Critical roles of Interfacial layers in stratified /non-stratified turbulent flows -Emil Hopfinger festschrift

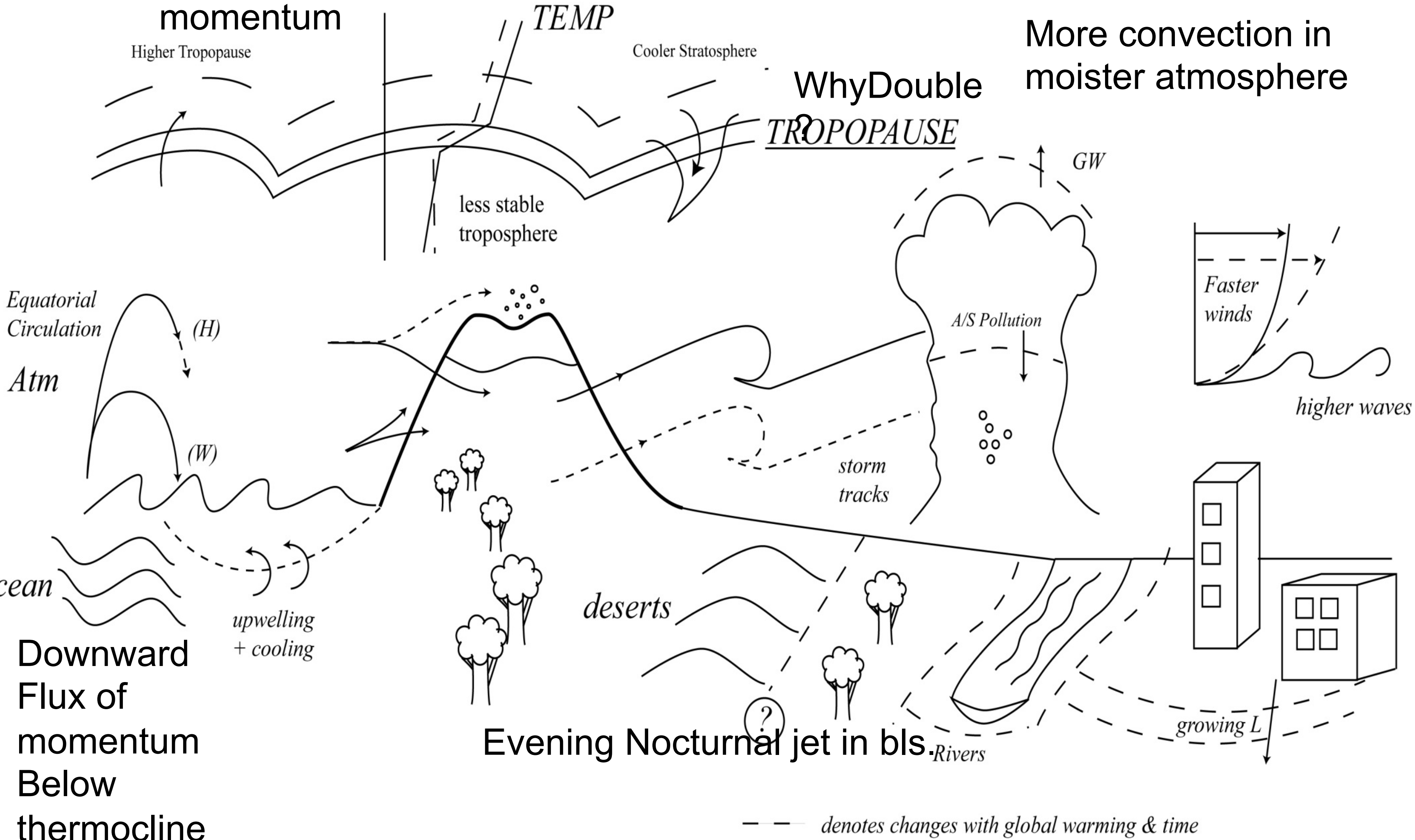
Julian Hunt
(with many colleagues)
UCL , and Trinity Coll, Camb

interfaces in modelling and computation stratified layers in ocean/atm

Upward flux of momentum

More convection in moister atmosphere

WhyDouble ?



Downward Flux of momentum Below thermocline

Evening Nocturnal jet in bls.

3 zones –external ;interfacial layers ;internal

-stratus clouds
Interfacial layers
convective eddies

Turbulent/non-turbulent interfaces

e.g.
Bisset, et al. (2002)
Da Silva & Pereira (2005)
Westerweel, et al. (2005, 2009)

The higher the Reynolds number, the sharper the interfaces-(Hunt Ishihara Kaneda)

Classification of clouds -1802 Lamarck (French) ; 1803 Howard(Latin)
'sport of winds' ; first description of eddies/coherent structures

Defining the location yI of the interface by jump in u velocity

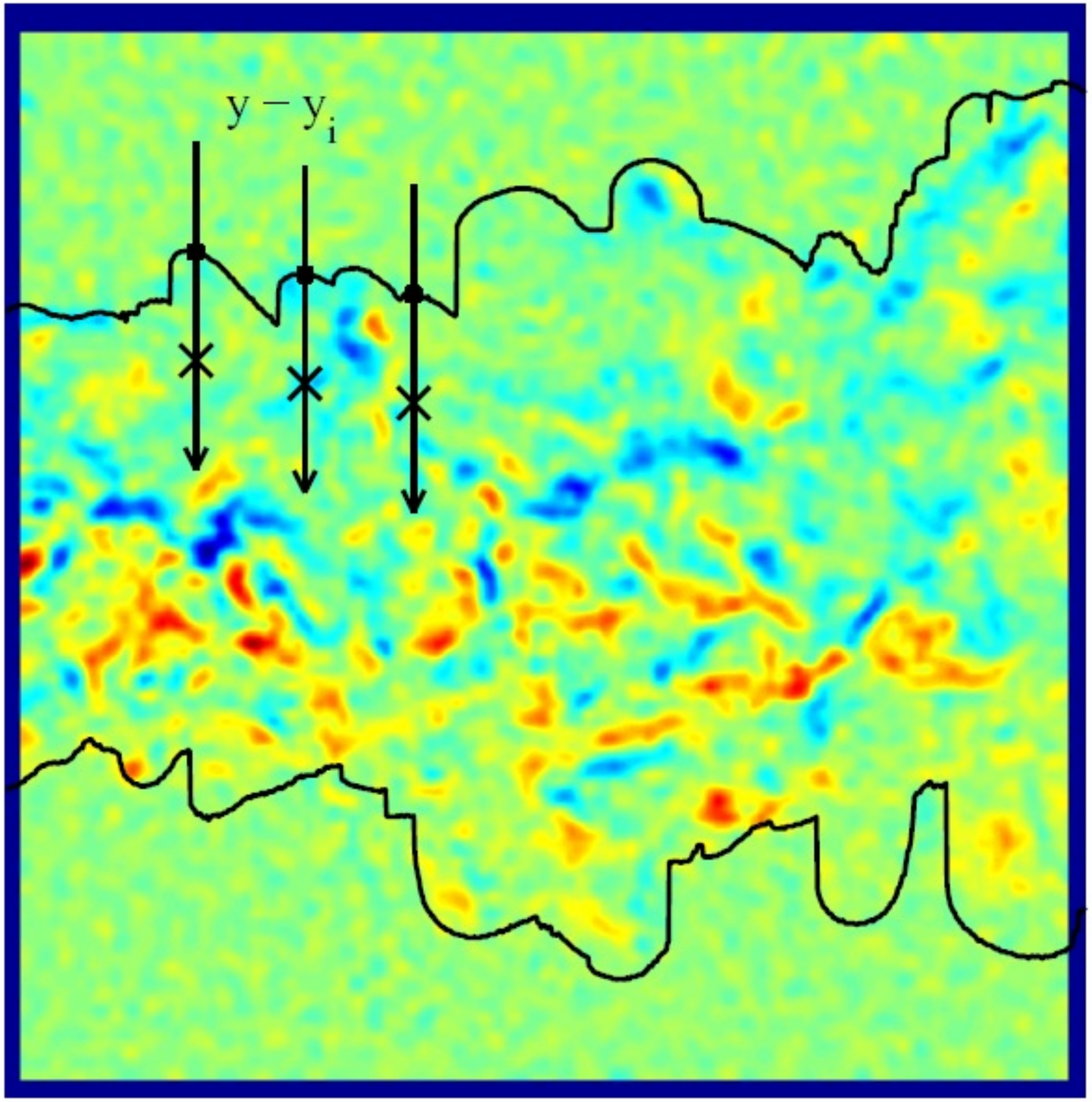


FIGURE 11. The vorticity Ω_z and the jet outer boundary (*continuous line*).

In Figure 11 the interface in Fig. 9b is superimposed on the (interpolated) vorticity field of the velocity field in Fig. 4.

Westerweel, Fukushima, Pedersen, Hunt

Interfacial layers –via new approaches

-organised internal and external(OXIL) layers (waves and fluctuations in exterior region)

and random internal layers (RIL) (with turbulence on both sides)

. BIL - Layers near boundaries (rigid/flexible)

-common features and differences between types of XIL

-new computational approaches for modelling when interfaces cannot be resolved?

(neg eddy viscosity + time delay j. steinhoff 1994 –

POD +local modelling Braza (2016) ->new aerofoil design)

Importance for overall flow : (i) barriers between characteristic flow zones –organised and random zones

(ii)flow processes (transport, sound , forces on structures)-

(iii) sensitivity to flow adjustments –eg two-phase, mhd …

Examples of Modelling across Interfacial Layers

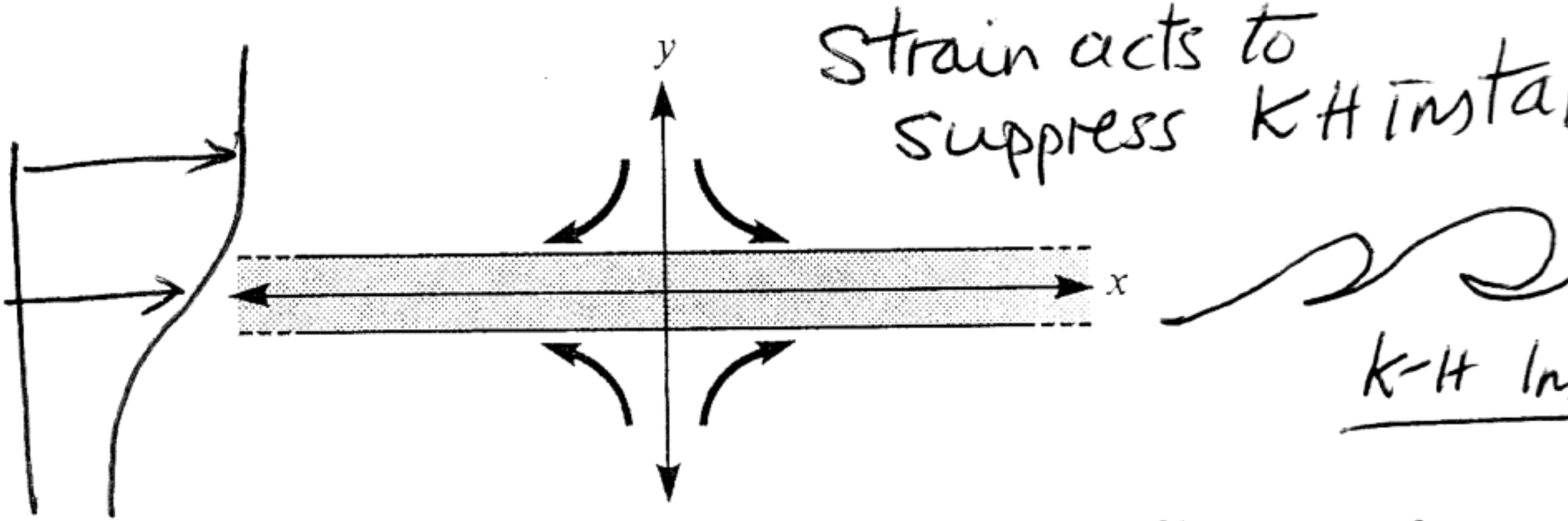
1, Turb +stratif'n

simple linear rdt model of turb ($y<y_l$) matching irrotational or stratified waves/rotational ($y>y_l$)

