A parameterization of sea spray contributions to mass and heat fluxes in hurricanes based on breaking wave properties.

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Ed Andreas

1. Background
2. Nature of droplet source
3. Scaling model of source
4. Droplet heat/moisture fluxes
5. Simpler Parameterization
6. Feedback
7. Newer stuff

Background

- Hurricane models are sensitive to representation of surface fluxes
- Basic Meteorological Direct fluxes:
  - Sensible Heat, H_s
  - Latent Heat, H_l
  - Momentum, τ
  - Kinetic Energy=$-\tau$*U(z)

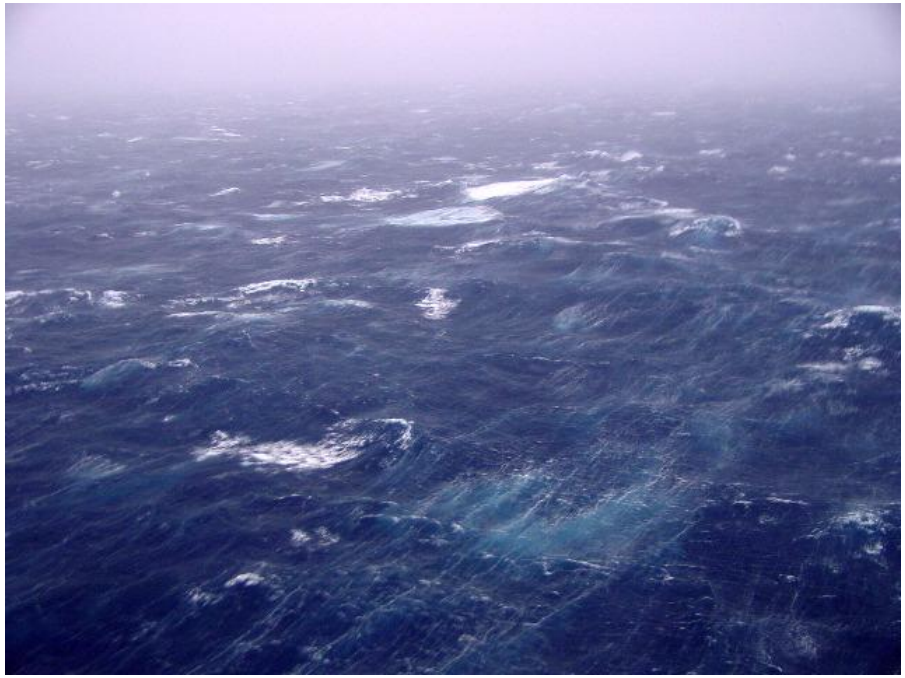
$$H_s = \rho_a c_{pa} C_H U_a (T_s - T_a)$$

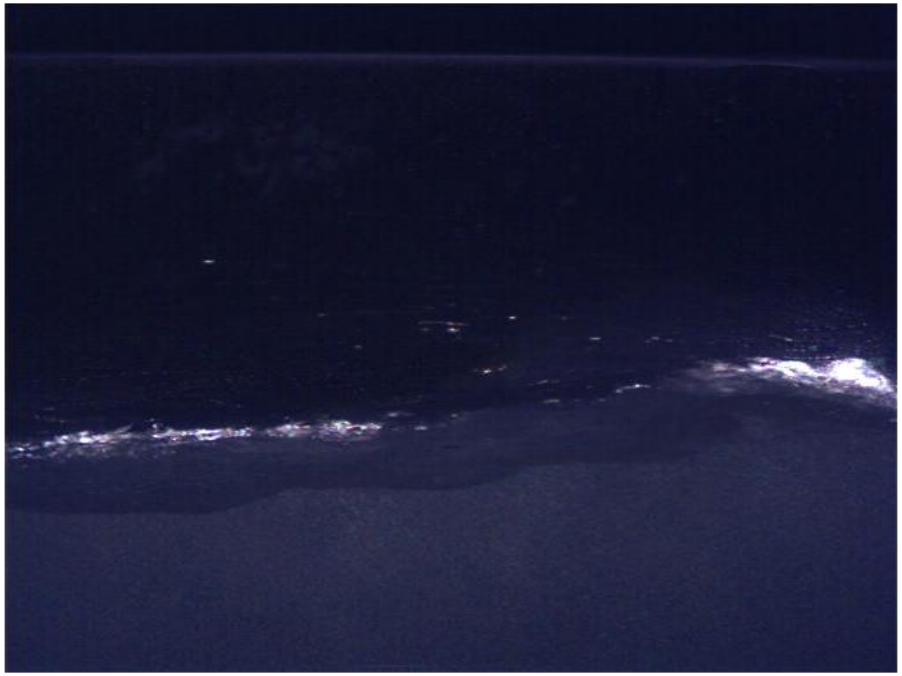
$$H_l = \rho_a L_e C_E U_a (q_s - q_a)$$

$$\tau = \rho_a C_D U_a^2$$

- Fluxes on Ocean Side
  - Momentum and Energy (waves and currents)
  - Thermodynamic
- At High Winds Sea Spray Becomes Relevant
  - How Much Sea Spray? Source function, $S_n(r)$
  - What does S_n do?
    - Direct Heat Q_s
    - Evaporation Heat Q_l
    - Effect on momentum flux through buoyancy

