An analysis of Hurricane Edouard SST sensitivity runs by HWRF in a neutral-shear environment

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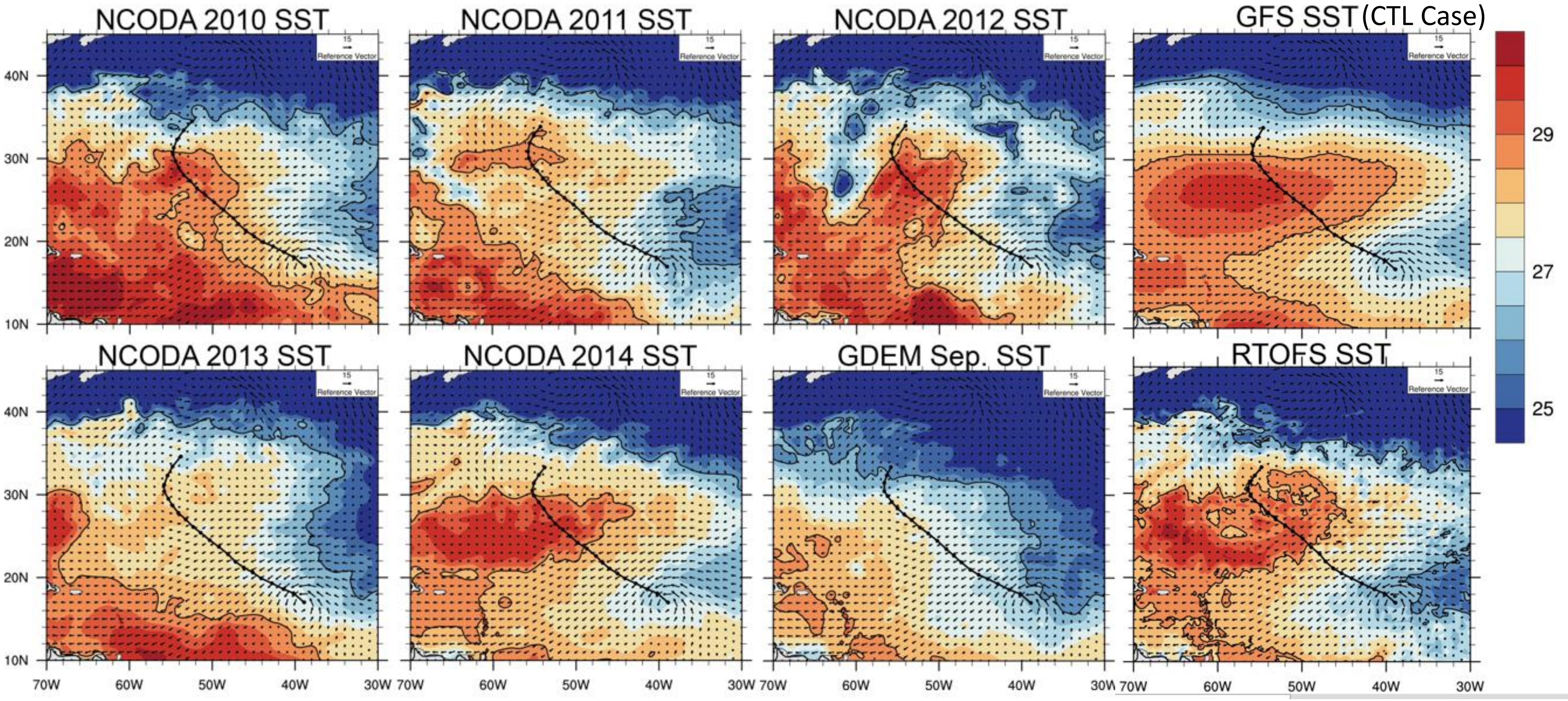
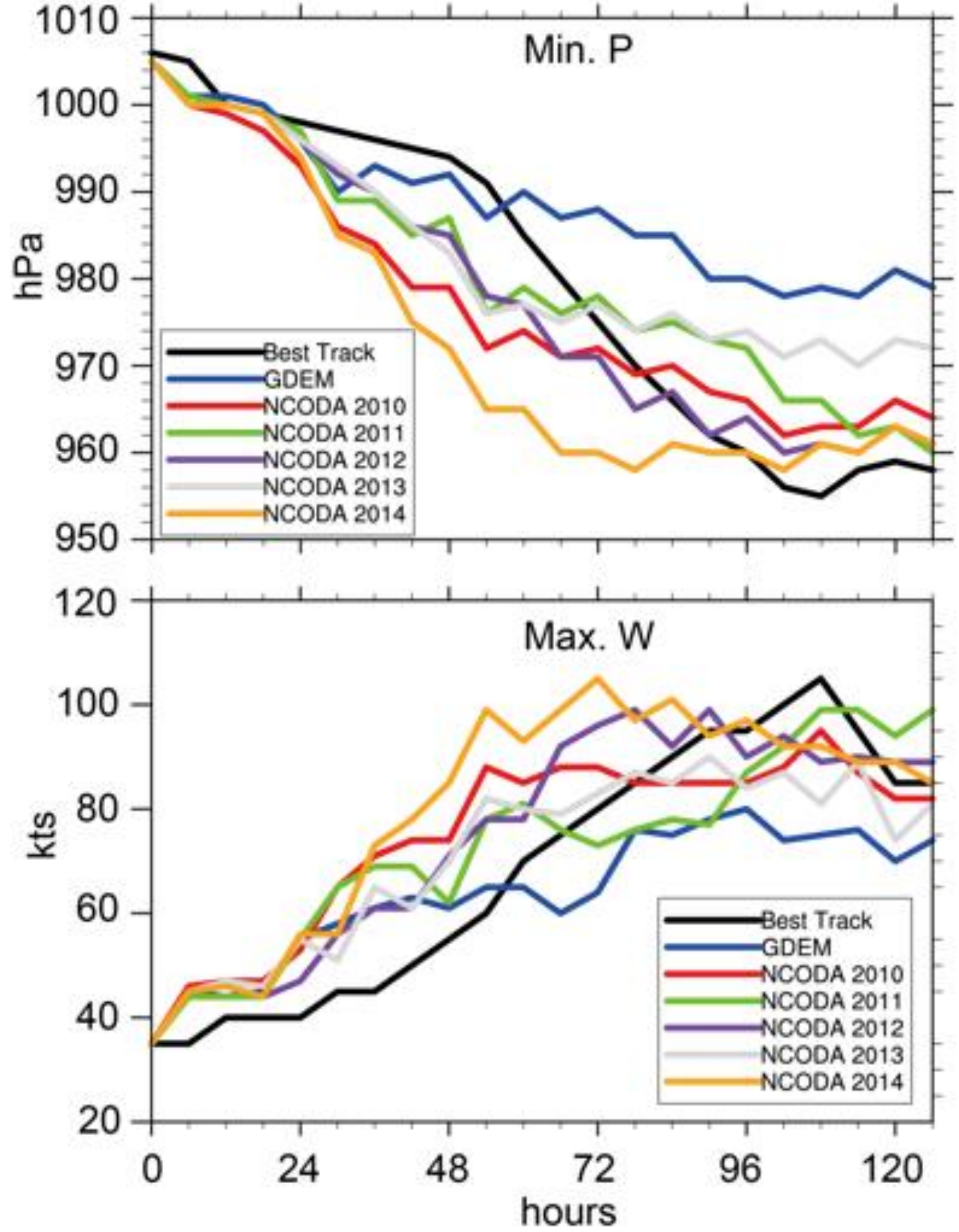
- Review of original sensitivity runs
- Shear calculation issues; modified Kurihara filter
- Time series analysis for shear<14 m/s
    - Goal is to assess if we can obtain a basic understanding of the intensity changes and steady-state conditions in sensitivity run performed with HWRF for Hurricane Edouard during favorable environmental conditions (i.e., low-to-neutral shear, moist background environment).
- Relationship analysis to V_{max} and 24-hr intensity change
    a. Also looked at 6-h and 12-h intensity change, results similar, lower correlations.
- Maximum Potential Intensity applications?

SST fields for HWRF simulations in Edouard (2014) environment



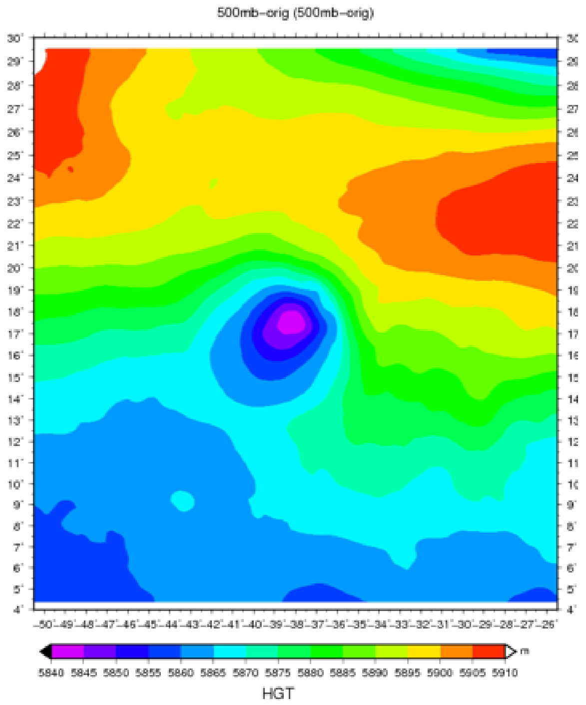
Intensity change



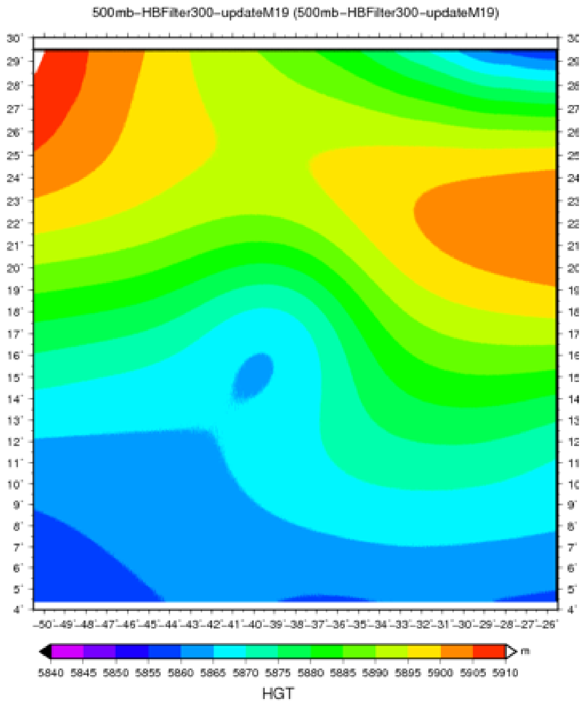
Shear calculation required filtering vortex

- Kurihara filter used to remove vortex (see below)
- We expanded the original Kurihara filter with the following weights: 2,3,4,2,5,6,7,2,8,9,2,10,11,2,12,13,2,3,2
- A periodic 2 is needed to stop numerical instabilities from the filter. More passes were required than the original scheme as well.
- Response function derivation and analysis available upon request

