Seasonal Pulsing of the Global Mesoscale Surface Wind Stress and Wind Speed Response to SST

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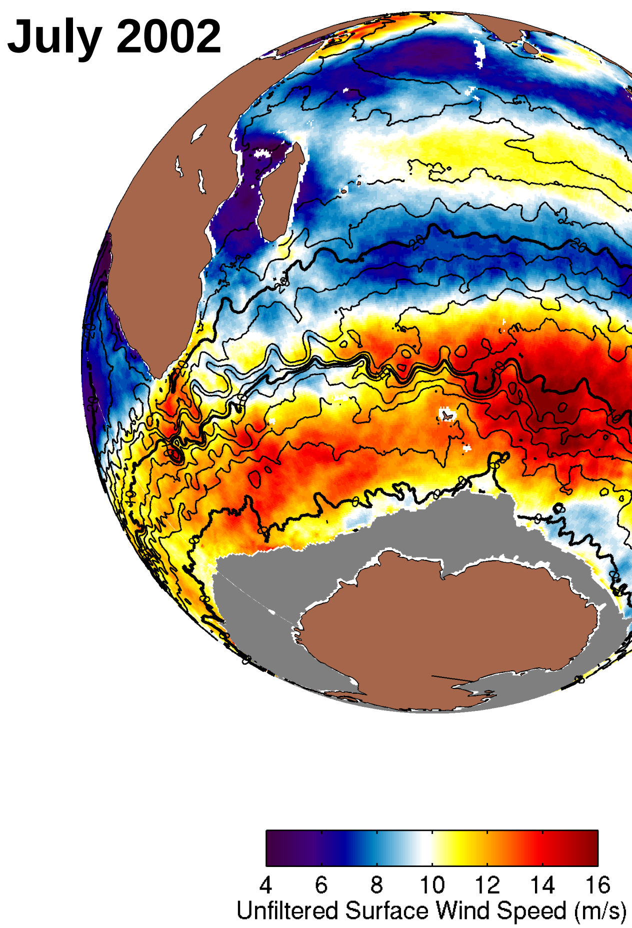
- Relative responses of surface wind stress magnitude and 10-m neutral wind speed to mesoscale SST perturbations from satellite observations
- Analytically relate surface wind stress magnitude perturbations to those of neutral wind speed
- Show that the ambient large-scale wind speed modulates the stress response relative to the wind speed response

Satellite Wind and SST Datasets



QuikSCAT measures the wind speed and direction over most of the ice-free global ocean in near all-weather conditions

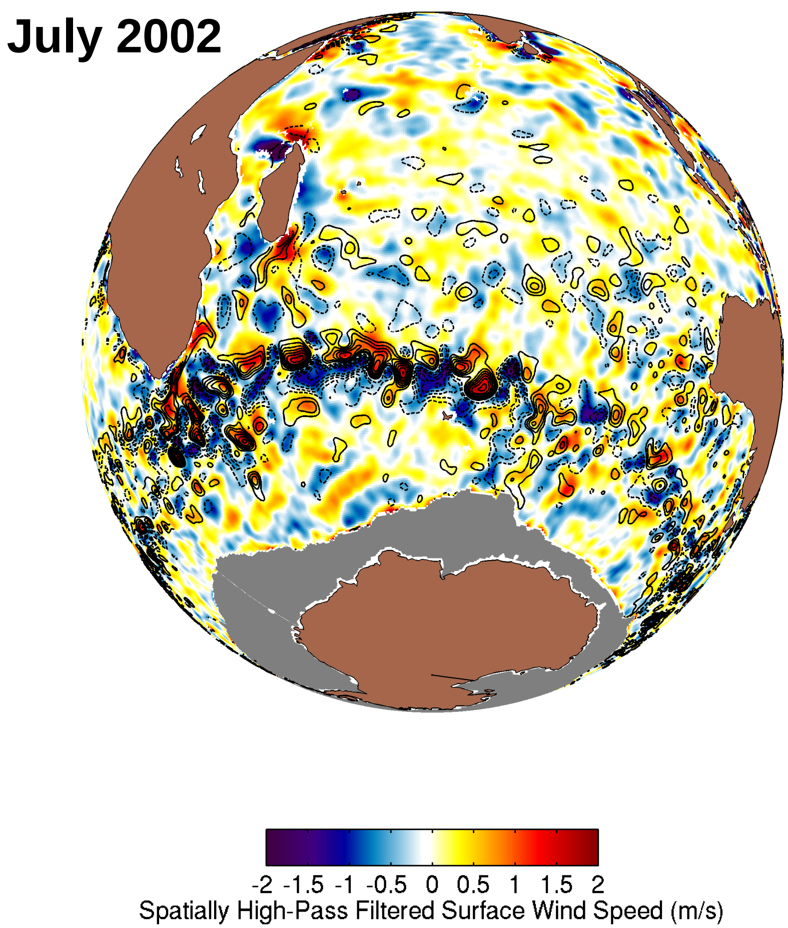
Advanced Microwave Scanning Radiometer on the EOS-Aqua satellite (AMSR-E) has measured SST globally since June 2002

