Energy transport and transfer in the wake of a tropical cyclone

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Objectives

1) Show how tropical cyclones affect air-sea energy fluxes
(on the short term and on the long term).

WAKE (SSTA, SSHA)

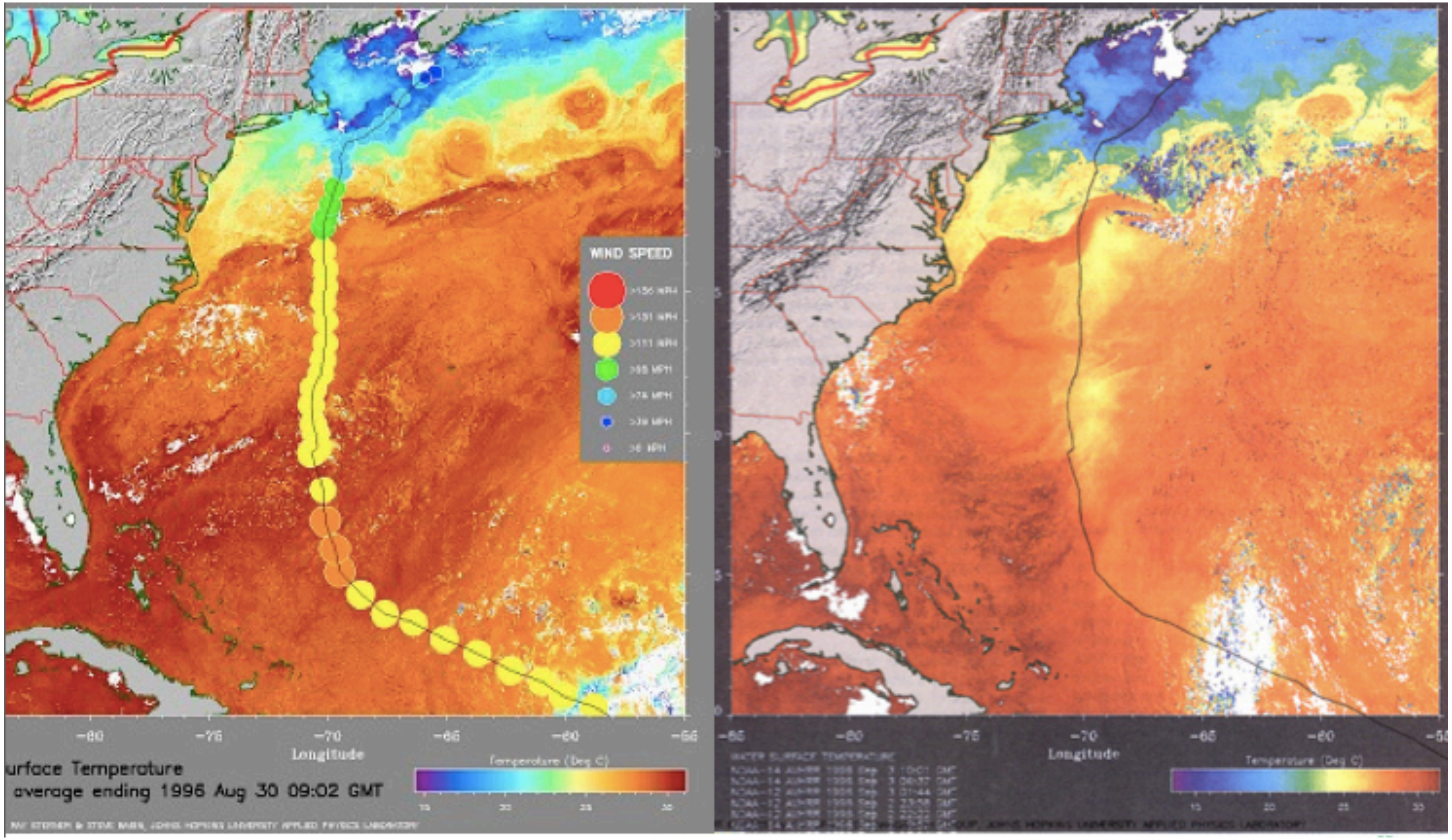
2) Show how tropical cyclones contribute to ocean mixing far away from their location.

INTERNAL WAVES

Cold wake: example

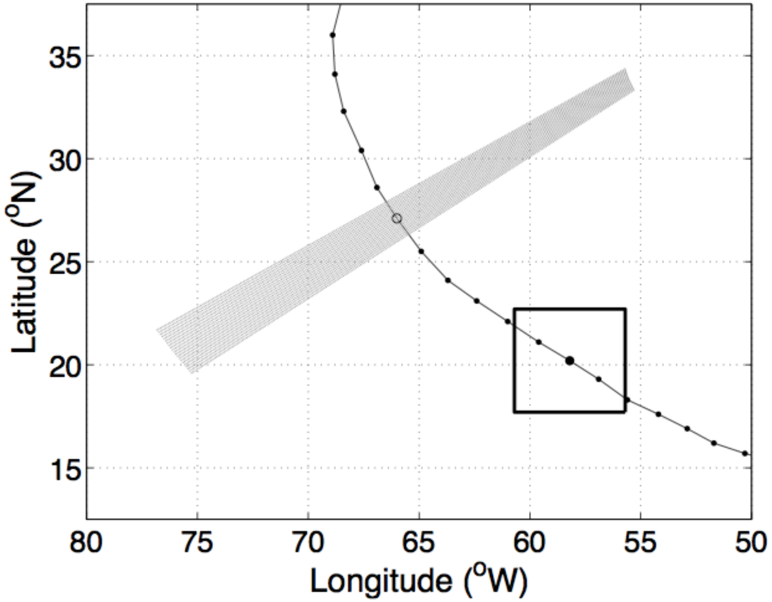
Cold wakes left by TC have SST anomalies up to -10°C. **[Chiang et al. JPO 2011]**

Sea Surface Temperature

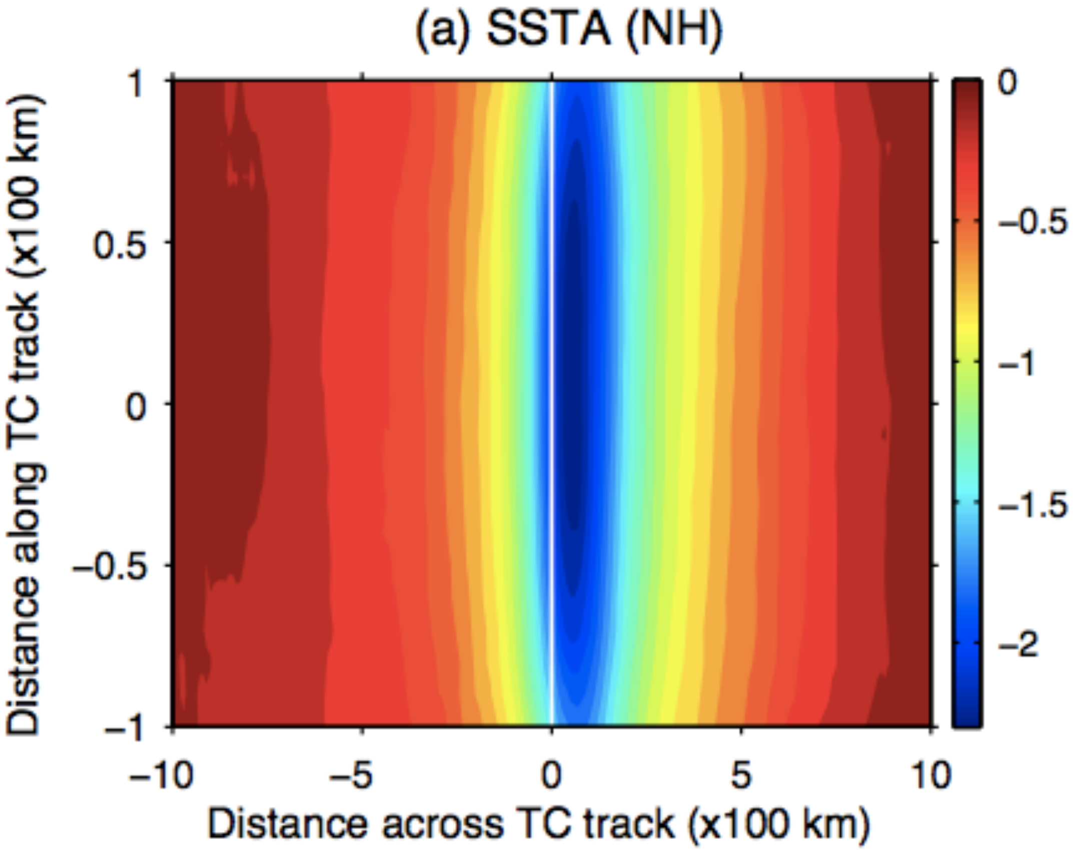


Hurricane Edouard, 1996 (30 august and 3 september)

Cold wakes: a composite study



Composite study of all NH TC wakes from 1997



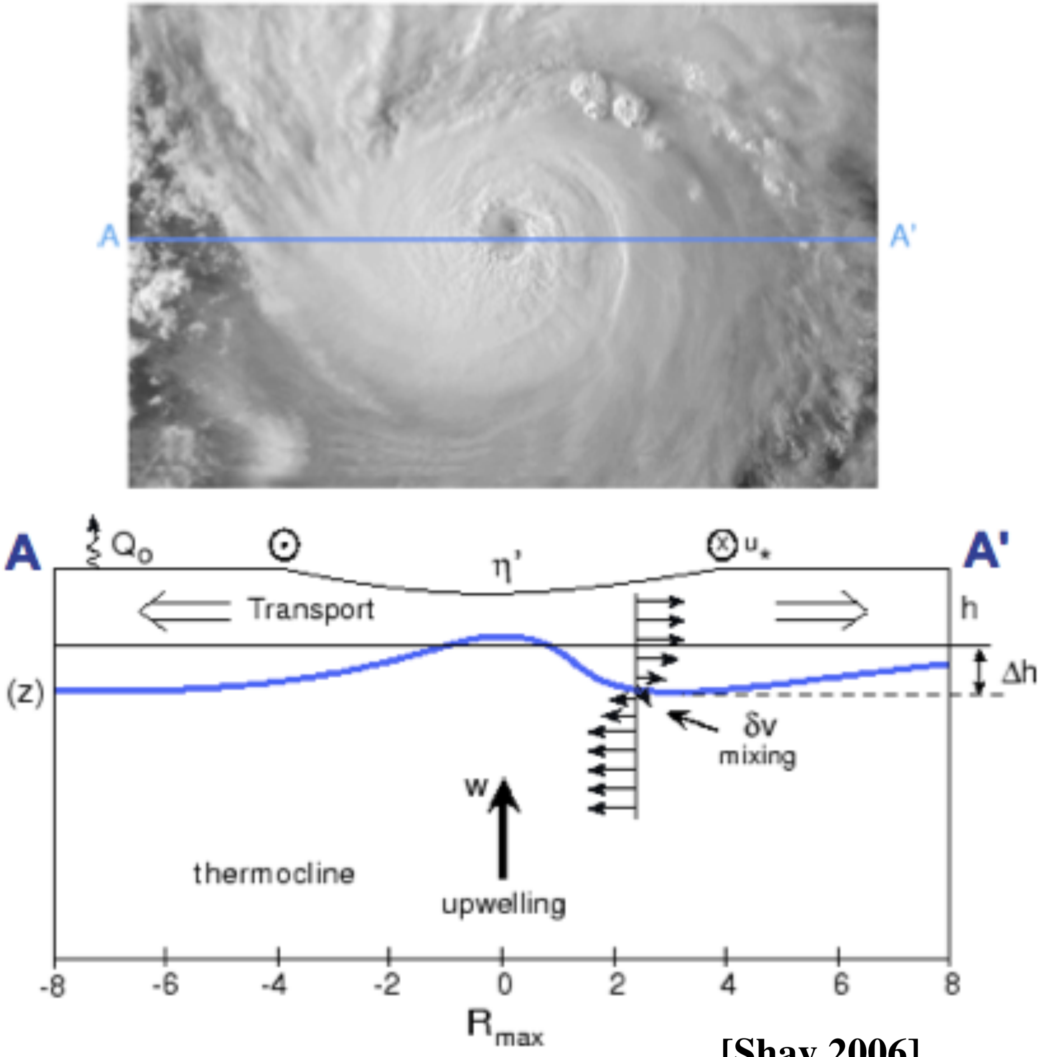
[Mei and Pasquero, J. Climate, 2013]

Generation of the cold wake [Price 1981]

Air-sea fluxes: strong winds increase the enthalpy flux between ocean and atmosphere

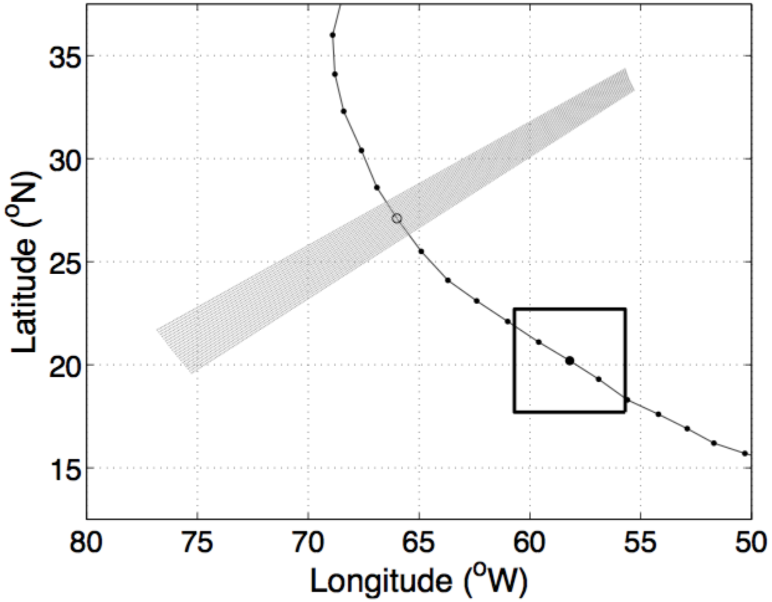
Mixing: shear instability induced by winds generates mixing between surface and subsurface water (down to 200 meters).