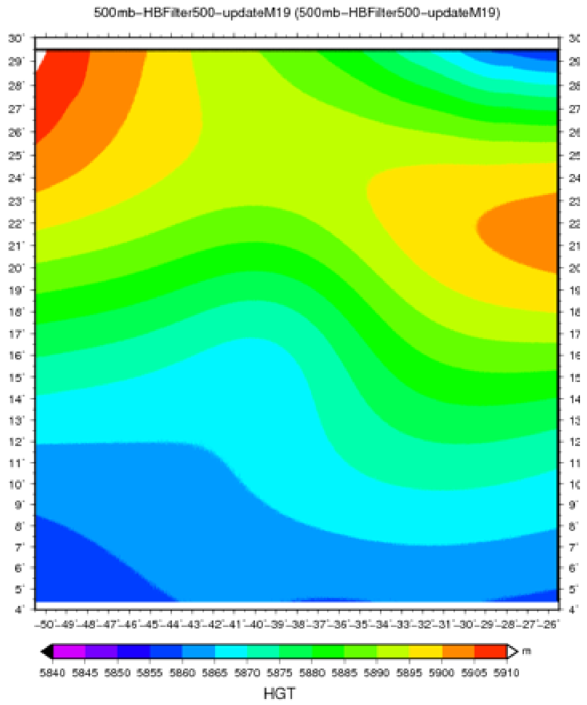
Original

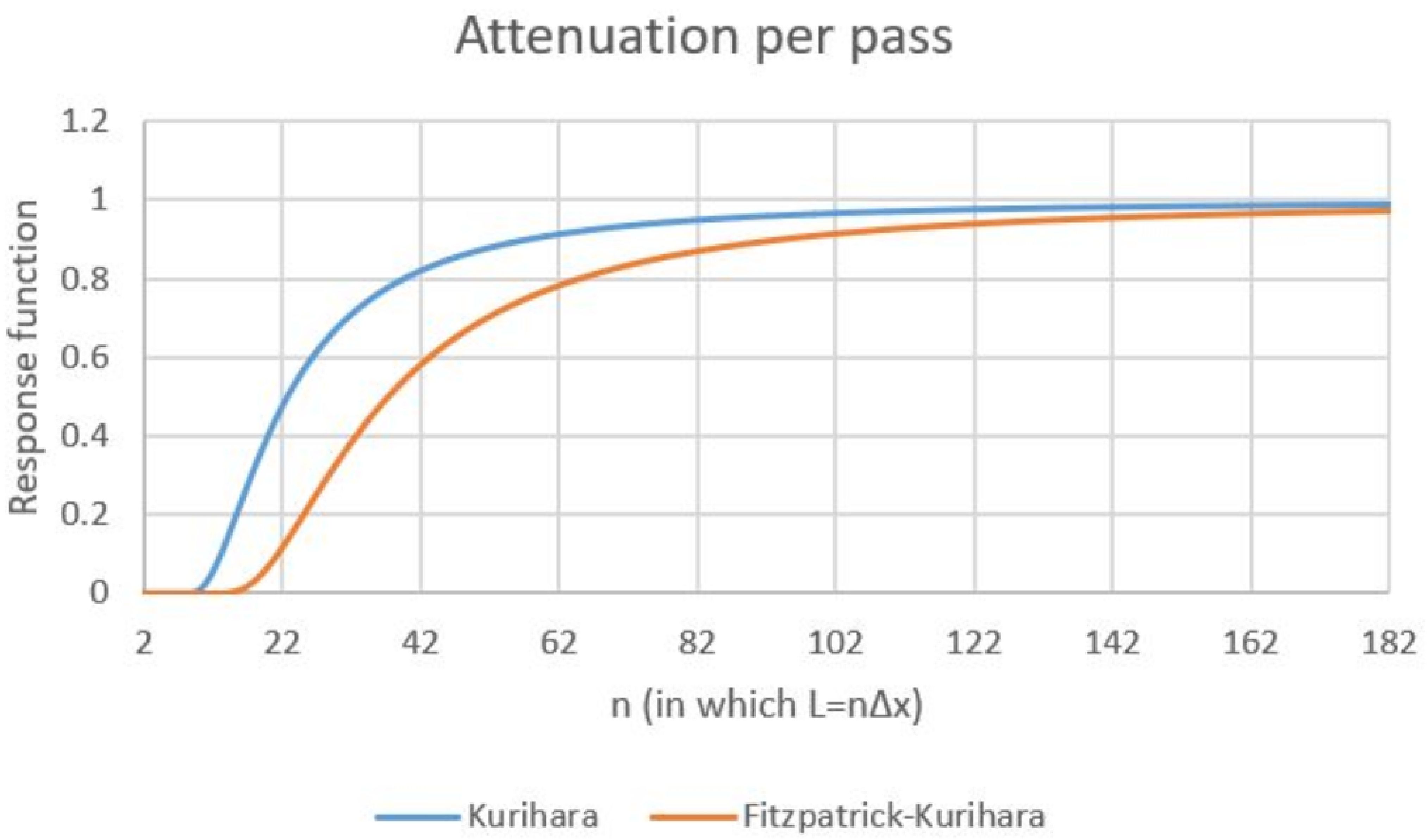


300 passes
Enhanced Kurihara filter



500 passes
Enhanced Kurihara filter



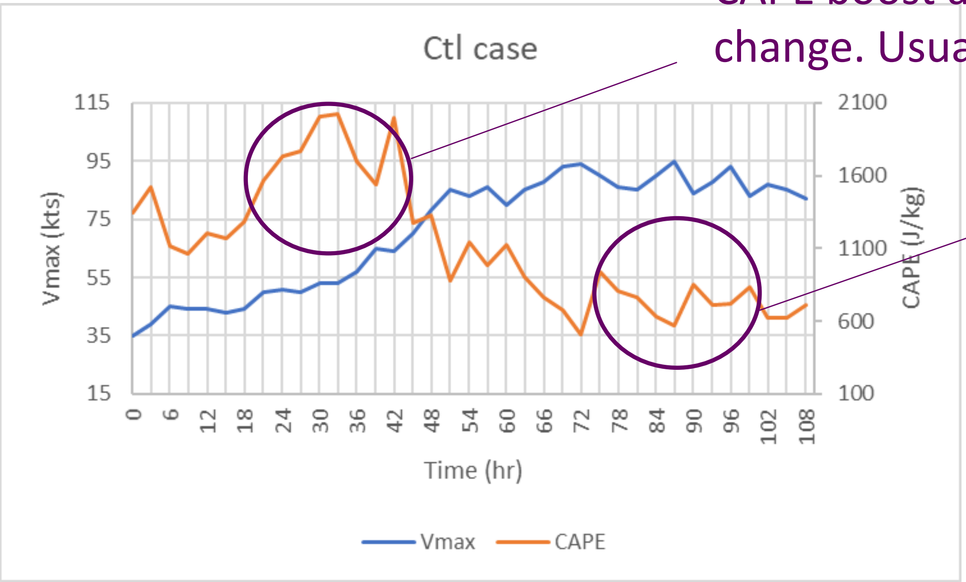

Attenuation per pass
Response function
1.2
1
0.8
0.6
0.4
0.2
0
2
22
42
62
82
102
122
142
162
182
n (in which L=nΔx)
Kurihara
Fitzpatrick-Kurihara

Time series analysis

Looked at fluxes, CAPE, dewpoint, and RH at Rmax averaged every 30 compass degrees, resulting in 12-point average.

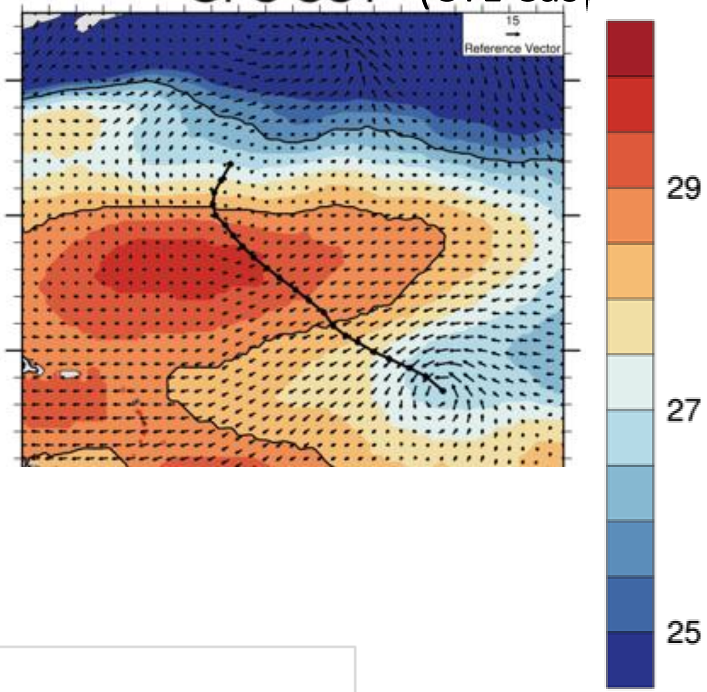
Looked at filtered wind shear and PW at 100, 200, 300, 400, and 500-km radii in 90 compass degrees, resulting in 20-point average

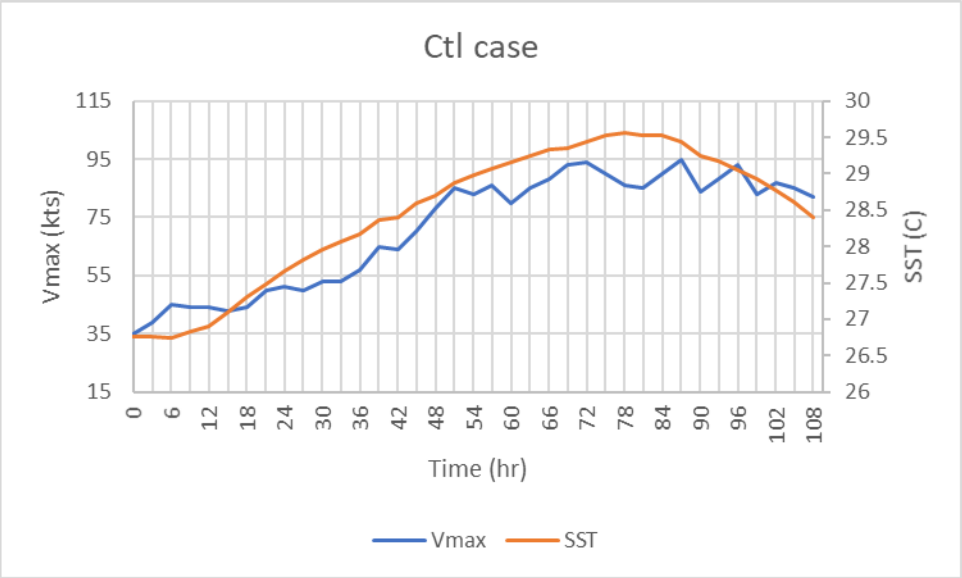
CAPE boost associated with faster intensity change. Usually when SST 27.5-28.5 C

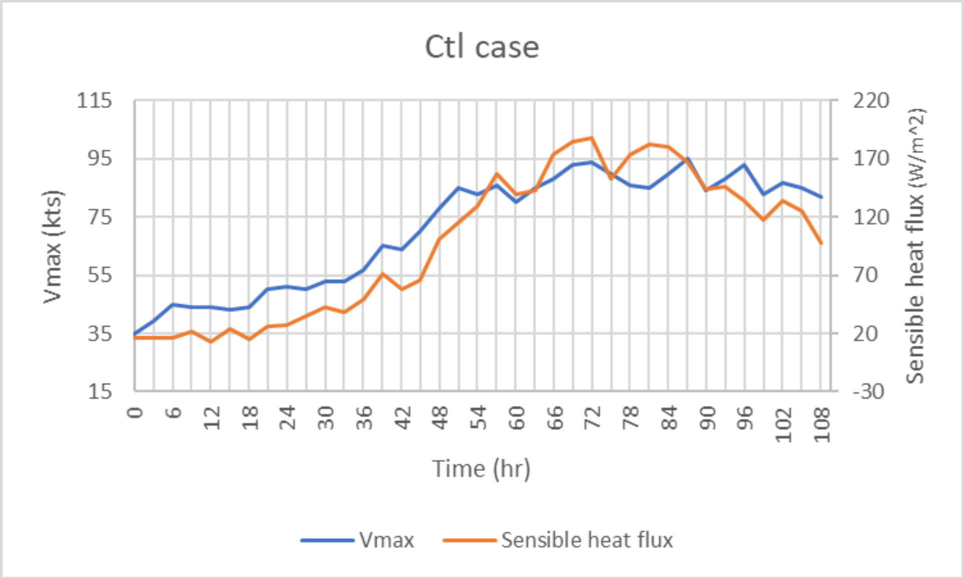


Steady state associated with relatively small CAPE

GFS SST (CTL Case)

