Impact of Air-Sea Interactions on Extra-Tropical Cyclones

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OBJECTIVES

synopsis of current knowledge of how air-sea interaction phenomena impact extratropical cyclones

- previous studies as examples, augmented with some previously unpublished material
- only the key points of numerous topics can be discussed - refer to bibliography

OUTLINE

0) surface fluxes NOT primary forcing factor for ETC

1) impact of surface fluxes

- timing relative to cyclone evolutionary stage
- different flux/PBL schemes (FASTEX case, off-line tests)

2) key sensitivity areas (relative to cyclone features), front-relative fluxes

3) impact of spatially and temporally varying ocean characteristics

- wave characteristics (surface roughness, stress-wind direction mismatch)
- sea spray
- sea-surface temperature

4) summary and suggestions for future work

Basic M-O Similarity Equations for Surface Flux

Definitions

$\tau = -\rho \overline{uw} \equiv \rho u_*^2$ stress

$H_s = \rho c_p \overline{wt} \equiv -\rho c_p u_* t_* ,$ Sensible heat flux

$H_L = \rho L_v \overline{wq} \equiv -\rho L_v u_* q_* .$ latent heat flux

Modeling - basic equations

$$\tau = \rho C_{Dr} S^2$$

$$H_s = \rho c_p C_{Hr} S(\Theta_s - \Theta_r)$$

$$H_L = \rho L_v C_{Er} S(Q_s - Q_r)$$

$$C_{Dr} = c_{Dr}^2 = \left[\frac{k}{\ln(r/z_0) - \psi_m(r/L)} \right]^2$$

$$C_{Hr} = c_{Dr} c_{Hr} = \left[\frac{k}{\ln(r/z_0) - \psi_m(r/L)} \right] \left[\frac{k}{\ln(r/z_T) - \psi_h(r/L)} \right]$$

$$C_{Er} = c_{Dr} c_{Er} = \left[\frac{k}{\ln(r/z_0) - \psi_m(r/L)} \right] \left[\frac{k}{\ln(r/z_Q) - \psi_h(r/L)} \right]$$

z_0 - surface roughness for momentum
z_T - surface roughness for temperature
z_Q - surface roughness for moisture
r - reference height (sometimes called z)
L - Monin-Obuhkov length
r/L (z/L) - M-O stability parameter

Impact of Surface Fluxes and Flux Timing

-seven western Atlantic Ocean rapid-deepening cases (Kuo et al 1991)
-rapid deepening starts at T = 0 h

<u>MM4 model</u>

ΔX = 80 km
Blackadar PBL scheme (Anthes et al 1987)
modified Arakawa-Schubert convective scheme (Grell et al. 1990).

<u>Experiments</u>

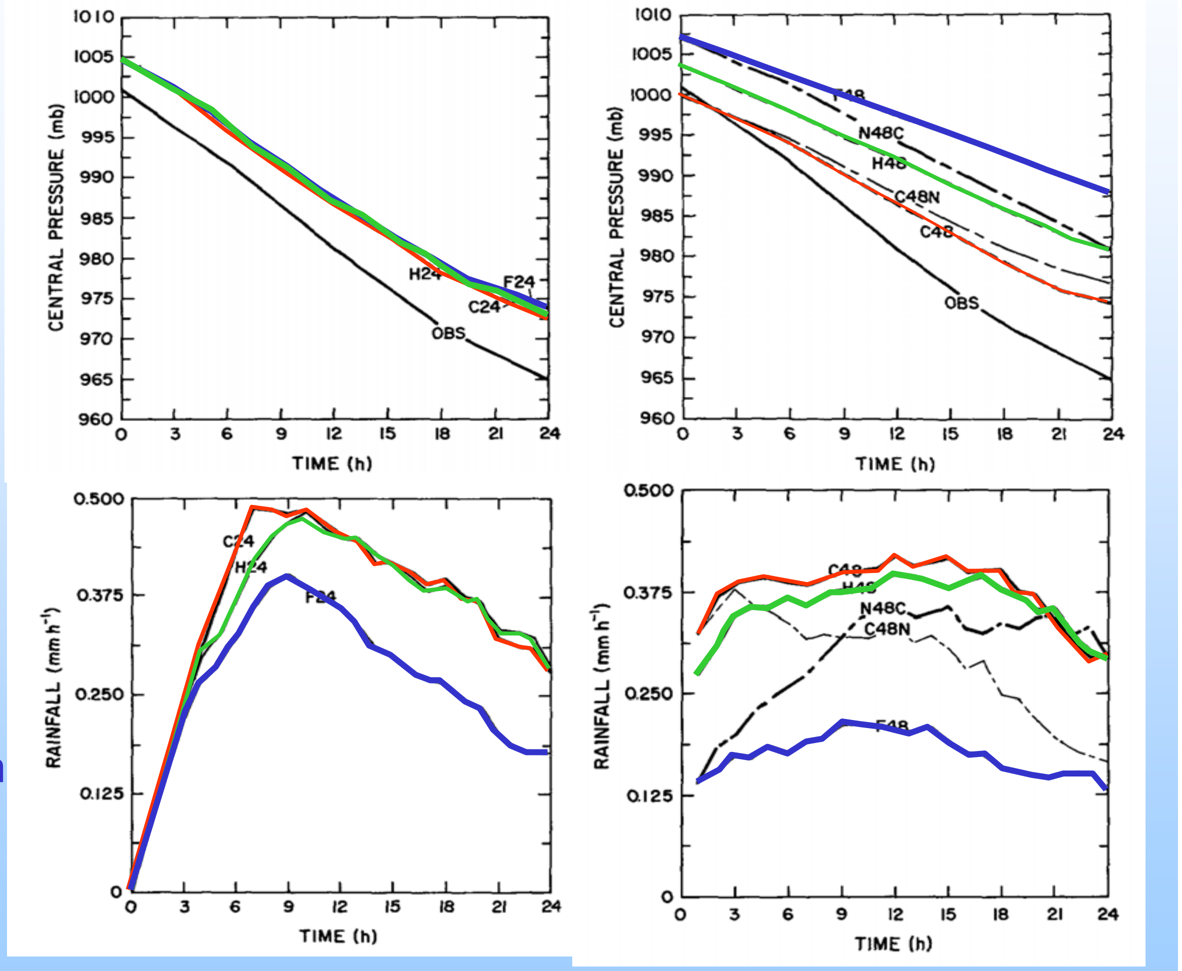
C24, C48-control runs
H24, H48 - no sensible heat flux
F24, F48 - no energy fluxes
C48N - no energy fluxes last 24 h
N48C - no energy fluxes first 24 h

Initial time: T = 0 h (24 h simulation)

T = -24 h (48 h simulation)

Central P (mb)

Rain rate (mm/h)
1600x1600 km region

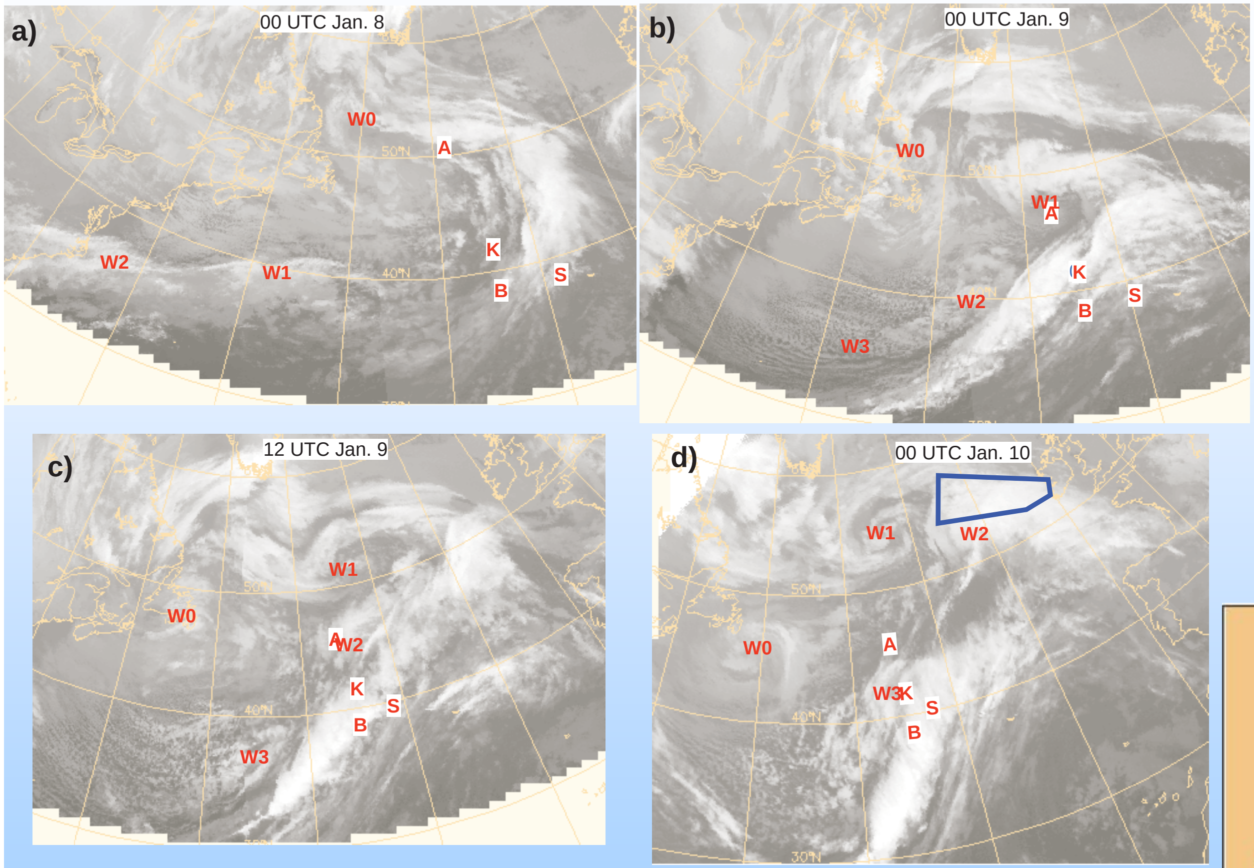


<u>Summary</u>

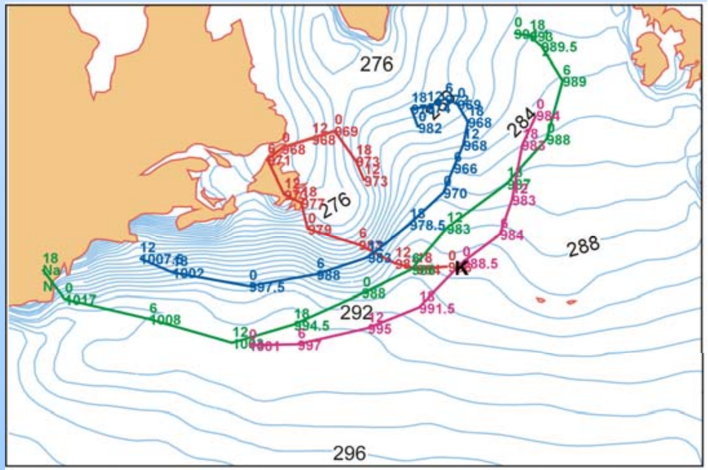
- sfc fluxes minimal impact on central p/ precipitation during rapid deepening stage
- significant impact 24 h before rapid deepening, whether or not done during rapid deepening

Storm Sensitivity to Flux/PBL Variations

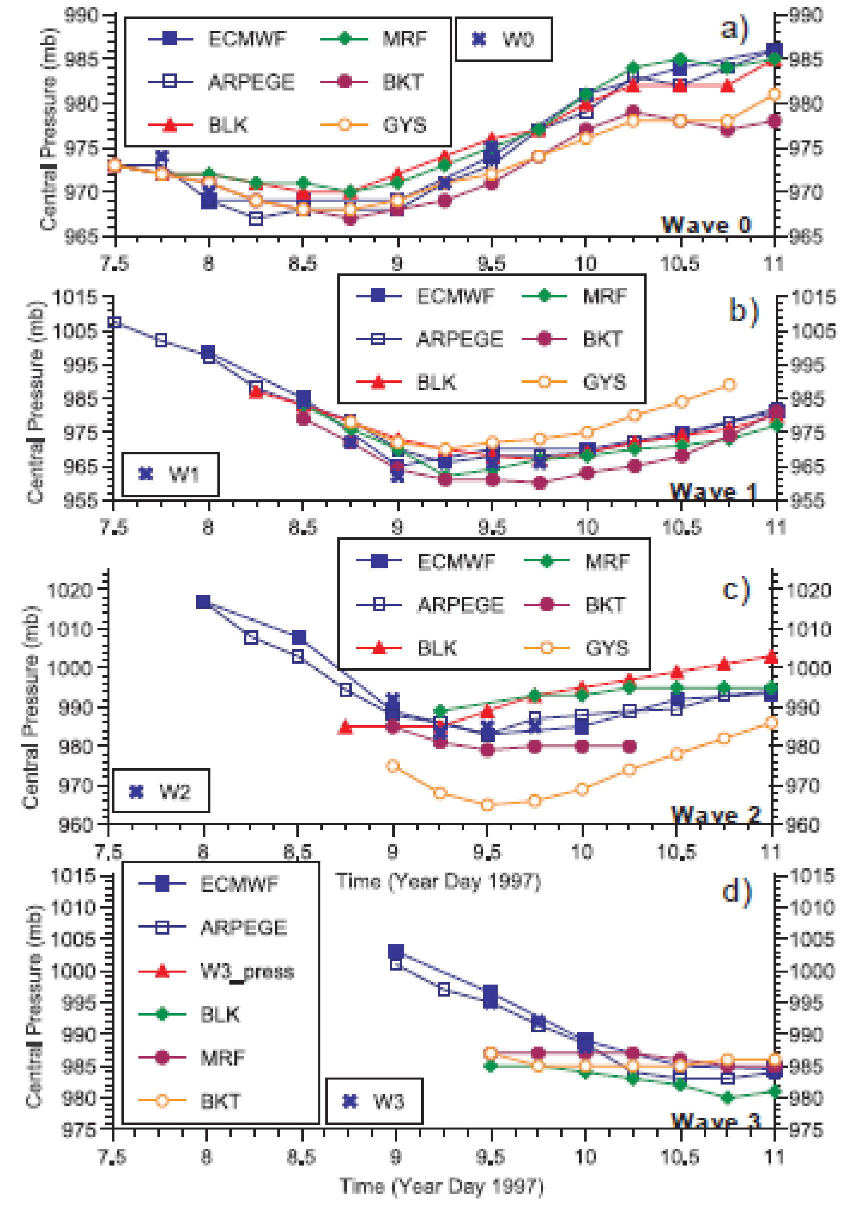
- IOP1 of FASTEX (North Atlantic Ocean, Jan. 8 - Jan. 11, 1997)
- development/movement of 1 parent cyclone (W0) and 3 frontal waves (W1, W2, W3)