2. Turb + strat +shear

requires local dynamical model across interface

Why do Interfacial shear layers form and persist with turbulence on one or both sides? Dritschel, Haynes et al



e simplest flow to be considered, in which a vorticity filament undergoes
n ($\Omega = 0$) whilst aligned parallel to the extensional axis ($\phi = \phi_0 = 0$).

Typical thickness is $L / \sqrt{(UL / \nu)} = L / \sqrt{\mathrm{Re}}$

Interfacial processes: non-linear analysis

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MECHANISMS (1) SHEAR SHELTERING ACTION OF VORTEX SHEET

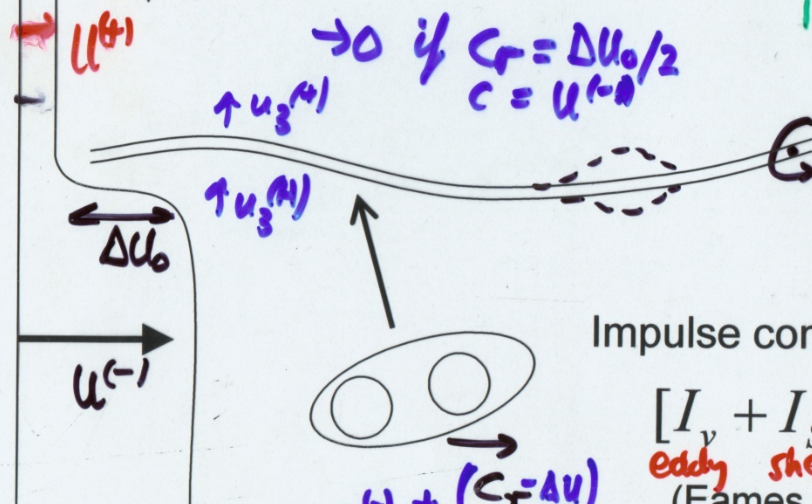
Non-linear processes: vortical interactions with interfaces

Linear calc'n

$$\frac{\sqrt{\overline{u_3^{(+)2}}}}{\sqrt{\overline{u_3^{(H)2}}}}(\hat{x}_3 \sim l) = \frac{b}{2}\left|\frac{\Delta U_0^2 - 4c_r^2}{\Delta U_0^2 + 4c_r^2}\right|$$

Hunt & Durbin 1999 Fluid Dyn Res.

$\to 0$ if $c_r = \Delta U_0/2$, $c = U^{(-)}$



$c = U^{(-)} + \left(c_r - \frac{\Delta U}{2}\right)$

- Response to disturb
- acts as a barrier if $c = U^{(-)}$
- by thickening/thinning
- depends on speed of disturb.

Impulse conservation

$$[I_v + I_S] = 0$$

eddy sheet

(Eames, Flor & Landeryou 2006 JFM under revision)

Sheltering versus blocking processes

Note response to ext. turb is not coupled to KH instab. in shear layer

Note ; max blocking if interface is a critical layer (Drazin)

HUNT . EAMES . WESTERWEEL . (IUTAM 2006

Interfacial processes: non-linear analysis

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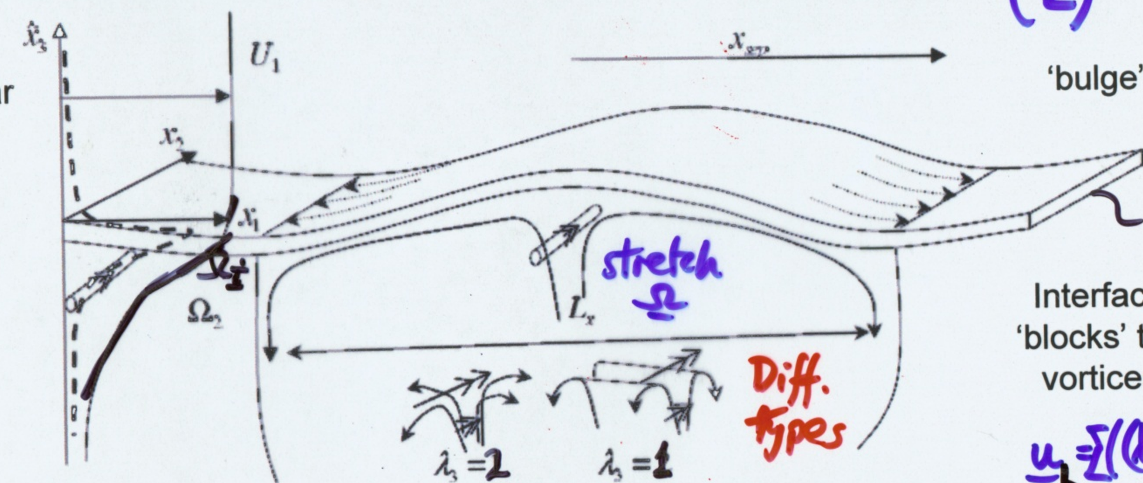
(2) HOW DOES SHARP INTERFACE PERSIST?



Free shear layer

Interface 'blocks' the vortices

$\Omega_{\hat{x}} \gg \Omega_2$

$u_0/L > \Omega_2$

Weak Non-uniform shear

Flow due to impinging eddy distorts the vorticity field, Ω_2

But eddy impacts on the interface

$\underline{u}_b = \Sigma((\lambda_3 - 1)x_1, x_2, -\lambda_3 x_3)$

$\underline{\Omega} = \nabla \wedge \underline{v}$

$\Rightarrow d\underline{\Omega}/dt = (\underline{\Omega} . \nabla)\underline{u}_b \Rightarrow \langle \Omega_2 \rangle \propto 1/x_3$ (note average)

COULD BE INTRO INTO RANS ETC

⇒ Impinging EDDY flow creates a straining flow amplifying the mean shear layer gradient

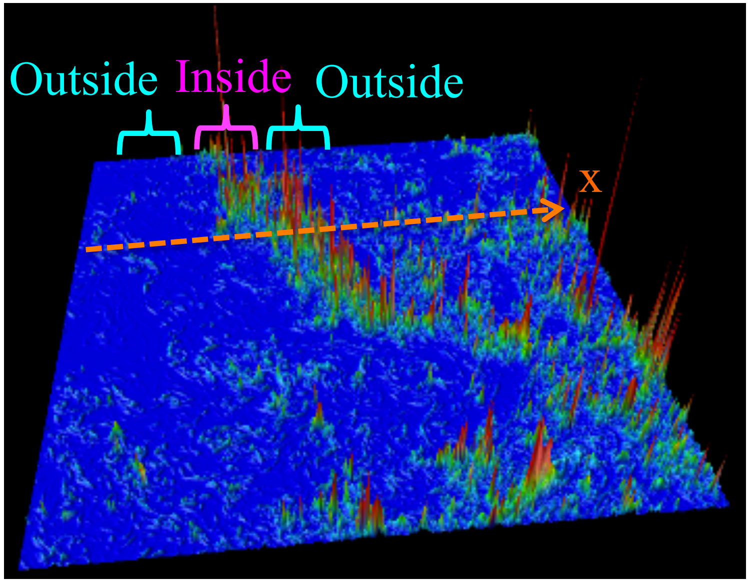
(Note consistent with log layer - even at interface - (steady)

$\frac{1}{2}(e^{\lambda t} + e^{-\lambda t}) \sim e^{\lambda t}$

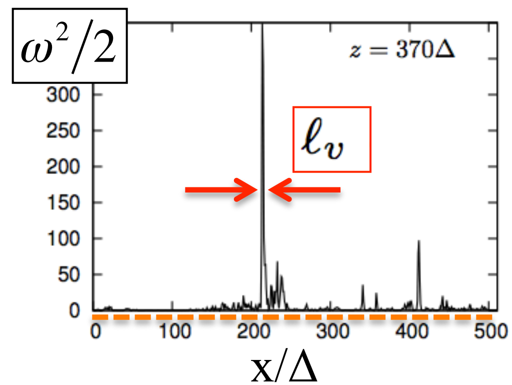
ONE SIDED (XIL) TURB INTERFACIAL LAYER - COULD BE LARGE

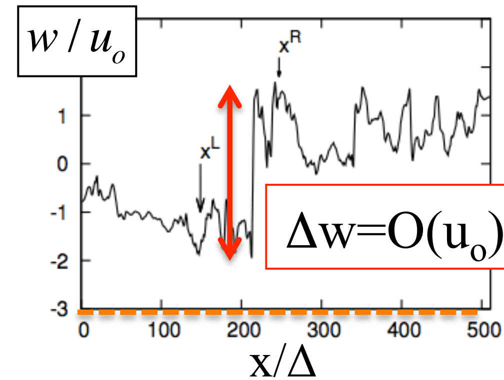
Interior interfacial layer – turb on both sides –double structure (TI,H)

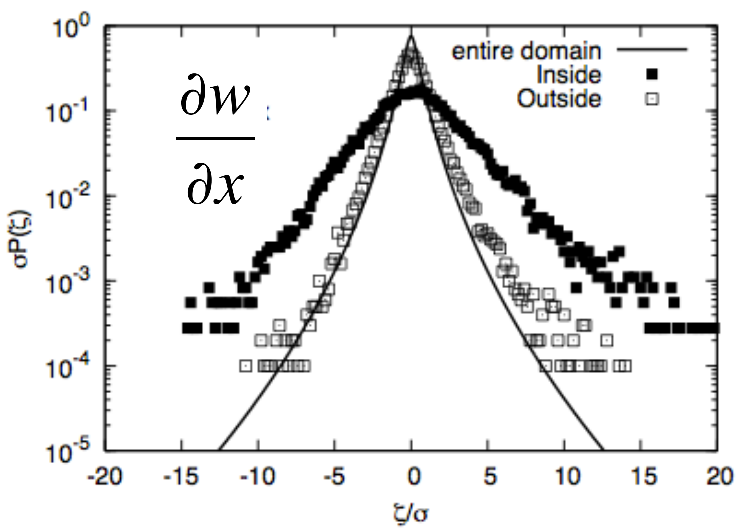
Distribution of the strong vortices inside the layer



