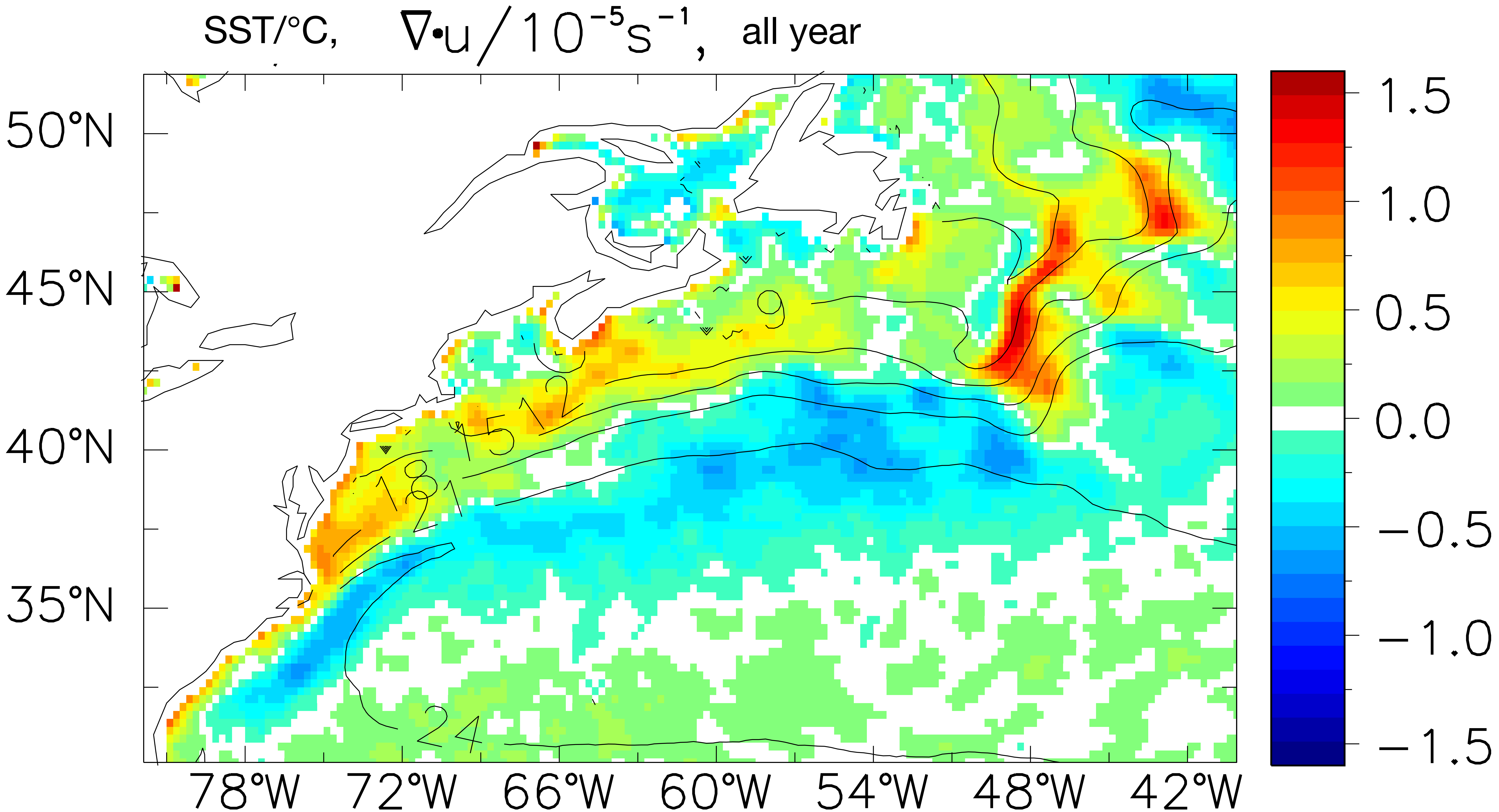
Mesoscale and Frontal-Scale Air-Sea Interactions Workshop, Boulder, CO, March 6-8, 2023

The Gulf Stream Convergence Zone

Niklas Schneider[1], Ryusuke Masunaga[2], Larry O'Neill[3], Bruce Cornuelle[4], Thomas Kilpatrick[4], Masami Nonaka[2], Justin Small[5], Shang-Ping Xie[4]
[1]University of Hawai`i at Mānoa , [2]Japan Agency for Marine-Earth Science and Technology, [3]Oregon State University, [4]Scripps Institution of Oceanography, [5]National Center for Atmospheric Research



QuikSCAT winds (o'Neill et al. 2017), AMSR-E sea surface temperatures, 2003-2008

- mean wind divergence dipole, divergence on cold, convergence on warm flanks of Gulf Stream (O'Neill et al. 2017)
- AGCMs require forcing by mesoscale Gulf Stream sea surface temperature front to simulate the Gulf Stream Convergence Zone (e.g. Minobe et al. 2008, Kuwano-Yoshida et al. 2010, Small et al. 2014)

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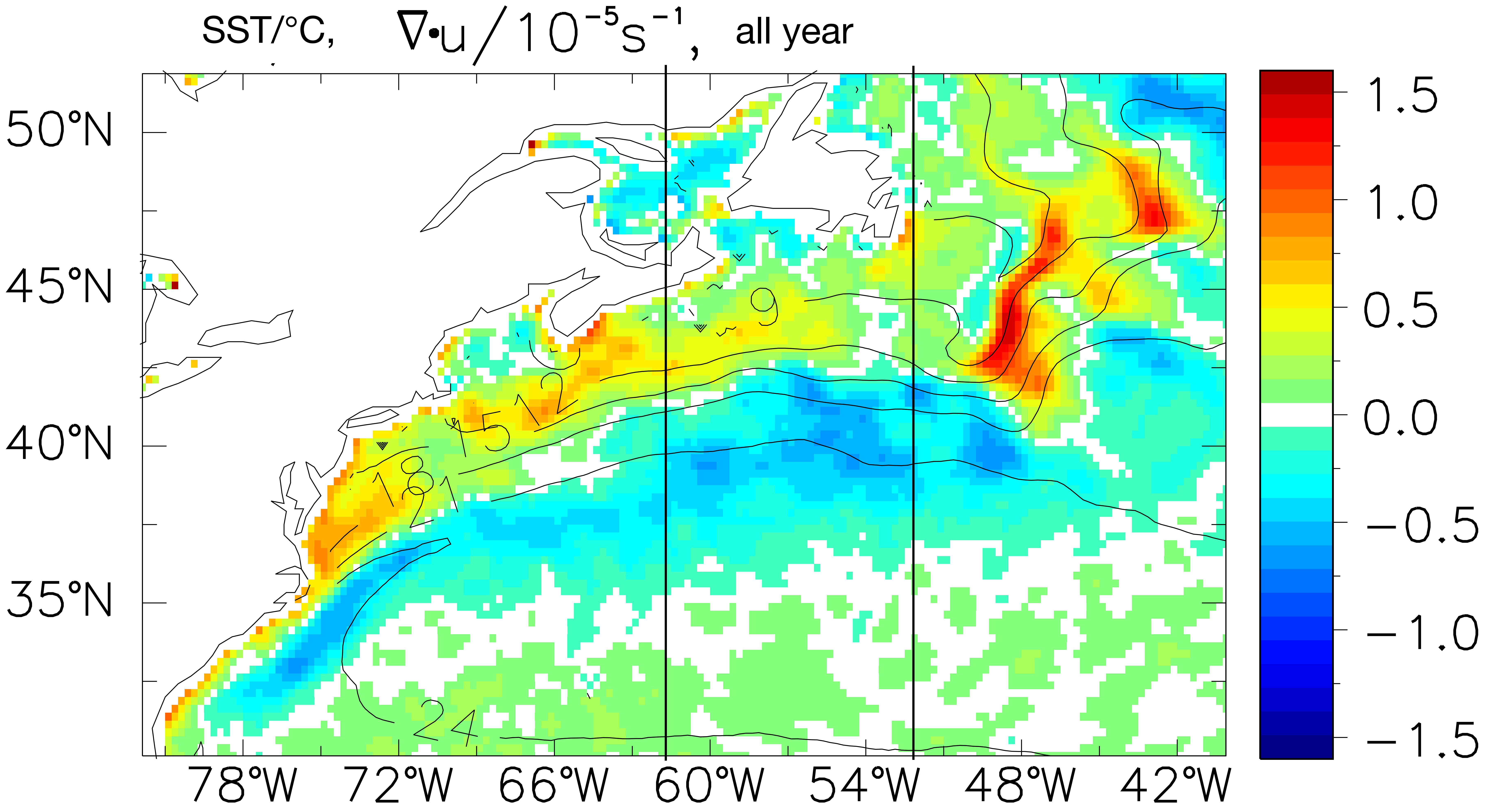