Definition of Droplet Source Flux At Sea-air Interface



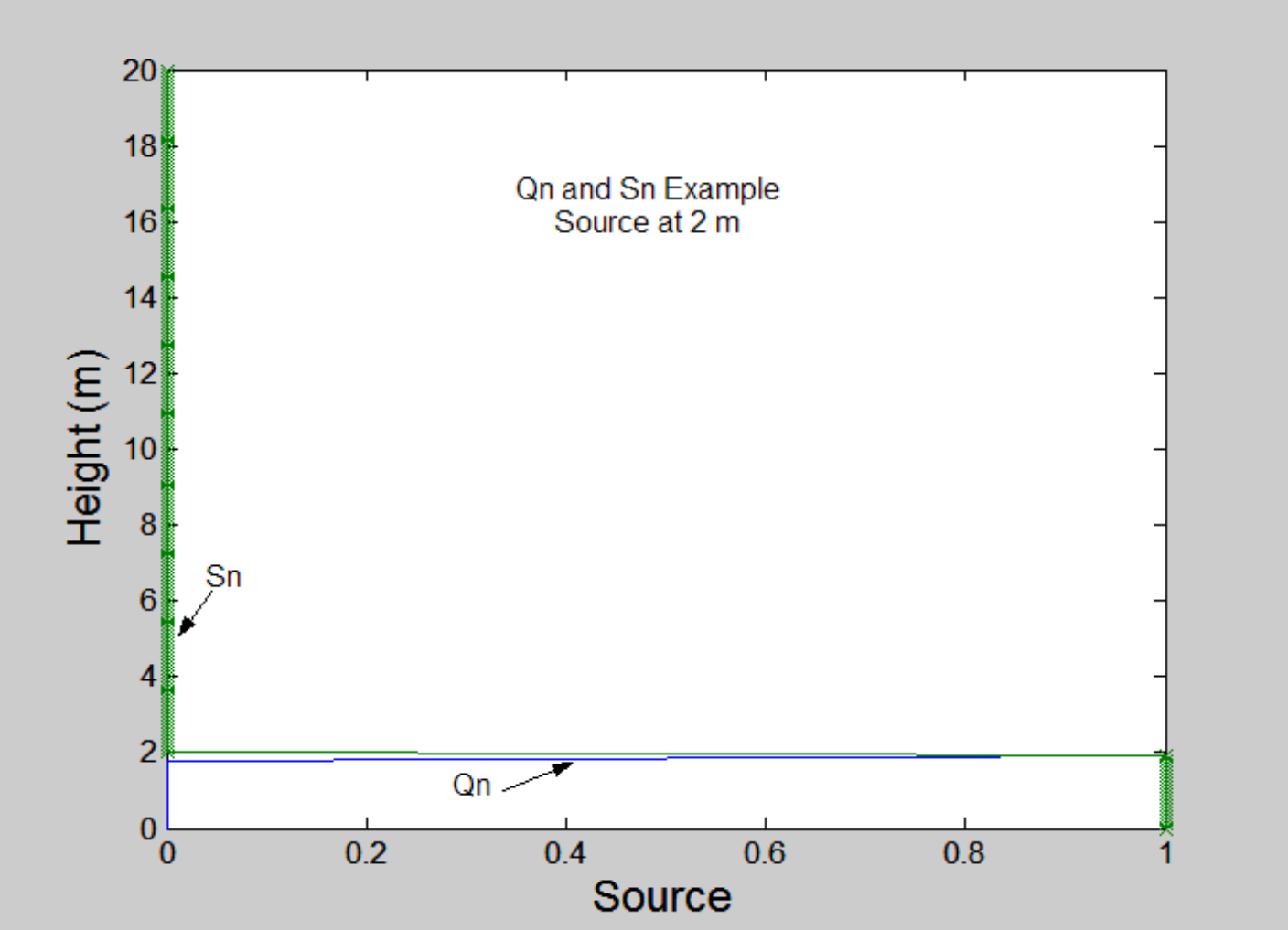


$$S_n(z,r) = \int_z^{\infty} Q_n(z)dz$$ Number(r)/m^2/sec

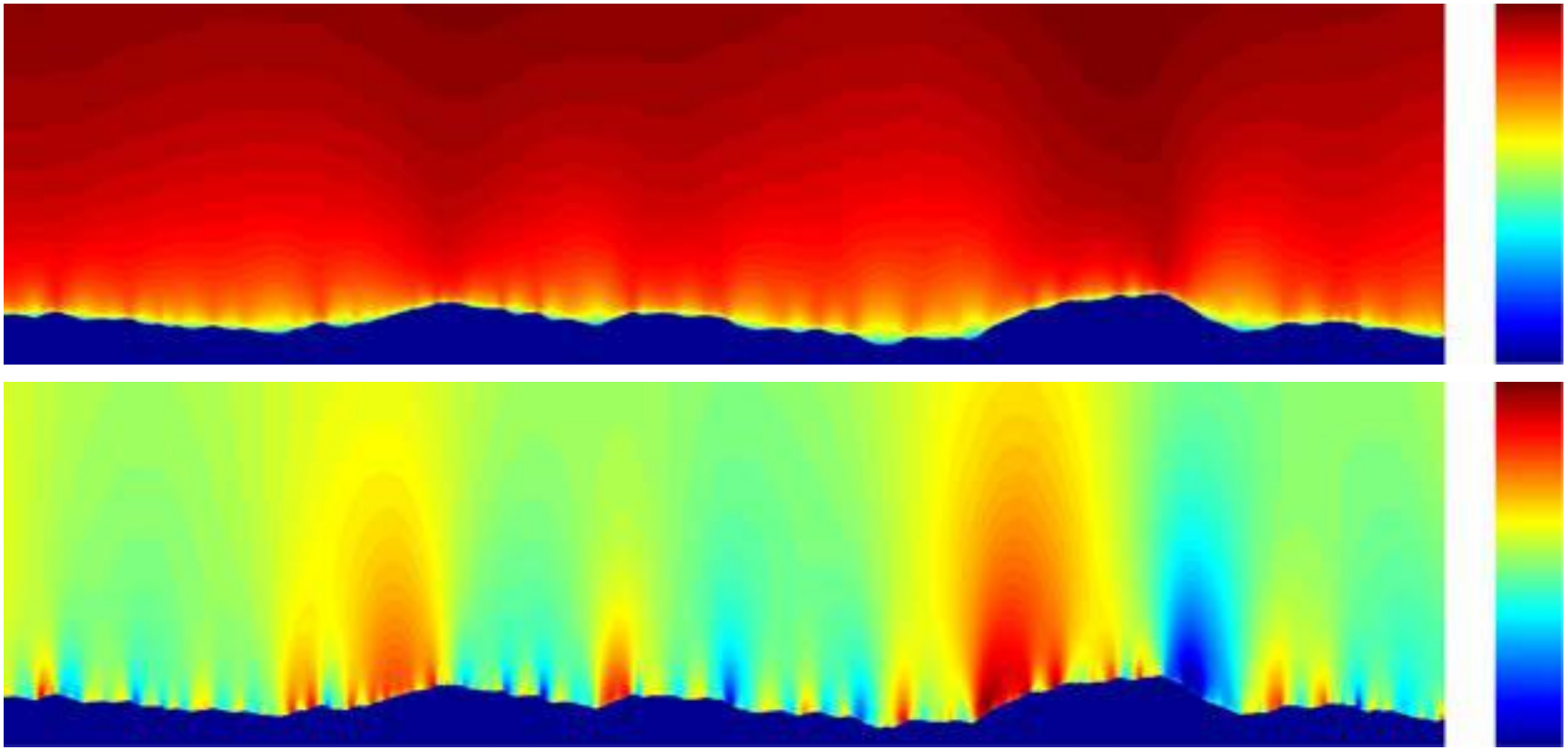
- HOWEVER:
- At least one additional piece of information is required to characterize the source.
- *Initial ejection velocity W_{ej}
- *Effective height h

Example: Q_n is delta-function source at height h=2m

$$S_n = \int_z^{\infty} Q_n(z)dz$$



Flow Over Waves



Horizontal speed – upper panel; Vertical speed – lower panel. Wind from left to right.

