Ocean Seminar Series
University Colorado
November 16, 2009

Air-sea fluxes - light winds to hurricanes

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Physics of air-surface interactions and coupling to ocean-ice/atmosphere BL

Aspects:

- Emphasize surface fluxes
- Similarity Scaling
- Bulk Flux Parameterizations
- Surface/subsurface processes
- Improve Observing Technologies
- Flux climatologies

Applications:

- Model lower BC (PBL, Meso, NWP, GCM)
- Ocean budgets (stress, heat, waves, sea-ice)
- Carbon budgets
- Pollution deposition (particle, ozone)
- Cloud microphysics (aerosol source, DMS)
- Atmos Propagation (Cn^2, ducting, extinction)
- Hurricane intensity

Why A Flux?

Budget equation for concentration *x=X+x'*

$$\frac{DX}{Dt} = -\frac{\partial}{\partial z}\left[\overline{w'x'} - D_x\frac{\partial X}{\partial z} - V_g X + \overline{w_s'x'}\right] + Q_x$$

Rate change = [turbulent + molecular + mean fall + slip covariance] + Source

Put source term inside derivative

$$\frac{DX}{Dt} = -\frac{\partial}{\partial z}\left[\overline{w'x'} - D_x\frac{\partial n}{\partial z} - V_g X + \overline{w_s'x'} + S_x\right]$$

Volume source becomes an area flux

$$S_x = \int_z^\infty Q_x(z)dz$$

Generalized flux variable

$$F_x = \left[\overline{w'x'} - D_x\frac{\partial X}{\partial z} - V_g X + \overline{w_s'x'} + S_x\right]$$

Source Examples:

Temperature – radiative flux, condensation

Water vapor – evaporation

Liquid water – condensation, sea spray

Ozone – reactions is air or water, eg Q_x=-$C_{xy}XY$

Particles – gas-particle, coalescence, sea spray, blowing dust, meteors

Flux Definitions

$$Sensible\ Heat: H_s = \rho_a c_{pa} \overline{w'T'}$$

$$Latent\ Heat: H_l = \rho_a L_e \overline{w'q'}$$

$$Stress: \vec{\tau} = \rho_a \overline{w'u_x'}\hat{i} + \rho_a \overline{w'u_y'}\hat{j}$$

$$Rain\ Heat: H_p = c_{pw} P(T_s - T_{wet})$$

$$BuoyAir: F_b = H_s / \rho_a c_{pa} + 0.61T\ H_l / \rho_a L_e$$

$$BuoyWater: F_b = -\alpha g H_{net} / \rho_w c_{pw} + \beta g(E - P)$$

$$Gas\ Exchange: F_x = \overline{w'r_x'}$$

$$Particle\ Exchange: F_n = \overline{w'n(r)'} - w_g \overline{n(r)} + \overline{w_s' n(r)'}$$

Present Status of *Surface* Flux Parameterizations

Turbulent Fluxes: Bulk Parameterization

Mean correlation of turbulent variables represented in terms of mean flow variables – wind speed, surface-to-air variable difference

MetFlux – Dominated by atmospheric turbulent xfer

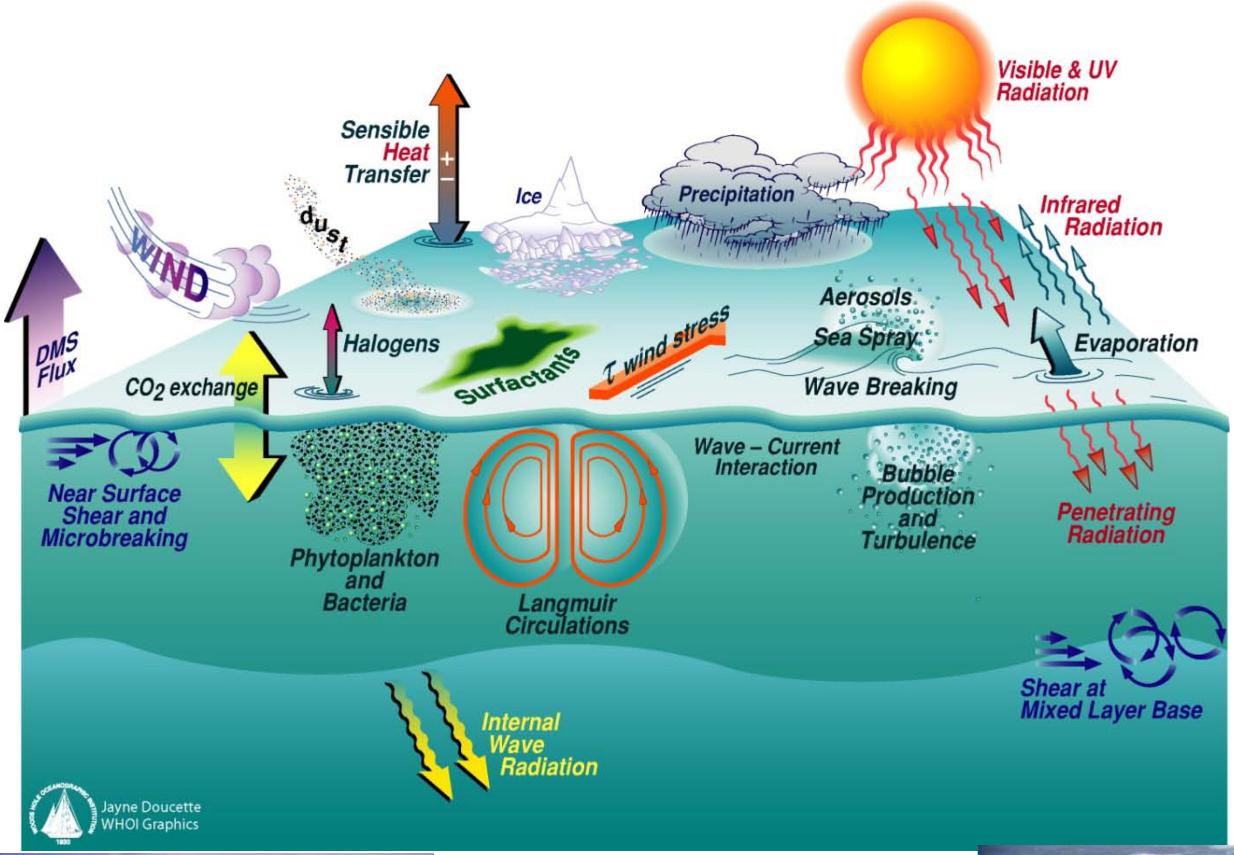
GasFlux – Dominated by oceanic molecular xfer; Enhanced by whitecap bubbles

$$Met\ Flux: \overline{w'x'} = C_x U (X_s - X_r) = C_x U \Delta X$$

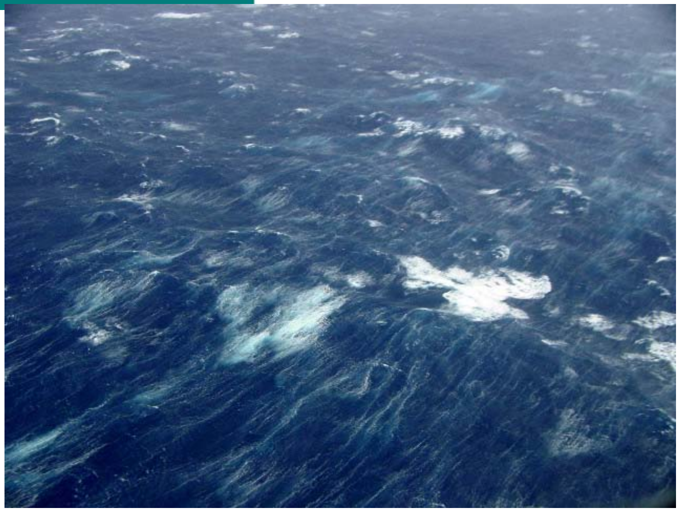
$$Gas\ Flux: \overline{w'x'} = k_x \alpha_x \Delta X \qquad \alpha = sol.$$

$$Particles: F_{deposition} = -V_d(r)\overline{n(r)};$$

$$F_{source} = F(f_{whitecap}, U, u_*, wave\ breaking, slope)$$



Do You Feel Lucky?
C_d=Constant



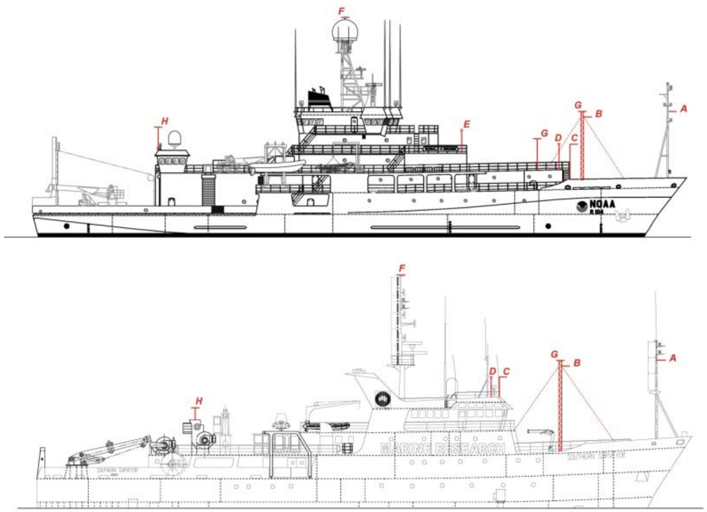
Sensing Technologies

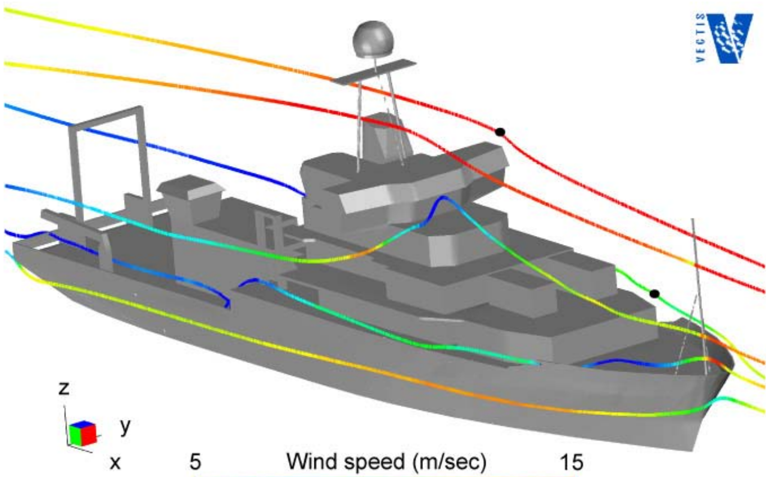
- Near-surface in situ
  - Sonic anemometer/thermometer
  - IR fast hygrometer, fast CO2
  - Chemilum. Fast ozone, DMS
  - High quality mean T, q, Ts
  - Eppley solar/IR radiometers
  - Surface waves
- Boundary Layer/column
  - Ceilometer
  - Wind profiling radar
  - Rawindsonde
  - Microwave radiometer
  - Doppler cloud radar

Unbelievable Number of Dirt Effects

- Motion corrections
- Contamination by salt, ship exhaust, sea gulls, …
- Flow distortion (Ship, tower, other sensors)
- Sensor separation, time delays, decorrelation, frequency response, path averaging,…
- Surface boundary conditions (currents, ocean/snow gradients)
- Extreme cold, icing, frost formation, fog/rain impact
- Poor signal to noise, weak stratified turbulence
- Sensor-variable crosstalk (Webb, motion, chemical)
- Artificial (self-) correlation

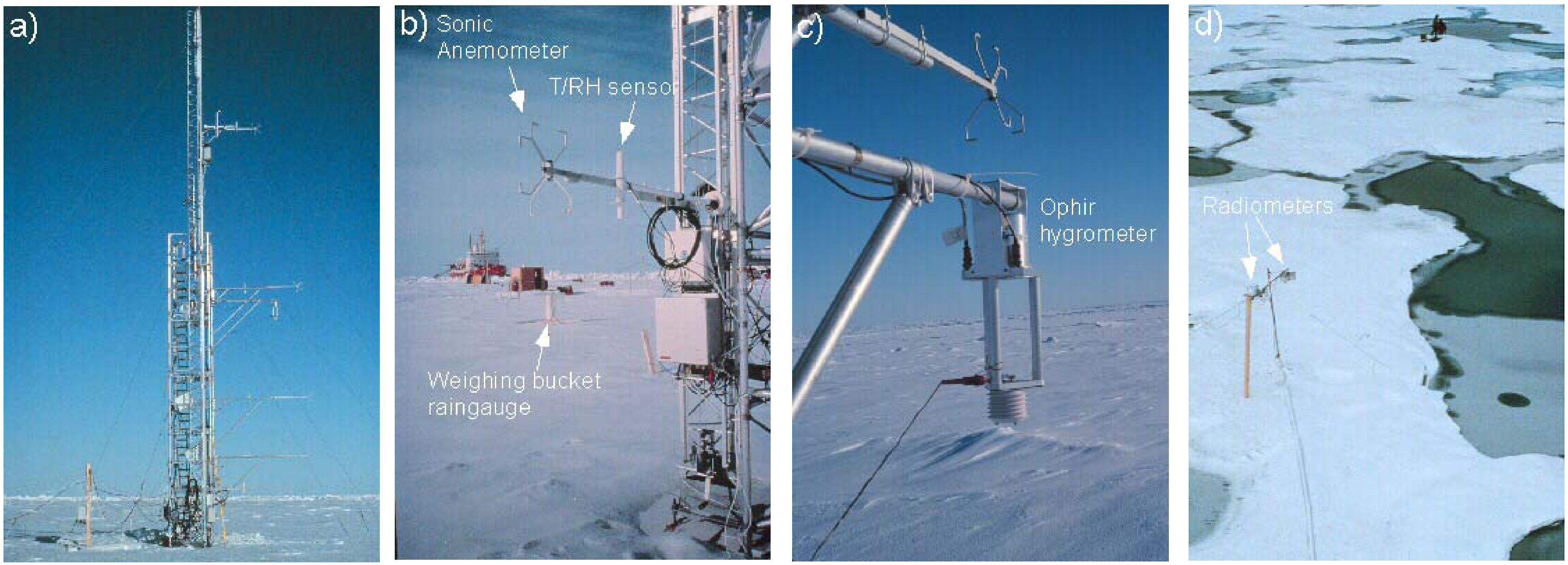
Turbulence Measurements from Ships



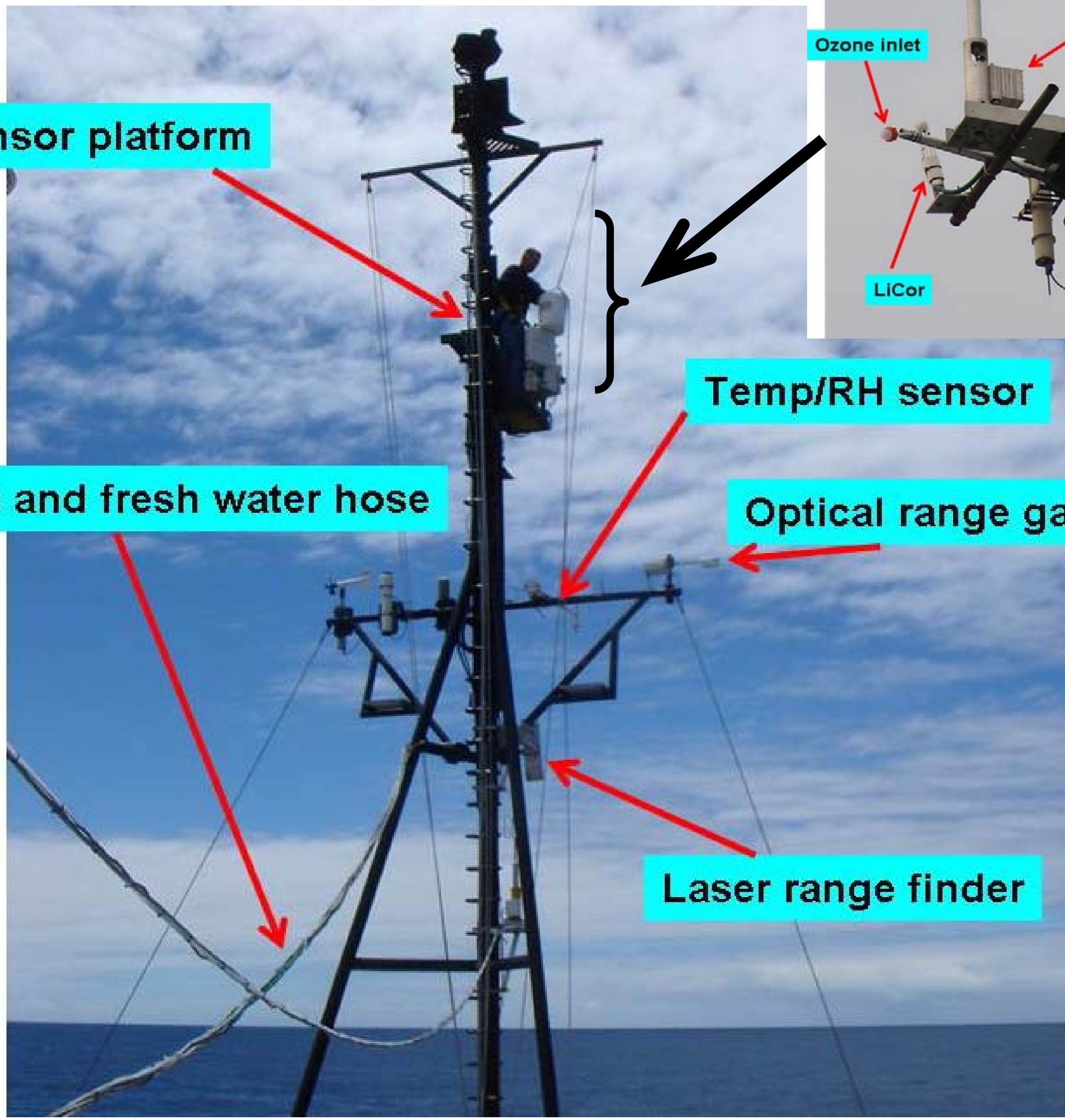


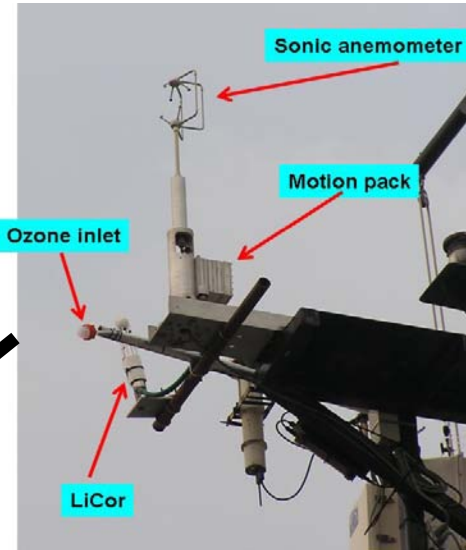
ASFG Air-Ice Flux Instrumentation SHEBA Field Program 1998-1999

- The Atmospheric Surface Flux Group (ASFG) deployed a 20-m main micrometeorological tower, two short masts, and several other instruments on the surface located 280 – 350 m from the *Des Groseilliers* at the far edge of the main ice camp.
- Turbulent and mean meteorological data were collected at five levels, nominally 2.2, 3.2, 5.1, 8.9, and 18.2 m (or 14 m during most of the winter).
- Each level had a Väisälä HMP-235 temperature/relative humidity probe (T/RH) and identical ATI three-axis sonic anemometers/thermometers.
- An Ophir fast infrared hygrometer was mounted on a 3-m boom at an intermediate level just below level 4 (8.1 m above ice).