Ekman upwelling: cyclonic winds generate surface divergence that induces upwelling of deeper and colder water

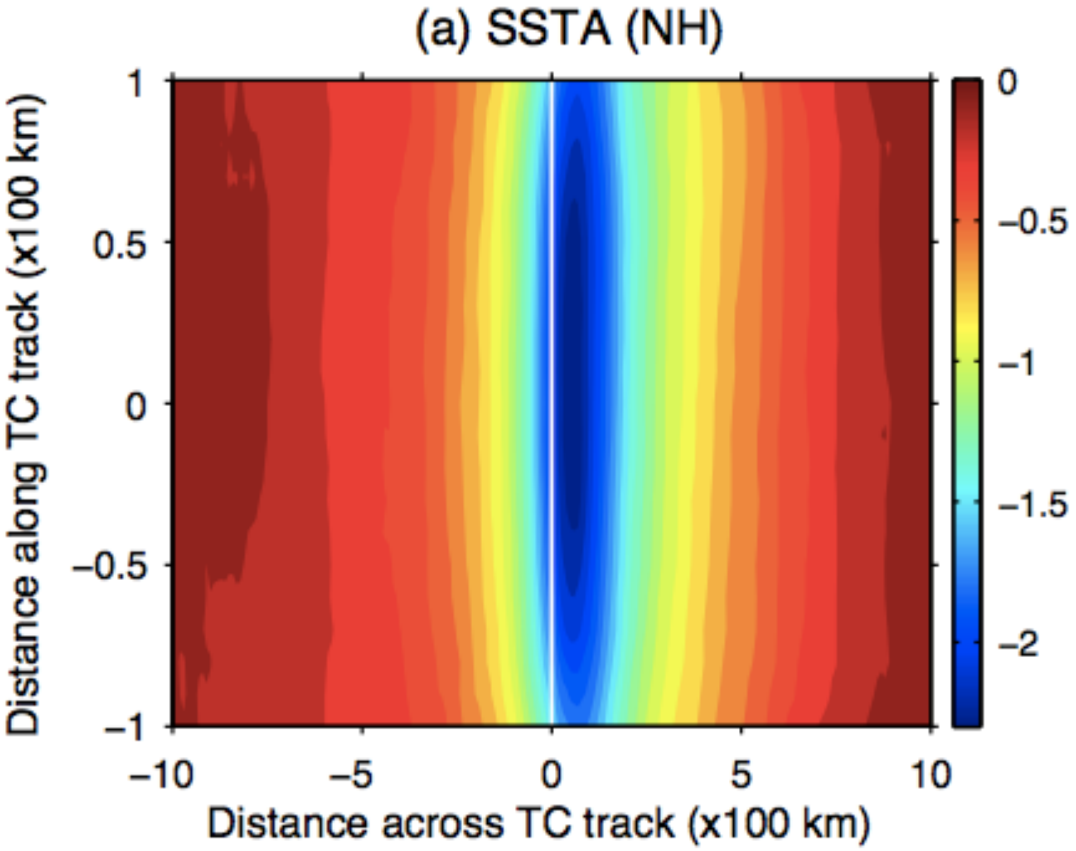


[Shay 2006]

Cold wakes: a composite study



Composite study of all NH TC wakes from 1997

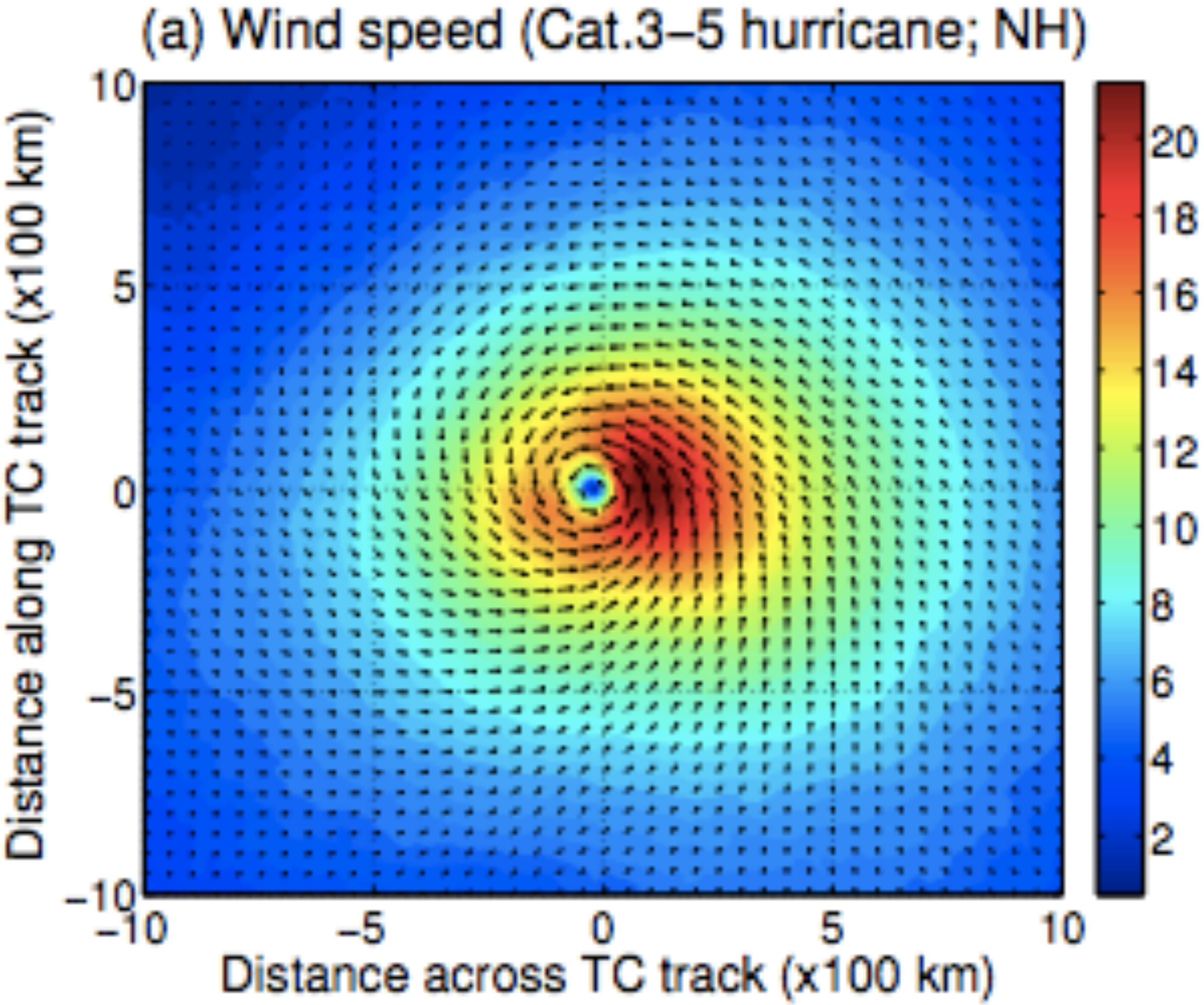


[Mei and Pasquero, J. Climate, 2013]

The cold wake is shifted to the right of the TC track in the Northern Hemisphere

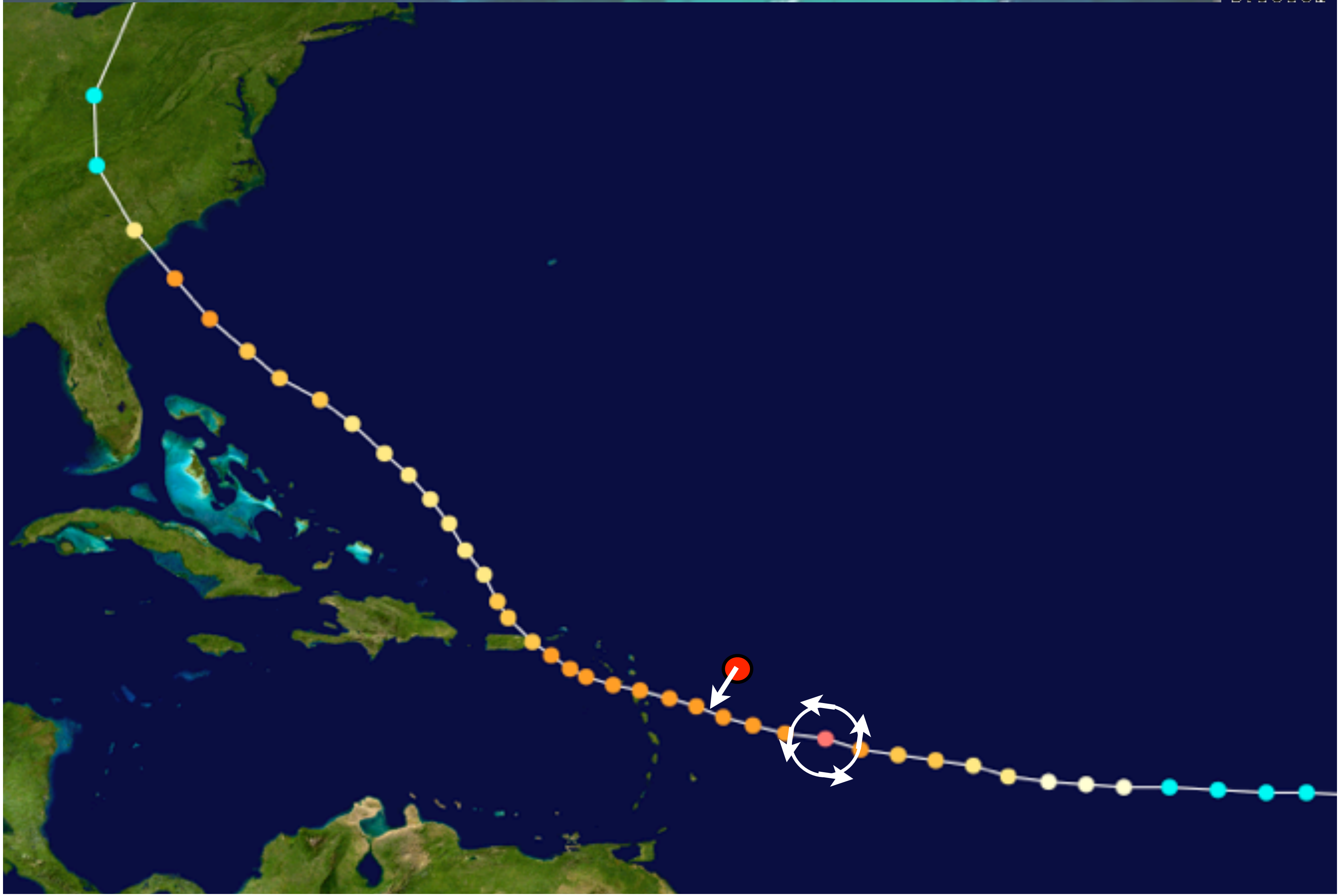
Rightward bias (NH)

Composite study of all NH TC winds from QuikSCAT data

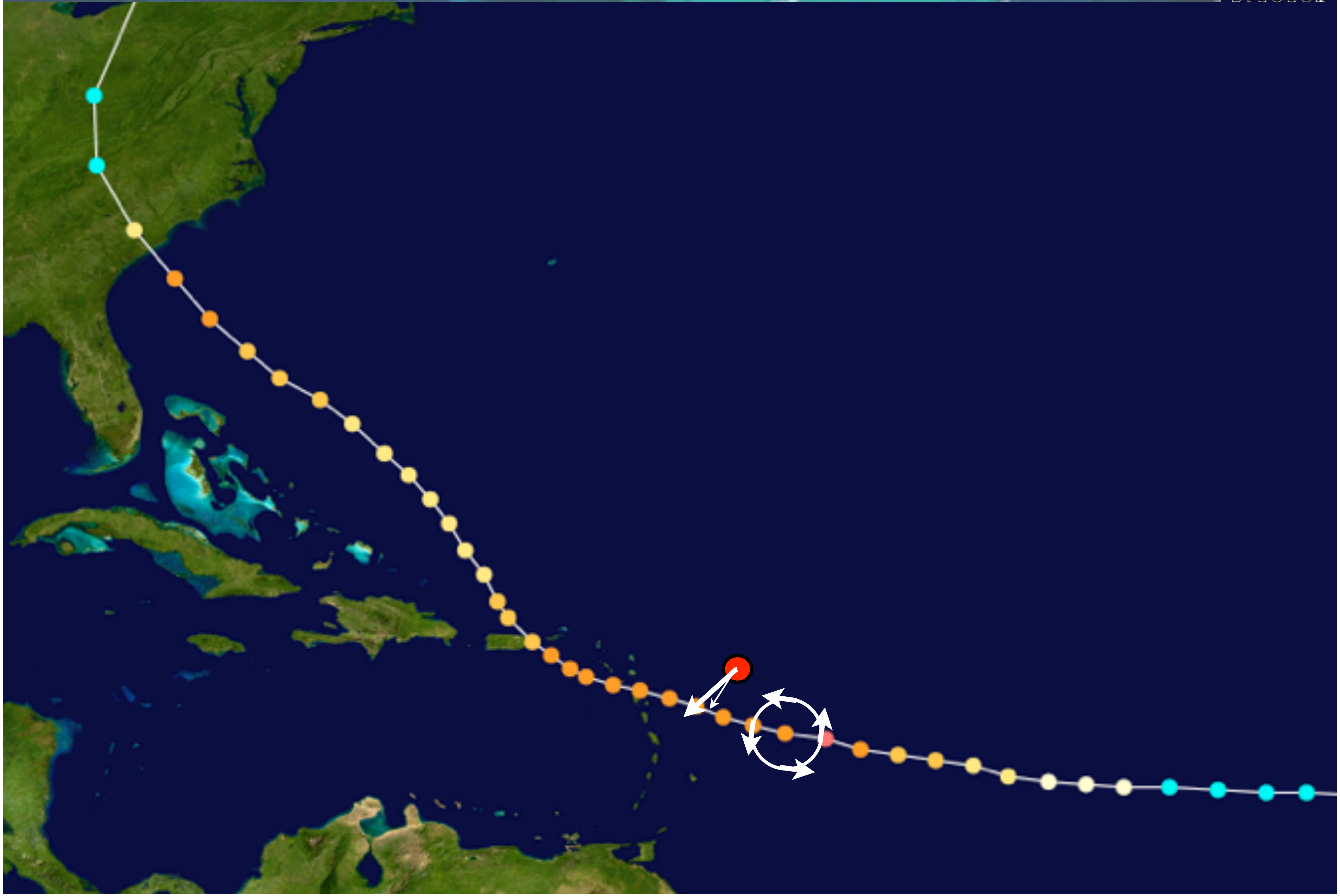


Rightward bias due to larger winds and resonance of near-inertial waves.

Excitation of near-inertial waves



Excitation of near-inertial waves



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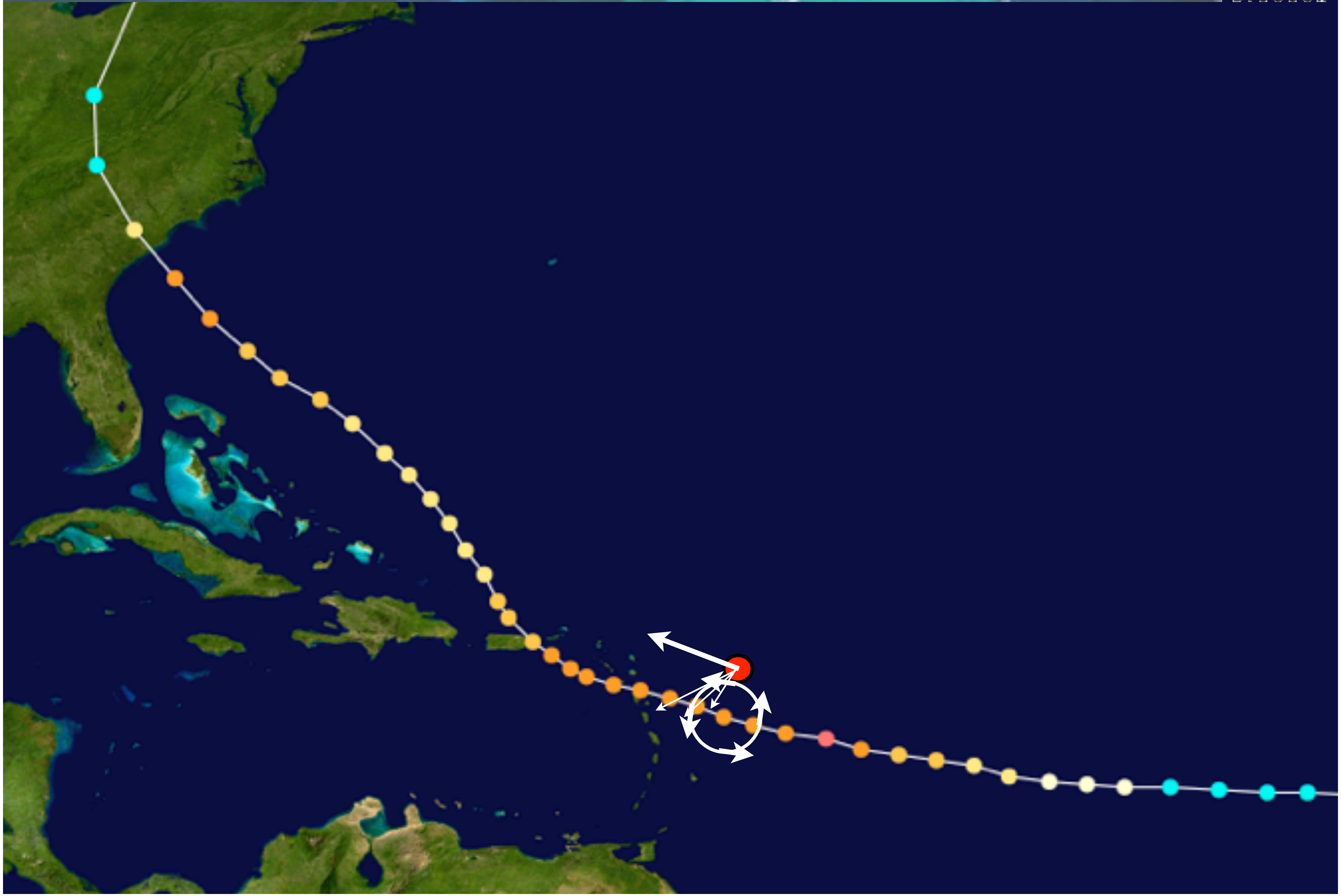