Energy Of Wave Breaking

- Wave Model
  - P computed from wave spectral model
- Energy flux from atmosphere

$$\dot{E}_a = \rho_a(\overline{wu} - \upsilon\frac{\partial U}{\partial z})U$$

$$\overline{\dot{E}_w} = C_{wave}\tau_{wave} + U_0(\tau_{total} - \tau_{wave})$$

$$P = -\overline{\dot{E}_w} \approx -C_{wave}\tau_{wave}$$

Droplet Source Functions

Fairall et al. 1994

$$S_n(r) = W_b(U) S_{n0}(r)$$

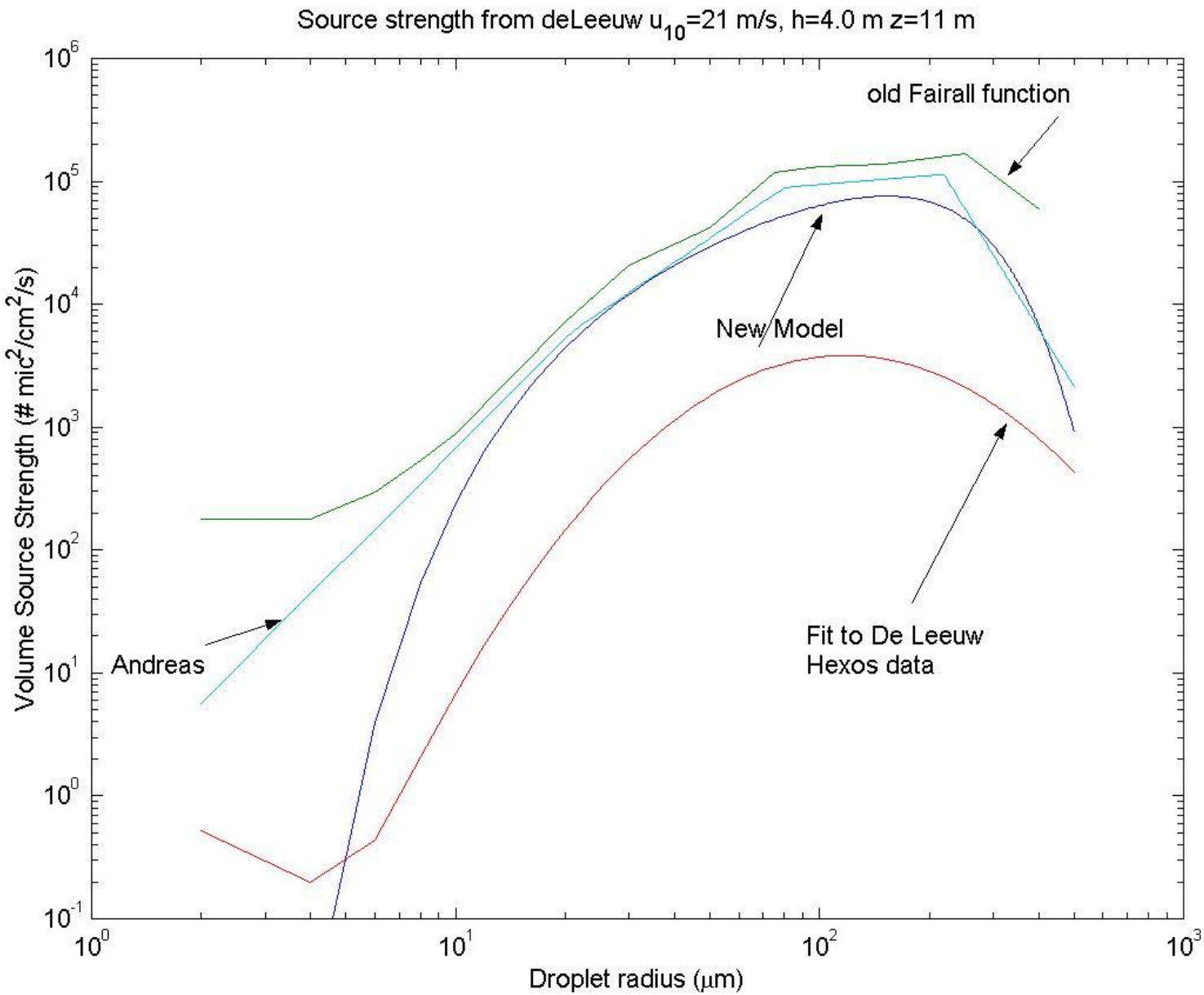
Fairall-Banner *Physical Model*:

Balance of **energy produced by wave breaking** and lost in production of drops and bubbles. *Error function* describes probability drop trajectory escapes surface.

$$\frac{4\pi r^3}{3} S_n(r) = \frac{r\ f\ P}{\sigma\Lambda} \exp[-\frac{9}{4}\alpha_k (\frac{\pi\eta}{r})^{4/3}] * [1 + erf(\frac{U_{top} + U_b - V_f / Slope}{\sigma_u})] / 2$$

P energy wave breaking
σ surface tension
r droplet radius
η Kolmogorov microscale in the ocean
f fraction of P going into droplet production
U_{top} wind speed near breaker top
U_b group speed of breaking wave
Λ Unspecified length scale (or, P/ Λ volume dissipation near surface)

S_n Surface Source Strength for Sea Spray Droplets



Simplified Steps in the Sea Spray Chain

- Droplets thrown in air: Source – $Q_n(r)$ at h

$$S_n = \int_z^{\infty} Q_n(z)dz$$

- Individual drops transfer heat/moisture to air

$$DropHeat = 4\pi f_p \rho_a c_{pa} D_h r(T_p - T_a)$$

$$DropMoisture = 4\pi f_p \rho_a D_v r(q_p - q_a)$$

- Cumulative effect computed by integrating over droplet spectrum:

$$Q_l' = hL_e \int n(r) DropMoisture * dr$$

$$n(r) = S_n(r)/V_f(r) \quad over\ depth\ h$$

$$Q_l' = \rho_a L_e F_a h(q_p - q_a)$$

$$F_a = 4\pi D_v \int \frac{f_p(r) r S_n(r)}{V_F(r)} * dr$$

Q_l'=Droplet latent heat flux

Q_s'=Drop sensible heat flux

$$Q_s' = \rho_w c_{pw} F_v (T_o - T_a)$$

$$F_v = 4\pi/3 \int r^3 S_n(r)dr$$

Original Droplet Equations: Wind Speed Driven
Fairall/Andreas/Kepert Early 1990's

