Surface Fluxes for Practitioners
Global Ocean Data Assimilation

"OBSERVATIONS"

Accuracy, Global, Near real time, Specified error

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OUTLINE : PART I

- Introduction
- The Ocean Surface Flux Problem
  - air-sea fluxes
  - ice-ocean fluxes
  - air-ice fluxes
- Measurements of Turbulent Air-Sea Fluxes
  - eddy covariance
  - inertial dissipation
- Bulk Aerodynamic Formulae
  - bulk flux estimates

OUTLINE PART II

- Satellite Flux Estimates
  - wind stress
  - radiation
  - precipitation
- A Merged Flux Climatology (NWP Re-analyses)
  - corrections
  - mean balances
- Variability of Ocean Surface Fluxes
  - annual cycle
  - interannual to decadal

1. Introduction

As with WGASF, primarily concerned with :

Q, the net surface heat flux into the ocean

F, the net surface freshwater flux into the ocean

$\tau = (\tau_\lambda, \tau_\phi)$, the horizontal stress vector

WGASF: Intercomparison and validation of ocean-atmosphere energy flux fields. Joint WCRP/SCOR Working Group on Air-Sea Fluxes, WCRP-112, WMO/TD-No. 1036, November 2000.

Other Ocean Surface Fluxes of Interest

- Gas fluxes (O_2, CO_2, CFCs, …….)
- Kinetic Energy = $\tau \bullet \mathbf{U_o}$
- Buoyancy = B_o = $g(\alpha Q + \beta F)$ [turbulence]
- Density = D_o = $-(\alpha Q + \beta F)$ with surface density → water mass transformation

The Global Constraints (the good news)

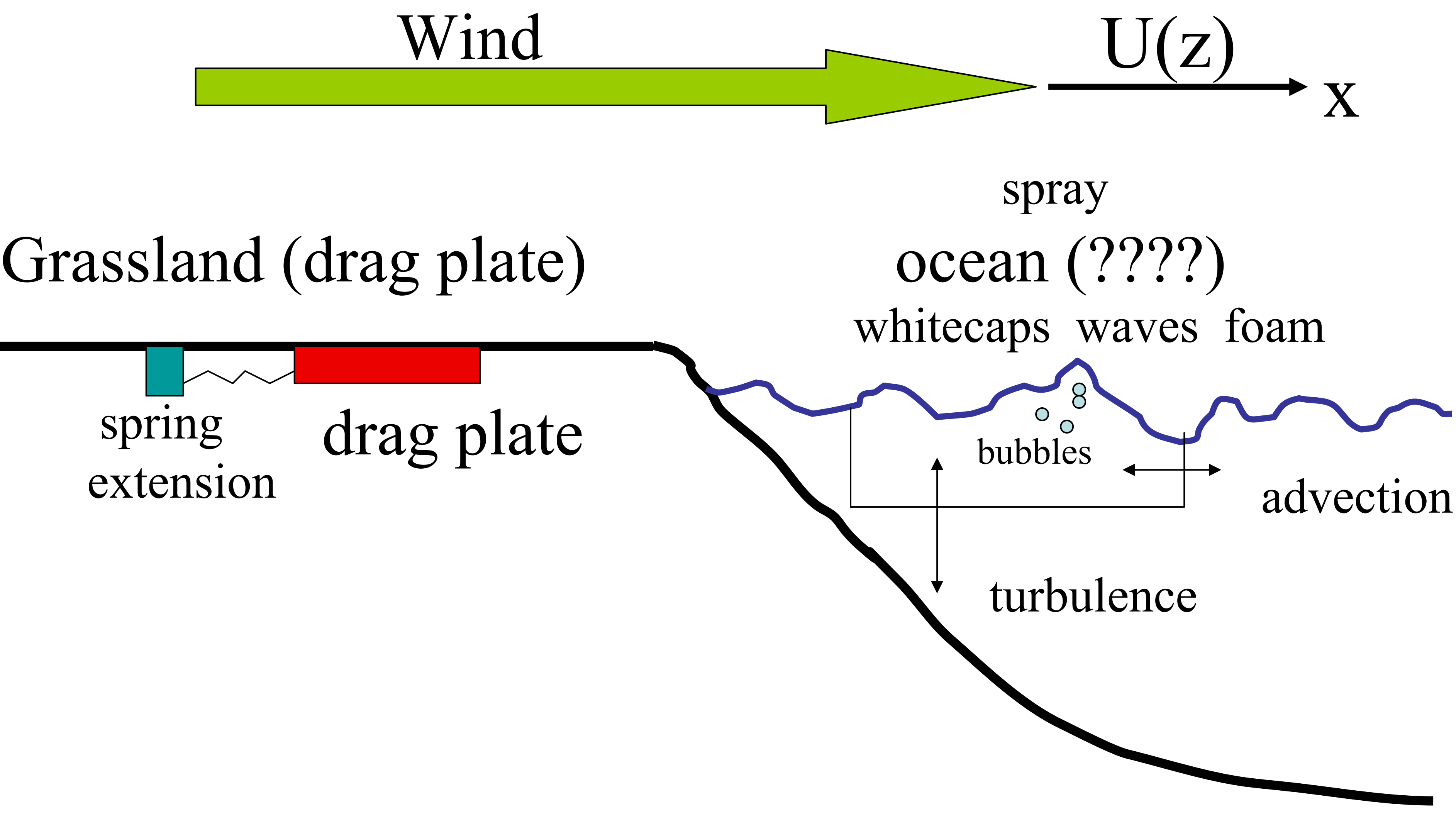
- The climatological net heat flux into the global ocean is ~0 W/m^2, to within order 1 W/m^2.
- The corresponding net freshwater flux is also near zero, to within order 1 $mg/m^2/s$.
(1 $mg/m^2/s$ ~0.085mm/day ~.25mm/mo ~3cm/year)

(1 $mg/m^2/s$ freshwater and 1 W/m^2 heat flux produce about the same density (buoyancy) flux.)

2.0 The Ocean Surface Flux Problem (the bad news)

- Uncertainty explodes at smaller scales
- Not directly Observed
- Must work at height above the surface
- High latitude sea-ice
- Proliferation of Data Sets

Turbulent Atmospheric Planetary Boundary Layer



Fluxes at height, h, are not equal to surface flux

Horizontally homogeneous flow with U aligned downstream :

$$\rho\, \partial_t U = \partial_z \tau(z) - \partial_x P_o$$

Geostrophic winds aloft, U_g

$$\rho \; f \; U_g = \partial_n \; P_o \quad ; \quad U_g = 1.3\ U\ @\ 16° \text{ rotation}$$

