





DYNAMICS OF DIURNAL WARM LAYERS

Ken Hughes, Jim Moum, Emily Schroyer

## Diurnal warm layers on a tabletop

#### Intro

Relevance

Near-surface

Wind speed dependence

Deriving turbulence

Magnitude of  $\epsilon$ 

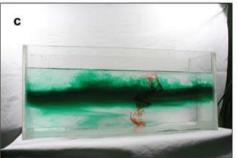
convergence

Heat transpo

Marginal instability

Critical wind speed





Franks and Franks (2009)

## Diurnal warm layers on a tabletop

#### Intro

Relevance

Near-surface

Wind speed dependence

Deriving turbulence

Magnitude of

Turbulent

Heat transpo

Marginal instability

Critical wind

Improved velocities

### **AUDIENCE**

Designed for graduate oceanography courses, this simulation is suitable for students as young as elementary school age, provided the level of discussion is appropriately scaled.

Franks and Franks (2009)

## Diurnal warm layers on a tabletop

#### Intro

Relevance

Near-surface

Wind speed

Deriving turbulence

Magnitude of

Turbulent

Heat transpo

Marginal instability

Critical wind

Improved velocities

### **AUDIENCE**

Designed for graduate oceanography courses, this simulation is suitable for a Zoom meeting of physical oceanographers, provided the level of discussion is appropriately scaled.

Franks and Franks (2009)

#### Intro

Relevance

Near-surface

Wind speed dependence

Deriving turbulence

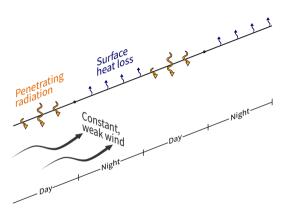
Magnitude of  $\epsilon$ 

Turbulent

Heat transpor

Marginal instability

Critical wind speed



#### Intro

Relevance

Near-surface

Wind speed dependence

Deriving turbulence

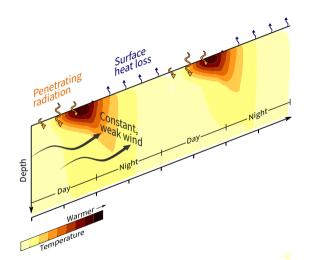
Magnitude of  $\epsilon$ 

Turbulent

Heat transpo

Marginal instability

Critical wind



#### Intro

Polovanco

Near-surface

Wind speed

Deriving turbulence

Magnitude of  $\epsilon$ 

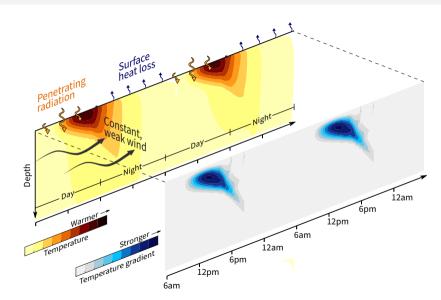
Turbulent

. . . . .

.

Marginal instability

Critical wind speed



#### Intro

Relevance

Near-surface

Wind speed

Deriving turbulence

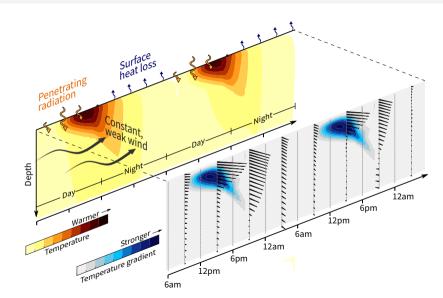
Magnitude of  $\epsilon$ 

Turbulent

Heat transpo

Marginal instability

Critical wind



### Published, submitted, and a vague idea

#### Intro

Relevance

Near-surface

Wind speed

Deriving turbulence

Magnitude of  $\epsilon$ 

Turbulent

Heat transpo

Marginal instability

Critical wind speed

Improved

### **Evolution of the Velocity Structure in the Diurnal Warm Layer**

KENNETH G. HUGHES, JAMES N. MOUM, AND EMILY L. SHROYER College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, Oregon

(Manuscript received 23 August 2019, in final form 18 December 2019)

### Heat transport through diurnal warm layers

- Kenneth G. Hughes,\* James N. Moum, and Emily L. Shroyer
- College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, Oregon

## Published, submitted, and a vague idea

#### Intro

Relevance

Near-surface

Wind speed

Deriving turbulence

Magnitude of  $\epsilon$ 

Turbulent

Heat transpo

Marginal instability

Critical wind speed

Improved velocities

### **Evolution of the Velocity Structure in the Diurnal Warm Layer**

KENNETH G. HUGHES, JAMES N. MOUM, AND EMILY L. SHROYER

College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, Oregon

(Manuscript received 23 August 2019, in final form 18 December 2019)

### Heat transport through diurnal warm layers

- Kenneth G. Hughes,\* James N. Moum, and Emily L. Shroyer
- <sup>3</sup> College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, Oregon

Something about shear instabilities?