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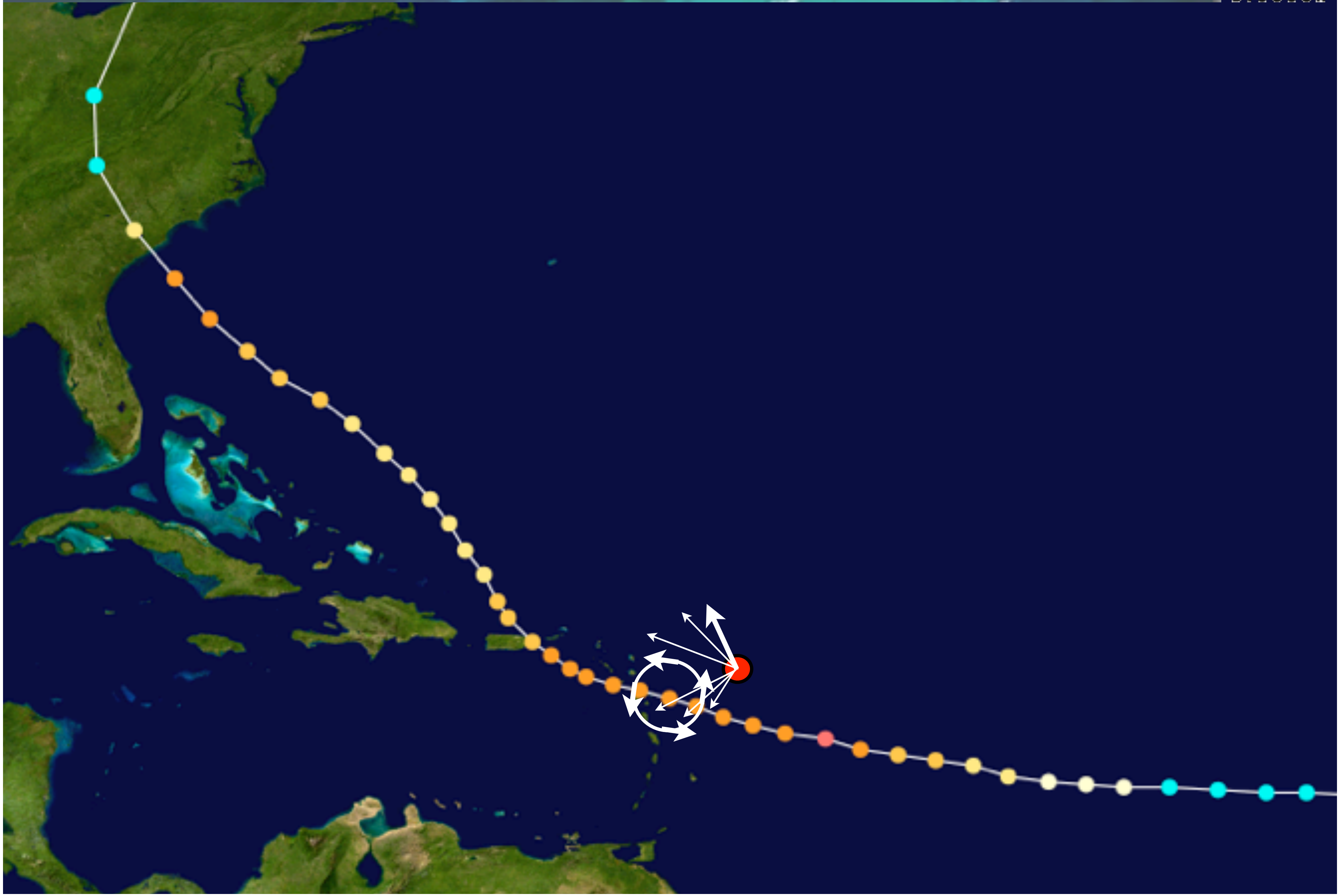
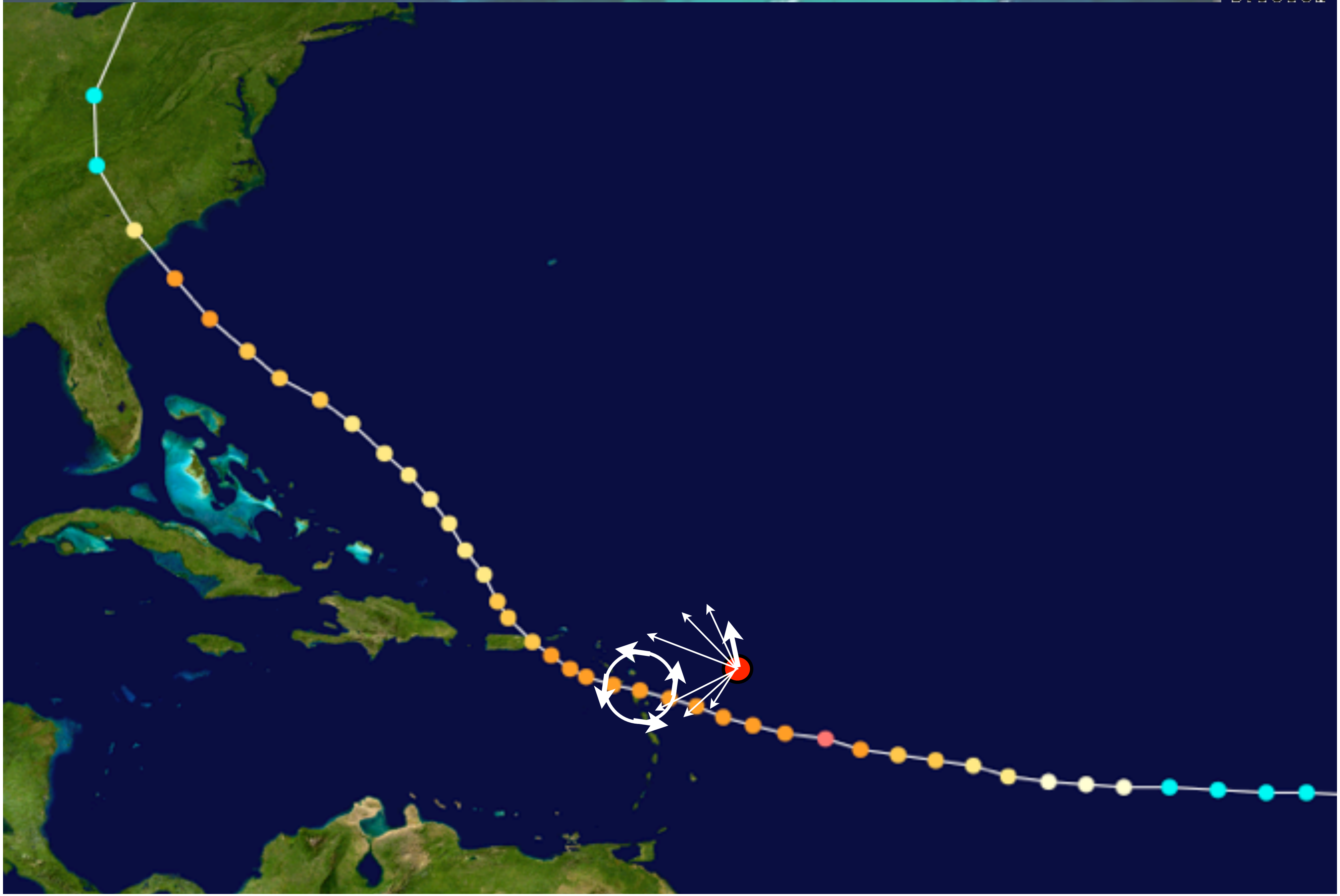