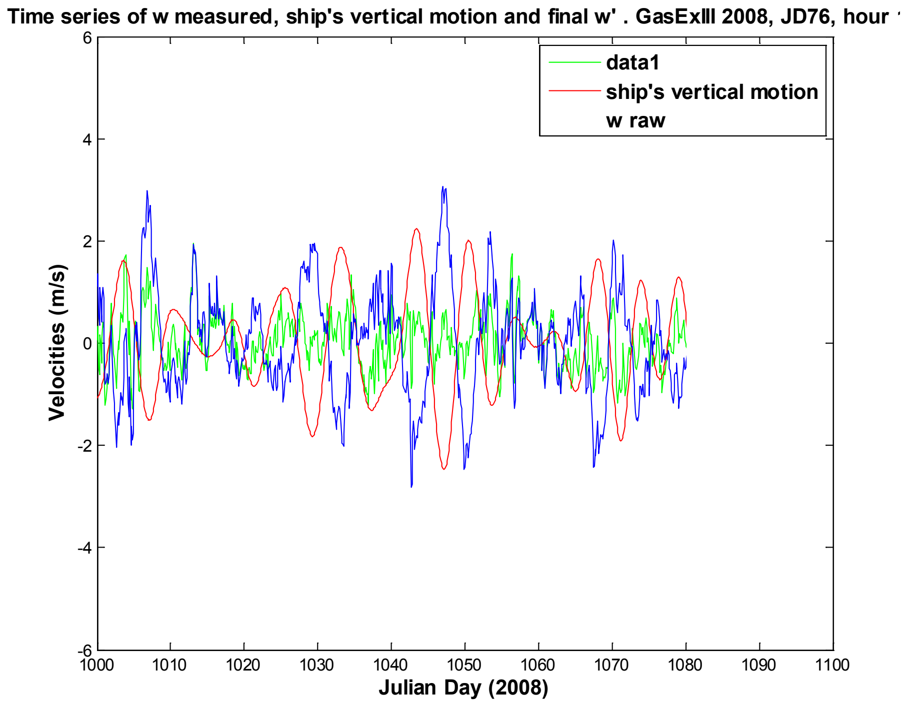


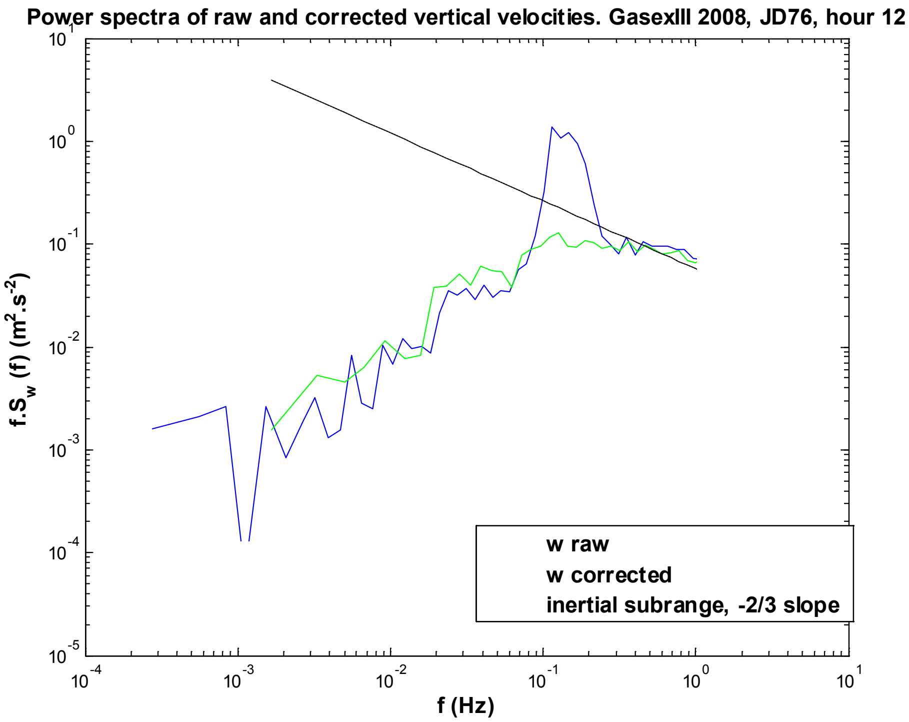
Example of Instrumented Mast



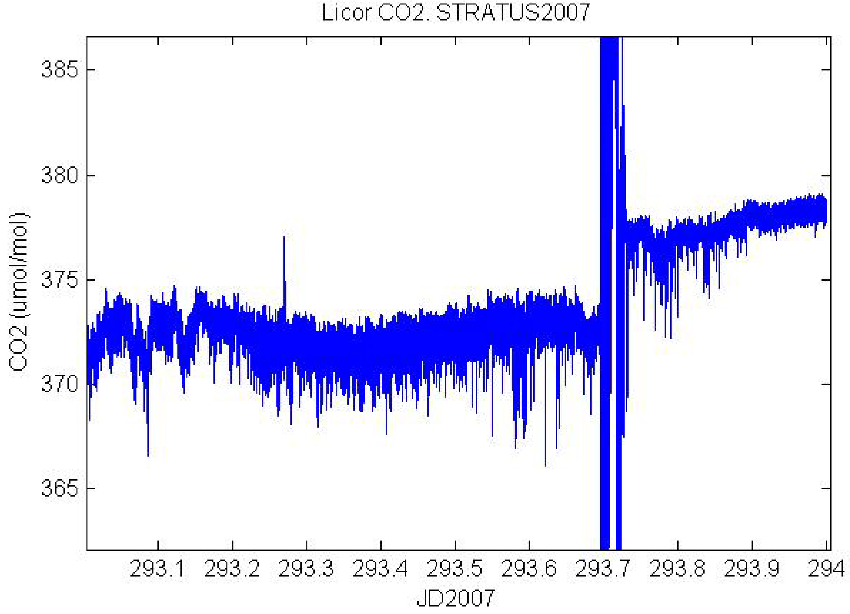


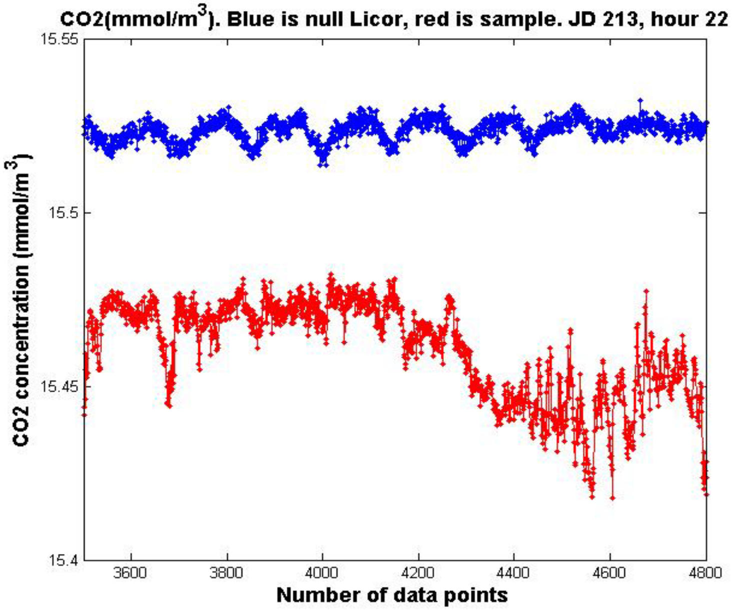
Ship Motion Corrections

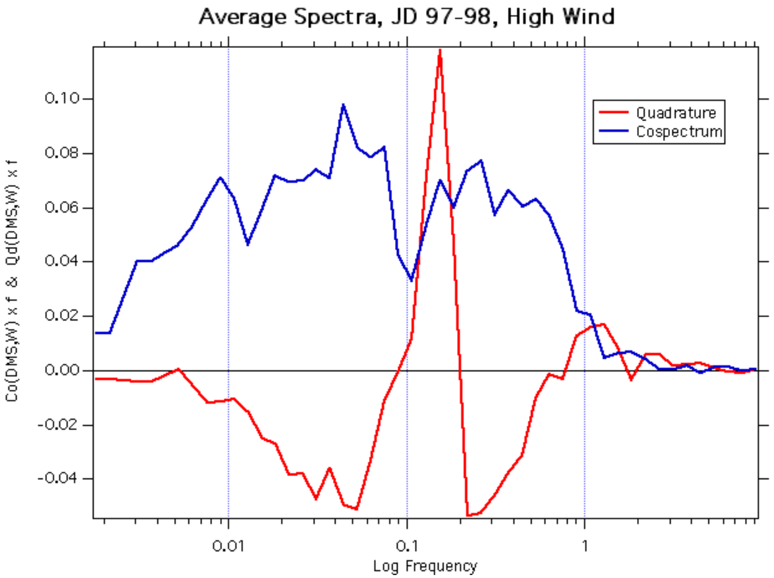




Sample Dirt/Crosstalk Effects







Historical perspective on turbulent fluxes: Typical moisture transfer coefficients

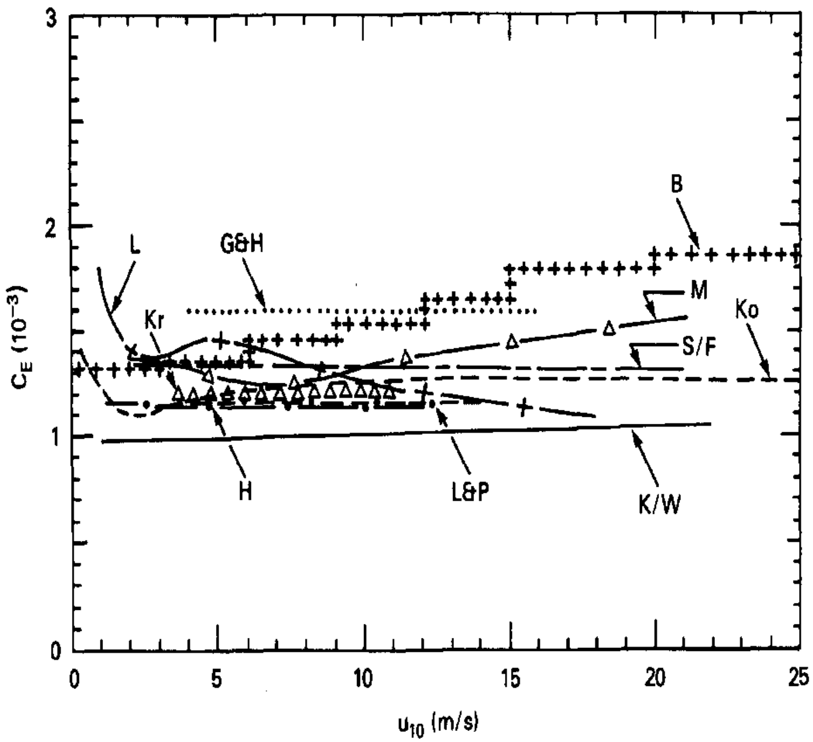
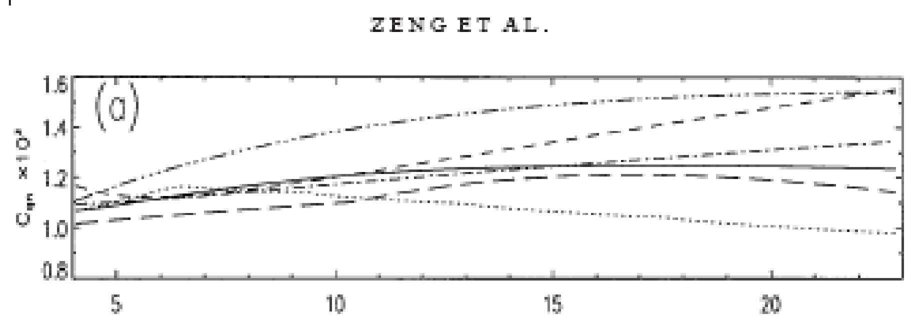
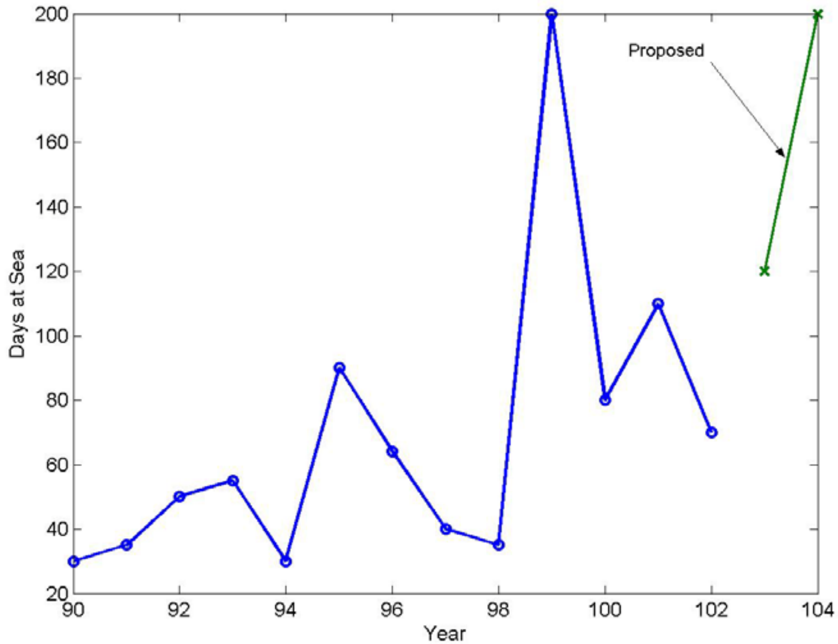


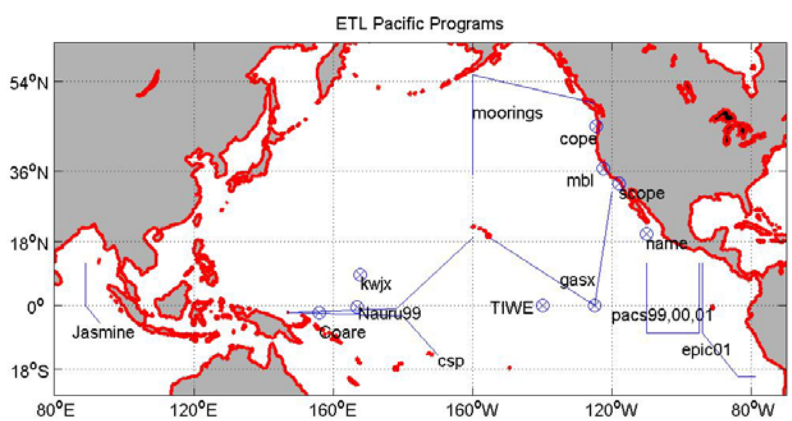
FIG. 3. Humidity coefficients (C_E) for the ten selected schemes under neutral or slightly unstable conditions as a function of the wind speed (u_{10}) at an altitude of 10 m. Scheme acronyms are given in Table 1.

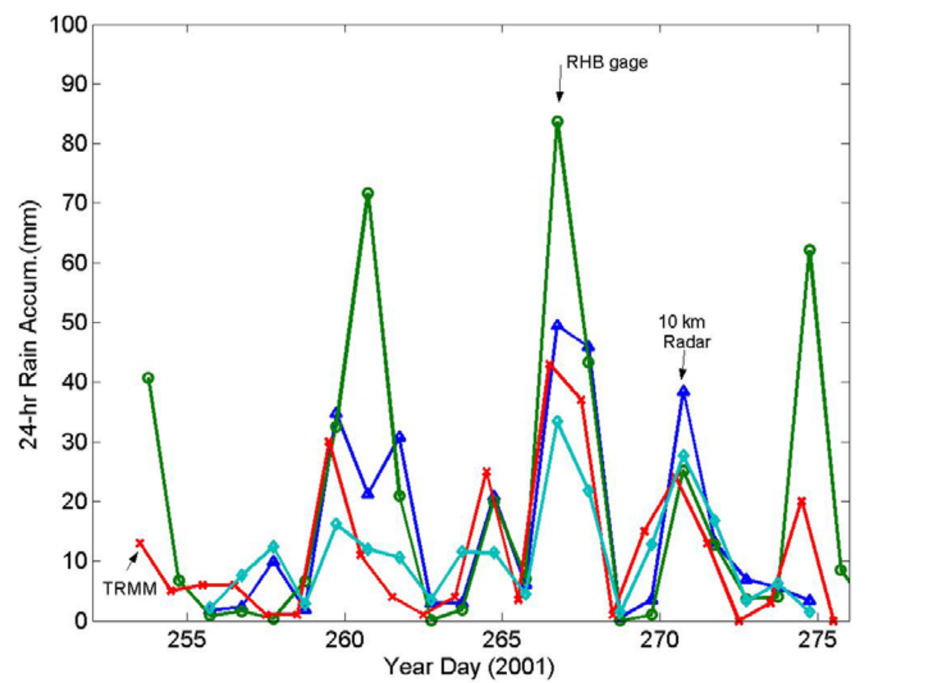


Algorithms of UA (solid lines), COARE 2.5 (dotted lines), CCM3 (short-dashed lines), ECMWF (dot-dashed lines), NCEP (tripledot-dashed lines), and GEOS (long-dashed lines) .