($\Delta=2\pi/4096\sim3\eta$: grid spacing)







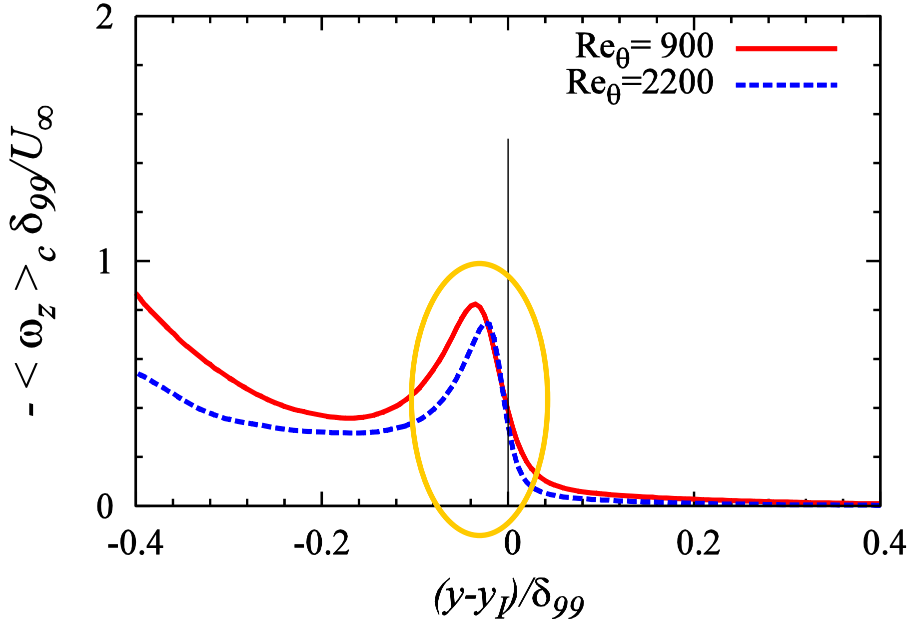
Thickness of the micro-scale vortices: $\ell_v \sim 10\eta$
(insensitive to their strength)

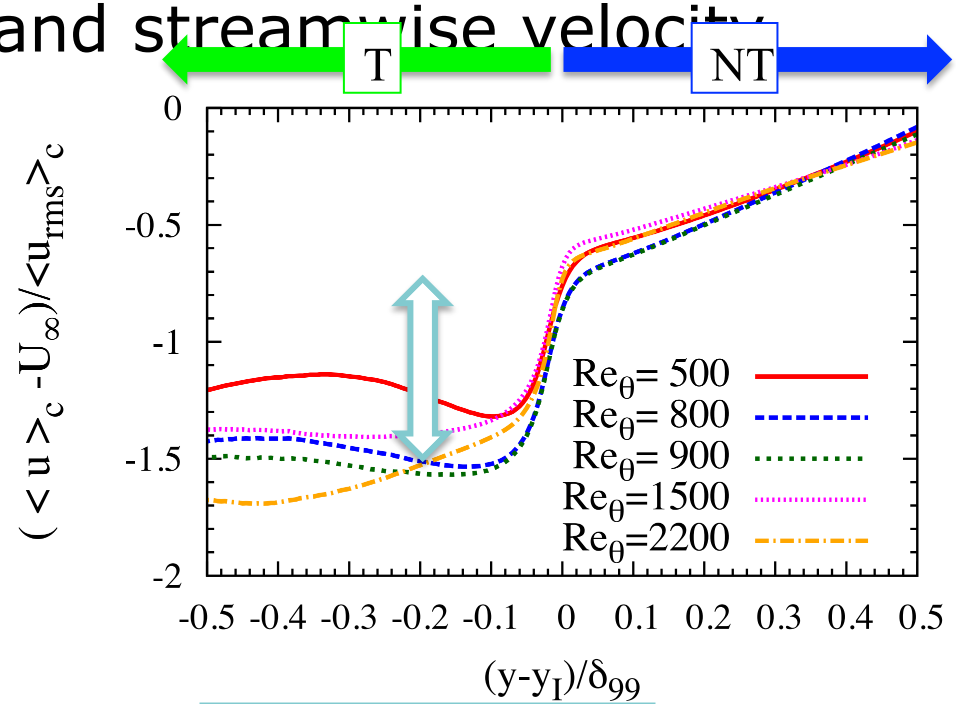
Very strong vorticity of $O(u_o/10\eta)$
$\gg u_{Kol}/\eta=1/\tau_{Kol}$ (K41)

Velocity jump of $O(u_o)$ over distances of $O(10\eta)$
$\gg u_{Kol} \sim u_o Re^{-1/4}$ (K41)

The layers may dominate the extreme point values of the statistical distributions of dissipation, velocity and vorticity fluctuations

Turb bl XIL T.Ishihara DNS The conditional averages of the spanwise vorticity and streamwise velocity





Note $\left\langle E_b' \cdot \Delta U' \right\rangle < 0$ – to be published)

$$\Delta U = O(u_{rms})$$

① Spanwise vorticity has a peak at the inside of the interface

cf. Bisset(2002), Da Silva(2008), Westerweel(2009)

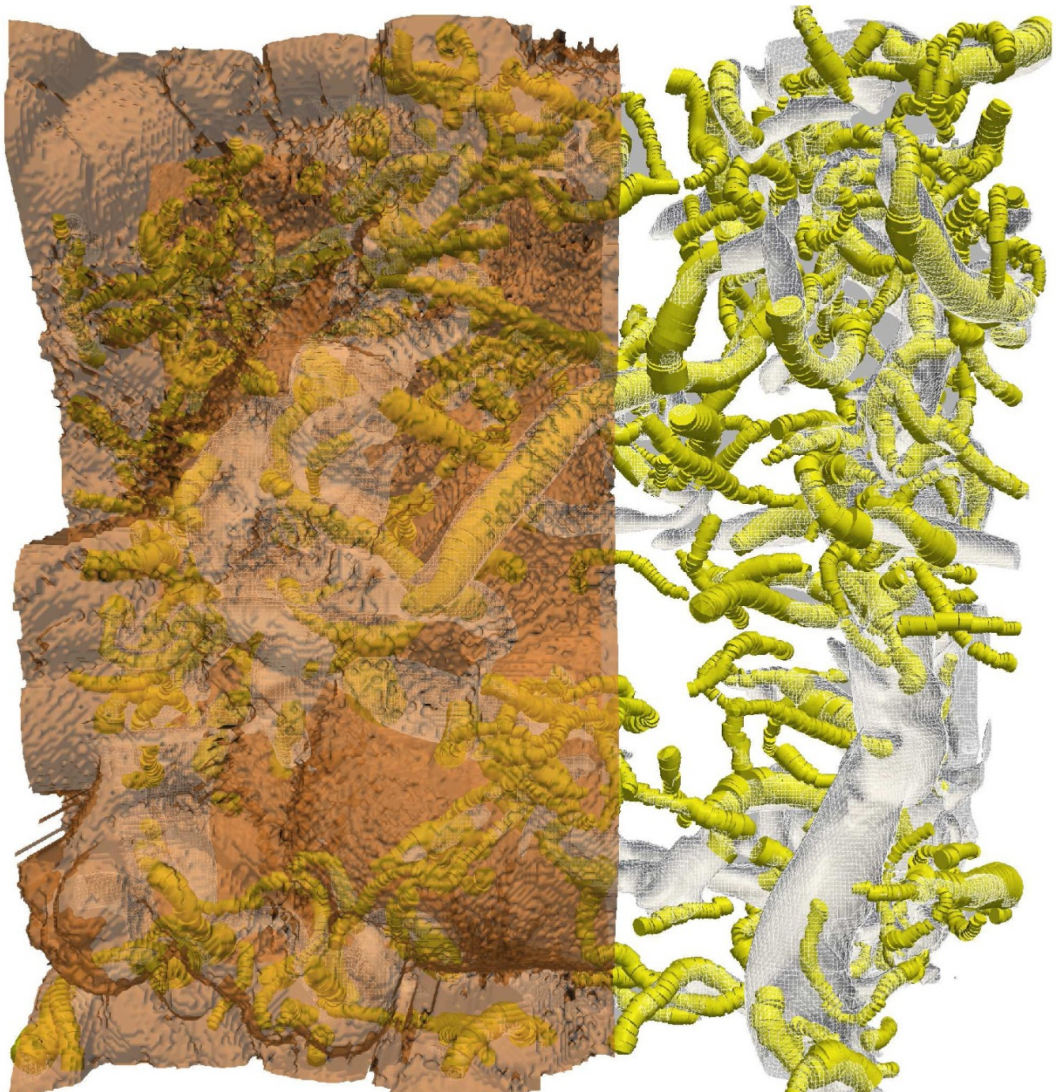
② There is a velocity jump near the interface

cf. Bisset(2002)