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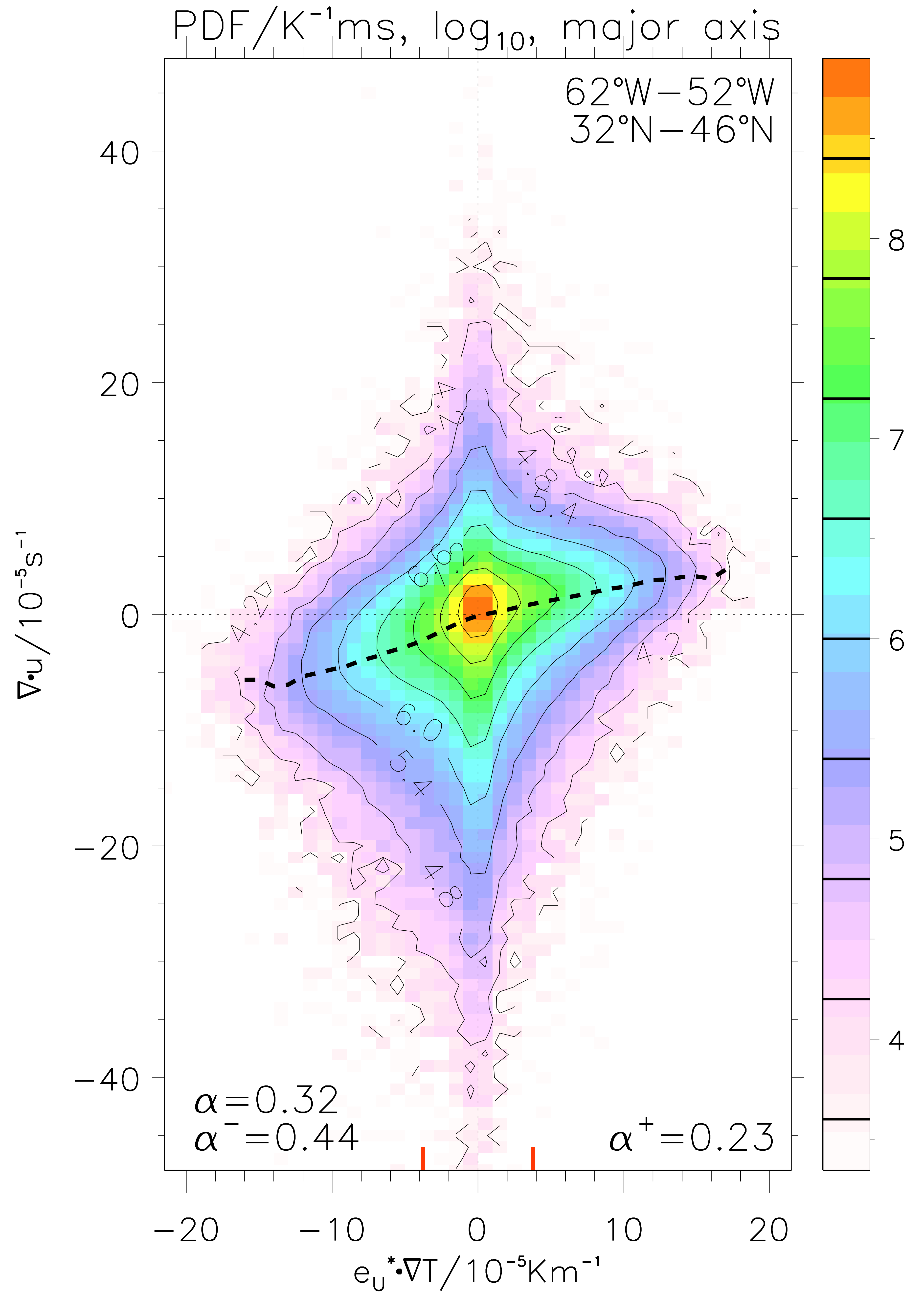
Impacts of storm track and sea surface temperatures



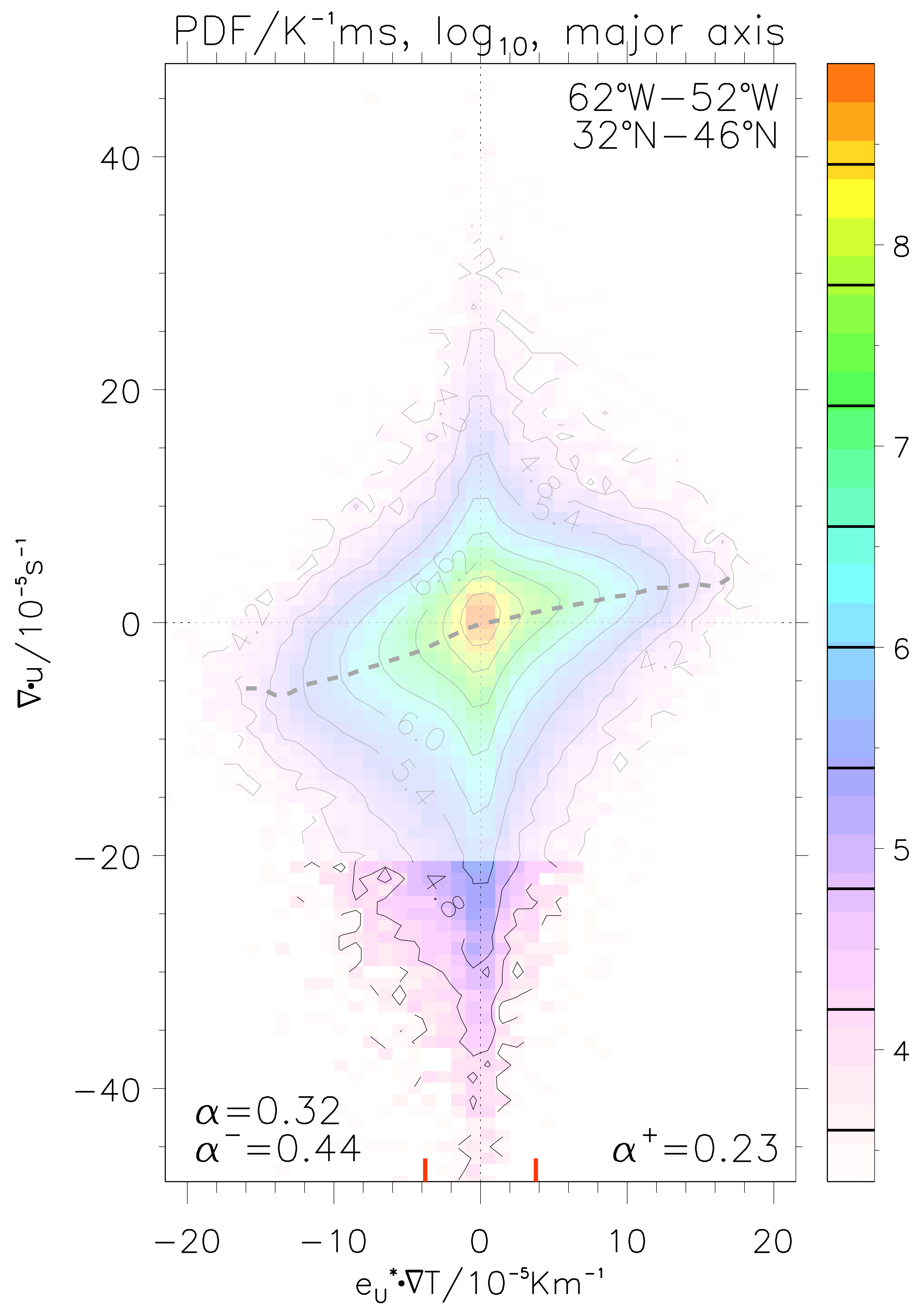
QuikSCAT and AMSR-E observations
32°N-46°N, 62°E-52°E
2003-2008, daily