Proposed
Days at Sea
Year
200
180
160
140
120
100
80
60
40
20
90
92
94
96
98
100
102
104


NOAA
R 104

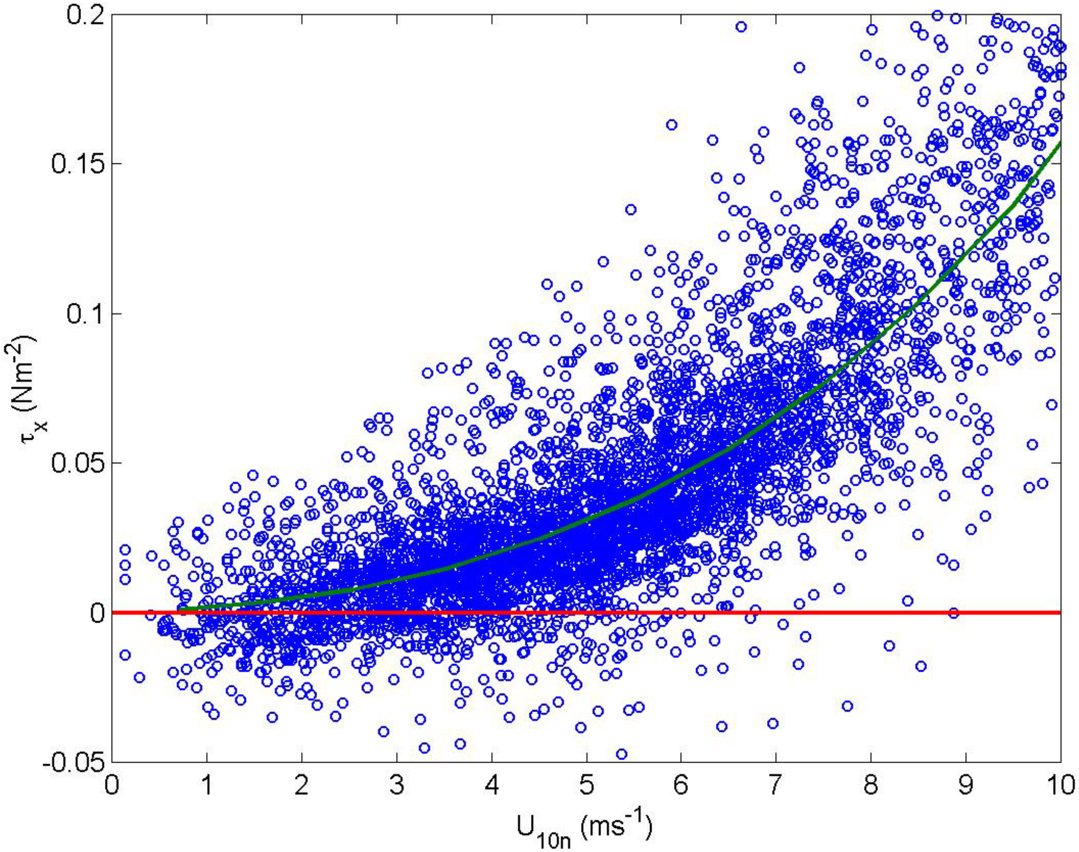

ETL Pacific Programs
54°N
36°N
18°N
0°
18°S
80°E
120°E
160°E
160°W
120°W
80°W
moorings
cope
mbl
scope
name
kwjx
Nauru99
TIWE
gasx
pacs99,00,01
Jasmine
Coare
csp
epic01


RHB gage
10 km
Radar
TRMM
24-hr Rain Accum.(mm)
Year Day (2001)
100
90
80
70
60
50
40
30
20
10
0
255
260
265
270
275

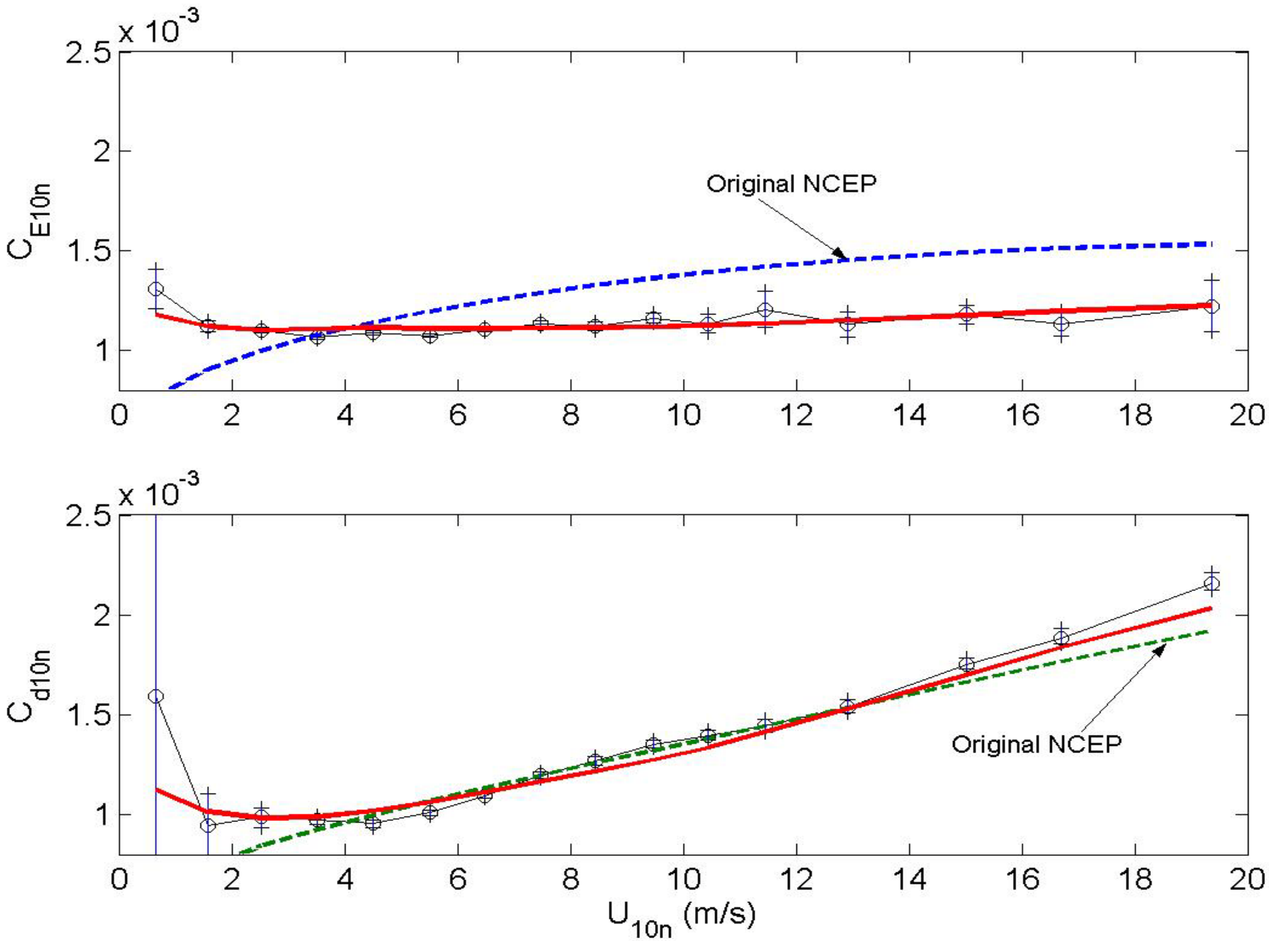
COARE MODEL HISTORY

- 1996 Bulk Meteorological fluxes ($k_u = u^* C_d$)
  - Update 2003 (8000 eddy covariance obs)
  - Oceanic cool skin module – molecular sublayer
- 2000 CO2
- 2004 DMS
- 2006 Ozone

$$\tau_x = C_d U^2 = -\rho_a \overline{w'u'}$$

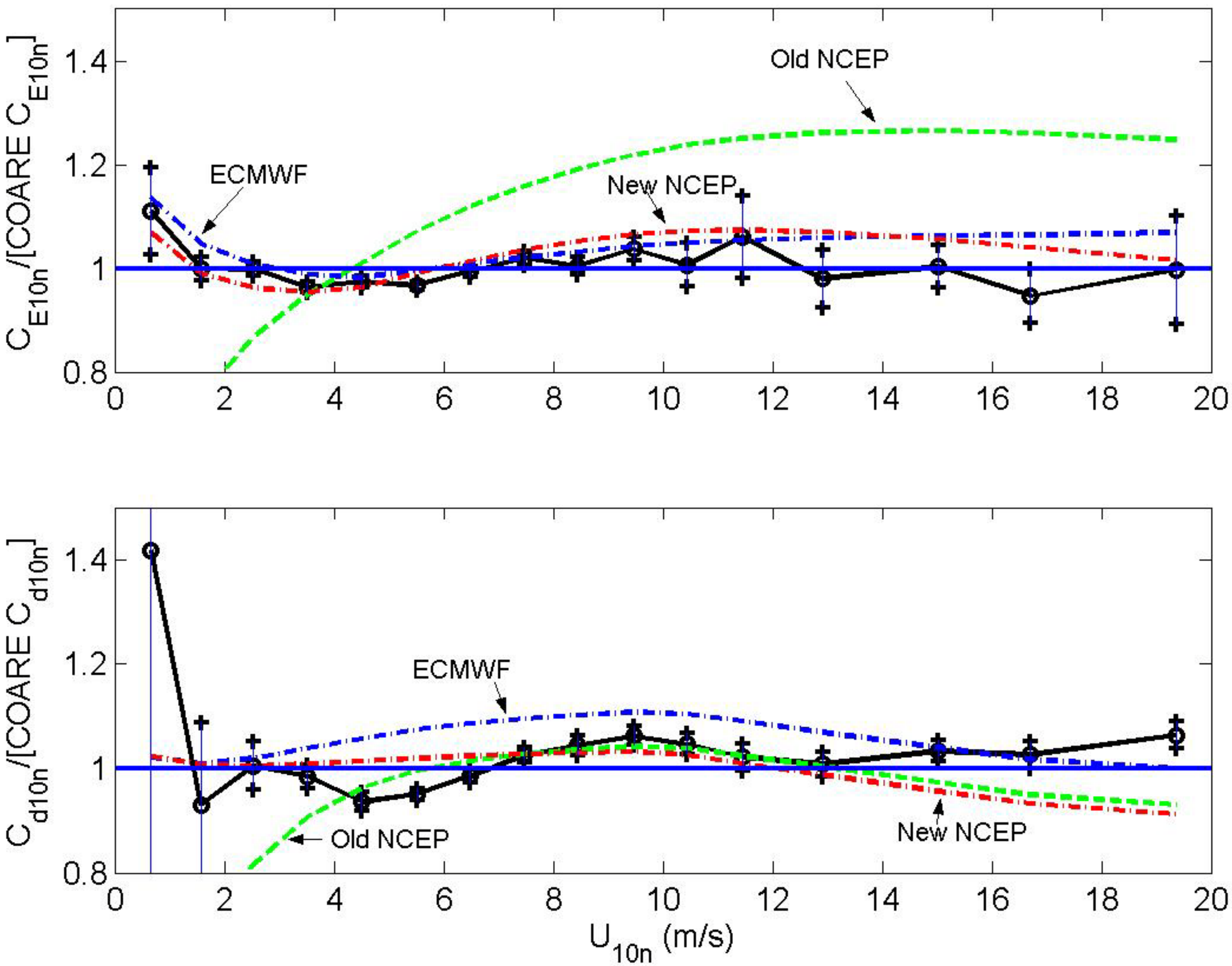


Results from 13 Cruises in 8 years

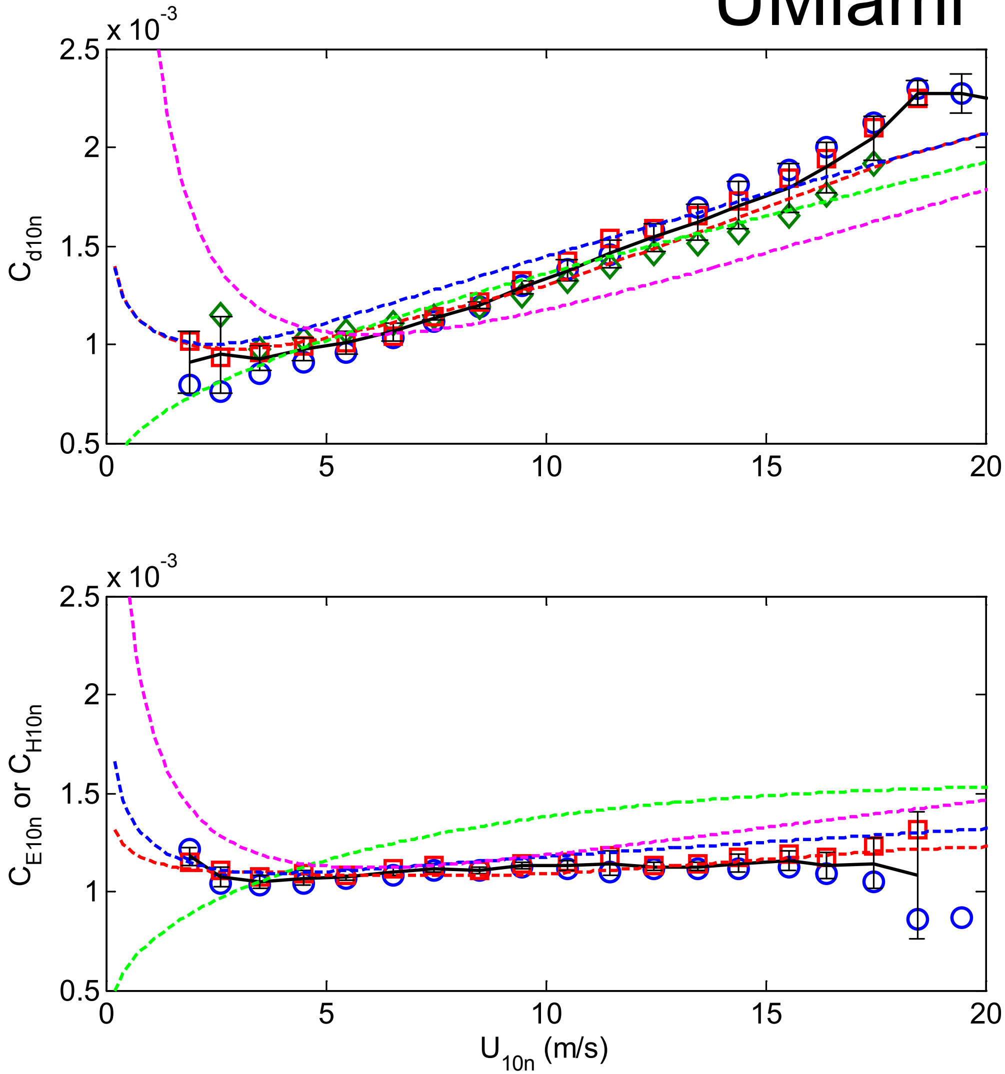


Air-Sea transfer coefficients as a function of wind speed: latent heat flux (upper panel) and momentum flux (lower panel). The red line is the COARE algorithm version 3.0; the circles are the average of direct flux measurements from 12 ETL cruises (1990-1999); the dashed line the original NCEP model.