Interface structure at edge of layer

- From da silva's paper- thickness of l_{Kol}

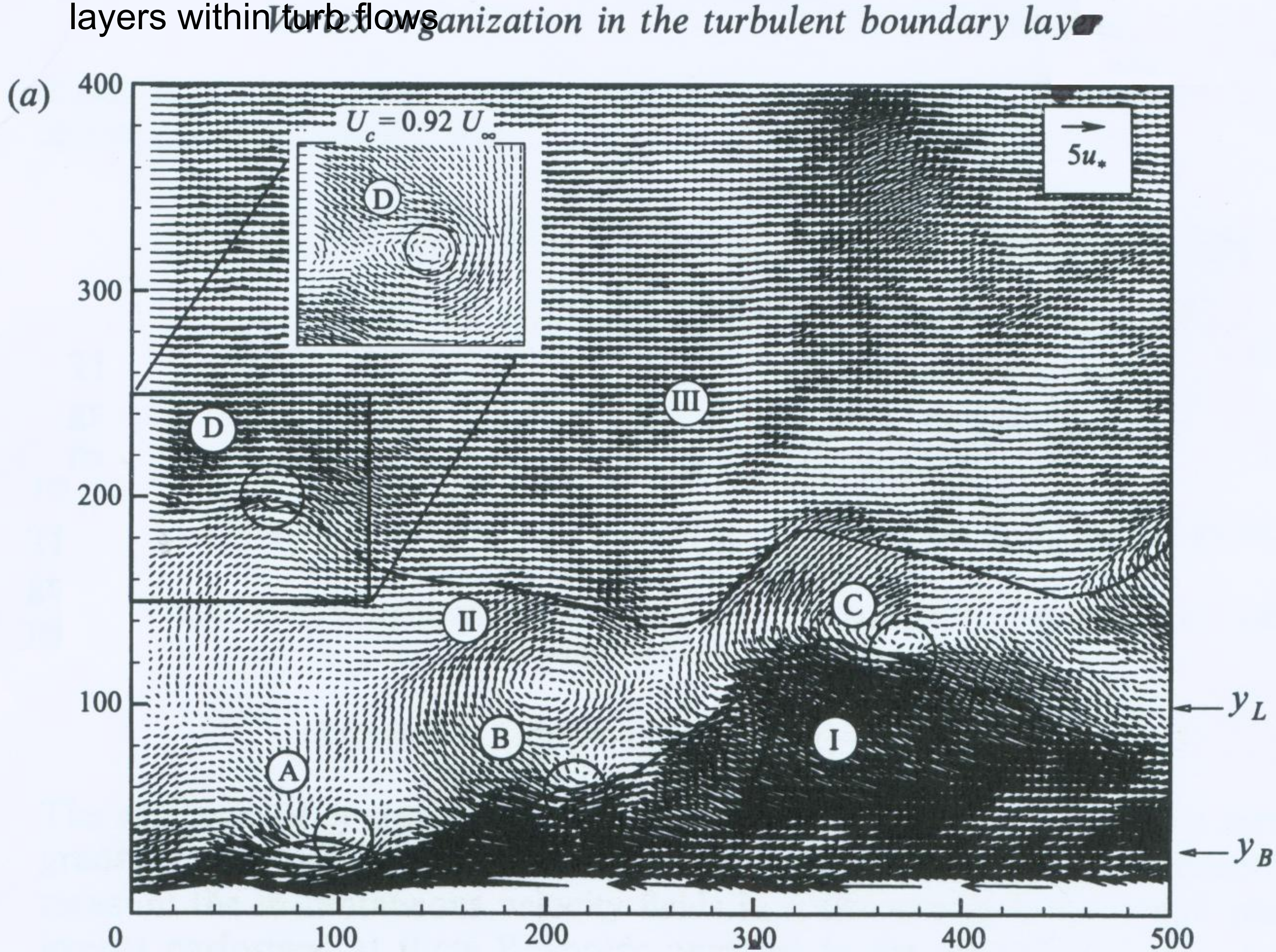
Thick
ness
Of
layer
$-l \sim \lambda$



Smallest
Scales

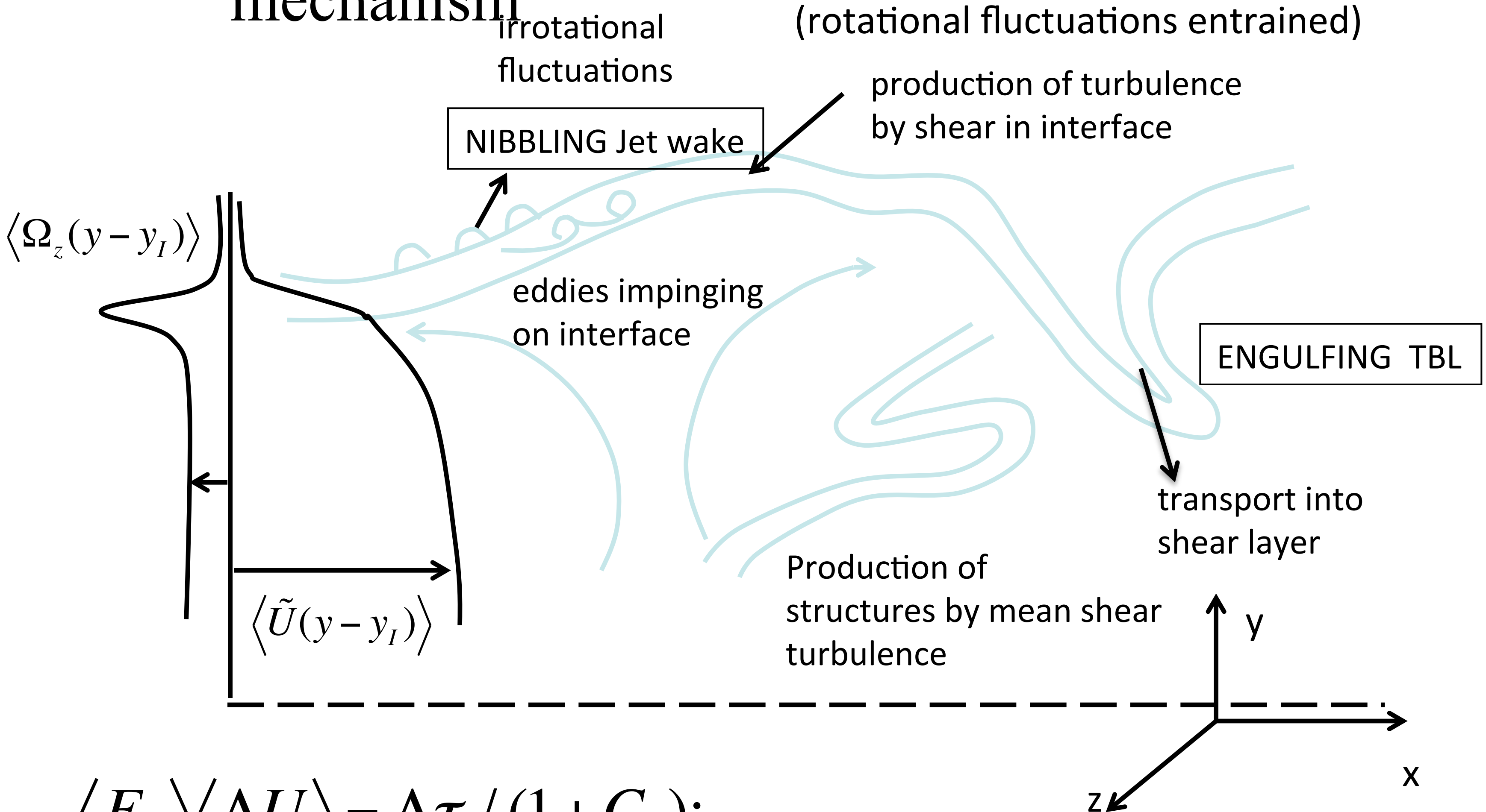
$- l_{\mathrm{Kol}}$
$l / \sqrt{R_\lambda}$

Adrian Eisma –DNS –shows interfacial shear layers within turb flows



Sharp interface at top of neutral bl. (Expts- also numerical -Ishihar

External –Internal/ interfacial layer +local dynamics → 'boundary entrainment mechanism'



$$\langle E_b \rangle \langle \Delta U \rangle = \Delta \tau / (1 + C_e);$$

$$C_e = \langle E_b' \cdot \Delta U' \rangle / \langle E_b \rangle \langle \Delta U \rangle; \quad \text{Note } C_e < 1 \quad \text{in turb bl}$$

$$|C_e| << 1 \;\; \text{nibbling M-B; W,} \; |C_e| \sim 1 \;\; \text{engulfing; (TI)}$$