## Warm layers are ubiquitous

Intro

#### Relevance

Near-surface

Wind speed

Deriving turbulence

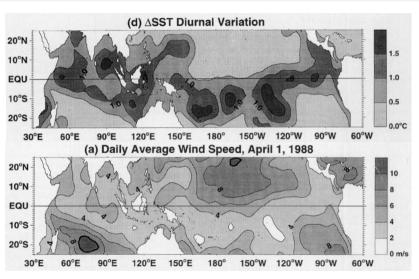
Magnitude of  $\epsilon$ 

Turbulent

Heat transpo

Marginal instability

Critical wind speed



## Warm layers are ubiquitous

Intro

#### Relevance

Near-surface

Wind speed

Deriving turbulence

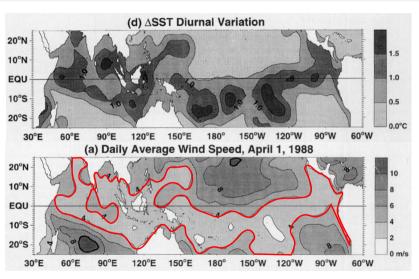
Magnitude of  $\epsilon$ 

Turbulent

Heat transpo

Marginal instability

Critical wind speed



## Warm layers are ubiquitous

Intro

#### Relevance

Near-surface

Wind speed

Deriving turbulence

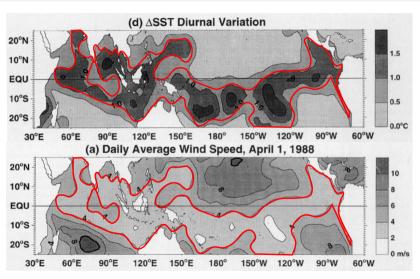
Magnitude of  $\epsilon$ 

Turbulent

Heat transpo

Marginal instability

Critical wind speed



## Wind speeds over the tropical ocean

Intro

#### Relevance

Near-surface

Wind speed

Deriving turbulence

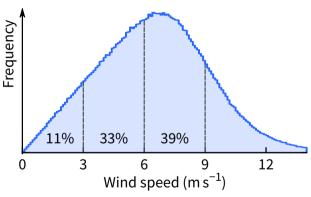
Magnitude of  $\epsilon$ 

Turbulent

Heat transpor

Marginal instability

Critical wind



Based on NCEP-DOE reanalysis

Intro

#### Relevance

Near-surface

Wind speed

Deriving turbulence

Magnitude of  $\epsilon$ 

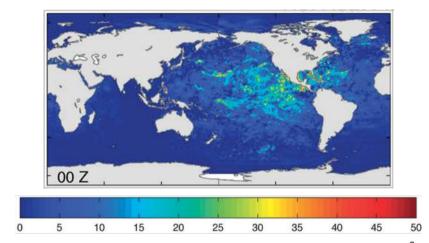
Turbulent

Heat transpo

Marginal instability

Critical wind speed

Improved velocities



Heat flux anomaly when excluding diurnal SST variability (W/m²)

Intro

#### Relevance

Near-surface

Wind speed

Deriving turbulence

Magnitude of  $\epsilon$ 

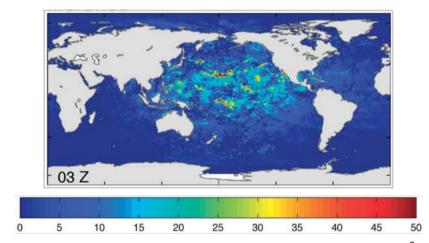
Turbulent

Heat transpo

Marginal instability

Critical wind speed

Improved velocities



Heat flux anomaly when excluding diurnal SST variability (W/m²)

Intro

#### Relevance

Near-surface

Wind speed

Deriving turbulence

Magnitude of  $\epsilon$ 

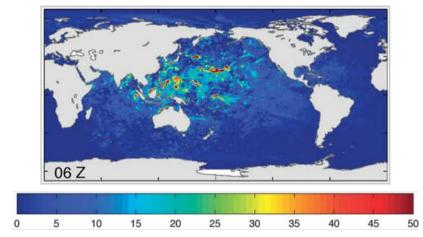
Turbulent

Heat transpo

Marginal instability

Critical wind speed

Improved velocities



Heat flux anomaly when excluding diurnal SST variability (W/m<sup>2</sup>)

Intro

#### Relevance

Near-surface

Wind speed

Deriving turbulence

Magnitude of  $\epsilon$ 

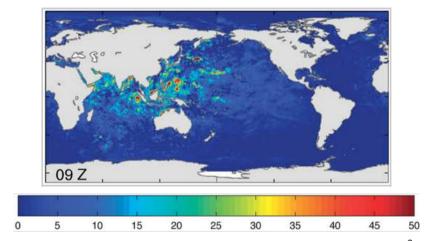
Turbulent

Heat transpo

Marginal instability

Critical wind speed

Improved velocities



Heat flux anomaly when excluding diurnal SST variability (W/m²)

