Sea-Air Transfer at Extreme Wind Speeds

Kerry Emanuel and Moshe Alamaro

- Importance to hurricane intensity prediction
- Similarity theory
- Laboratory measurements

Steady State Energy Balance

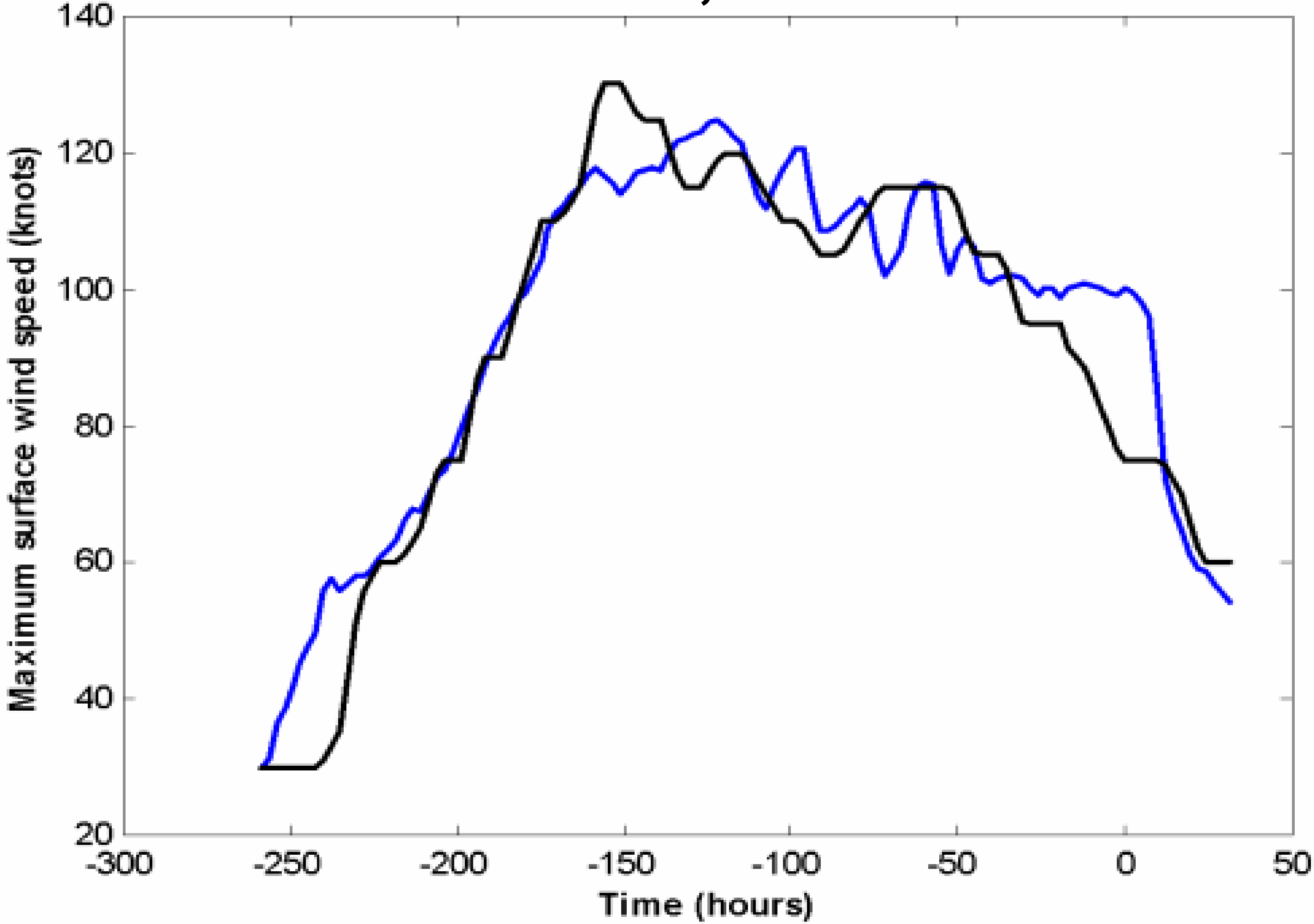
$$\mathcal{D} \approx C_D \rho |V|^3$$

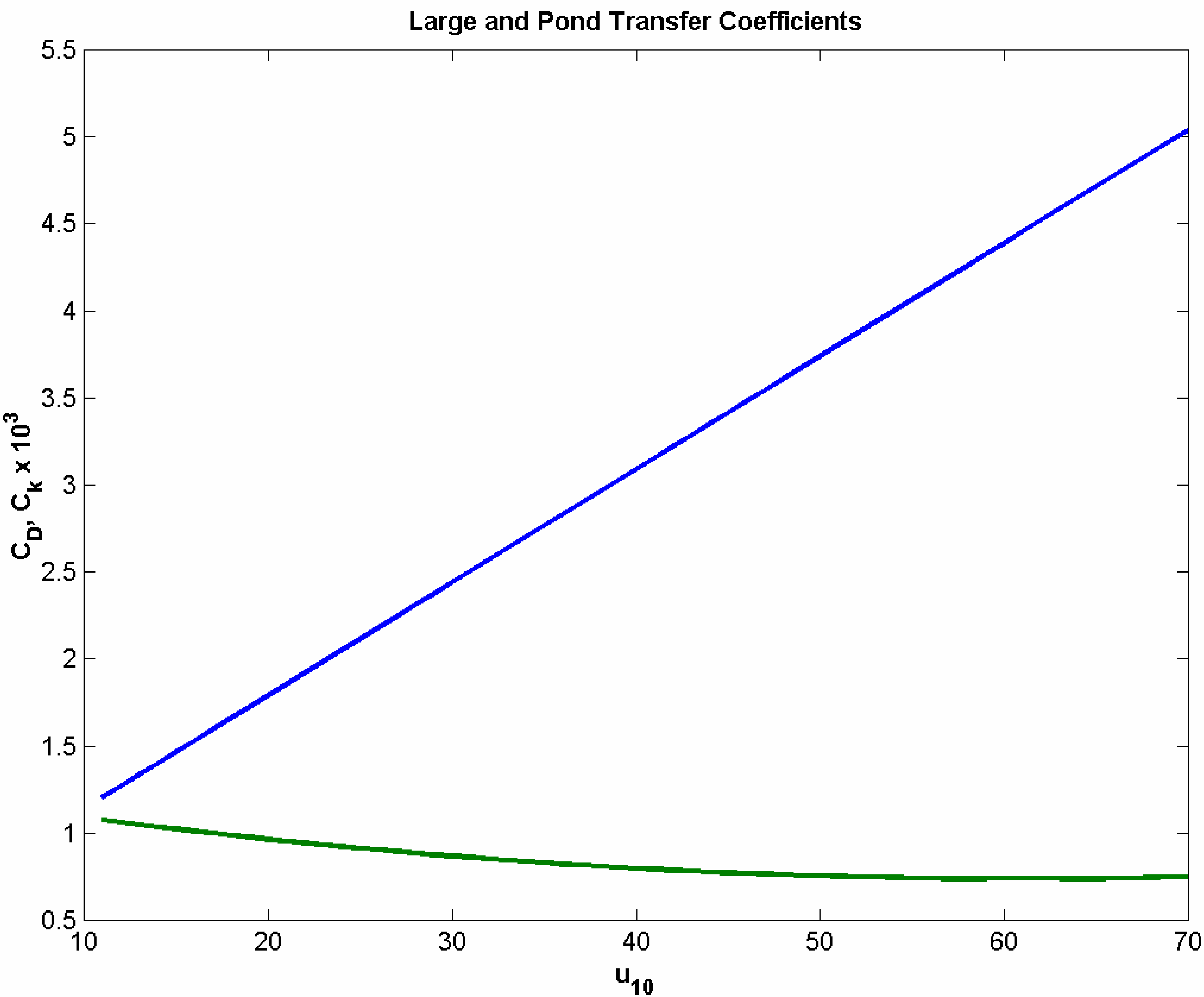
$$\mathcal{G} \approx C_k \rho |V| \frac{T_s - T_o}{T_o} \left(k_0{}^* - k \right)$$

$$\rightarrow |V_{\max}|^2 \cong \frac{C_k}{C_D} \frac{T_s - T_o}{T_o} \left(k_0{}^* - k \right)$$

A numerical simulation assuming equal exchange coefficients of enthalpy and momentum. Coupled model of Emanuel, Nature, 1999