Conditional Profiles Jet Interface

Mean Vel $\frac{\langle \Delta U \rangle}{U}$

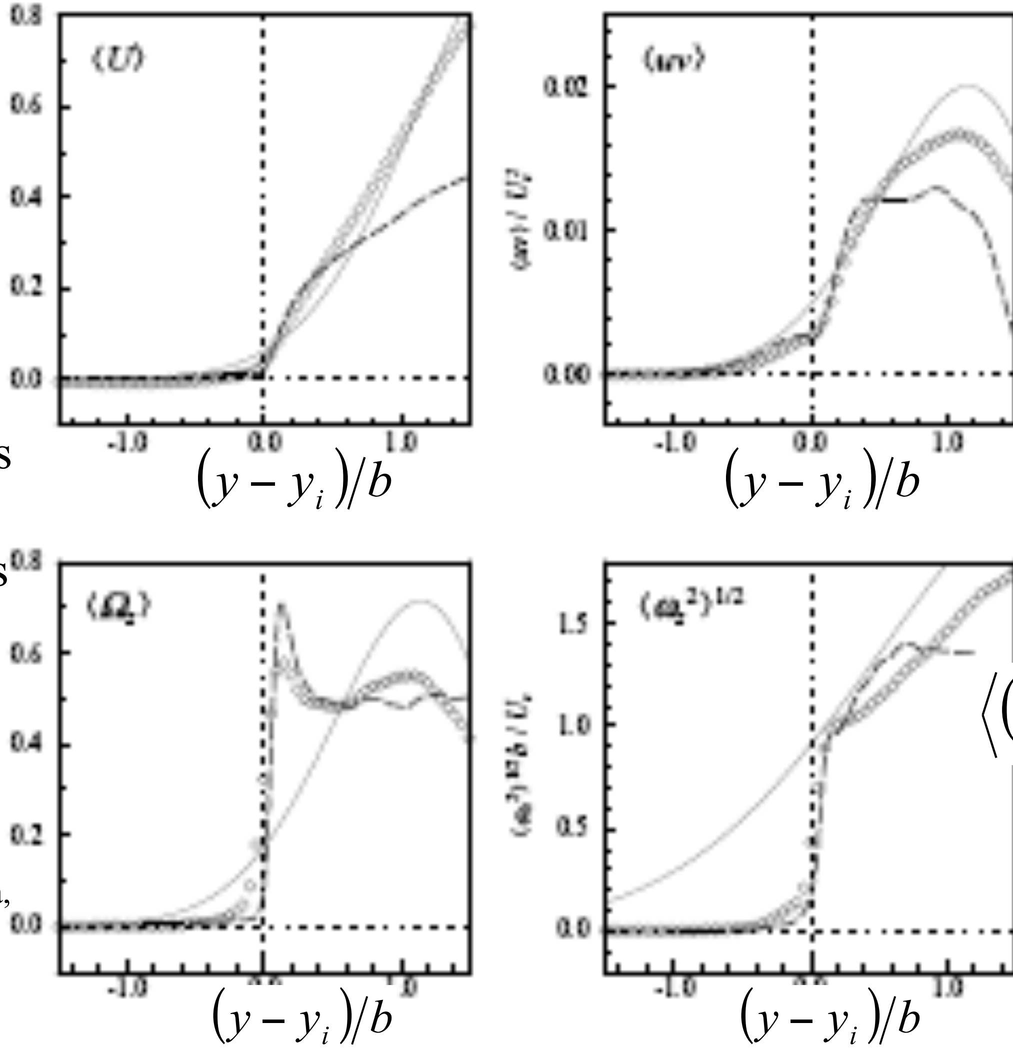
Vorticity

Reynolds stress

Vorticty fluctns

$\frac{\langle \Omega \rangle}{bU_0}$

Westerweel, Fukushima, Pedersen, Hunt



$\frac{\langle \Delta \tau \rangle}{u^2}$

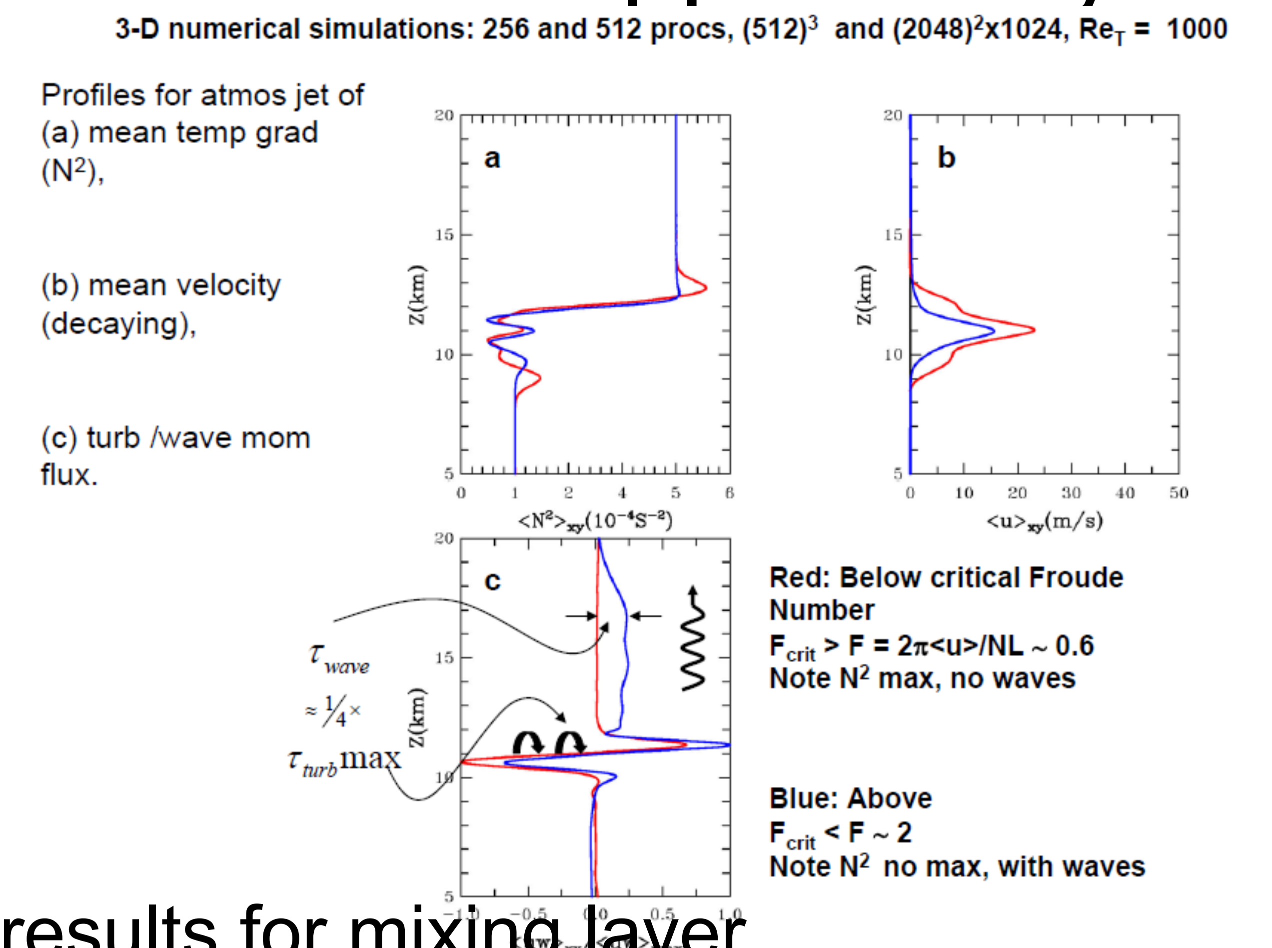
$\left\langle (\Delta \omega)^{1/2} \right\rangle$

Shows Similar Cond Profiles For Jet (expt) Averaged Wake(sim

Thickness of layer is Taylor microscale $L/\sqrt{\mathrm{Re}}$

but internal vortices thickness $L/\mathrm{Re}^{3/4}$ = Kol microscale - (da silva DNS)

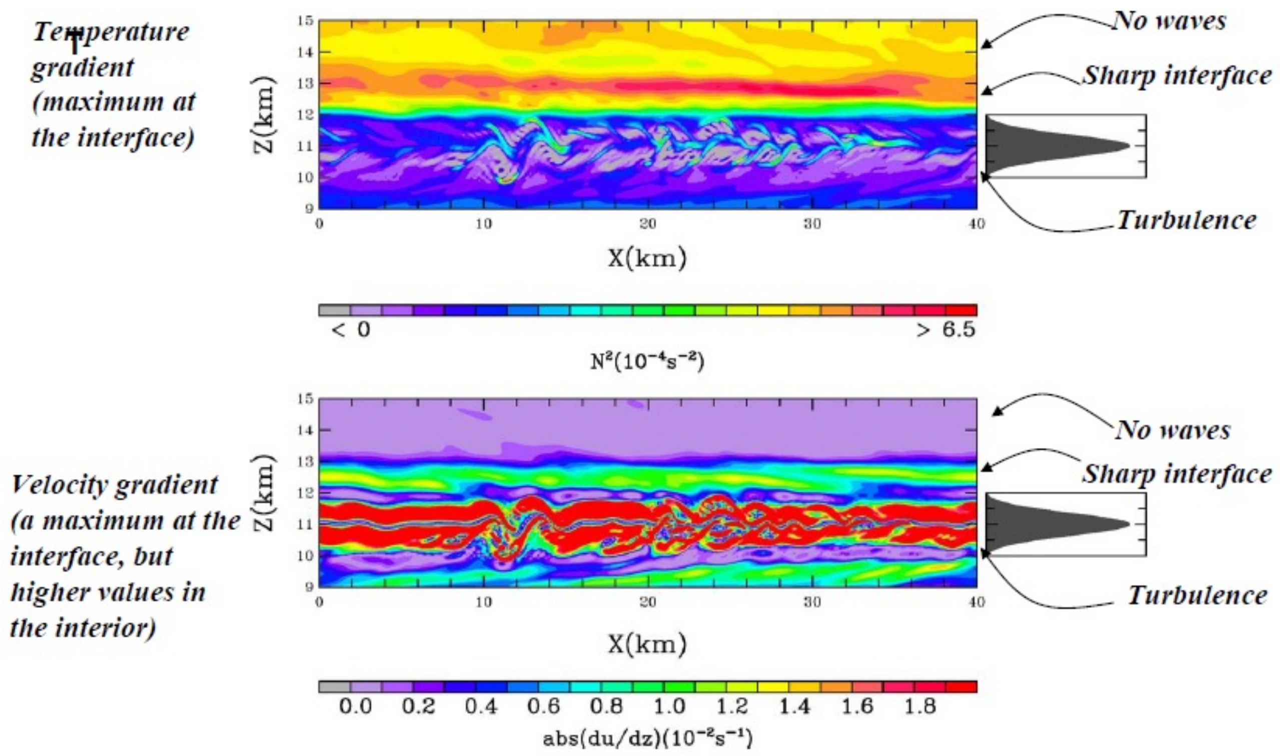
Shear + turb.Interface below stratified layer -3D comput'n with interface approxn by M M



Similar results for mixing layer

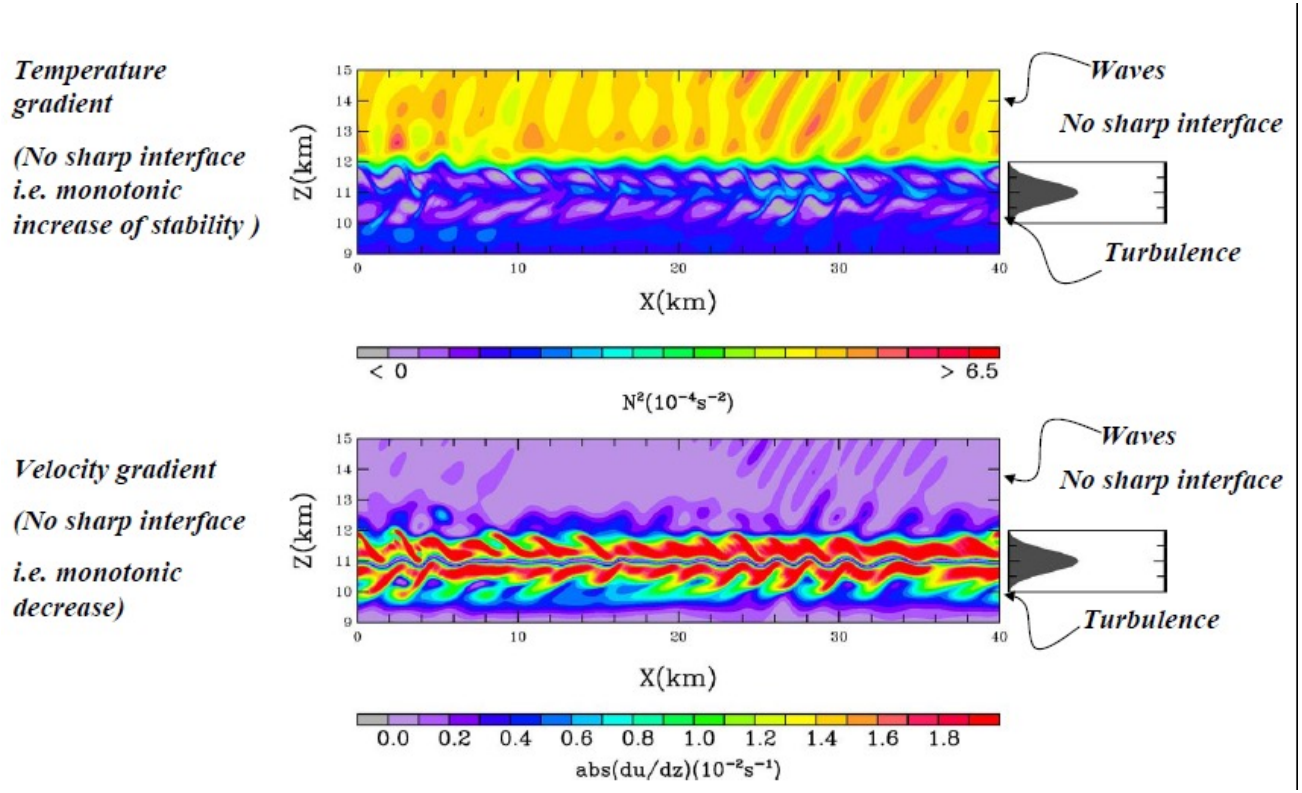
$U(z) \sim U_o H(z)$

Instantaneous fields and gradients for moderate Ri and no significant waves



Double Inversion layer-like stratus/tropopause?