- Knorr in warm sector of W1 & W2
- low over Knorr for W3



Storm Sensitivity to Flux/PBL Variations



MM5 modified version 3-5

ΔX = 81, 27 km; 2-way nest
50 levels, 20 levels below 1500 m
Grell (1993) cumulus param
Mixed-phase explicit moisture (Reisner et al 1998)
ECMWF I.C. , B.C. enhanced with obs
84 h simulation (12Z 1/7/97- 00Z 1/11/97)

Surface Flux/PBL schemes

BLK (Blackadar 1979; Zhang & Anthes 1982) -1st order, Ri-dep. sfc flux
MRF (Hong & Pan 1996) -1st order, Ri-dep. sfc flux
GYS (Shafran *et al.* 2000) -2nd order (TKE), Ri-dep sfc flux
BKT (Burk & Thompson 1989) - 2nd order (TKE), Louis (1979) sfc flux

Key Results

- frontal waves replicated
- evolutions different
- none produced correct central p & track for all 3
- GYS & BKT tend to be further off for central p

Storm Sensitivity to Flux/PBL Variations

-Varying PBL/sfc fluxes impacted W1 & W2 tracks most (~ 1000 km difference)

-GYS & BKT track tend to be further off

-MRF best for W1 track & W2 central p

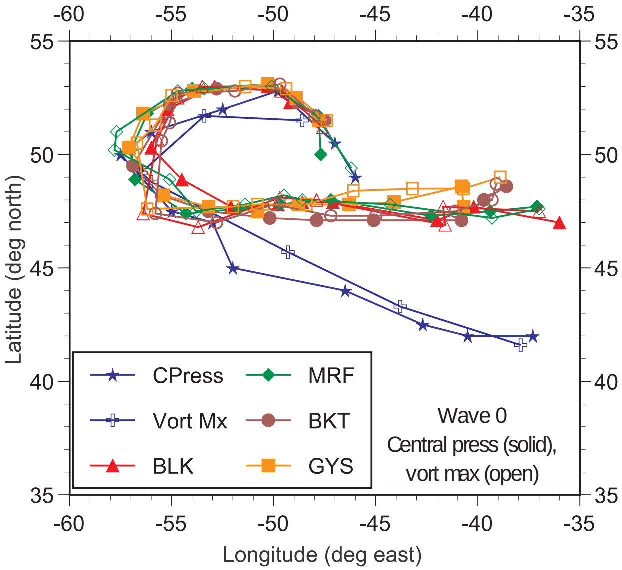
Summary

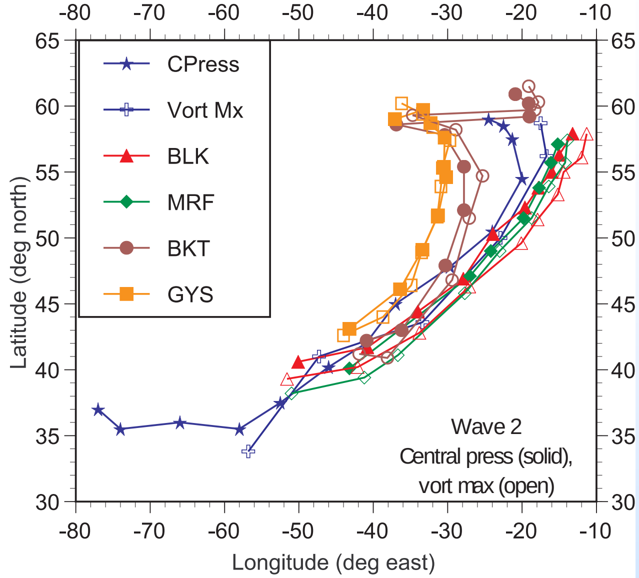
-Central p & track differences of 30 mb & 1000 km

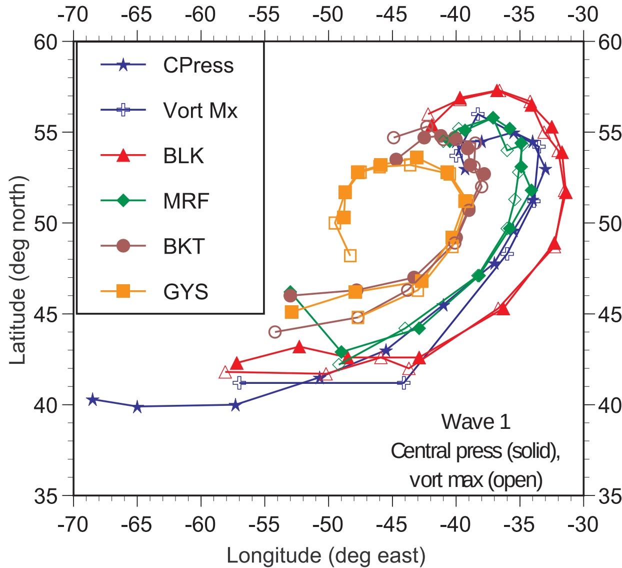
- MRF run performed best

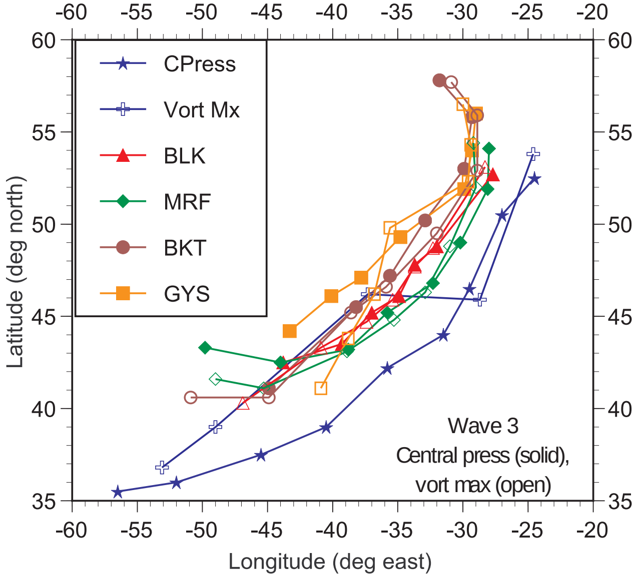
- error similarities for GYS & BKT suggest common problem for 2nd order schemes

-Large differences between GYS, BLK, and MRF despite having same surface flux scheme suggest PBL redistribution more important than surface fluxes





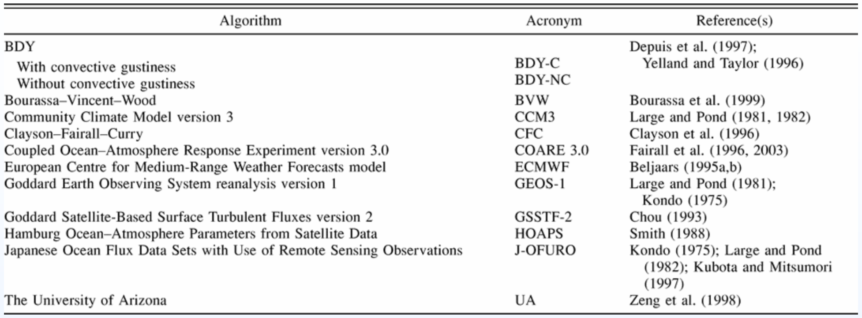




Off-line flux testing

Brunke et al (2003)

- 12 different surface flux parameterization schemes:

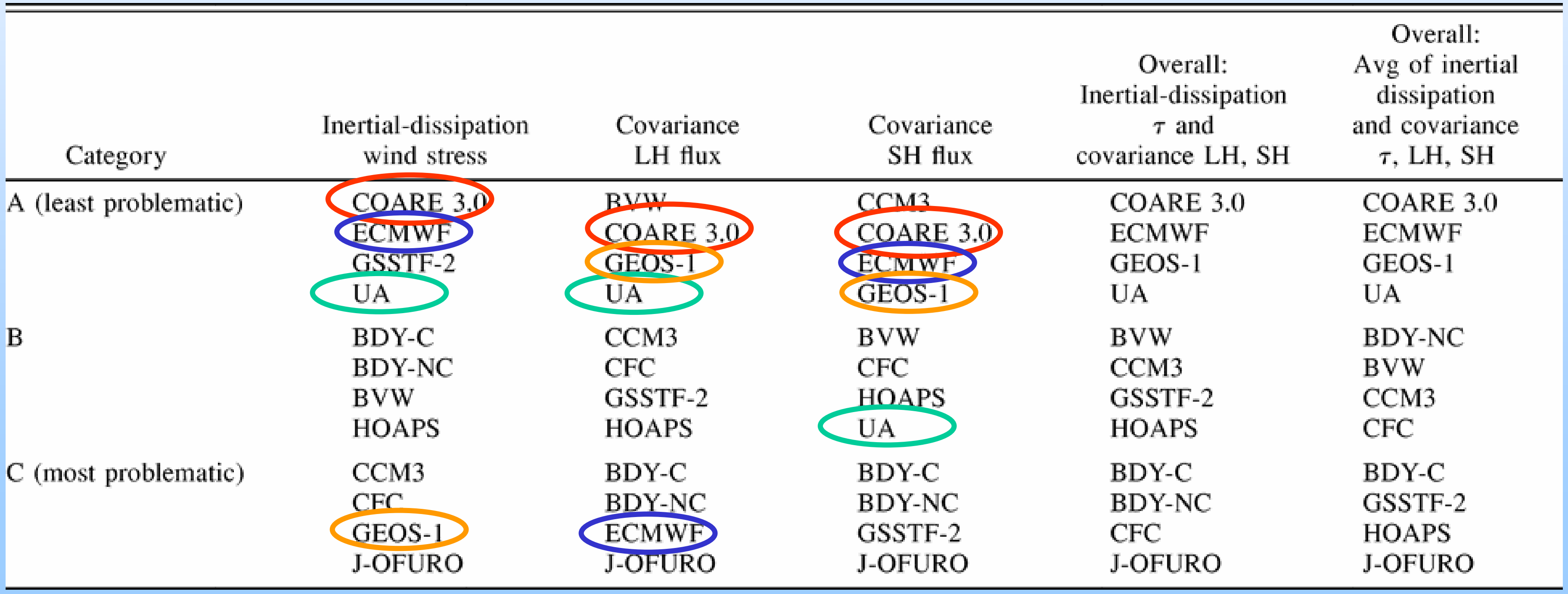


Algorithm	Acronym	Reference(s)
BDY		Depuis et al. (1997); Yelland and Taylor (1996)
With convective gustiness	BDY-C	
Without convective gustiness	BDY-NC	
Bourassa–Vincent–Wood	BVW	Bourassa et al. (1999)
Community Climate Model version 3	CCM3	Large and Pond (1981, 1982)
Clayson–Fairall–Curry	CFC	Clayson et al. (1996)
Coupled Ocean–Atmosphere Response Experiment version 3.0	COARE 3.0	Fairall et al. (1996, 2003)
European Centre for Medium-Range Weather Forecasts model	ECMWF	Beljaars (1995a,b)
Goddard Earth Observing System reanalysis version 1	GEOS-1	Large and Pond (1981); Kondo (1975)
Goddard Satellite-Based Surface Turbulent Fluxes version 2	GSSTF-2	Chou (1993)
Hamburg Ocean–Atmosphere Parameters from Satellite Data	HOAPS	Smith (1988)
Japanese Ocean Flux Data Sets with Use of Remote Sensing Observations	J-OFURO	Kondo (1975); Large and Pond (1982); Kubota and Mitsumori (1997)
The University of Arizona	UA	Zeng et al. (1998)

- 12 maritime tropical and midlatitude measurement programs, incl. FASTEX/CATCH (U <30 m s^{-1})
- objectively evaluated ability to reproduce observed τ, H_s and H_l

Conclusions:

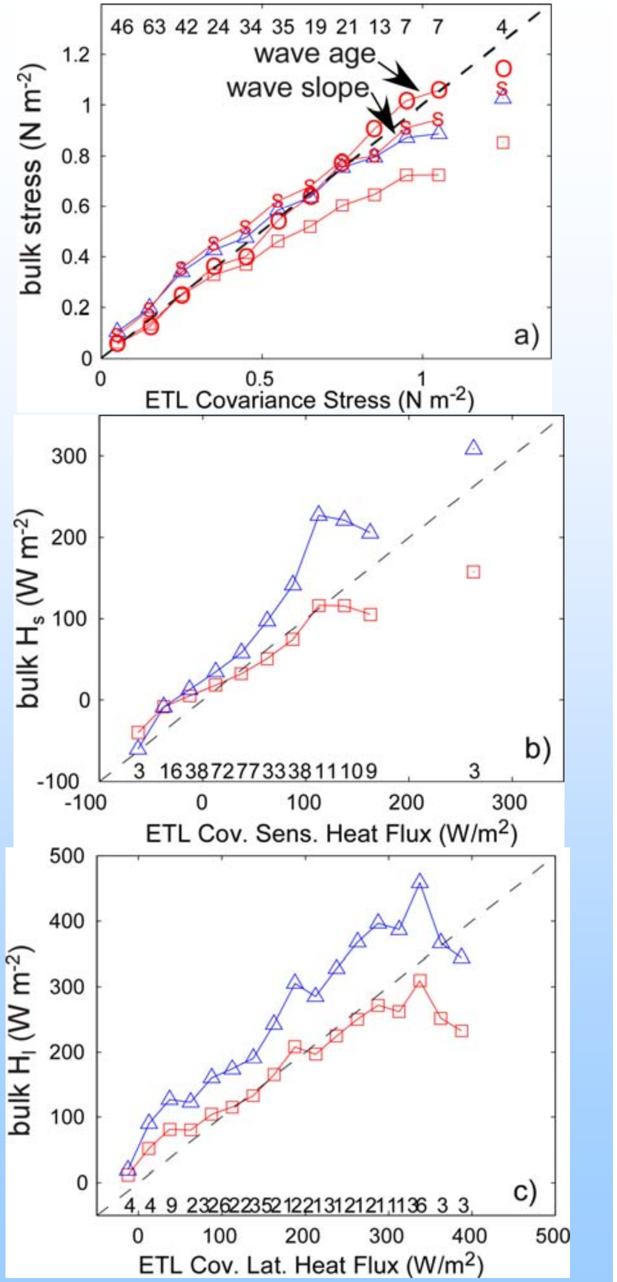
- four least problematic: COARE 3.0, University of Arizona (UA), ECMWF, NASA Goddard (GEOS-1)
- only COARE ranked in top 4 for each of three flux categories