Time average surface wind divergence:

- of order of $0.5 \cdot 10^{-5} s^{-1}$
- a tiny residual of wind divergence due to
  - synoptic winds from warm to cold and cold to warm surface temperatures (Chelton et al. 2001)
  - mid-latitude cyclones and atmospheric fronts (e.g. O'Neill et al. 2017, Masunaga el al. 2020a,b)
- same size as difference of median and mean of negatively skewness distribution (Small et al. 2023)

Impacts of mesoscale sea surface temperatures extend to large-amplitude surface wind divergences

Impacts of storm track and sea surface temperatures



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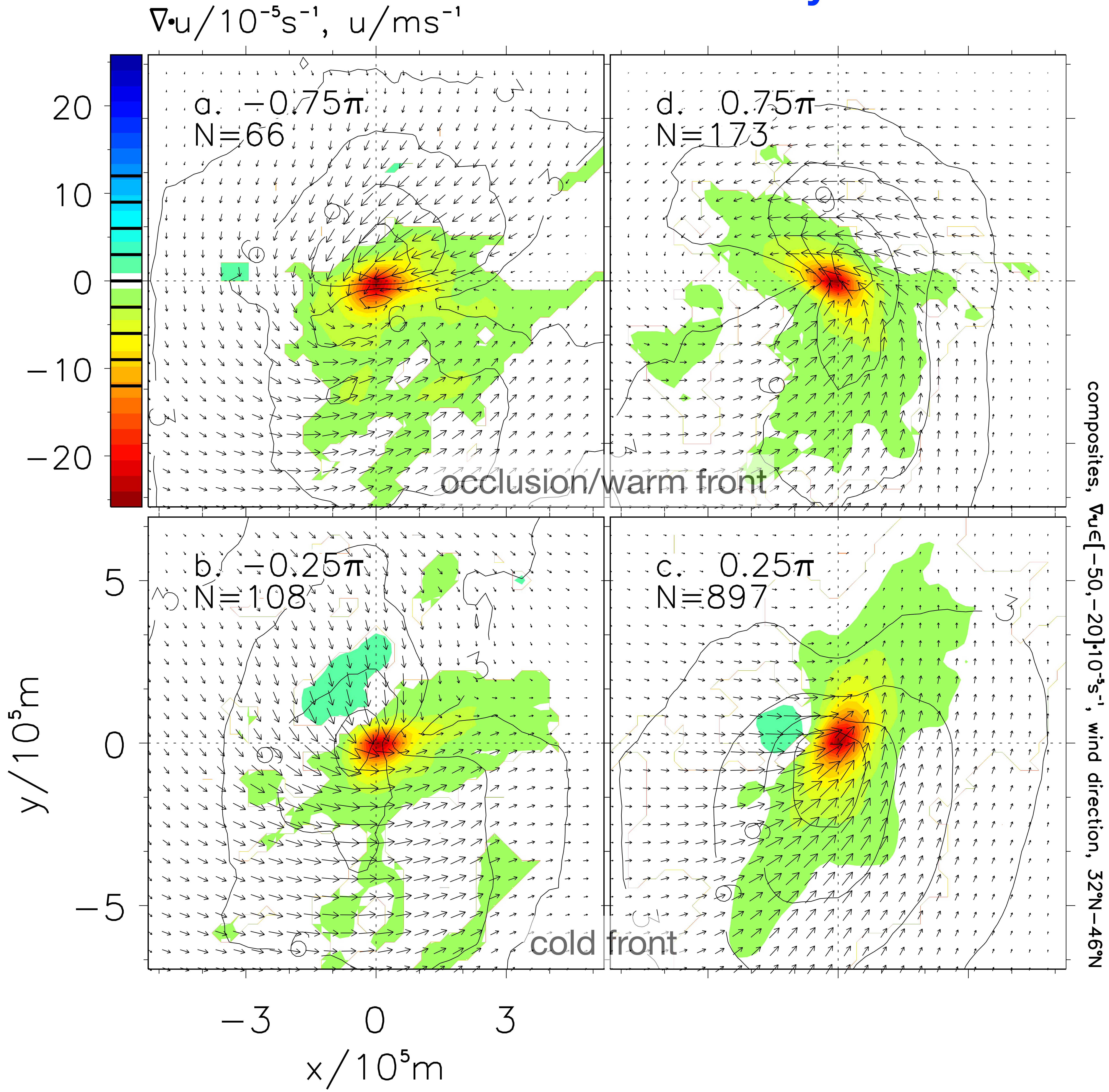
Mid-latitude cyclones and fronts



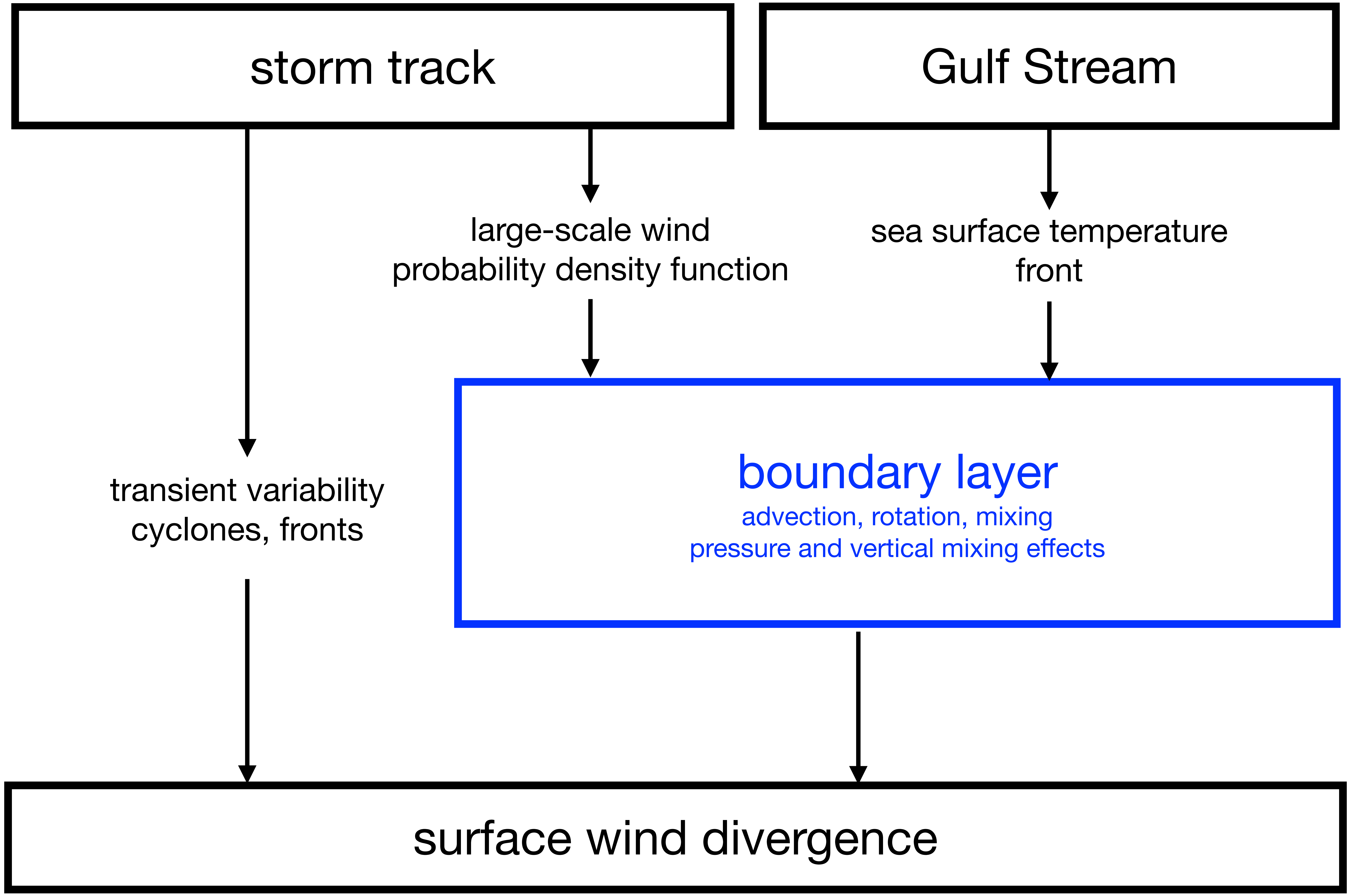
Spatial composites of wind divergence ($10^{-5}s^{-1}$, colors), and of surface winds (vectors) and speeds (ms^{-1}, contours)