Excitation of near-inertial waves

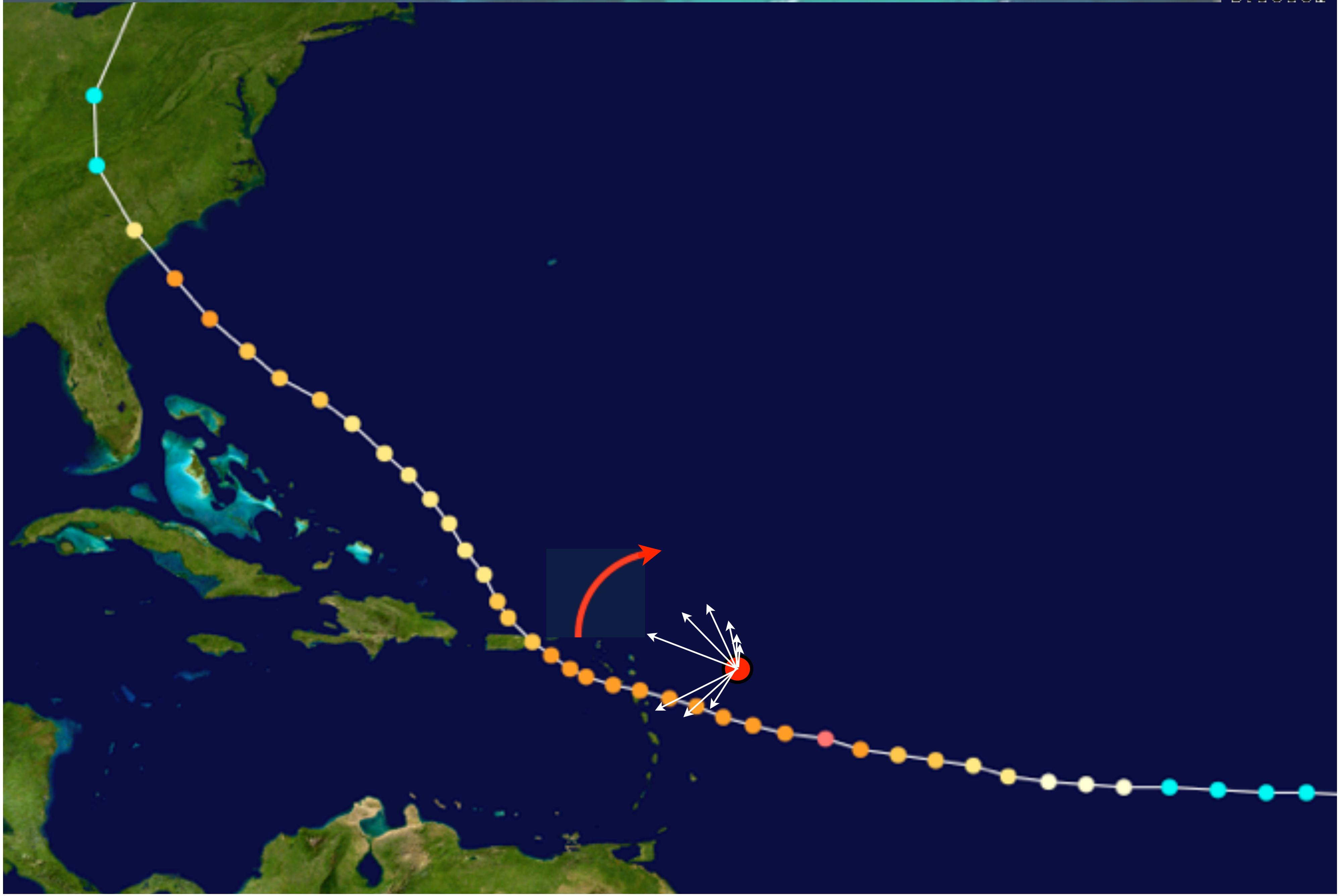


Excitation of near-inertial waves

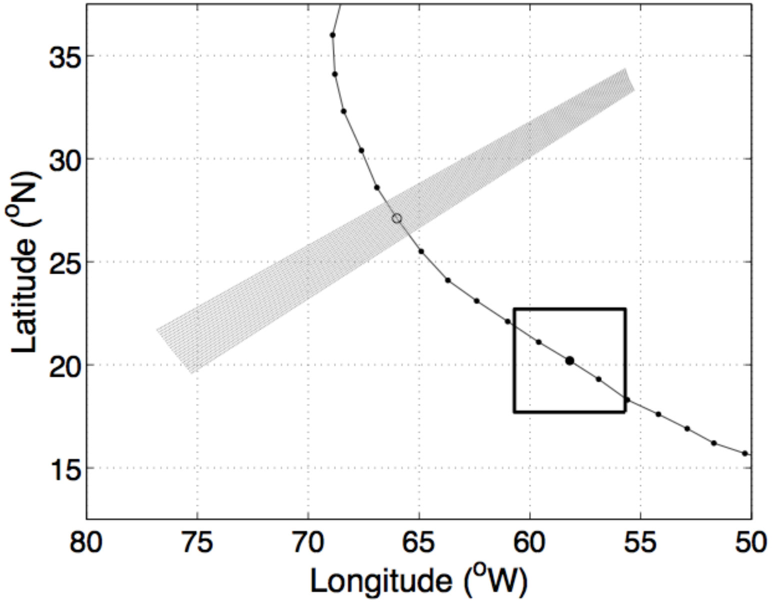
Occ@m

Excitation of near-inertial waves

Excitation of near-inertial waves



Cold wakes: a composite study



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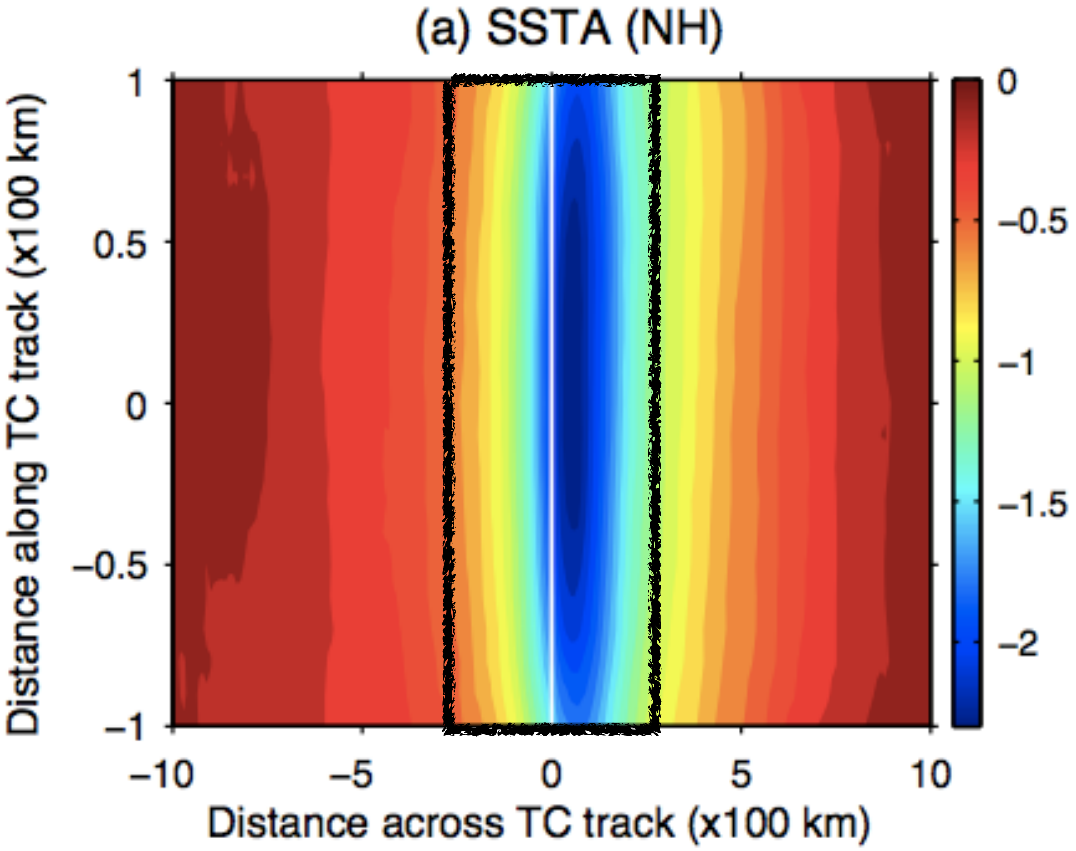
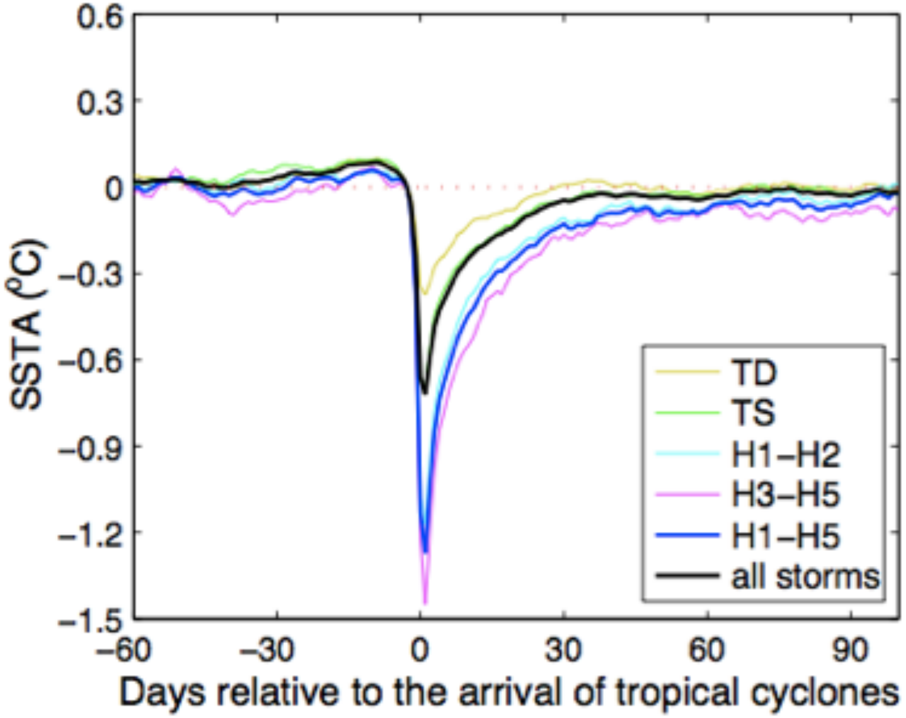
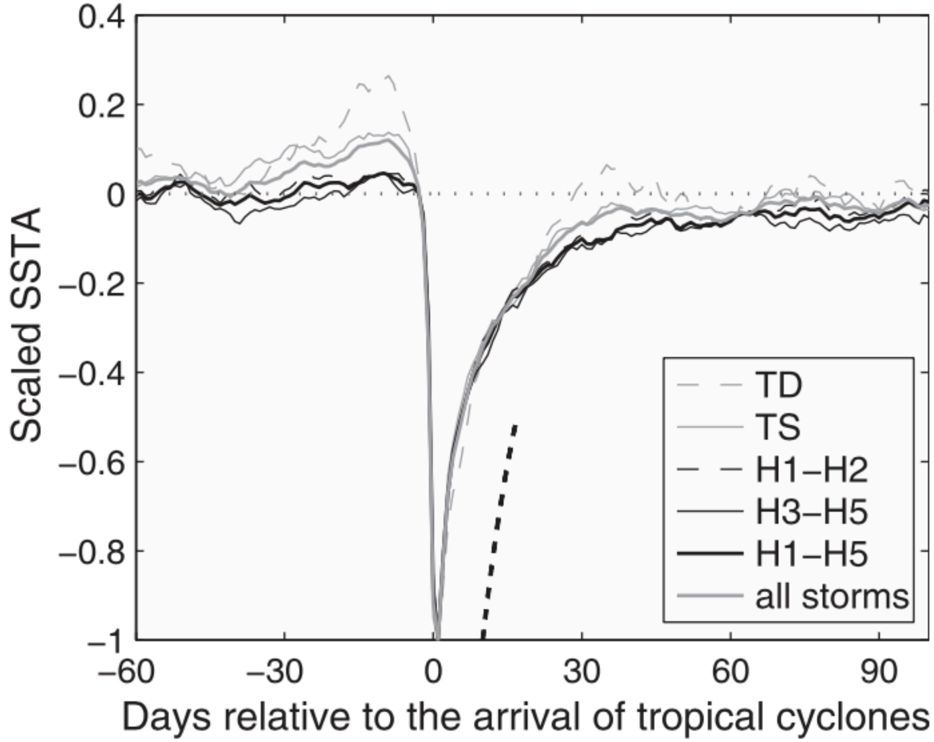


[Mei and Pasquero, J. Climate, 2013]

Wake recovery

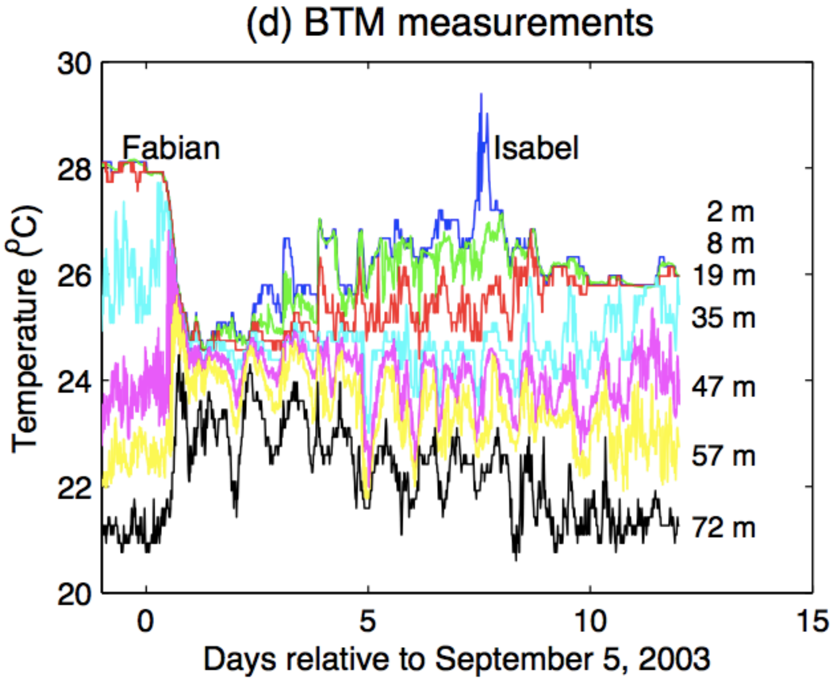


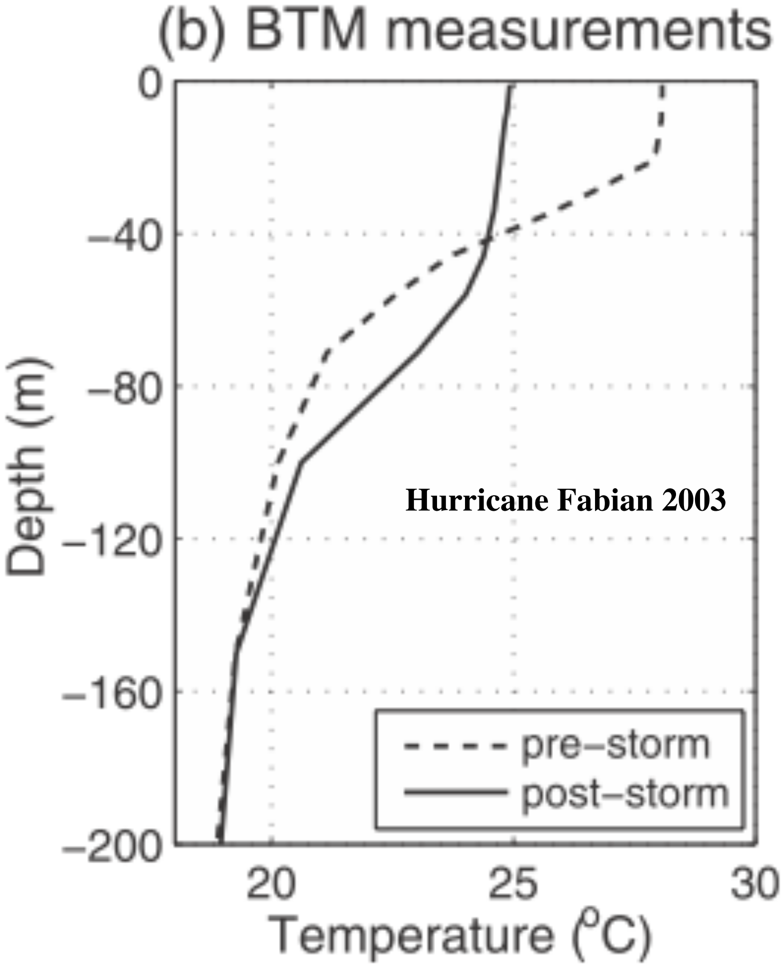


[Wei and Pasquero J.Climate 2013]

Temperature profile

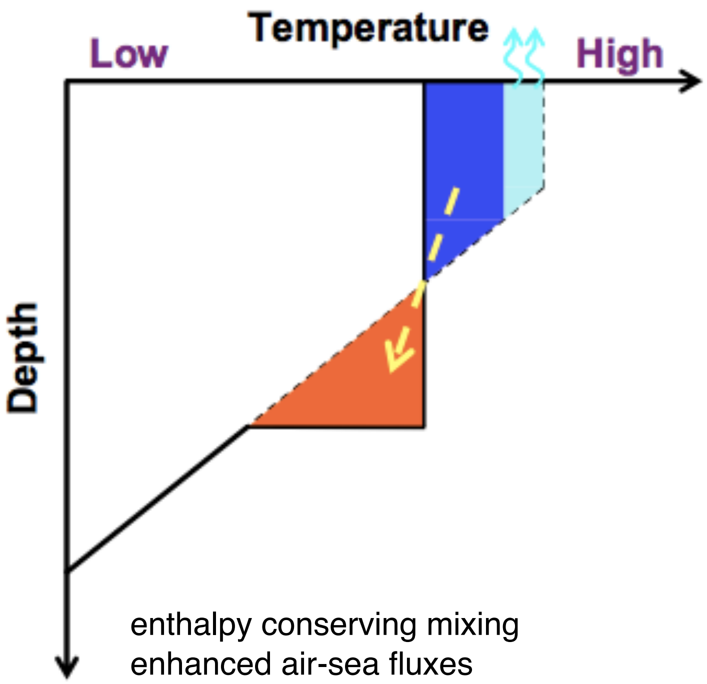
Vertical mixing cools the surface and warms part of the thermocline.



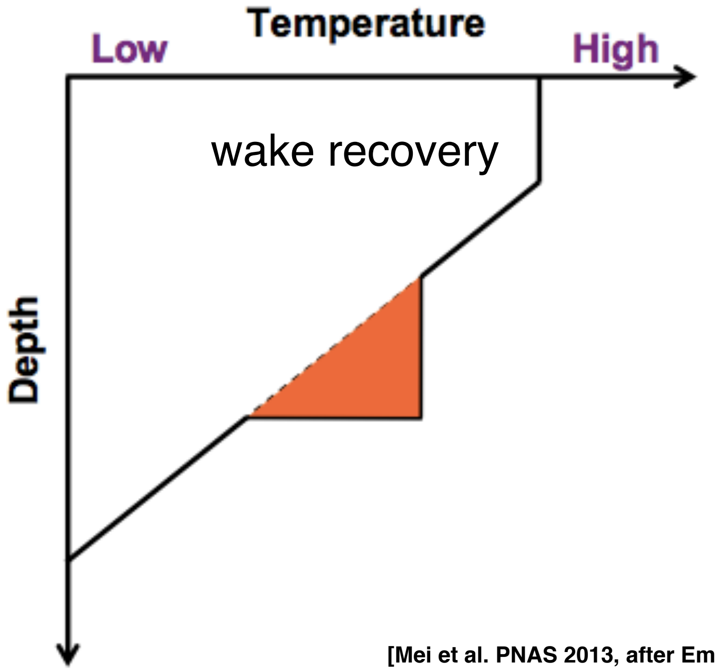


[Wei and Pasquero JPO 2012, data courtesy of T. Dickey, UCSB]

Wake recovery



enthalpy conserving mixing
enhanced air-sea fluxes



[Mei et al. PNAS 2013, after Emanuel 2001]

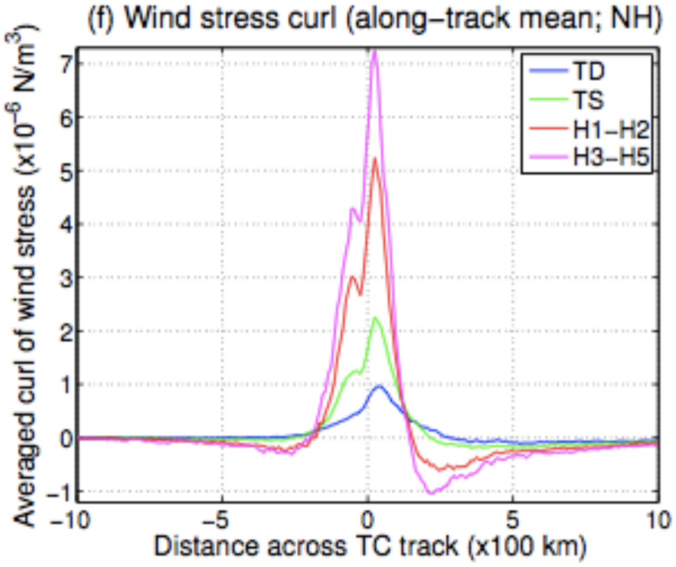
Sea surface height response

SSH **during** passage of the TC affected by:

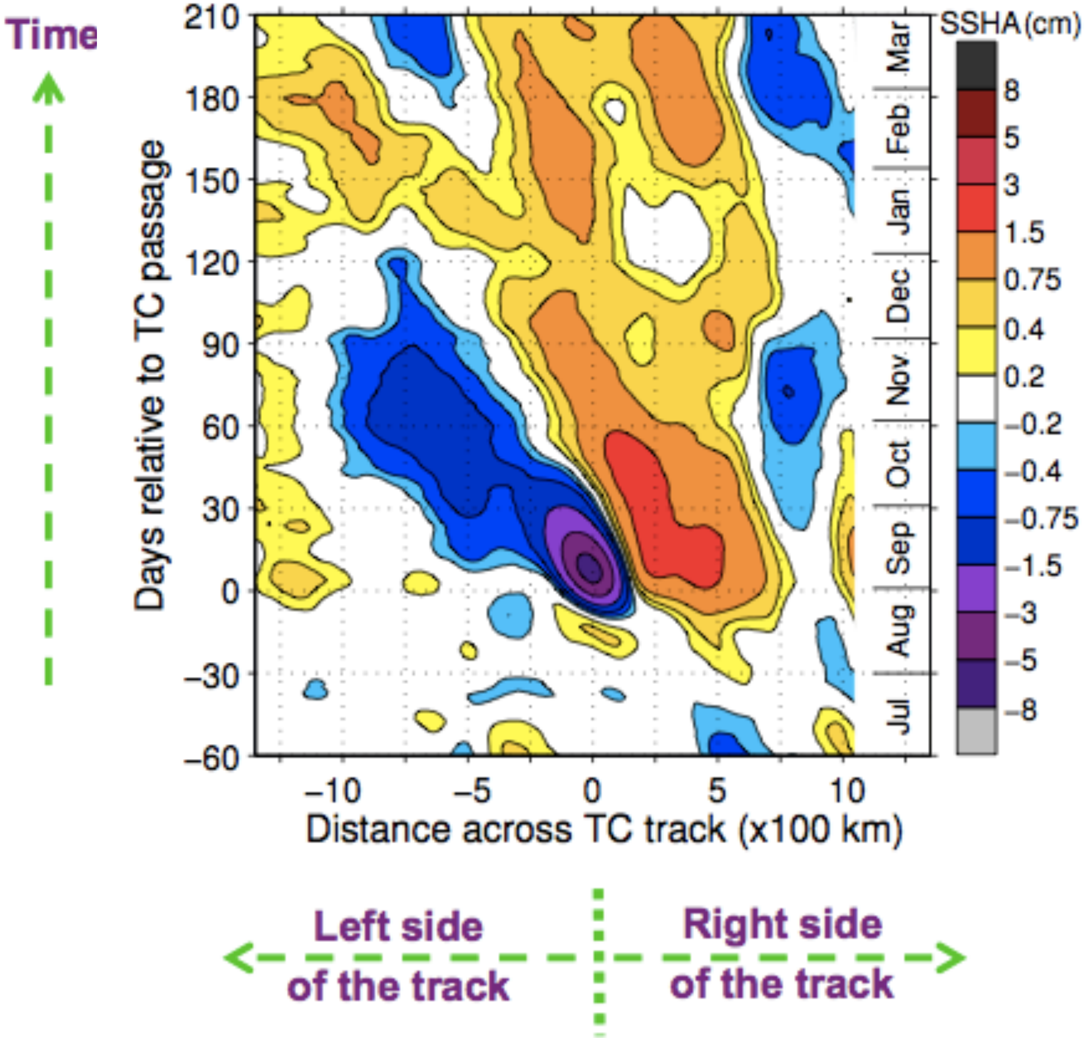
- Ekman transport (divergence below the eye, convergence further away, larger on the right side of the track)

- net air-sea heat flux

- water mass loss (evaporation minus precipitation)



Composite study on all NH TC from 1993 and AVISO SSH data



[**Mei, Primeau, McWilliams, Pasquero, PNAS** ***2013***]

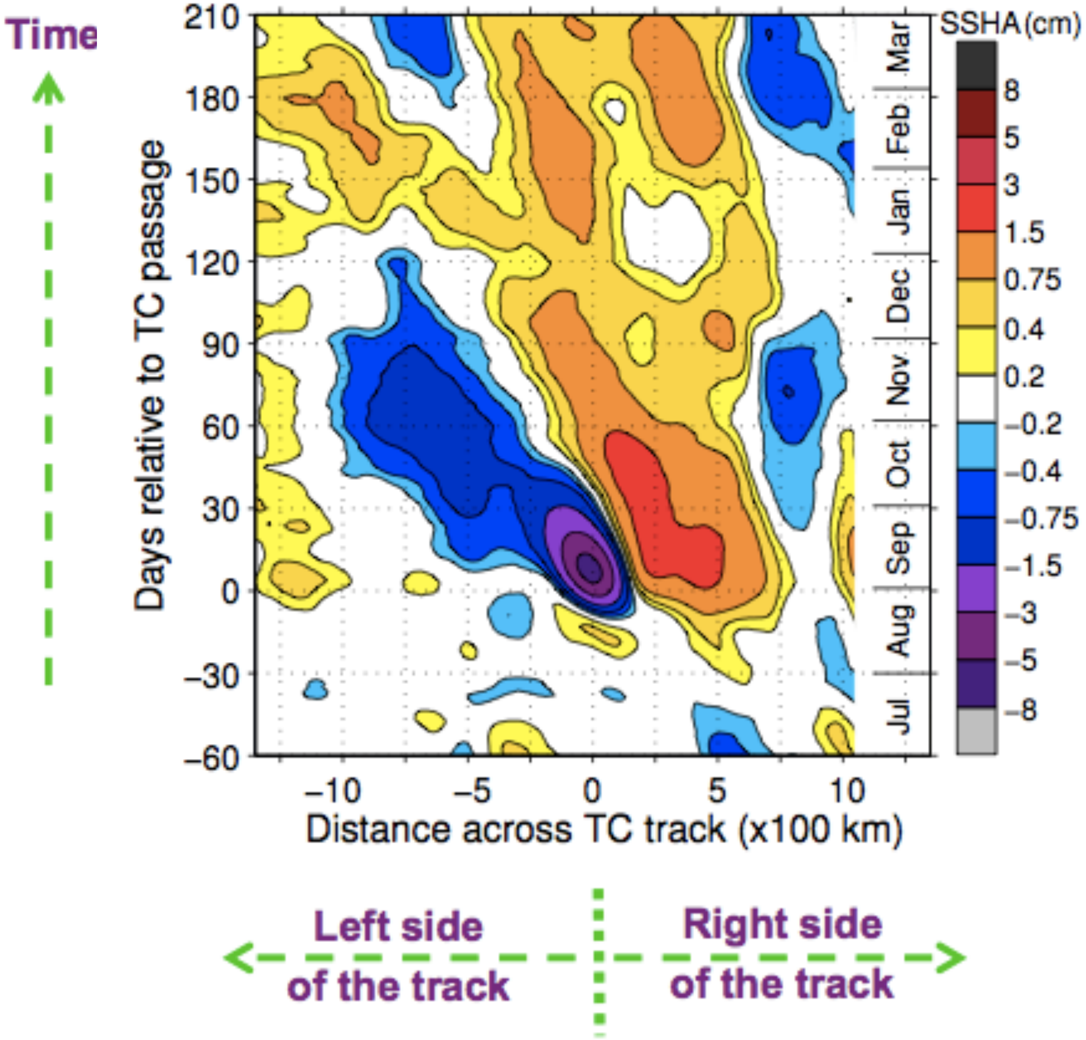
Sea surface height response

SSH **after** passage of the TC affected by:

- geostrophic adjustment

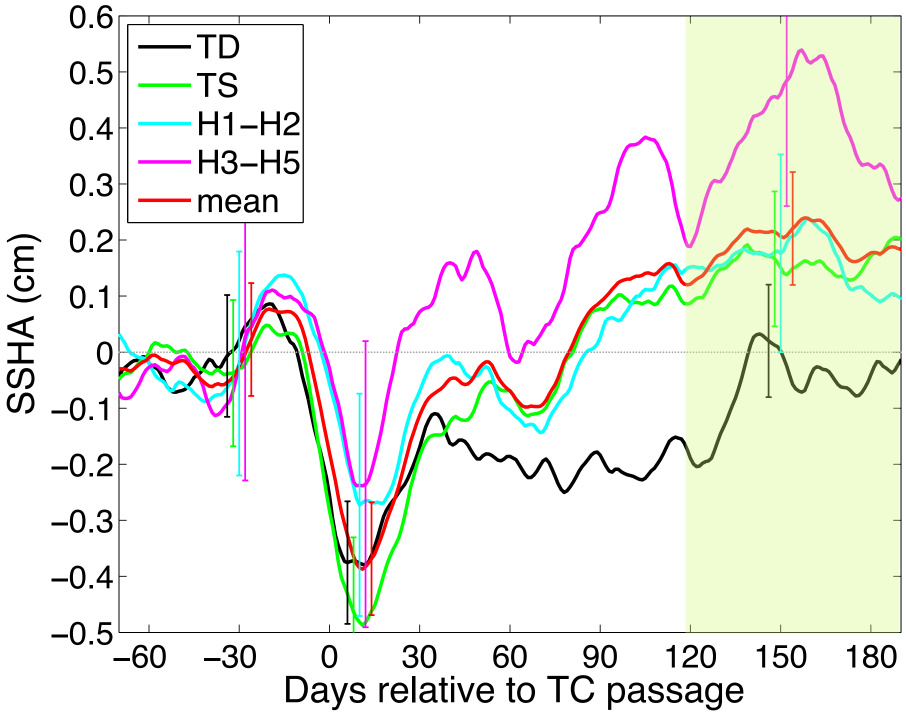
- net air-sea heat flux

Composite study on all NH TC from 1993 and AVISO SSH data



[Mei, Primeau, McWilliams, Pasquero, PNAS *2013*]

Ocean heat uptake



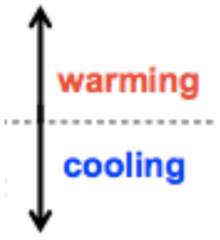
- During the passage of the TC: cooling due to heat and water extraction by the storm

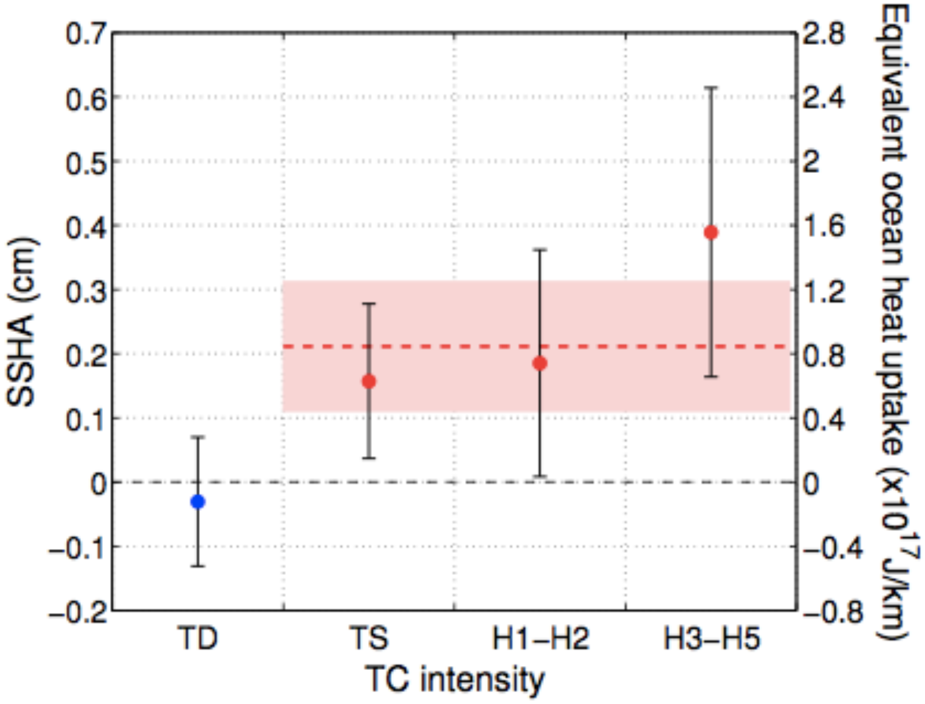
- Gradual recovery after negative SSHA peaks

- Quasi-stable state after about 4 months (winter)

Today, TCs have a global long term warming effect on the ocean of 0.32 ± 0.15 PW

(at least one order of magnitude larger than the cooling by sensible heat extraction during the storm)





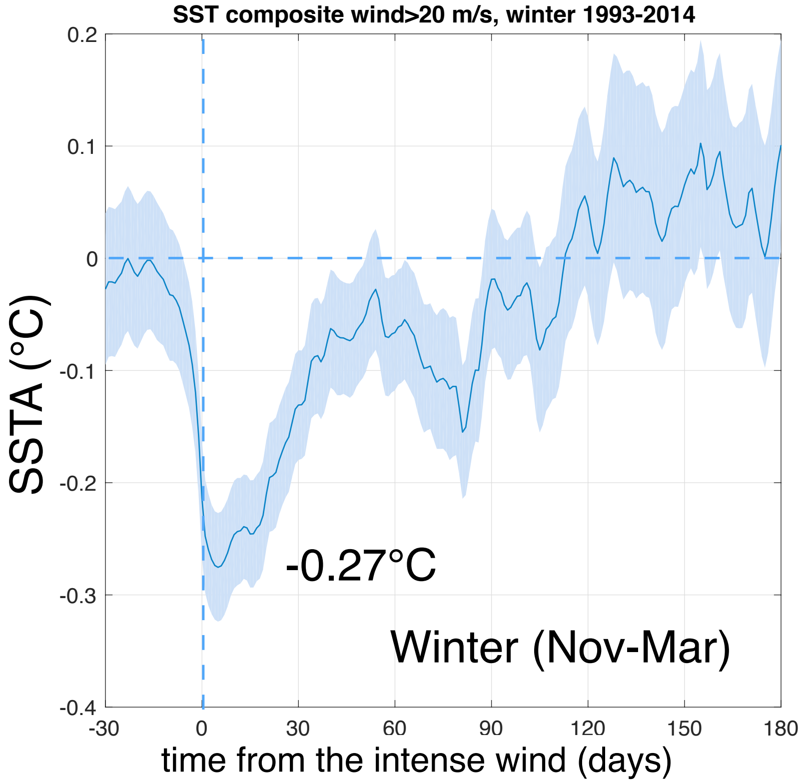
[Mei, Primeau, McWilliams, Pasquero, PNAS *2013*]

The Mediterranean case: SSTA

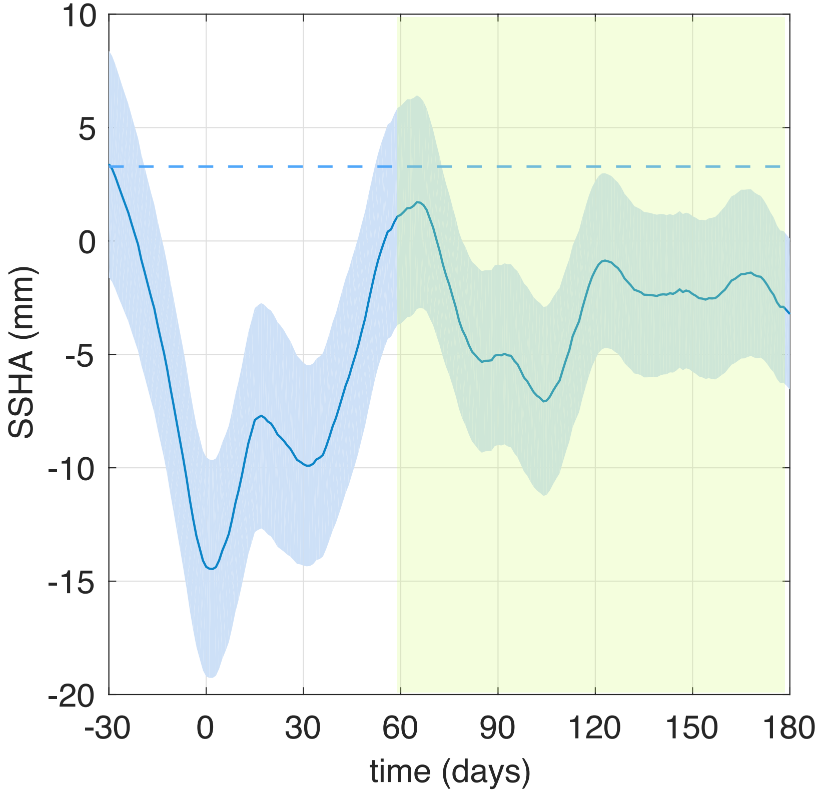
Gulf of Lion intense winds

(above 20 m/s, from Cross Calibrated Multi Platform data - CCMP. SST data from NOAA OISST)