$$H_s' = \rho_a c_{pa} C_H U (T_o - T_a)$$ Direct sensible

$$H_l' = \rho_a L_e C_E U (q_s(T_o) - q_a)$$ Direct Latent

$$Q_s' = \rho_a c_{pa} F_v [T_o - T_a]$$ Raw Droplet Sensible

$$Q_l' = \rho_a L_e F_a h [q_s(T_{wet}) - q_a]$$ Raw Droplet Latent

$$S_n(r) = W_b(U) S_{n0}(r)$$

$$F_a = 0.125 s^{-1} W_b \qquad F_v = 5X10^{-6} ms^{-1} W_b$$

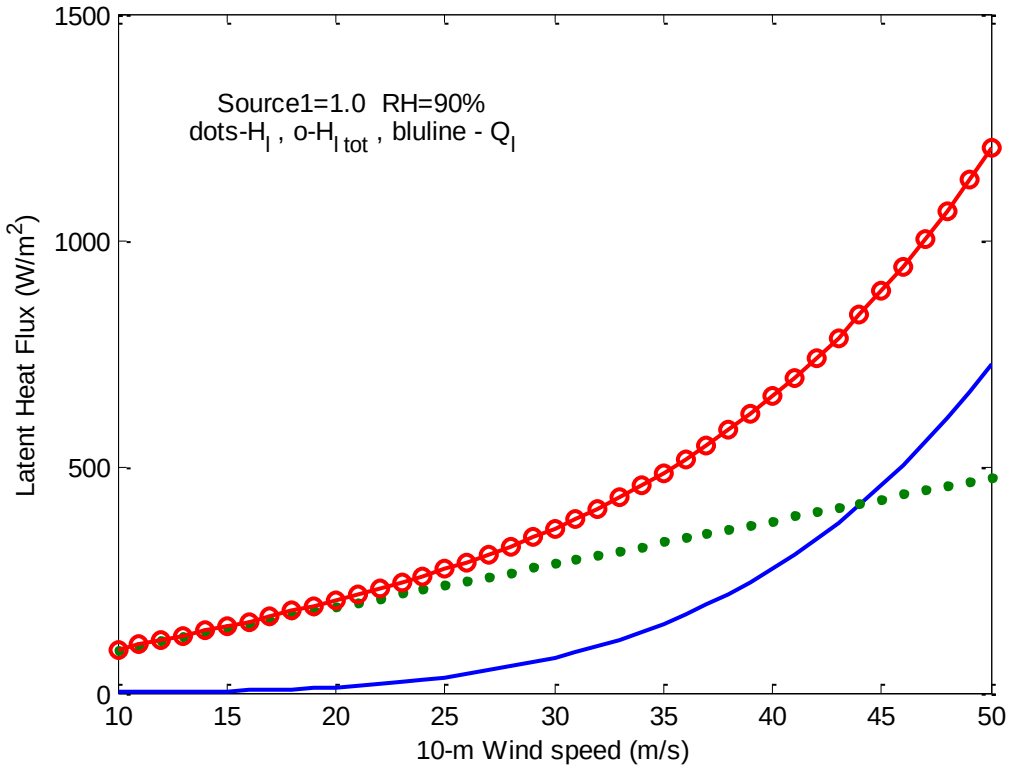
NO FEEDBACK DROP FLUXES

Version 2.0: Wave parameters related to U, u*

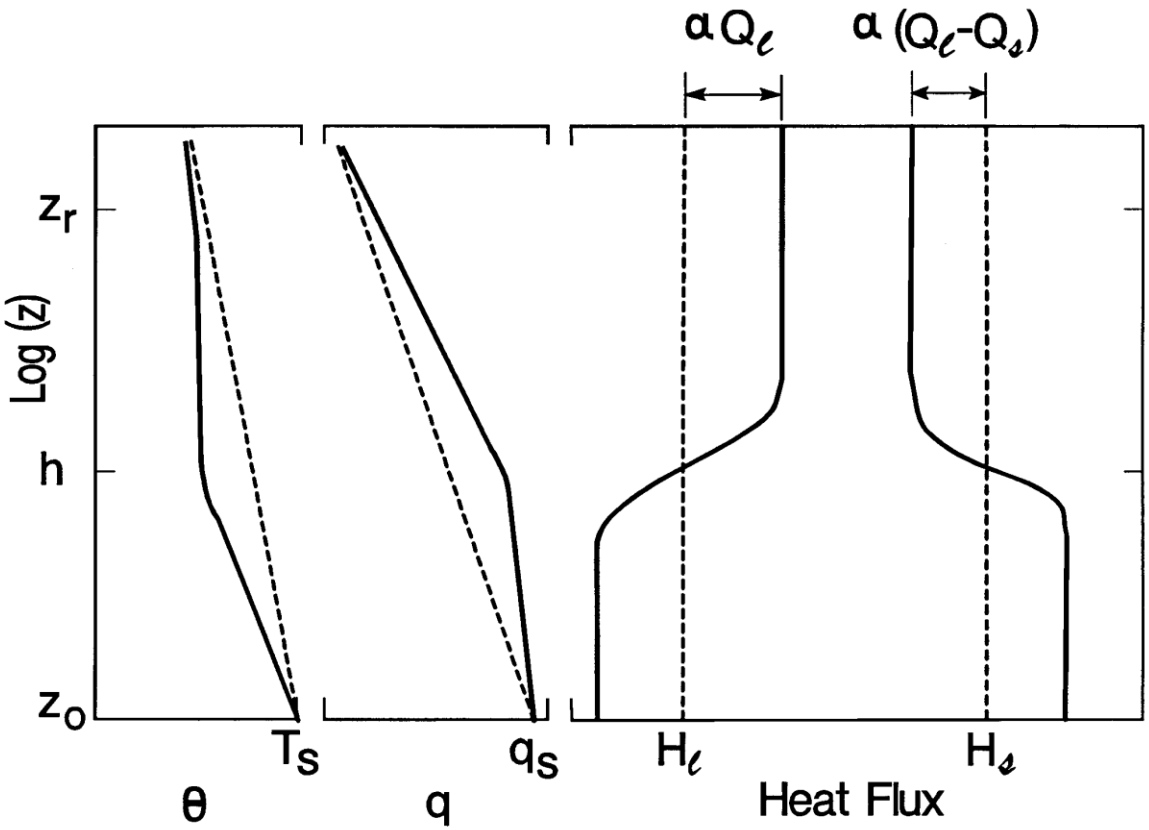
Parameters fit to Couple Atmosphere-Wave Models: *U Miami* – Hurricane *URI* - Idealized

- cwave=1*(10+0.16*u); Wave Phase Speed
- hwave=1.*(1+.25*u); Wave Height
- P=rhoa*3.5*usr.^3.5/rhow; Energy Flux to Breaking Waves

$$\frac{4\pi r^3}{3} S_n(r) = \frac{r\ f\ P}{\sigma\Lambda} \exp[-\frac{9}{4}\alpha_k (\frac{\pi\eta}{r})^{4/3}]*[1+erf(\frac{U_{top}+U_b-V_f\ /\ Slope}{\sigma_u})]/2$$



Feedback



Defined by distortions of the temperature & humidity profiles in the Droplet evaporation zone: δT δq