Gert, 1999

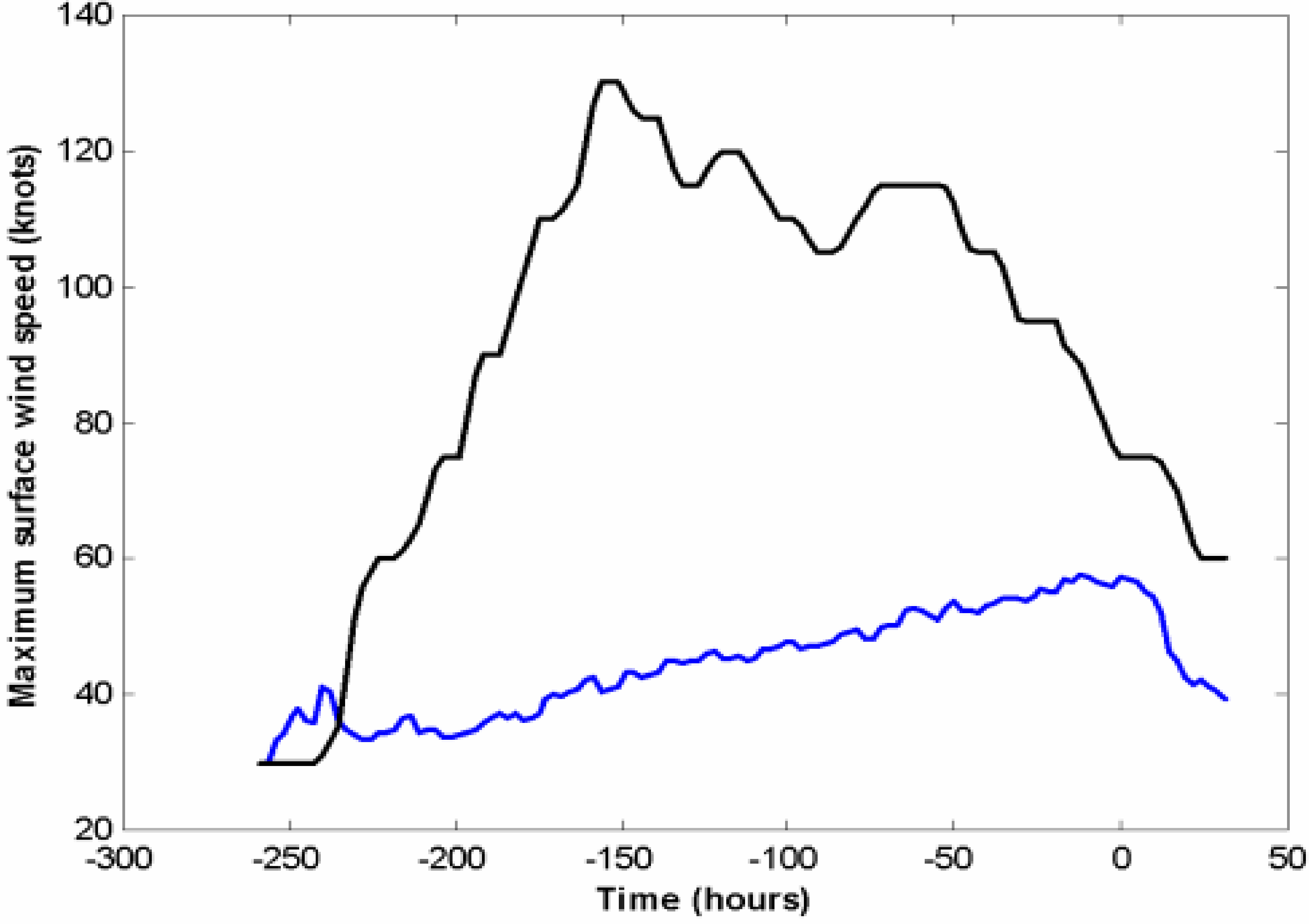


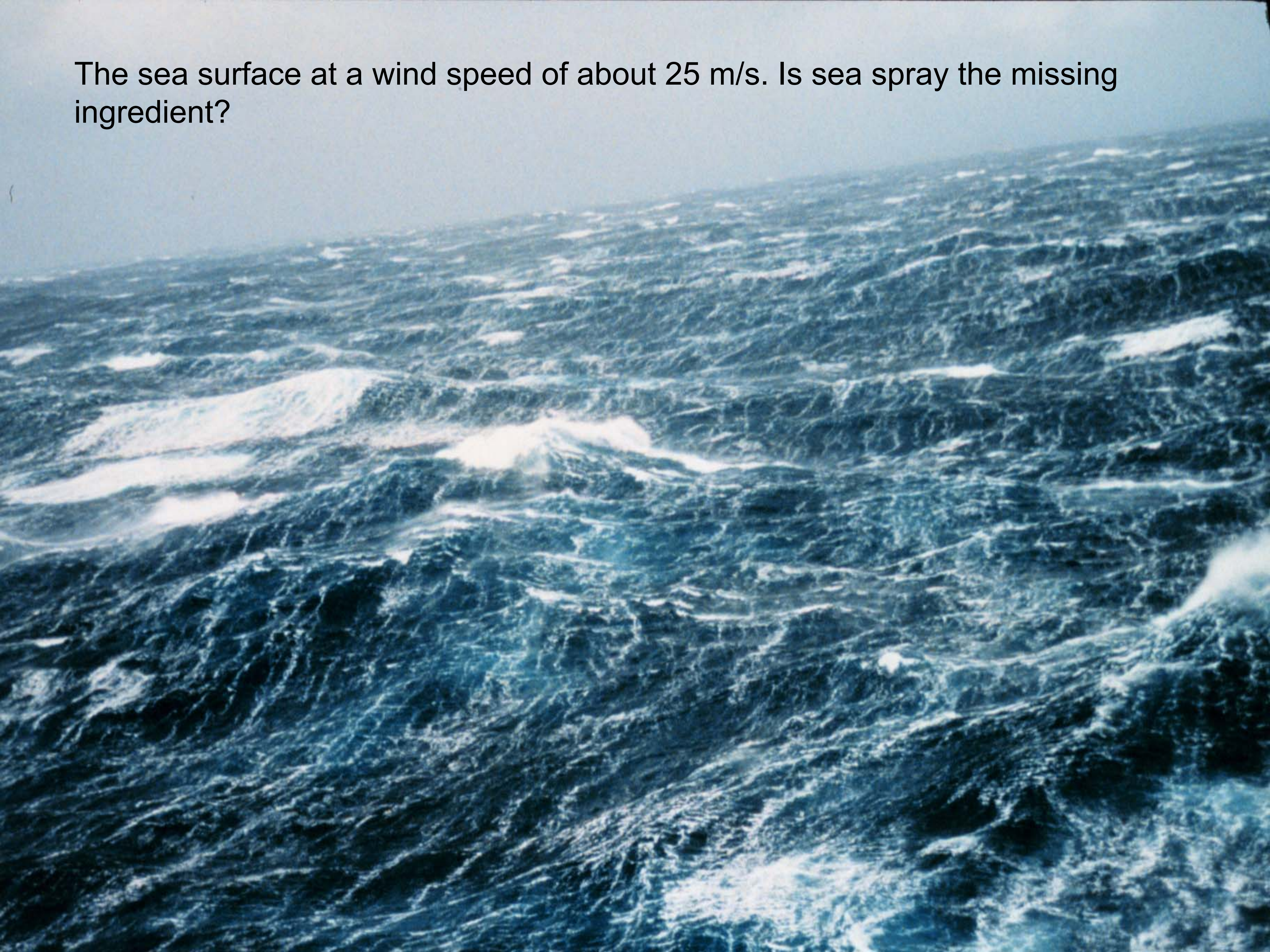


Large and Pond Transfer Coefficients
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
10
20
30
40
50
60
70
C_D, C_k x 10^3
u_{10}