Fields and gradients with higher Ri with significant wave motion.

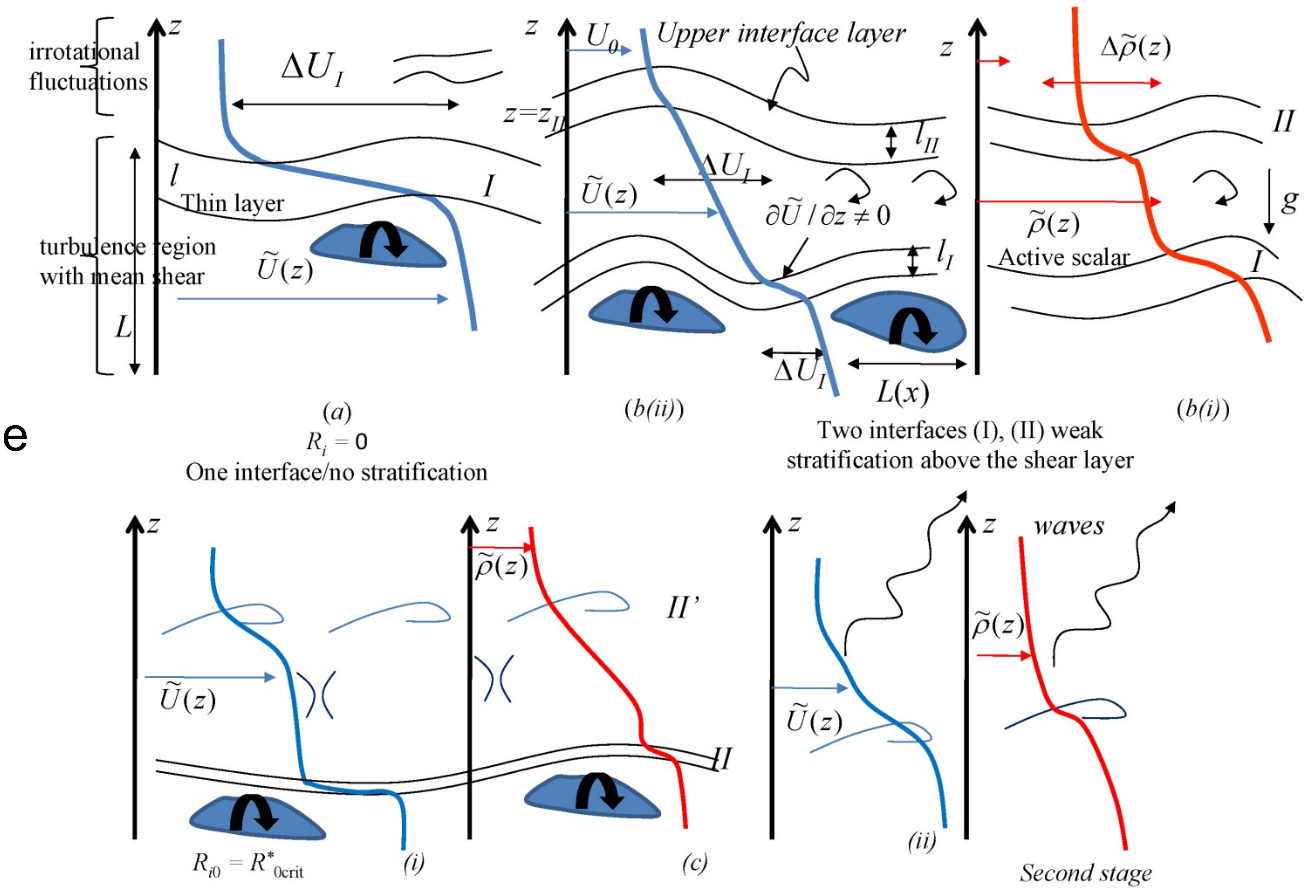


Note signifricant

Weak stratification(Ri<Ri')=0), moderate(Ri'<Ri<Ri*); transition (Ri~Ri*)

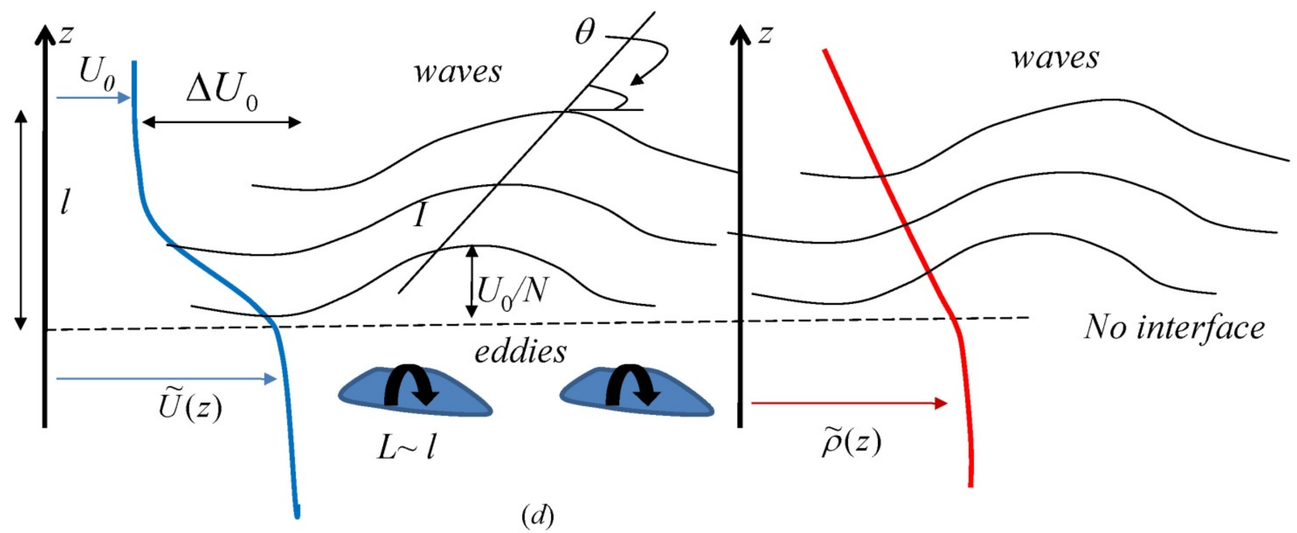
Randell
Et al 2007
Double
Tropopause
 Trapped
pollution

Stratus
Layer
Dynamics
(add
to thermo
Dyn)

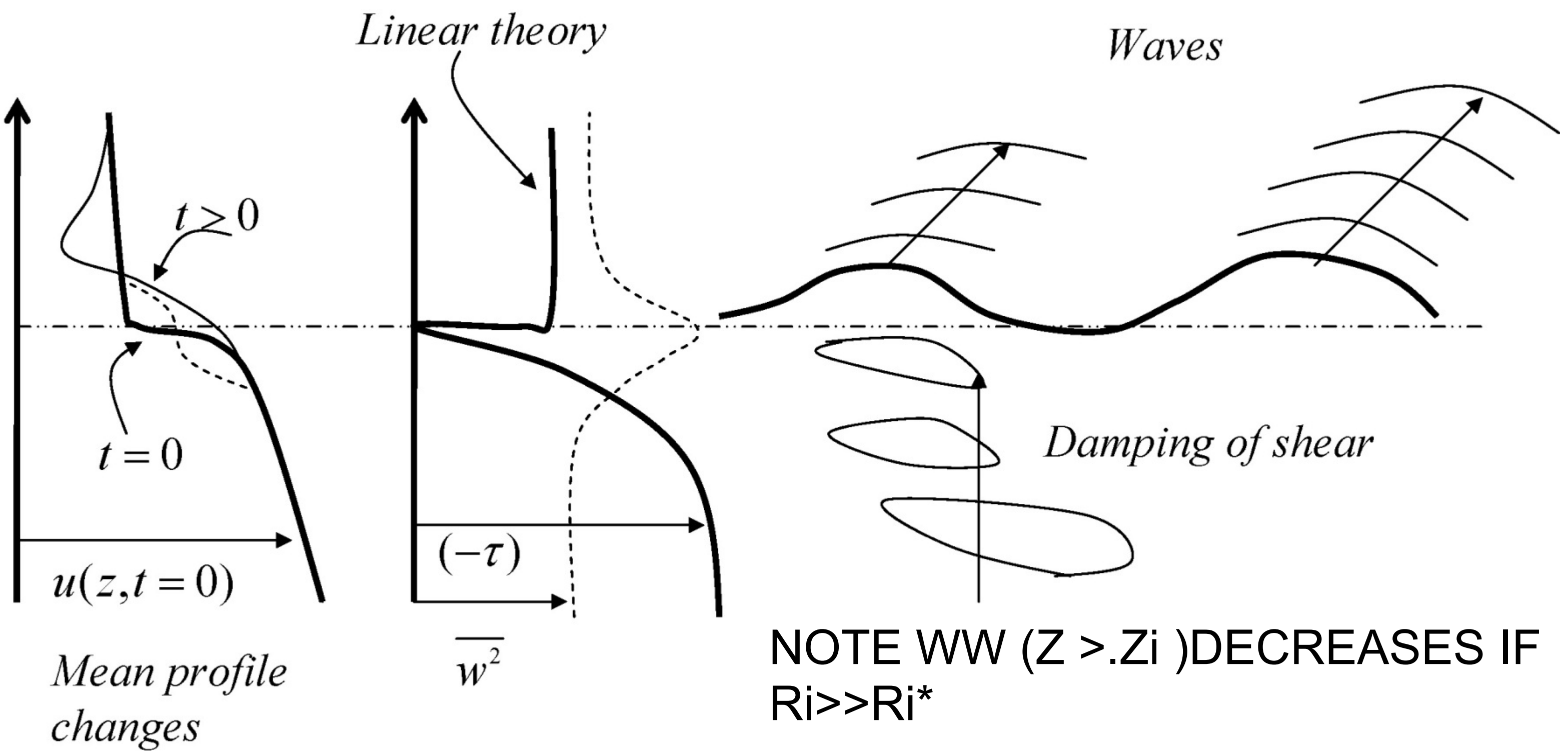


(c) Transition from strong interface to waves –stage (*i*) upper interface (*II*) breaks up
- stage (ii) waves form above I and I thickens.