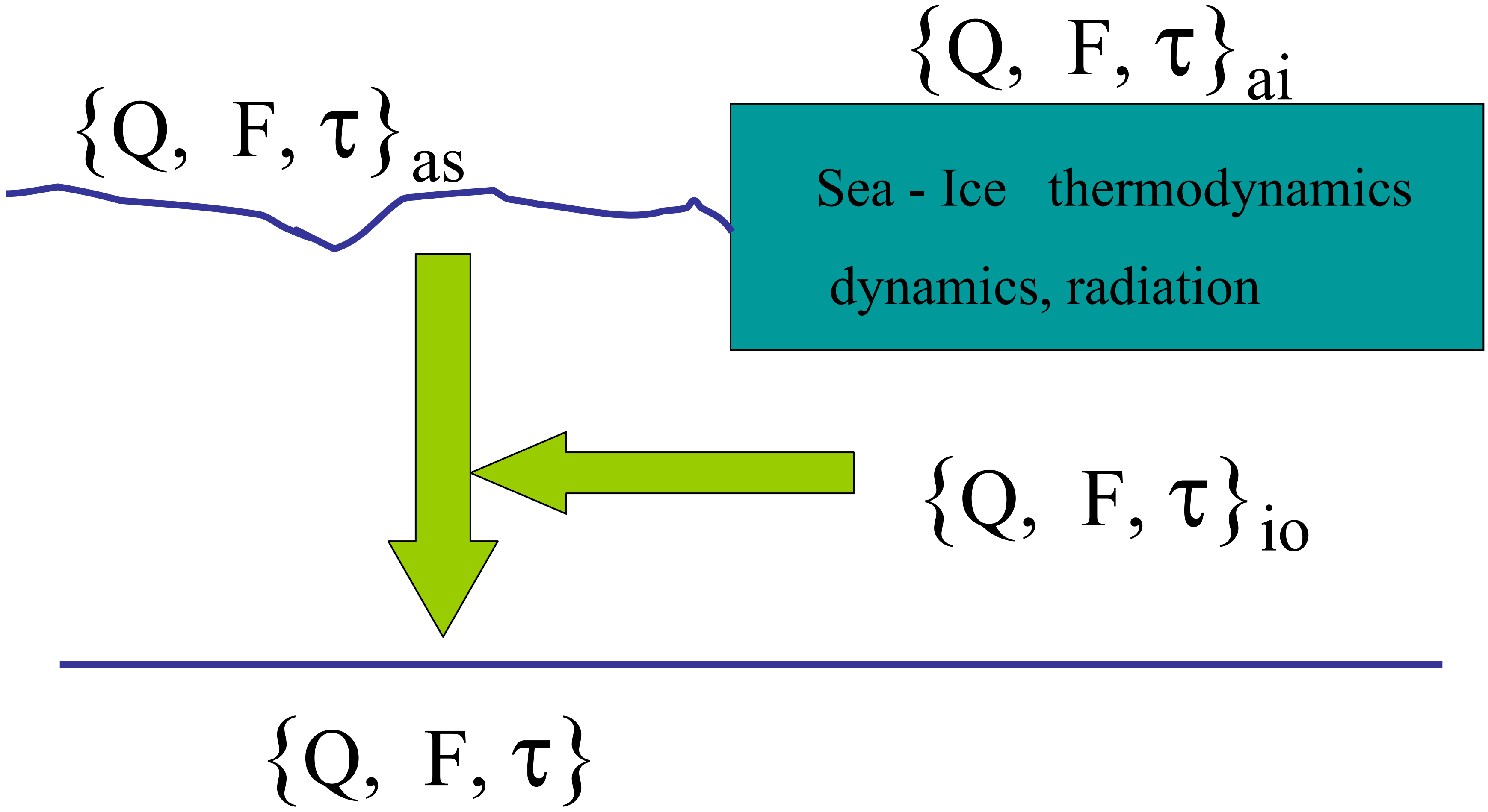
Steady Wind

Percent error $\quad \delta = -130\ h\ f\ \sin(16°)\ (\rho\, U / \tau_o)$

$$= -4 s^{-1}\ h\ /\ U$$

Falling Wind ?????? Rising Wind ??????

High latitude sea-ice



$4 \rightarrow 9$ fields

$$Q = f_o \, Q_{as} + f_i \, Q_{io}$$

$$F = f_o \, F_{as} + f_i \, F_{io}$$

$$\tau = f_o \, \tau_{as} + f_i \, \tau_{io}$$

$$f_o = 1 - f_i$$

2.1 Air - Sea Fluxes : $2 \rightarrow 9$ fields

$$Q_{as} = Q_S + Q_L + Q_E + Q_H + Q_P$$

$Q_P \rightarrow -\Lambda_f P_S$

$Q_L \rightarrow Q_A - \varepsilon \sigma (SST)^4$

$Q_S \rightarrow Q_I \; [\, 0.6 \,(1 - \alpha_{dr}) + 0.4 \,(1 - \alpha_{df}) \,]$

$$F_{as} = E + P$$

$P \rightarrow P_R + P_S$

$E \rightarrow Q_E \; \Lambda^{-1}$

2.2 Ice - Ocean Fluxes : $2 \rightarrow 6$ fields

$$Q_{io} = Q_M + Q_F + Q_B + Q_{PS}$$

- Q_{PS} → Penetrating Solar
- Q_B → Basal ice formation
- Q_F → Frazil ice formation
- Q_M → Melt

$$F_{io} = F_M + F_F + F_B$$

Ice - Ocean Fluxes :

$$Q_F = -\Lambda_f \; F_F = \rho_o \, c_p \, (T_f - SST) \, \Delta_1 / \Delta t$$

Other melt/freeze terms are ice modeling issues, including the physics that sea water freezes at lower temperature, T_f, than it melts.

Ocean model numerics are known to produce spurious temperatures much lower than freezing,

2.3 Air - Ice Fluxes : 2$\rightarrow$ 8n + 2 fields

$$Q_{ai}^{n} = (Q_S + Q_L + Q_E + Q_H)^{n} + Q_P$$

$Q_P \rightarrow -\Lambda_f P_R$

$Q_L \rightarrow Q_A - \varepsilon\, \sigma\, (SIT^{n})^{4}$

$Q_S \rightarrow Q_I\ [\, 0.6\, (\, 1 - \alpha_{dr}^{\;n}) + 0.4\, (1 - \alpha_{df}^{\;n})\,]$

$$F_{ai}^{n} = E^{n} + P$$

$P \rightarrow P_R + P_S$

$E^{n} \rightarrow Q_E\ \Lambda^{-1}$

Q	Q_{as}	Q_S	Q_I		SW↓
			α		albedo
		Q_L	QA		LW↓
			SST_S		SkinSST
		Q_E*		q	humidity
		Q_H*		θ	temp
τ	τ_{as}*			**U**	wind
				SLP	pressure
				SST_B	BulkSST
F	F_{as}	P	P_R		Rain
			P_S		Snow
			R		Runoff
		E*			Evap

3. Measuring Turbulent Air-Sea Fluxes

Monin - Obukhov Similarity Theory for turbulent flow in the atmospheric surface layer above the direct influence of the boundary and below where large scale synoptic features influence the flow. Over the ocean the layer is ($\sim$1m $<$ z $<$ $\sim$100m)

HYPOTHESIS : The turbulence knows only the surface fluxes and height, z.

Dimensional analysis → the turbulent scales :

$$u^* u^* = |\tau| / \rho$$

$$u^* \theta^* = Q_H / (\rho C_p)$$

$$u^* q^* = E / \rho = Q_E / (\rho \Lambda)$$

Dimensional analysis $\rightarrow$ the turbulent scales :

$$u^* u^* = |\tau| / \rho$$

$$u^* \theta^* = Q_H / (\rho C_p)$$

$$u^* q^* = E / \rho = Q_E / (\rho \Lambda)$$

$$L = u^{*3} / (\kappa B_o)$$

$$B_o = g u^* [\theta^* / \theta_v + q^* / (q(z) + .608^{-1})]$$

$$\theta_v = \theta(z) (1 + .608 q(z))$$

$$\zeta = z/L$$

Dimensionless Profiles

$$\kappa\, z\, \partial_z U \;/\; u^* \;=\; \phi_m(\zeta) \;:\; \phi_m(0) = 1;\;\; \kappa = 0.4$$

$$\kappa\, z\, \partial_z \theta \;/\; \theta^* \;=\; \phi_s(\zeta) \;:\; \phi_s(0) = 1$$

$$\kappa\, z\, \partial_z q \;/\; q^* \;=\; \phi_s(\zeta)$$

$$\phi_m = \phi_s \sim 1 + 5\,\zeta \quad ; \quad \zeta > 0 \quad \text{stable}$$

$$\phi_m^{\,4} = \phi_s^{\,2} \sim (1 - 16\,\zeta)^{-1} \quad ; \quad -1 < \zeta < 0 \quad \text{unstable}$$

"Logarithmic Profiles"

$$U(z) = SSU + u^*/\kappa \; [\ln(z/z_0) - \psi_m(\zeta)]$$

$$\theta(z) = SST + \theta^*/\kappa \; [\ln(z/z_\theta) - \psi_s(\zeta)]$$

$$q(z) = SSQ + q^*/\kappa \; [\ln(z/z_q) - \psi_s(\zeta)]$$

$$\psi(\zeta) = \int_0^\zeta [1-\phi(\xi)] \, \xi^{-1} \, d\xi$$

$z \rightarrow 0$????? $(\ln (z+z_0)/z_0)$???