At center $(x, y) = 0$:

- surface wind divergence
  $\nabla \cdot \vec{u} < -20 \cdot 10^{-5} s^{-1}$
- surface wind directions within a $\pi/4$ sector of NE, NW, SW and SE

see also O'Neill et al, 2017, Masunaga et al. 2020a,b

Hypothesis for Gulf Stream Convergence Zone

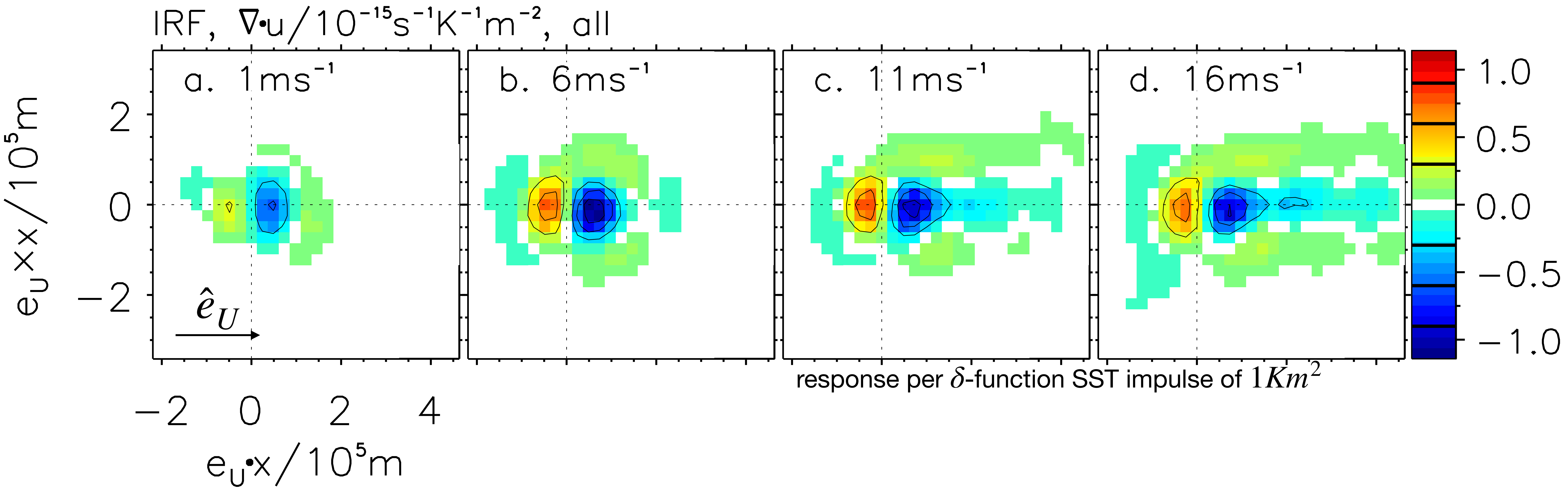


Boundary layer

Impulse response function (Schneider 2020, Masunaga and Schneider 2021)

$$\nabla \cdot \vec{u}(\vec{x}) = \int d\vec{x}' \cdot \hat{e}_3 \;\; A\left(\vec{x}', \hat{e}_U, U\right) \;\; T(\vec{x} - \vec{x}')$$

Ansatz consistent with linear theory (Schneider and Qiu JAS 2015)
QuikSCAT equivalent neutral winds (O'Neill et al. JC 2017)
AMSR-E sea surface temperatures
Gulf Stream 30°N-52°N, 68°E-46°E, 2003-2008 daily
scales < 1000km