Analyze monthly-averaged satellite data from June 2002 to August 2007

1-month averaged unfiltered wind speed (colors) and SST (contours) for July 2002

SST contour interval is 2℃

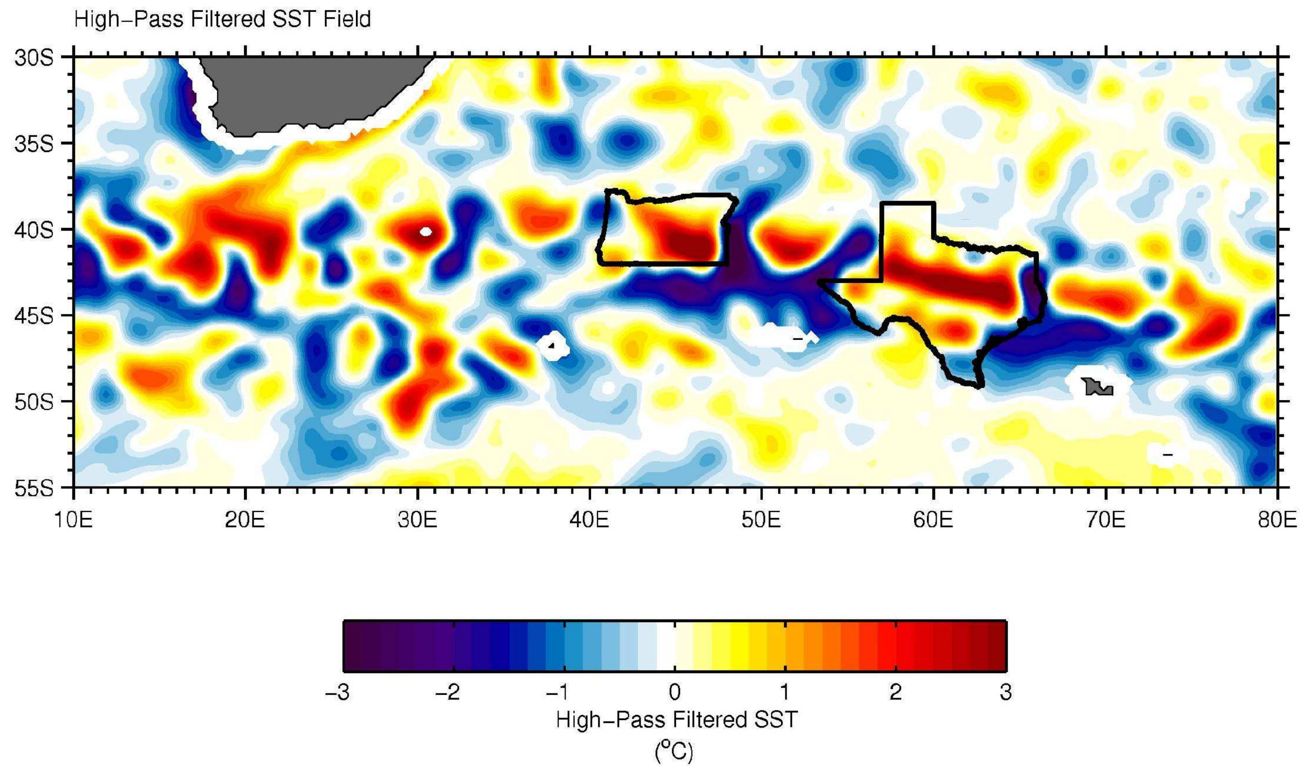
QuikSCAT Neutral Wind Speed (colors) and AMSR-E SST (contours) over the South Indian Ocean



- July 2002 mean spatially high-pass filtered neutral wind speed (colors) and SST (contours)
- Neutral wind speed and SST perturbations are very highly correlated
- Spatial filter removes spatial variability larger than 20° lon by 10° lat