3.1 Eddy Covariance

"semi direct" $x=\{u,\theta,q\}$

$$u^* x^* = \int_{k1}^{k2} \Phi_{wx}(k)\, dk = \int_{f1}^{f2} \Phi_{wx}(f)\, df$$

Issues - non-zero mean $\overline{W} \rightarrow \overline{W}\,\overline{X}$ contribution

3.1 Eddy Covariance

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Issues - non-zero mean $\overline{W}$ → $\overline{W}\,\overline{X}$ contribution

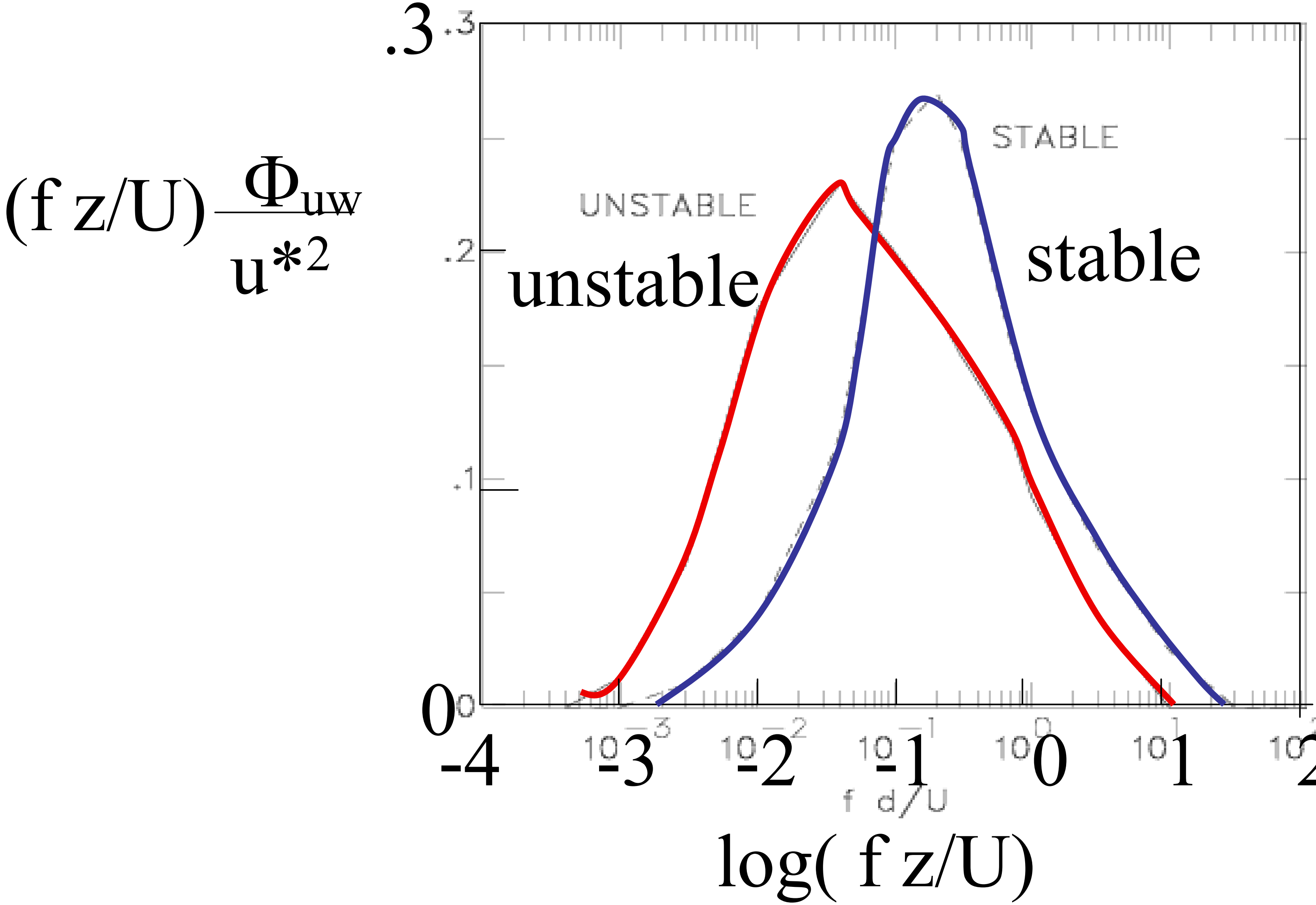
-$\Phi_{wx}(f)$ are universal in f d/U space, because eddies must fit within the distance, d, above the surface.

- f2 ≥ 30U/d to capture all the covariance

- f1 ≤ .0004U/d to capture the low frequency, which is highly scattered and can transcend flow regimes.

- fixed f1 and f2 →

Universal Cospectra



3.2 Inertial Dissipation

TKE budget, dissipation = production - buoyancy

$$\varepsilon = u*^2\,\partial_z U - B_o$$

$$u*^3 = \kappa\ z\ \varepsilon\ /\ [\phi_m(\zeta) - \zeta]$$

3.2 Inertial Dissipation

TKE budget, dissipation = production - buoyancy

$$\varepsilon \quad = \quad u^{*2}\, \partial_z U \quad - \quad B_o$$

$$u^{*3} \quad = \quad \kappa \; z \; \varepsilon \; / \; [\phi_m(\zeta) - \zeta]$$

Similarly, the scalar variance budgets, for N_θ and N_q the dissipation of scalar fluctuations, give

$$\theta^{*2}\, u^* \; = \kappa\, z \;\; N_\theta \;\, / \; \phi_s(\zeta)$$

$$q^{*2}\, u^* \; = \kappa\, z \;\; N_q \;\, / \; \phi_s(\zeta)$$

Kolmogoroff Inertial (-5/3) Subrange

Scales faster (smaller) than large scale energy sources, and slower (larger) than dissipation range.

Measure spectra of scalar fluctuations and of downstream velocity, which in this range depend only on the eddy size (wavenumber, $k = 2\pi f / U$, byTaylor's frozen turbulence hypothesis), and the total dissipation, ε.

Dimensional Analysis

$$\Phi_u(f) = K' \;\; \varepsilon^{2/3} \;\; (2\pi/U)^{-2/3} \;\; f^{-5/3}$$

$$\Phi_\theta(f) = \beta_\theta \;\; N_\theta \;\; \varepsilon^{-1/3} \;\; (2\pi/U)^{-2/3} \;\; f^{-5/3}$$

$$\Phi_q(f) = \beta_q \;\; N_q \;\; \varepsilon^{-1/3} \;\; (2\pi/U)^{-2/3} \;\; f^{-5/3}$$

Empirically $K' = 0.55, \quad \beta_\theta = \beta_q = 0.80$

$$.2\, U / z \;<\; f \;<\; 20\text{Hz}$$

$$5\, z \;>\; \lambda$$

4. Bulk Aerodynamic Formulae

$C_D = (u^*/\Delta U)^2$; $C_E = \sqrt{C_D}\, q^*/\Delta q$

$= (\kappa/[\ln(z/z_o)-\psi_m])^2$; $= \sqrt{C_D}\, \kappa/[\ln(z/z_q)-\psi_s]$

$C_{DN} = (\kappa/\ln(10m/z_o))^2$; $C_{EN} = \sqrt{C_{DN}}\, \kappa/\ln(z/z_q)$

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$= (\kappa/[\ln(z/z_o)-\psi_m])^2$; $= \sqrt{C_D}\,\kappa/[\ln(z/z_q)-\psi_s]$