Observations Normalized by Model

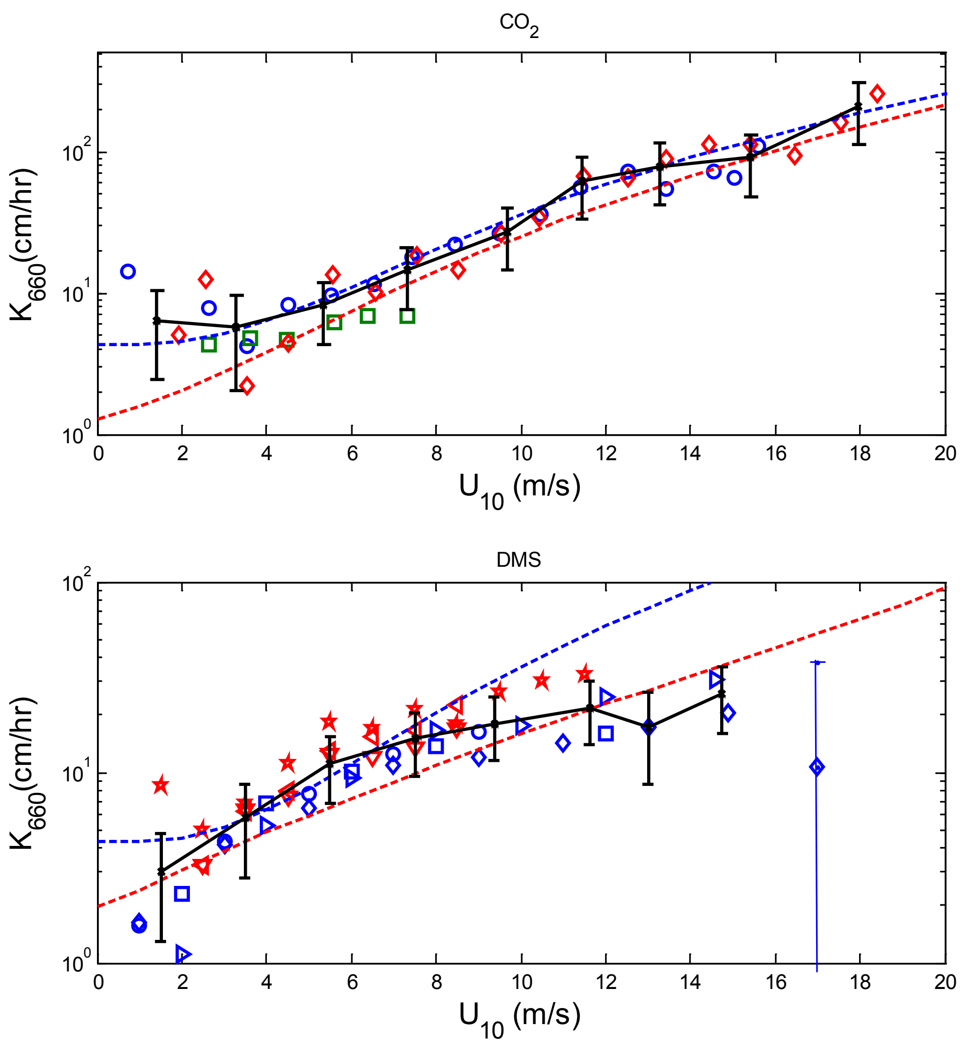


Combined Observations from Three Research Groups: ESRL, UConn, UMiami



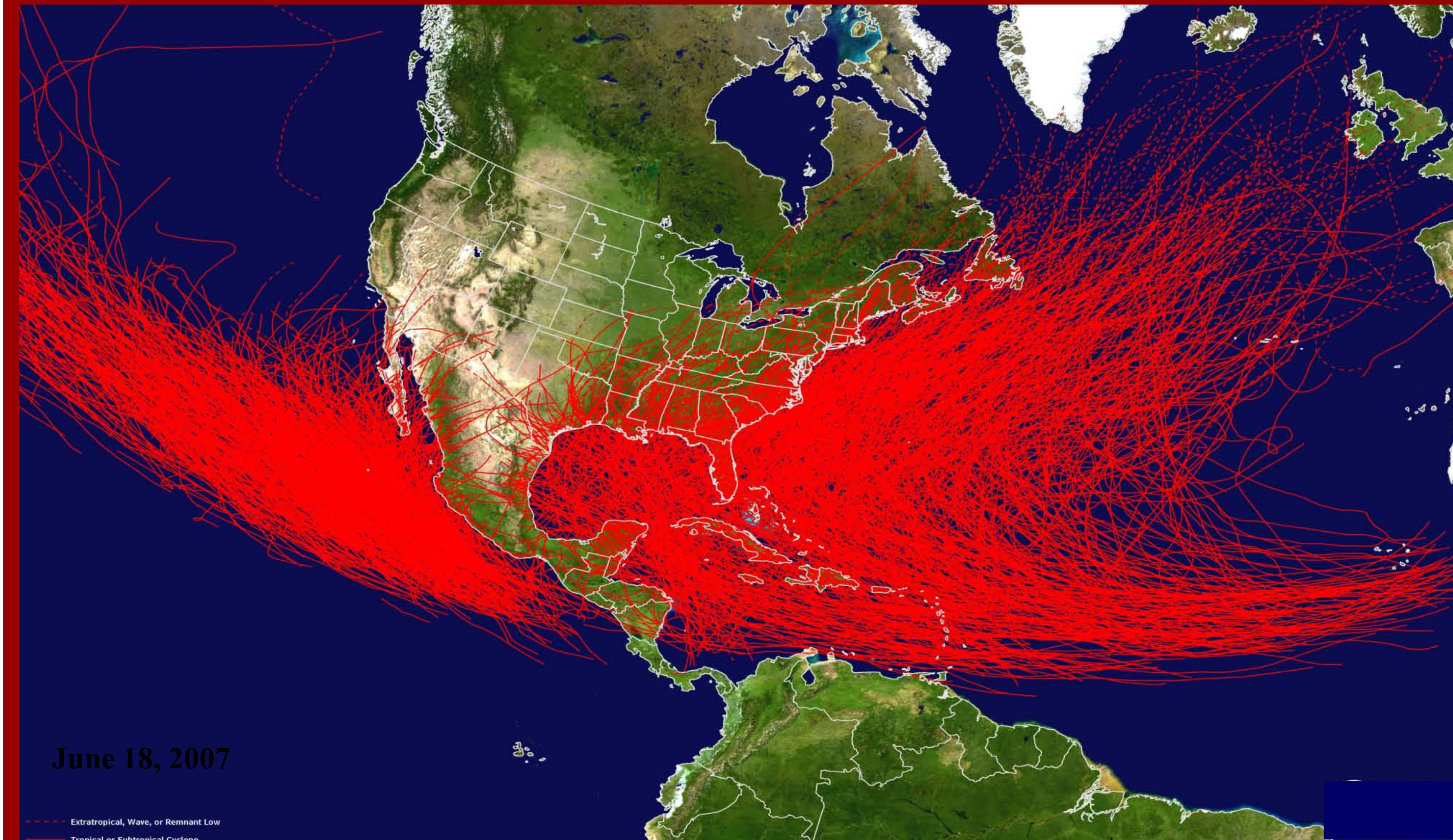
10-m neutral turbulent transfer coefficients as a function of 10-m neutral wind speed from direct surface-based observations. Symbols are: circle – U. Connecticut (FLIP, Martha's Vineyard Observatory, and moored buoys), diamond – U. Miami (ASIS spar buoy), and square – NOAA/ESRL (ships). Upper panel: C_{d10n}; Lower panel: C_{E10n} (ESRL) and C_{H10n} (U. Connecticut). The black line is the mean of the data sets; the error bars are statistical estimates of the uncertainty in the mean. The parameterizations shown are **COARE** algorithm (red), **NCEP** reanalysis (green), **ECMWF** (blue), **Large and Yeager** (magenta).

Combined Observations from 6 Research Groups



Gas transfer coefficient coefficients as a function of 10-m neutral wind speed from direct surface-based observations. The black line is the mean of the data sets; the error bars are statistical estimates of the uncertainty in the mean. Upper panel CO2, symbols are: circle - GASEX98, square - GASEX01, diamond – GASEX08 (data courtesy J. Edson, W. McGillis). The parameterizations shown are: blue dashed line - McGillis et al 2001, red dashed line – NOAA/COARE *CO2*. Lower panel DMS, symbols are: square- Sargasso, circle - TAO, right triangle – DOGEE, diamond – GASEX08, left triangle - Wecoma04, down triangle - Knorr 06, pentagram - Knorr 07 (data courtesy B. Huebert - blue symbols) and E. Saltzman - red symbols)). The parameterizations shown are: blue dashed line - McGillis et al 2001, red dashed line – NOAA/COARE *DMS*.

NOAA/NWS Hurricane Forecasting



Representations of Air-Sea Fluxes Suitable for Incorporation in Operational Hurricane Forecast Model

ESSENTIAL POINT:
Representations Must Include All Relevant Physical Properties

How Do Models Work?

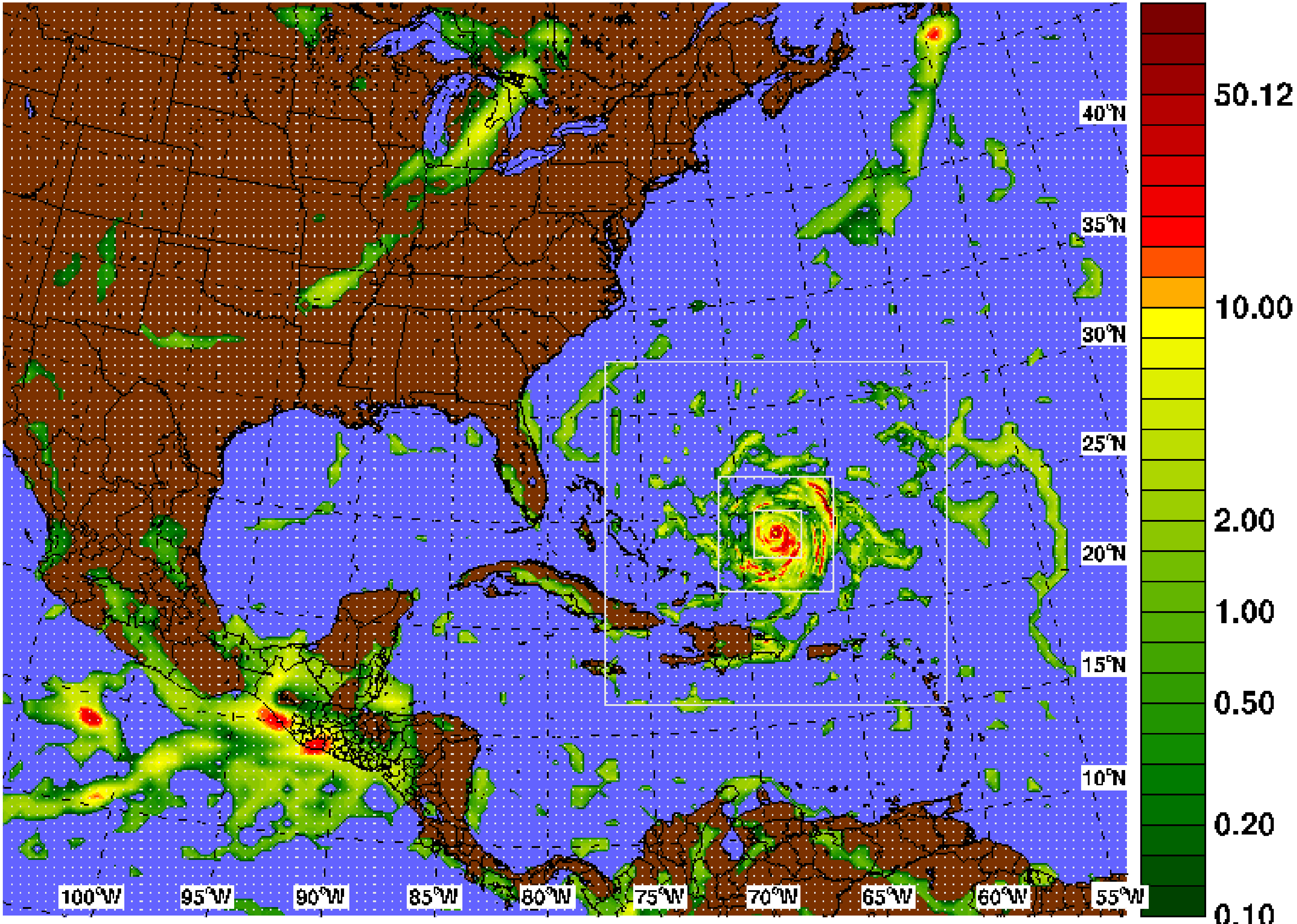
- Define an **initial field** of variables (X - winds, temperature, humidity,..) on a 3-D grid (time=0)
- Compute how X changes in one time step: $\delta X = \frac{\partial X}{\partial t} * \delta t$

$$\frac{\partial X}{\partial t} = -\frac{\partial}{\partial z}\left[\overline{w'x'} - D_x \frac{\partial X}{\partial z}\right] + Q_x - \vec{U} * \nabla X$$

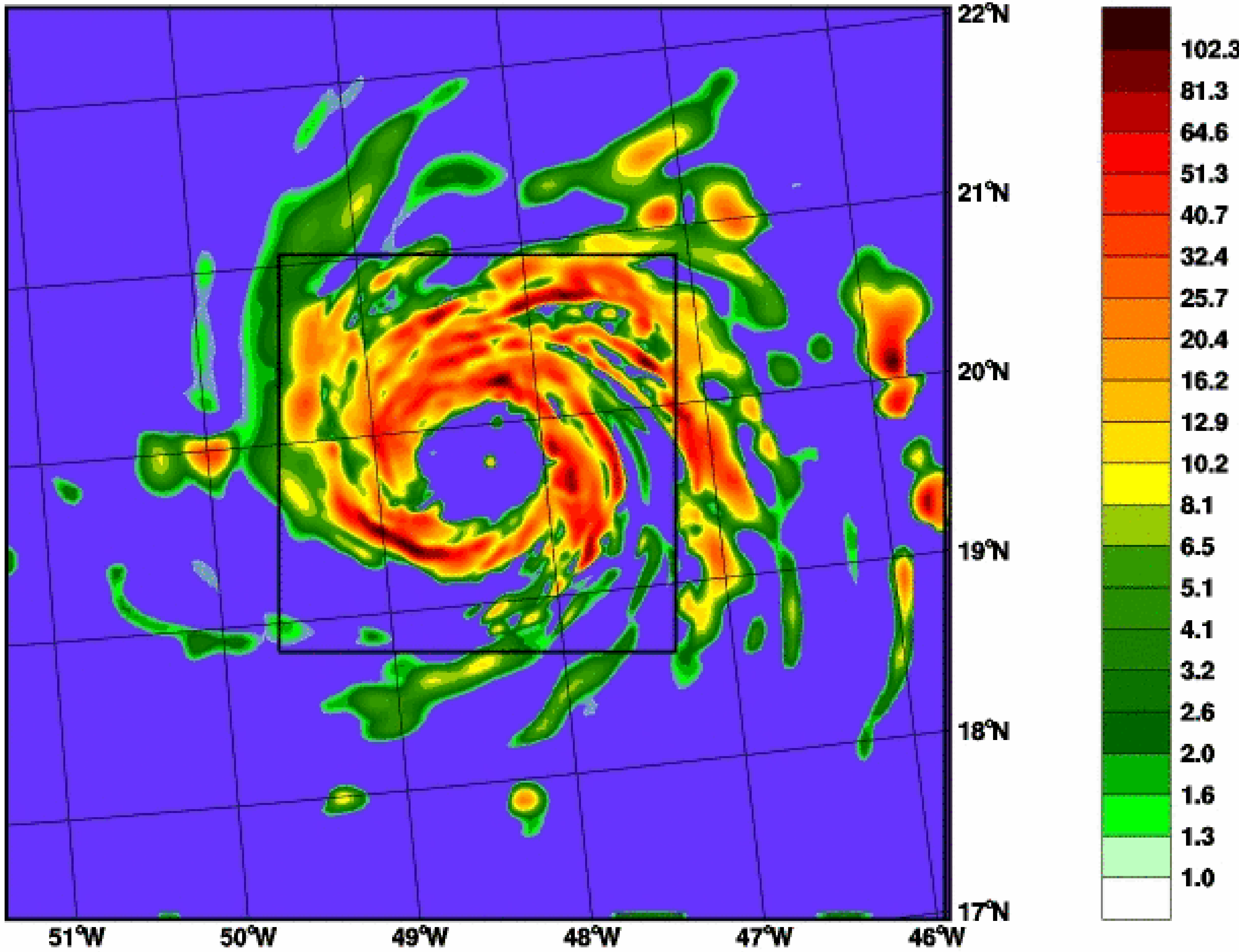
Conservation Eq for X

Flux Source

Hourly Rainfall Accumulation (mm) for 01Z Mon 13 Sep 1999

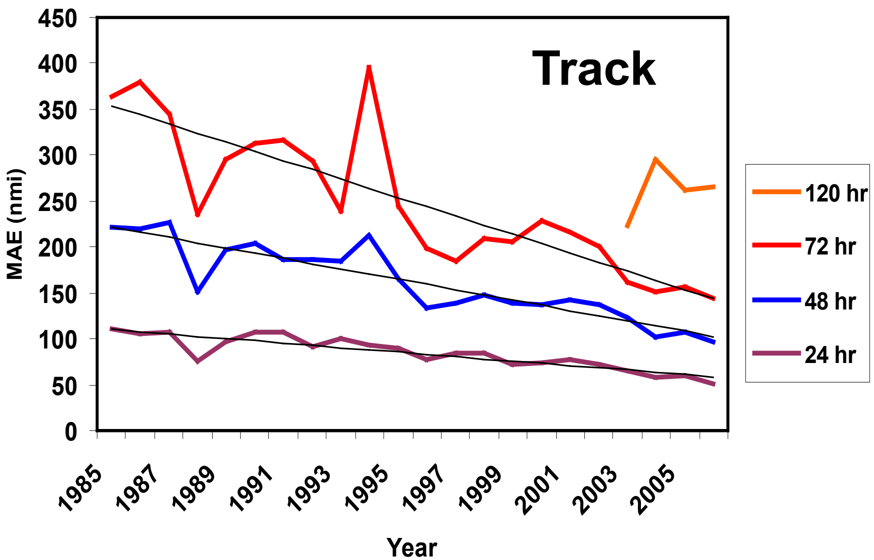


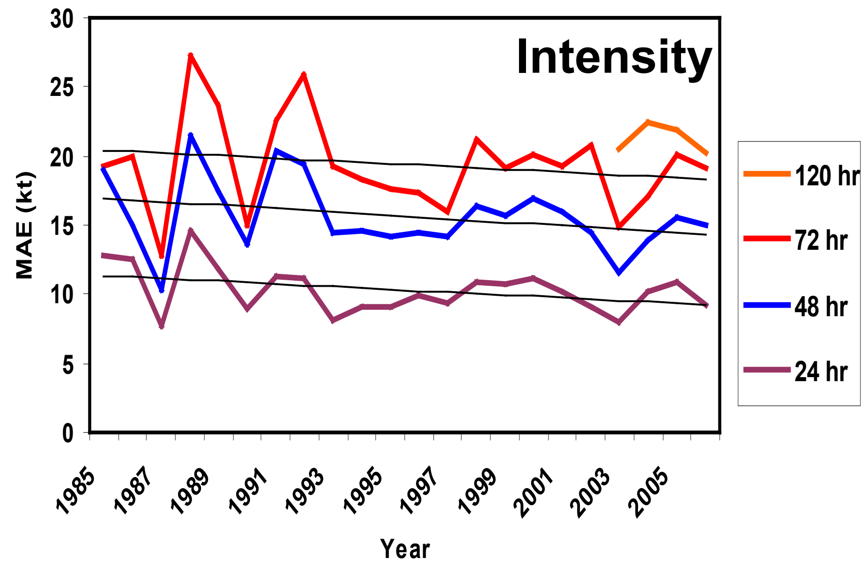
MM5 Rain Rate (mm h^{-1}) 0100 UTC 10 Sep 2003