Mean SST anomaly



Mean SSH anomaly



The Mediterranean case: SSTA

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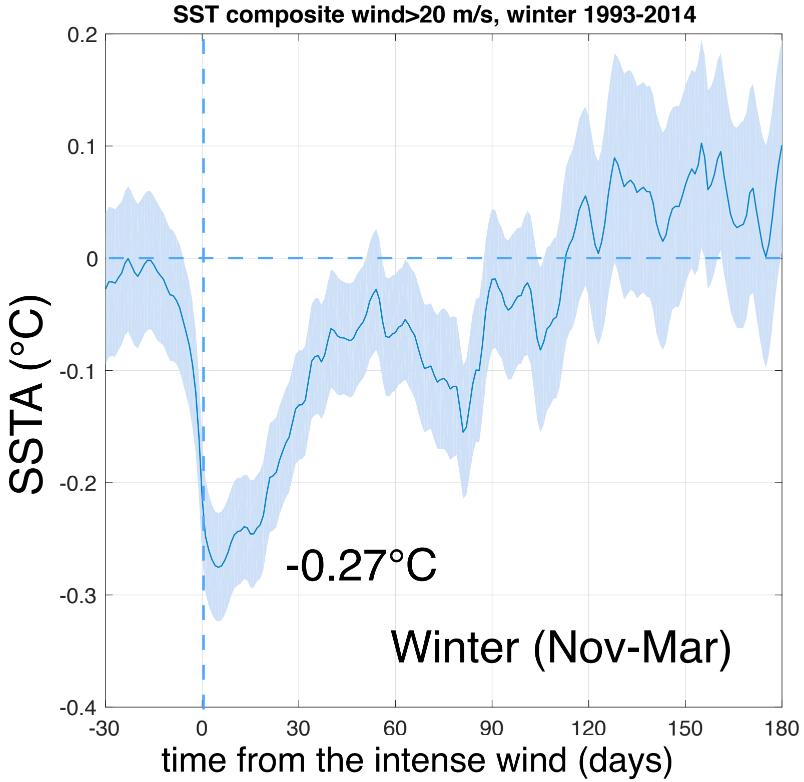
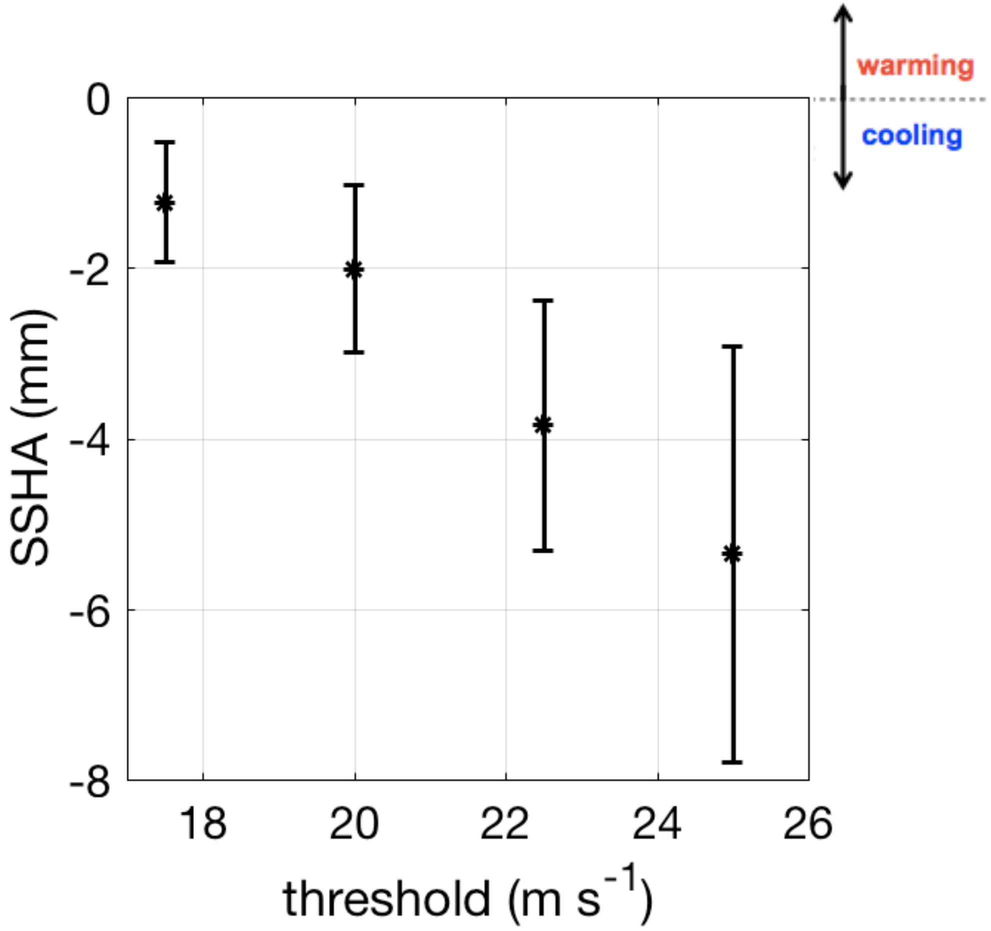


Mean SSHA (months 2-6)



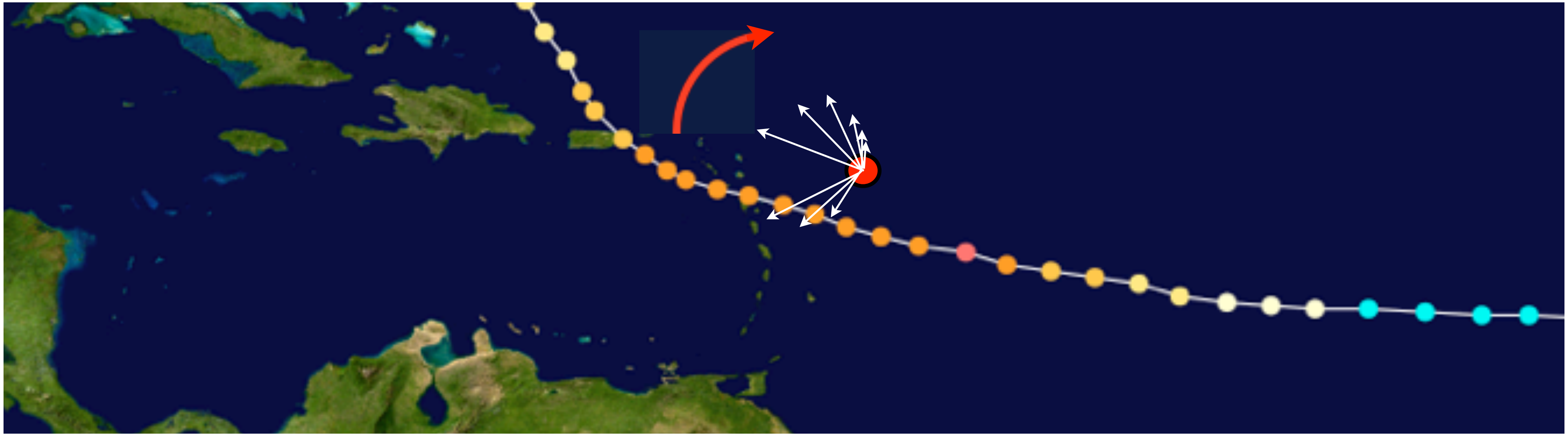
Excitation of near-inertial internal waves

Tropical cyclones are good exciters of near inertial internal waves $\omega \simeq f = 2\Omega \sin\phi$

Breaking internal waves mix water, even far from the source region.

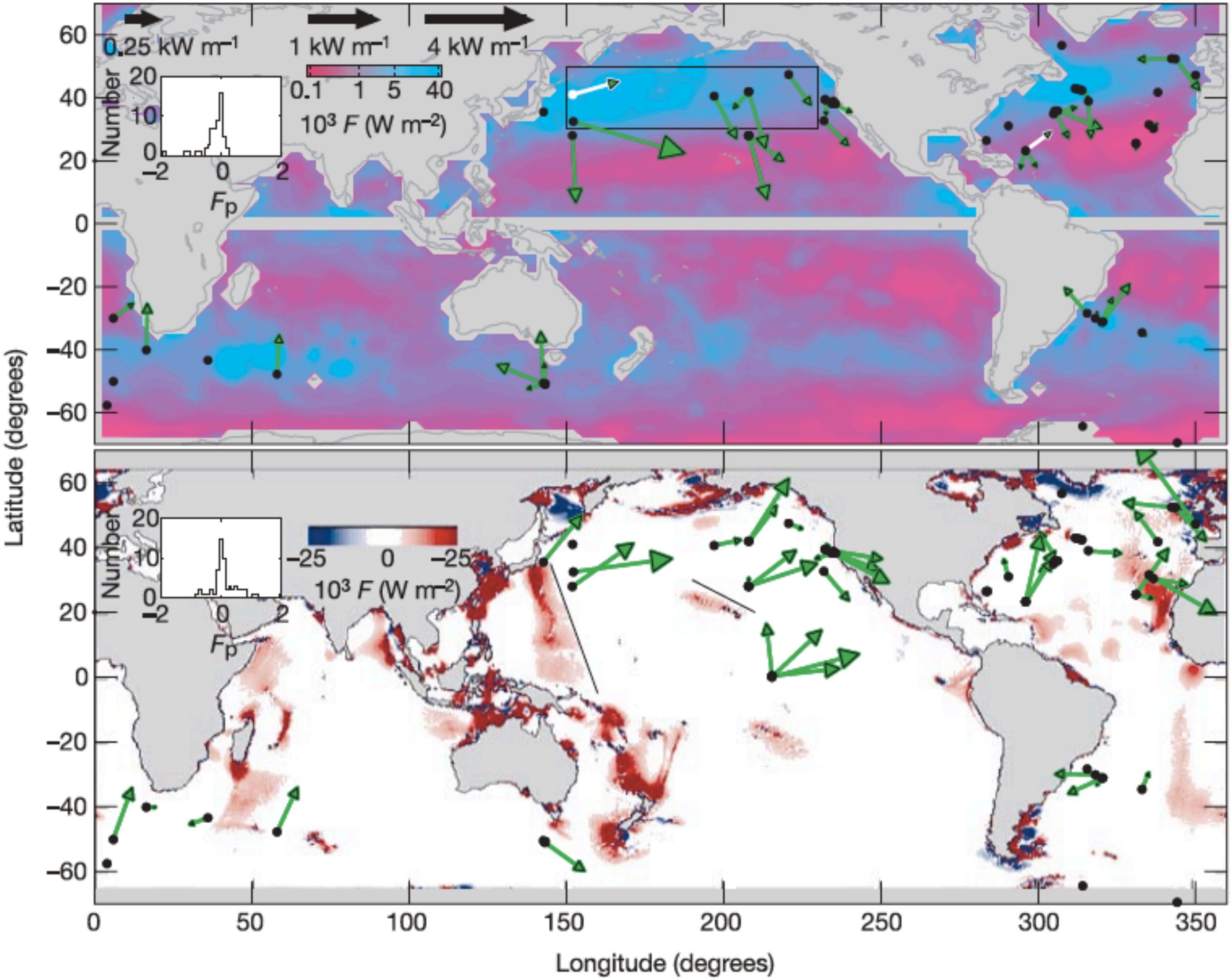
Internal waves propagate only if $f^2 \lesssim \omega^2 \lesssim N^2$.

Near-inertial internal waves do not propagate poleward.



Energy flux by internal waves

Annual mean source terms (color) and depth-integrated, annual-mean energy flux vectors, from 60 mooring stations

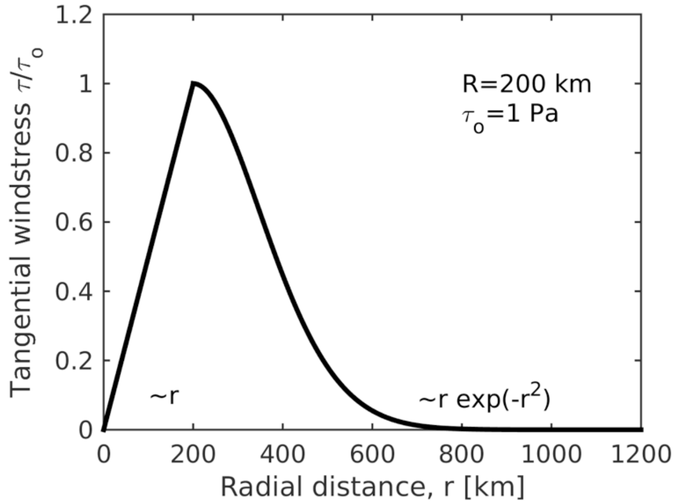


Near-inertial

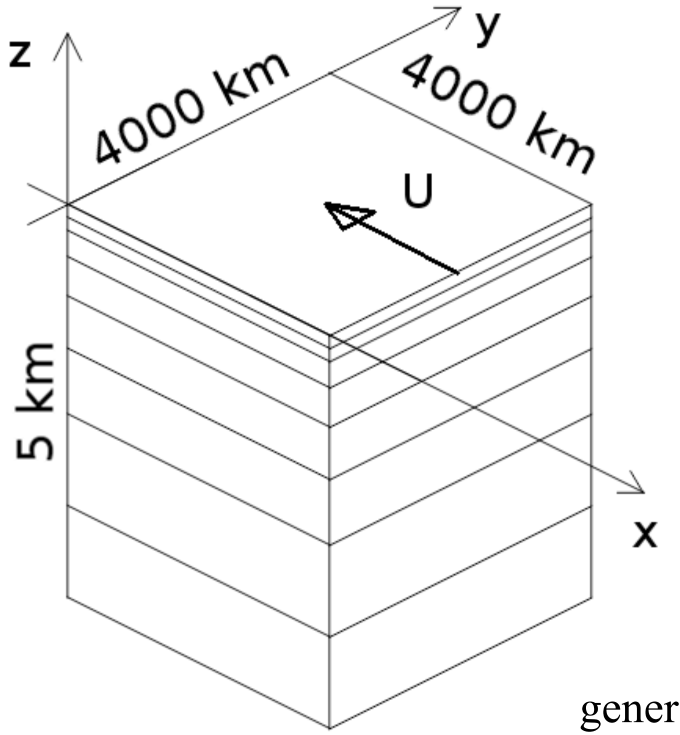
Higher frequencies

[*Alford*, Nature 2003]

The model



Flat ocean
Open lateral boundaries
Zero initial velocity in the ocean
Surface tangential windstress
f-plane
Hydrostatic Boussinesq equations