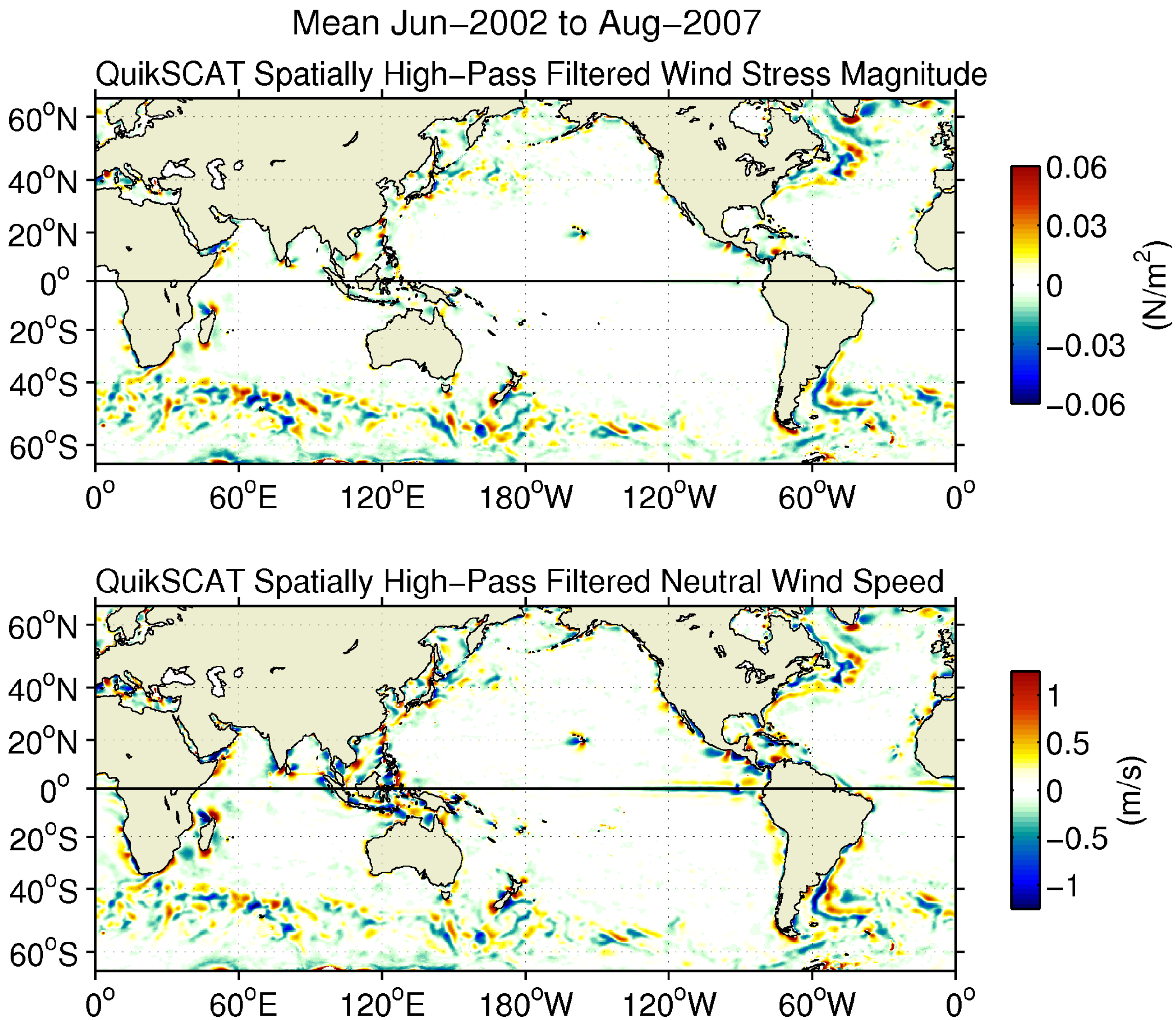
Perturbation SST contour interval is 0.25℃