Hurricane Forecast Performance

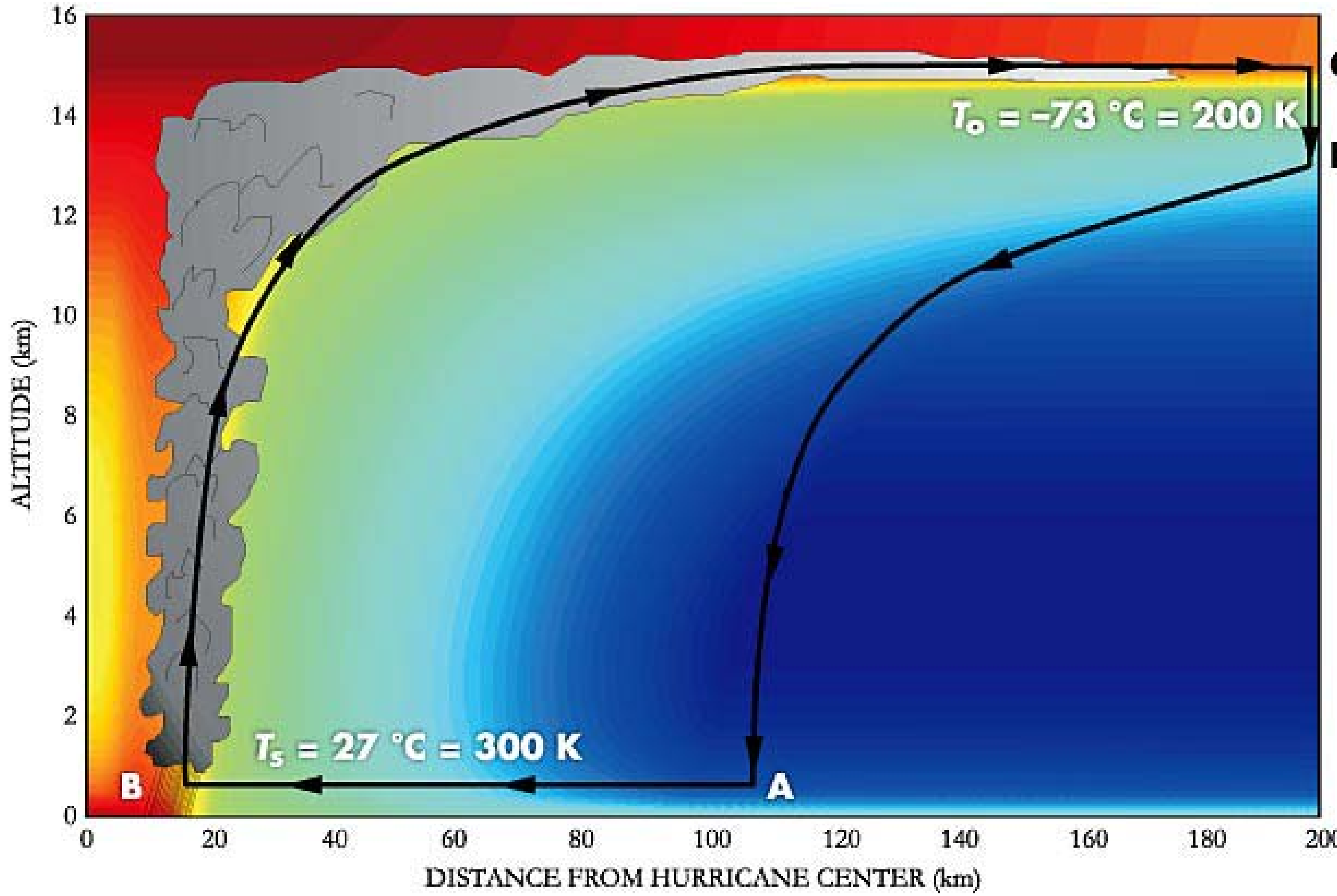
Mean Absolute Error of the 1985-2006 NHC Atlantic Intensity and Track Forecasts





48-hour track forecasts have improved 3.5% per year on average since 1985, while intensity forecasts have improved about 0.8% per year

Intensity: Balance of Energy Input vs Frictional Drag
Hurricane: Carnot Cycle Engine
Driven by heat extracted from the Ocean

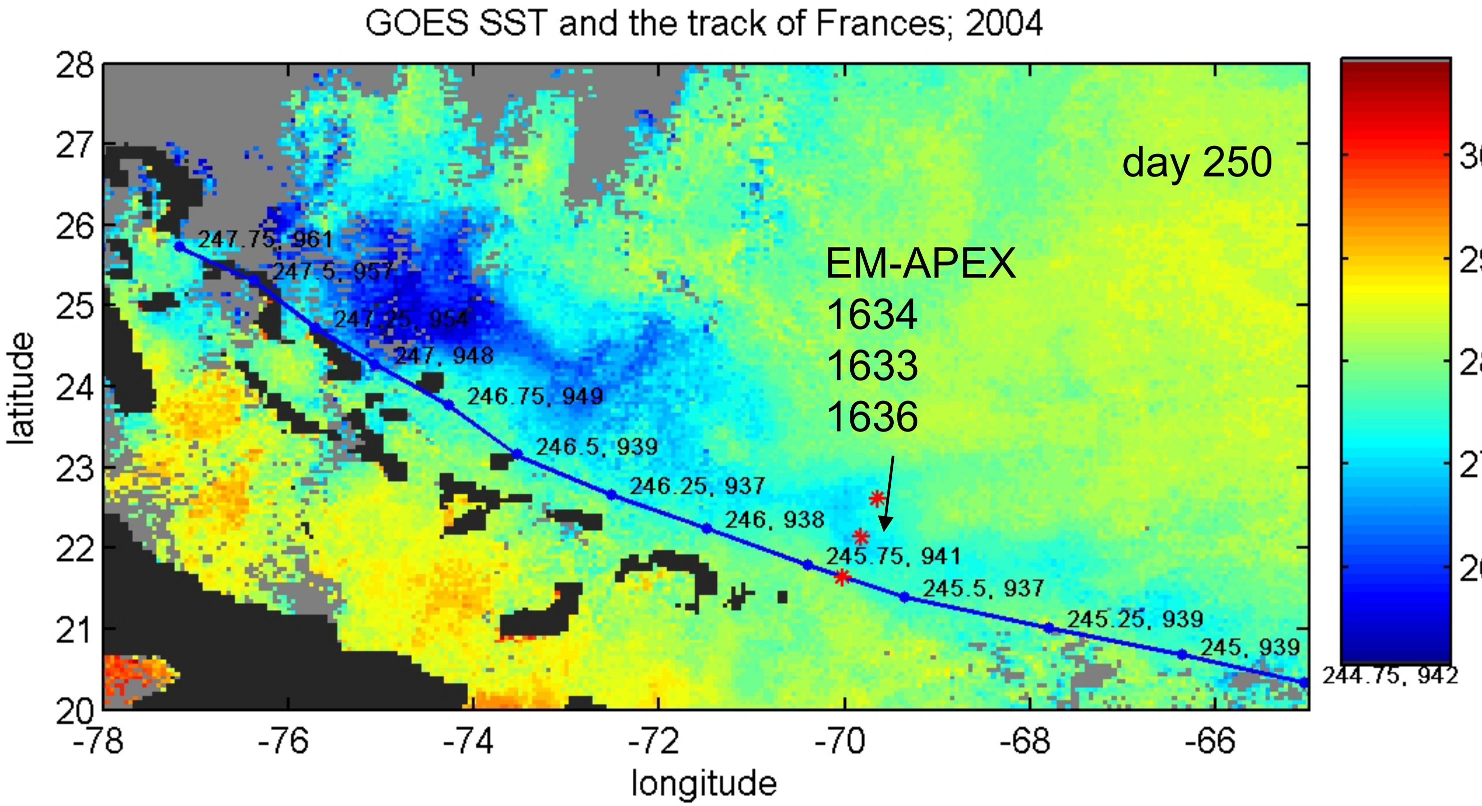


OCEAN Enters the Problem Through

Directly: SST, Waves, and Sea Spray

Indirectly: Entrainment of cold, deep water and Bubbles

4 deg C, 50 m deep, 12 hrs = **1800 W/m²**



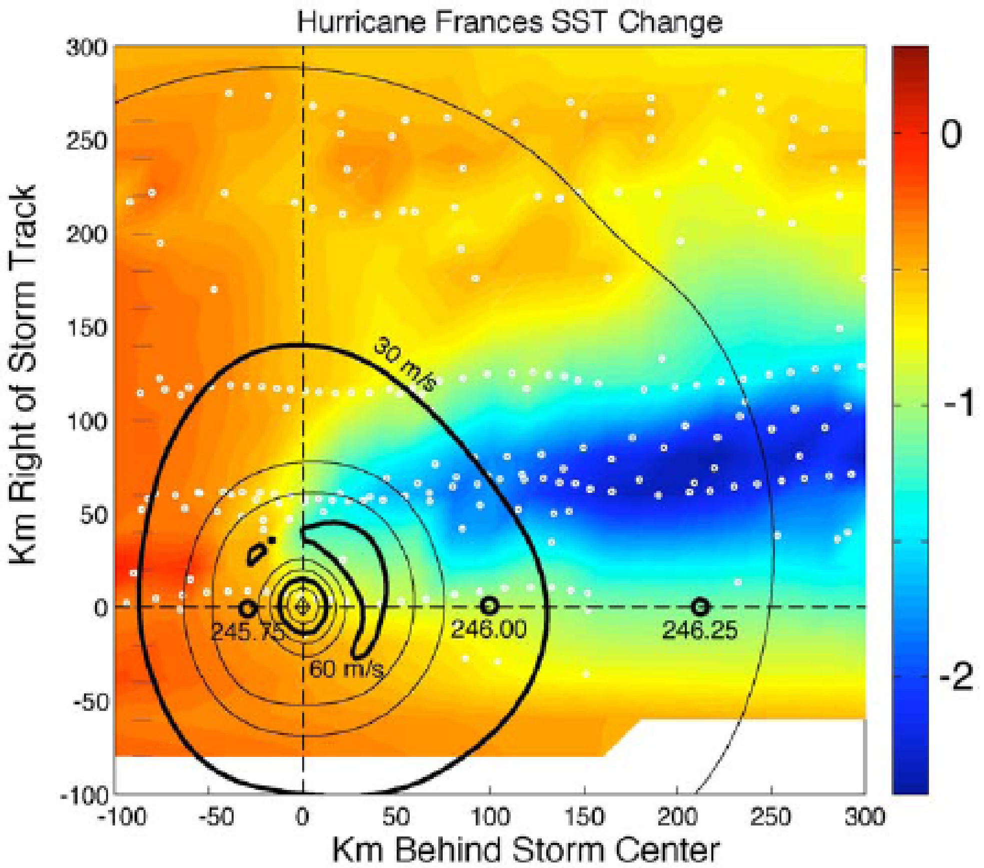
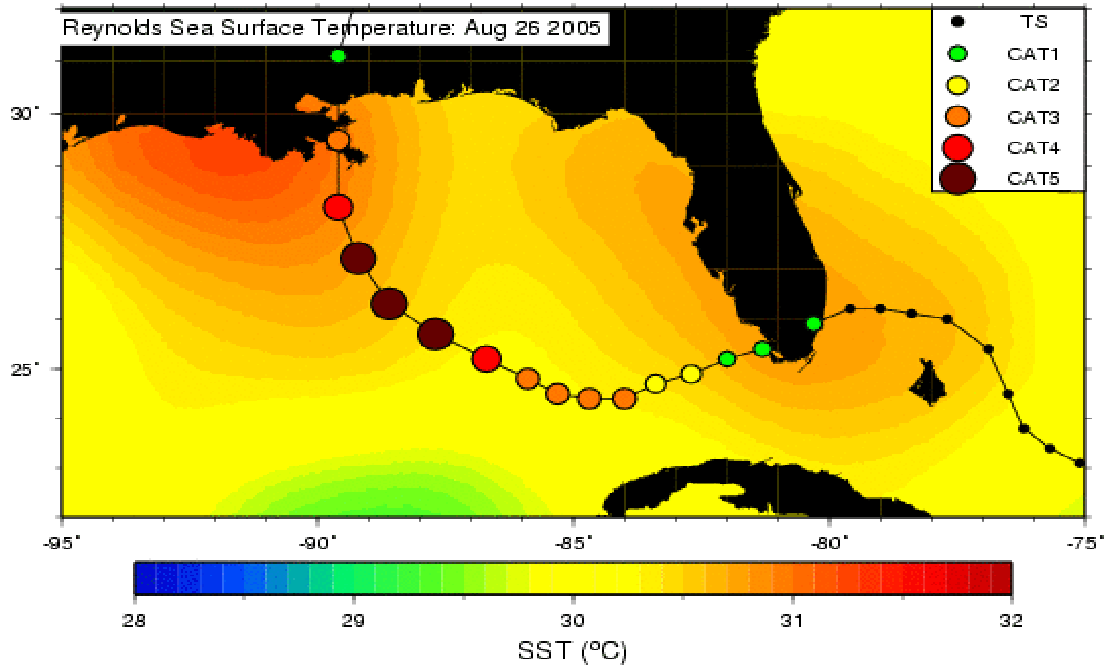
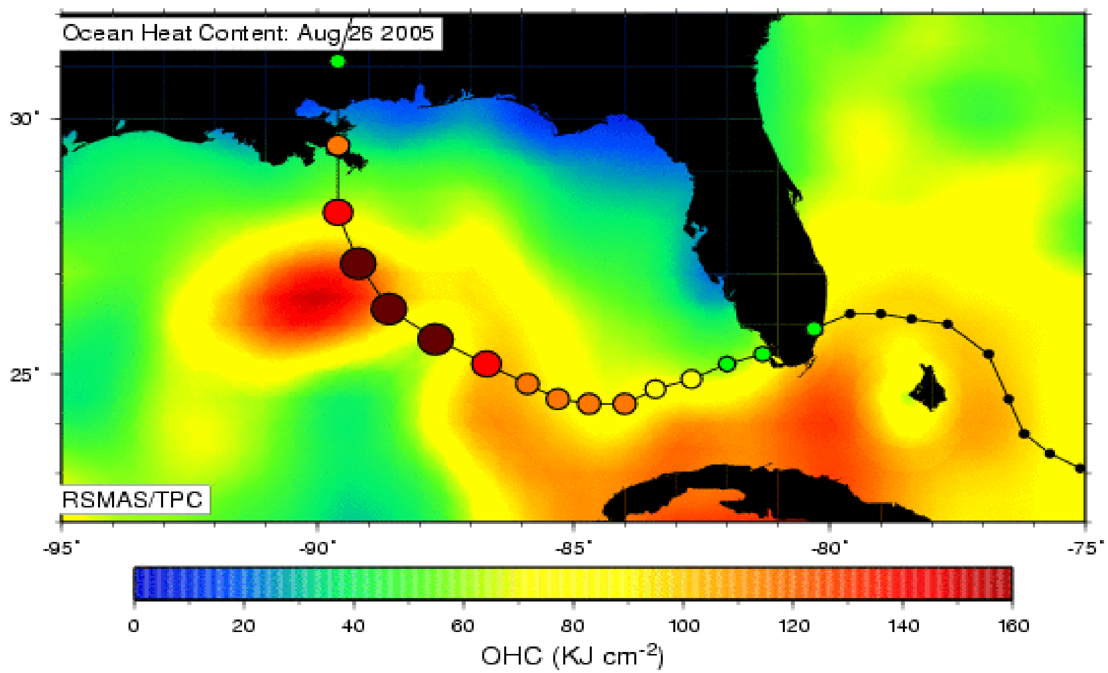


Figure 18. SST decreases (C) beneath hurricane Frances (2003) in storm-centered coordinate system. White dots show storm-relative locations of float and drifter data. Storm motion is to left. Colors show mapped SST change from pre-storm value. Contours show wind speed in ms^{-1} from H*WIND analysis. Storm positions are in increments of one-quarter Julian Days (JD), or 6 hours, where JD 245 is Sept 1.

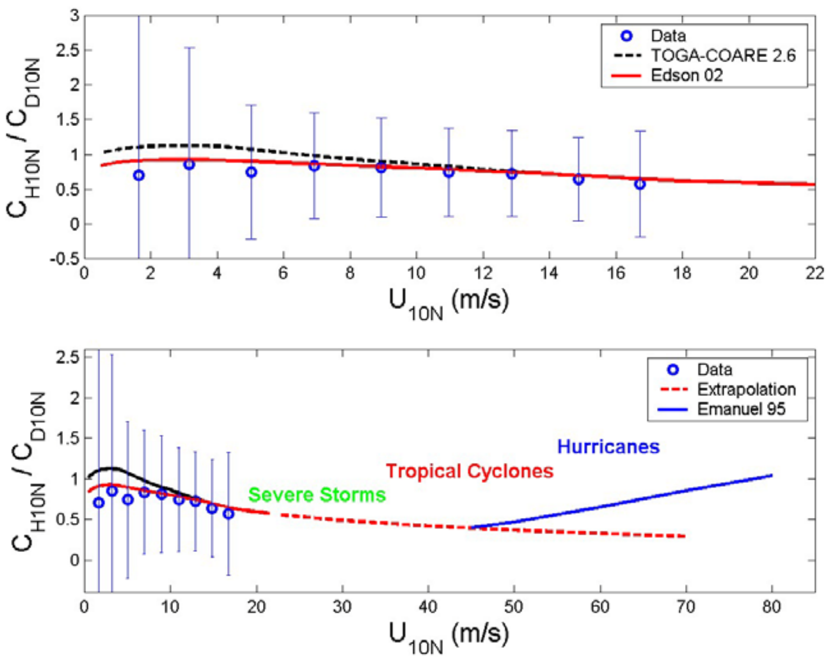

Reynolds Sea Surface Temperature: Aug 26 2005
TS
CAT1
CAT2
CAT3
CAT4
CAT5
30°
25°
-95°
-90°
-85°
-80°
-75°
28
29
30
31
32
SST (°C)