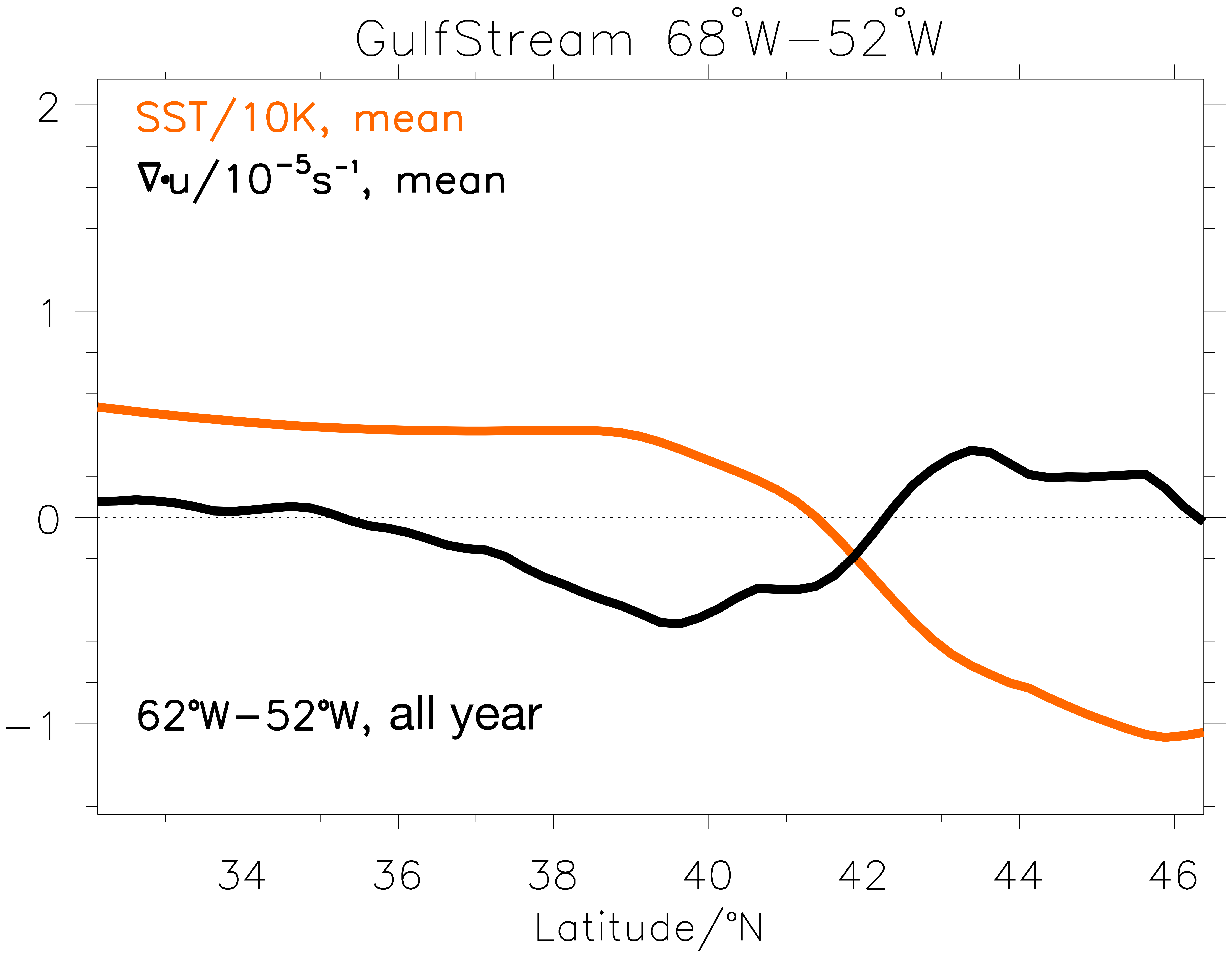


response per δ-function SST impulse of $1Km^2$

Damped, doppler-shifted, near-inertial lee-wave, in response to changes of vertical mixing and hydrostatic pressure associated with the plume of warm air downwind of the SST perturbation (Schneider JAS 2020)

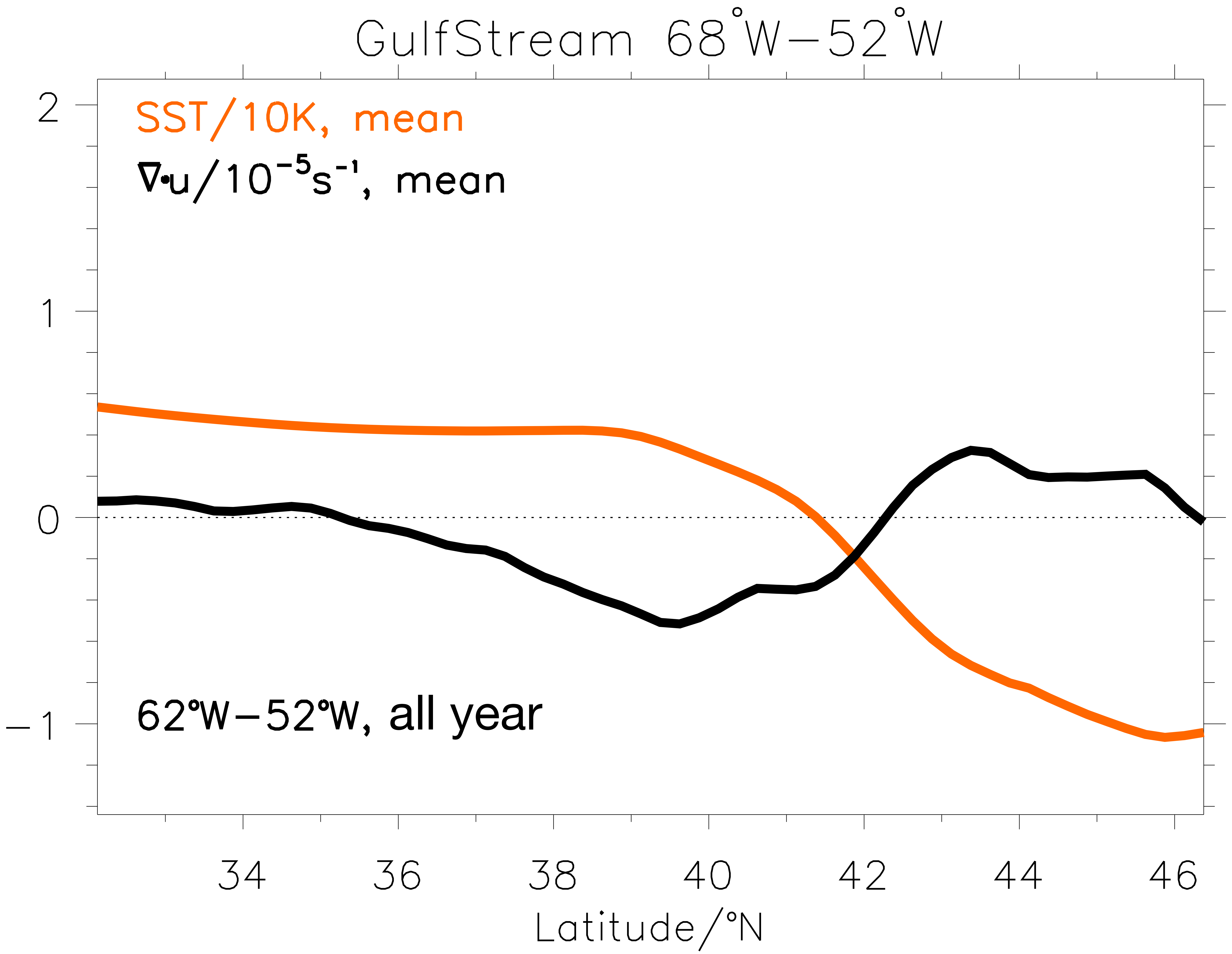
Time mean, zonal Gulf Stream front

$$\nabla \cdot \vec{u}(\vec{x}) = \int d\vec{x}' \cdot \hat{e}_3 \; A\left(\vec{x}', \hat{e}_U, U\right) \; \overline{T}_{GulfStr}(\vec{x} - \vec{x}') \; + \; \textbf{transients}$$