Category	Inertial-dissipation wind stress	Covariance LH flux	Covariance SH flux	Overall: Inertial-dissipation τ and covariance LH, SH	Overall: Avg of inertial dissipation and covariance τ, LH, SH
A (least problematic)	COARE 3.0	BVW	CCM3	COARE 3.0	COARE 3.0
	ECMWF	COARE 3.0	COARE 3.0	ECMWF	ECMWF
	GSSTF-2	GEOS-1	ECMWF	GEOS-1	GEOS-1
	UA	UA	GEOS-1	UA	UA
B	BDY-C	CCM3	BVW	BVW	BDY-NC
	BDY-NC	CFC	CFC	CCM3	BVW
	BVW	GSSTF-2	HOAPS	GSSTF-2	CCM3
	HOAPS	HOAPS	UA	HOAPS	CFC
C (most problematic)	CCM3	BDY-C	BDY-C	BDY-C	BDY-C
	CFC	BDY-NC	BDY-NC	BDY-NC	GSSTF-2
	GEOS-1	ECMWF	GSSTF-2	CFC	HOAPS
	J-OFURO	J-OFURO	J-OFURO	J-OFURO	J-OFURO

Off-line flux testing

- using FASTEX (*R/V Knorr*) data (incl. wave data)



Blackadar (BLK)

$z_0 = 0.032\, u_*^2 / g \quad + .0001$

$S = [(u^2 + v^2) + U_c^2]^{0.5}$

$U_c = 2^*(\theta_s - \theta_a)^{0.5}$

uses $z/L = Ri_b \ln(z/z_0)$ to circumvent need for iteration

$z_T = z_Q = z_0$

COARE 3.0 - iterates using z/L (M-O) to converge

$z_0 = \alpha\, u_*^2 / g \quad + 0.11\nu / u_*$

where ν is the molecular viscosity and

$\alpha = .011$ for $U \leq 10$ m s^{-1}

$= .011 + (U\text{-}10)^*(.018\text{-}.011)/(18\text{-}10)$ for 10 m s$^{-1} < U < 18$ m s^{-1}

$= .018$ for $U \geq 18$ m s^{-1}

$z_T \neq z_Q \neq z_0$

COARE Options:

wave age (Oost et al 2001) (O)

$z_{0Oe} = (50/2\pi)\, L_p\, (u_* / C_p)^{4.6} + 0.11\nu / u_*$

wave slope (Taylor and Yelland 2001) (S)

$z_{0TY} = 1200\, h_{sig}\, (h_{sig}/L_p)^{4.5} + 0.11\nu / u_*$

L_p - wavelength associated with the peak of the wave frequency-size spectrum ("dominant wave period", T_p)

C_p - phase speed of the dominant wave

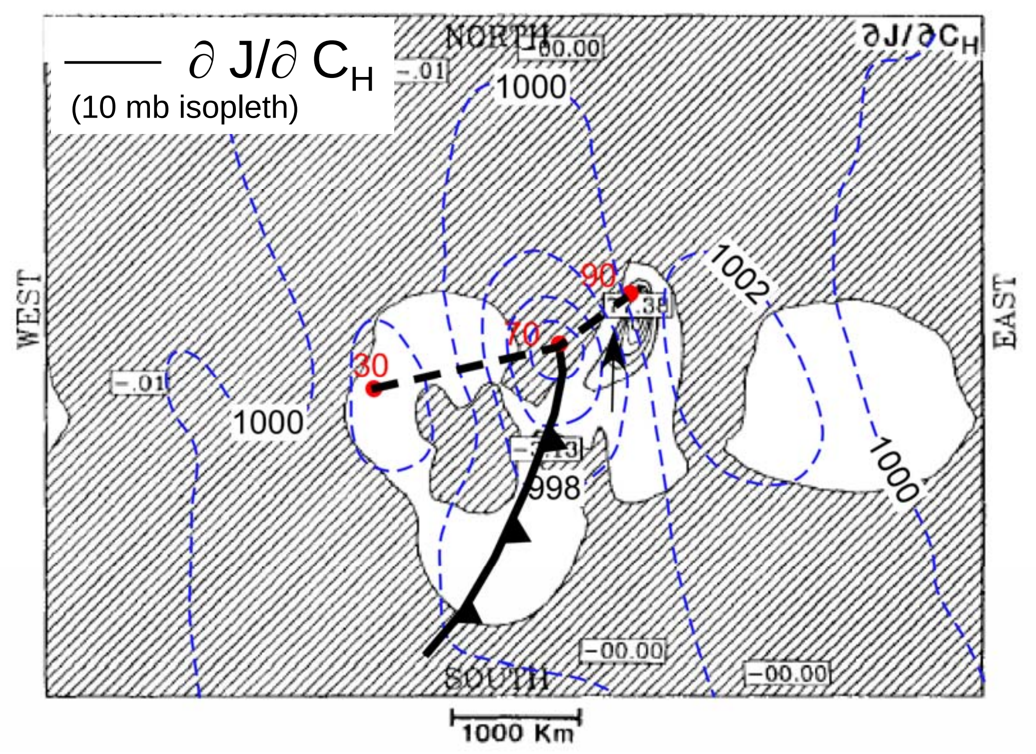
Key Flux Regions of Extratropical Cyclones

"In advance of developing Pacific cyclones" - surface fluxes in advance of developing Pacific cyclones, and before the rapid deepening stage, preconditioned the near-surface environment to the extent that explosive deepening occurred. Reed and Albright (1986) and Gyakum and Danielson (2000)

Warm sector, ahead of cold front, S of storm track - with adjoint model, idealized maritime cyclone, Langland *et al.* (1995) showed that surface sensible heat fluxes in the warm sector just ahead of the cold front and south of storm track produced the main impact on the cyclone evolution

J - cost function

C_H - sensible heat transfer coefficient



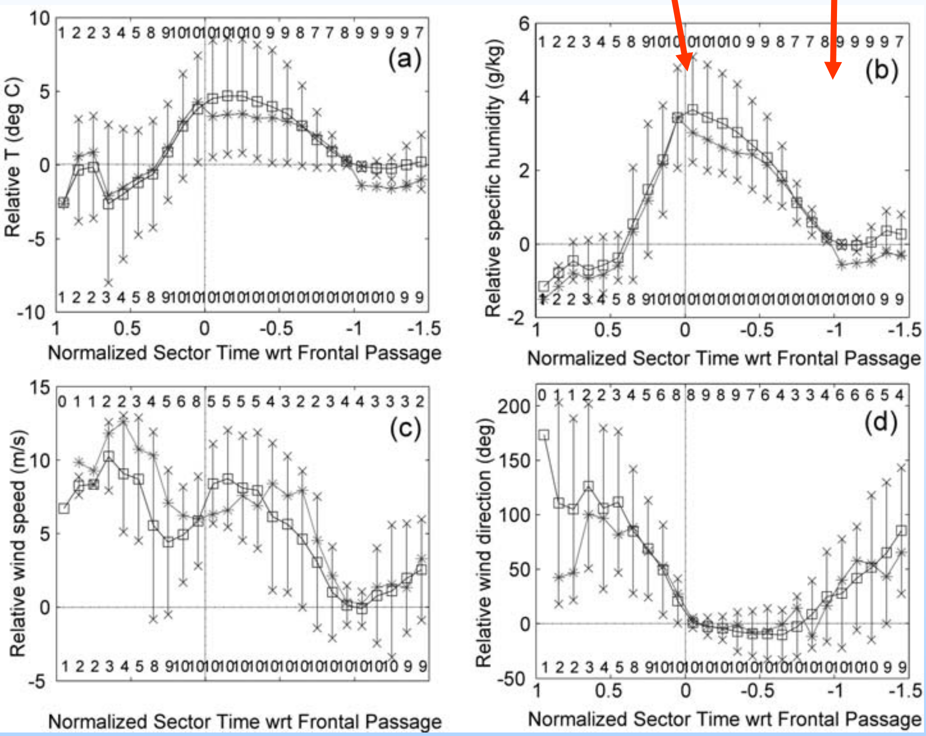
Field of sensitivity to surface heat-transfer coefficient, ∂ J/∂ C_H, (isopleth = 10 hPa) accumulated between 60 and 90 h. Positive ∂ J/∂ C_H indicates H_s is anticyclogenetic for 90 h central pressure. Negative values are hatched. Blue dashed isopleths show surface pressure at 70 h. Red dots show location of low at 30 h, 70 h, and 90 h in this non-linear forecast with sea-surface-temperature anomaly. Heavy dashed line shows the low center track. The approximate location of the surface front and a low-level, warm sector wind vector are also depicted. J is the cost function for the adjoint model. **Adapted from Langland et al (1995).**

Front-Relative Fluxes - Observations

Composite of 10 FASTEX cases for *R/V Knorr* path through open wave of cyclone (Persson et al 2005)

Time normalized by warm sector duration (onset of moistening, frontal wind shift)

Warm Sector



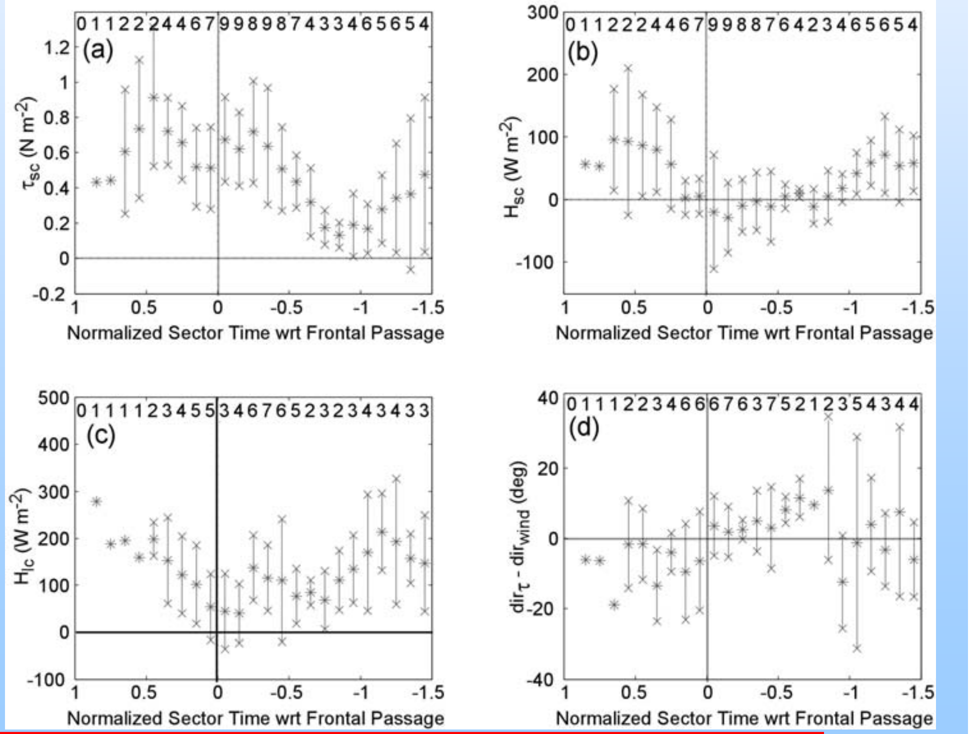
Conclusions:

a) moistening & warming lead to minima in H_{sc} and H_{lc} just before frontal passage, despite the strong surface winds at this time

b) though warm-sector H_{sc} minimum negative, H_{sc} and $H_{lc} > 0$ - positive impact on synoptic development

c) τ_{sc} maximum just before frontal passage during the ws peak (LLJ)

d) second τ_{sc} maximum of comparable magnitude in middle of post-frontal regime.



Conclusions (cont.):

e) patterns of heat and momentum fluxes should affect surface potential vorticity generation, and have dynamical implications for stability of the frontal zone for frontal wave development.

f) wave heights increase from eastern half of warm sector to frontal passage, remaining high through most of post-frontal regime before decreasing

Spatially/Temporally Varying Ocean Characteristics

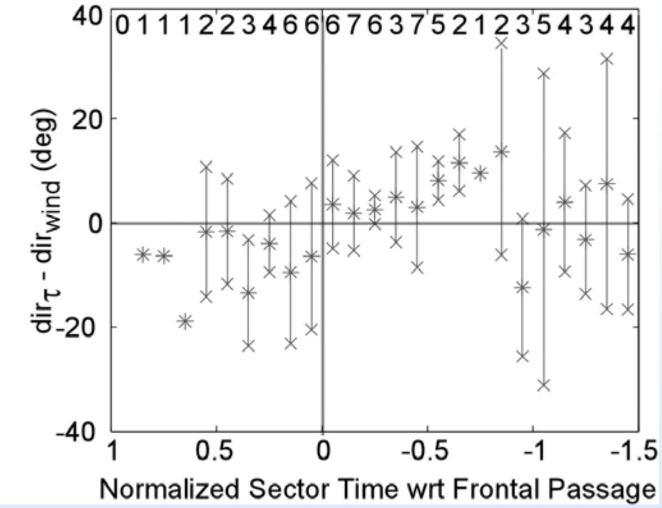
Wave characteristics
-stress-wind direction mismatch
-surface roughness - wave height, wave age, wave slope