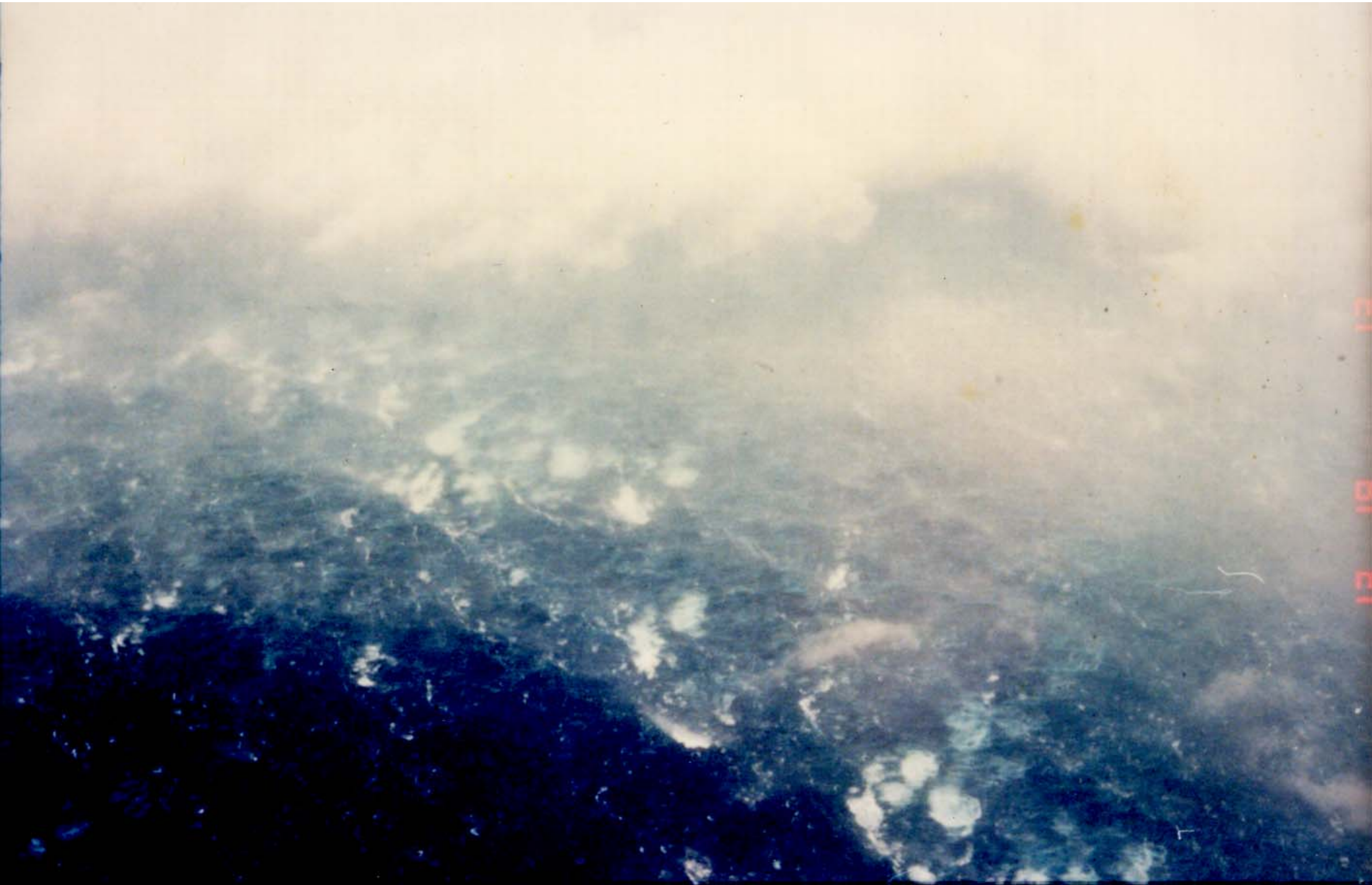
Same simulation, but using the Large and Pond transfer coefficients

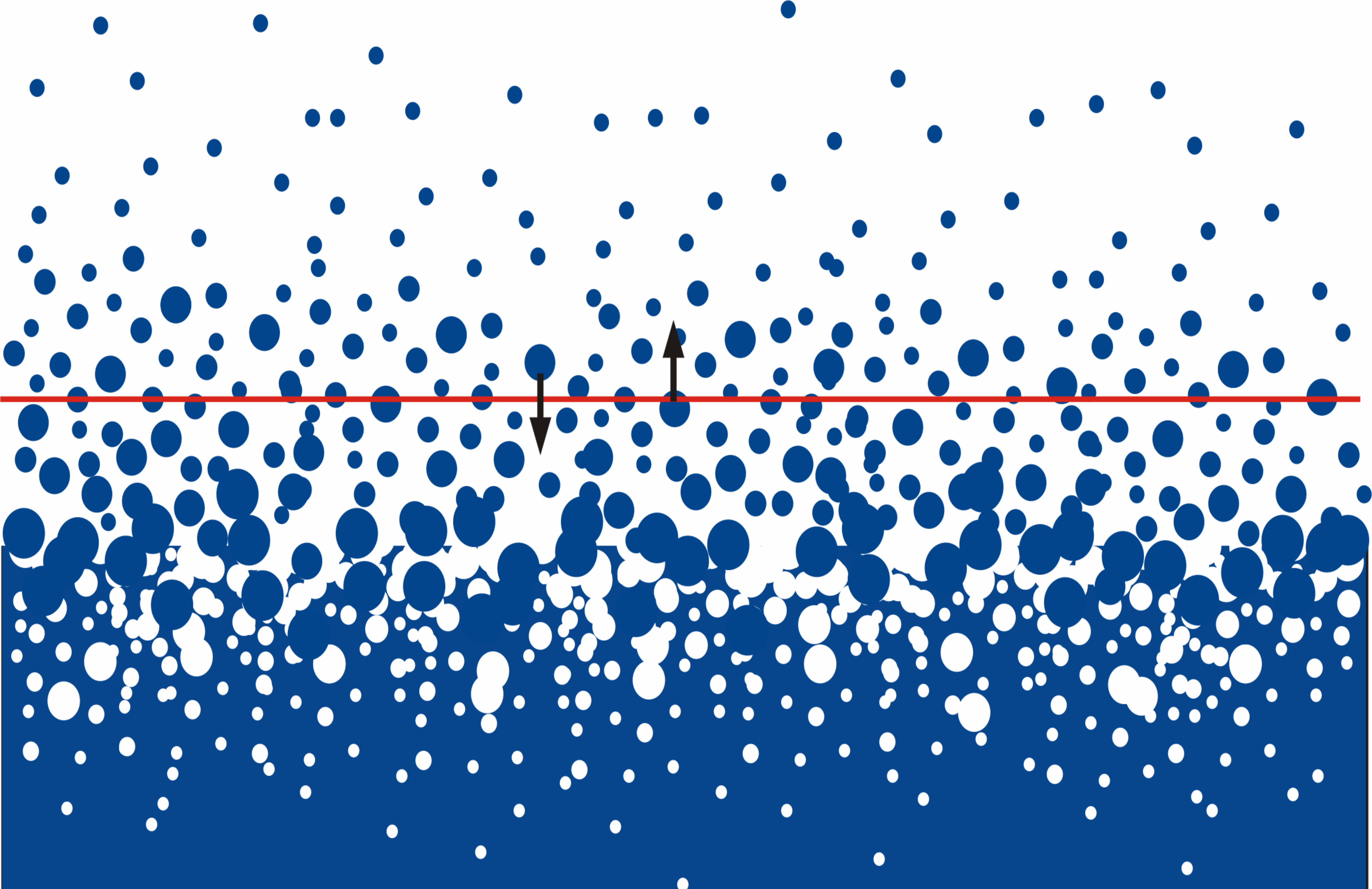
Gert, 1999




The sea surface at a wind speed of about 25 m/s. Is sea spray the missing ingredient?