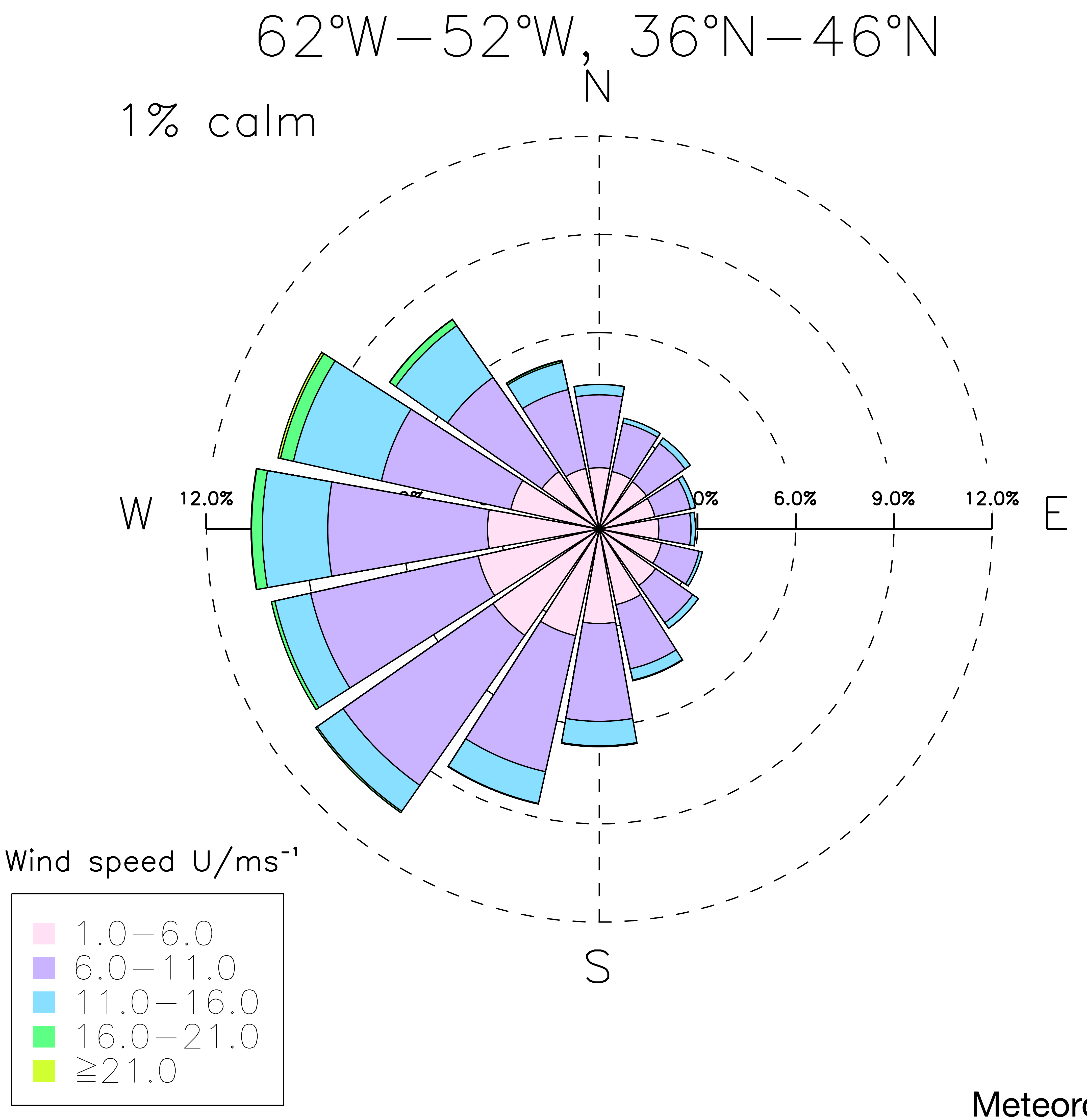
Time mean, zonal Gulf Stream front

$$\overline{\nabla \cdot \vec{u}(\vec{x})} = \int d\vec{x}' \cdot \hat{e}_3 \; \overline{A\left(\vec{x}', \hat{e}_U, U\right)} \; \overline{T}_{GulfStr}(\vec{x} - \vec{x}') + \overline{\textbf{transients}}$$



Large-scale winds

$$\overline{A}(\vec{x}') = \int d\hat{e}_U \, dU \, A\left(\vec{x}', \hat{e}_U, U\right) \; p(\hat{e}_U, U)$$