Intro

#### Relevance

Near-surface

Wind speed

Deriving turbulence

Magnitude of  $\epsilon$ 

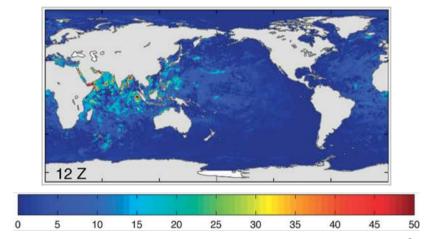
Turbulent

Heat transpo

Marginal instability

Critical wind speed

Improved velocities



Heat flux anomaly when excluding diurnal SST variability (W/m<sup>2</sup>)

Intro

#### Relevance

Near-surface

Wind speed

Deriving turbulence

Magnitude of  $\epsilon$ 

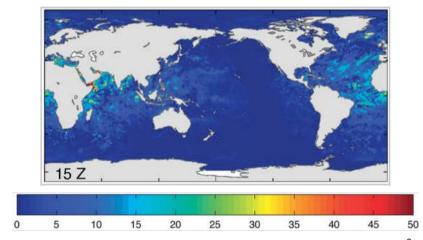
Turbulent

Heat transpo

Marginal instability

Critical wind speed

Improved velocities



Heat flux anomaly when excluding diurnal SST variability (W/m²)

Intro

#### Relevance

Near-surface

Wind speed

Deriving turbulence

Magnitude of  $\epsilon$ 

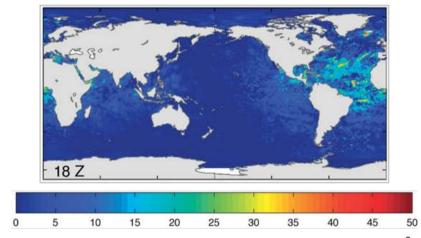
Turbulent

Heat transpo

Marginal instability

Critical wind speed

Improved velocities



Heat flux anomaly when excluding diurnal SST variability (W/m²)

Intro

#### Relevance

Near-surface

Wind speed

Deriving turbulence

Magnitude of  $\epsilon$ 

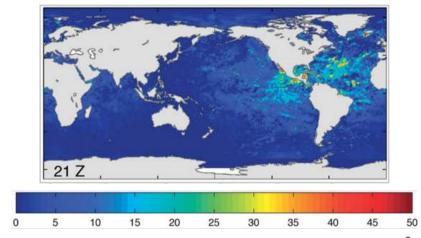
Turbulent

Heat transpo

Marginal instability

Critical wind speed

Improved velocities



Heat flux anomaly when excluding diurnal SST variability (W/m²)

Intro

#### Relevance

Near-surface

Wind speed

Deriving turbulence

Magnitude of  $\epsilon$ 

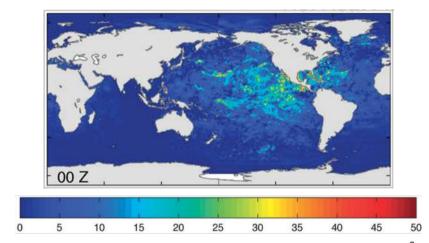
Turbulent

Heat transpo

Marginal instability

Critical wind speed

Improved velocities



Heat flux anomaly when excluding diurnal SST variability (W/m²)

## Altered near-surface dynamics

Intro

#### Relevance

Near-surface

Wind speed dependence

Deriving turbulence

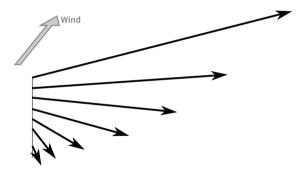
Magnitude of  $\epsilon$ 

Turbulent convergence

Heat transpor

Marginal instability

Critical wind



## Altered near-surface dynamics

Intro

#### Relevance

Near-surface

Wind speed

Deriving turbulence

Magnitude of  $\epsilon$ 

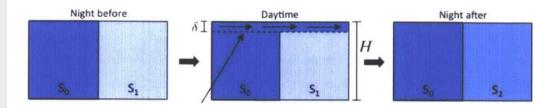
mag.mad.ore

convergence

Heat transpor

Marginal instability

Critical wind speed



Bogdanoff (2017)

# Surface measurements are difficult

Intro

Relevance

Near-surface observations

Wind speed dependence

Deriving turbulence

Magnitude of  $\epsilon$ 

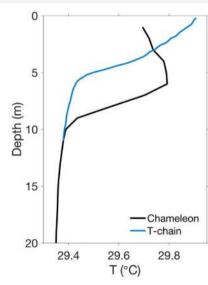
Turbulent

Heat transport

Marginal instability

Critical wind

Improved



Moulin et al. (2018)