Net fluxes emerging from top of droplet layer

$$H_{s_tot} = H_s' + \alpha_s Q_s' - \alpha_l Q_l' \qquad H_{l_tot} = H_l' + \alpha_l Q_l'$$

Alpha accounts for *feedback* (droplet – T/q profile interactions)

Feedback Characterization δT_a
Droplet Layer cooling and moistening

- EXAMPLE: Sea Spray enthalpy balance from Andreas and Emanuel 2002

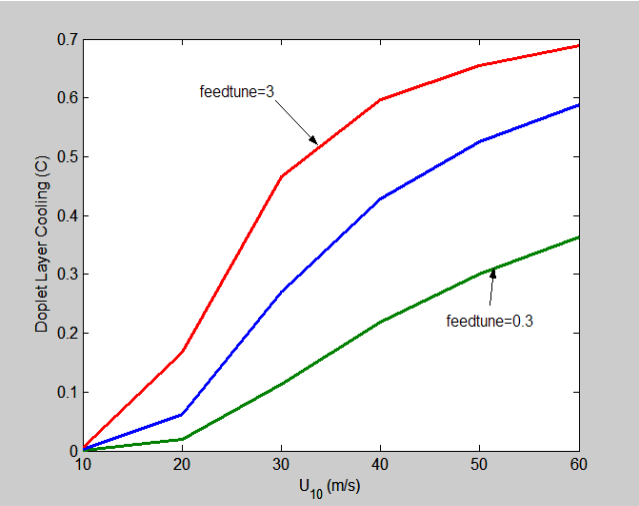
$$\delta T_a = \frac{c_w \delta m_i / D[(T_0 - T_a) + (1 - f_e)(T_a - T_w)] - L_e f_e \delta m_i / D}{c_{pd} \rho_d + c_{pv}(\rho_v + f_e \delta m_i / D)}$$

$$H_s = \rho_a L_e C_E U[T_o - (T_a - \delta T_a)]$$

$$H_l = \rho_a L_e C_E U[q_s(T_o) - q_s(T_d + \delta T_d)]$$

$$Q_s = \rho_w c_{pw} F_V (T_o - T_a + \delta T_a)$$

$$Q_l = \rho_w L_e G(U) h \beta(T_o) W_b [q_s(T_a - \delta T_a) - q_s(T_d + \delta T_d)]$$



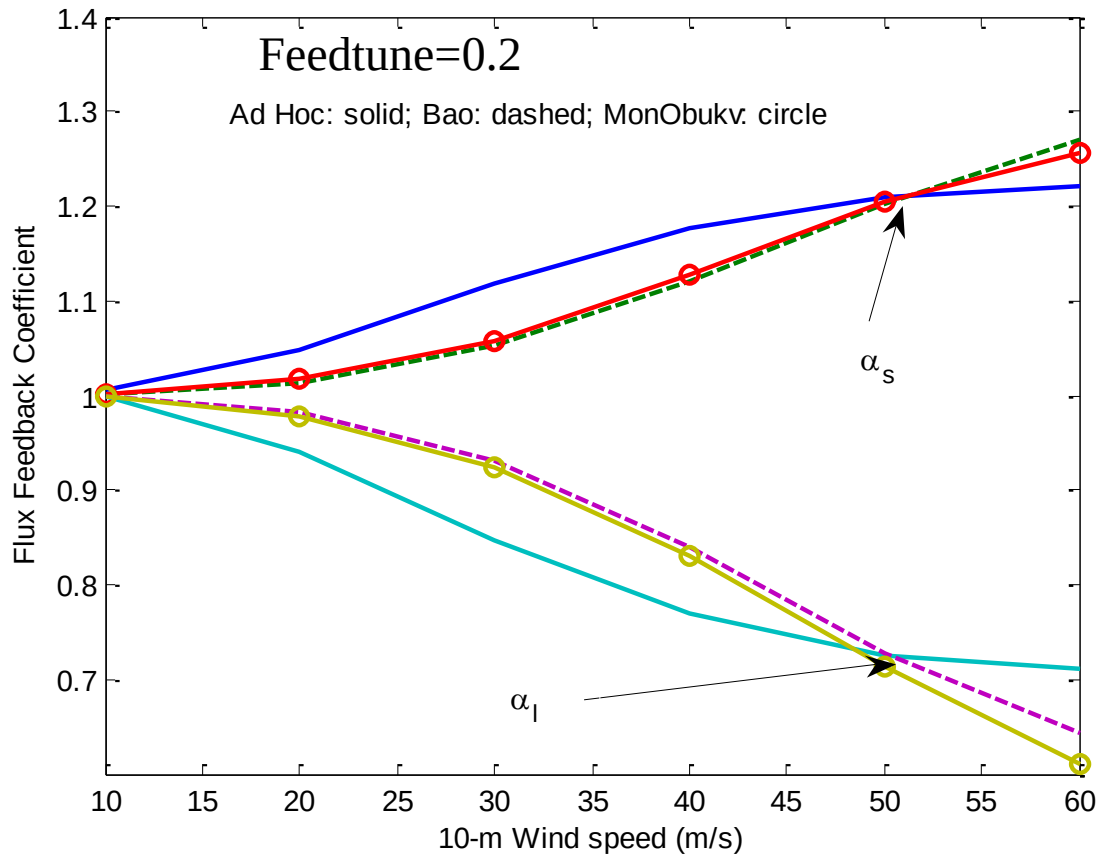
Feedback Effects: Three Representations

- From δT & δq compute new values of droplet sensible and latent heat values: Q_s and Q_l
- This defines feedback coefficients in terms of original raw fluxes

$$H_{s_tot} = H_s' + \alpha_s Q_s' - \alpha_l Q_l' \qquad H_{l_tot} = H_l' + \alpha_l Q_l'$$

