The Gulf Stream Convergence Zone

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- 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)
The Gulf Stream Convergence Zone

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SST/°C, \( \nabla \cdot u \times 10^{-5} \text{s}^{-1} \), all year

QuikSCAT winds (O’Neill et al. 2017), AMSR-E sea surface temperatures, 2003-2008
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 et 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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Impacts of mesoscale sea surface temperatures extend to large-amplitude surface wind divergences
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
  \[ \nabla \cdot \vec{u} < -20 \cdot 10^{-5}\text{s}^{-1} \]

- surface wind directions within a $\pi/4$ sector of NE, NW, SW and SE

see also O'Neil et al, 2017, Masunaga et al. 2020a,b
Hypothesis for Gulf Stream Convergence Zone

storm track

Gulf Stream

large-scale wind probability density function

sea surface temperature front

boundary layer
advection, rotation, mixing pressure and vertical mixing effects

transient variability cyclones, fronts

surface wind divergence
Boundary layer

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

\[ \nabla \cdot \vec{u}(\vec{x}) = \int d\vec{x}' \cdot \hat{e}_3 \cdot A(\vec{x}', \hat{e}_U, U) \cdot T(\vec{x} - \vec{x}') \]

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
scales < 1000km

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

\[ \nabla \cdot \vec{u}(\vec{x}) = \int d\vec{x}' \cdot \hat{e}_3 \ A(\vec{x}', \hat{e}_U, U) \ T_{\text{GulfStr}}(\vec{x} - \vec{x}') + \text{transients} \]
\[ \nabla \cdot \overline{\mathbf{u}(\mathbf{x})} = \int d\mathbf{x}' \cdot \mathbf{\hat{e}}_3 \ A(\mathbf{x}', \mathbf{\hat{e}}_U, U) \ T_{GulfStr}(\mathbf{x} - \mathbf{x}') + \text{transients} \]
Large-scale winds

\[ \overline{A}(\vec{x}') = \int d\hat{e}_U \, dU \, A(\vec{x}', \hat{e}_U, U) \, p(\hat{e}_U, U) \]

62°W–52°W, 36°N–46°N

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

\[ \nabla \cdot \vec{u}(\vec{x}) = \int d\vec{x}' \cdot \hat{e}_3 A(\vec{x}') \ T_{\text{GulfStr}}(\vec{x} - \vec{x}') + \text{transients} \]
Time mean, zonal Gulf Stream front

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

\[ \mathbf{\nabla} \cdot \mathbf{u}(\vec{x}) = \int d\vec{x}' \cdot \hat{e}_3 \bar{A}(\vec{x}') \bar{T}_{\text{GulfStr}}(\vec{x} - \vec{x}') + \text{transients} \]

Gulf Stream

SST/10K, mean
\[ \nabla \mathbf{u}/10^{-5}\text{s}^{-1}, \text{mean} \]

residual convergence consistent with bias induced by mid-latitude cyclones (O’Neill et al. 2017, Parfitt and Seo 2018, Masunaga et al. 2020)

62°W–52°W, all year

observed

reconstructed

observed - reconstructed
Winds from cold to warm/warm to cold

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

![Graph showing surface temperatures for northerlies and southerlies over the Gulf Stream region.](image)
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
\[ \nabla \cdot \vec{u} \left( \hat{e}_U \cdot \nabla T, \ (\hat{e}_U \times \hat{e}_U) \cdot \nabla T \right) \]
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

\[ \bar{A}^\phi(\vec{x}') = \int_{\phi} d\hat{e}_U \, dU \, A(\vec{x}', \hat{e}_U, U) \, p(\hat{e}_U, U) \]