### Surface measurements are difficult

Intro

Polovanco

### Near-surface observations

Wind speed dependence

Deriving turbulence

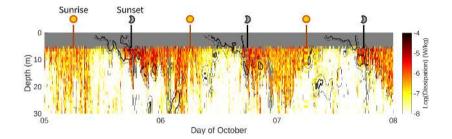
Magnitude of  $\epsilon$ 

Turbulent convergence

Heat transpo

Marginal instability

Critical wind



### **Enter SurfOtter**

Intro

Polovanco

Near-surface observations

Wind speed dependence

Deriving turbulence

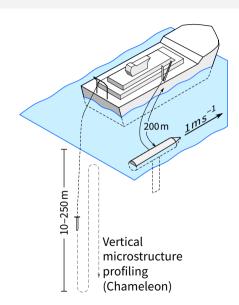
Magnitude of  $\epsilon$ 

Turbulent convergence

Heat transpor

Marginal instability

Critical wind speed



### **Enter SurfOtter**

Intro

Polovanco

Near-surface observations

Wind speed

Deriving turbulence

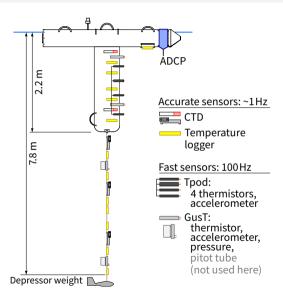
Magnitude of  $\epsilon$ 

Turbulent convergence

Heat transpor

Marginal instability

Critical wind speed



### SurfOtter follows the surface well

Intro

Polovanco

## Near-surface observations

Wind speed dependence

Deriving turbulence

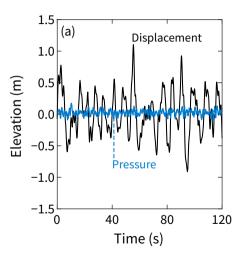
Magnitude of  $\epsilon$ 

Turbulent

Heat transpo

Marginal instability

Critical wind speed



### SurfOtter follows the surface well

Intro

Polovanco

## Near-surface

Wind speed

Deriving turbulence

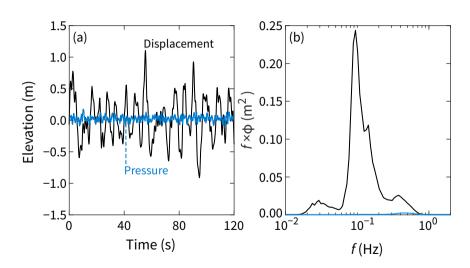
Magnitude of  $\epsilon$ 

Turbulent

Heat transpo

Marginal instability

Critical wind speed



Intro

Relevance

Near-surface

Wind speed dependence

Deriving turbulence

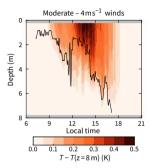
Magnitude of  $\epsilon$ 

Turbulent

Heat transpor

Marginal instability

Critical wind



Intro

Polovance

Near-surface

Wind speed dependence

Deriving turbulence

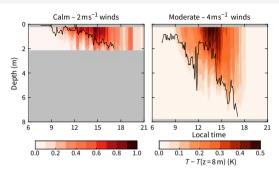
Magnitude of  $\epsilon$ 

Turbulent convergence

Heat transpo

Marginal instability