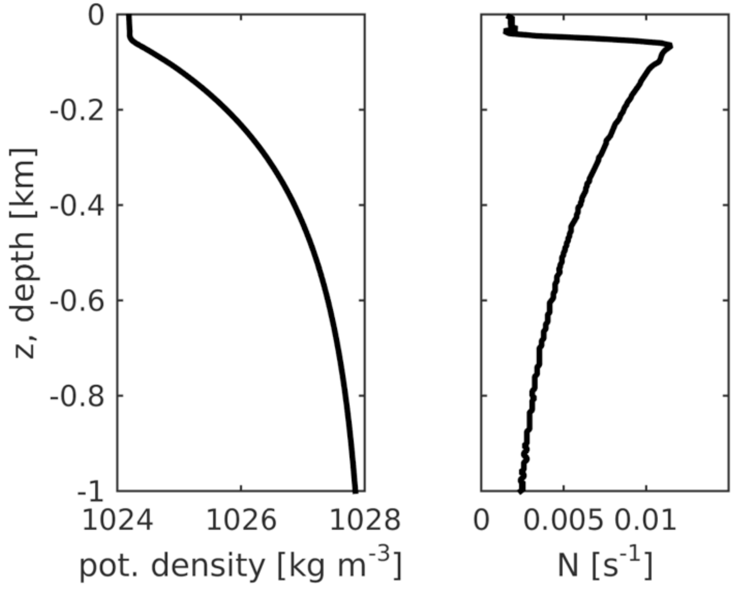


$$
\begin{aligned}
\frac{Du}{Dt} - fv &= -\frac{1}{\rho_o}\frac{\partial p}{\partial x} + \frac{1}{\rho_o}\frac{\tau_s^x}{H_{mix}}\sigma(z) \\
\frac{Dv}{Dt} + fu &= -\frac{1}{\rho_o}\frac{\partial p}{\partial y} + \frac{1}{\rho_o}\frac{\tau_s^y}{H_{mix}}\sigma(z) \\
0 &= -\frac{1}{\rho_o}\frac{\partial p}{\partial z} - \frac{\rho}{\rho_o}g \\
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} &= 0 \\
\frac{g}{\rho_o}\frac{D\rho}{Dt} - wN^2 &= 0
\end{aligned}
$$

ROMS-Agrif [*Penven et al*. 2006]

generalization of *Niwa and Hibiya 1997* study with constant stratification

Stratification and mode decomposition

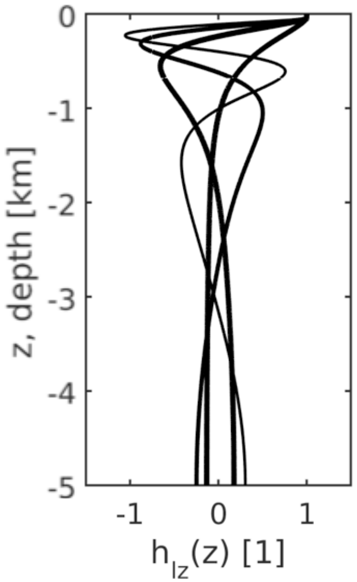


$$\frac{dp_o}{dz}+(\tilde{\rho}+\rho_o)g=0$$

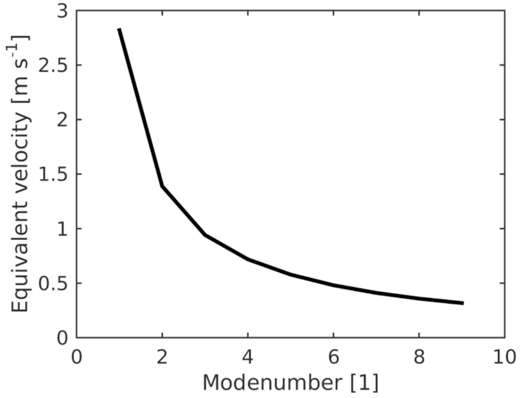
$$N=\sqrt{-\frac{g}{\rho_o}\frac{d}{dz}(\tilde{\rho}+\rho_o)_{pot}}$$

Vertical modes [*Gill,* 1982]

$$\frac{h_{lzz}}{N^2}+\frac{h_l}{c_l^2}=0 \quad \text{with} \quad h_l(-H)=h_l(0)=0$$



eigenspeed $\propto 1/l$

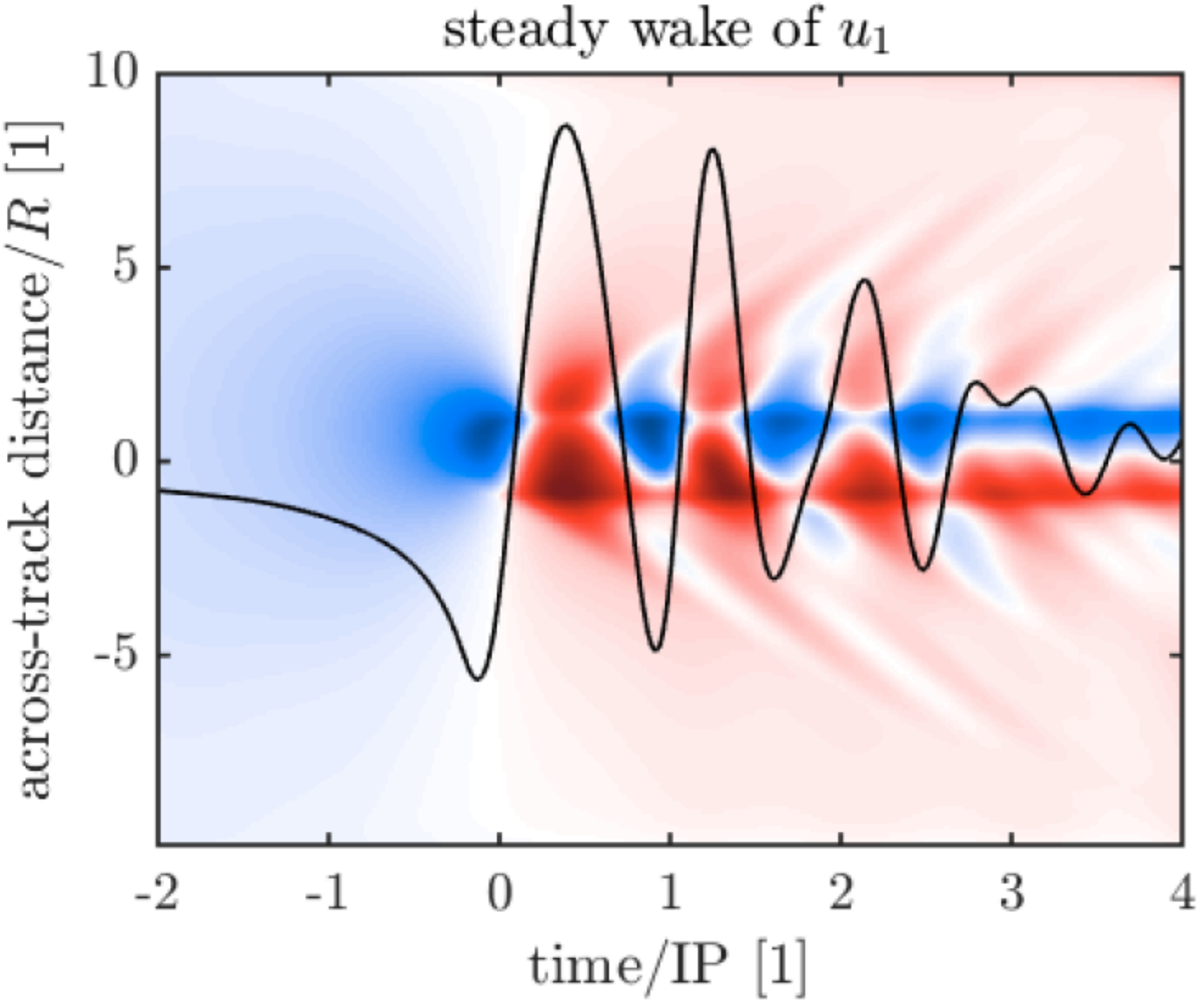


$$w=\sum_{l=1}^{+\infty} w_l h_l,$$

$$[u,v,p/\rho_o,\sigma]=\sum_{l=1}^{+\infty}[u_l,v_l,p_l,\sigma_l]h_{lz},$$

$$-\rho/\rho_o=\sum_{l=1}^{+\infty}\eta_l h_{lzz}, \qquad r_l=g\eta_l/c_l$$

The wake (first mode)



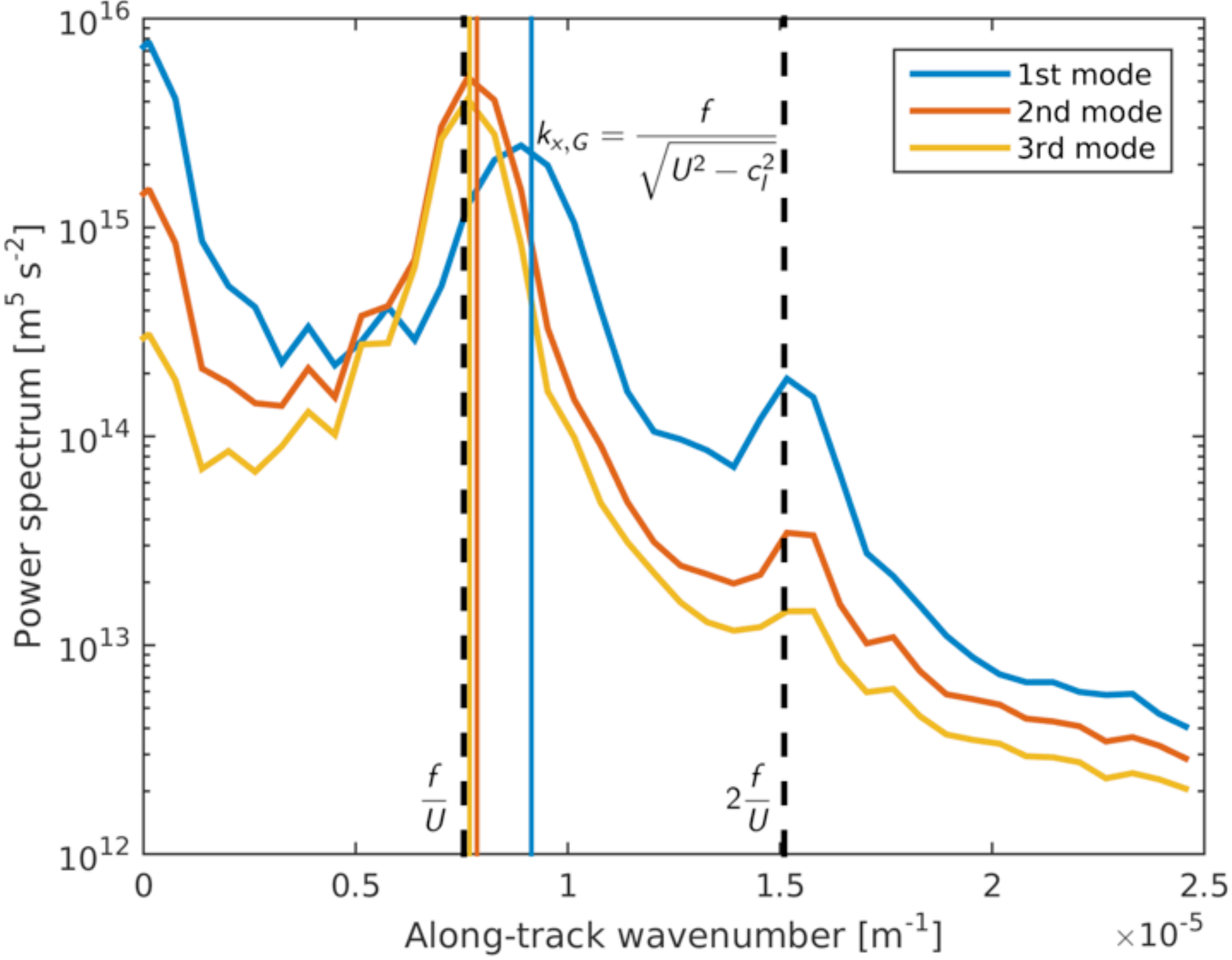
Power spectra

The solution is steady in the frame of reference of the storm

$$\omega = -k_x U$$

NEAR INERTIAL

DOUBLE INERTIAL



1st and 2nd mode are nearly equally energetic.

Far from the wind forcing region, double inertial peaks dominate.

Linear solution

Power spectrum equation:

$$\hat{F}(k_x, k_y) = \frac{1}{2\pi} \iint_{-\infty}^{+\infty} \mathrm{d}x\mathrm{d}y \, F(x + Ut, y) \mathrm{e}^{-i[k_x(x+Ut)+k_y y]}$$

$$\begin{bmatrix} ik_x U & -f & ik_x c_l \\ f & ik_x U & ik_y c_l \\ ik_x c_l & ik_y c_l & ik_x U \end{bmatrix} \begin{pmatrix} \hat{u}_l \\ \hat{v}_l \\ \hat{r}_l \end{pmatrix} = \begin{pmatrix} \hat{\tau}_l^x \\ \hat{\tau}_l^y \\ 0 \end{pmatrix}$$

$$A\mathbf{x} = \mathbf{b} \Rightarrow \mathbf{x} = A^{-1}\mathbf{b}$$

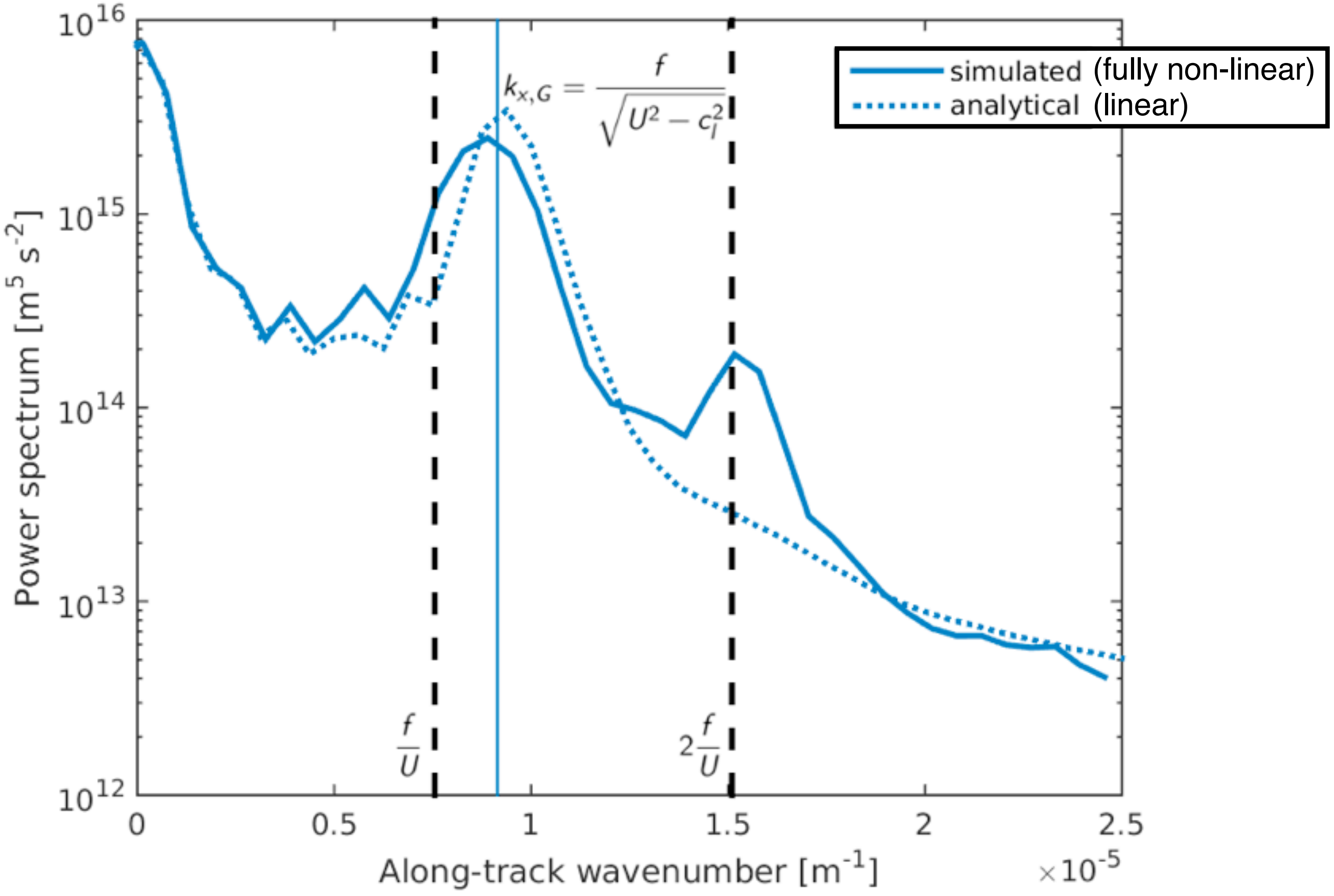
$$\hat{E}_l(k_x, k_y) = \frac{1}{2}(|\hat{u}_l|^2 + |\hat{v}_l|^2 + |\hat{r}_l|^2) = \frac{1}{2}(\mathbf{x}^{*T}\mathbf{x}) = \boxed{\frac{1}{2}(\mathbf{b}^{*T}(-AA)^{-1}\mathbf{b})} = \Psi_l^0$$