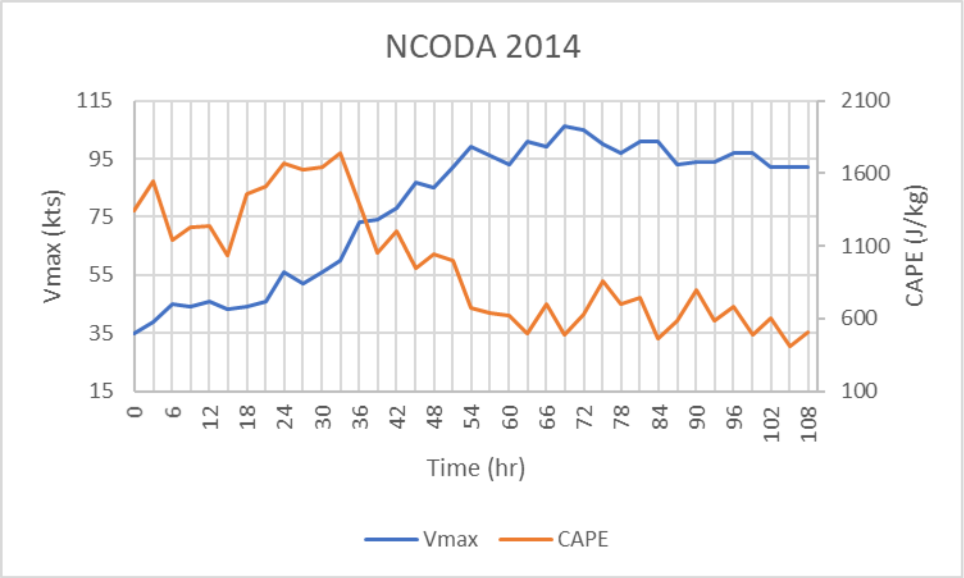


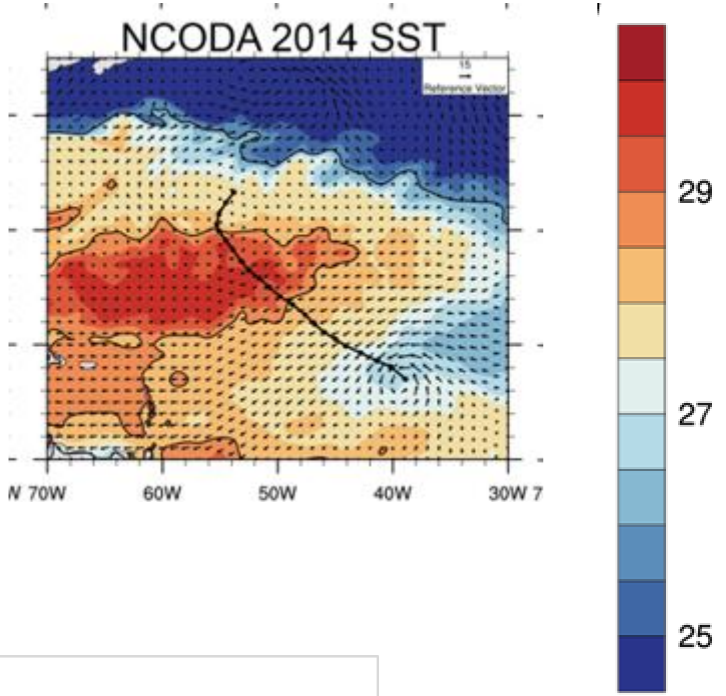


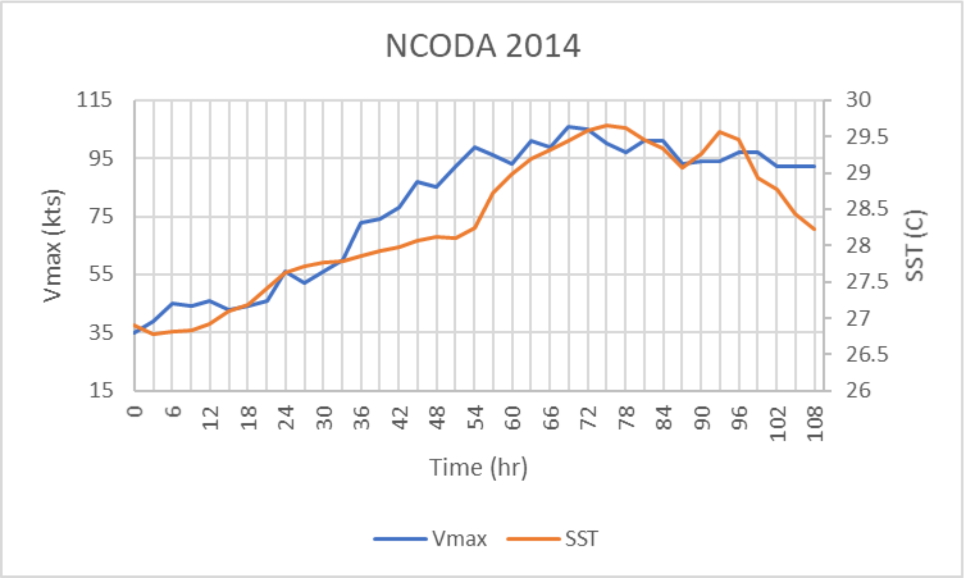


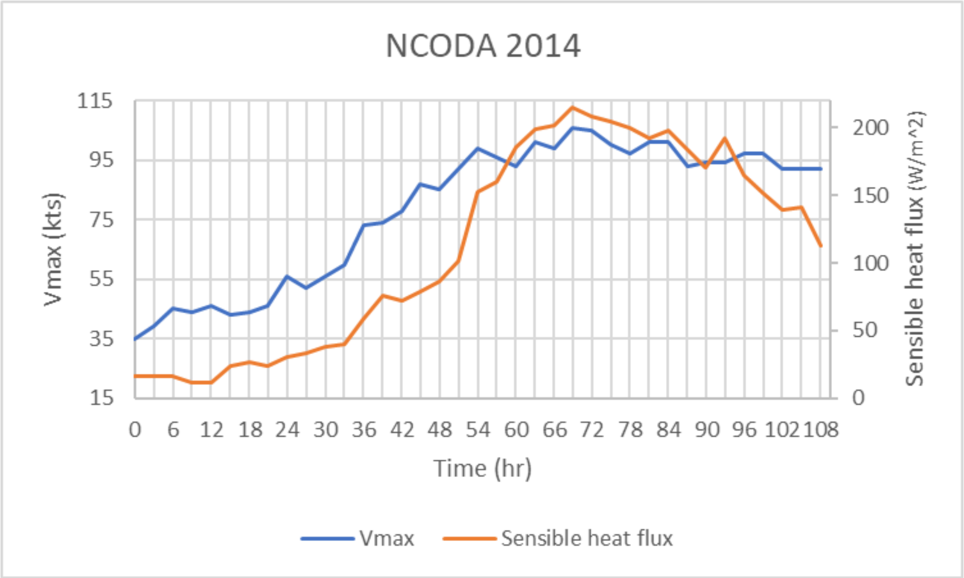
Linear relationship of V_{max} to SST obvious
r=0.77 to instantaneous SST, n=313 (r^2=58.8%)
r=0.78 for 24-hr avged SST, n=280 (r^2=60.9%)

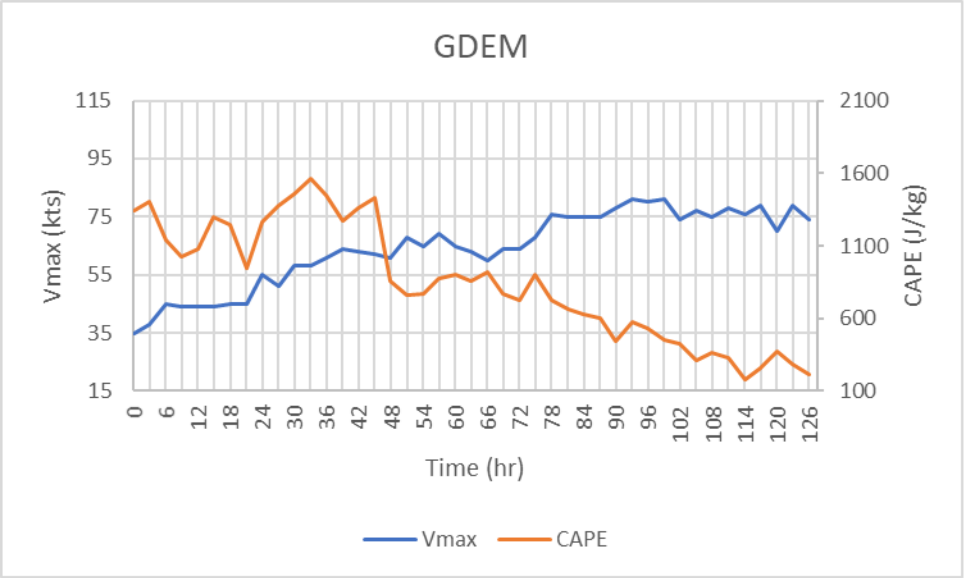
Linear relationship of V_{max} to heat flux higher than SST
r=0.89 to instantaneous heat flux, n=313 (r^2=79.6%)
r=0.85 for 24-hr avged heat flux, n=280 (r^2=71.6%)

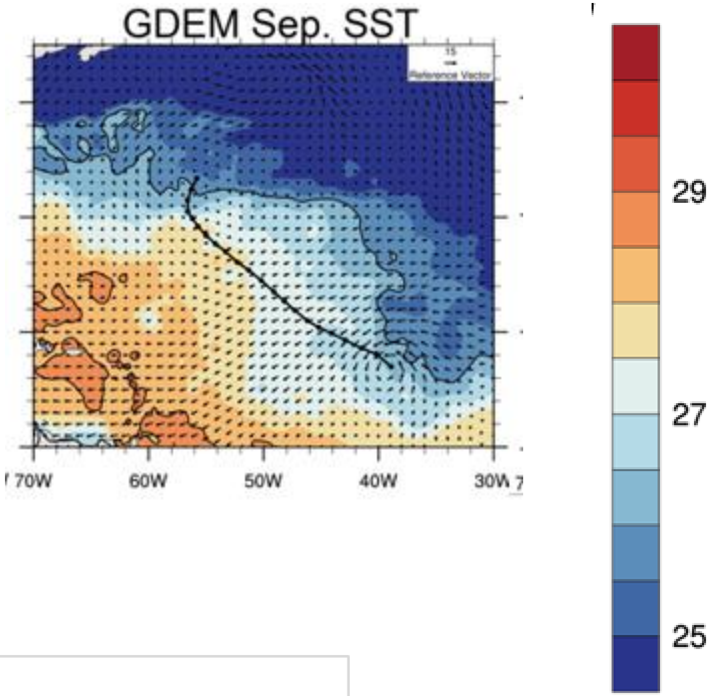

NCODA 2014
Vmax (kts)
CAPE (J/kg)
Time (hr)
Vmax
CAPE

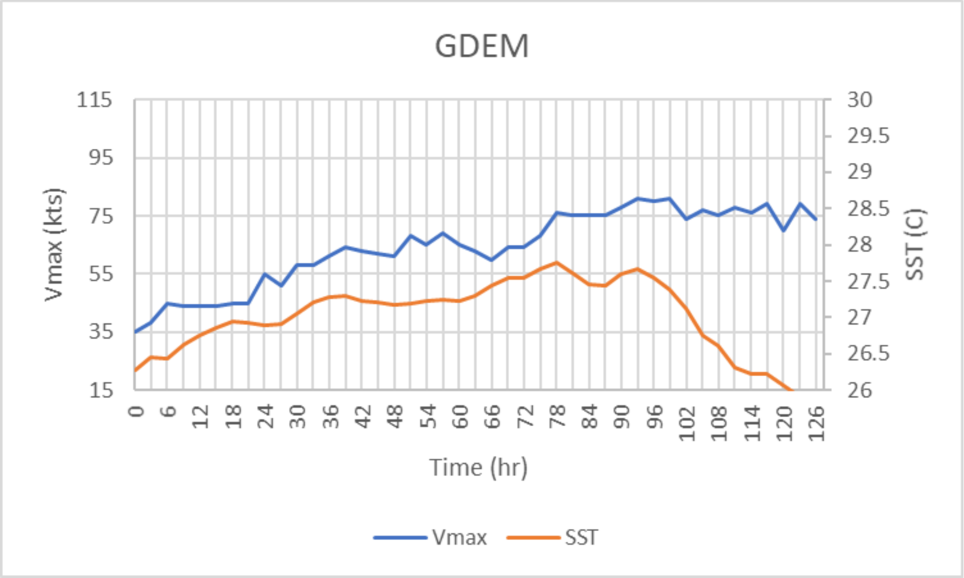

NCODA 2014 SST
70W
60W
50W
40W
30W
29
27
25

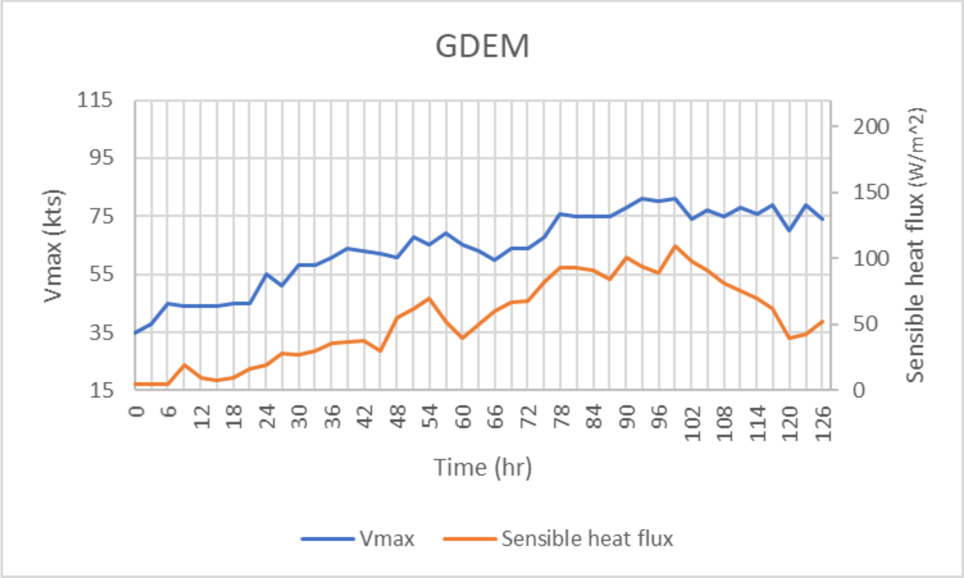

NCODA 2014
Vmax (kts)
SST (C)
Time (hr)
Vmax
SST


NCODA 2014
Vmax (kts)
Sensible heat flux (W/m^2)
Time (hr)
Vmax
Sensible heat flux