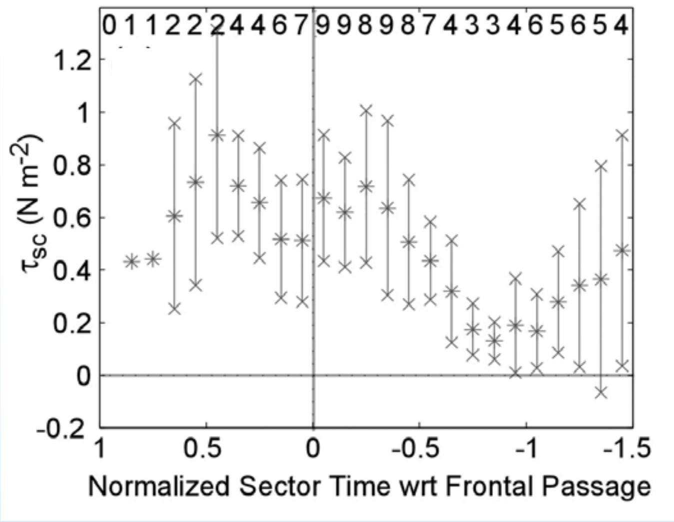
Sea spray

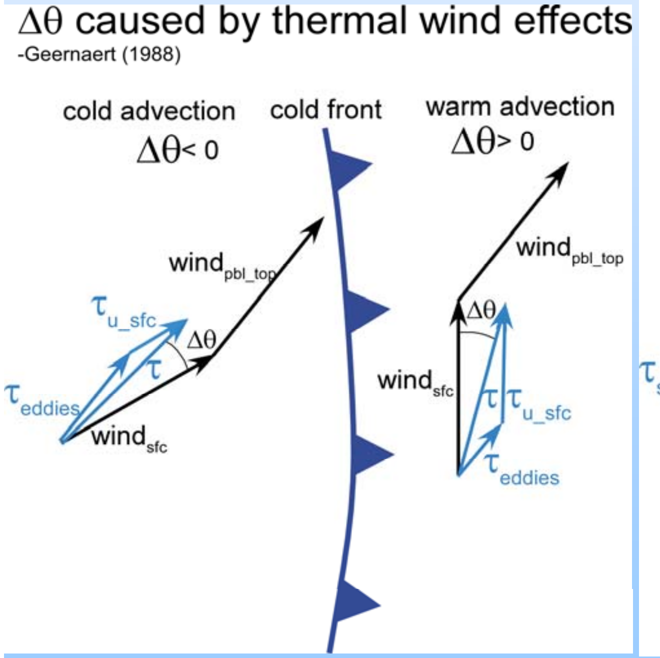
Sea-surface temperature

Spatially/Temporally Varying Ocean Characteristics

Wave characteristics - stress-wind direction mismatch (Persson *et al*. 2004)

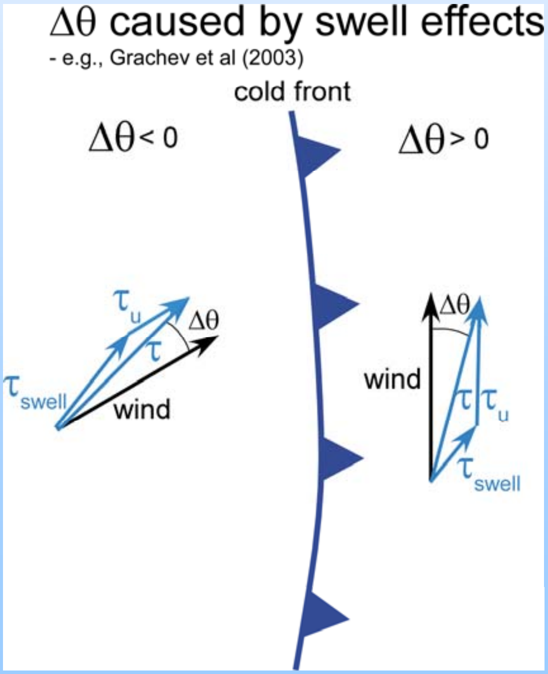






$\Delta\theta$ caused by thermal wind effects

-Geernaert (1988)



$\Delta\theta$ caused by swell effects

- e.g., Grachev et al (2003)

Implies

a) stress parameterizations may need to consider directional aspects in vicinity of frontal zones

b) satellite-based scatterometer wind directions may be in error and will underestimate the surface directional wind shift across the front. Derivative fields (convergence and vorticity) will also be underestimated

Storm Sensitivity to Wave Stress

- idealized cyclone development coupled with wave model (Doyle 1995)

<u>CHZSST</u>

$z_0 = \alpha\tau / (g\ \rho)$

τ - total stress

α - Charnock constant = 0.0185

<u>COZSST (WAM Model)</u>

$z_0 = \beta\tau / [\ g\ \rho\ (1-\tau_w/\tau)^{0.5}\ ]$

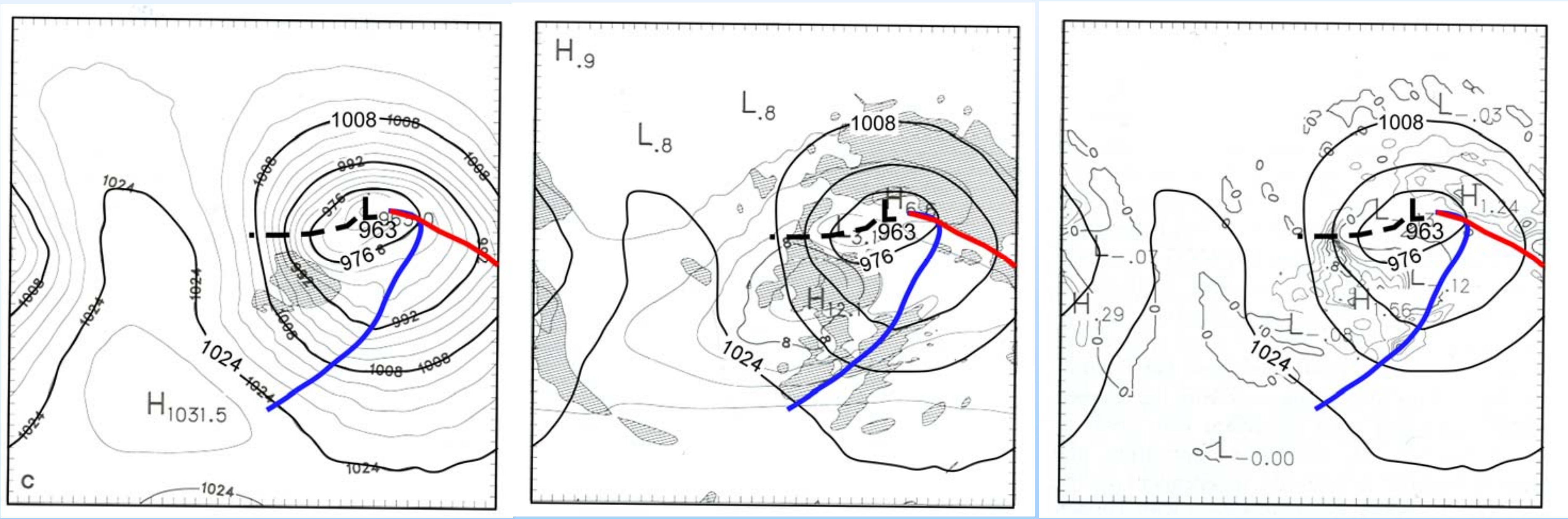
τ - total stress

τ_w - wave induced stress (from WAM)

COZSST Sfc P
ws > 25 m/s

COZSST Sig wave ht (m)
$\tau_w/\tau > 0.9$ (young waves, z_0 large)

Δz_0 (COZSST-CHZSST)



-Young waves significantly increase z_0, esp. near cold front, ahead of warm front, & in SW storm sector (behind cold front)

-Wind speed decreased 12-20%, central p response complex but varied 8-10 mb

-Increase τ despite decreased winds, H_s & H_l increased 30-60% in SW quadrant

Effects of Spatially/Temporally Varying Ocean Characteristics

Wave characteristics- surface roughness (wave age) (Zhang et al 2006)

MC2; $\Delta x = 0.25°$

Uncoupled: $Z_{0m} = \beta u_*^2/g$, $\beta = 0.018$

Coupled: WW3 wave model

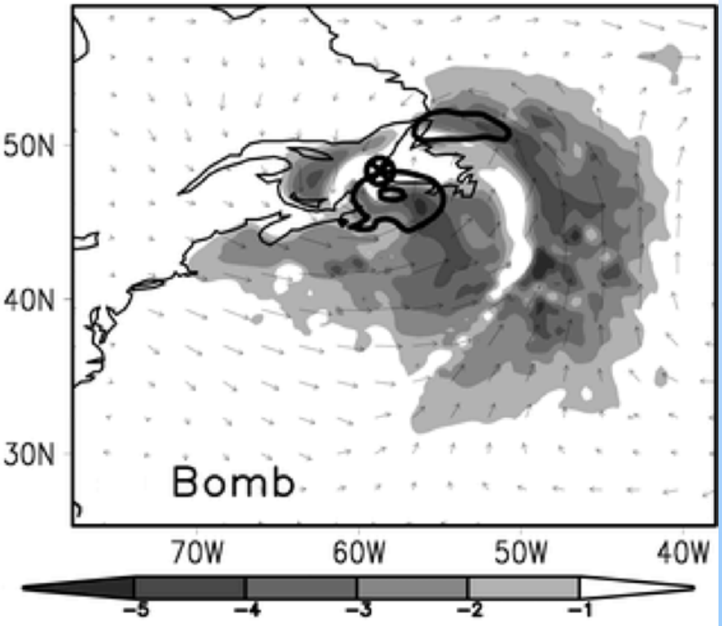
$$Z_{0m} = 0.48\,(C_p/u_*)^{-1}\,(u_*^2/g)$$

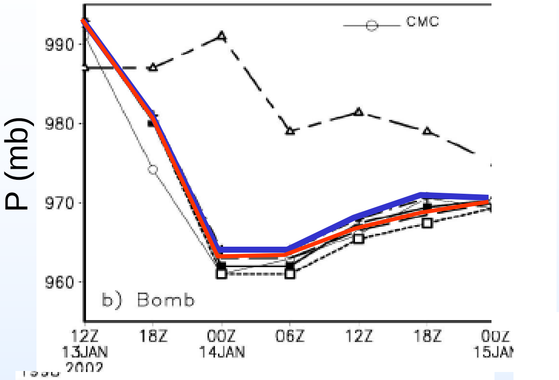
C_p – peak phase velocity

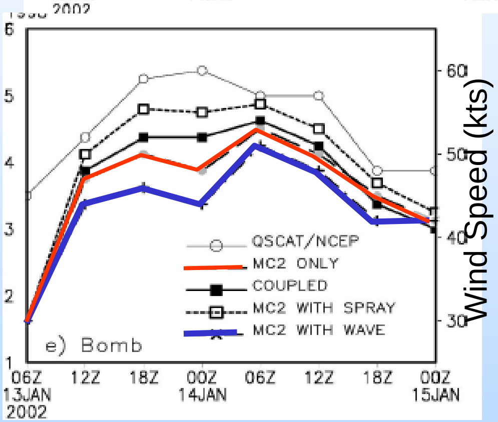
$$Z_{0m} = 0.0034 \text{ m}, U_{10} > 30 \text{ m s}^{-1}$$

$$Z_{0t} = Z_{0q} = 4 \times 10^{-5} \text{ m}$$

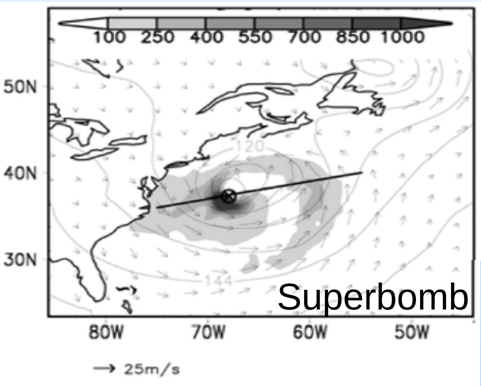
ΔSLP (contour)
ΔU_{10} (shading)
MC2_wave - MC2

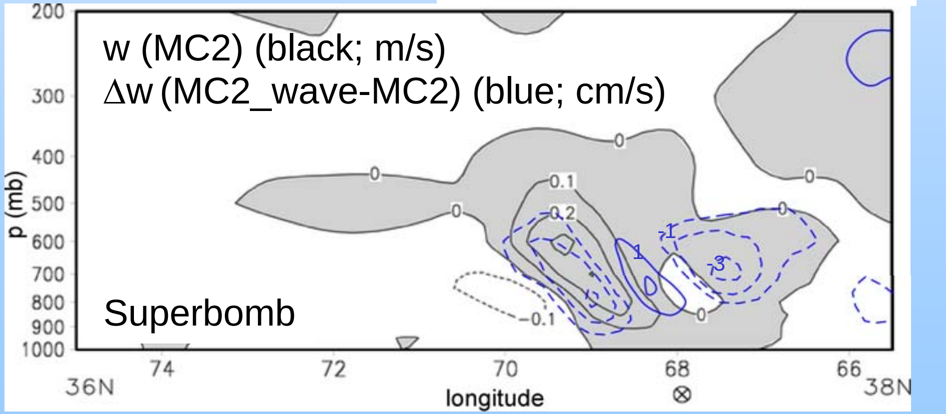






X-section location





Spatially/Temporally Varying Ocean Characteristics

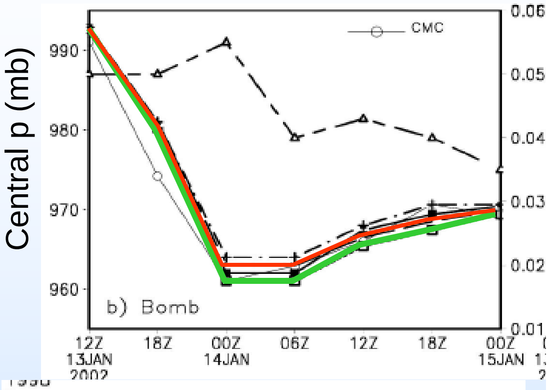
Sea spray (Andreas 2003; Zhang et al 2006)

$$\tau_T = \tau + \tau_{sp}, \qquad \tau_{sp} = 6.2 \times 10^{-5} \rho_w u_*^4$$

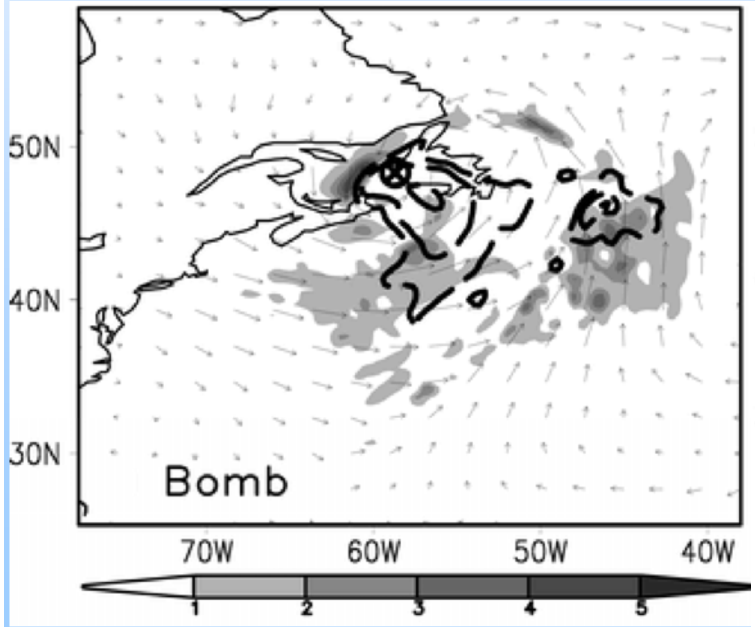
(negligible for U < 40 m/s)

$$H_{L,T} = H_L + Q_{L,sp}, \qquad Q_{L,sp} = \rho_w L_v \left[1 - \left(\frac{r_{eq,50}}{50\ \mu\mathrm{m}} \right)^3 \right] V_L(u_*)$$