QuikSCAT equivalent neutral winds

O'Neill et al. 2017

2003-2008 daily

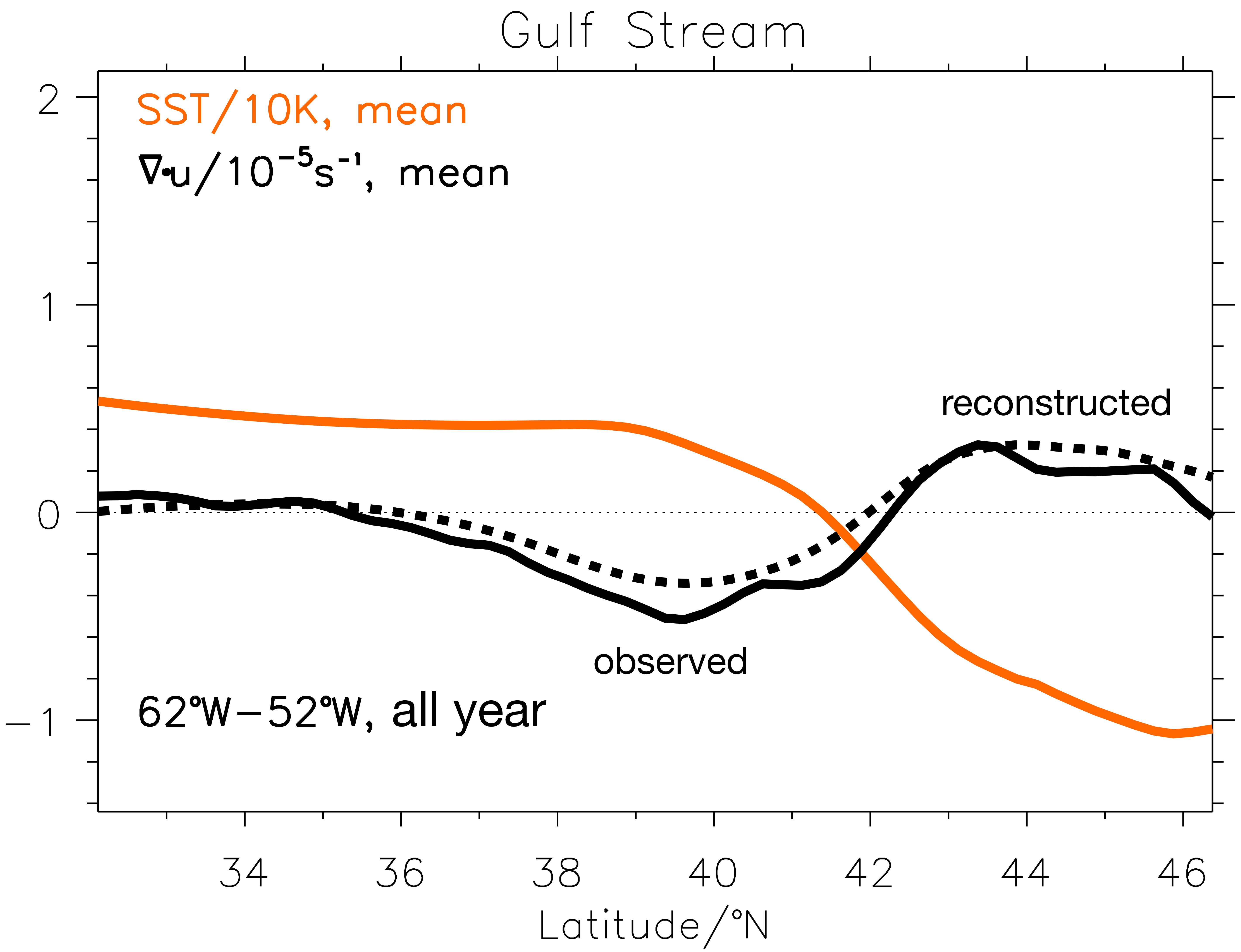
Gulf Stream 30°N-52°N, 68°E-46°E

scales > 1000km

Meteorological convention: where winds are coming from

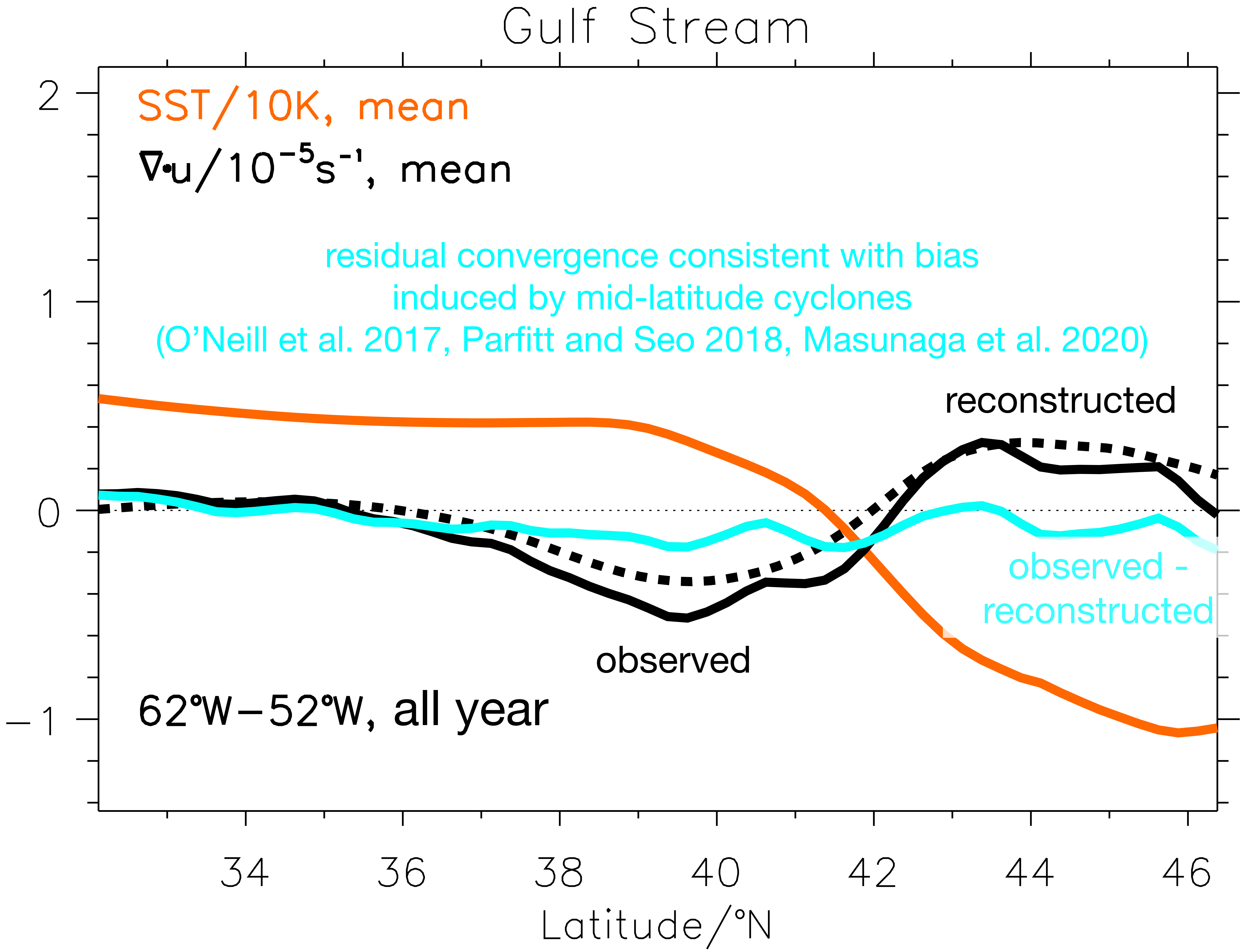
Time mean, zonal Gulf Stream front

$$\overline{\nabla \cdot \vec{u}(\vec{x})} = \int d\vec{x}' \cdot \hat{e}_3 \, \overline{A}(\vec{x}') \, \overline{T}_{GulfStr}(\vec{x} - \vec{x}') + \overline{\textbf{transients}}$$



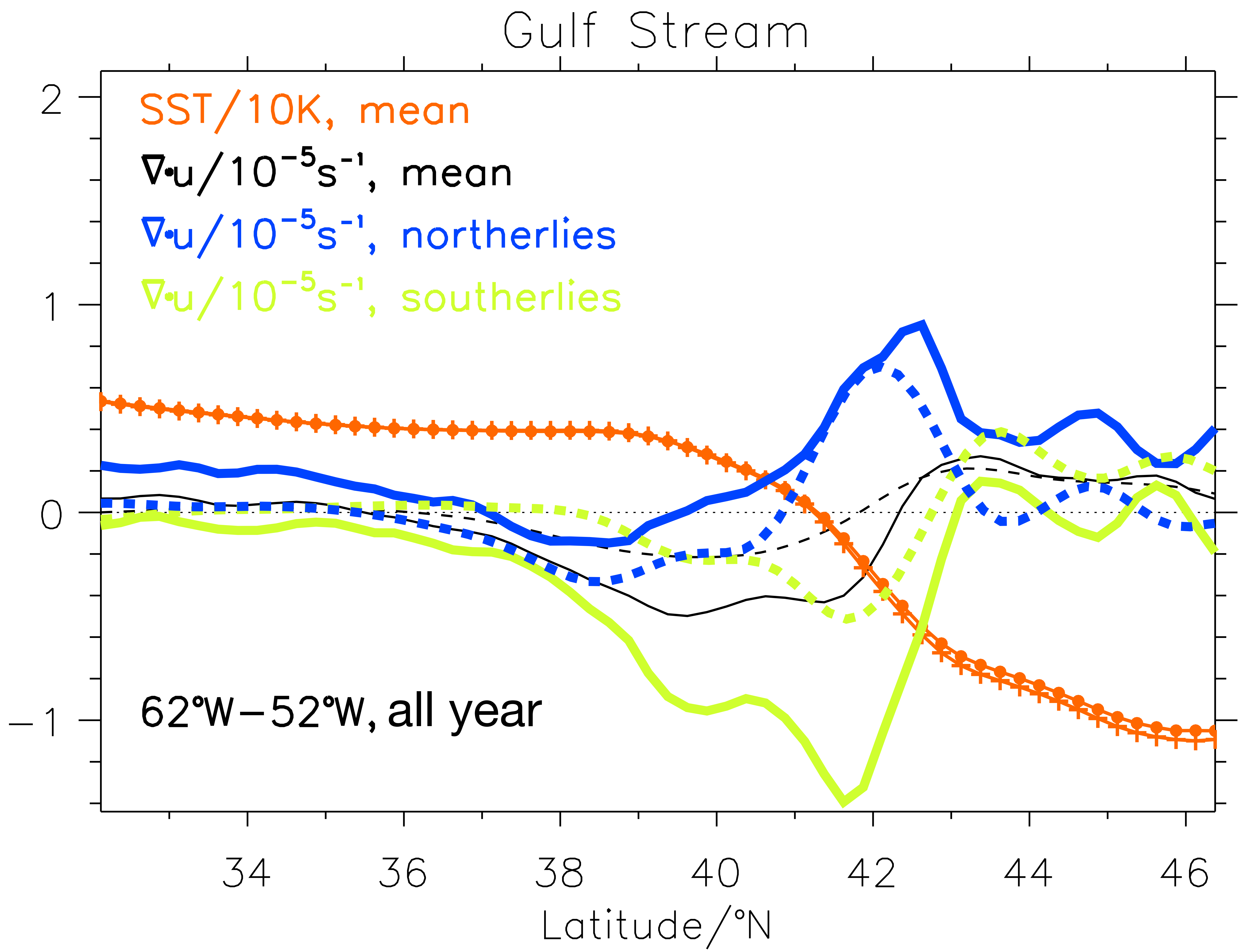
Time mean, zonal Gulf Stream front

$$\overline{\nabla \cdot \vec{u}(\vec{x})} = \int d\vec{x}' \cdot \hat{e}_3 \, \overline{A}(\vec{x}') \, \overline{T}_{GulfStr}(\vec{x} - \vec{x}') + \overline{\text{transients}}$$



Winds from cold to warm/warm to cold

Averages $\overline{\nabla \cdot \vec{u}}$ conditioned by sign of $\hat{e}_U \cdot \nabla \overline{T}_{GulfStr}$



solid: observed
dashed: reconstructed

surface temperatures for
● northerlies
+ southerlies

Conclusions

The Gulf Stream Convergence Zone results from

- cyclones and fronts associated with the storm track

and from aggregated responses of the atmospheric boundary layer to

- the sea surface temperature front
- large-scale winds associated with the storm track