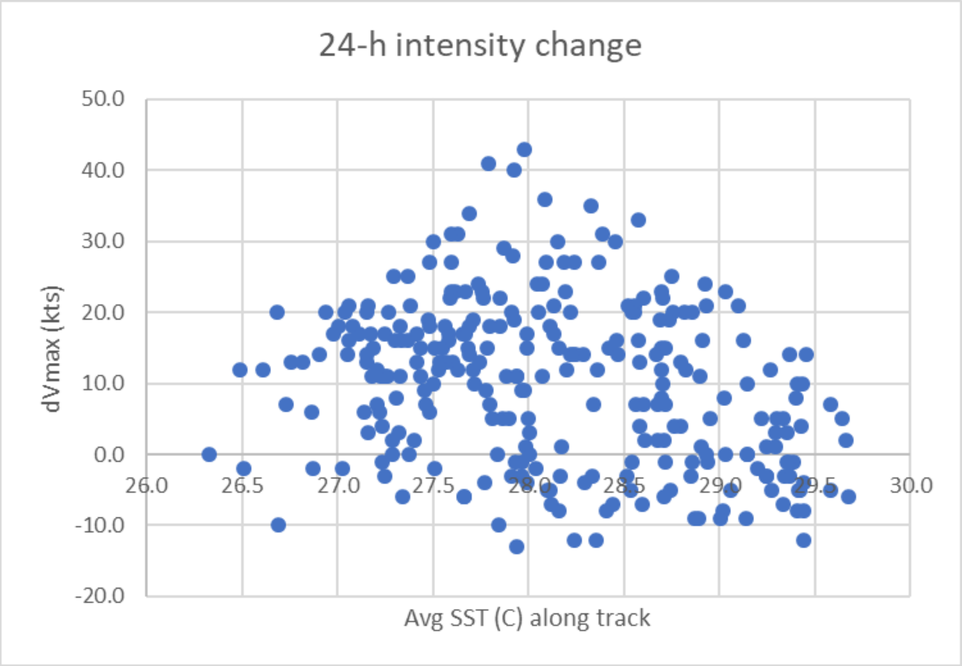

GDEM
Vmax (kts)
CAPE (J/kg)
Time (hr)
Vmax
CAPE

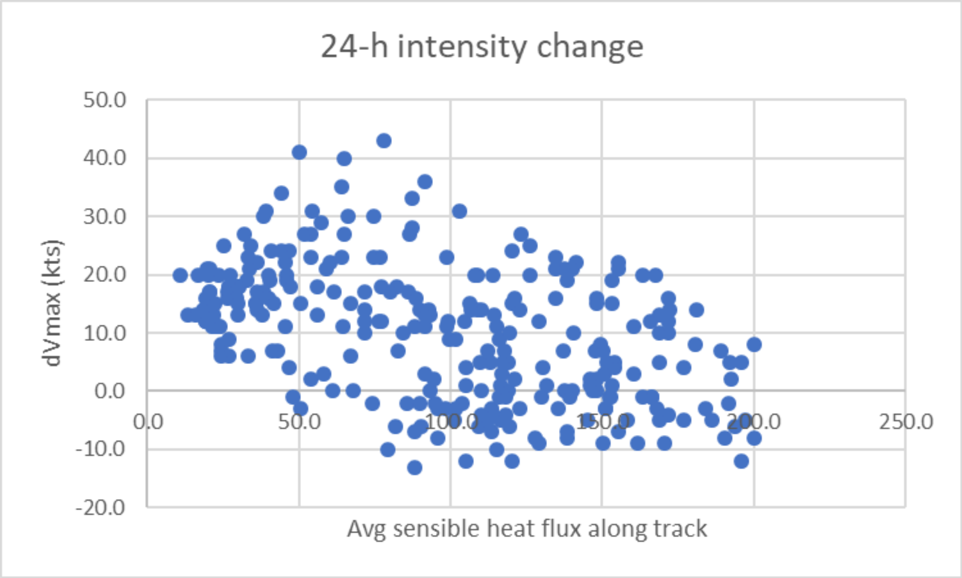

GDEM Sep. SST
70W
60W
50W
40W
30W
29
27
25

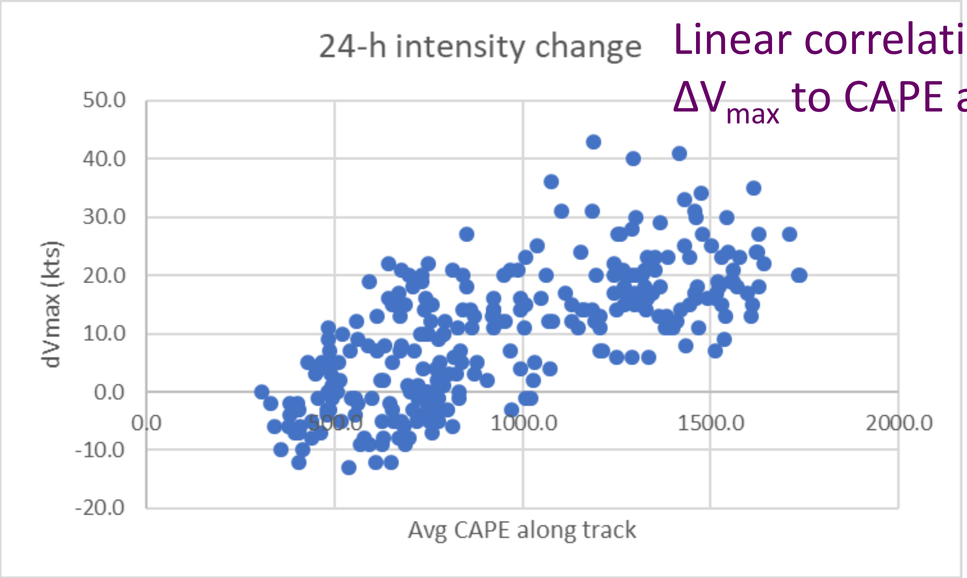

GDEM
Vmax (kts)
SST (C)
Time (hr)
Vmax
SST


GDEM
Vmax (kts)
Sensible heat flux (W/m^2)
Time (hr)
Vmax
Sensible heat flux

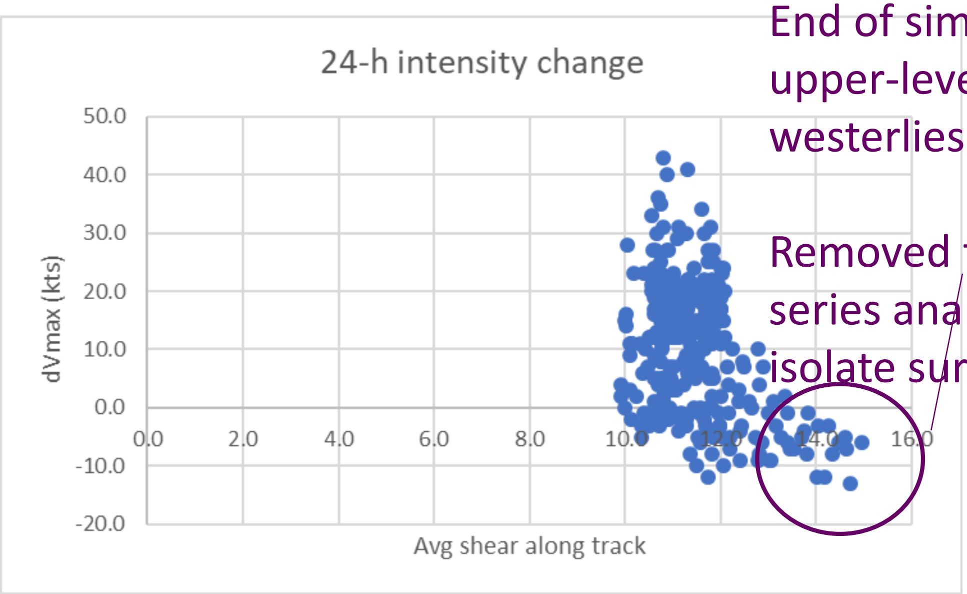
Relationship analysis







Linear correlation of ΔV_{max} to CAPE apparent



End of simulations, upper-level westerlies?

Removed from time series analysis to isolate surface forcing

24-h intensity change correlations, shear>14 m/s removed

	linear regression	variance
SST to dVmax	-0.28	7.6
PW to dVmax	0.02	0.0
heat flux to dVmax	-0.46	21.4
latent flux to dVmax	-0.51	25.7
CAPE to dVmax	0.70	49.4
DPT to dVmax	-0.04	0.1
RH to dVmax	0.00	0.0
shear to dVmax	-0.44	19.5

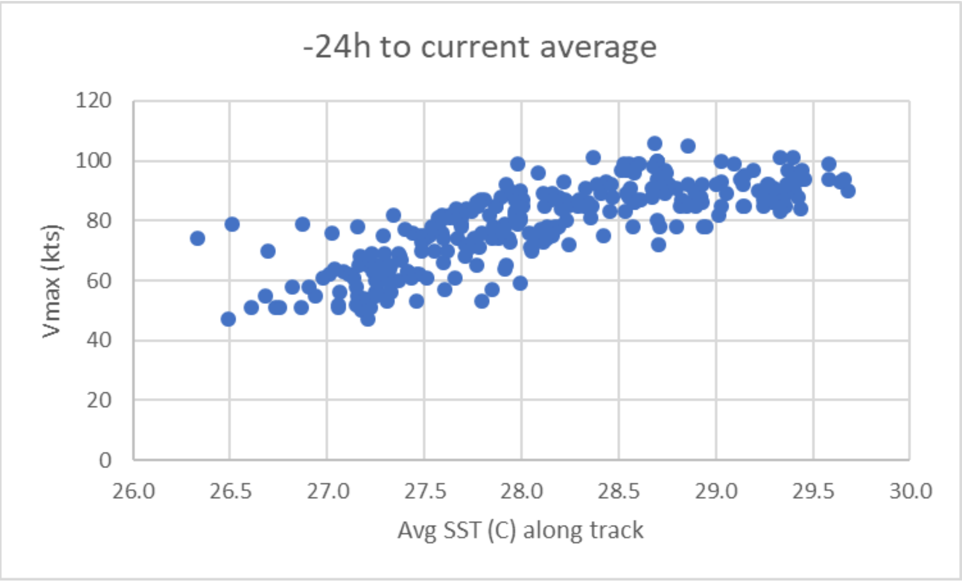
$$\Delta V_{max} = -10.2 + .02\overline{CAPE}$$

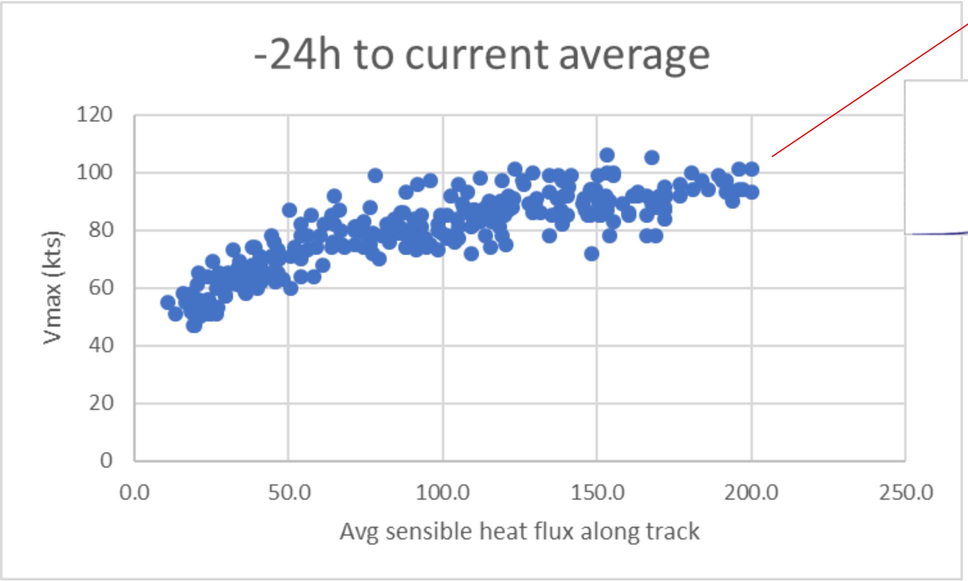
More complicated regressions did not increase correlation

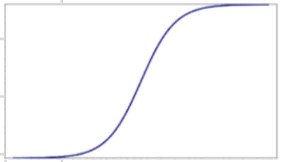
correlation matrix

	SST	PW	heat flux	latent flux	CAPE	DPT	RH	shear
SST		0.26	0.90	0.89	-0.38	0.25	-0.41	0.14
PW			0.24	0.27	-0.14	0.05	-0.11	0.00
heat flux				0.97	-0.68	0.17	-0.47	0.09
latent flux					-0.74	0.11	-0.46	0.20
CAPE						0.07	0.25	-0.29
DPT							0.45	-0.26
RH								0.30
shear								