Critical wind speed



Intro

D - I - - - - - -

Near-surface

Wind speed dependence

Deriving turbulence

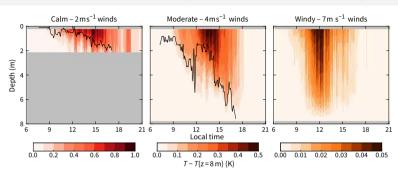
Magnitude of  $\epsilon$ 

Turbulent

Heat transpo

Marginal instability

Critical wind



Intro

Polovanco

Near-surface

Wind speed dependence

Deriving turbulence

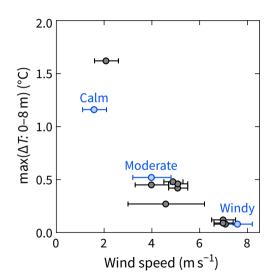
Magnitude of  $\epsilon$ 

Turbulent

Heat transpor

Marginal instability

Critical wind



Intro

D - I - - - - - -

Near-surface

Wind speed dependence

Deriving turbulence

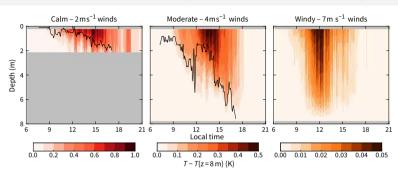
Magnitude of  $\epsilon$ 

Turbulent

Heat transpo

Marginal instability

Critical wind



## Wind speed controls warm layer structure

Intro

D = I = . . = = =

Near-surface

Wind speed dependence

Deriving turbulence

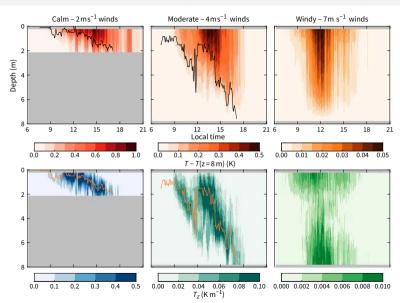
Magnitude of  $\epsilon$ 

Turbulent

Heat transpo

Marginal instability

Critical win



## Wind speed controls warm layer structure

Intro

D-1----

Near-surface

Wind speed dependence

Deriving turbulence

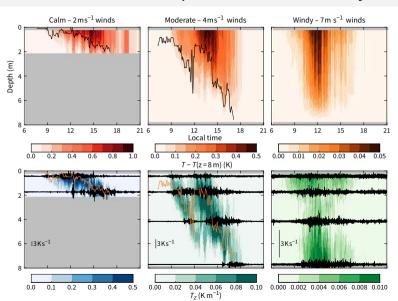
Magnitude of  $\epsilon$ 

Turbulent

Heat transpo

Marginal instability

Critical win



Intro

Relevance

Near-surface

Wind speed

## Deriving turbulence

Magnitude of  $\epsilon$ 

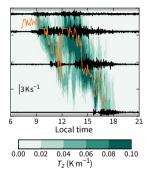
.....

convergence

Heat transno

Marginal instability

Critical wind



Intro

Polovance

Near-surface

Wind speed dependence

### Deriving turbulence

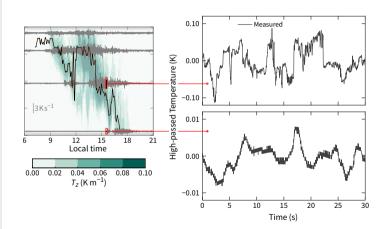
Magnitude of  $\epsilon$ 

Turbulent

convergence

Marginal

Critical wind



Intro

Polovance

Near-surface

Wind speed

### Deriving turbulence

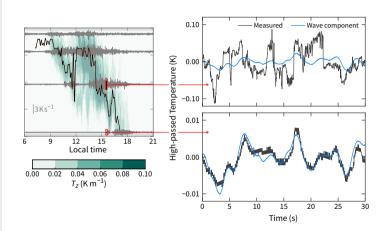
Magnitude of  $\epsilon$ 

Turbulent

.........