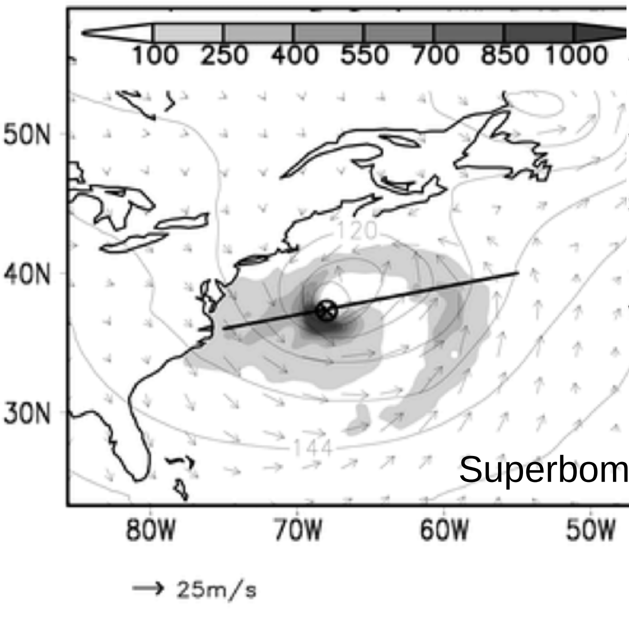
$$H_{S,T} = H_S + Q_{S,sp}. \qquad Q_{S,sp} = \rho_w c_w (\theta_0 - T_{eq,100}) V_S(u_*)$$

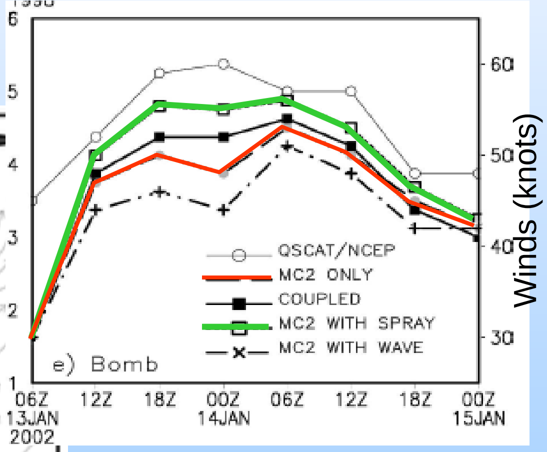


ΔSLP (contour)
ΔU_{10} (shading)
MC2_spray - MC2



$\Delta H_s + \Delta H_l$ (shading)
MC2_spray - MC2



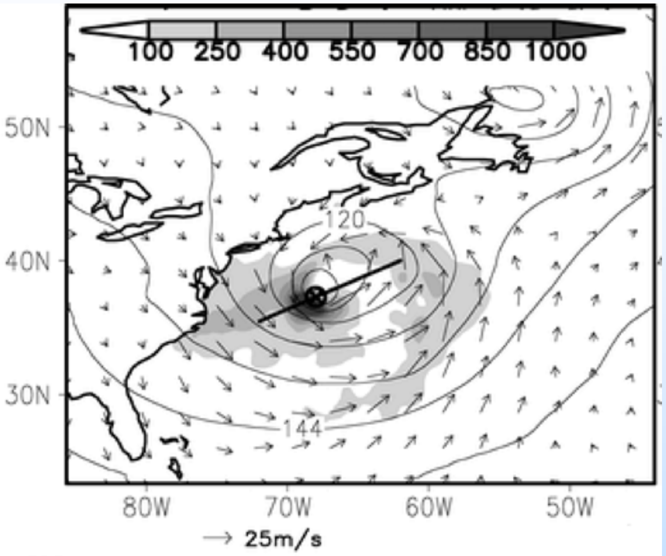


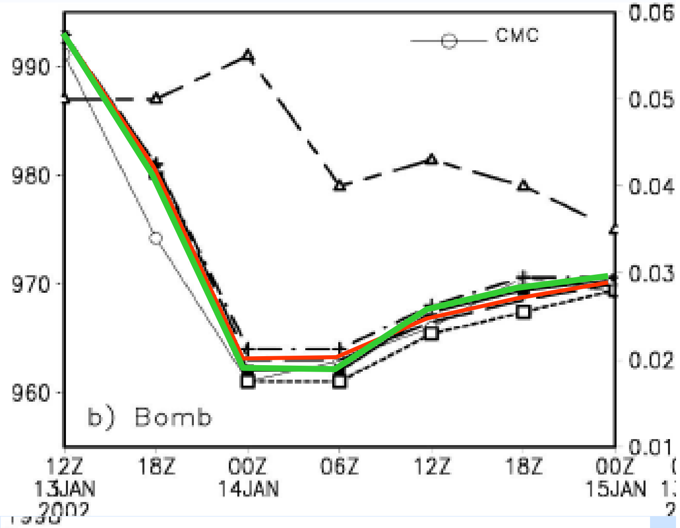
Spatially/Temporally Varying Ocean Characteristics

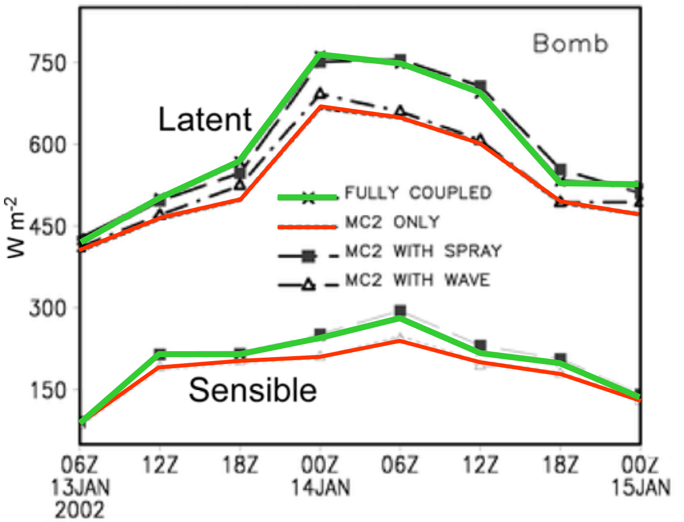
Wave age & Sea spray (Zhang et al 2006)

$\Delta H_s + \Delta H_l$ (W m^{-2}; shading)
MC2_wave_spray - MC2

-similar flux distribution and magnitude as for spray only
-cyclone impact closer to spray only than wave drag only

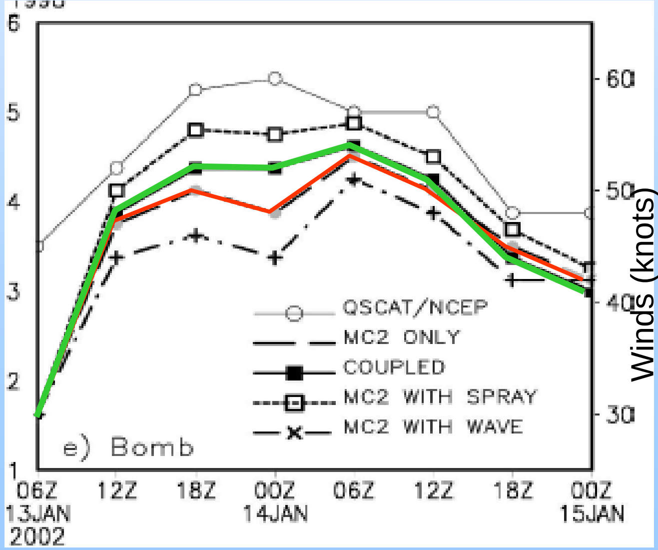






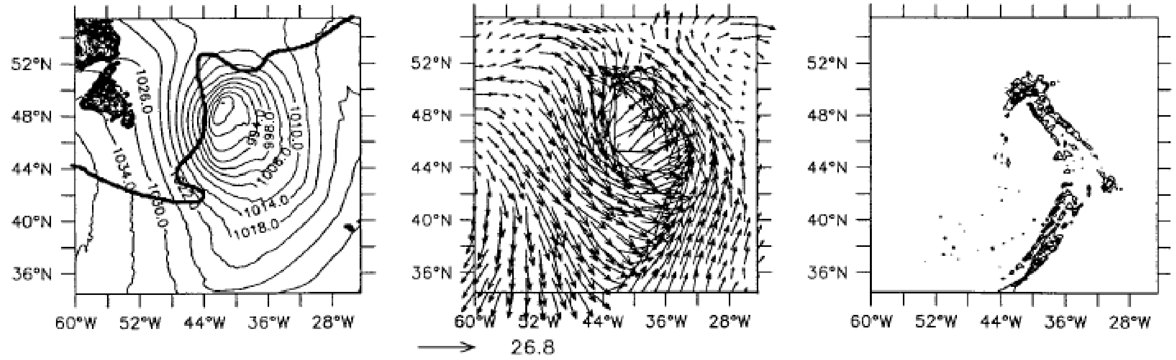
impact on H_l greater than on H_s – contrary to param

200 × 200 km² area-averaged H_s (bottom four) and H_l (top four) following maximal flux center



Spatially/Temporally Varying Ocean Characteristics

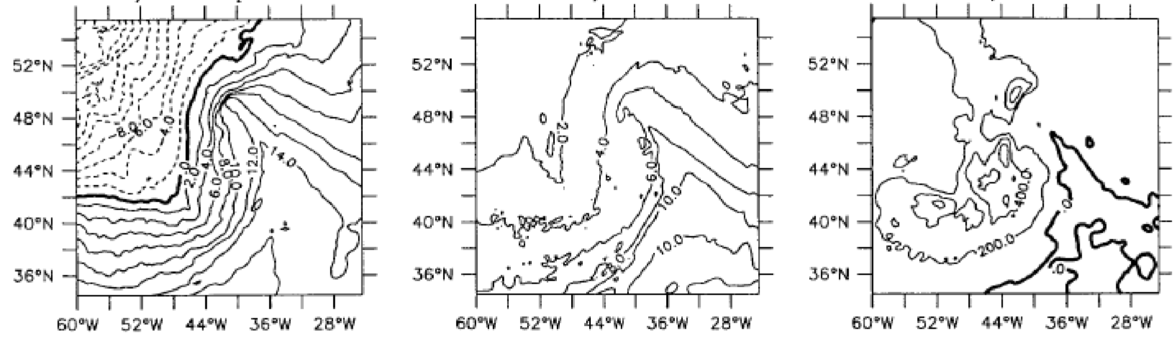
Sea Surface Temperature – North Atlantic Gulf Stream (Giordani and Caniaux 2001)



a). Surface pressure.

b). Wind.

c). Rain.

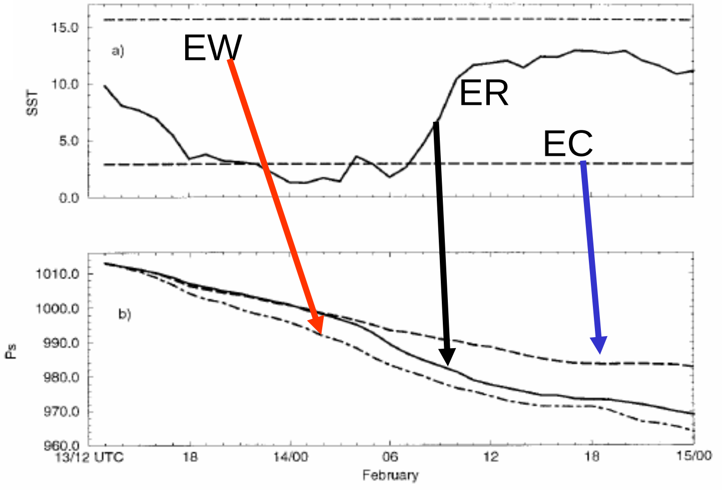


d). Theta.

e). Qa.

f). BUO.

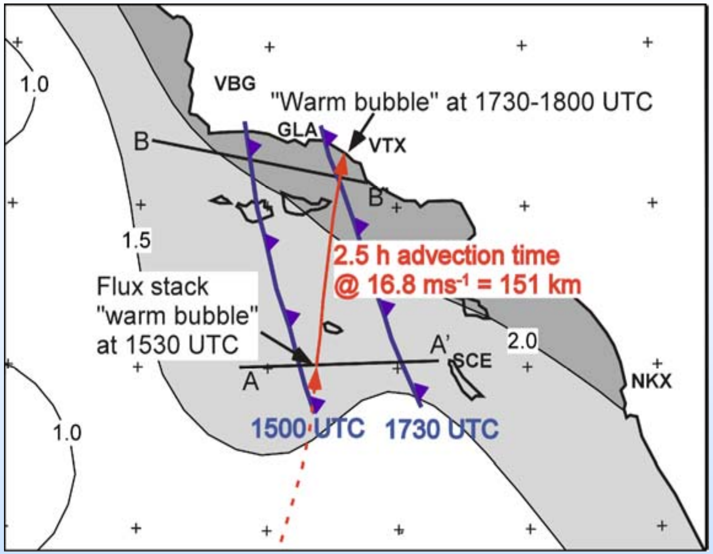
Simulated (a) surface pressure (hPa), (b) wind at 20 m (m s21), (c) surface rainfall rate (mm h21), (d) potential temperature at 20 m (Q) (8C), (e) specific humidity at 20 m (*Qa*) (g kg21), and (f) surface buoyancy flux (BUO) (W m22), for 1200 UTC 14 Feb. The oceanic front is symbolized by the isotherm 108C (solid line) in the surface pressure field.