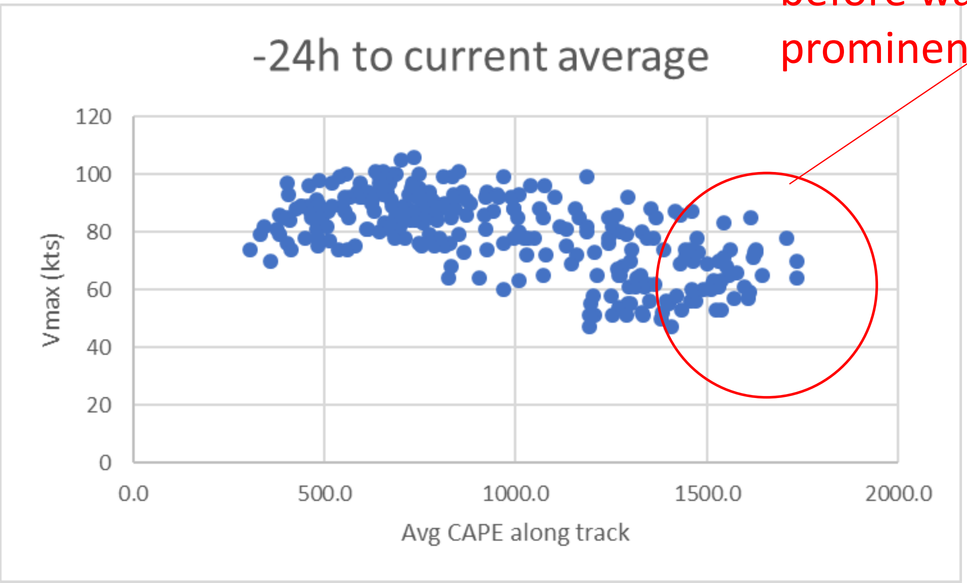
Sigmoidal relationship

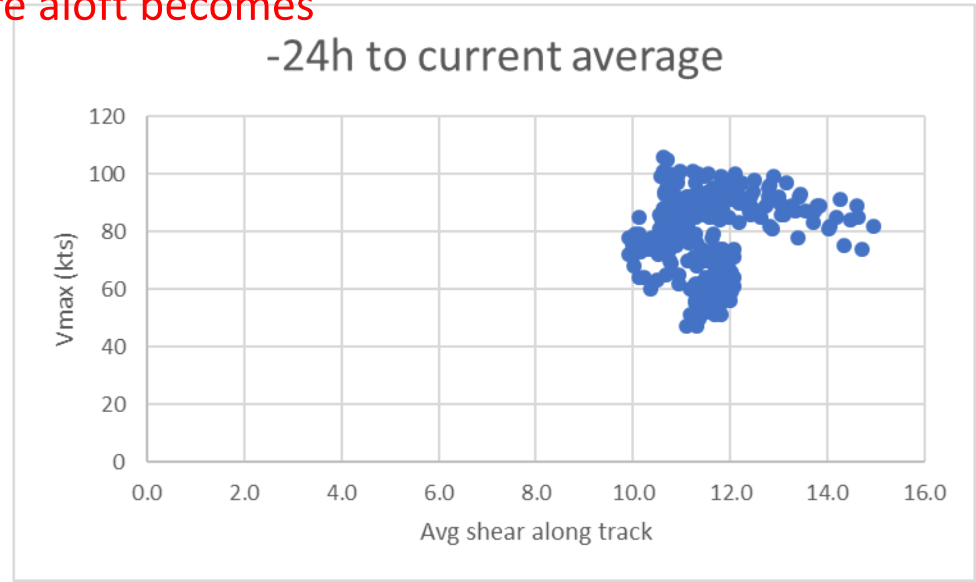






Associated with SST=27.5-28.5C, and before warm core aloft becomes prominent





V_{max} correlations, shear>14 m/s removed

Sigmoidal equation fit for heat flux gives r=.94, r^2=87.5%

	linear regression	variance
SST to Vmax	0.78	60.9
PW to Vmax	0.27	7.2
heat flux to Vmax	0.85	71.6
latent flux to Vmax	0.88	77.5
CAPE to Vmax	-0.63	39.1
DPT to Vmax	-0.11	1.2
RH to Vmax	-0.61	37.1
shear to Vmax	0.10	1.0

correlation matrix

	SST	PW	heat flux	latent flux	CAPE	DPT	RH	shear
SST		0.26	0.90	0.89	-0.38	0.25	-0.41	0.14
PW			0.24	0.27	-0.14	0.05	-0.11	0.00
heat flux				0.97	-0.68	0.17	-0.47	0.09
latent flux					-0.74	0.11	-0.46	0.20
CAPE						0.07	0.25	-0.29
DPT							0.45	-0.26
RH								0.30
shear								

Fitted equation for CAPE, constrained by heat flux sigmoidal relationship

Integrate CAPE linear regression equation

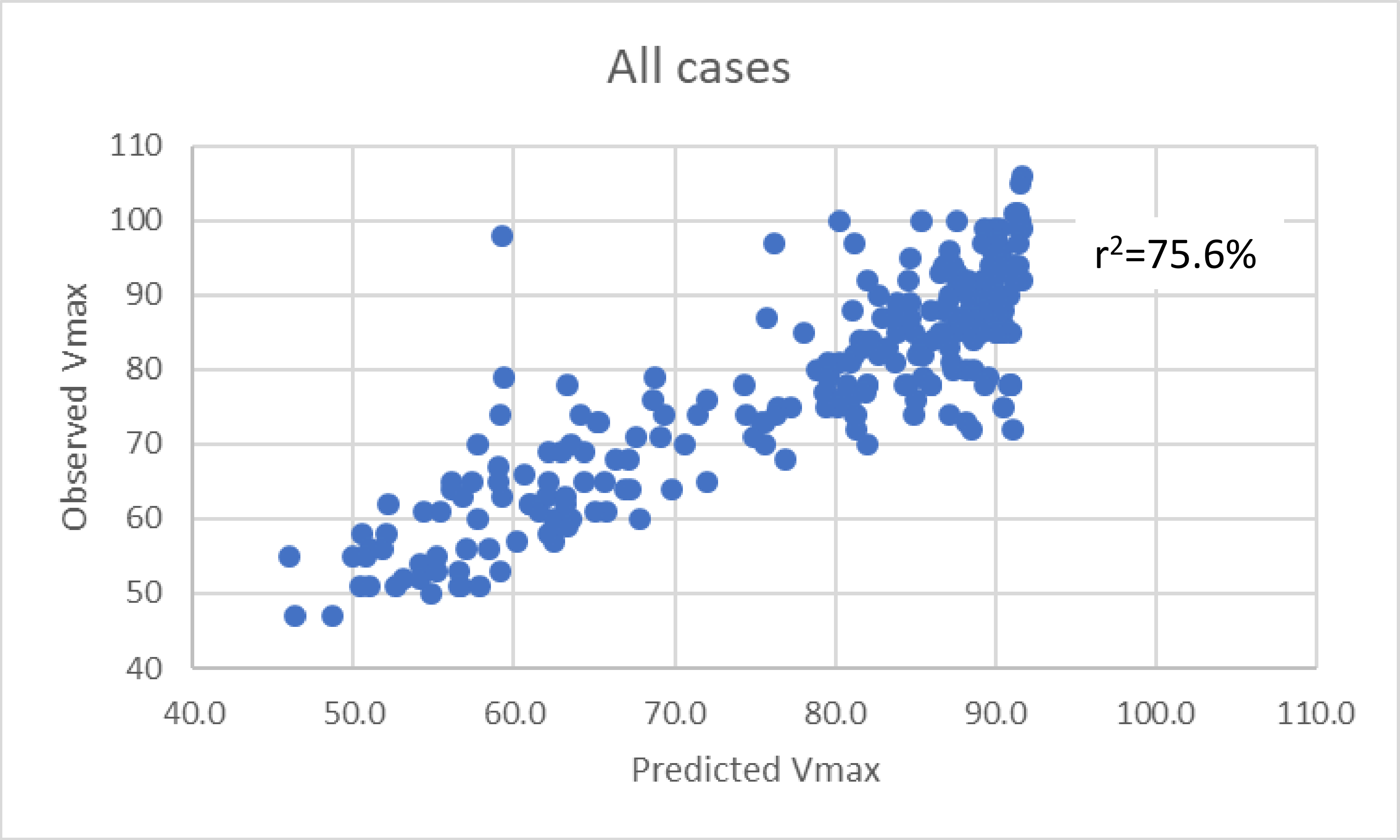
$$V_{max}(24) = V_{max}(0) - 10.2 + 0.02\overline{CAPE}$$

If $\overline{CAPE}$ <75 J/kg, or $V_{max}(H)<V_{max}(24)$, then

$$V_{max}(H) = \frac{92.34}{1 + e^{-(H-19.77)/39.17}}$$

In a simplistic nutshell, possibly explains HWRF sensitivity to SST in a favorable PW, low-to-moderate shear environment.

CAPE boost from increasing SST (in this study 27.5-28.5C, but probably environment- and storm-specific) results in faster intensity change. As CAPE is depleted, steady-state occurs depending on critical flux thresholds.



Maximum Potential Intensity studies?

Assume general sigmoidal relationship

$$V_{max}(H) = \frac{\varepsilon\, MPI}{1+e^{-(H-A)/B}} = \frac{\varepsilon\, MPI}{1+\frac{e^{A/B}}{e^{H/B}}}$$

where H is sensible heat flux, ε is an environmental inhibitor (ε =1 is MPI conditions), and A, B are empirically-derived constants.

Assume bulk equation for $H = \rho C_E c_p V \Delta T$, where $\Delta T = T_{air} - SST$
ρ=1.18 kg/m^3, C_E=0.00118, c_p=1004 J/kg-K . One obtains an implicit equation:

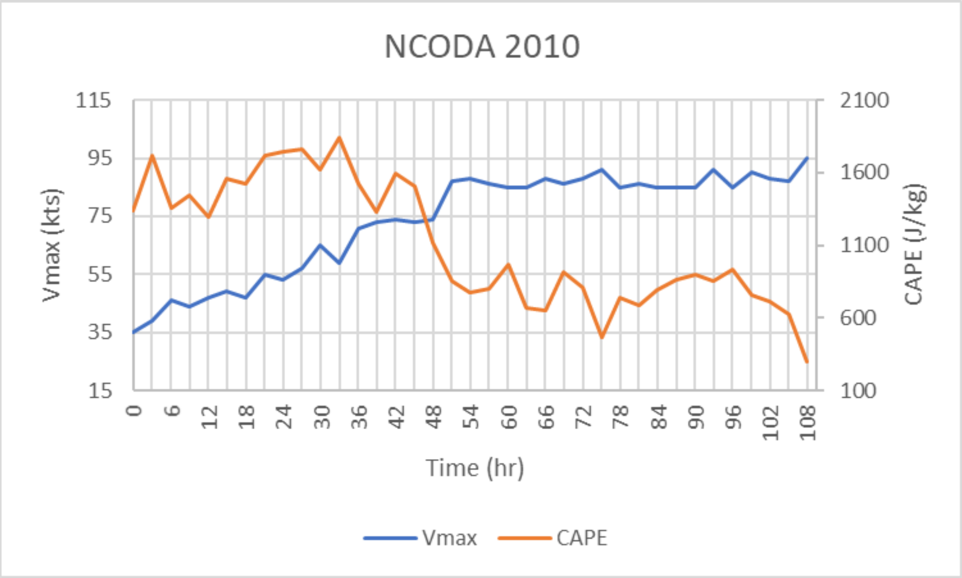
$$V_{max}(H) = \frac{\varepsilon\, MPI}{1+\exp(-\frac{1.4 V_{max}\Delta T + A}{B})} = \frac{\varepsilon\, MPI}{1+\frac{\exp(\frac{A}{B})}{\exp(\frac{1.4 V_{max}\Delta T}{B})}}$$

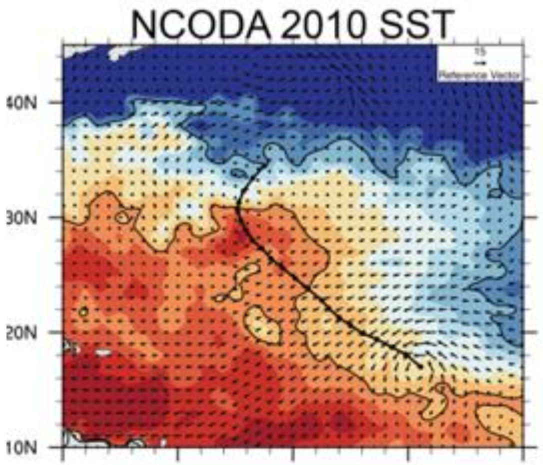
A large HWRF SST-sensitivity database could elucidate steady-state and MPI functionality with surface fluxes through empirical application.