Marginal

Critical wind



# SurfOtter temperatures always have a wave component

Intro

Polovanco

Near-surface

Wind speed dependence

# Deriving turbulence

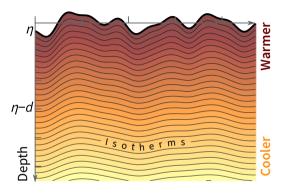
Magnitude of  $\epsilon$ 

Turbulent

Heat transpo

Marginal instability

Critical wind speed



# SurfOtter temperatures always have a wave component

Intro

Polovanco

Near-surface

Wind speed dependence

# Deriving turbulence

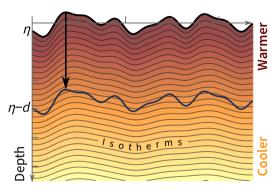
Magnitude of  $\epsilon$ 

Turbulent

Heat transpo

Marginal instability

Critical wind speed



## SurfOtter temperatures always have a wave component

Intro

Polovanco

Near-surface

Wind speed

## Deriving turbulence

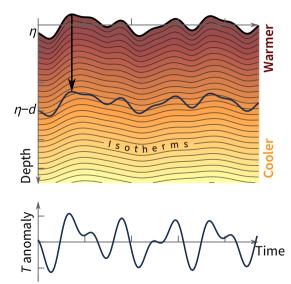
Magnitude of  $\epsilon$ 

Turbulent

Heat transpo

Marginal instability

Critical wind speed



Intro

Dolovonoo

Near-surface

Wind speed

#### Deriving turbulence

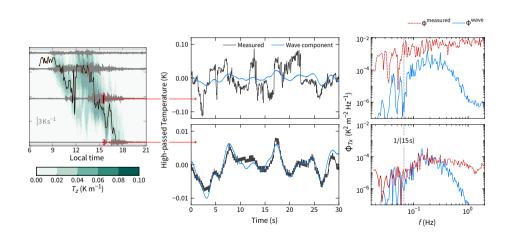
Magnitude of  $\epsilon$ 

Turbulent

Heat transp

Marginal instability

Critical wind speed



Intro

Dolovonoo

Near-surface

Wind speed

#### Deriving turbulence

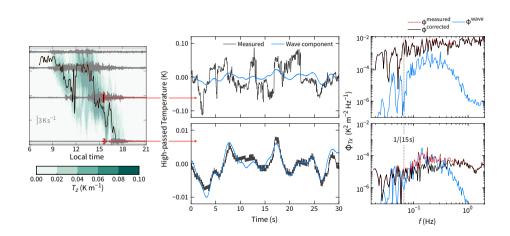
Magnitude of  $\epsilon$ 

Turbulent

Heat transp

Marginal instability

Critical wind speed



Intro

Dolovonoo

Near-surface

Wind speed

#### Deriving turbulence

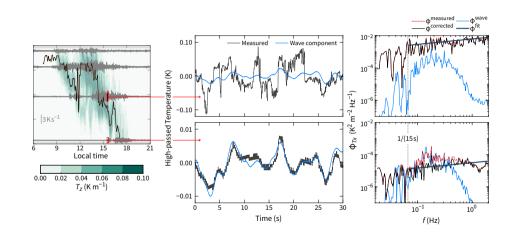
Magnitude of  $\epsilon$ 

Turbulent

Heat transp

Marginal instability

Critical wind speed



# Compare with typical boundary layer turbulence

Intro

Relevance

Near-surface

Wind speed

Deriving turbulence

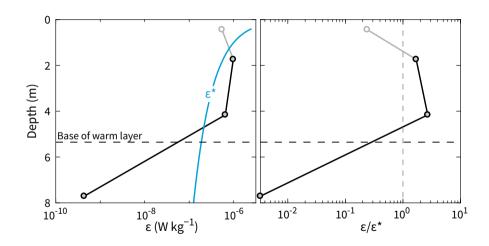
#### Magnitude of $\epsilon$

Turbulent

Heat transp

Marginal instability

Critical wind



## Compare with typical boundary layer turbulence

Intro

D-I----

Near-surface

Wind speed

Deriving turbulence

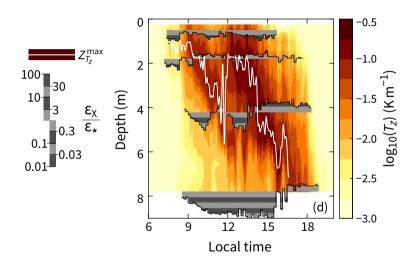
#### Magnitude of $\epsilon$

Turbulent

Heat transpo

Marginal instability

Critical wind



# Turbulent buoyancy fluxes completely shut off?

Intro

Dalawanaa

Near-surface

Wind speed

Deriving turbulence

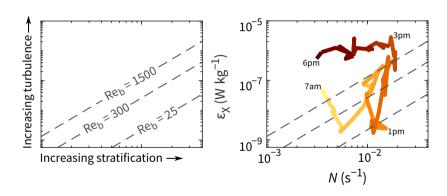
#### Magnitude of $\epsilon$

Turbulent

Heat transp

Marginal instability

Critical wind



# Mixing with constant diffusivity

Intro

Polovanco

Near-surface

Wind speed dependence

Deriving turbulence

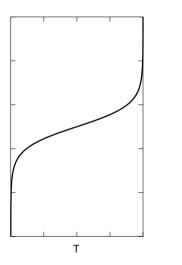
Magnitude of  $\epsilon$ 

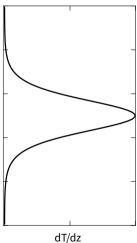
## Turbulent convergence

Heat transport

Marginal instability

Critical wind





# Mixing with surface-intensified diffusivity

Intro

D-1----

Near-surface

Wind speed dependence

Deriving turbulence

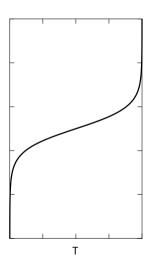
Magnitude of  $\epsilon$ 

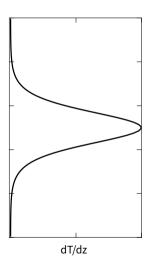
# Turbulent convergence

Heat transport

Marginal instability

Critical wind