Eddies near shear interface
Ri> Ri*-smooth turb-wave transition



Profiles of vertical turbulence and shear stress when waves are generated in the upper region

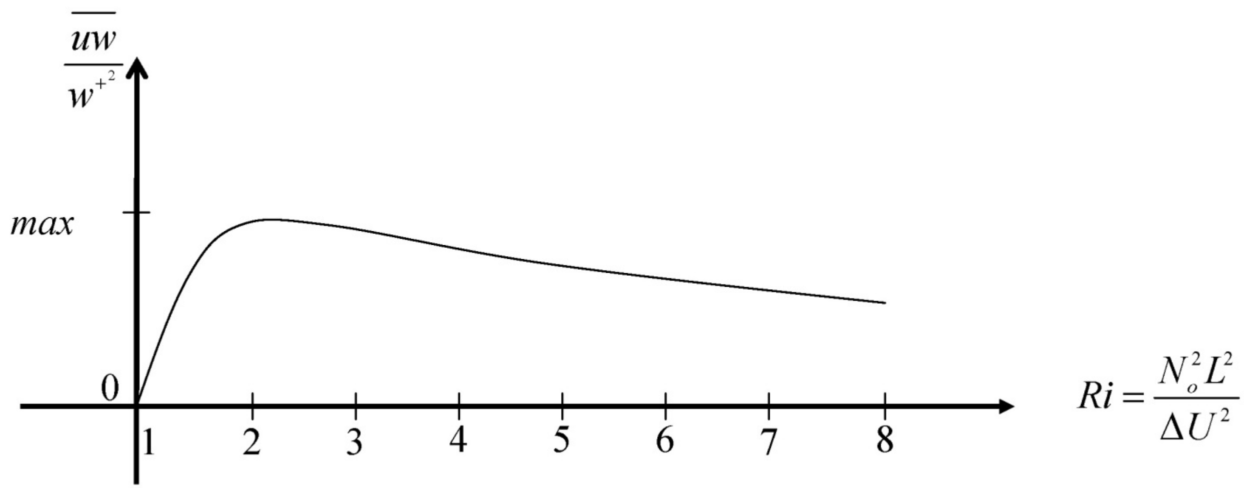


NOTE WW (Z >.Zi)DECREASES IF Ri>>Ri*

Showing the profiles of vertical turbulence and shear stress when waves are generated in the upper regions i.e. $Ri = N_o L/\Delta U$

NOTE Ri >Ri* ; profiles change with non-linear effects –see DNS results

Wave shear stress-normalised on turb in shear layer-RDT model $\sim\mu/(1+\mu^2)$;μ=sqrt(Ri/Ri*-1)

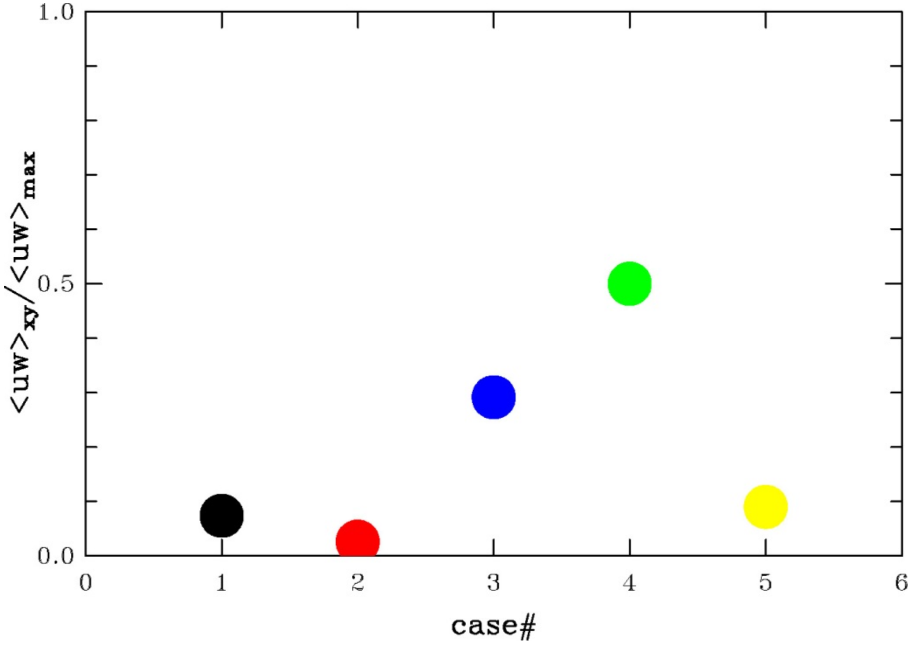


Variation of the normalized wave Reynolds stress with Ri for Ri > Ri = 1*

Shear stress in wave region above shear layer as Ri (>Ri*) increases. Note peak value at certain Ri.

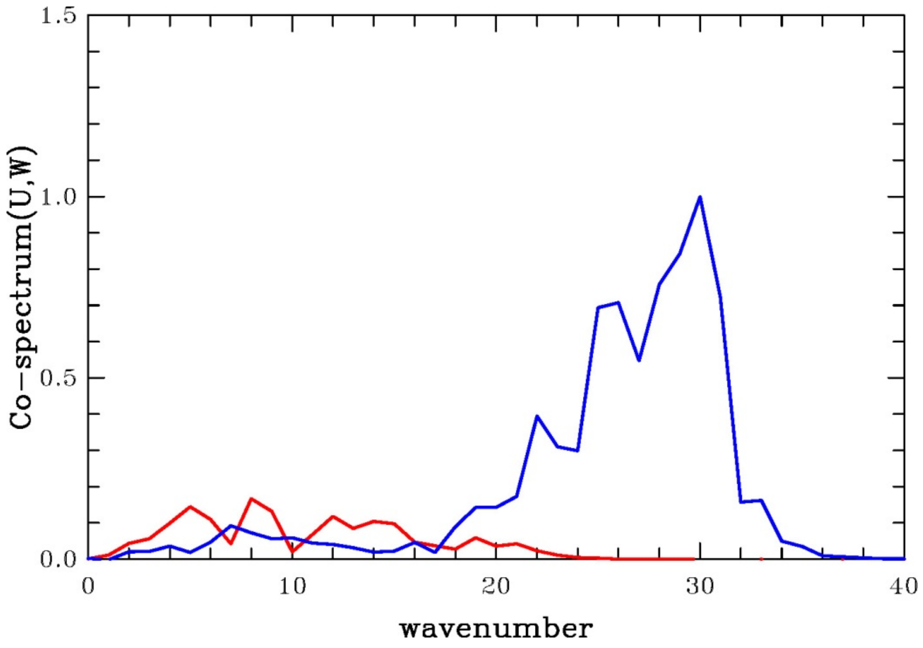
STRESS(Z)/

STRESS(Zi)



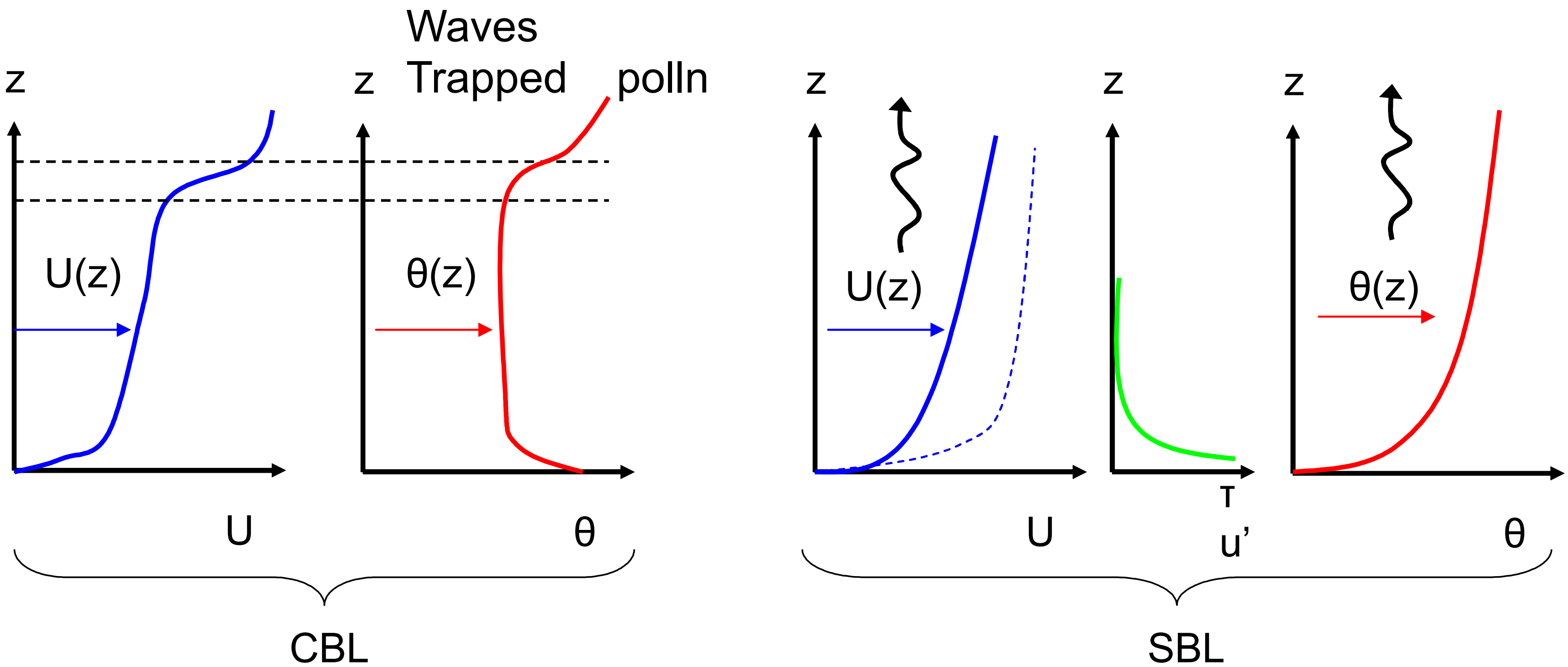
Ri --→

Cospectrum of shear-stress waves for moderate and strong stratification (Z>Zi) as Ri changes