Inner edge of eyewall of Hurricane Gilbert, 1988, from recon aircraft

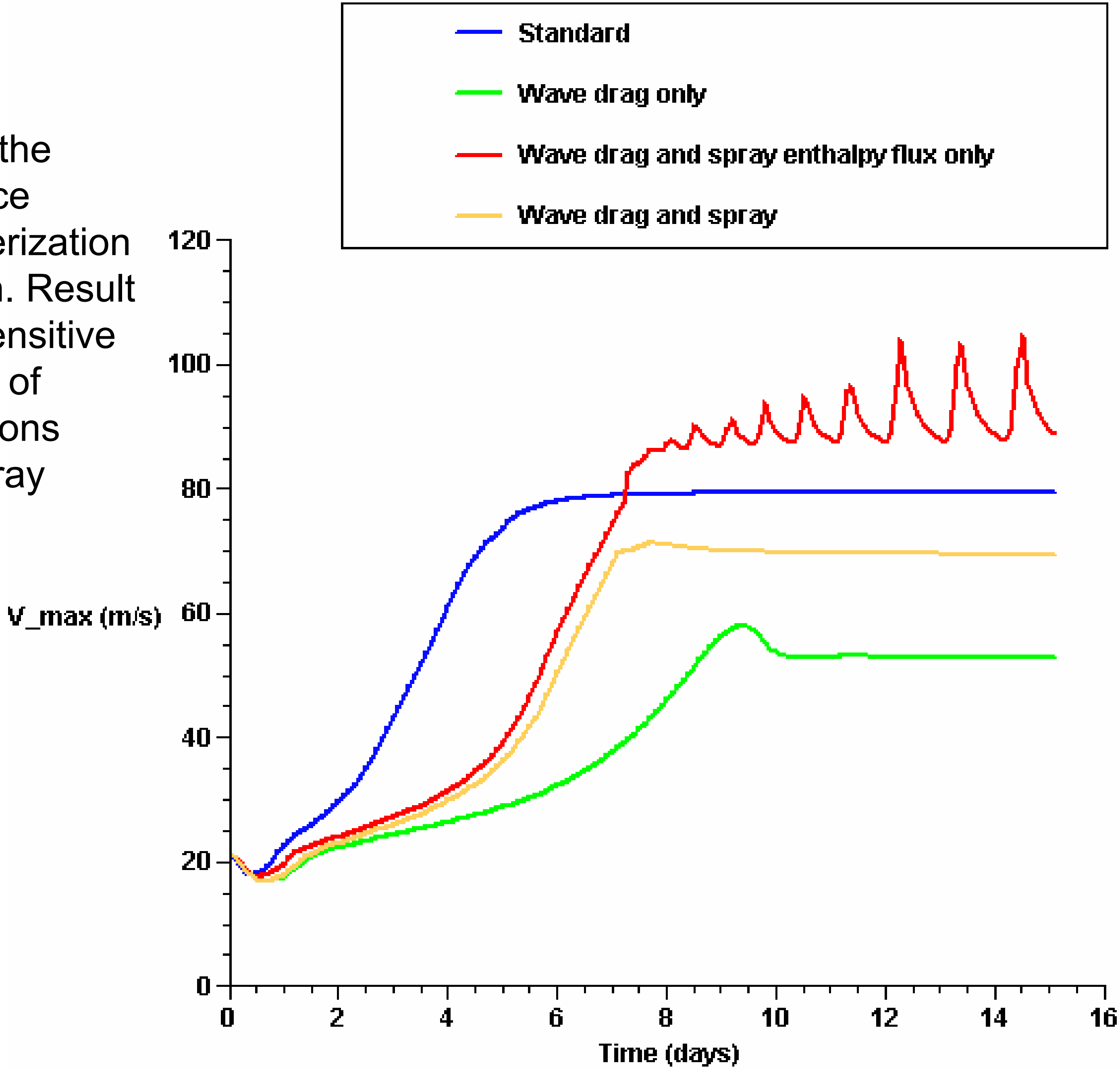




At very high winds speeds, the air-sea interface is replaced by an emulsion, with a gradual transition from spray-filled air to bubble-filled water.

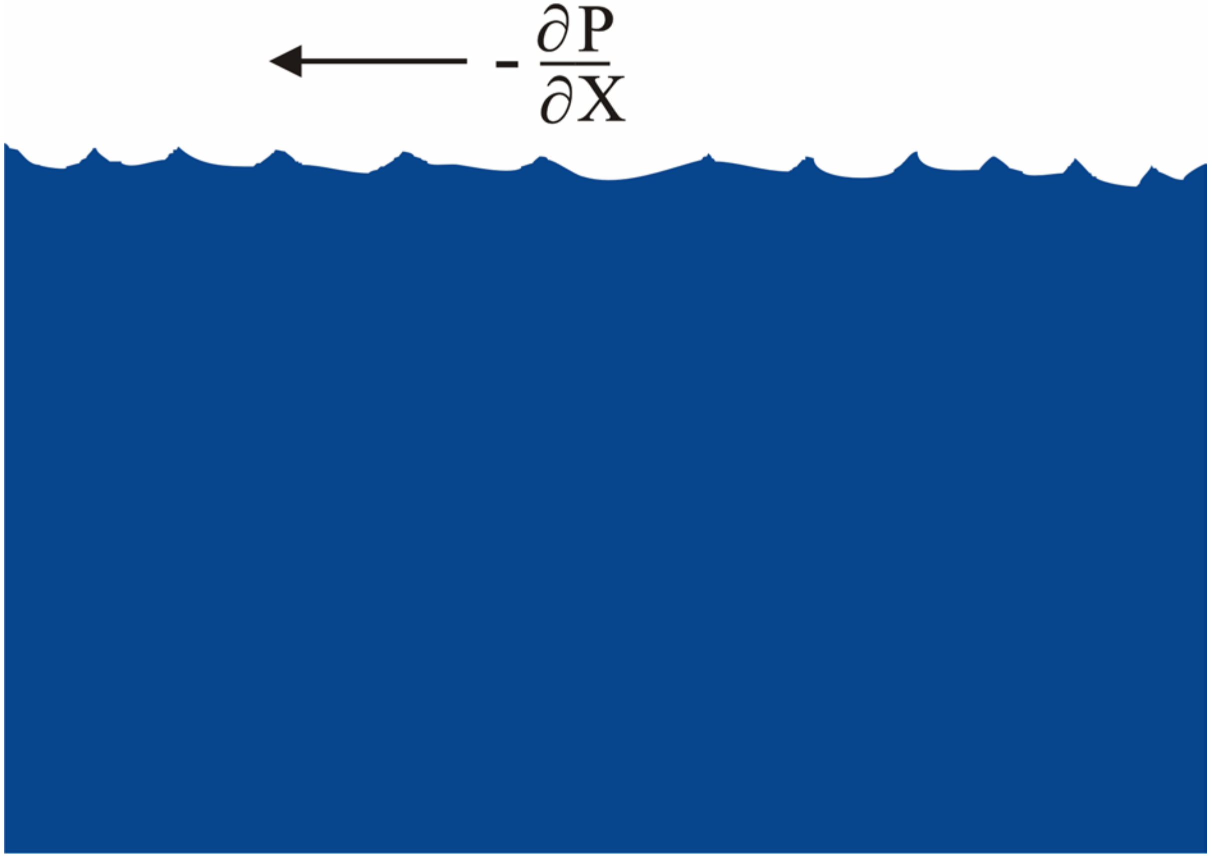
Andreas and Emanuel, 2001, *J. Atmos. Sci.*

We tried the brute-force parameterization approach. Result is very sensitive to details of assumptions about spray physics



We advance a similarity hypothesis, using this very reduced system as a model. Both the water and the atmosphere have neutral stratification. A constant horizontal pressure gradient is applied to the atmosphere.

$$\int_0^\infty \frac{1}{\rho_a} \frac{\partial P}{\partial X} \, dz = u^{*2}$$



Nondimensional Control Parameters:

$$R_u \equiv \frac{u^{*4}}{\sigma g'}$$

$$R_\sigma \equiv \frac{\sigma}{\nu_l^{4/3} g'^{1/3}}$$

$$R_\nu \equiv \frac{\nu_l}{\nu_a}$$

Similarity Hypothesis:

All quantities become independent of molecular properties in limit of large R_u

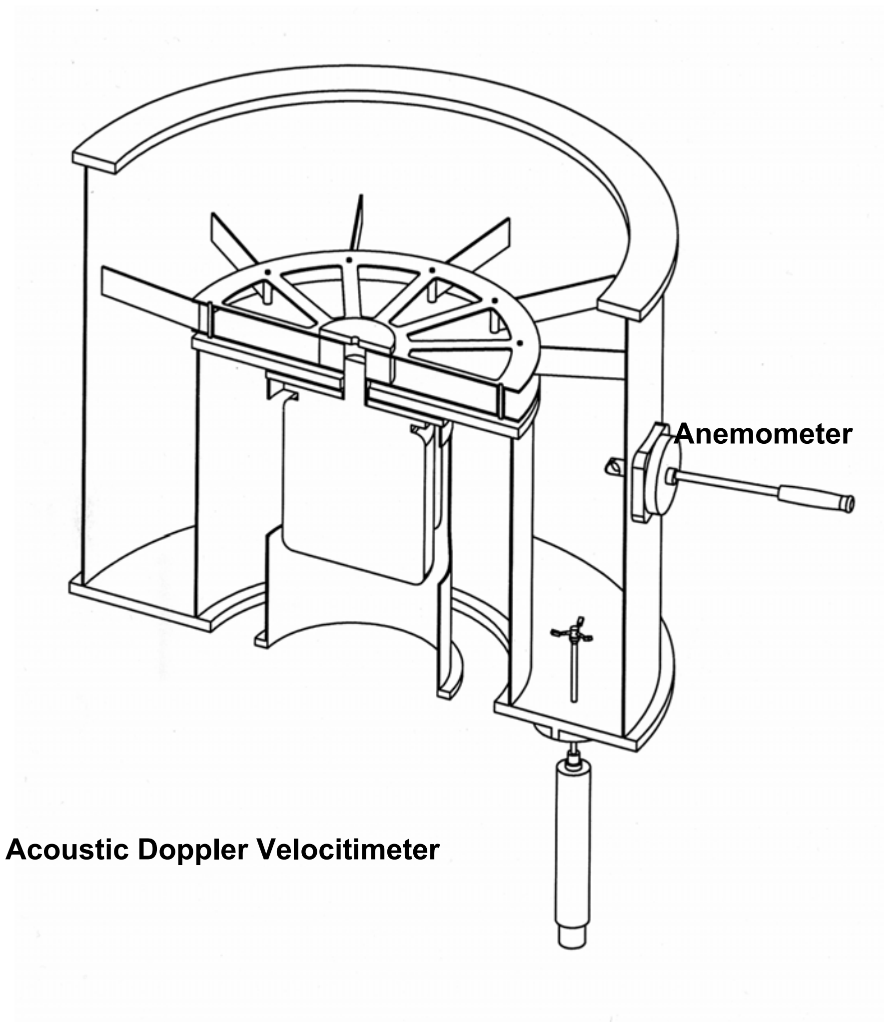
Sea surface becomes self-similar, with all length scales scaling as u^{*2}/g