Relative Size of SST Perturbations

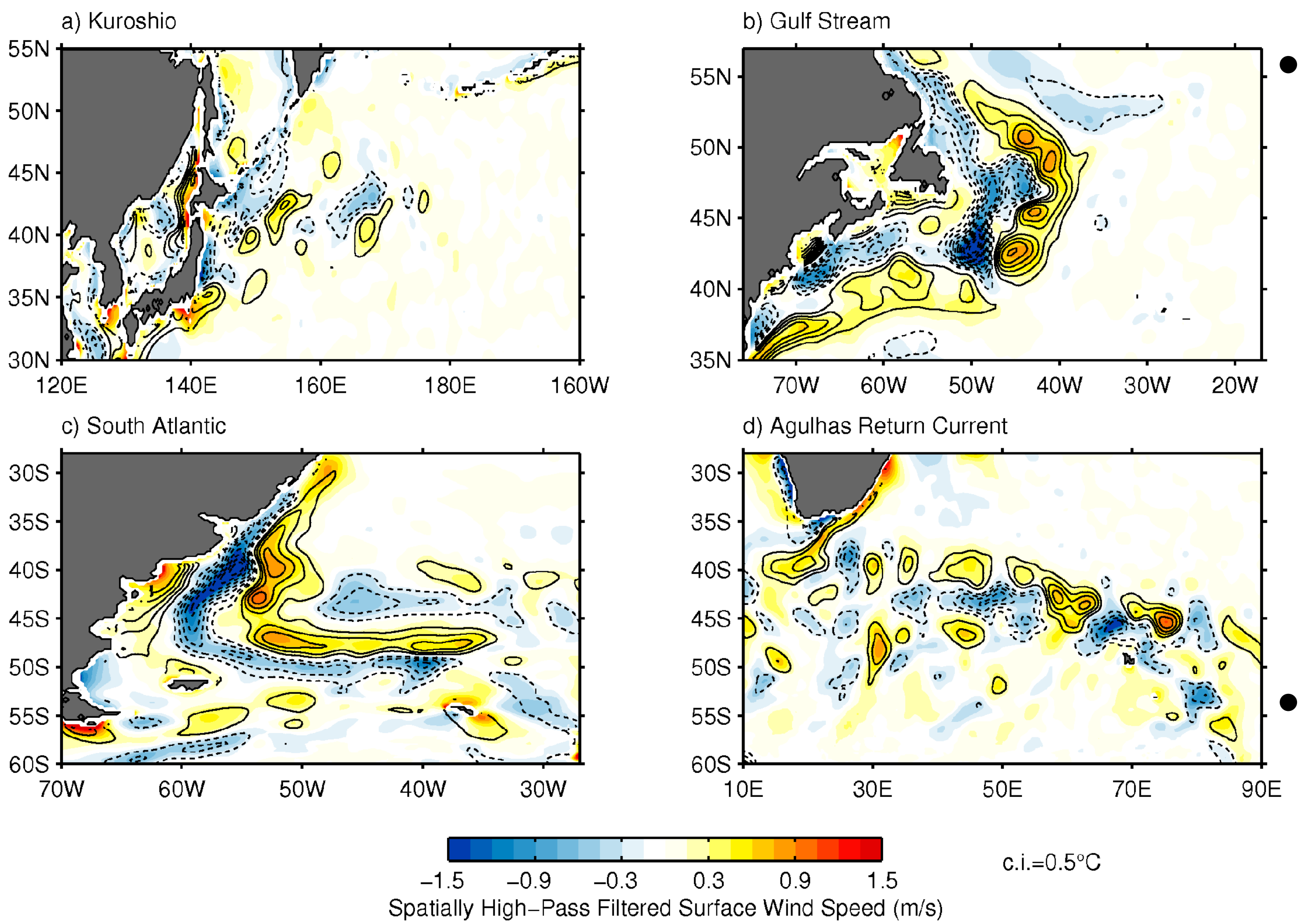


• SST perturbations in this 1-yr average for 2003 are on the order of 100-1000 km across

5-yr Average Spatially High-Pass Filtered QuikSCAT 10-m Neutral Wind Speed



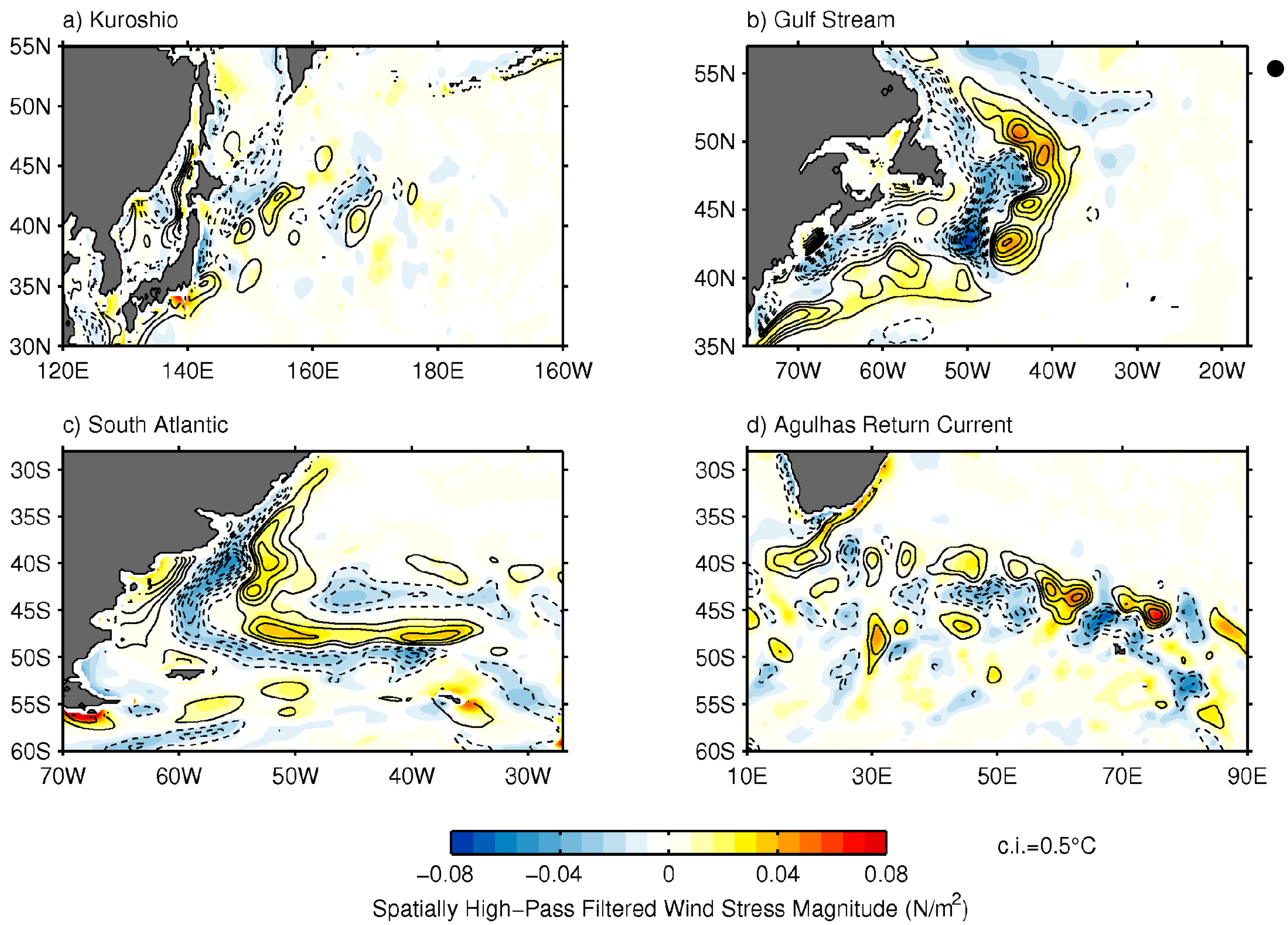
SST-Induced Perturbations of QuikSCAT Neutral Wind Speed (colors) and AMSR-E SST (contours) averaged for 5 years