Ri < Ri* -red –no significnt waves; Ri > Ri* (x4) waves on scale of shear layer

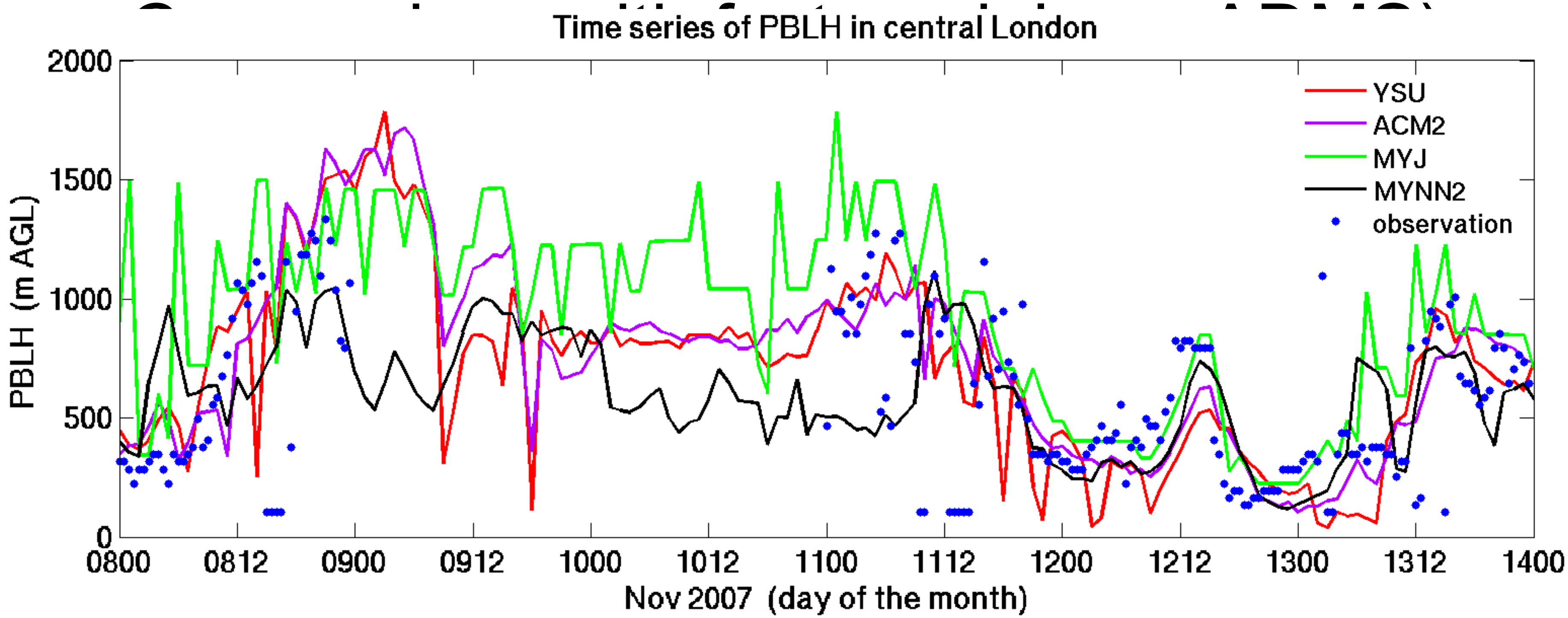
Boundary layers with stably stratified inversion layers



ATM BL –TURB SHEAR LAYER BELOW Zi ; STABLE REGION ABOVE Zi- DRIVEN BY PRESSURE FIELD –BUT AFFECTED BY WAVES-IN STRATOSPHERE.---ALSO AVALANCHES

OCEAN ML-TURB SHEAR LAYER ABOVE Zi; STABLE REGION BELOW Zi;DRIVEN BY INTERNAL WAVES FROM SHEAR LAYER(NOT IN GCM ?!)

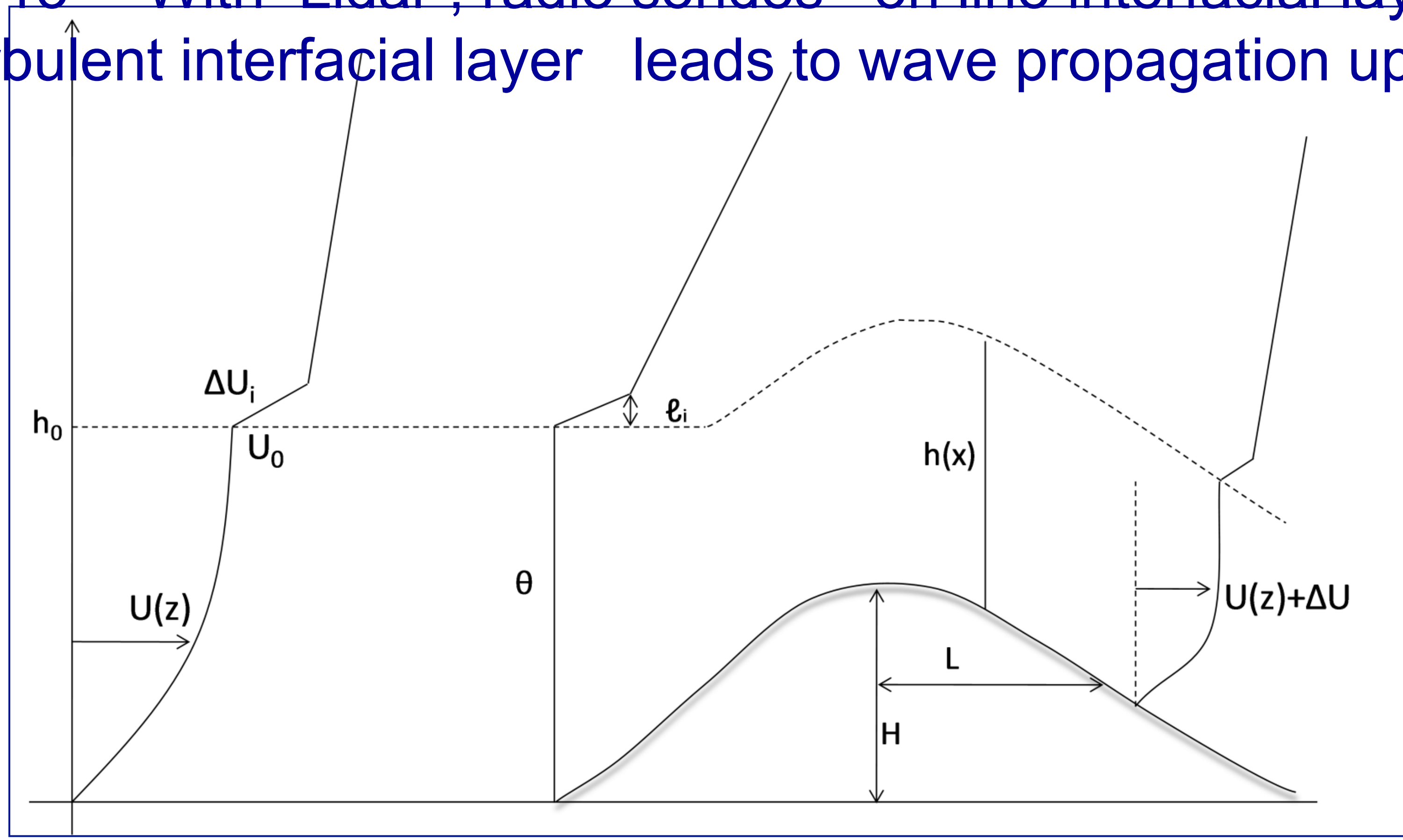
- Interfacial layer -Mixing height h for Atm BL   large changes in diurnal structure ; critical for dispersion and concentration. (numericalmodelling; BT Tower obs)



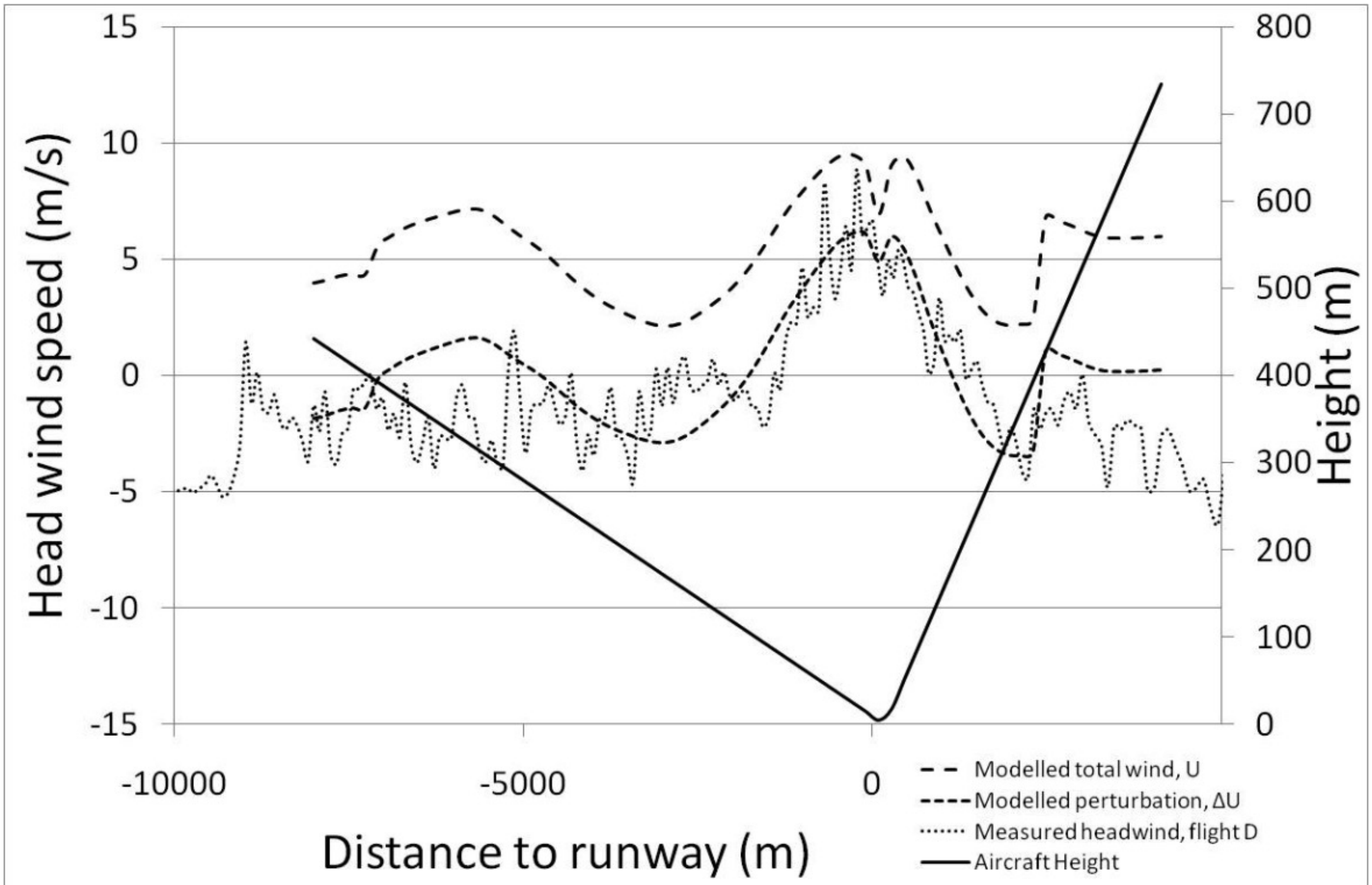
Essential concept of adms, aermod is to represent abl parameters as functions of z/ h and h/L $_{MO}$; Xie bo et al 2013 (cerc, hk, reading) J Geo Res (atm) 118

Schematic of Inversion /shear layer flow over mountains: application of idealised (thin layer) perturbation modelling for 800 m terrain near Hong Kong International airport Carruthers et al 2013 -*With Lidar , radio sondes –on line interfacial layer

*Turbulent interfacial layer leads to wave propagation upwards



Perturbation to head wind speed and total head wind compared to Aircraft Measurement φ =140°, h0=400m, ΔT=7.19°C- on line application



Modelling and computation of flow within and near interfaces