Nondimensional coefficients become constant

Laboratory Experimental Apparatus for Measuring Enthalpy and Momentum Fluxes at Extreme Wind Speeds

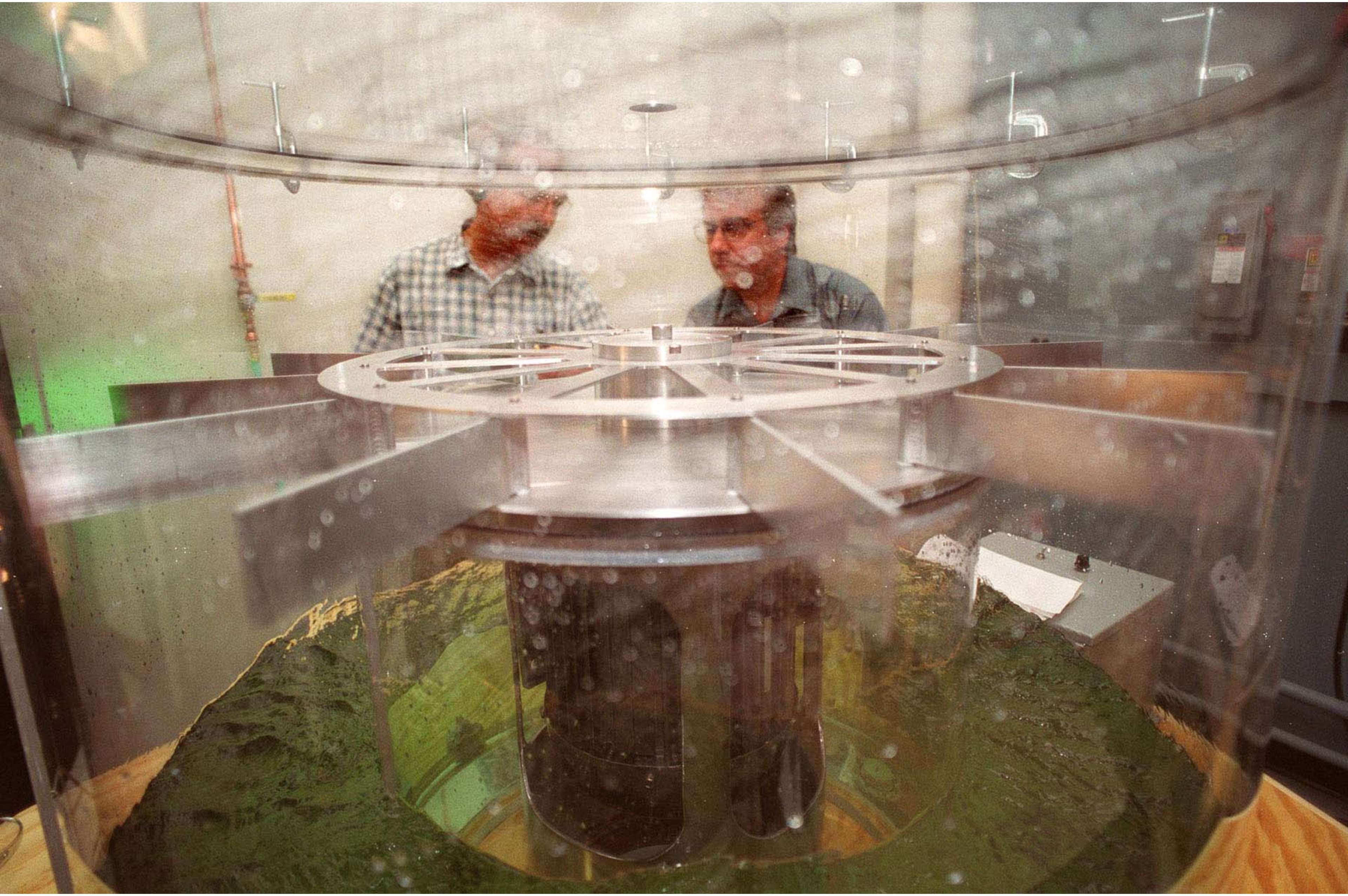
<u>Wind wave tank apparatus</u>

Outer Diameter	0.96 meter
Inner Diameter	0.57 meter
Annulus Width	0.20 meter
Water Depth	0.11-0.16 Meter
Electric Motor	
Nominal Power	1 HP
RPM with Lid	60-800
RPM without Lid	60-480
Paddle Blades	12



Experimental Test:

(Note: We did not actually use champagne; this photo was taken at the tank's christening ceremony.)

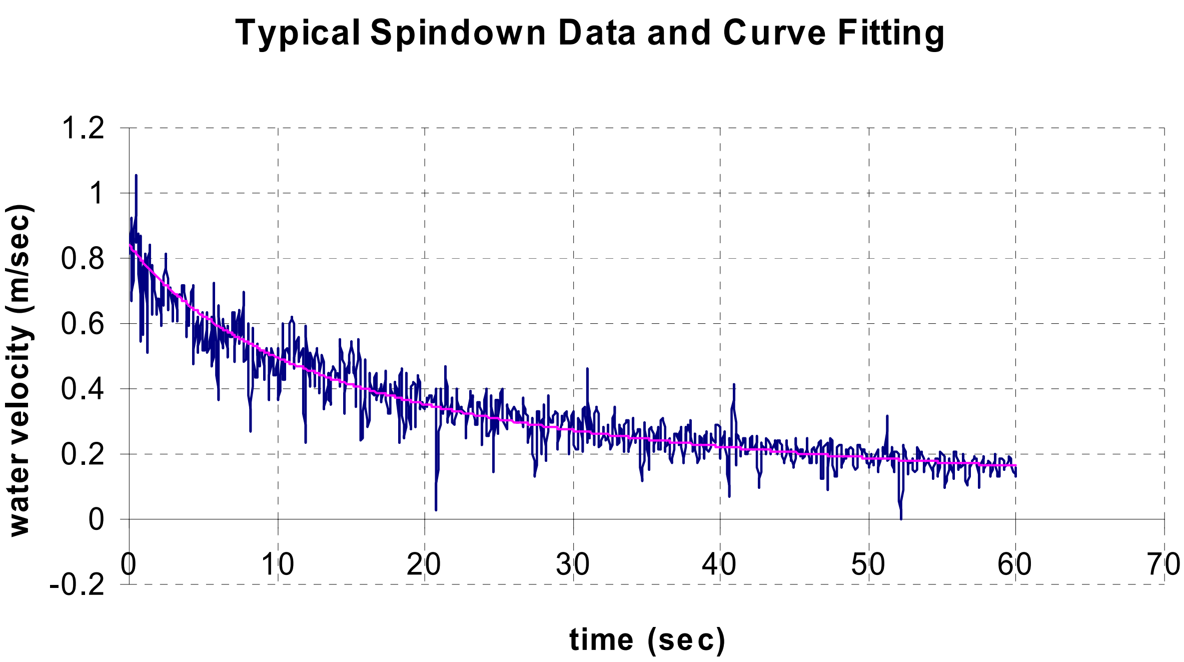


procedure for measuring and calculating the propelling stress

1. Bring the water to a steady state rigid body rotation under certain relative air velocity over the moving water surface.

2. Cut the power of the electric motor.

3. Measure the decelerating water velocity due to retarding stress.

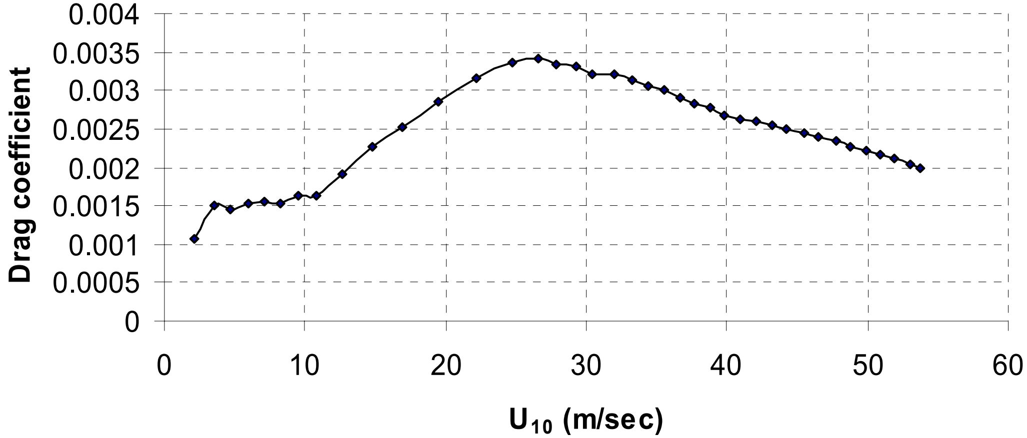


The water velocity during the spindown is:

$$V_w(t) = \frac{V_m}{(1 + k \cdot t)^n} \qquad n>1$$

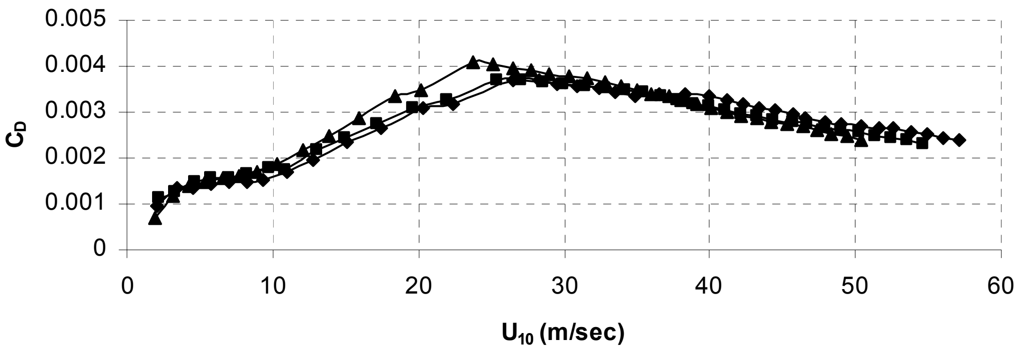
n and k are found by least square curve fitting