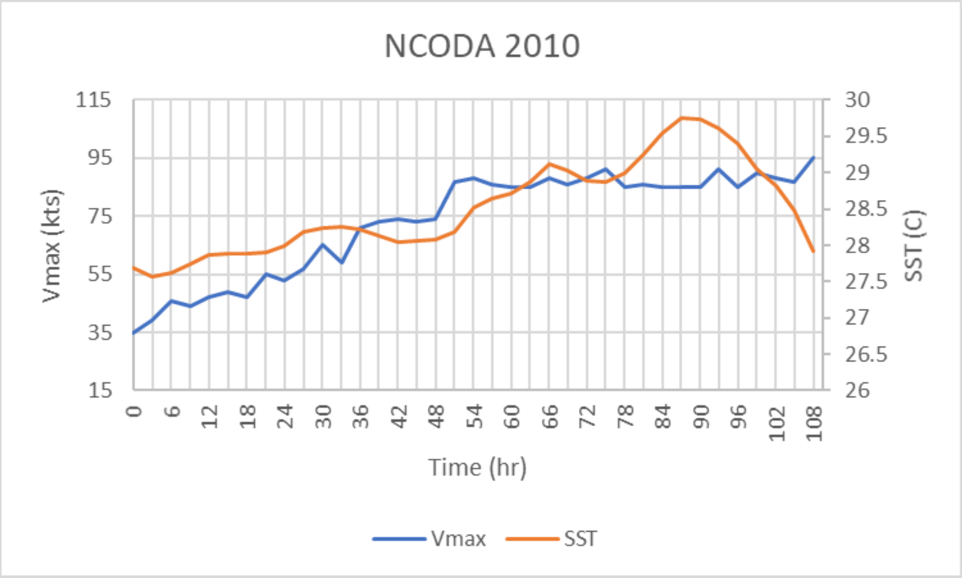
Recommendations

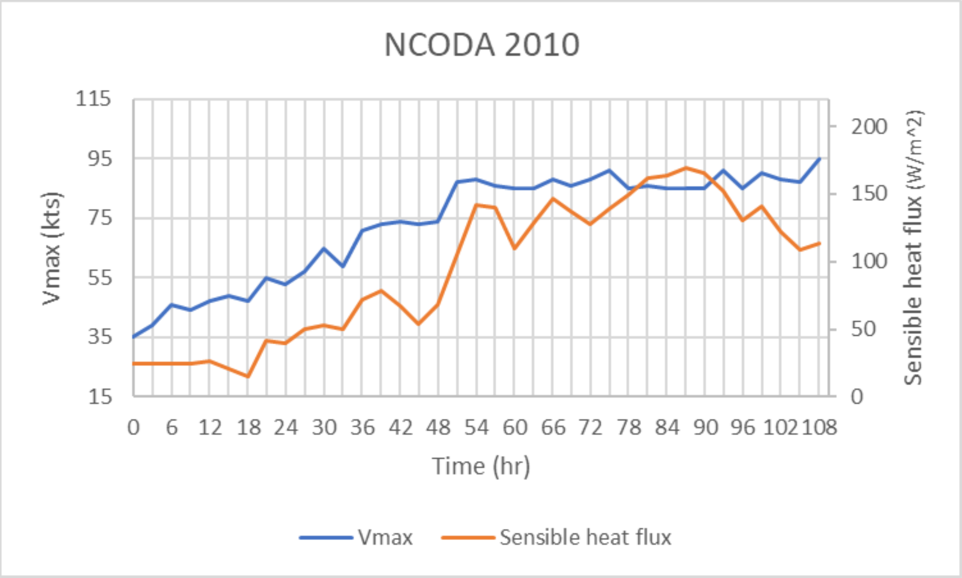
1) HWRF intensity skill has exceeded SHIPS and LGEM two years in a row. Its plausible a large database of HWRF simulations could now glean an understanding of rapid intensification situations.
2) Suggests using model CAPE may be useful in statistical schemes such as SHIPS, LGEM, and Rapid Intensification Index.
3) Studies will also be useful for understanding Maximum Potential Intensity theory.
4) Study supports the Ocean Model Impact Tiger Team (OMITT) emphasis on surface forcing processes to improve intensity forecasts. Events such as Harvey's unexpectedly rapid intensification, possibly due to an under-analyzed warm pool, illustrate the need for better coupling processes.

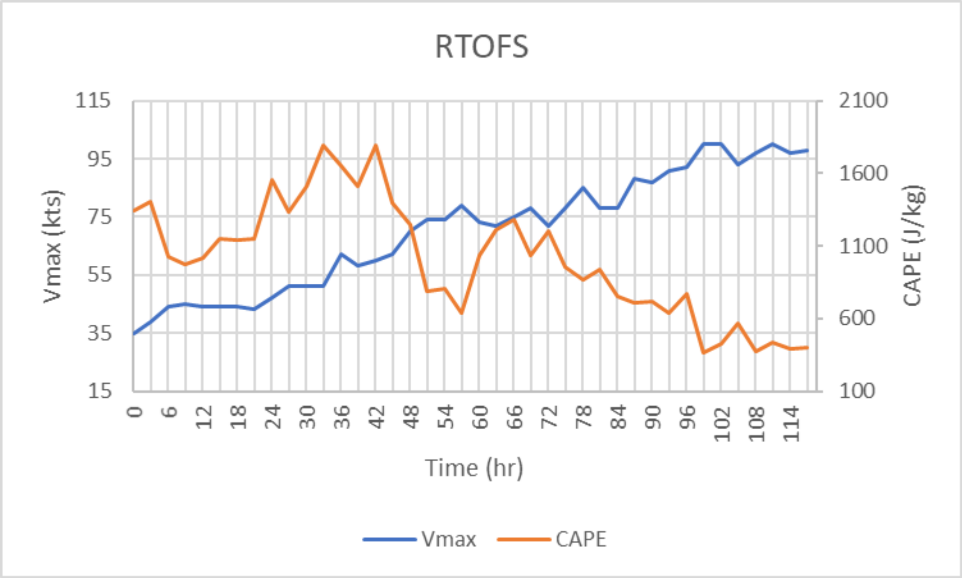
Extra slides

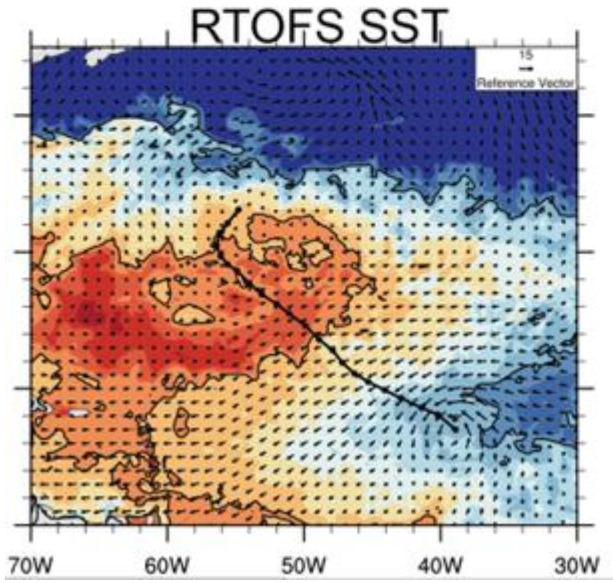

NCODA 2010
Vmax (kts)
CAPE (J/kg)
115
95
75
55
35
15
2100
1600
1100
600
100
0 6 12 18 24 30 36 42 48 54 60 66 72 78 84 90 96 102 108
Time (hr)
Vmax
CAPE

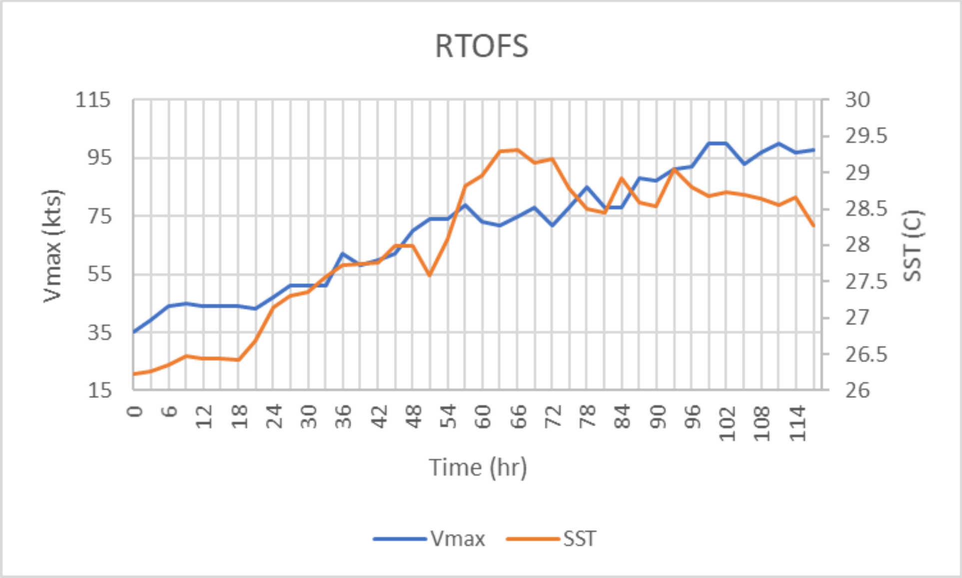

NCODA 2010 SST
40N
30N
20N
10N

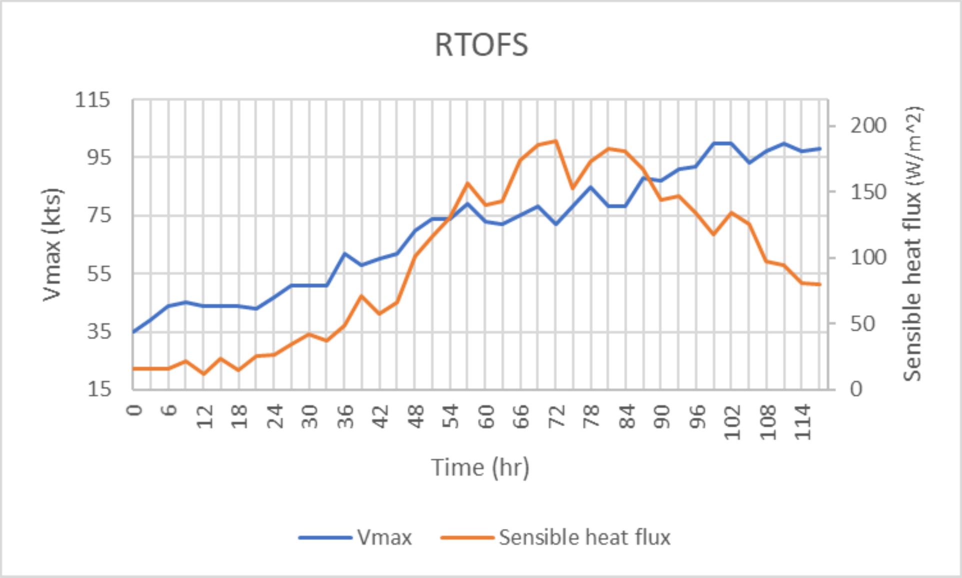

NCODA 2010
Vmax (kts)
SST (C)
115
95
75
55
35
15
30
29.5
29
28.5
28
27.5
27
26.5
26
0 6 12 18 24 30 36 42 48 54 60 66 72 78 84 90 96 102 108
Time (hr)
Vmax
SST

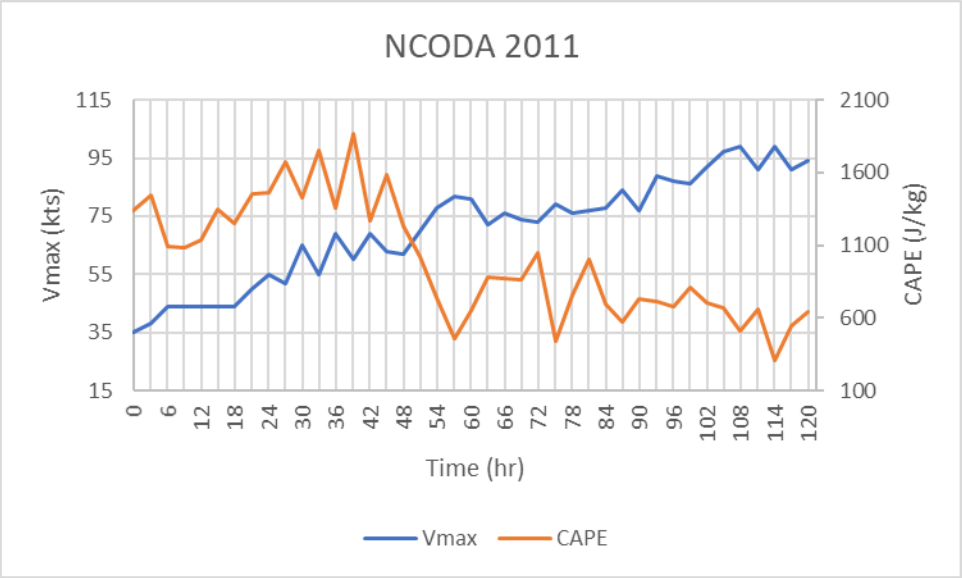

NCODA 2010
Vmax (kts)
Sensible heat flux (W/m^2)
115
95
75
55
35
15
200
150
100
50
0
0 6 12 18 24 30 36 42 48 54 60 66 72 78 84 90 96 102 108
Time (hr)
Vmax
Sensible heat flux