- On the oceanic mesoscale, neutral wind speed perturbations have a high, positive correlation with those of SST
- Neutral wind speed increases over warm SST perturbations and decreases over cool SST

Contours are spatially high-pass filtered AMSR-E SST with a contour interval of 0.5°C

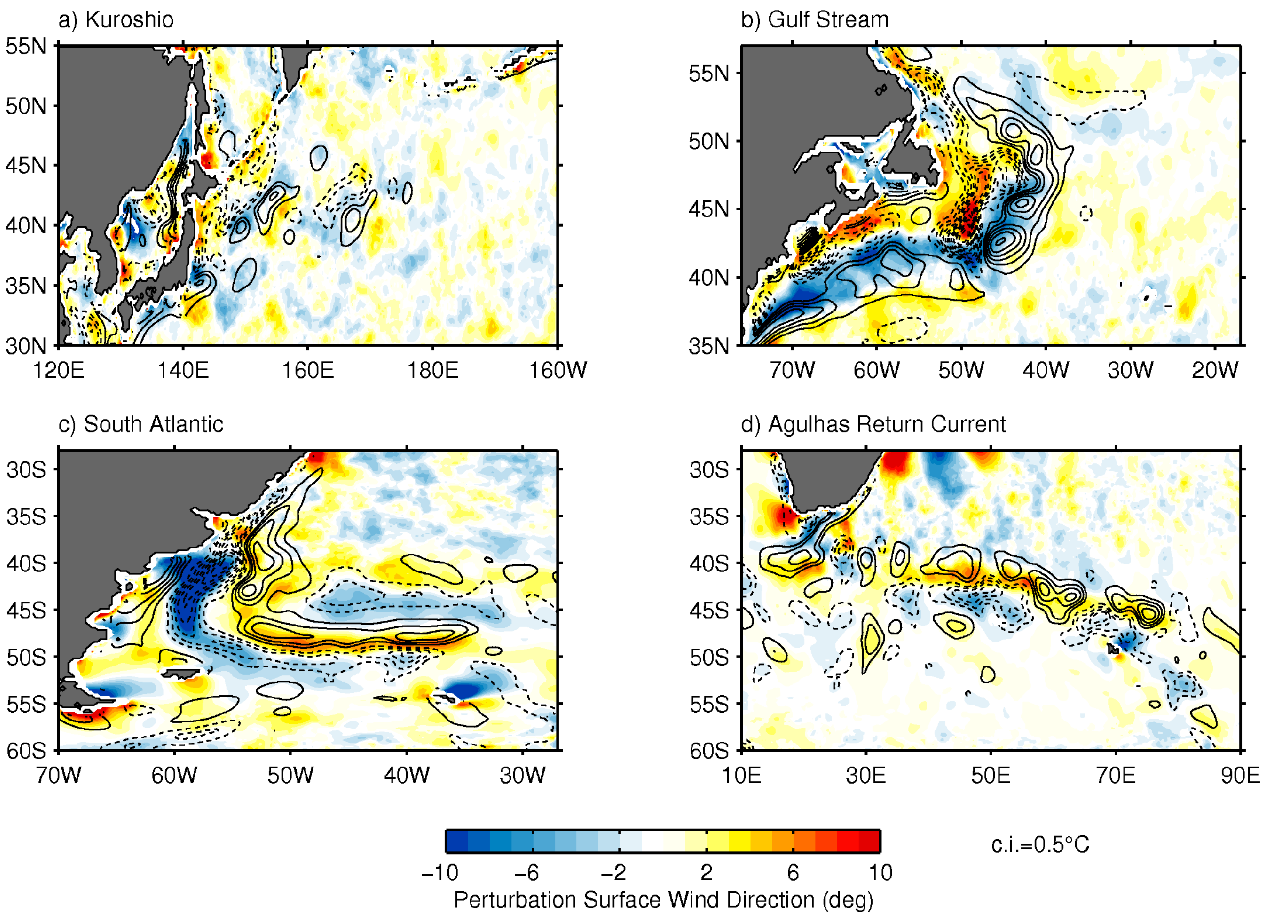
SST-Induced Perturbations of QuikSCAT Wind Stress Magnitude (colors) and AMSR-E SST (contours)



- Wind stress magnitude is likewise correlated highly with SST perturbations

Contours are spatially high-pass filtered AMSR-E SST with a contour interval of 0.5℃