$$\alpha_s = \frac{Q_s + \rho_a c_{pa} C_H U \delta T}{Q_s'}$$

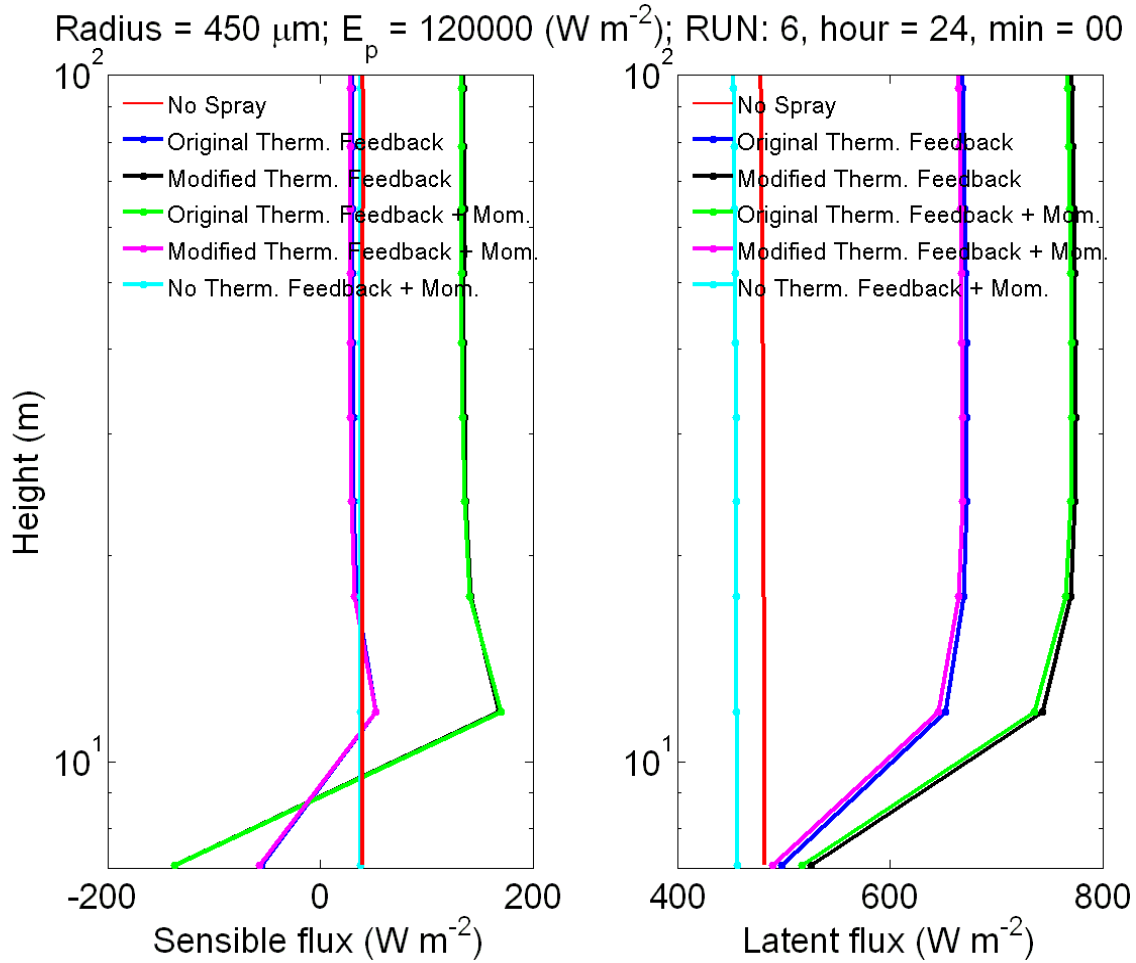
$$\alpha_l = \frac{Q_l - \rho_a c_{pa} C_E U \delta q}{Q_l'}$$



Recent Work

- Added droplet mass stratification effect – suppresses momentum transfer and decreases stress and droplet production
- Bao, J.-W., C. W. Fairall, S. A. Michelson, L. Bianco, 2010: Parameterizations of sea-spray impact on the air-sea momentum and heat fluxes.
- Bianco, L., J.-W. Bao, C. W. Fairall, and S. A. Michelson, 2010: Impact of sea spray on the surface boundary layer.
- SPANDEXII
  - CIP velocity analysis
  - IR droplet imager
  - Ocean dissipation profiles – TKE flux
- NOAA P-3 Near-surface observing systems
  - PSD W-band Doppler radar
  - NASA WSRA (waves)
  - Controlled Tethered Vehicle

Coupled Bin microphysics droplet, 1-D 1.5 order high res PBL model

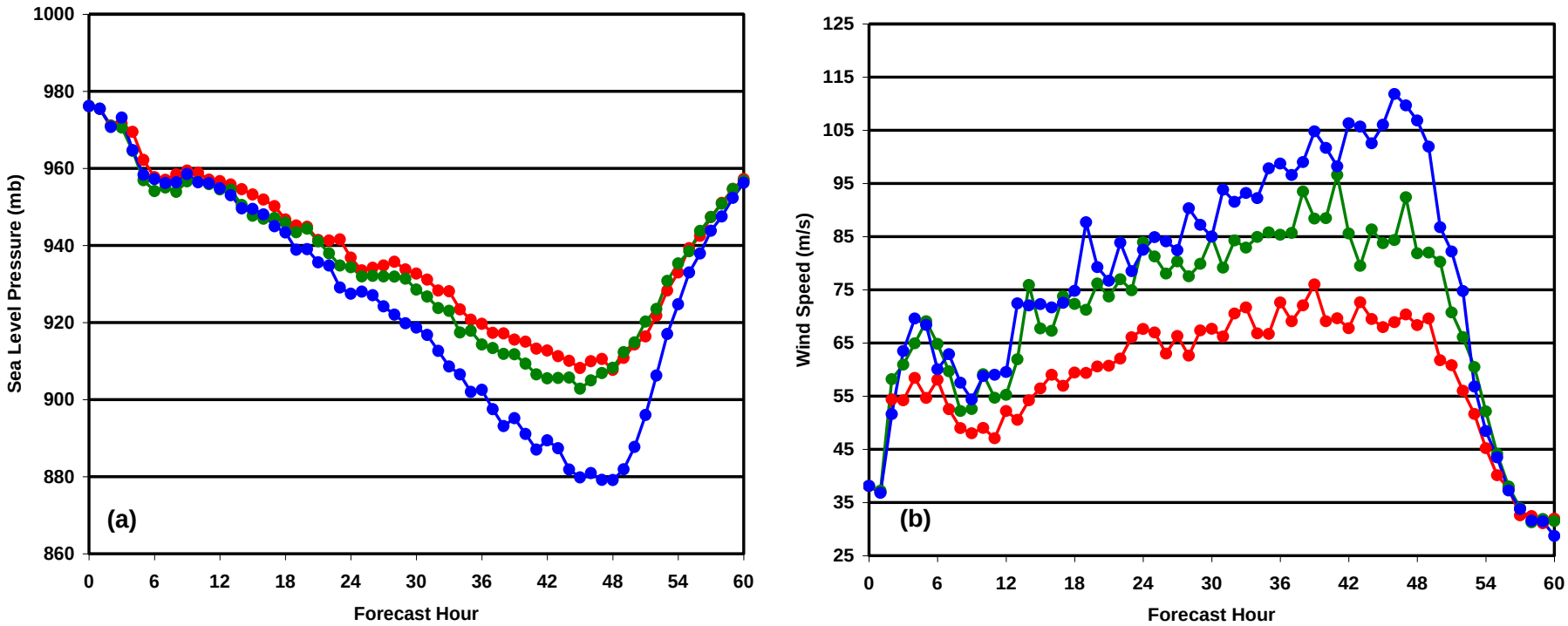


Vertical profiles of heat fluxes associated with various feedback effects of sea spray for 10-m wind speed = 50 ms-1, droplet radius = 500 mm, mass of the droplets = 4.8*10-2 Kg/m2/s, and potential evaporation = 120000 (W m-2).