Typical Drag coefficient vs. U_{10}

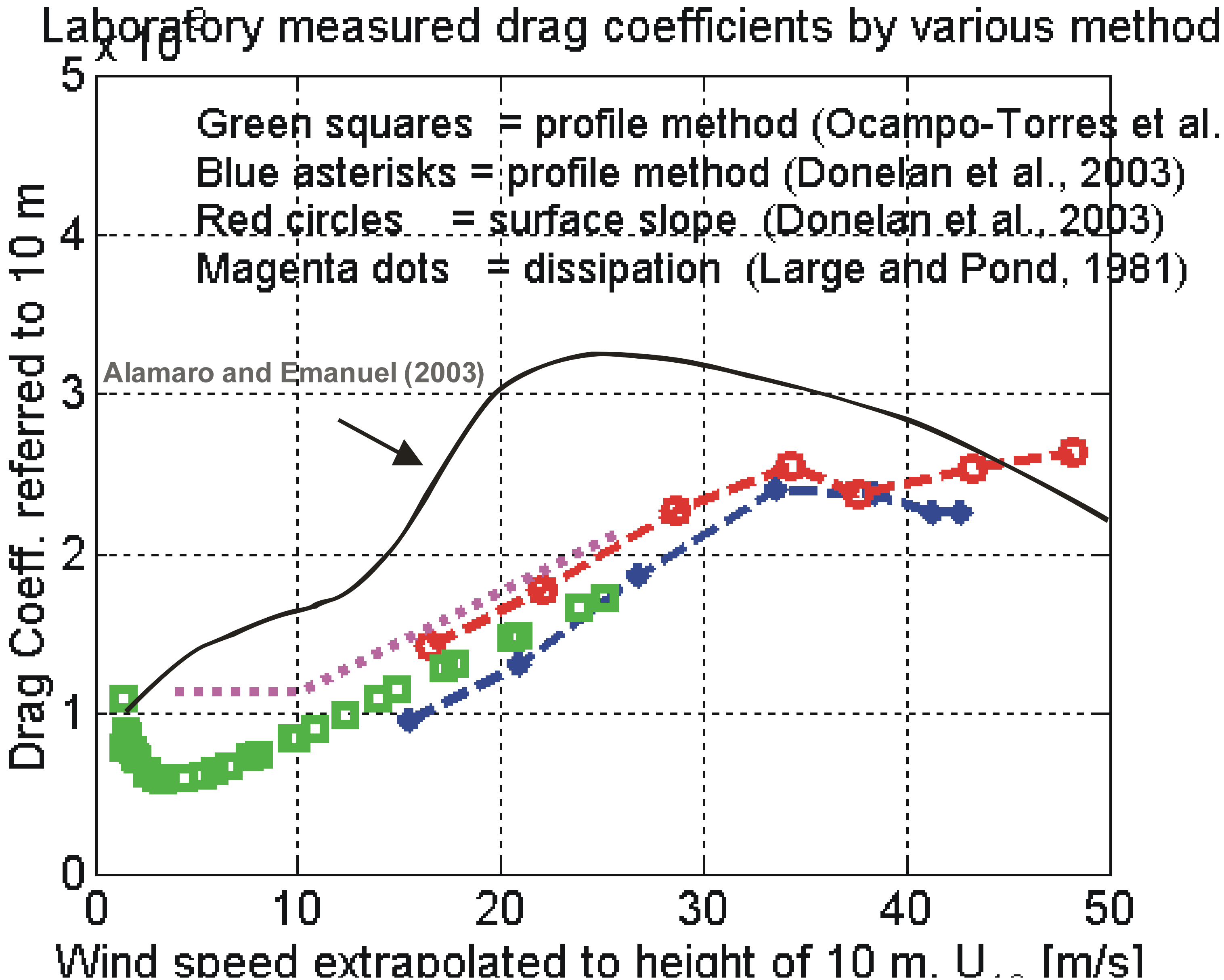


The U_{10} is obtained by extrapolation assuming logarithmic velocity profile

C_D vs. U_{10} - water depth 14 cm
For various height of False bottom



The centrifugal acceleration of water spray is about 100-200 m/sec^2. The flight time scale of the spray is 0.1 sec.

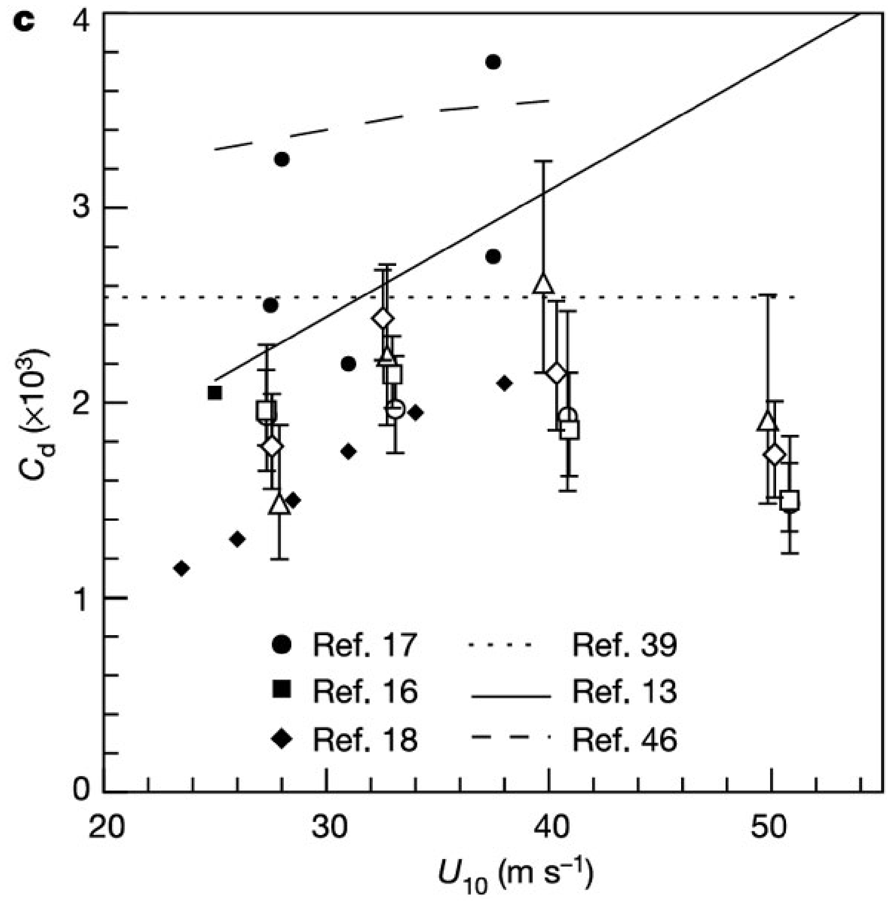


Laboratory measured drag coefficients by various method
x 10
Green squares = profile method (Ocampo-Torres et al.,
Blue asterisks = profile method (Donelan et al., 2003)
Red circles = surface slope (Donelan et al., 2003)
Magenta dots = dissipation (Large and Pond, 1981)
Alamaro and Emanuel (2003)
Drag Coeff. referred to 10 m
0
1
2
3
4
5
0
10
20
30
40
50
Wind speed extrapolated to height of 10 m, U [m/s]

nature
20 March 2003

Reduced drag coefficient for high wind speeds in tropical cyclones

MARK D. POWELL*, PETER J. VICKERY† & TIMOTHY A. REINHOLD



Wind Wave Tank Setting for Enthalpy Transfer Experiments

The heating elements keep the temperature of the water equal to the temperature of the lab ambient during the experiment that last 24 - 48 hours. The temperature of the water, ambient air, relative humidity and the energy provided to the heating elements are recorded once a Minute.