RTOFS
Vmax (kts)
CAPE (J/kg)
Time (hr)
Vmax
CAPE

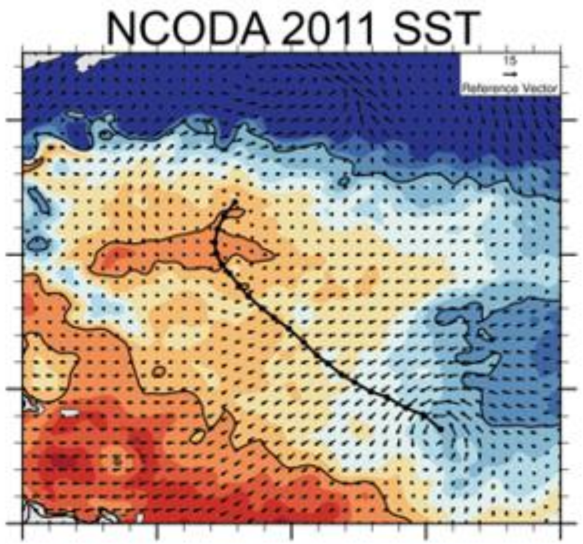

RTOFS SST
70W
60W
50W
40W
30W


RTOFS
Vmax (kts)
SST (C)
Time (hr)
Vmax
SST

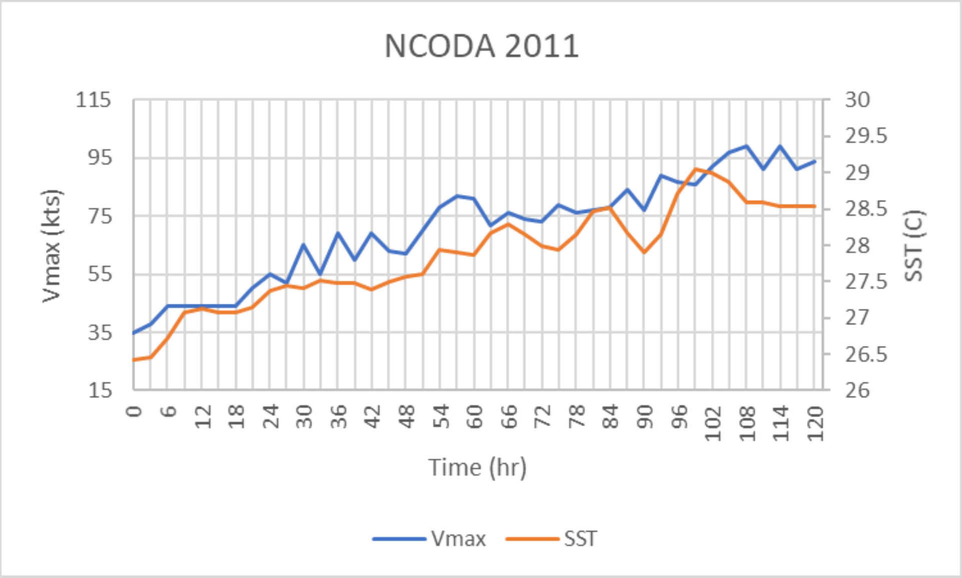

RTOFS
Vmax (kts)
Sensible heat flux (W/m^2)
Time (hr)
Vmax
Sensible heat flux



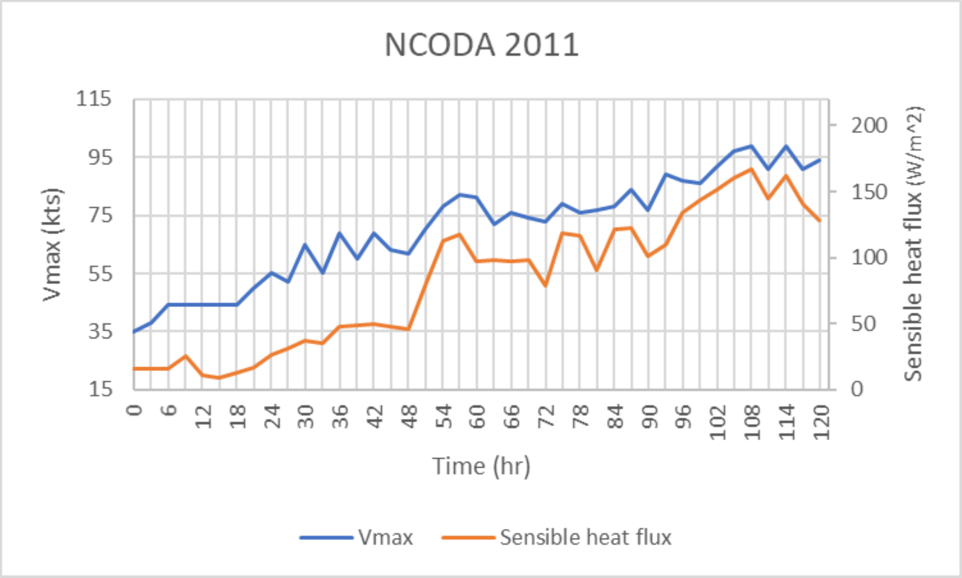
NCODA 2011
Vmax (kts)
CAPE (J/kg)
Time (hr)
Vmax
CAPE



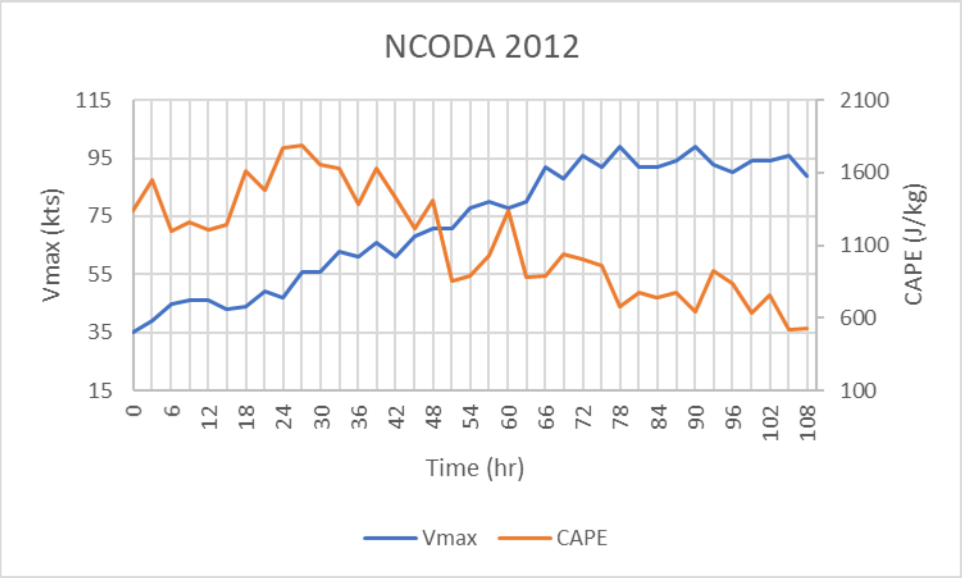
NCODA 2011 SST
Reference Vector

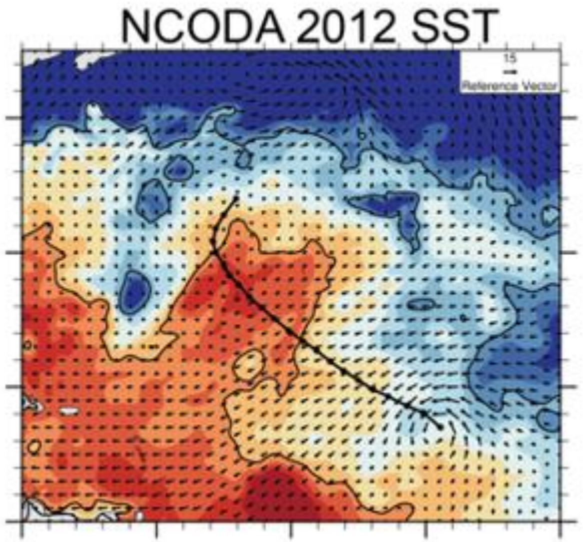


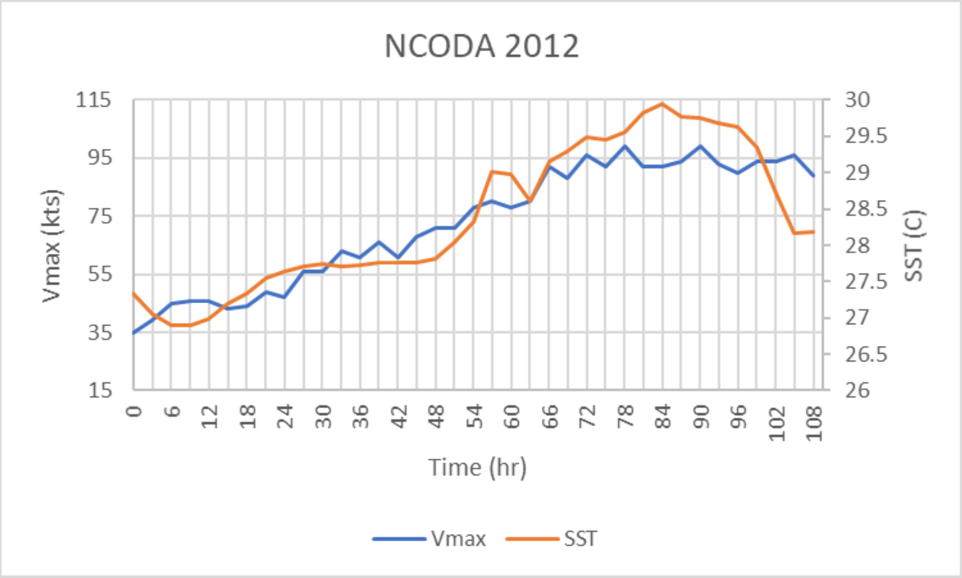
NCODA 2011
Vmax (kts)
SST (C)
Time (hr)
Vmax
SST

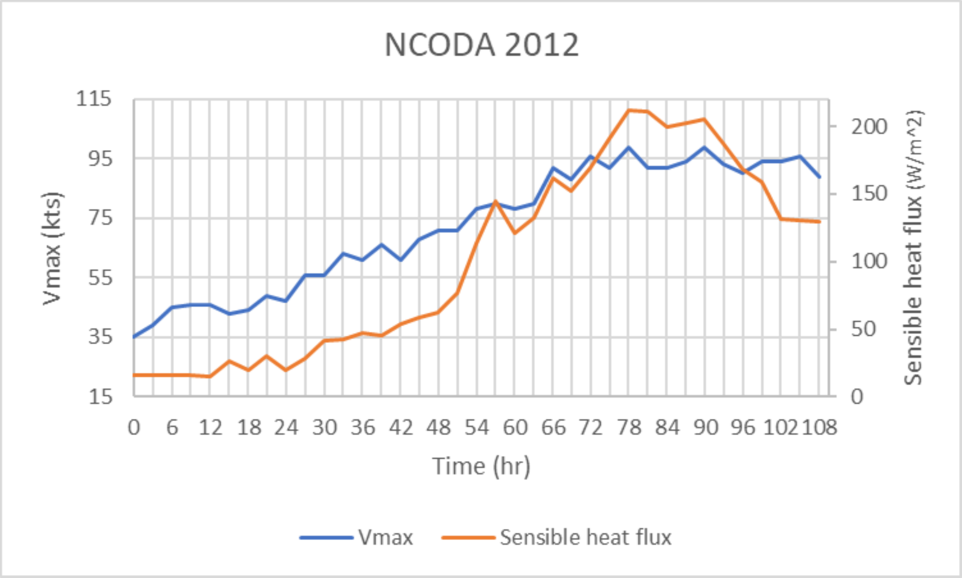


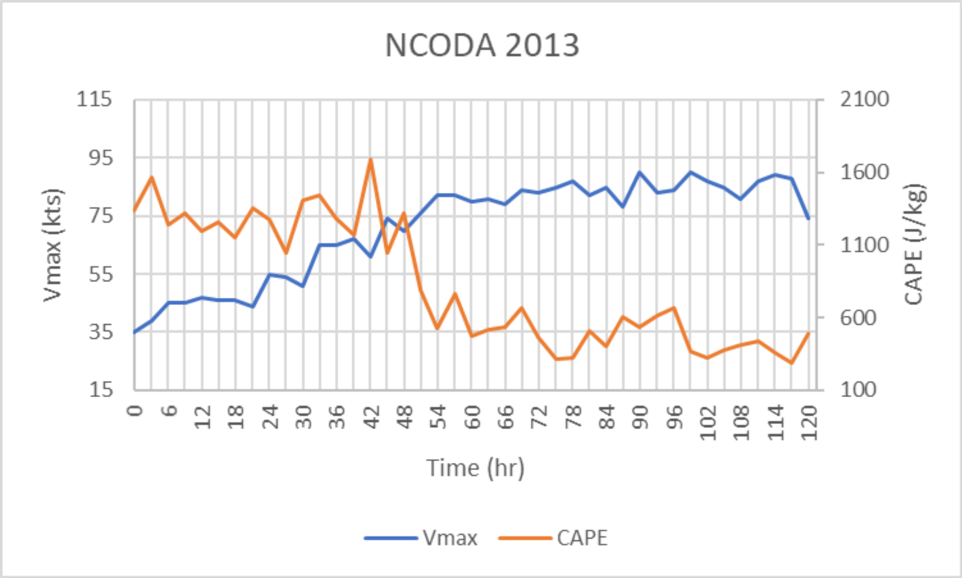
NCODA 2011
Vmax (kts)
Sensible heat flux (W/m^2)
Time (hr)
Vmax
Sensible heat flux


NCODA 2012
Vmax (kts)
CAPE (J/kg)
Time (hr)
Vmax
CAPE


NCODA 2012 SST
Reference Vector


NCODA 2012
Vmax (kts)
SST (C)
Time (hr)
Vmax
SST


NCODA 2012
Vmax (kts)
Sensible heat flux (W/m^2)
Time (hr)
Vmax
Sensible heat flux