HWRF Sensitivity Studies

Parameterizations of Sea-Spray Impact on the Air-Sea Momentum and Heat Fluxes

J.-W. Bao, C. W. Fairall, S. A. Michelson, L. Bianco

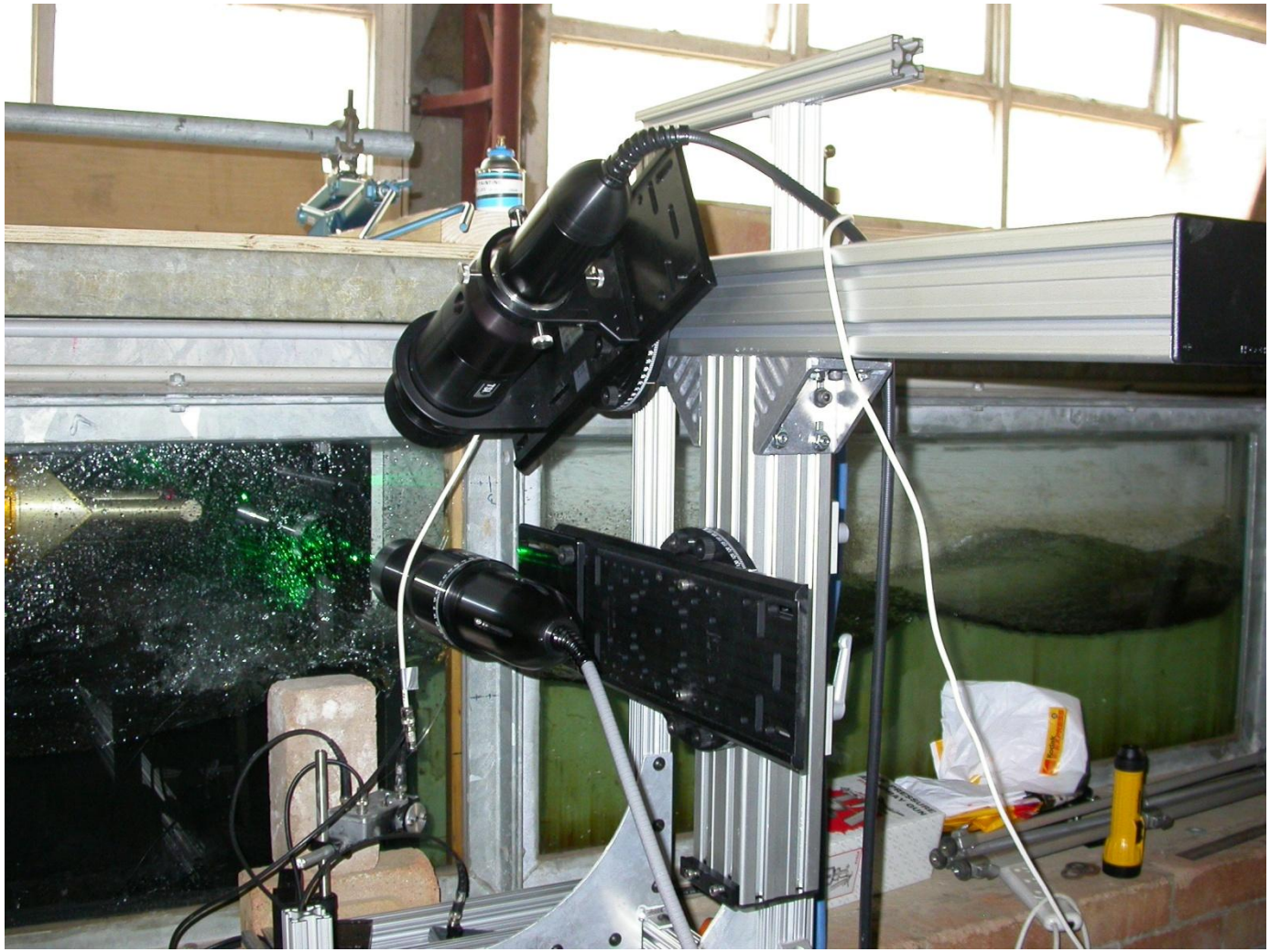


(a) Minimum sea-level pressure (mb) and (b) maximum wind speed (ms^{-1}). The control run (without the sea spray parameterization) is in red; the no impact on heat run (with the feedback of sea spray to the momentum flux only) is in green; and the full impact run (with the feedback of sea spray to both momentum and heat fluxes) is in blue.

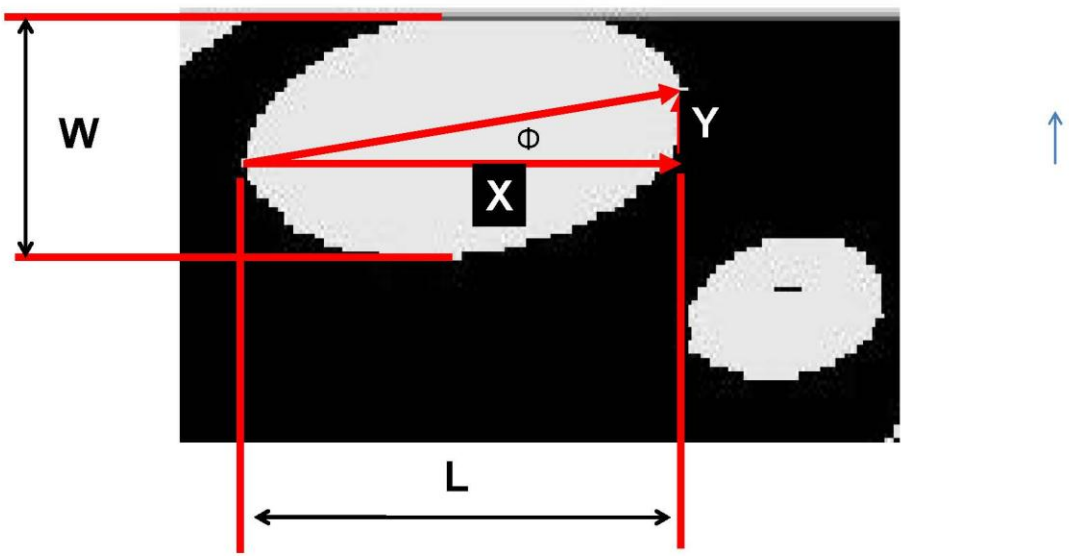
SPANDEX I and II

Photograph of PDA and DMT probes for the Spray Production and Dynamics Experiment (Water Research Facility, Manly, Australia; January 2003 and June 2009).