$C_{DN} = (\kappa/\ln(10m/z_o))^2$; $C_{EN} = \sqrt{C_{DN}}\,\kappa/\ln(z/z_q)$

Use profile equations to eliminate roughness lengths :

Eg. $C_{DN} = C_D\,(1 + (\sqrt{C_D}/\kappa)\ [\ln(10m/z) + \psi_m])^{-2}$

$C_D = C_{DN}\,(1 - (\sqrt{C_{DN}}/\kappa)\ [\ln(10m/z) + \psi_m])^{-2}$

Formulating Bulk Transfer Coefficients

$$U_N^2 = u^{*2} / C_{DN} = (C_D/C_{DN})\,\Delta U^2$$

$$\theta_N = u^*\theta^*/(C_{HN}\,U_N) = (C_D/C_{DN})\,(\Delta U/U_N)\,\Delta\theta$$

$$q_N = u^*q^*/(C_{EN}\,U_N) = (C_D/C_{DN})\,(\Delta U/U_N)\,\Delta q$$

A Multiple Regression Formulation

$$u*^2 = a_0 + a_1 U_N + a_2 U_N^2 + a_3 U_N^3 + \ldots.$$

$$C_{DN} = a_1 / U_N + a_2 + a_3 U_N$$

$$a_1 = .00270\,; \quad a_2 = .000142; \quad a_3 = .0000764$$

$$z_0 = 10\text{m}\ e^{-\kappa/\sqrt{CDN}}$$

Roughness Length Formulations

Flow over Smooth surface :

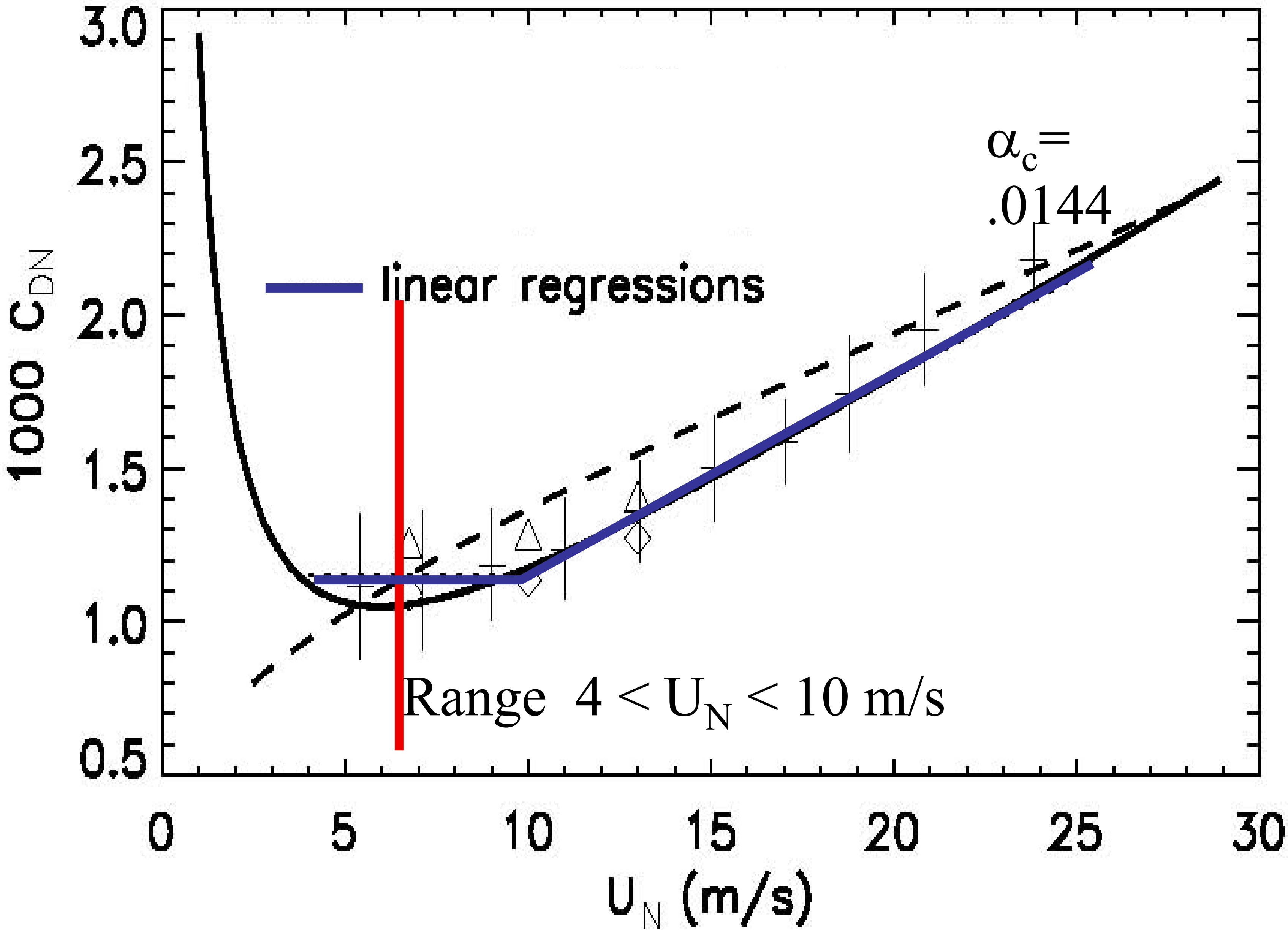
$$z_0\, u^*/\nu \;=\; \alpha_s \;=\; 0.11$$

Flow over waves governed solely by u* and gravity :

$$z_0\, g\,/\,u^{*2} \;=\alpha_c \;=\; 0.0144$$

???? Add $z_0 = \alpha_s\, \nu\,/\,u^* \;+ \alpha_c\, u^{*2}\,/\,g$

Versus $z_0 \;=\; 10\text{m}\;\; e^{-\kappa/\sqrt{\text{CDN}}}$



3.0
2.5
2.0
1.5
1.0
0.5
1000 C_DN
0
5
10
15
20
25
30
U_N (m/s)
linear regressions
αc=
.0144
Range 4 < U_N < 10 m/s