Spectral features

The solution is steady in the frame of reference of the storm $\omega = -k_x U$

NEAR INERTIAL

DOUBLE INERTIAL



Non linear advection terms

Occ@m

$$\left(u\frac{\partial}{\partial x}+v\frac{\partial}{\partial y}+w\frac{\partial}{\partial z}\right)u=-\sum_{l,m,n}h_{lz}\mathcal{U}_{nml}$$

with

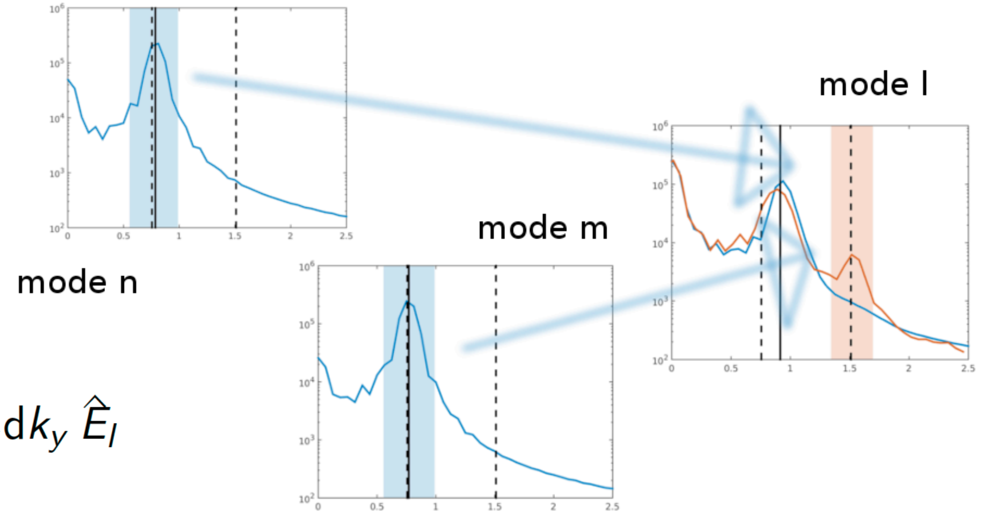
$$\mathcal{U}_{nml}=\left[\alpha_{nml}\left(u_n\frac{\partial}{\partial x}+v_n\frac{\partial}{\partial y}\right)+\beta_{nml}\left(\frac{\partial u_n}{\partial x}+\frac{\partial v_n}{\partial y}\right)\right]u_m$$

$\alpha_{nml}, \beta_{nml}$ geometrical coefficients that impose the triangle condition $l=|m\pm n|$ strictly if $N=const.$

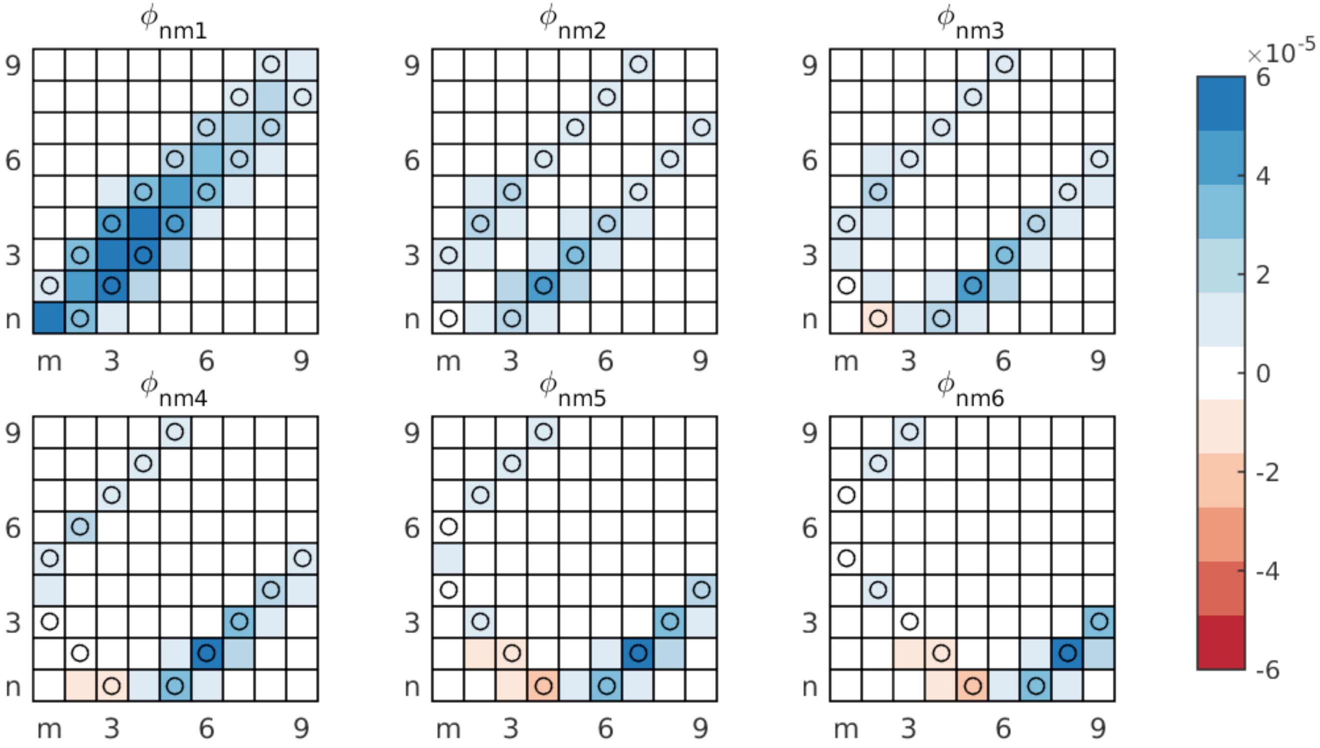
$$\begin{bmatrix} ik_xU & -f & ik_xc_l \\ f & ik_xU & ik_yc_l \\ ik_xc_l & ik_yc_l & ik_xU \end{bmatrix}\begin{pmatrix}\hat{u}_l\\ \hat{v}_l\\ \hat{r}_l\end{pmatrix}=\begin{pmatrix}\hat{\tau}_l^x\\ \hat{\tau}_l^y\\ 0\end{pmatrix}+\sum_{n,m}^{+\infty}\begin{pmatrix}\hat{\mathcal{U}}_{nml}\\ \hat{\mathcal{V}}_{nml}\\ \hat{\mathcal{R}}_{nml}\end{pmatrix}$$

$$\Rightarrow\boxed{\hat{E}_l=\Psi_l^0+\sum_{n,m}^{+\infty}\Psi_{nml}^1}$$

Energy transfer coefficients

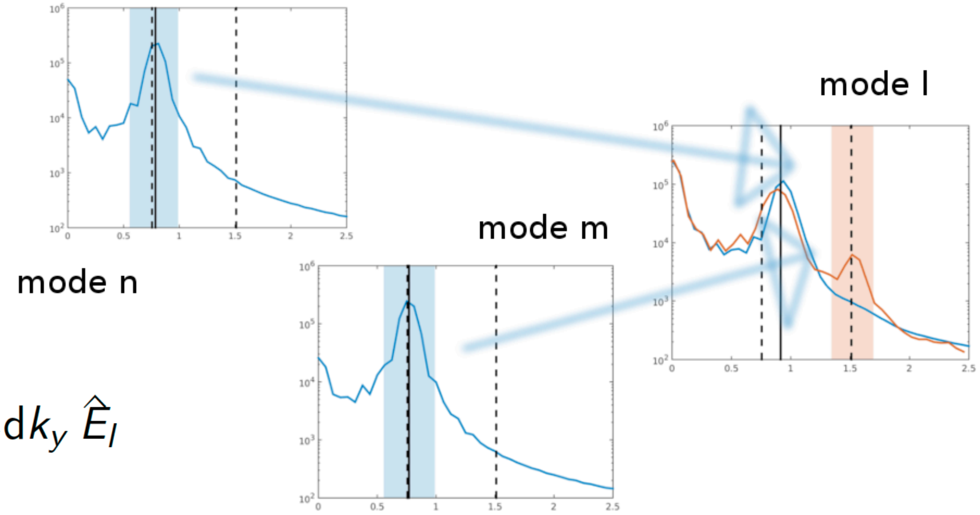


$$\phi_{nml} = \int_{2f/U-\Delta}^{2f/U+\Delta} \mathrm{d}k_x \left\{ \int_{-\infty}^{+\infty} \mathrm{d}k_y \, \Psi^1_{nml} \right\} \Big/ \iint_{-\infty}^{+\infty} \mathrm{d}k_x \mathrm{d}k_y \, \hat{E}_l$$

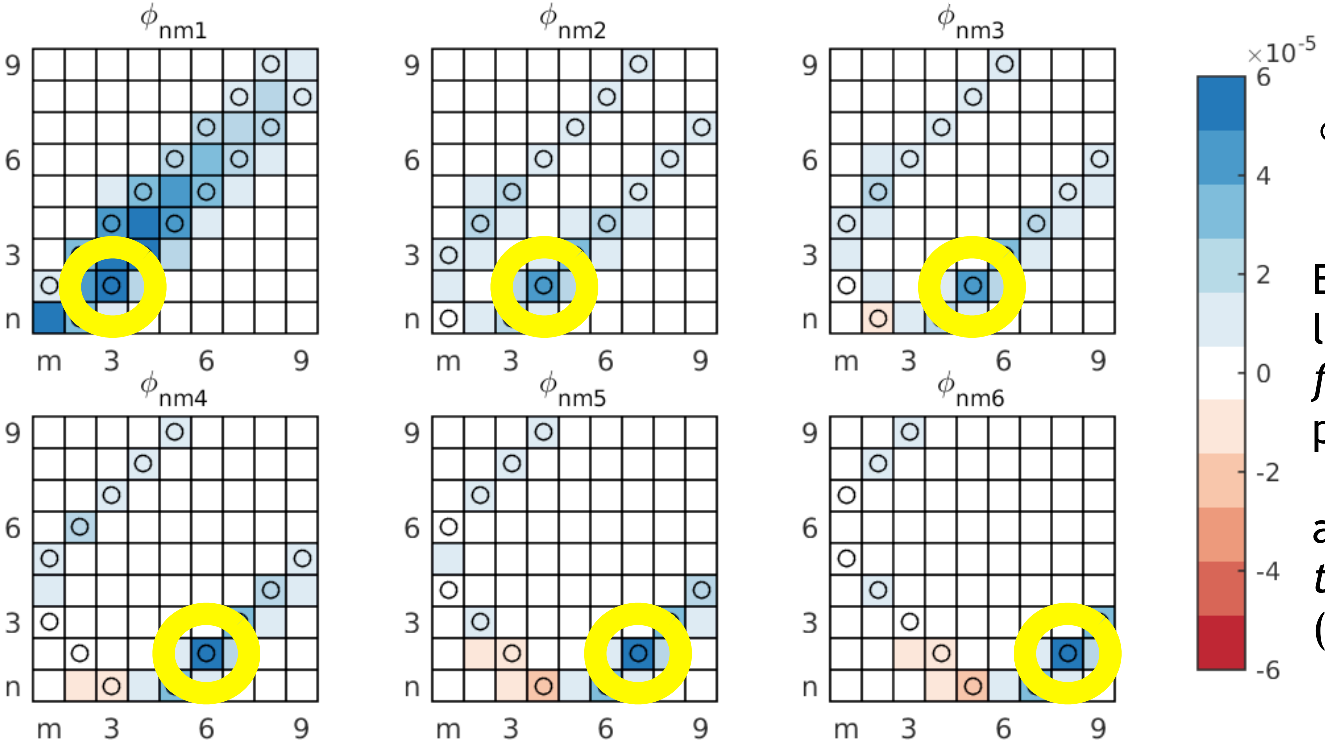


○ $|n \pm m| = l$

Energy transfer coefficients



$$\phi_{nml} = \int_{2f/U-\Delta}^{2f/U+\Delta} \mathrm{d}k_x \left\{ \int_{-\infty}^{+\infty} \mathrm{d}k_y\, \Psi^1_{nml} \right\} \Big/ \iint_{-\infty}^{+\infty} \mathrm{d}k_x \mathrm{d}k_y\, \hat{E}_l$$



○ $|n \pm m| = l$

$n = 2$

$m = l + 2$

Energy is transferred from low frequency *to higher frequencies* (poleward propagation becomes possible)

and from higher mode numbers *to lower mode numbers* (faster propagation speed)

Conclusions

Locally, tropical cyclones on the short term (hours and days) cool the ocean, but on the long term they warm the ocean (on average, their effect is a fraction of a petawatt).

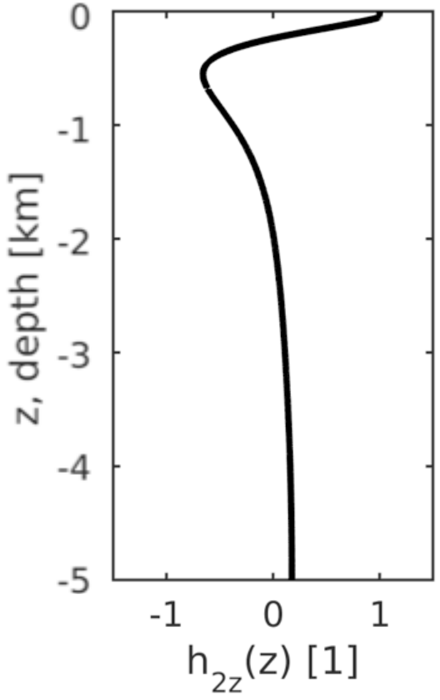
Far away from tropical cyclone location, wind induced waves break and mix the waters:

- locally, near inertial waves are generated; all vertical modes are excited;

- energy is transferred to double inertial frequencies of mode 1 and 2 (most energetic) from near inertial frequencies of same or higher modes (this increases propagation speed of disturbances);

- mode 2 is the most important “advecting mode”: non-linear interactions are important in the mixed layer and in the thermocline;

- parametric subharmonic instability (PSI) efficiently transfers energy to high wave numbers where energy gets dissipated.



[*Wagner and Young, JFM 2017*]

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