NCODA 2013
Vmax (kts)
CAPE (J/kg)
115
95
75
55
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2100
1600
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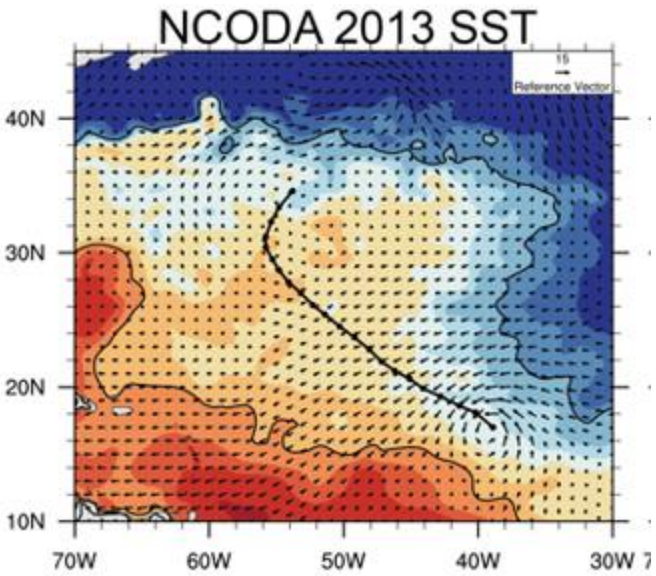
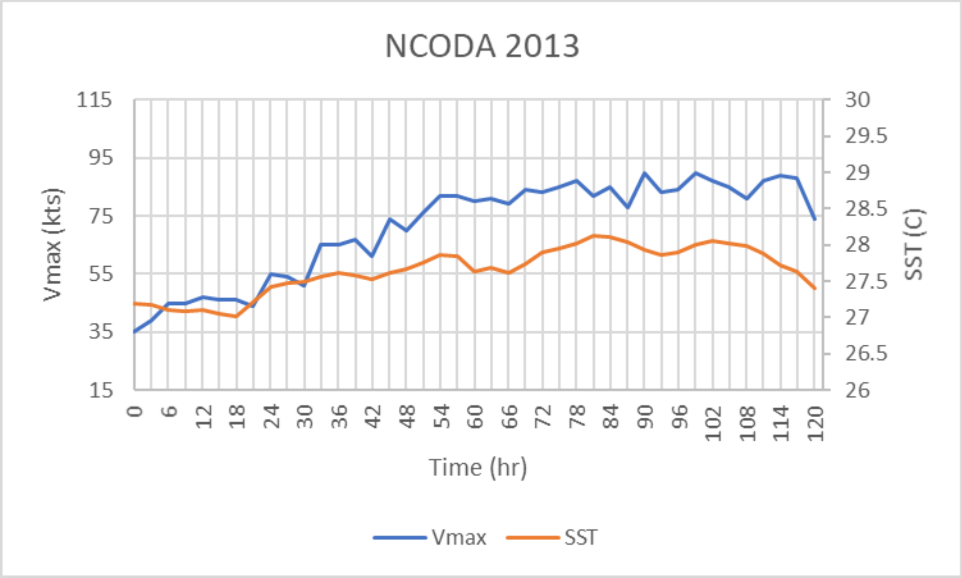
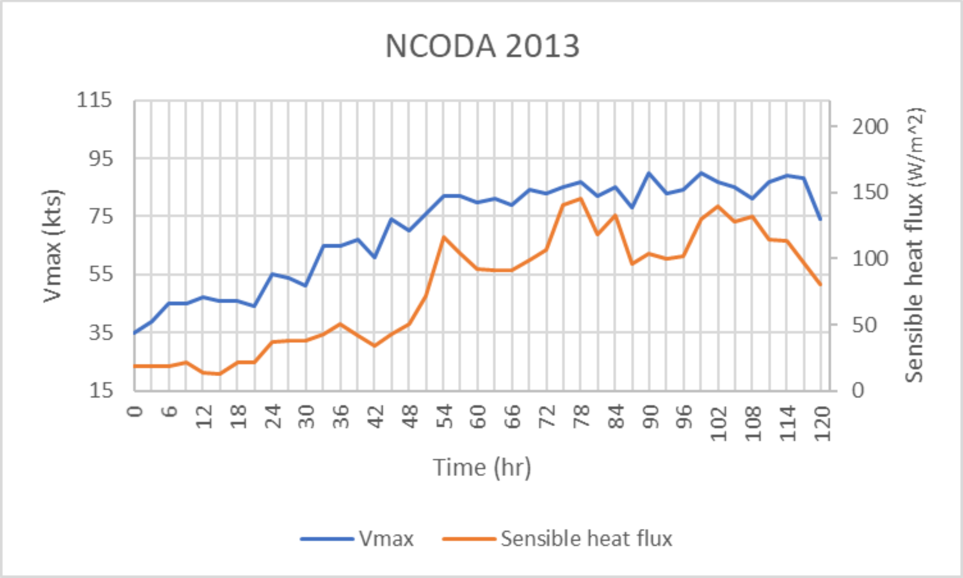
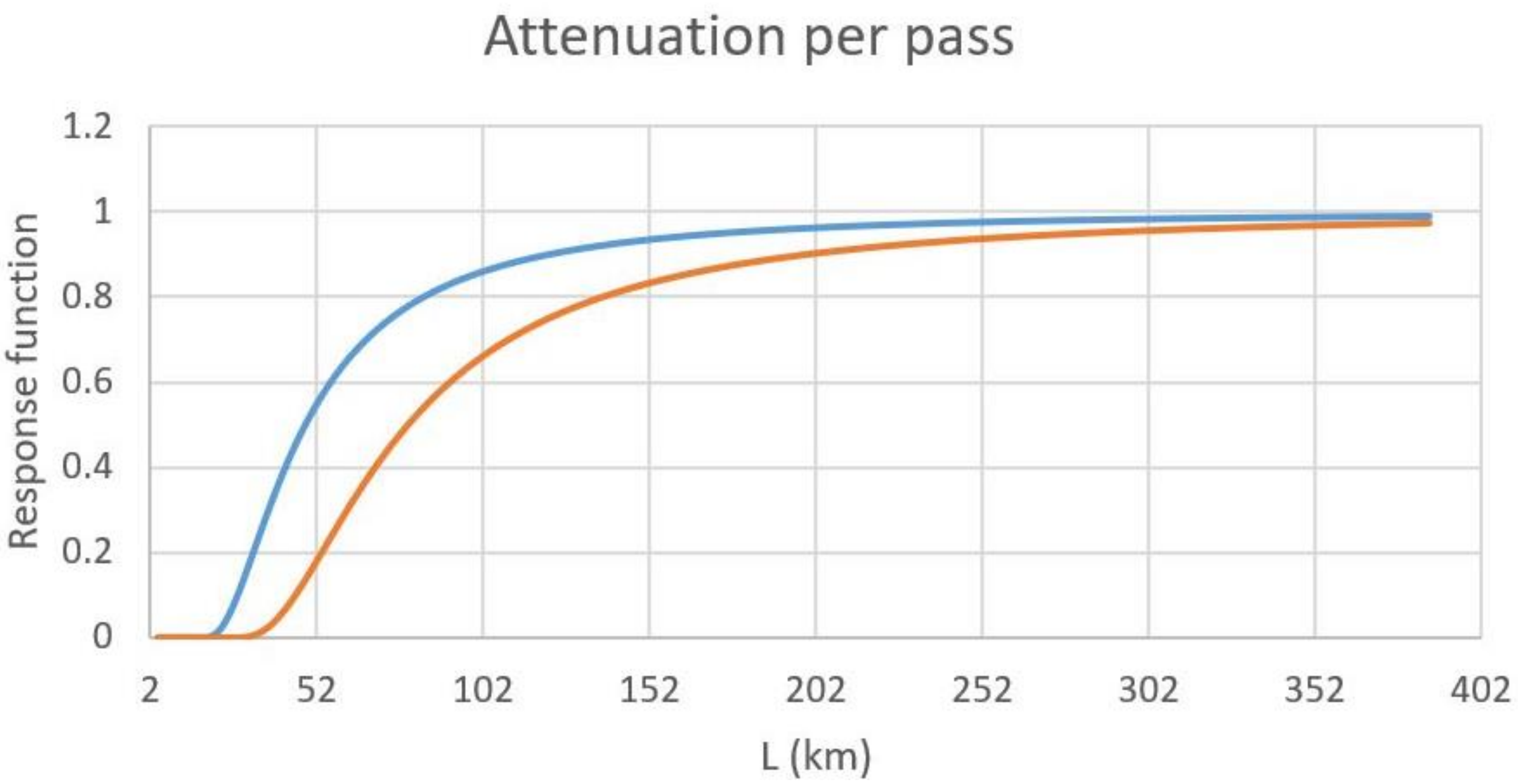
600
100
0 6 12 18 24 30 36 42 48 54 60 66 72 78 84 90 96 102 108 114 120
Time (hr)
Vmax
CAPE


NCODA 2013 SST
40N
30N
20N
10N
70W
60W
50W
40W
30W


NCODA 2013
Vmax (kts)
SST (C)
115
95
75
55
35
15
30
29.5
29
28.5
28
27.5
27
26.5
26
0 6 12 18 24 30 36 42 48 54 60 66 72 78 84 90 96 102 108 114 120
Time (hr)
Vmax
SST


NCODA 2013
Vmax (kts)
Sensible heat flux (W/m^2)
115
95
75
55
35
15
200
150
100
50
0
0 6 12 18 24 30 36 42 48 54 60 66 72 78 84 90 96 102 108 114 120
Time (hr)
Vmax
Sensible heat flux



Attenuation per pass
Response function
1.2
1
0.8
0.6
0.4
0.2
0
2
52
102
152
202
252
302
352
402
L (km)

Spatial filter analysis

This type of equation tries to remove the shortest waves but leaves the longer ones relatively unaffected, and has analogies to diffusion

$$\text{①} \quad \phi_i^{\tilde{\tau}+1} = \phi_i^{\tilde{\tau}} + K\left(\phi_{i+1}^{\tilde{\tau}} + \phi_{i-1}^{\tilde{\tau}} - 2\phi_i^{\tilde{\tau}}\right)$$

The properties of this filter can be explored by representing waves in terms of complex variables

$$\text{②} \quad \phi(x,t) = \hat{\phi}(k,\omega)\, e^{i(kx+\omega t)}$$

where $\hat{\phi}$, k, and ω can be complex and when discretized:

$x = n\Delta x$, $n = \pm 1, \pm 2, \ldots\ldots$
$t = \tilde{\tau}\Delta t$, $\tilde{\tau} = 0, 1, 2 \ldots\ldots$ either as a time step or # passes
ω = frequency
k = wavenumber

Denote :

$$\phi_i^{\tilde{\tau}+1} = \phi_i^{\tilde{\tau}}\phi_0^{1} \; ; \; \phi_{i+1}^{\tilde{\tau}} = \phi_i^{\tilde{\tau}}\phi_1^{0} \; ; \; \phi_{i-1}^{\tilde{\tau}} = \phi_i^{\tilde{\tau}}\phi_{-1}^{0}$$

Substitute (2) into (1), and cancel common $\tilde{\phi_i}$ and $\hat{\phi}$ factors

(3) $$\underbrace{e^{i\omega\Delta t}}_{\text{Decompose into real and imaginary parts } \omega=\omega_r+i\omega_i} = 1 + K\left(\underbrace{e^{ik\Delta x} + e^{-ik\Delta x}}_{=2\cos(k\Delta x)} - 2\right)$$

because of $i^2=-1$

$$e^{i\omega\Delta t} = e^{i(\omega_r + i\omega_i)\Delta t} = e^{i\omega_r\Delta t}\, e^{-\omega_i\Delta t}$$

(4) Denote $\lambda = \pm e^{-\omega_i\Delta t} \equiv$ amplitude change of the solution per time step or for each pass.

Use Euler's formula

(5) $$e^{i\omega_r\Delta t} = \cos(\omega_r\Delta t) + i\sin(\omega_r\Delta t)$$

Substitute (4) and (5) into (3)

$$\lambda\left(\cos(\omega_r\Delta t) + i\sin(\omega_r\Delta t)\right) = 1 + 2K\left(\cos(k\Delta x) - 1\right)$$

Solve for real and imaginary parts

$$\lambda\cos(\omega_r\Delta t) = 1 + 2K\left(\cos(k\Delta x) - 1\right)$$
$$\lambda\sin(\omega_r\Delta t) = 0$$

Second equation shows that $\omega_r = 0$, and there is no propagation. Also, then $\cos(\omega_r \Delta t) = 1$

Therefore

$$\lambda = 1 + 2K\left(\cos(k\Delta x) - 1\right)$$

Since $k = \frac{2\pi}{L}$ where $L \equiv$ wavelength, and $L = n\Delta x$

6 $$\boxed{\lambda = 1 + 2K\left(\cos\left(\frac{2\pi}{n}\right) - 1\right)}$$

For a value of $K = \frac{1}{4}$

n	2	3	4	6	8	10	15	20	32
λ	0	0.25	0.5	0.75	0.85	0.9	0.96	0.975	0.99

Hence the $2\Delta x$ wave is removed, the $3\Delta x - 6\Delta x$ is extremely attenuated, and longer wavelengths are retained.

But suppose $K = 1.707107$, corresponding to $K = 0.5/\left(1-\cos\left(\frac{2\pi}{m}\right)\right)$ where $m=8$

n	2	3	4	6	8	10	15	20	32
λ	-5,8	-4,1	-2.4	-0,71	0	0,35	0,71	0,83	0,93

$n=2$ to $n=5$ are unstable, $n=6$ to $n=7$ are negatively attenuated, $n=8$ is removed, $n=9$ to $n=16$ are extremely attenuated, and longer wavelengths are retained

Hence, if $m=n$, the $n\Delta x$ wavelength is removed
if $m>n$, the $n\Delta x$ wavelength is either negatively attenuated or unstable.

Generally, if $n>m+3$, attenuation is minimal
Generally, if $m>n+3$, unstable (but depends on n, can be $n+2$ or $n+4$)

Kurihara sequentially tries to remove $n=2$ to $n=9$, but because new $2\Delta x$ waves are generated by round-off error for $m=3$ to $m=9$, to keep scheme stable and to remove the $2\Delta x$ waves, he periodically applies a $m=2$

Note also that as model grid spacing decreases, the effectiveness of the original Kurihara scheme will decrease. This is why Fitzpatrick and Lau added new weights, shown in red.

$m = 2, 3, 4, 2, 5, 6, 7, 2, 8, 9, 2, 10, 11, 2, 12, 13, 2, 3, 2$