Stanton and Dalton Numbers

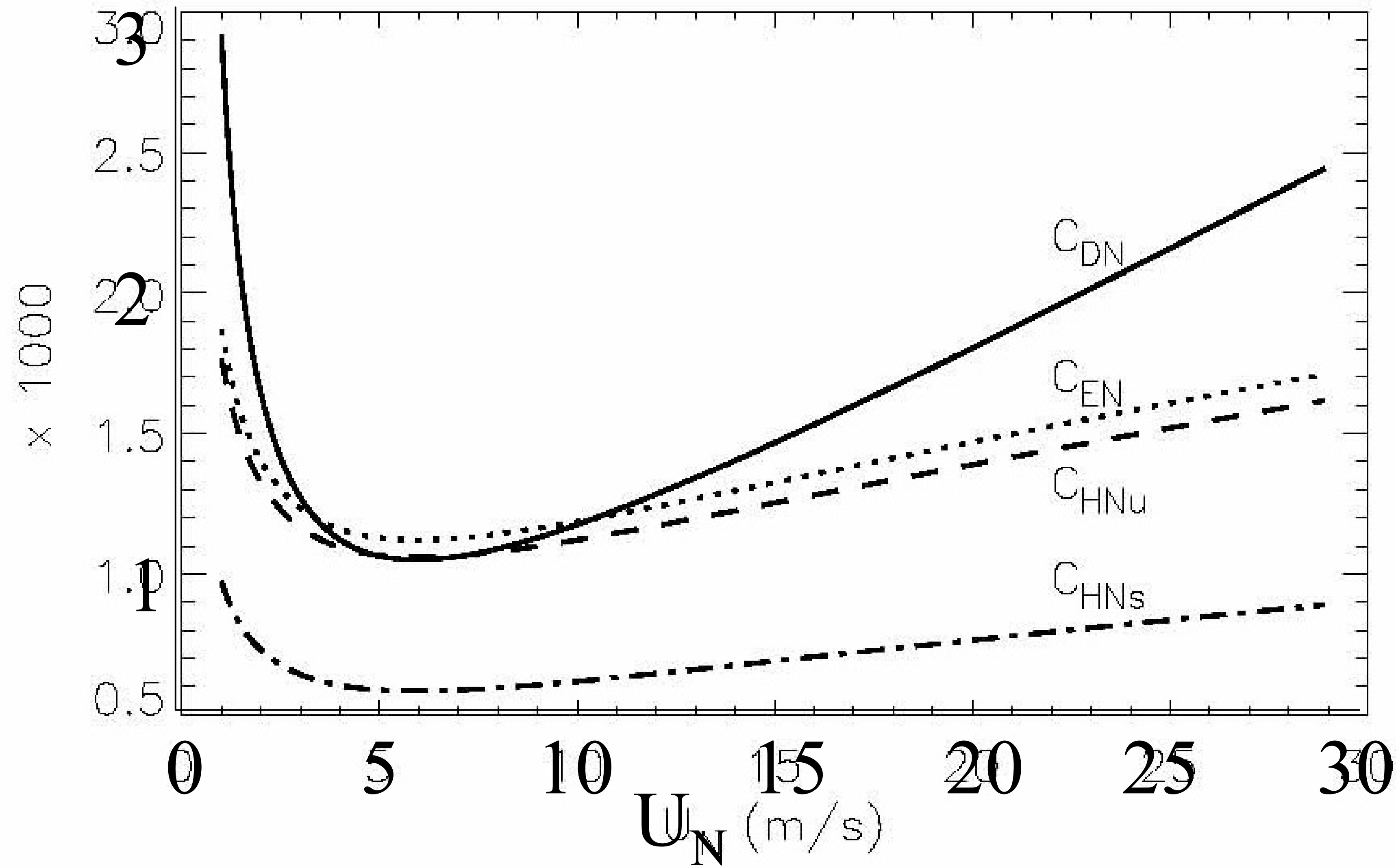
$C_E = \sqrt{C_D}\, q^*/ \Delta q$; $C_H = \sqrt{C_D}\, \theta^*/ \Delta\theta$

$C_{EN} = \sqrt{C_{DN}}\, \kappa/\ln(z/z_q)$; $C_{HN} = \sqrt{C_{DN}}\, \kappa/\ln(z/z_\theta)$

$\kappa/\ln(z/z_q) = 0.0346$

$\kappa/\ln(z/z_\theta) = 0.0327$ unstable

$= 0.0180$ stable



C_DN
C_EN
C_HNu
C_HNs
× 1000
3
2.5
2
1.5
1
0.5
0
5
10
15
20
25
30
U_N (m/s)