A reconstruction of the surface wind divergence recovers

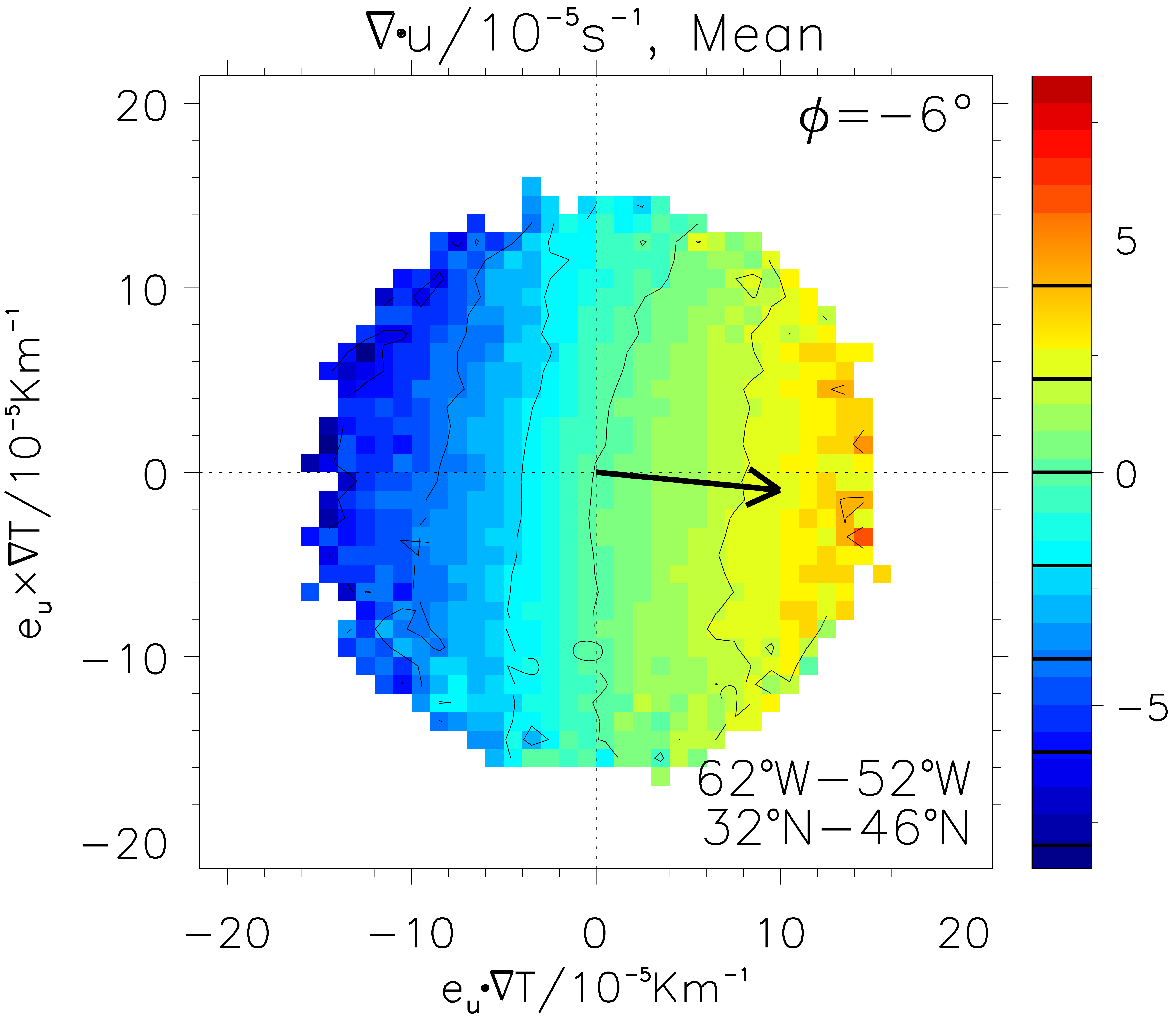
- the mean surface wind divergence dipole
- residuals consistent with cyclones and fronts
- conditional averages as a function of wind direction
- *sensitivities to sharpness of the Gulf Stream sea surface temperature front (not shown)*
- *emergence of pressure effect for averages over time scales longer than ~10 days (not shown)*

Implications and limitations

- nonlocal approach captures linear/first order dynamics
  both vertical mixing and pressure effects are involved
  transient winds organize boundary layer responses (e.g. Foussard et al 2019, Masunaga et al. 2020)
- averages combine boundary layer processes, large-scale wind probability density functions and geometry of sea surface temperatures
- *Ansatz* only captures linearized responses of boundary layer height, precipitation and winds
- feedbacks to large-scale & transient winds relegated to higher order dynamics (e.g. Czaja et al. 2019, Seo et al. 2023)

Extra Slides

$$\overline{\nabla \cdot \vec{u}}\left(\hat{e}_U \cdot \nabla T,\ \ (\hat{e}_U \times \hat{e}_U) \cdot \nabla T\right)$$



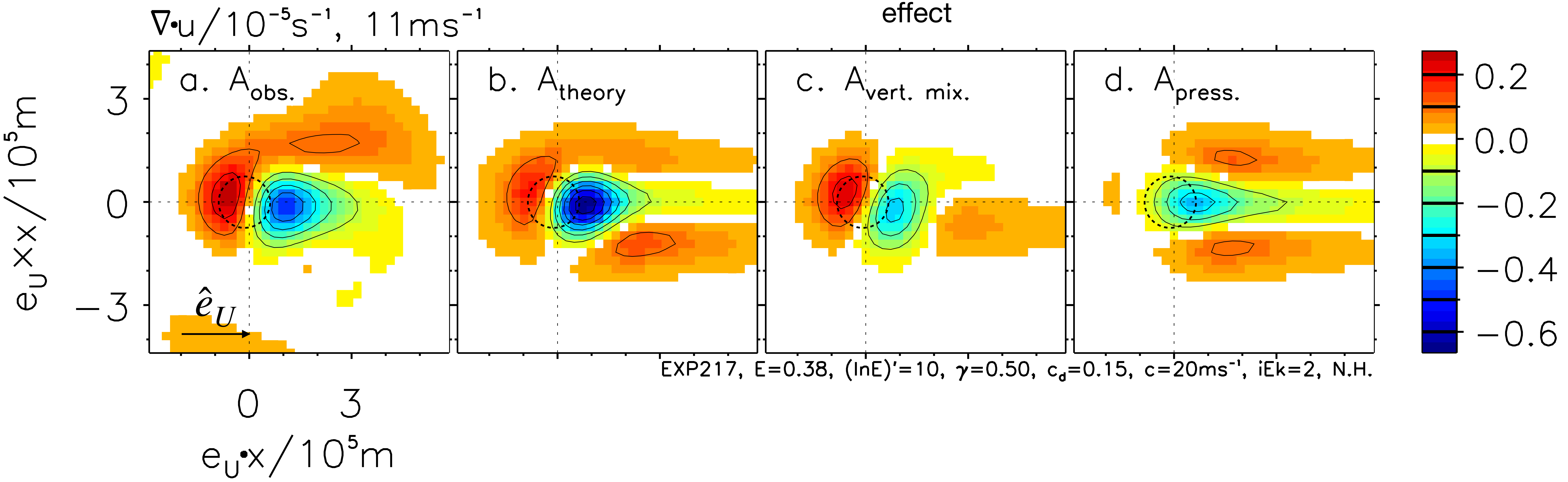
Comparison with theory

Schneider and Qiu, JAS, 2015; Schneider, JAS, 2020

Surface wind divergence response to a Gaussian SST monopole

$$\nabla \cdot \vec{u}(\vec{x}) = \int d\vec{x}' \cdot \hat{e}_3 \, A\left(\vec{x}', \hat{e}_U, 11ms^{-1}\right) \; 1K \, e^{-\frac{(\vec{x}-\vec{x}')\cdot(\vec{x}-\vec{x}')}{2\cdot(75km)^2}}$$

A observed — *A* theory = *A* vertical mixing effect + *A* pressure effect



Doppler-shifted, damped, near-inertial lee-wave, in response to vertical mixing and pressure effects in the plume of warm air downwind of the SST perturbation

Averaged Impulse Response Functions

$$\overline{A}^{\phi}(\vec{x}') = \int_{\phi} d\hat{e}_U \, dU \, A\left(\vec{x}', \hat{e}_U, U\right) \; p(\hat{e}_U, U)$$