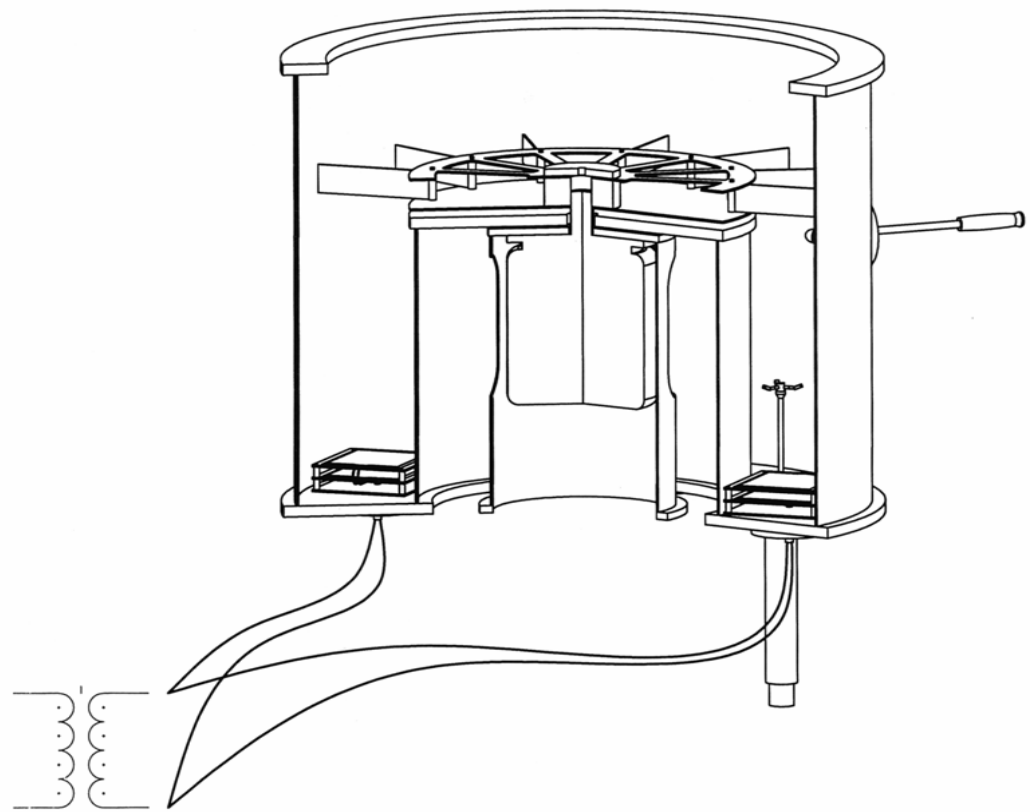
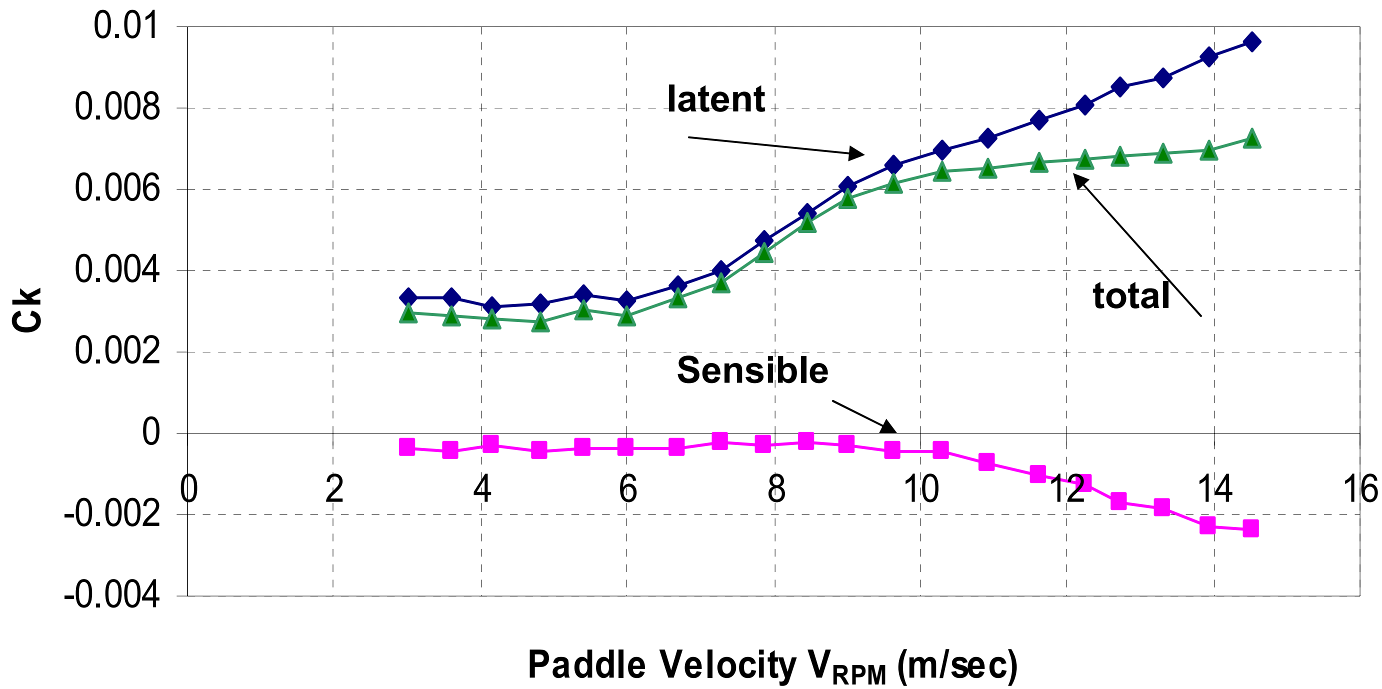


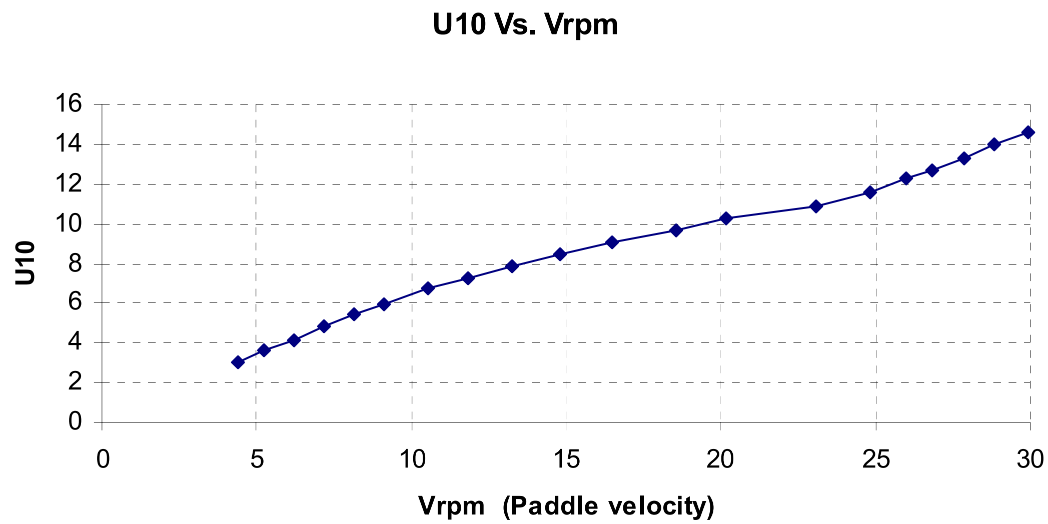
Figure 1.4: Multiple heating elements inside the wind wave tank. A transformer provides power at 24 Volts.

$$C_{K_{tot}} = \frac{\frac{1}{L_v}\sum_1^n E_i}{V_a A\Delta t \sum_1^n \rho_{sat,wi}(1-\phi_i)} \qquad or \qquad \sum_1^n E_i = \left(\frac{1}{L_v} V_a A\Delta t\right) C_{K_{tot}} \sum_1^n \rho_{sat,wi}(1-\phi_i)$$