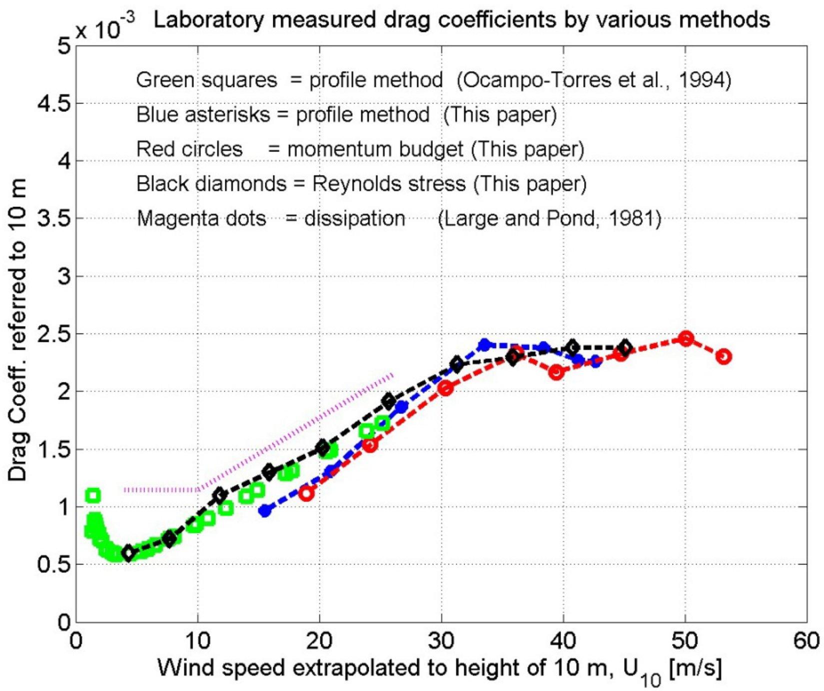

Ocean Heat Content: Aug 26 2005
RSMAS/TPC
30°
25°
-95°
-90°
-85°
-80°
-75°
0
20
40
60
80
100
120
140
160
OHC (KJ cm-2)

Language of Surface Flux Parameterizations

- Turbulent Flux of X=<w'x'>, function of x,y,z
- Flux of X at the SURFACE (z=0)=AIRSEA INTERACTION
- Hurricane is a heat engine
  - Energy input – heat of the ocean, spins vortex
  - Energy loss – stress, friction force at the surface
- Represented with Bulk Parameterization
  - **Heat Flux**=Energy input=C_e*U*[(Tsea-Tair)+Le/Cp(Qs(Tsea)-Qa)]
  - **Energy Flux**=Energy loss=C_d*U^3
- Hurricane thresholds:
  - Tsea>27 C
  - $C_e/C_d > 0.75$ at high wind speed
- **C_d and C_e** are measurement by direct (eddy covariance) method in the surface layer –
  - Measure w', measure T', compute <w'T'>

Turbulent Fluxes at High Winds: The FACT GAP





Results from the CBLAST program

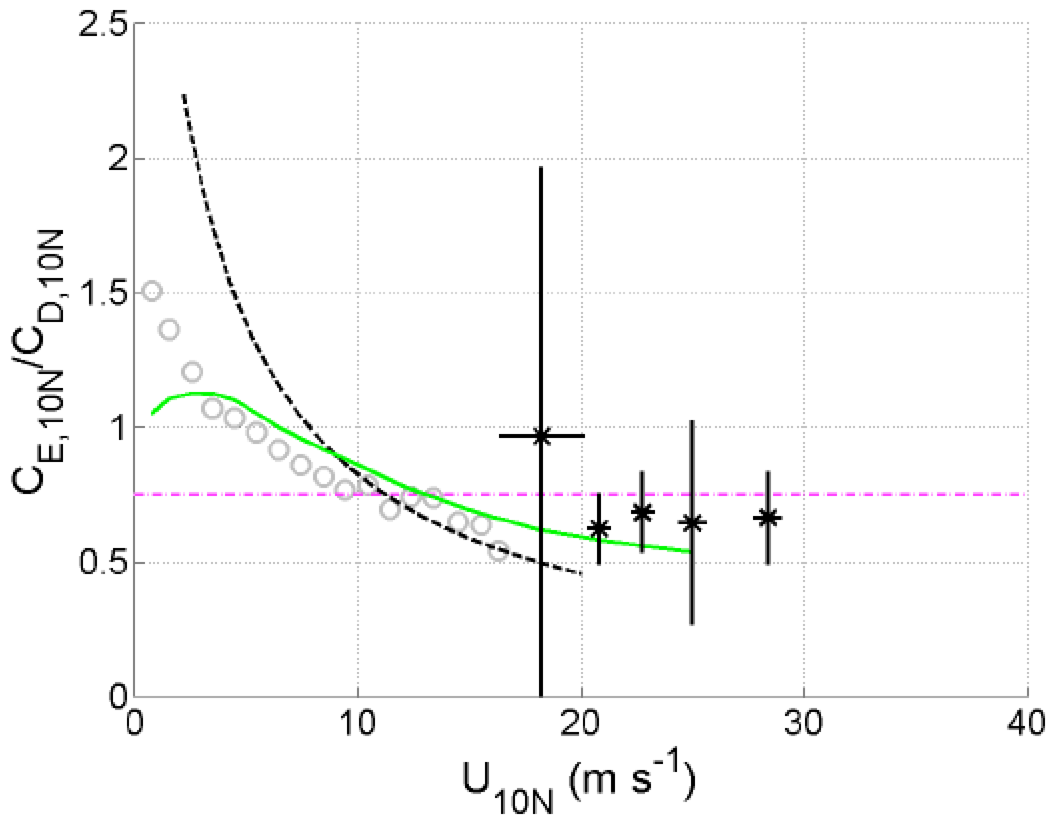
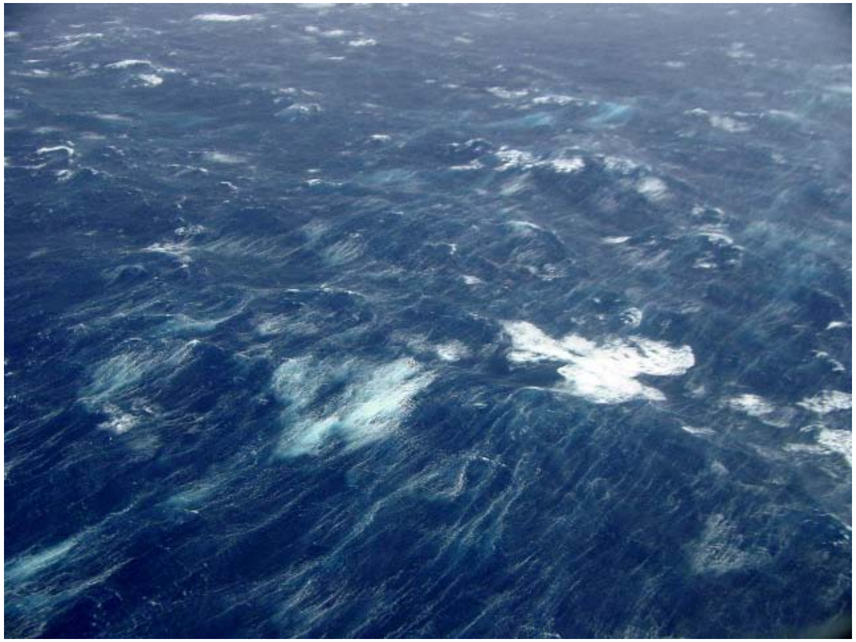
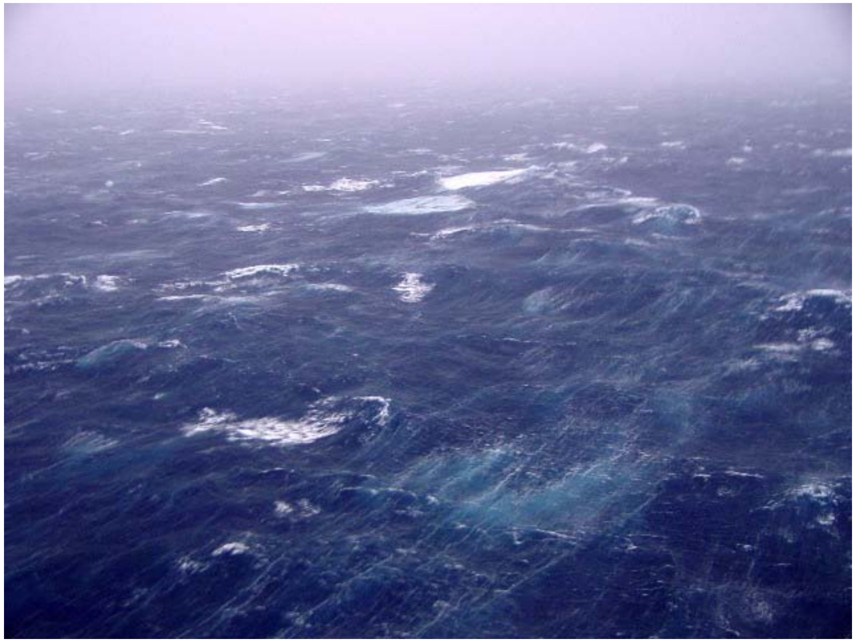


Figure 7. Ratio of C_E/C_D derived from CBLAST measurements. The asterisks represent average values in 2.5 ms^{-1} bins, and the bars show 95% confidence limits. The black dashed curve is the mean ratio from HEXOS (DeCosmo et al. 1996, modified as per Fairall et al. 2003; Smith et al. 1992). The solid green line is the ratio values from COARE 3.0 (Fairall et al. 2003). The grey circles are from CBLAST-Low (Edson et al. 2006). The dash-dot horizontal magenta line is the 0.75 threshold for TC development proposed by Emanuel (1995).

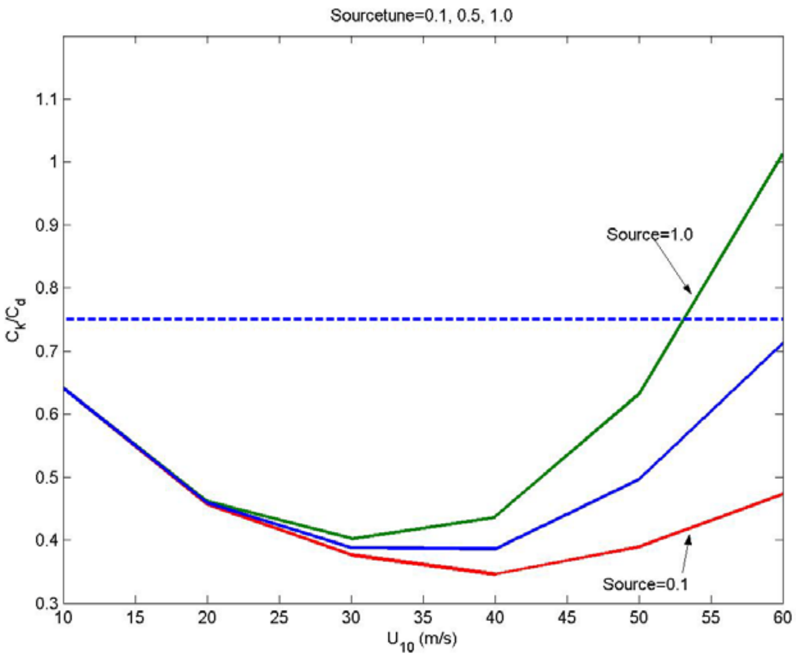
Droplet Effects Model Estimates





- [USATODAY.com]

Sea spray whips winds to hurricane strength
By Michelle Lefort, USA TODAY
In a study out last week, researchers from the University of California, Berkeley, and a Russian colleague argue that **sea spray** kicked up by storms actually has a **lubricating effect** that helps accelerate wind. Suppress the sea spray, as ancient sailors tried to do with oil tossed on the water, and you may be able to affect the strength in the wind, the research suggests. The computer model by Berkeley mathematician Alexandre Chorin and his colleagues appears in the current *Proceedings of the National Academy of Sciences*. Chorin says that sea spray reduces turbulence — chaotic fluctuations in wind velocity and direction — like a comb through unruly hair.



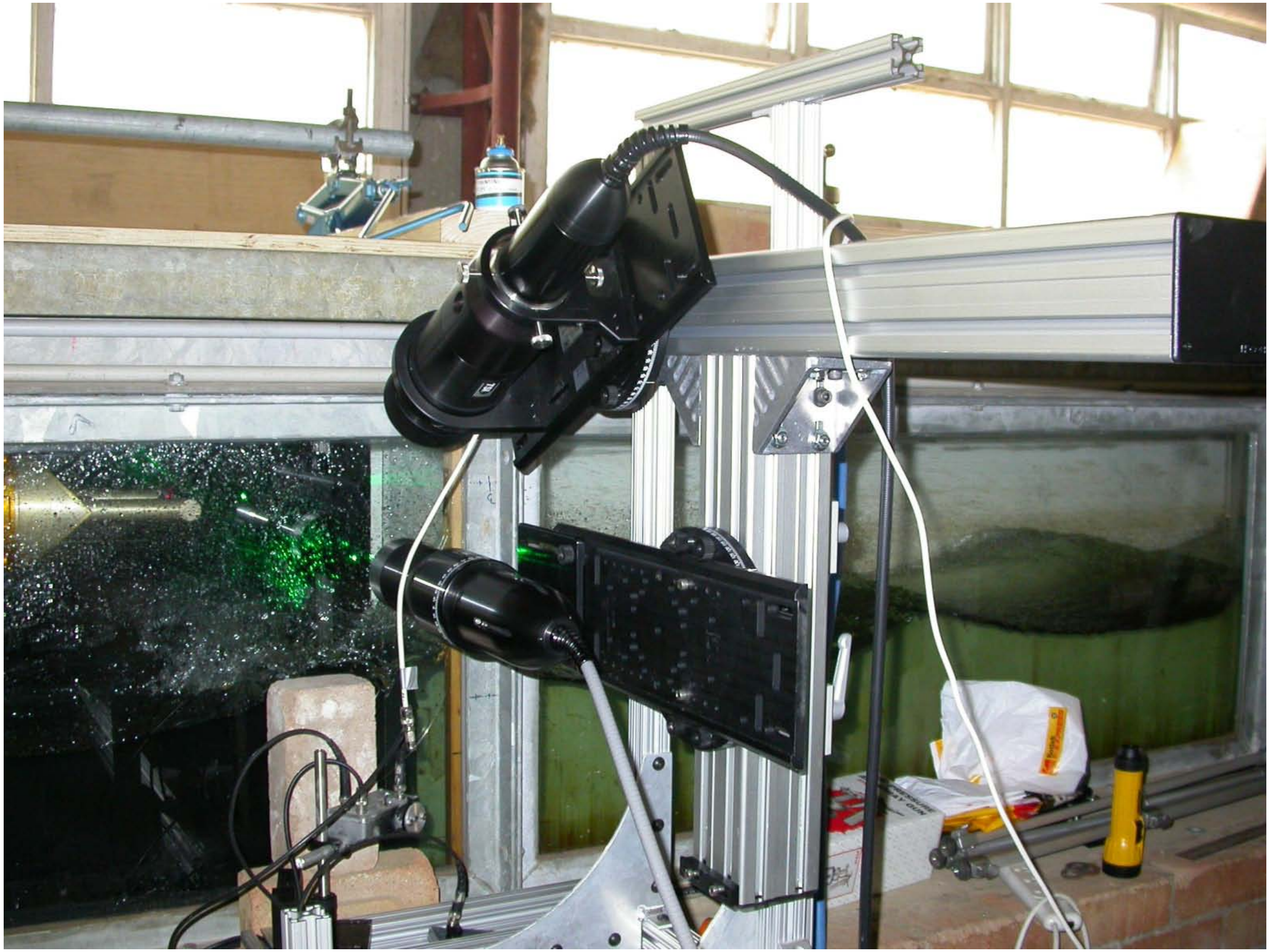
AIR-SEA FLUX RESEARCH OBSERVATIONAL REQUIREMENTS:

- Direct fluxes in the atmospheric surface layer
- Profiles T, Q, U, sea spray in the atmospheric surface layer
- Wave 2-D Spectra, Breaking statistics
- Ocean Mixing/Entrainment

Platforms

- Sampling Strategy
  - Drive around on a ship and get into a hurricane (volunteers?)
  - Sit there until hurricane runs over you
    - Buoys, coastal platforms [return period]
  - Fly out into the hurricane
    - NOAA P-3, etc [altitude minimum]
    - UAS [payload/performance/altitude minimum]
  - Get dropped right in front of the hurricane
    - CBLAST drifters, floats, etc [
- Sensing Strategy
  - In situ - direct
  - Remote - indirect
  - Aircraft deployed Dropsondes, Towed bodies

Photograph of PDA and DMT probes for the Spray Production and Dynamics Experiment (Water Research Facility, Manly, Australia; January 2003).
Bill Asher, Mike Banner, Chris Fairall, Bill Peirson



NOAA P-3 Flux and Sea Spray Sensors

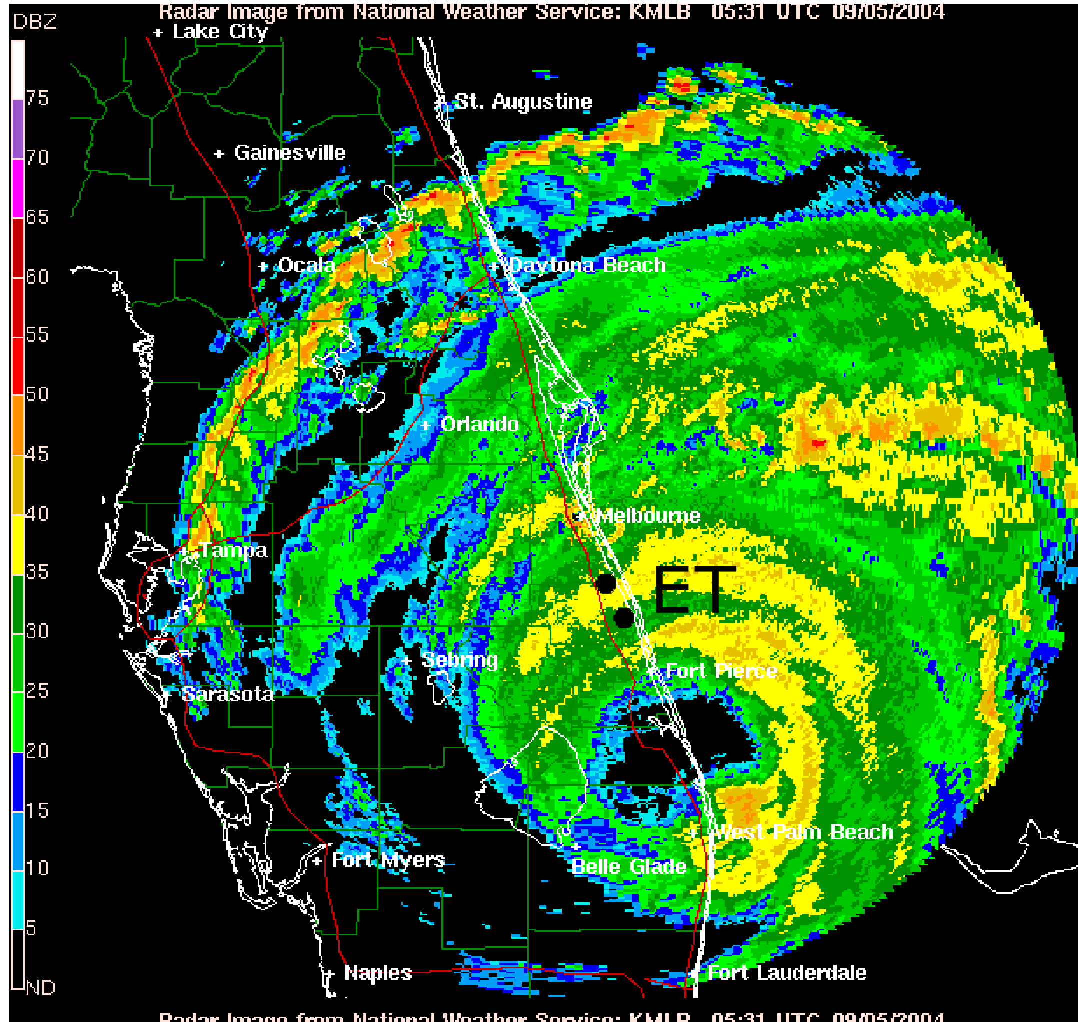
- First deployed in CBLAST program
- Value for **surface** fluxes limited by minimum flight altitudes