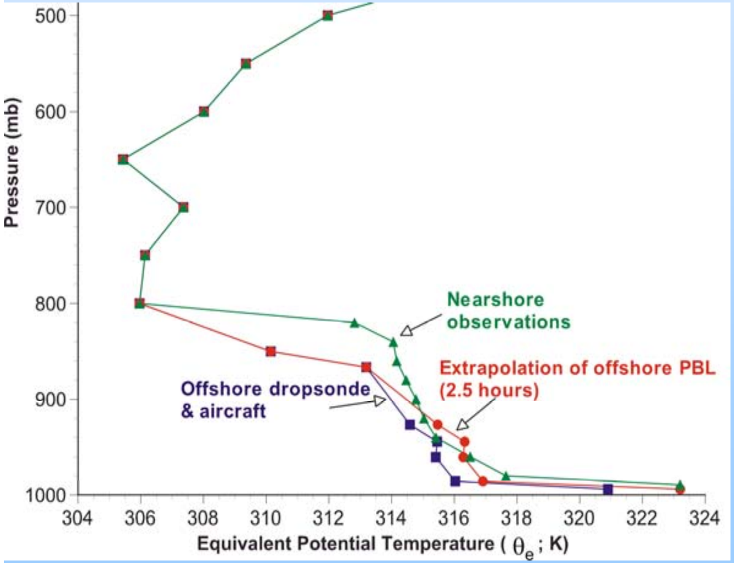


The ER (solid line), EC (dashed line), and EW (long-short dashed line) (a) SST (8C) and (b) surface pressure (hPa) along the low center trajectories between 1200 UTC 13 Feb and 0000 UTC 15 Feb.

Spatially/Temporally Varying Ocean Characteristics

Sea Surface Temperature - Coastal California & El Niño (Persson et al 2005)

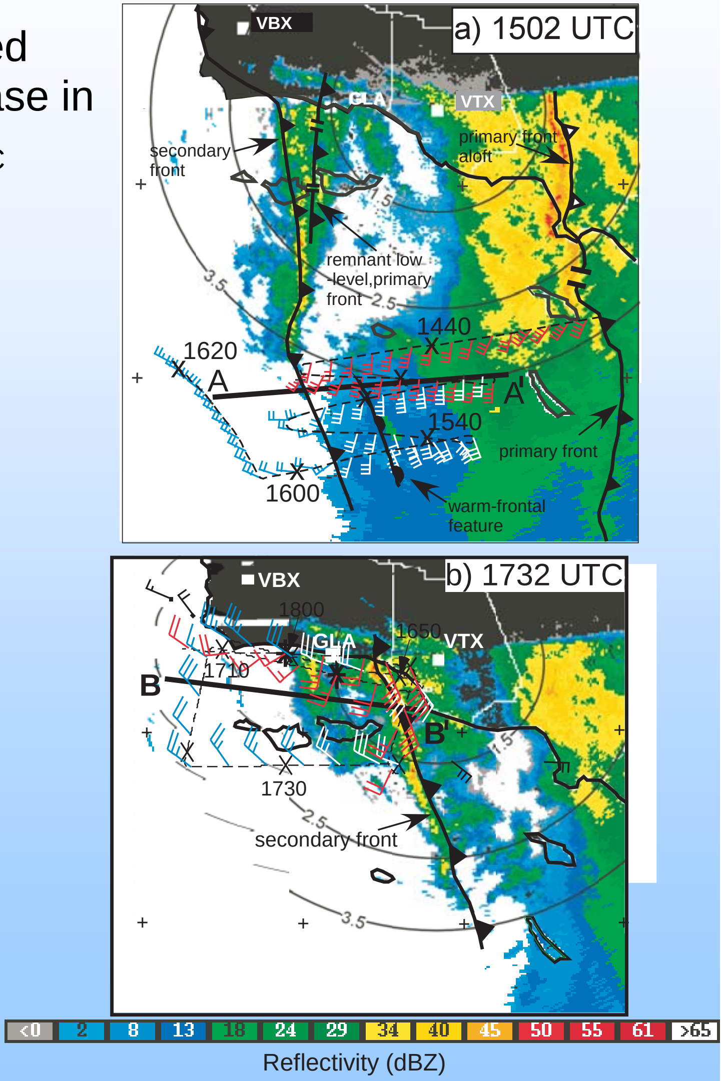




-cold front in CA Bight (2/2/98)

- coastal fluxes produced $\Delta\theta_e$ = 0.8 K, 26% increase in CAPE, decrease of z_{LFC}

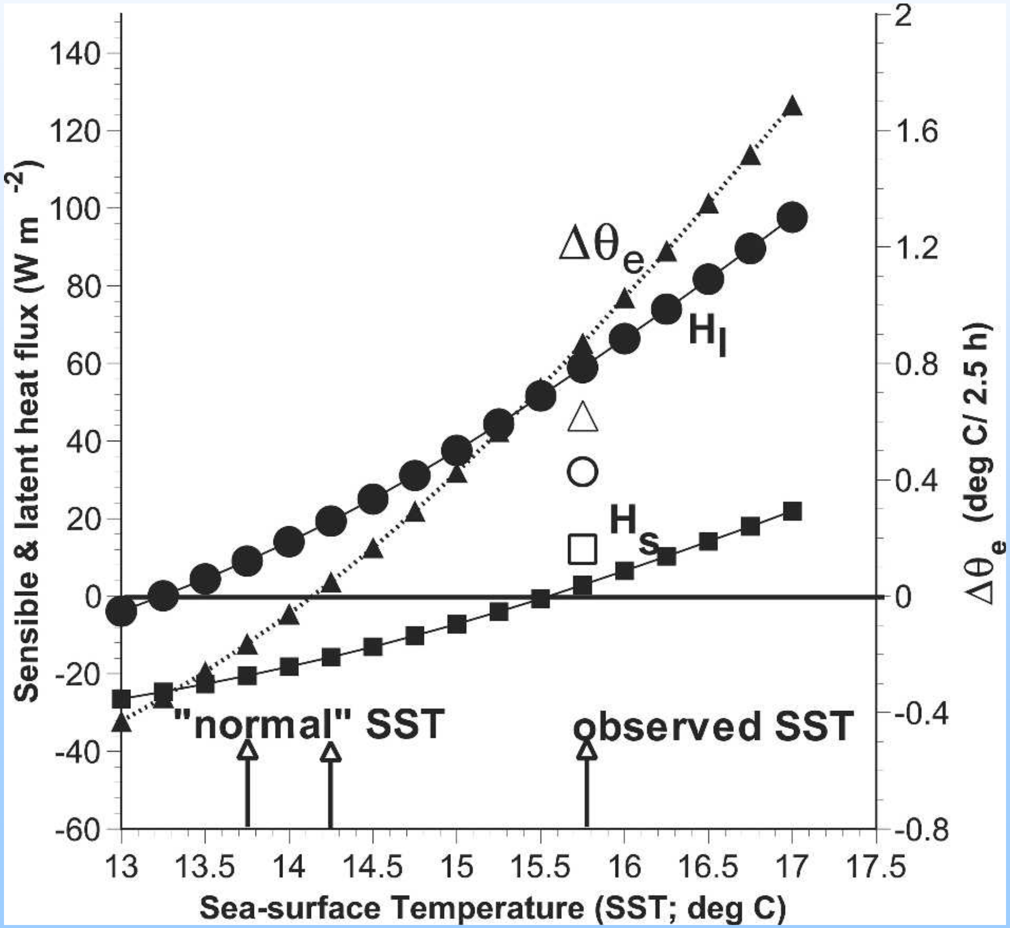
- heavy rains, flooding



Spatially/Temporally Varying Ocean Characteristics

Sea Surface Temperature - Coastal California & El Niño (Persson et al 2005)

- normal (non- El Niño) SST would have produced $\Delta\theta_e$ that was 0 K or < 0 K, & no increase in CAPE
- less recognized mechanism for enhancing CA precip during El Niño years



Summary

A. Impact on ETCs determined by timing and location of fluxes wrt evolution & key structures

- larger impact before the rapid deepening phase.
- storm intensity sensitive to heat fluxes occurring in warm sector & near the surface warm front
- storm track and intensity more sensitive to vertical redistribution by PBL schemes than to magnitude differences between surface flux parameterizations (tentative)

B. Intensity sensitivity to surface fluxes clearly illustrated by impacts of coupled wave models and sea-spray parameterizations

- wave drag decrease near-surface winds (few m/s) & often increase storm's central pressure (few mbs)
- sea-spray increases extratropical storm intensity (increase winds, decrease central pressure) by magnitudes comparable to wave-drag effects.
- largest sensible/latent heat flux increases occur in favored warm sector & SW quadrant
- only former region corresponds to maximum sensitivity area
- when wave drag and sea-spray effects both included, results similar to effects of just sea spray early in simulation and just wave drag late (ETC filling phase)

C. Spatial variability of SST also impacts evolution of ETCs and resulting precipitation

- SST gradients near North Atlantic Gulf Stream significantly impact storm evolution
- California coastal fluxes impact coastal precip from landfalling front
- temporal SST variability (e.g., ENSO effects in coastal CA) suggested
- no studies done on feedback effects of more rapid SST changes possibly occurring with strong ETCs (though such effects important for tropical hurricanes)

Future Work

A. Focus on better understanding of impacts of spatially and temporally variable surface characteristics

- clearer elucidation of sensitivity of cyclone evolution & structure to flux location relative to frontal features & life-cycle stage
- separate impacts of surface flux interfacial schemes from the PBL schemes
- may be necessary to use sophisticated modeling techniques or dynamically important diagnostic parameters (e.g., adjoint model; PV diagnostics)

B. Incorporate best off-line flux schemes into three-dimensional models

- if surface flux parameterization improvements needed, do additional off-line tests that include more sea-surface characteristics (e.g., wave characteristics, sea-spray, stress-wind direction mismatch)
- to facilitate off-line tests, additional measurements in high-wind conditions associated ETCs needed, where the storm-relative environment is well documented

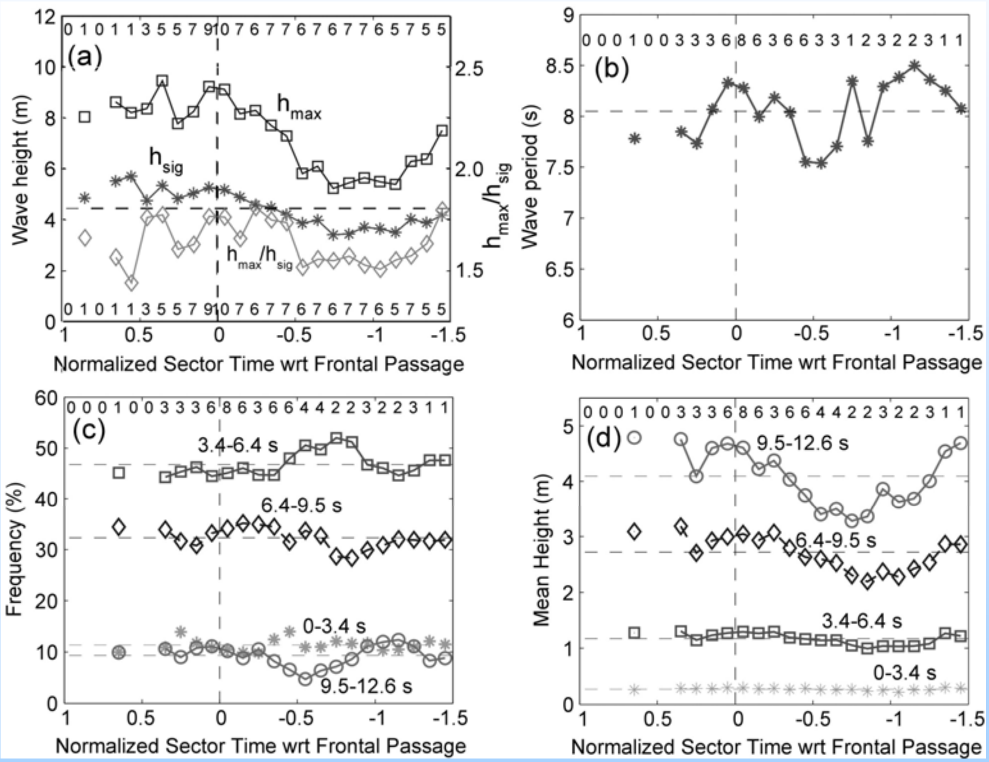
C. Conduct studies of impacts of aerosol fluxes (e.g., sea salt)

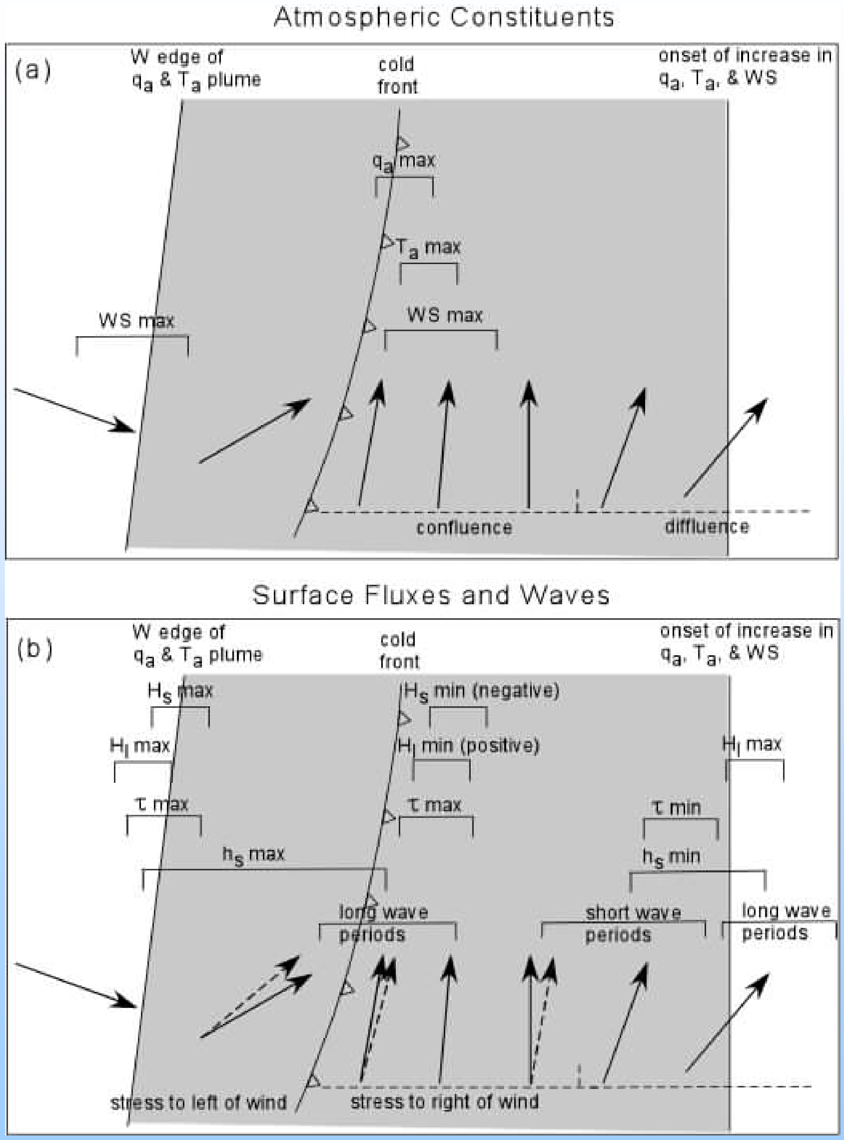
- effects likely on microphysics and possibly evolution
- require use of models such as the WRF/Chem model (Grell *et al.* 2005)