# Heat converges where turbulence drops off

Intro

Polovanco

Near-surface

Wind speed

Deriving turbulence

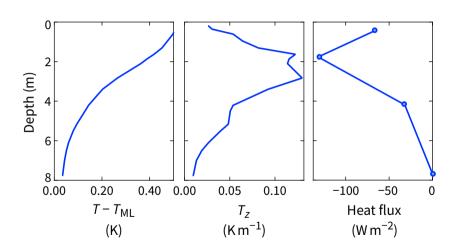
Magnitude of  $\epsilon$ 

Turbulent convergence

Heat transpor

Marginal instability

Critical wind speed



# Heat converges where turbulence drops off

Intro

Dalawanaa

Near-surface

Wind speed

Deriving turbulence

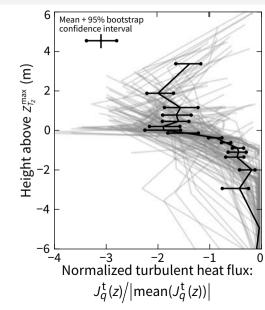
Magnitude of Turbulent

convergence

ricat transpor

instability

Critical wind speed



# Heat converges where turbulence drops off

Intro

Dalawanaa

Near-surface

Wind speed

Deriving turbulence

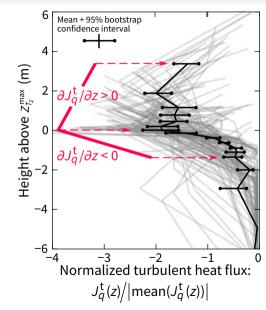
Magnitude of

Turbulent convergence

Heat transpor

Marginal instability

Critical wind speed



Intro

Relevance

Near-surface

Wind speed dependence

Deriving turbulence

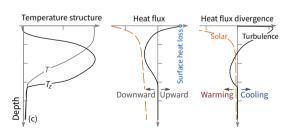
Magnitude of  $\epsilon$ 

## Turbulent convergence

Heat transpor

Marginal instability

Critical wind speed



Intro

Relevance

Near-surface

Wind speed

Deriving turbulence

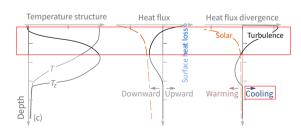
Magnitude of  $\epsilon$ 

#### Turbulent convergence

Heat transpor

Marginal instability

Critical wind



Intro

Relevance

Near-surface

Wind speed dependence

Deriving turbulence

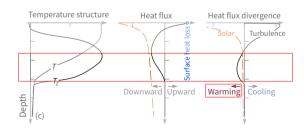
Magnitude of  $\epsilon$ 

#### Turbulent convergence

Heat transpor

Marginal instability

Critical wind



Intro

Dolovoneo

Near-surface

Wind speed

Deriving turbulence

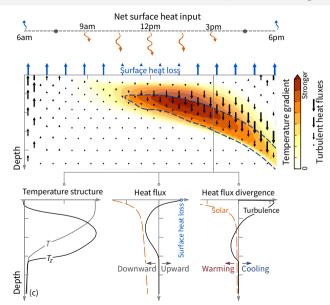
Magnitude of  $\epsilon$ 

# Turbulent convergence

Heat transpor

Marginal instability

Critical wind speed



Intro

Dalawanaa

Near-surface

Wind speed

Deriving turbulence

Magnitude of  $\epsilon$ 

Turbulent

Heat transport

rieat transport

instability

critical wind

$$\frac{-\partial H}{\partial t} = \frac{\partial J_q^{t}}{\partial z} + \frac{\partial J_q^{s}}{\partial z}$$

## Independent estimates of heat transport agree

Intro

Polovanco

Near-surface

Wind speed

Deriving turbulence

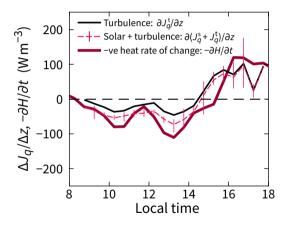
Magnitude of  $\epsilon$ 

Turbulent

#### Heat transport

Marginal instability

Critical wind speed



# Warm layers exhibit marginal instability

Intro

Relevance

Near-surface

Wind speed dependence

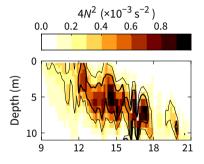
Deriving turbulence

Magnitude of  $\epsilon$ 

Heat transpo

# Marginal instability

Critical win



# Warm layers exhibit marginal instability

Intro

Relevance

Near-surface

Wind speed dependence

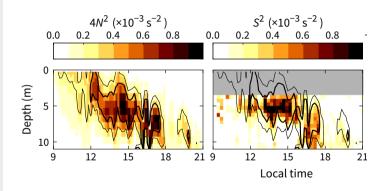
Deriving turbulence

Magnitude of  $\epsilon$ 

Turbulant

Marginal instability

Critical wind speed



# Warm layers exhibit marginal instability

Intro

Relevance

Near-surface

Wind speed dependence

Deriving turbulence

Magnitude of  $\epsilon$ 

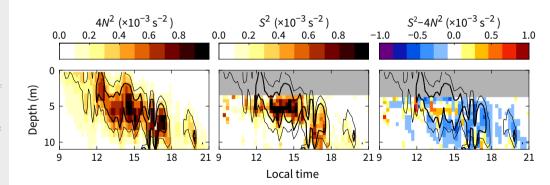
....g......