Linear regression of heat flux on $U_N \Delta\theta_N$

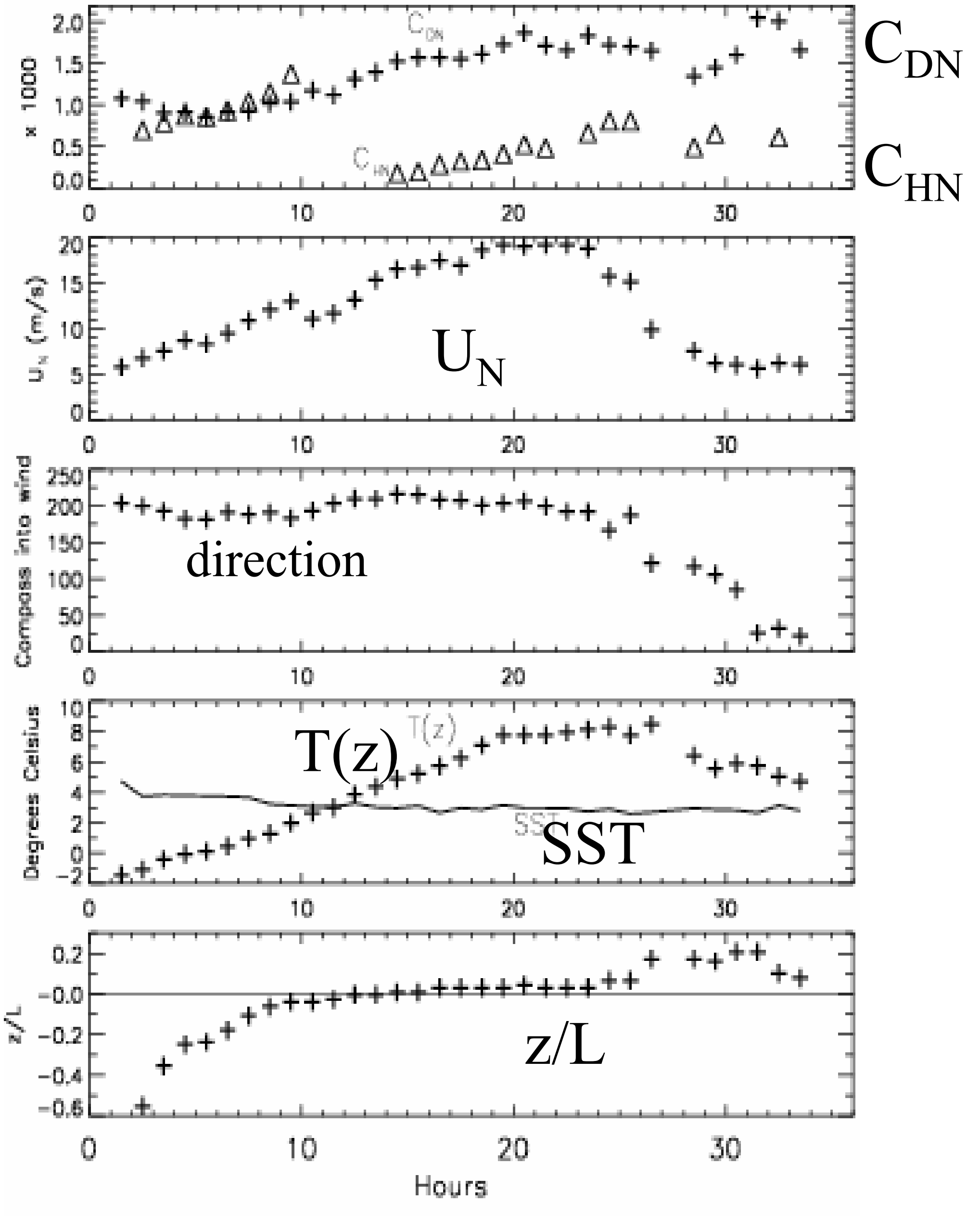
$u^*\theta^*$

$= 0.00075\, U_N\ \theta_N + 0.002$ K W/m^2 stable

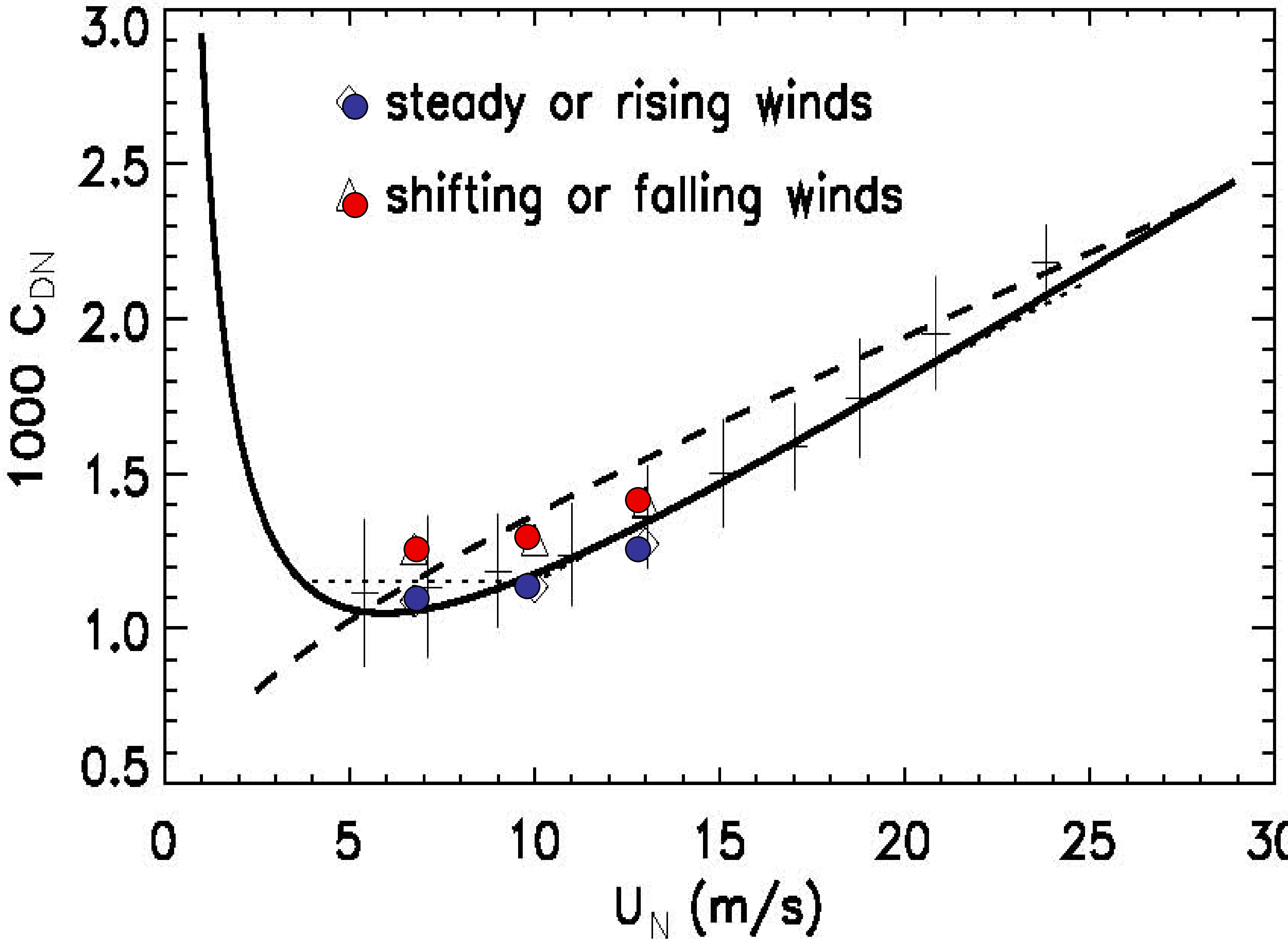
$= 0.00100\, U_N\ \theta_N + 0.003$ K W/m^2 unstable

$C_{HN} \rightarrow \infty$ as $U_N\ \theta_N \rightarrow 0$

Time Series



C_{DN}
C_{HN}
x 1000
U_N
U_N (m/s)
Compass into wind
direction
Degrees Celsius
T(z)
SST
z/L
Hours



steady or rising winds
shifting or falling winds
1000 C_{DN}
U_N (m/s)
3.0
2.5
2.0
1.5
1.0
0.5
0
5
10
15
20
25
30

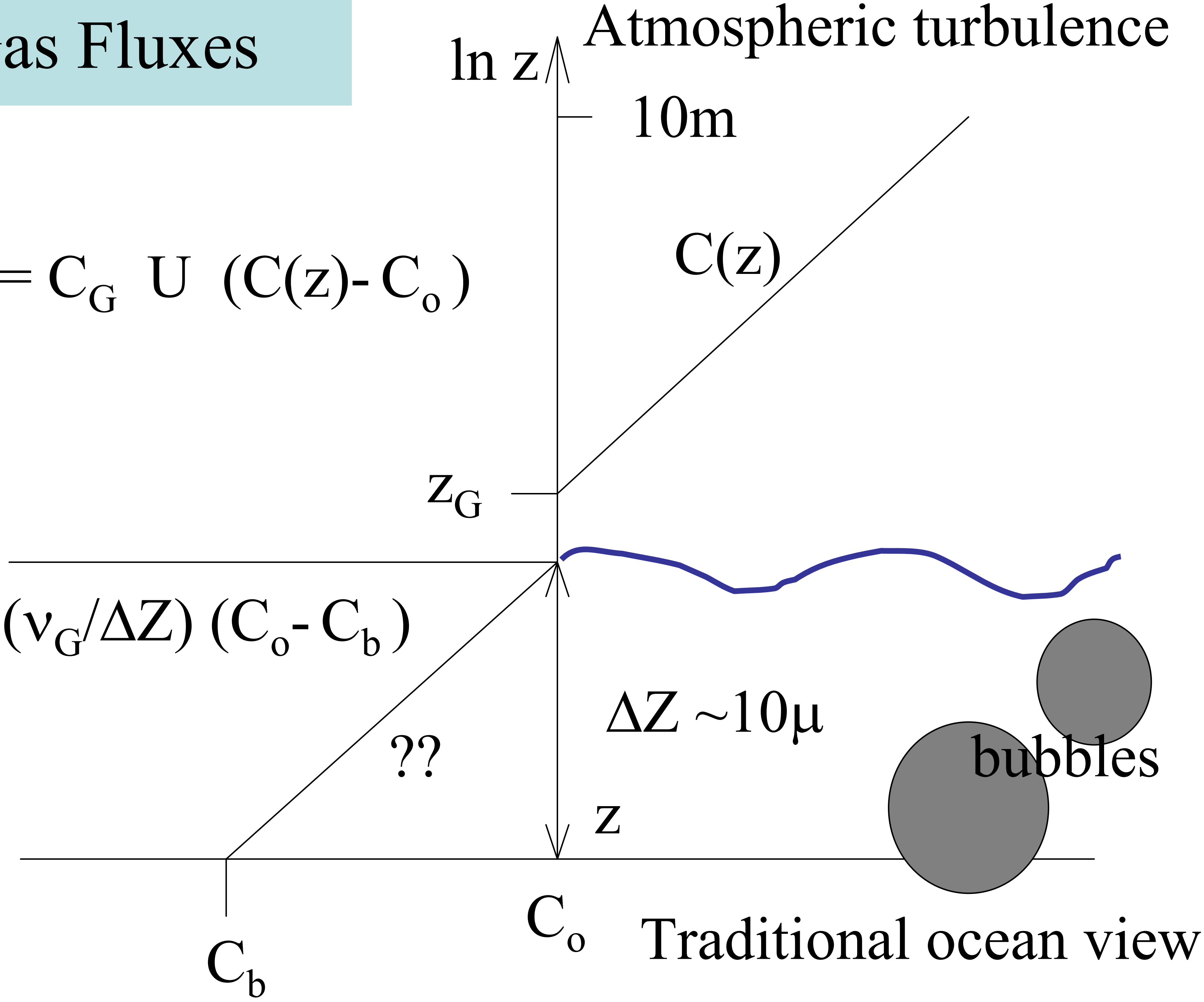
Fetch

Fetch (km)	Data hours	Mean	Sigma	Min	Max
10 - 20	200	1.14	.18	.75	2.03
20-100	54	1.10	.22	.73	1.87
100-200	85	1.13	.24	.64	1.76
∞	291	1.14	.21	.62	1.75
all	590	1.13	.21	.62	2.03

Gas Fluxes

$$F_G = C_G \; U \; (C(z) - C_o)$$

$$F_G = (\nu_G / \Delta Z)\,(C_o - C_b)$$



Traditional : $F_G = U_G \, (\alpha_G \, P_G(z) - G_o)$

Surface saturation : $G_o = \alpha_G \, P_G(z)$

Empirical Piston Velocity : $U_G = \nu_G / \Delta Z$

a function of gas, wind speed, bubbles

Traditional :

$F_G = U_G \, (\alpha_G \, P_G(z) - G_o)$

Surface saturation : $G_o = \alpha_G \, P_G(z)$

Empirical Piston Velocity : $U_G = \nu_G / \Delta Z$

a function of gas, wind speed, bubbles

Atmospheric turbulence :

$F_G = \kappa \sqrt{C_D} \, [\ln(z/z_G) - \psi_s]^{-1} \, U(z) \, (G(z) - \alpha_G \, P_G(z))$

Empirical z_G, but $U(z)$ and $\sqrt{C_D}$ already account for first and second order wind speed dependencies.

