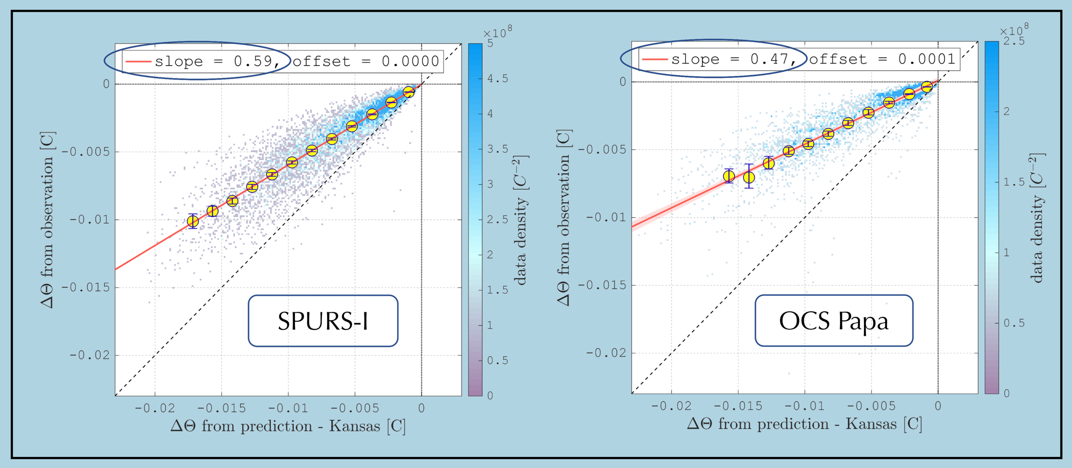
$$\Delta\Theta^{ij}_{observation} = \Theta(z_i) - \Theta(z_j)$$

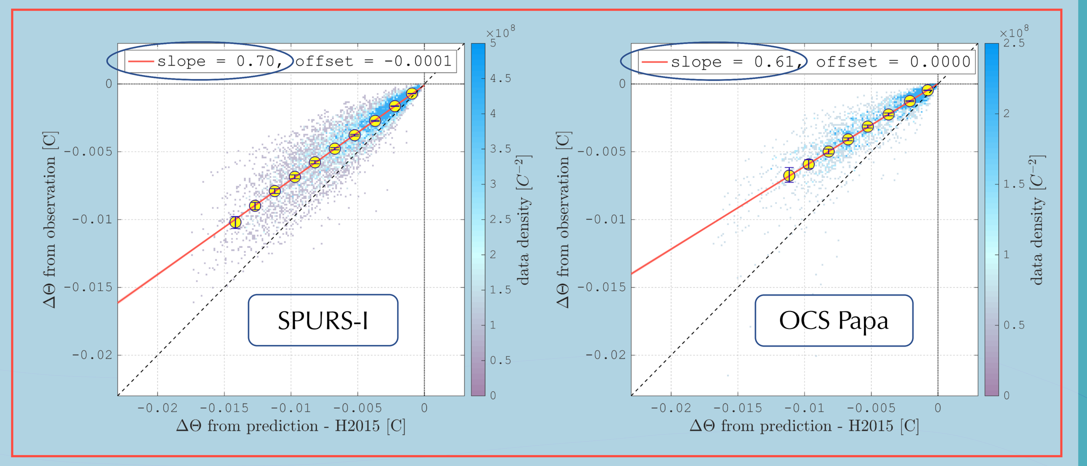
Results

SPURS-I & OCS Papa ϕ_h



- Observed ϕ_h diverge from Kansas curve in forced convection regime ($-1 \le \zeta < 0$). Predictions from Harcourt 2015 model with zero f_z^S (~ 2013 version) have similar magnitude as observations.





- Observations are about 50~60% of **Monin-Obukhov** predictions.
- Observations are about 60~70% of **Harcourt 2015 model** predictions.

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see my poster online

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