Bill Asher, Mike Banner, Chris Fairall, Bill Peirson



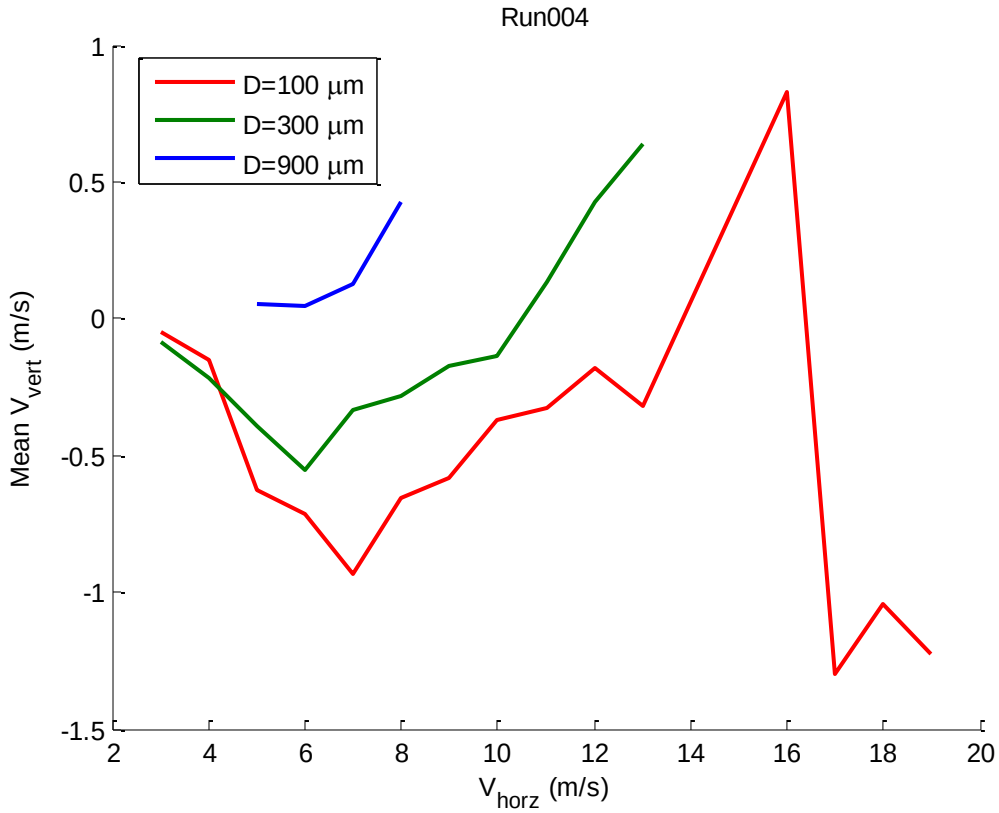
Preliminary look at some SpandexII CIP drop processing. This is based on the image processed files provided (with incredible generosity) by Darrel Baumgardner (darrel.baumgardner@gmail.com).

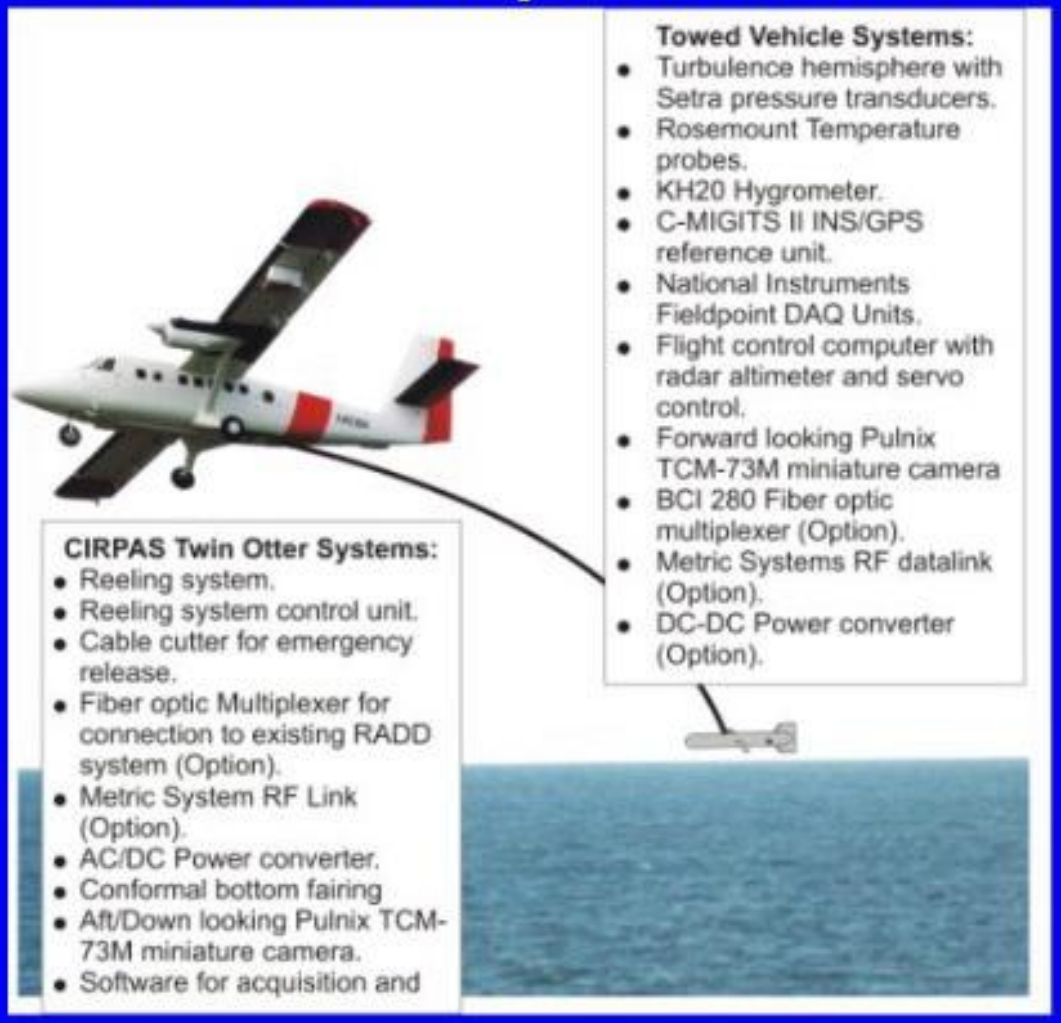


$$\Phi = \mathrm{Tan}^{-1}(Y/X) = V_T/V_H$$

$$V_H = \text{Airspeed Clock } (W/L)$$

Run 004: Wind speed u*=1.3 m/s.
Mean vertical motion for different drop sizes as a function of horizontal droplet speed. Small drops tend to have downward motion (max for horizontal speed of 7 m/s) while large drops near-zero to upward.



CIRPAS SCIENTIFIC INSTRUMENTATION

Low Altitude Atmospheric Flux Platform