4.1 Bulk Flux Estimates

$X = \{\theta, q\}$

Given : $\mathbf{U}(h_u)$, $\Delta\mathbf{U} = |\mathbf{U} - \mathbf{U}_o|$; $\theta(h_\theta)$, $q(h_q)$, SST,

ΔX, $SSQ = 765638\, e^{(-5107K/SST)}$

ISSUE !!!! SST ($\mathbf{U}_o$)

assimilate observations ????

take from model ?????

ignore ?????

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ΔX, $SSQ = 765638\ e^{(-5107K/SST)}$

Initialize: $\theta_v = \theta(h_\theta)\ (1+.608q(h_q))$

$U_N = |\Delta\mathbf{U}|$; $\zeta = 0$; $h = z_q$

$C_D = C_{DN}(U_N)$; $C_H = .0327\ \sqrt{C_D}$; $C_E = .0346\ \sqrt{C_D}$

$u^* = \sqrt{C_D}\ U_N$; $x^* = (C_X / \sqrt{C_D})\ \Delta X$;

Iteration loop

1. Stability : $\zeta_x = g\ h_x\ u^{*-2}\ [\theta^*/\theta_v + q^*/(q(h)+.608^{-1})]$

2. Height shifts :

$$U_N = |\Delta \mathbf{U}|\ \{1+(\sqrt{C_D}/\kappa)\ [\ln(z/10m) - \psi_m(\zeta_u)]\ \}^{-1}$$

$$X(z_u) = X(z_x) - (x^*/\kappa)\ [\ln(z_x/z_u) + \psi_x(\zeta_u) - \psi_x(\zeta_x)\ ]$$

Iteration loop

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3. Coefficient update : $C_{DN}(U_N)$; $C_{XN}(C_{DN}, \zeta_u)$

$$C_D(z_u, \zeta_u) = C_{DN}\ \{1 + [\ln(z_u/10m) - \psi_m(\zeta_u)]\ \}^{-2}$$

$$C_X(z_u, \zeta_u) = C_{XN}\ (\sqrt{C_D}/\sqrt{C_{DN}})\{1+[\ln(z_u/10m) - \psi_m(\zeta_u)]\}^{-1}$$

Iteration loop

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$$C_X(z_u, \zeta_u) = C_{XN}\ (\sqrt{C_D}/\sqrt{C_{DN}})\ \{1+[\ln(z_u/10m) - \psi_m(\zeta_u)]\}^{-1}$$

4. Update scales : $u^* = \sqrt{C_D}\ |\Delta \mathbf{U}|$; $x^* = (C_X/\sqrt{C_D})\ \Delta X$

5. Loop (twice) to 1, with $h = h_x = h_u$

Compute Bulk Fluxes :

$$\boldsymbol{\tau} = \rho \; u^{*2} \; (\Delta \mathbf{U} \; / \; |\Delta \mathbf{U}|)$$

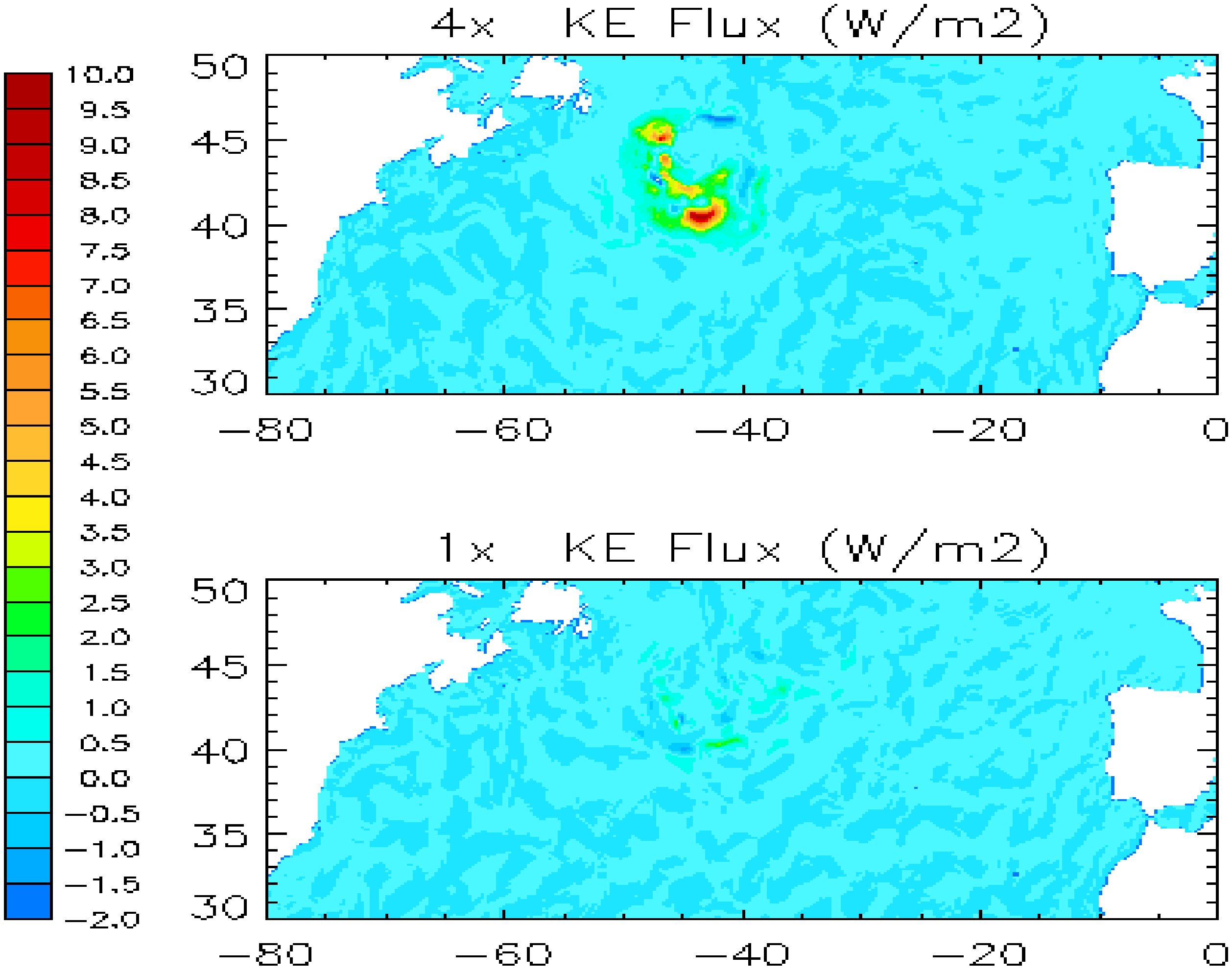
$$Q_H = \rho \; C_p \, u^* \, \theta^*$$