NOAA ARL Best Atmospheric Turbulence (BAT) Probe

Droplet Measurement Technology Drizzle and Sea Spray Probe

NOAA ARL Extreme Turbulence (ET) Probe
Surface-based Version of BAT

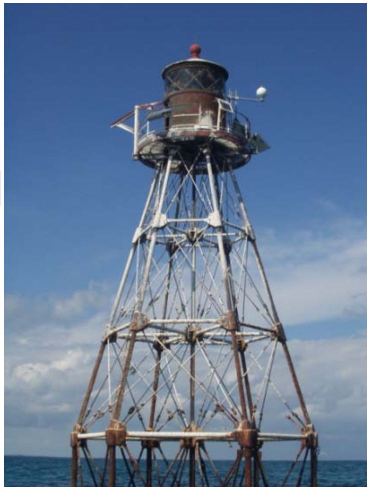
Measures Turbulent Stress at Hurricane Wind Speeds in the Presence of Rain



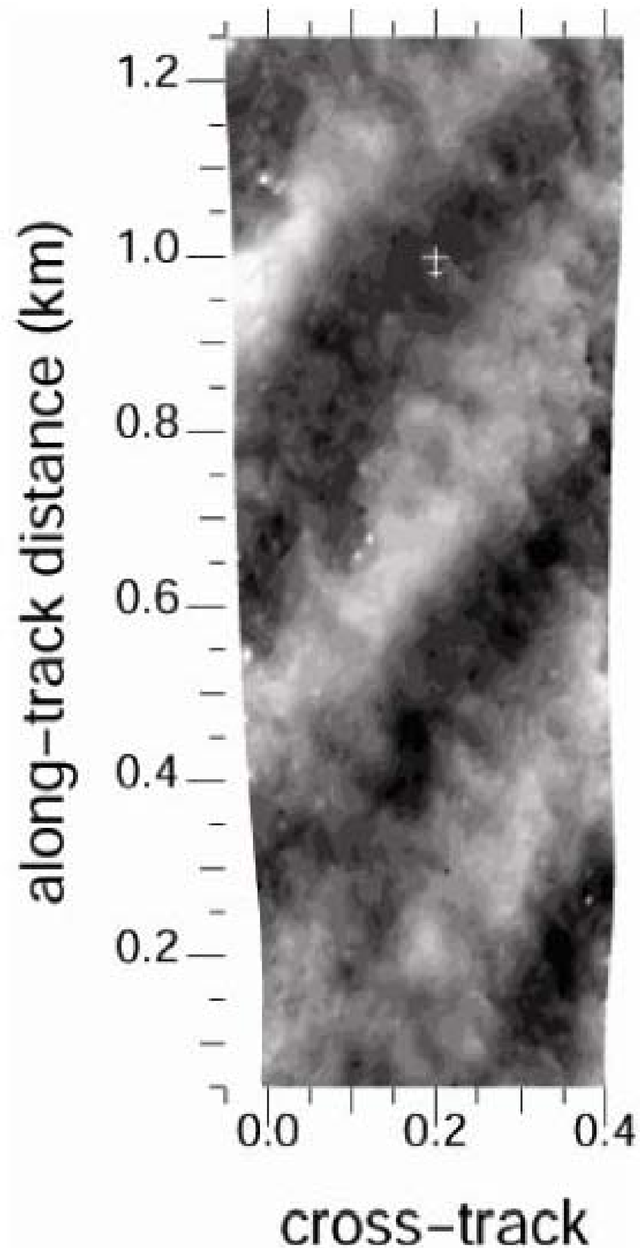
Hurricane Frances CAT2 2004

Extreme Turbulence (ET) Probe
R. Eckman ARL

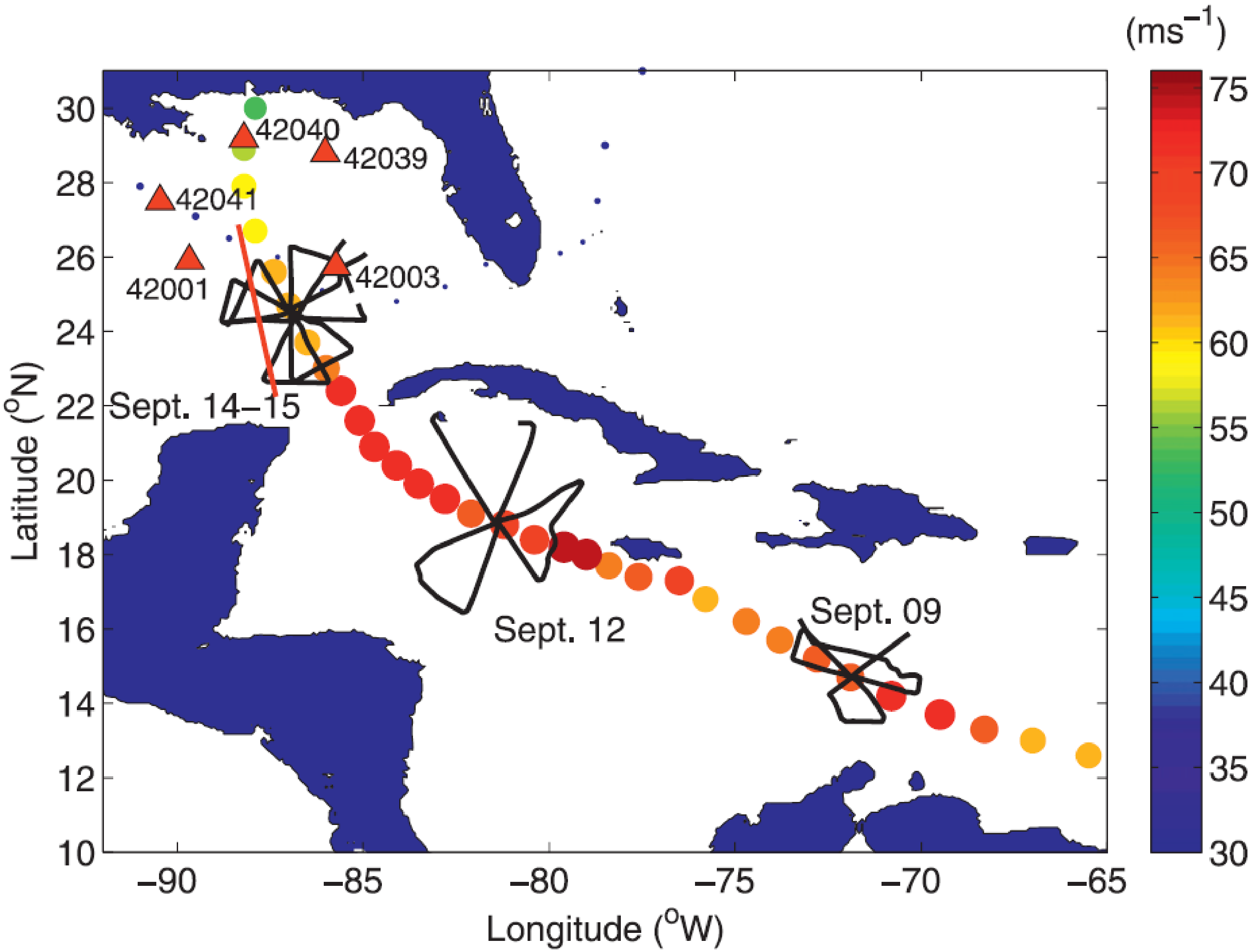
- FY09 first year of OAR funding
- Goal: upgrade & test probes for extended marine deployments
- Upgraded probes use Linux single board computer. 12 W total power
- Two upgraded probes deployed: 560 m pier in Duck, NC and Tennessee Reef in Florida Keys
- Probes still deployed and functioning with some data gaps mainly due to site power issues

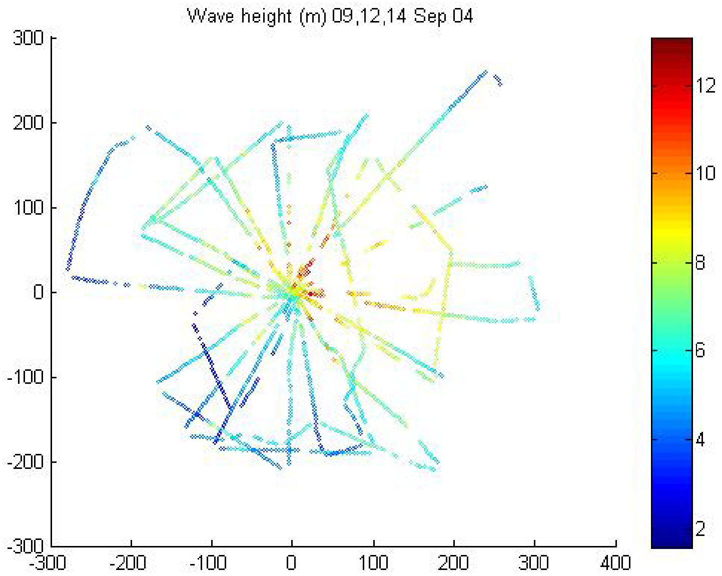


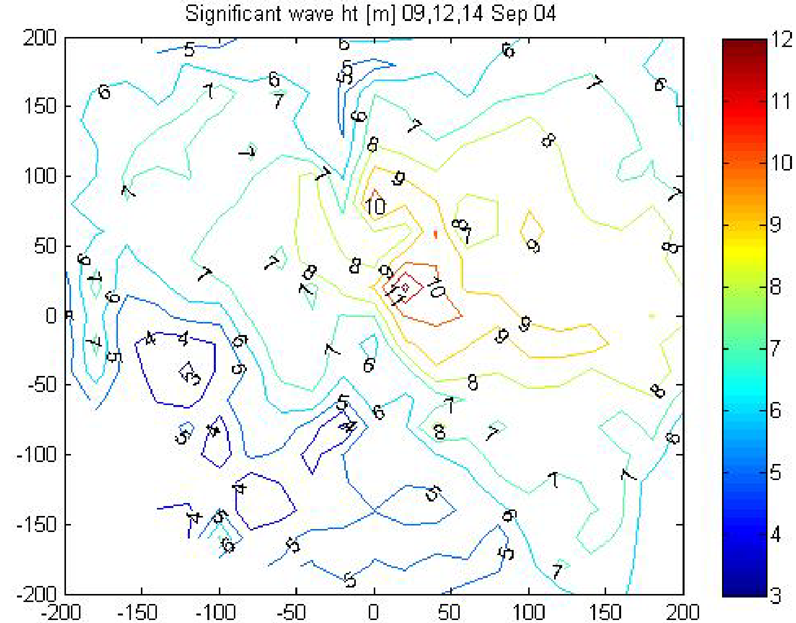
NASA/NOAA Airborne Scanning Radar Altimeter

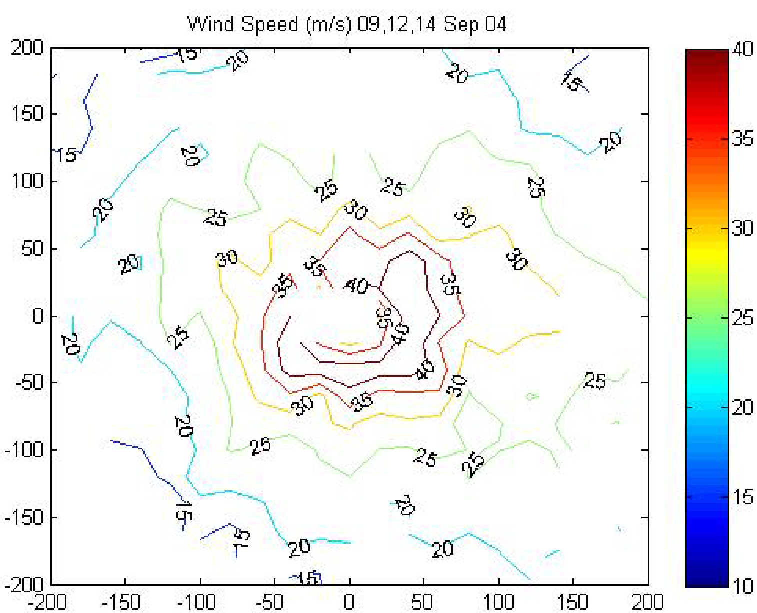


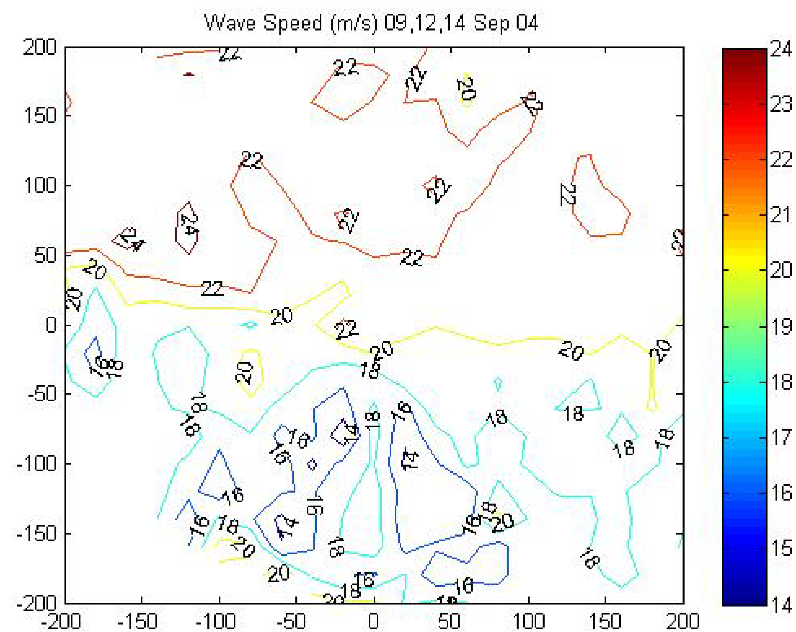
Wave Measurements in Hurricane Ivan




Wave height (m) 09,12,14 Sep 04


Significant wave ht [m] 09,12,14 Sep 04


Wind Speed (m/s) 09,12,14 Sep 04

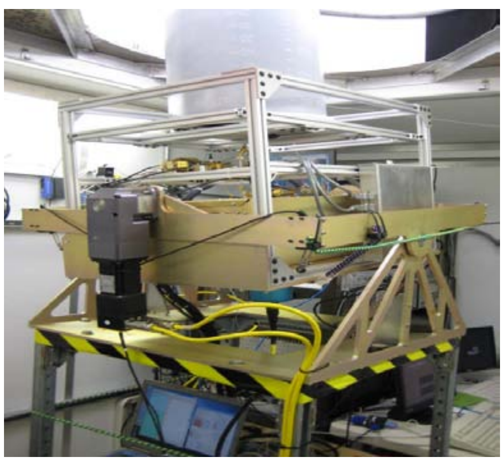

Wave Speed (m/s) 09,12,14 Sep 04

W-Band (94 – GHz) Doppler Radar for P-3

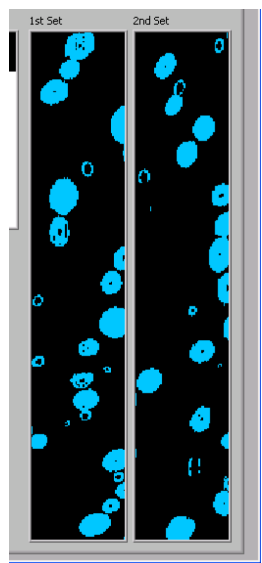
Sea Spray & Cloud Microphysics: Ship-based Field Tests November 2008

C. Fairall & K. Moran (ESRL)

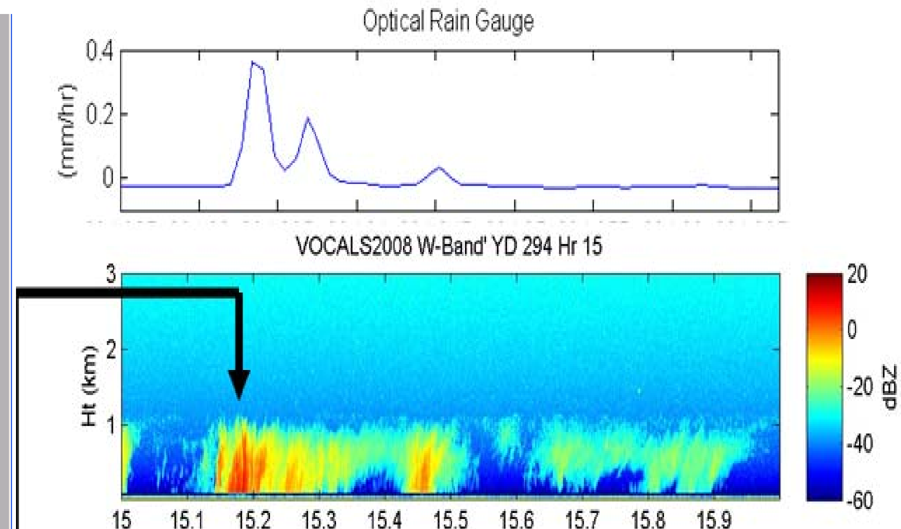
- Radar construction completed August 2008
- Field deployed on shipboard Oct-Nov 2008 and June 2009
- Sensitivity in full Doppler mode = -36 dBZ at a range of 1 km
- Typical sea spray drops: 0 to +15 dBZ
- Processing of Doppler time series yields in-cloud turbulence profiles
  - Velocity variance, TKE dissipation, velocity skewness (not shown but available)
- Processing of Doppler spectra
  - Cloud and Sea Spray microphysics (Frisch et al. 1995/1996)