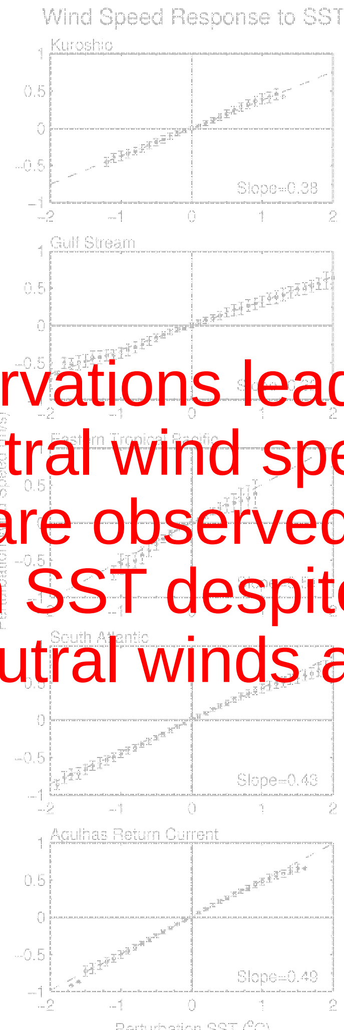
Perturbation QuikSCAT Wind Direction



- Wind direction perturbations of 5-10° are also associated with SST
- Displaced meridionally and are of opposite sign between hemispheres
- Creates rather significant vorticity/divergence perturbations through diffluence and curvature (O'Neill et al 2009 JCLI)

Contours are spatially high-pass filtered AMSR-E SST with a contour interval of 0.5℃

Statistical Relationships Between Perturbations of Neutral Wind Speed, Wind Stress Magnitude and SST



- Both the surface wind speed and wind stress magnitude perturbations are related linearly to SST:

- These observations lead to <u>perplexing observation #1</u>: The neutral wind speed and wind stress magnitude are observed to be related linearly to the perturbation SST despite the nonlinear relationship between neutral winds and stress

Geographical Variability of Neutral Wind Speed and Wind Stress Magnitude Coupling Coefficients

Region	α_τ N m^{-2} per °C	α_v m s^{-1} per °C
Kuroshio	[illegible]	0.38
Gulf Stream	0.014	0.32
Eastern Tropical Pacific	0.008	0.51
South Atlantic	0.016	0.46
Agulhas Return Current	0.022	0.49

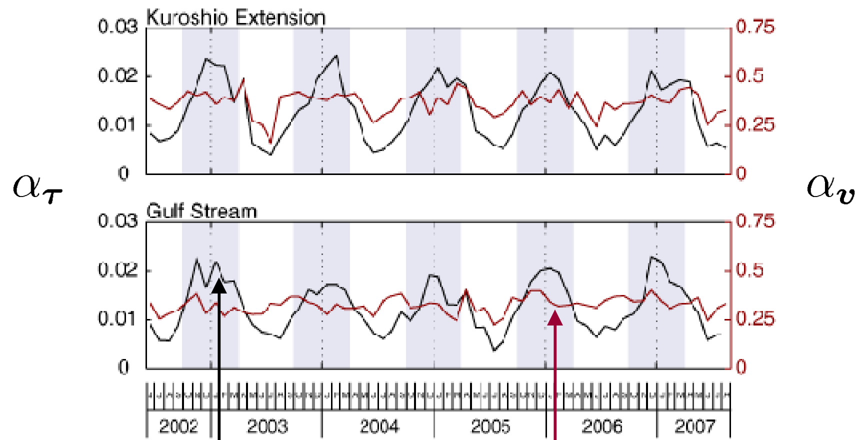
- Perplexing observation #2: Stress coupling coefficients not well related to neutral wind speed coupling coefficients; for instance, the stress coefficient is smallest where the neutral wind speed coefficient is largest (over the eastern tropical Pacific)