convergence

Heat transpor

# Marginal instability

Critical win



# Marginal instability only if wind >2 m s<sup>-1</sup>

ntro

Relevance

Near-surface

Wind speed dependence

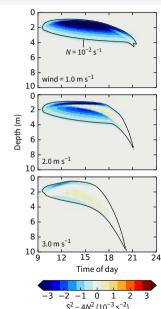
Deriving turbulence

Magnitude of  $\epsilon$ 

Heat transport

Marginal instability

Critical wind speed



Intro

Relevance

Near-surface observations

Wind speed dependence

Deriving turbulence

Magnitude of

Turbulent convergence

Heat transpo

Marginal instability

Critical wind speed

Improved velocities

Kinetic energy input:

$$\frac{u^2 + v^2}{2} = \frac{1}{2} \left( \frac{\tau}{h \rho_{\rm w} f} \right)^2 (2 - 2 \cos(ft))$$

Potential energy input:

$$J_b t = \frac{g\alpha}{\rho_{\rm w} c_p} J_q t,$$

$$U_{\rm cr} \approx 2 \, {\rm m \, s^{-1}}$$

## Other evidence for $2 \text{ m s}^{-1}$

Intro

Relevance

Near-surface

Wind speed dependence

turbulence

Magnitude of  $\epsilon$ 

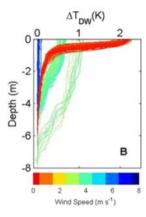
Turbulent convergence

Heat transpor

Marginal instability

## Critical wind speed

Improved



Gentemann et al. (2009)

Intro

Relevance

Near-surface

Wind speed dependence

Deriving turbulence

Magnitude of  $\epsilon$ 

Turbulent convergence

Heat transpo

instability

Critical wind speed

Improved velocities

 $dSST = f + a(PS) + b(P) + c \ln(U) + d(PS) \ln(U) + e(U)$ 

TABLE 5. Coefficients for determination of diurnal sea surface temperature amplitude (dSST) from (6).

Coefficient	$U > 2 \text{ m s}^{-1}$ value	$U \le 2 \text{ m s}^-$ value
f	0.262	0.328
a	0.002 65	0.002
b	0.028	0.041
c	-0.838	0.212
d	-0.00105	-0.000185
e	0.158	-0.329

Webster et al. (1996)

#### Other evidence for $2 \text{ m s}^{-1}$

Intro

Relevance

Near-surface

Wind speed dependence

Deriving turbulence

Magnitude of  $\epsilon$ 

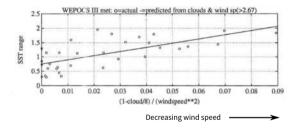
convergence

Heat transpor

Marginal instability

## Critical wind speed

Improved velocities



Lukas (1991)

#### Other evidence for $2 \text{ m s}^{-1}$

Intro

Relevance

Near-surface

Wind speed dependence

Deriving turbulence

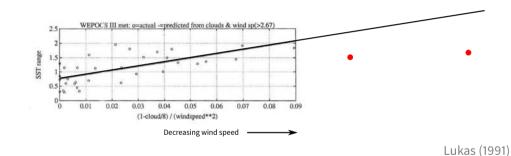
Magnitude of  $\epsilon$ 

convergence

Heat transpor

Marginal instability

## Critical wind speed



#### Velocities almost to the surface

Intro

Relevance

Near-surface

Wind speed

Deriving turbulence

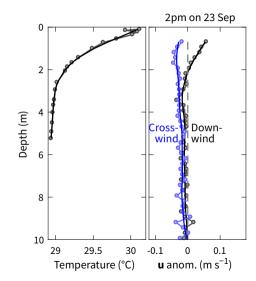
Magnitude of  $\epsilon$ 

Turbulent

Heat transpo

Marginal instability

Critical wind



#### Velocities almost to the surface

Intro

Polovanco

Near-surface

Wind speed dependence

Deriving turbulence

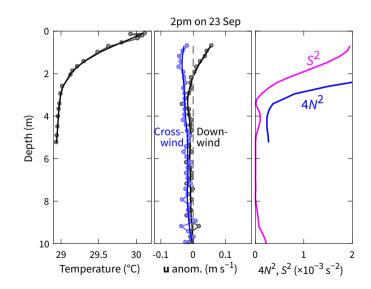
Magnitude of  $\epsilon$ 

Turbulent

Heat transpo

Marginal instability

Critical wind



#### Velocities almost to the surface

Intro

Relevance

Near-surface

Wind speed

Deriving turbulence

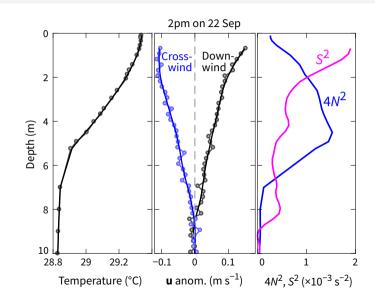
Magnitude of  $\epsilon$ 

Turbulent convergence

Heat transpor

Marginal instability

Critical wind



# Dynamics of the diurnal thermocline

Intro

Relevance

Near-surface

Wind speed

Deriving turbulence

Magnitude of  $\epsilon$ 

convergence

Heat too see

Marginal

Critical wind