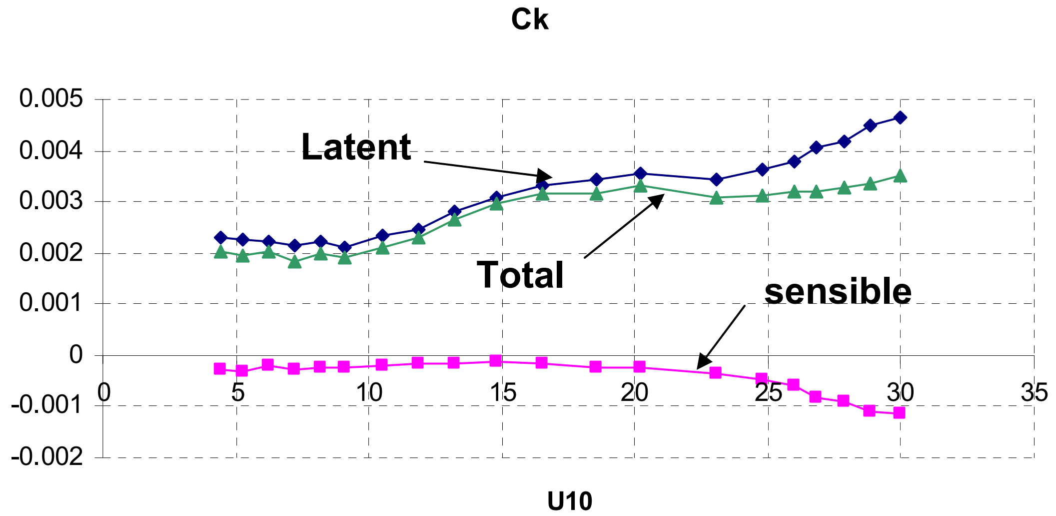
$$C_{K,latent} = \frac{m_{tot}}{V_a A\Delta t \sum_1^n \rho_{sat,wi}(1-\phi_i)} \qquad C_{K,sensible} = C_{K_{tot}} - C_{K,latent} \qquad C_K \neq C_K(t)$$

For water quality that does not change during the experiment



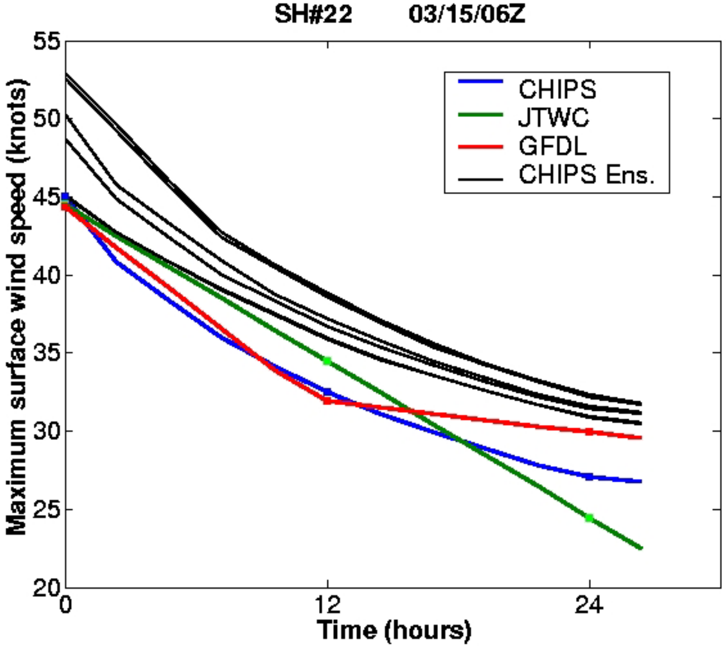


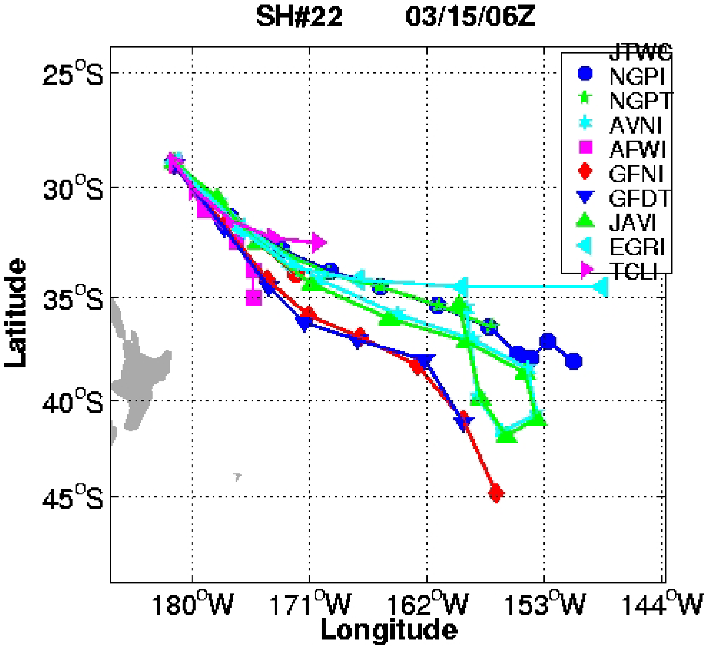
U10 Vs. Vrpm
16
14
12
10
8
6
4
2
0
U10
0
5
10
15
20
25
30
Vrpm (Paddle velocity)



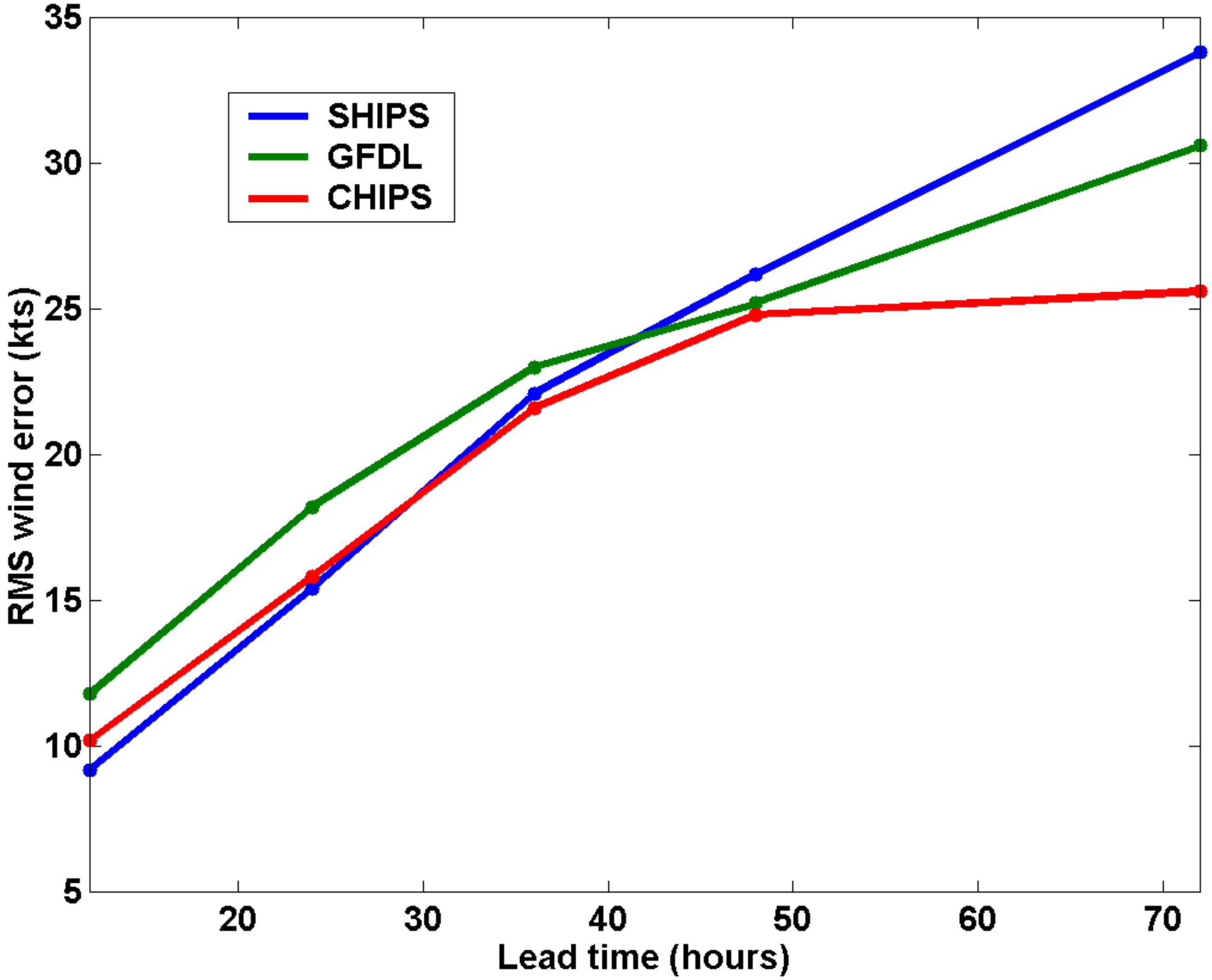
Ck
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
Latent
Total
sensible
0
5
10
15
20
25
30
35
U10

Real-Time Forecasts Posted at http://wind.mit.edu/~emanuel/storm.html





Overall Forecast Performance: 2002 Atlantic Intensity Errors



Summary

- Sea-air transfer dominated by spray effects at wind speeds >~ 25 m/s
- Dimensional reasoning predicts that exchange coefficients should become asymptotically constant at high wind
- Laboratory measurements roughly confirm this prediction
- Constant exchange coefficients work well in hurricane intensity prediction model