$$Q_E = \Lambda \, E = \rho \; \Lambda \, u^* \, q^*$$

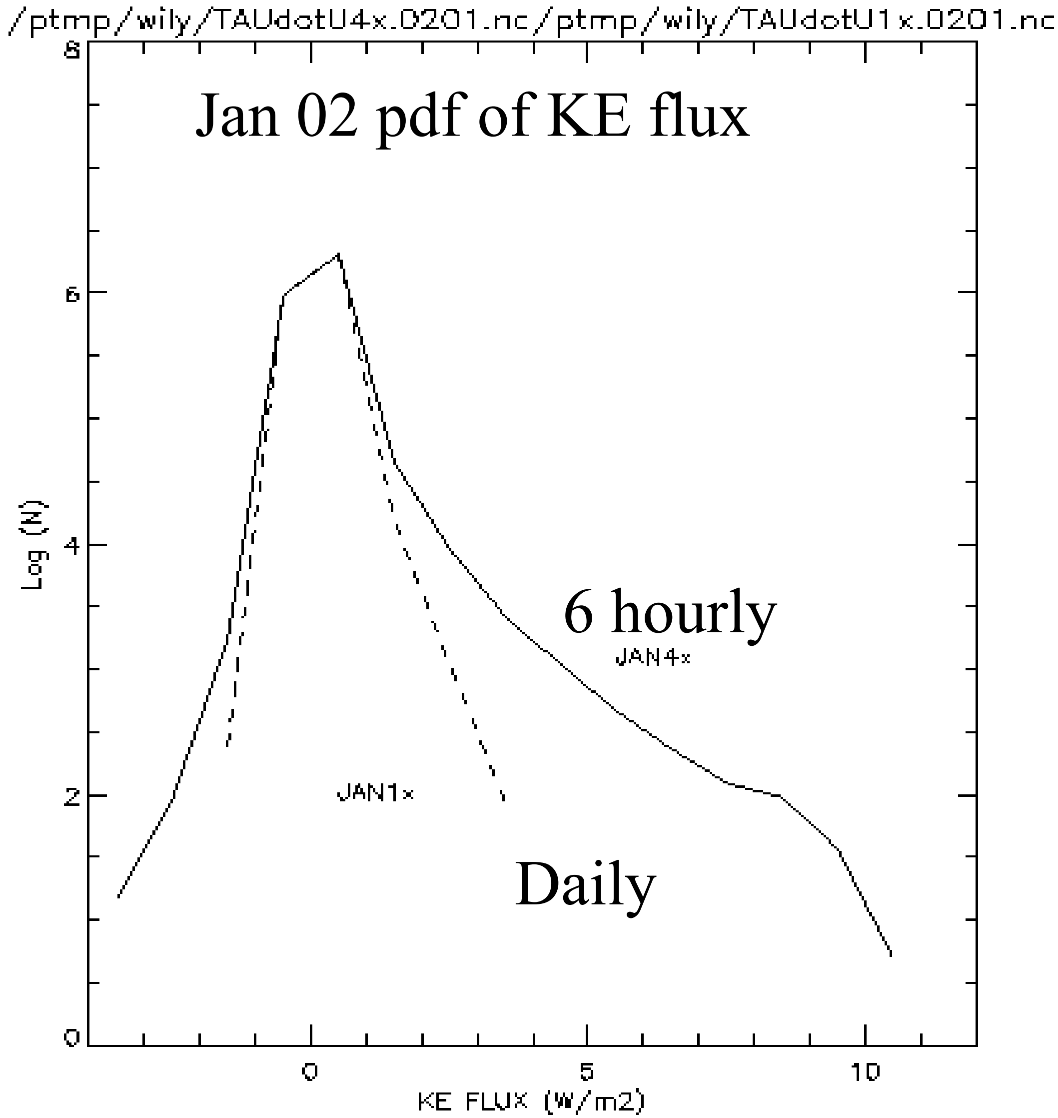
$$KE = \boldsymbol{\tau} \bullet \mathbf{U} \neq m_0 \, u^{*3}$$

January 22 2002

0.1° N. Atlantic POP (τ•Uo)



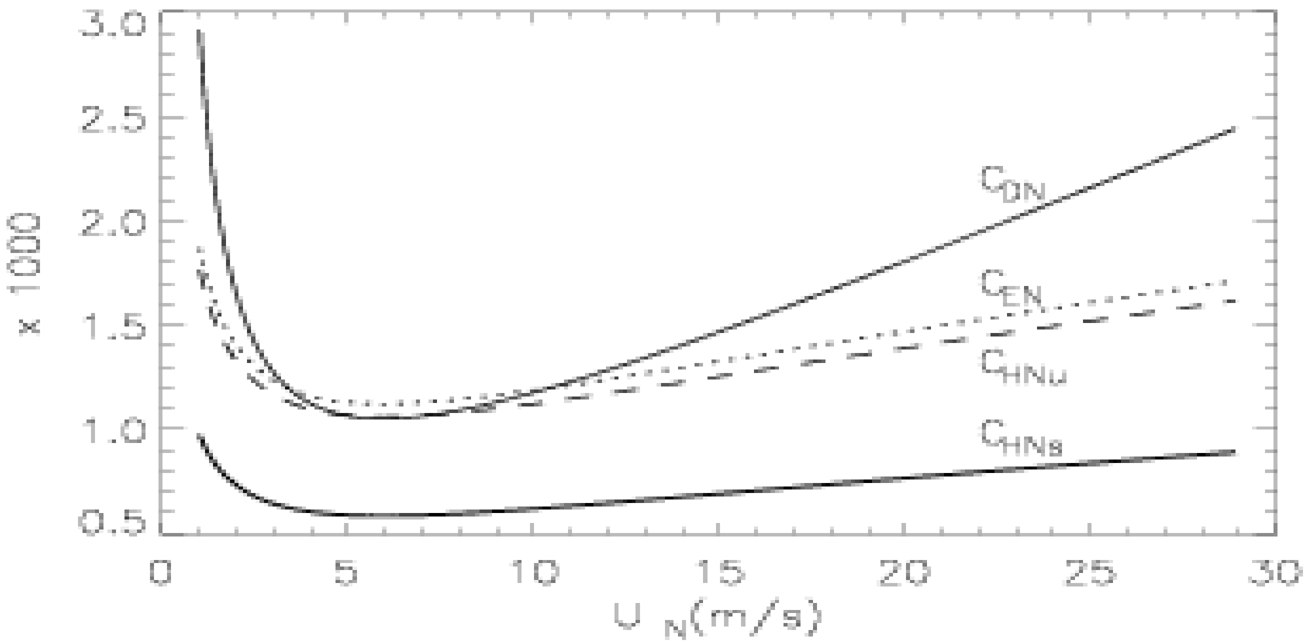
Log N



/ptmp/wily/TAUdotU4x.0201.nc/ptmp/wily/TAUdotU1x.0201.nc
Jan 02 pdf of KE flux
6 hourly
JAN4x
JAN1x
Daily
Log (N)
KE FLUX (W/m2)
8
6
4
2
0
0
5
10

End of Part I

C_{XN} (U_N)



Linear regression : $3 < U_N < 10$ m/s; $10^3\, C_{DN} \sim 1.15$

$10 < U_N < 25$ m/s; $10^3\, C_{DN} = .5 + .065\, U_N$

$2 < U_N < 25$ m/s; larger offset, smaller slope depending on the data distribution.

FLUXES		Components		Bulk	
Q					Net Surface Heat Flux
	Q_{as}				Air-Sea Heat Flux
		Q_S			Net Solar Radiation
			Q_I		Solar Insolation
			α		Solar Albedo
		Q_L			Net Longwave Radiation
			Q_A		Downwelling Longwave
			SST_s		Skin SST
		Q_E^*			Latent Heat Flux
		Q_H^*			Sensible Heat FLux
F					Net Surface Freshwater Flux
	F_{as}				Air-Sea Freshwater Flux
		P			Total Precipitation
			P_R		Rainfall
			P_S		Snowfall
		E^*			Evaportation
		R			Continental Runoff
$\vec{\tau}$					Surface Wind Stress
	$\vec{\tau_{as}}^*$				Air-Sea Wind Stress
				$U(\vec{h})$	Wind Vector
				$t_a(h)$	Air Temperature
				$q_a(h)$	Air Specific Humidity
				P_o	Atmospheric Pressure
				SST_b	Bulk SST
				$S\vec{S}U$	Sea Surface Current

Table 1: Poliferation of air-sea flux fields.