Time Series of Coupling Coefficients Northern Hemisphere Mid-Latitudes

$$\overline{|\boldsymbol{\tau}|}' = \alpha_{\boldsymbol{\tau}} \overline{T}'$$

$$\boxed{\overline{V}' = \alpha_{\boldsymbol{v}} \overline{T}'}$$

- Large seasonal cycle in α_τ but not in α_v over mid-latitudes



α_τ is more than 4x larger during the wintertime compared to summertime

Little seasonality in α_v

Time Series of Coupling Coefficients Southern Hemisphere Mid-Latitudes

$$\overline{|\boldsymbol{\tau}|}' = \alpha_{\boldsymbol{\tau}} \overline{T}'$$

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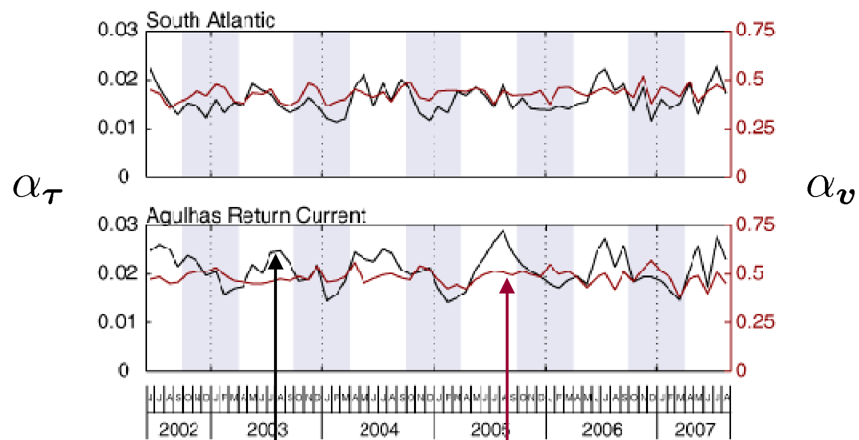
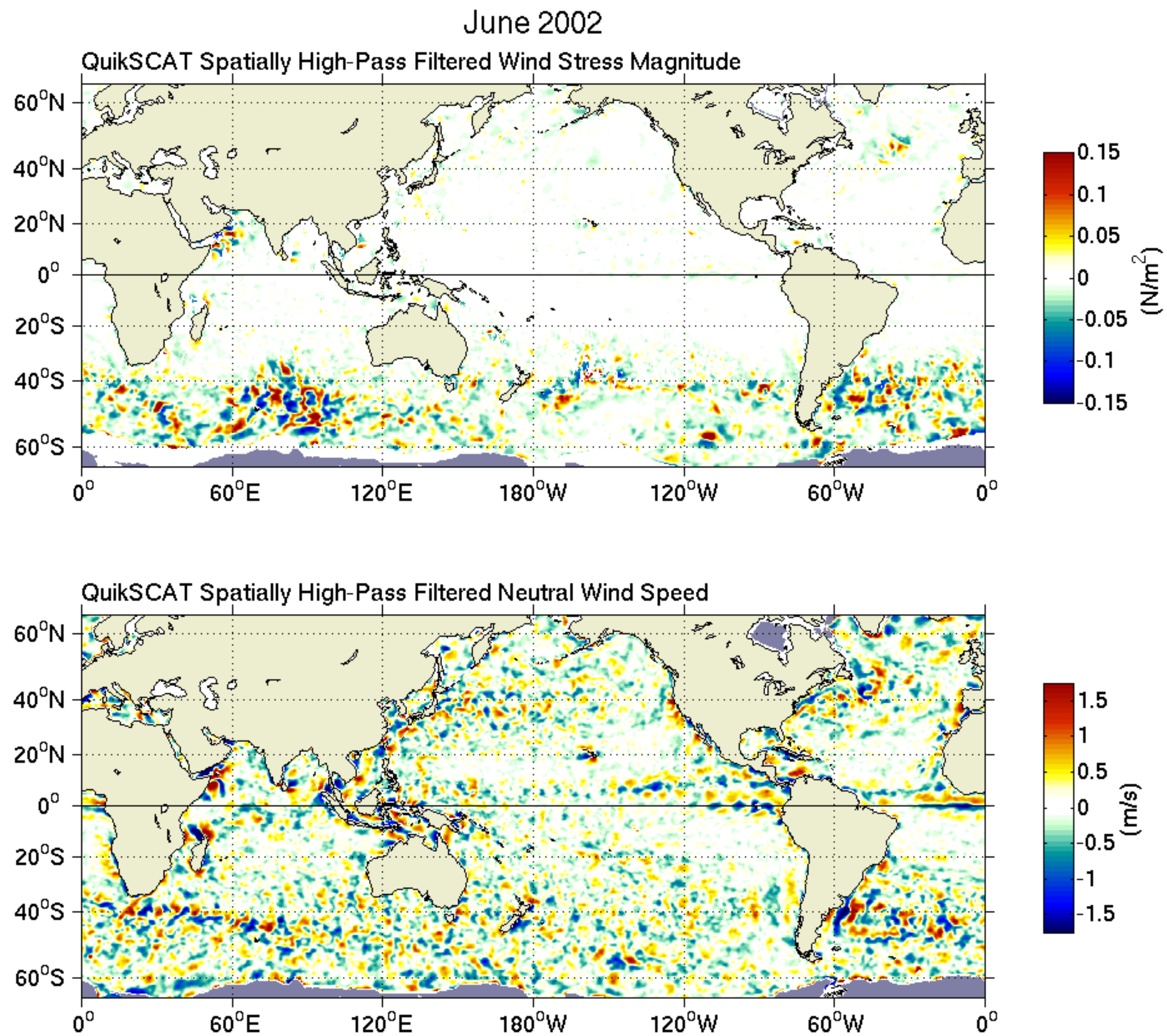
- Large seasonal cycle in α_τ but not in α_v over mid-latitudes