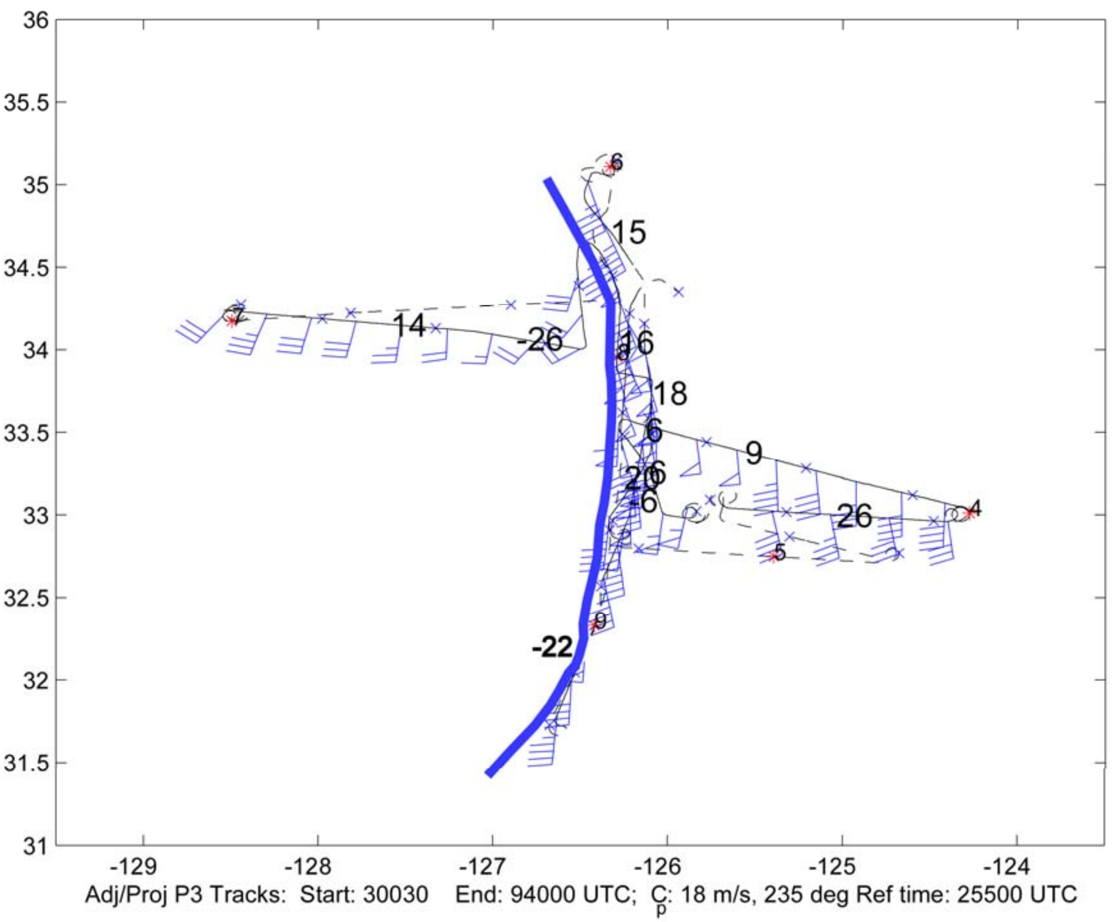
D. Consider impacts of surface flux transitions at sea-ice edge

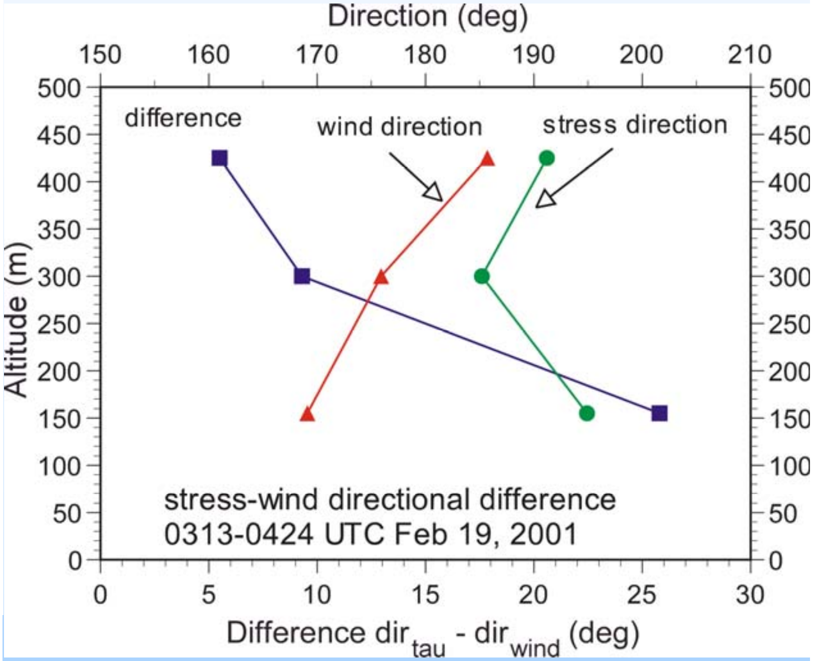
- surface flux impacts on polar low development have been studied (flow from the sea ice to the open ocean)
- more work needed understanding impact of surface flux changes as ETCs move from open water to over the sea ice - potentially important for understanding ETC impact on disappearing sea ice and as Arctic Ocean includes more open water
- require improved coupled sea-ice dynamics & fluxes for potentially very stable conditions

Front-Relative Fluxes – Wave Observations



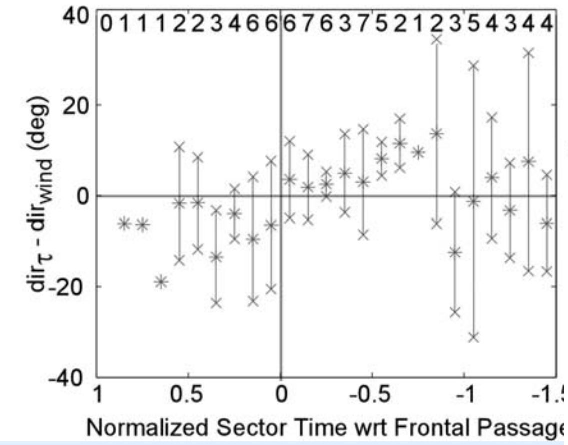


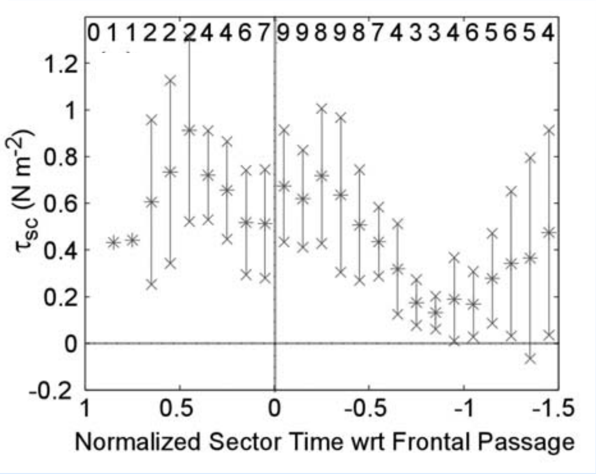

36
35.5
35
34.5
34
33.5
33
32.5
32
31.5
31
-129
-128
-127
-126
-125
-124
6
15
7
14
-26
16
18
6
9
20
6
-6
4
26
5
9
-22
Adj/Proj P3 Tracks: Start: 30030 End: 94000 UTC; C_p: 18 m/s, 235 deg Ref time: 25500 UTC

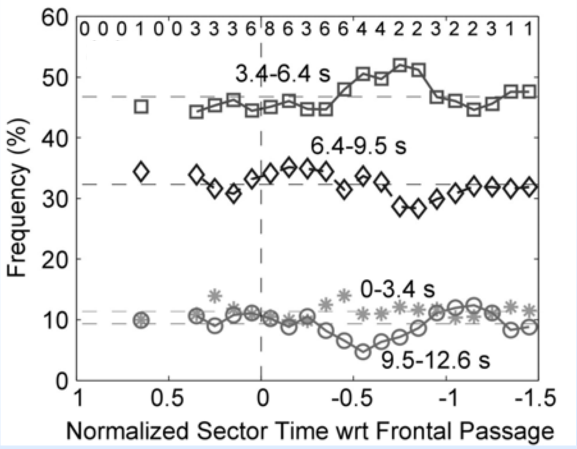

Direction (deg)
150
160
170
180
190
200
210
Altitude (m)
500
450
400
350
300
250
200
150
100
50
0
difference
wind direction
stress direction
stress-wind directional difference
0313-0424 UTC Feb 19, 2001
0
5
10
15
20
25
30
Difference dir_{tau} - dir_{wind} (deg)

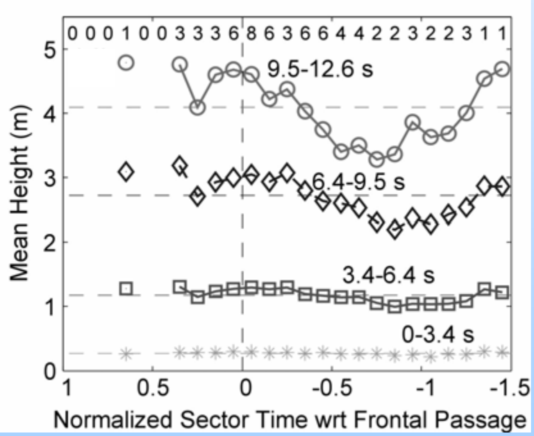
Spatially/Temporally Varying Ocean Characteristics

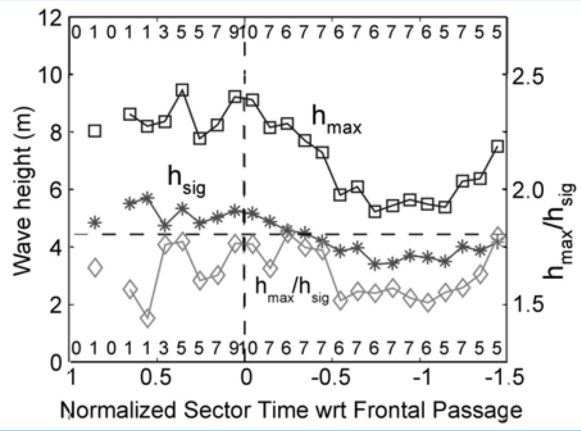
Wave characteristics - stress-wind direction mismatch (Persson *et al*. 2004)



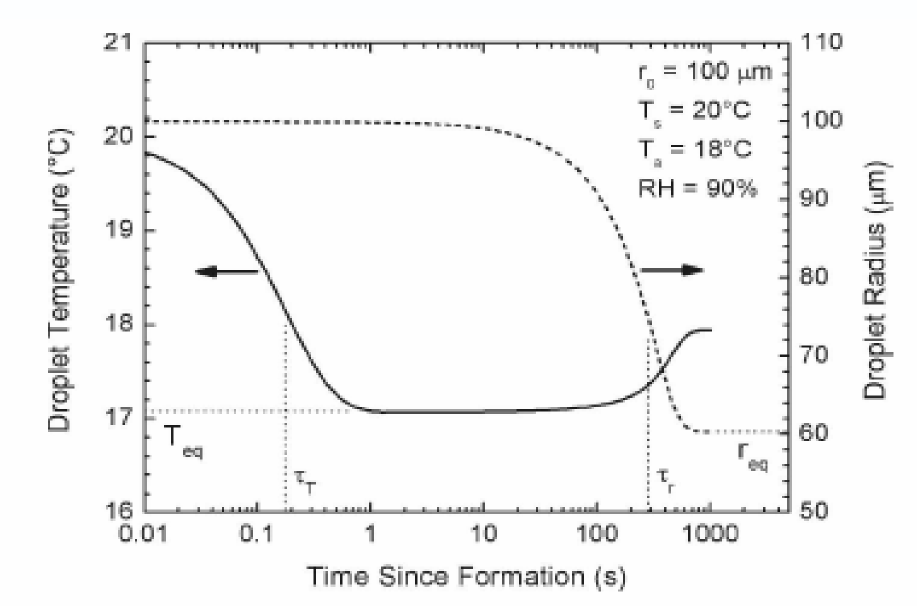








Sea Spray Parameterization (Andreas et al 2008)



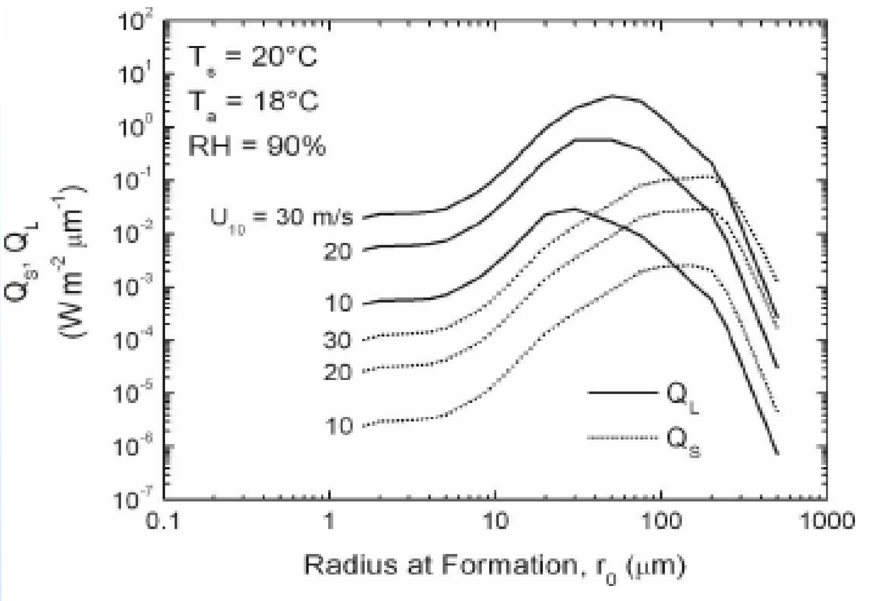


FIG. 1. Temperature and radius evolution of a spray droplet with initial radius 100 µ (r_0), initial temperature 20°C (T_s), and initial salinity 34 psu. This droplet is flung into air with temperature 18°C (T_a) and relative humidity 90% (RH); the barometric pressure is 1000 mb. The microphysical quantities T_{eq}, r_{eq}, T, and r characterize the evolution [see (2.1) and (2.2)].