Radar deployed in motion stabilizer on NOAA *Ship Ron Brown* VOCALS2008 field program



CIP Drizzle droplet spectrum coincident with radar return. Droplets shown are about 0.3 mm Diameter



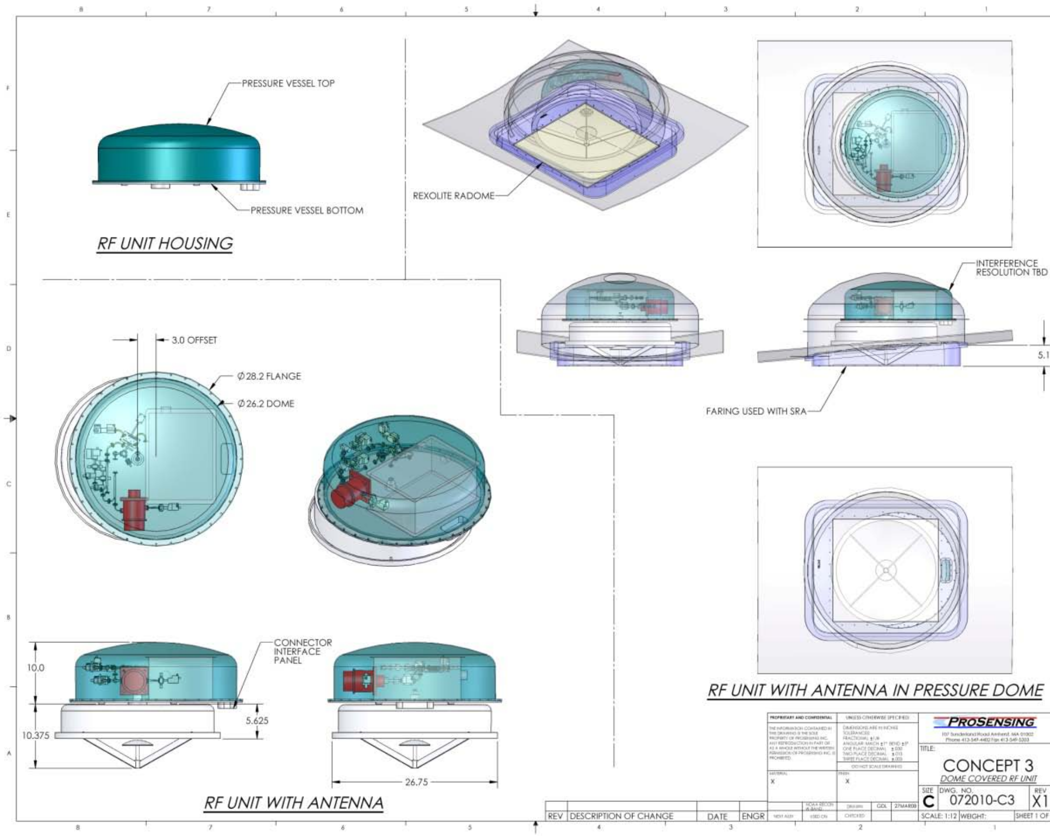
1-hr Time height cross section of backscatter intensity from light drizzle (~.3 mm/hr) during VOCALS2008 featuring Sea Spray sized droplets

W-Band (94 – GHz) Doppler Radar for P-3

Sea Spray & Cloud Microphysics: Preparations for P-3 Installation

C. Fairall & K. Moran (ESRL)

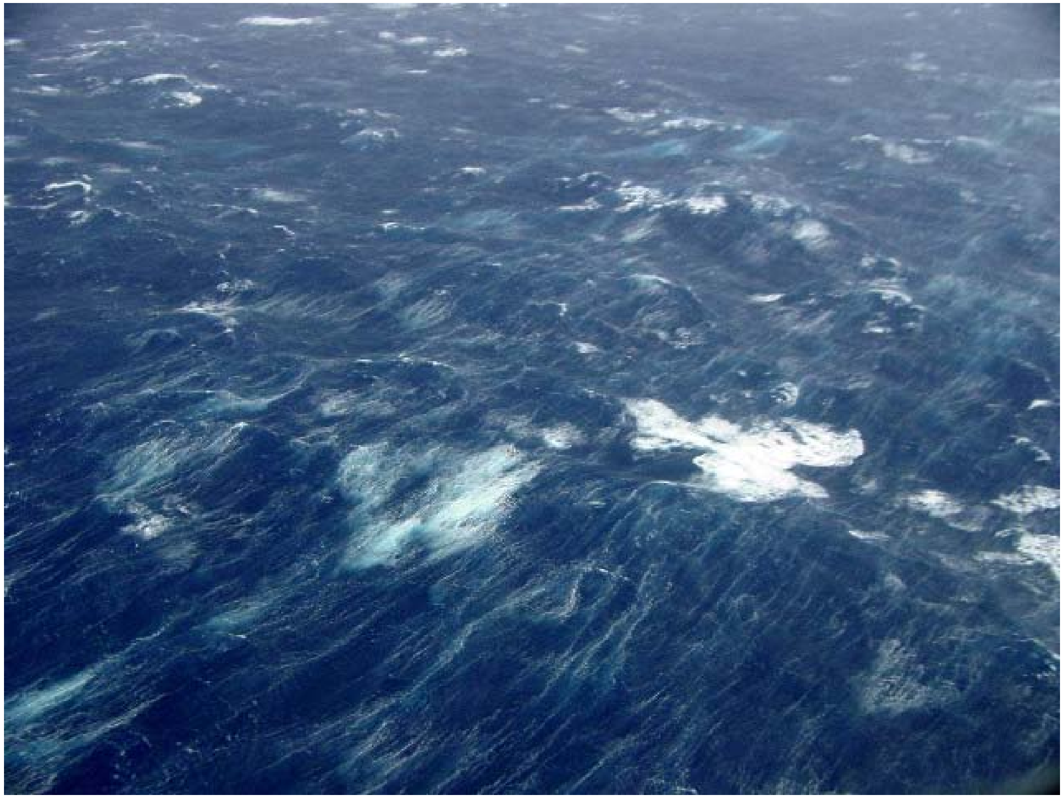
- Contract let to ProSensing Inc
  - Design new layout for RF sections
  - Repackage for P-3 pressure cell
  - Coordinate planning for installation
- Radar dissembled and shipped to ProSensing
- Receiver/calibration upgraded
- Operating characteristics re-spec'd for Sea Spray mission

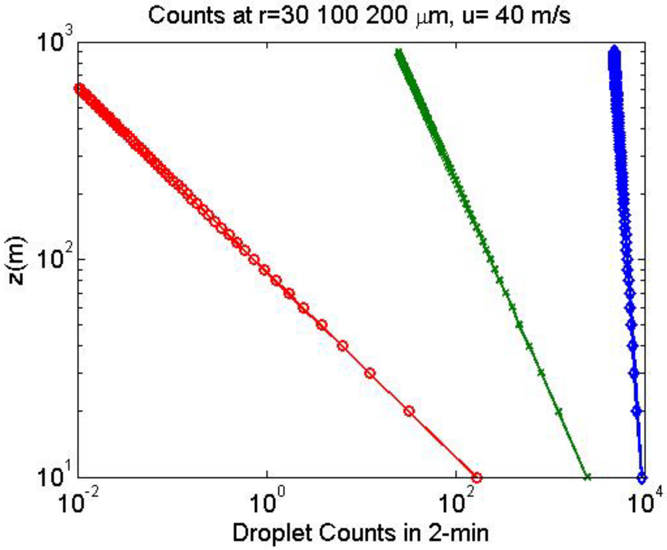


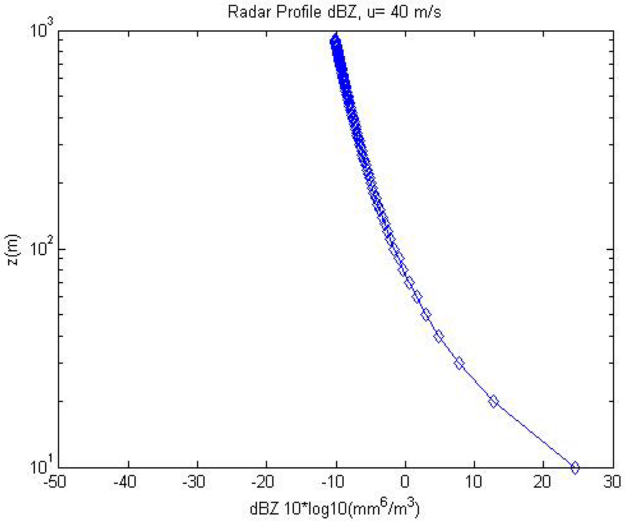
Operating characteristics for ESRL W-band airborne Doppler radar.

Frequency	Peak/Avg Power	PRF $_{MAX}$	Antenna	Range Cell Size	Number of Range Cells	Velocity Resolution	Signal Processing	Data Archive	Sensitivity
94.56 GHz	1200/1 W	10 KHz	24 in Cassegrain	**10-m**	200	6.2 cms^{-1}	Average FFT; **0.2 s dwell time**	Avg. Spectra	-30 dBz (R = 1km)

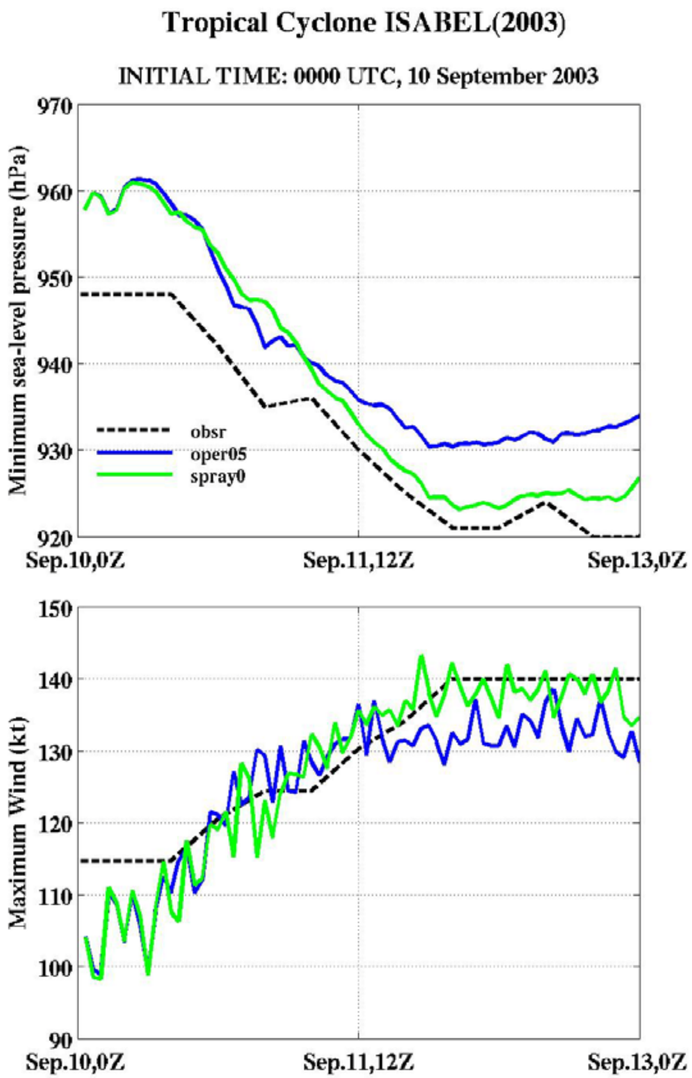
Sea Spray Profiling
Estimates Based on Fairall-Banner Model

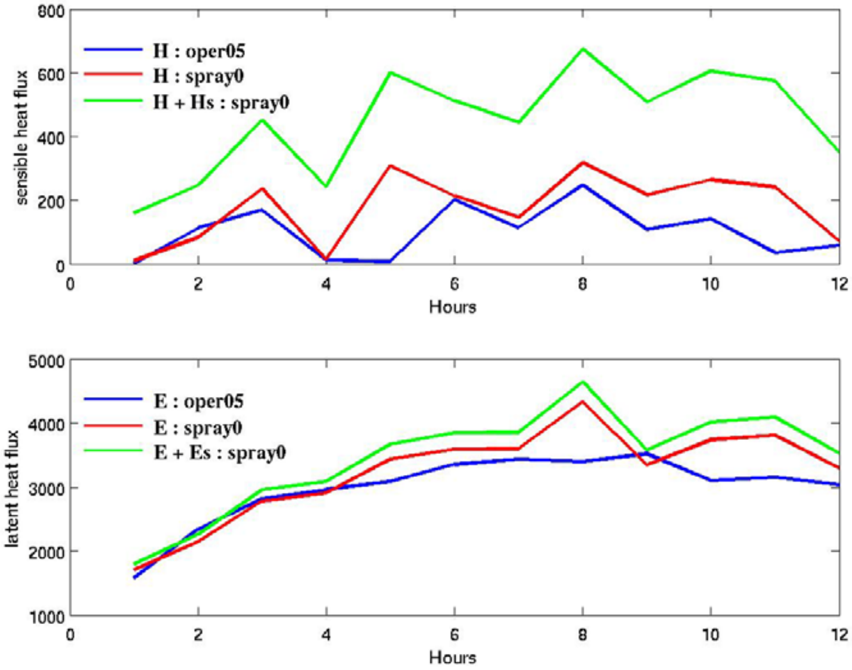




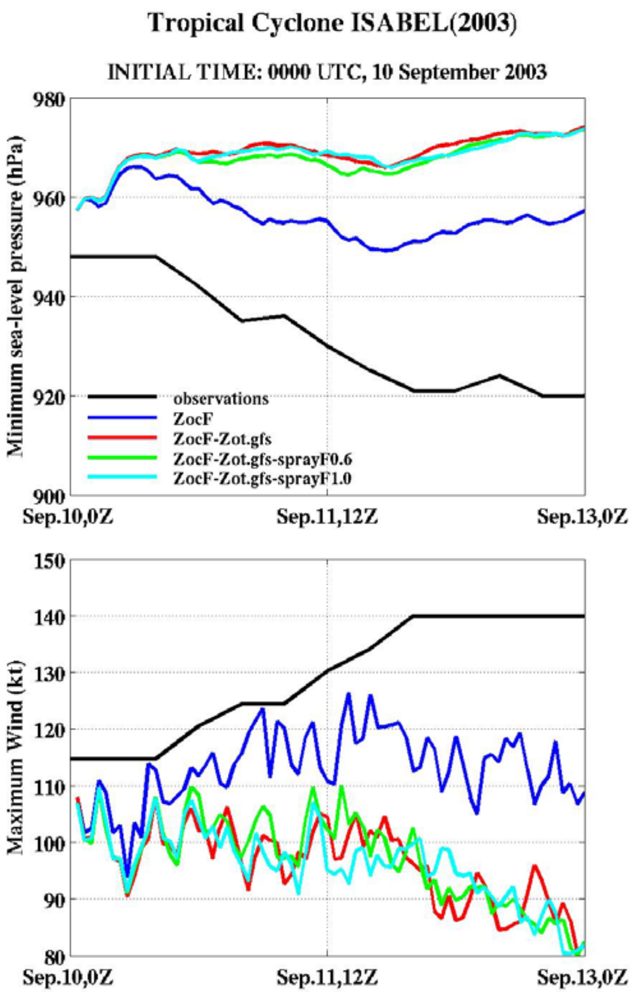


Simulation with GFDL Operational Model: Isabel

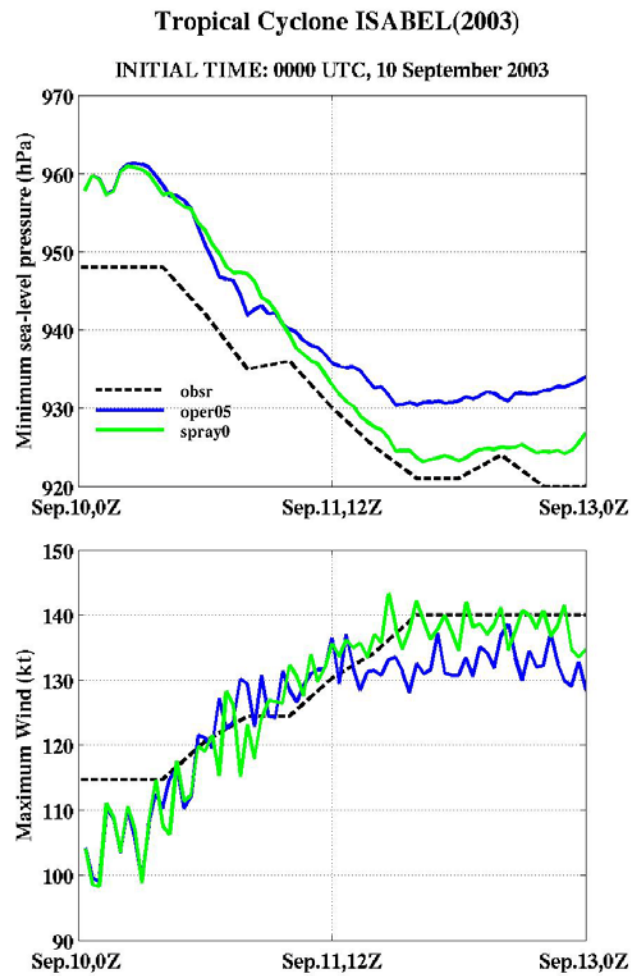




But:
Simulations with New Cd and Ce/Ch



New Cd Ce/Ch



Old Cd Ce/Ch