FIG. 2. The radius-specific spray sensible (Q_S) and latent (Q_L) heat fluxes [from (2.4) and (2.6)] as functions of the radius at formation (r_0) for three values of the wind speed at a 10-m reference height (U_{10}). For these calculations, the water temperature (T_s) is 20°C, the air temperature (T_a) is 18°C, the RH is 90%, the barometric pressure is 1000 mb, and the surface salinity is 34 psu.

H_l from ocean for evaporating drop

$$H_{L,T} = H_L + \alpha\overline{Q}_L,$$

H_s due to ΔT of spray drop

H_s from atmosphere for evaporating drop

$$H_{s,T} = H_s + \beta\overline{Q}_S - (\alpha - \gamma)\overline{Q}_L$$

H_s due to bulk T_a-T_s change from evaporating drop

$$Q_{L,\mathrm{sp}} \equiv \alpha\overline{Q}_L = \rho_s L_v\left\{1 - \left[\frac{r(\tau_{f,50})}{50\ \mu\mathrm{m}}\right]^3\right\}V_L(u_*)$$

$$V_L(u_*) = 1.10 \times 10^{-7}u_*^{2.22}$$

$$H_{L,T} + H_{s,T} = H_L + H_s + \beta\overline{Q}_S + \gamma\overline{Q}_L$$

$$Q_{S,\mathrm{sp}} \equiv \beta\overline{Q}_S - (\alpha - \gamma)\overline{Q}_L = \rho_s c_{\mathrm{ps}}(T_s - T_{\mathrm{eq},100})V_S(u_*)$$

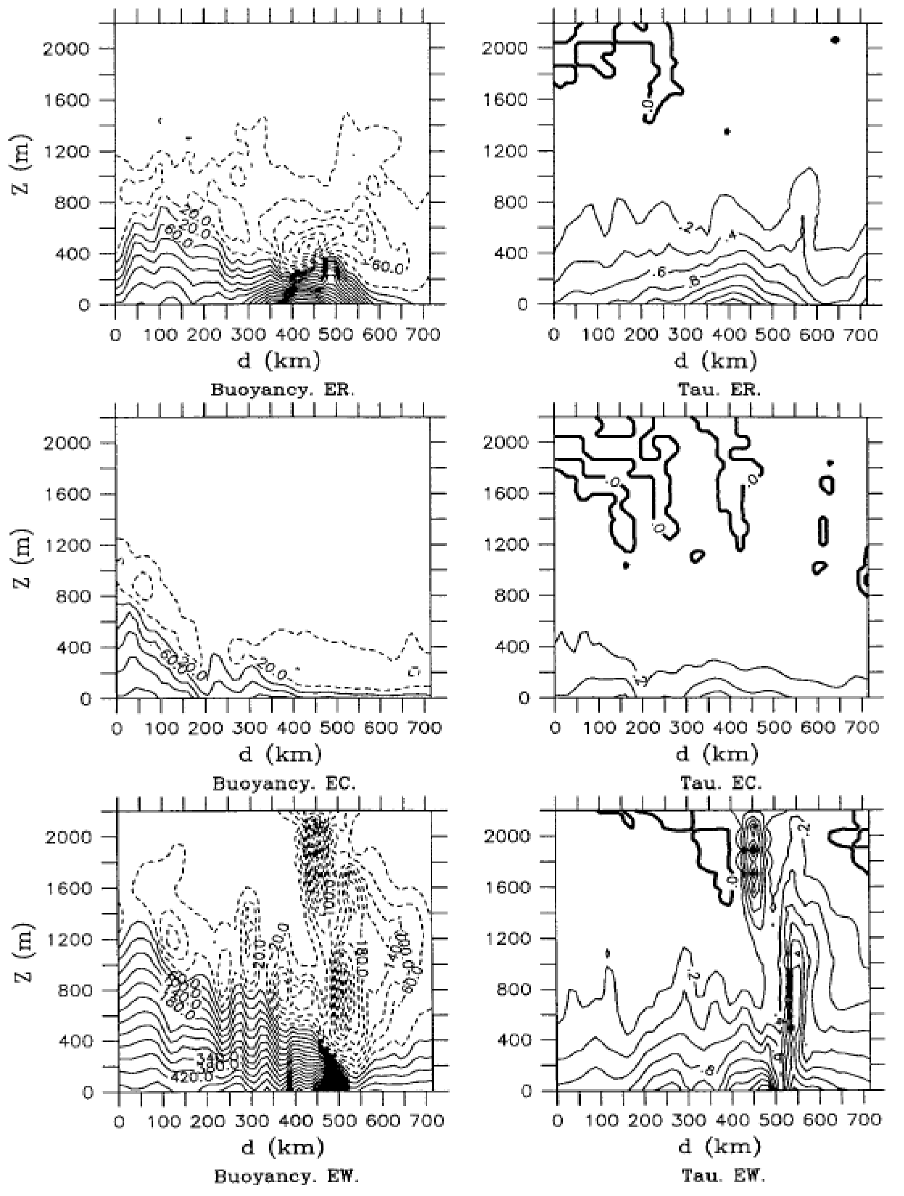
$$V_S(u_*) = 2.30 \times 10^{-6}u_*^3$$

$$H_{L,T} = H_L + Q_{L,\mathrm{sp}},$$

$$H_{s,T} = H_s + Q_{S,\mathrm{sp}}.$$

Spatially/Temporally Varying Ocean Characteristics

Sea Surface Temperature - Gulf Stream (Giordani and Caniaux 2001)



Vertical section across the occlusion (48°–38° W at the latitude 50°N) of the turbulent buoyancy flux (W m^{-2}) and turbulent momentum flux (N m^{-2}) in (a) ER, (b) EC, and (c) EW, for 1200 UTC 14 Feb.

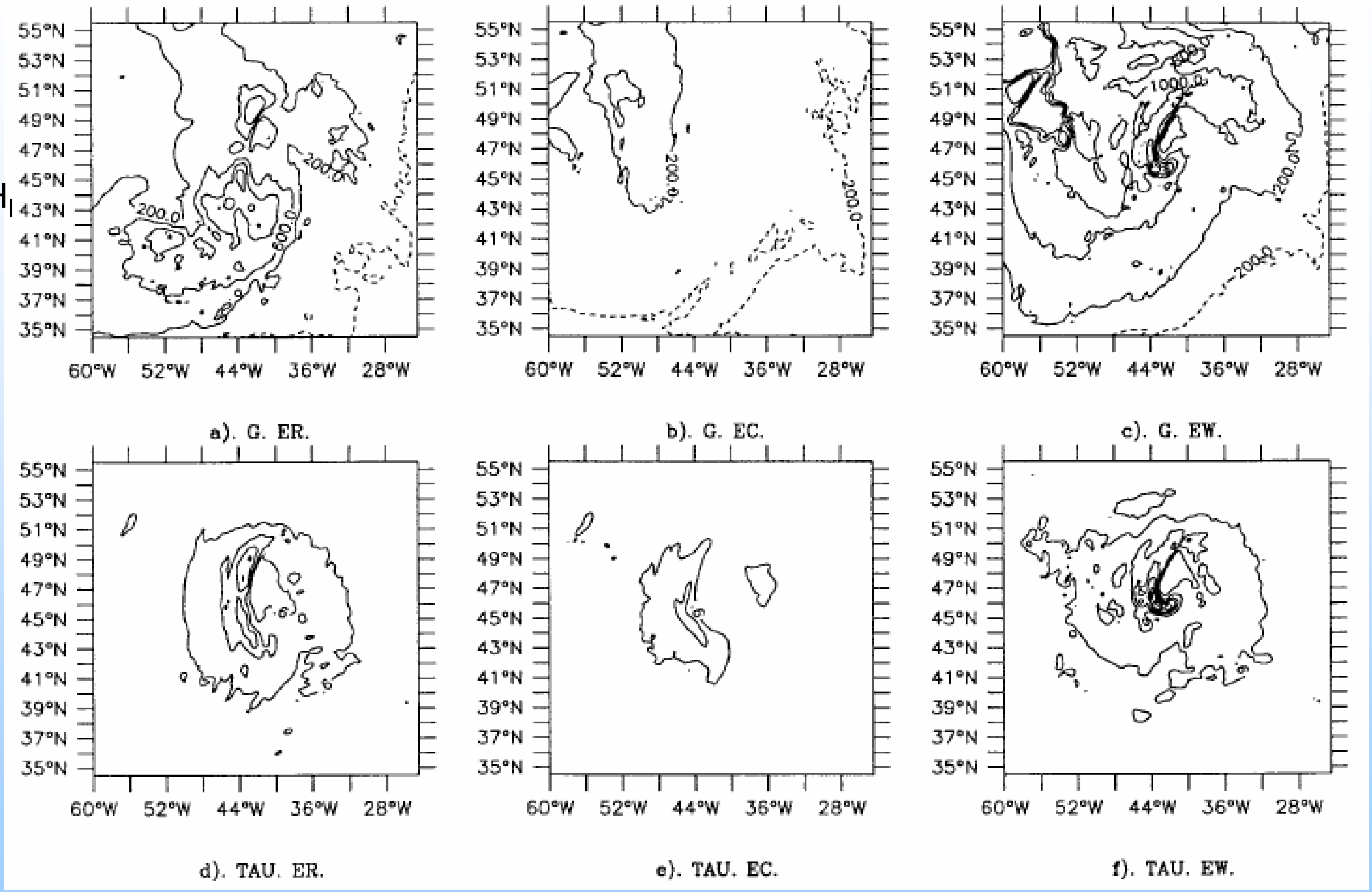
Spatially/Temporally Varying Ocean Characteristics

Sea Surface Temperature - Gulf Stream (Giordani and Caniaux 2001)

ER EC EW

$H_s + H_l$

τ



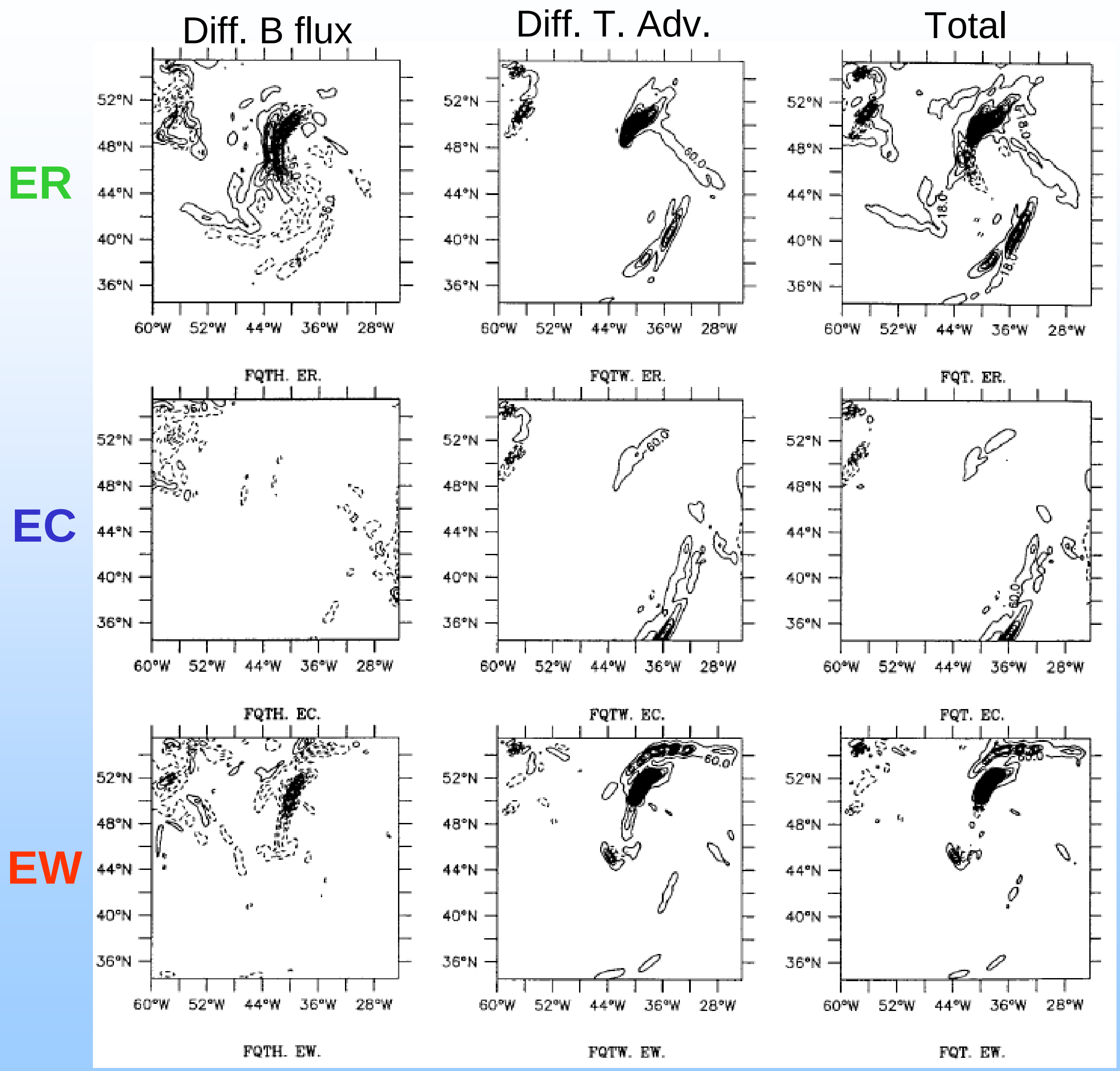
a). G. ER. b). G. EC. c). G. EW.

d). TAU. ER. e). TAU. EC. f). TAU. EW.

FIG. 10. Surface net heat budget (*G*) (W m^{-2}) in (a) ER, (b) EC, (c) EW, and surface stress (τ) (N m^{-2}) in (d) ER, (e) EC, and (f) EW, for 1200 UTC 14 Feb.

Spatially/Temporally Varying Ocean Characteristics

SST effect on frontogenesis
(Giordani and Caniaux 2001)



Vertical average (0, 1000 m) of the frontogenetic function FQ_t and its components FQ_{th} and FQ_{tw} (K^2 100 km^{-2} day^{-1}) in (a) ER, (b) EC, and (c) EW for 1500 UTC 14 Feb.