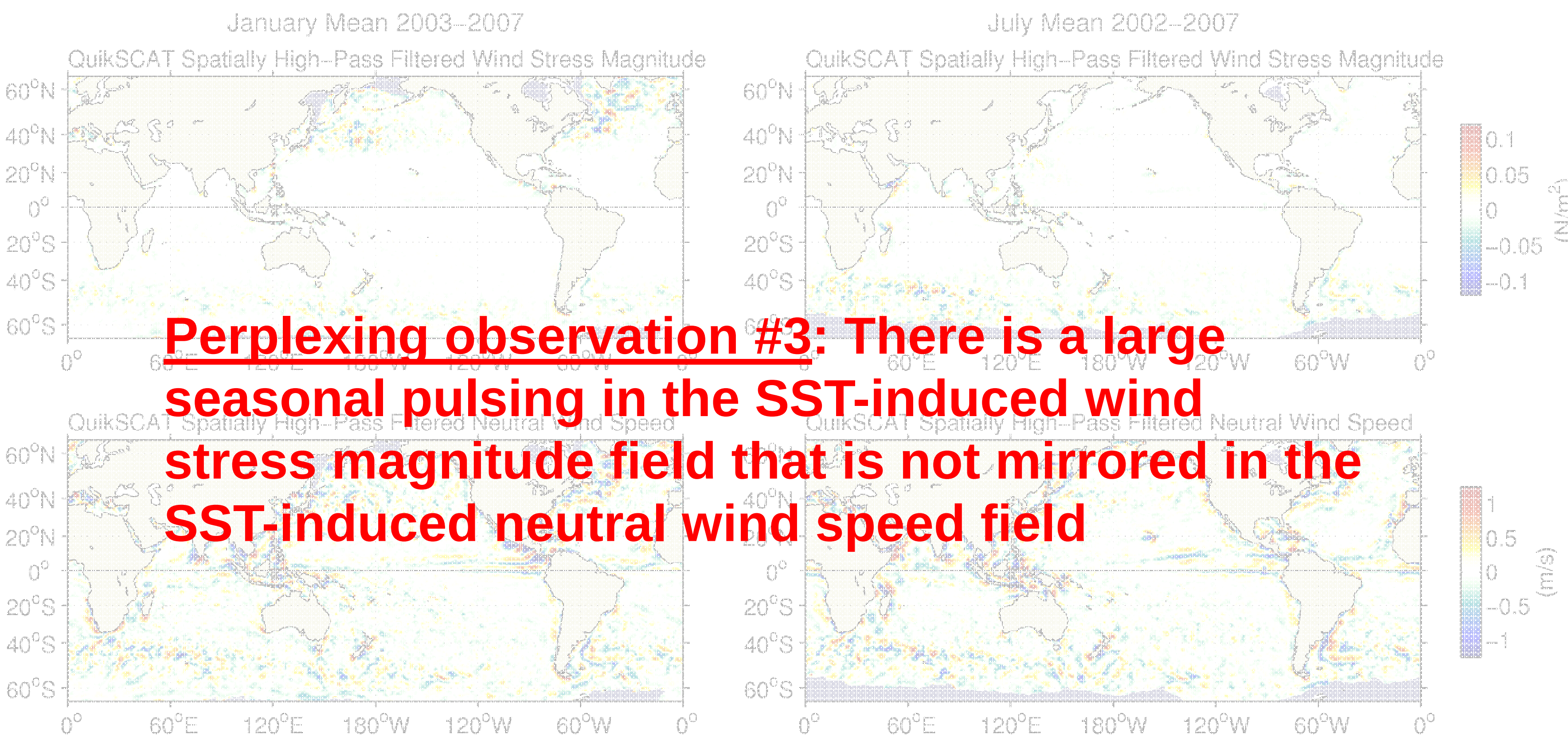
α_τ is more than 2x larger during the austral wintertime

Little seasonality in α_v

Animation of Monthly-Averaged QuikSCAT Spatially High-Pass Filtered Wind Stress Magnitude and Neutral Wind Speed



Seasonal Variations of SST-Induced Wind Stress Magnitude and Neutral Wind Speed Perturbations



<u>Perplexing observation #3</u>: There is a large seasonal pulsing in the SST-induced wind stress magnitude field that is not mirrored in the SST-induced neutral wind speed field

Analytical Relationship Between Time-Averaged Spatially High-Pass Filtered Neutral Wind Speed and Stress Magnitude

$$|\boldsymbol{\tau}| = \rho_0 C_{d10n} V_n^2 \qquad C_{d10n} = \frac{a_0}{V_n} + b_0 + c_0 V_n \quad \longrightarrow \quad \frac{|\boldsymbol{\tau}|}{\rho_0} = a_0 V_n + b_0 V_n^2 + c_0 V_n^3$$

Drag Coefficient from Large et al. 1994

$$V_n = \underbrace{\widetilde{\overline{V_n}}}_{\substack{\text{Time Mean}\\ \text{Low–Pass}}} + \underbrace{\widetilde{V_n^*}}_{\substack{\text{Time Varying}\\ \text{Low–Pass}}} + \underbrace{\overline{V_n'}}_{\substack{\text{Time Mean}\\ \text{High–Pass}}} + \underbrace{V_n'^*}_{\substack{\text{Time Varying}\\ \text{High–Pass}}}$$

$$\begin{aligned}\overline{|\boldsymbol{\tau}|}' \;&=\; \rho_0 \left(a_0 + 2b_0\overline{V_n} + 3c_0\widetilde{\overline{V_n}}\;\overline{V_n}\right)\left(1 - \cancel{\frac{b_0\overline{V_n}' - c_0\overline{V_n}'^2}{a_0 + 2b_0\overline{V_n} + 3c_0\widetilde{\overline{V_n}}\;\overline{V_n}}}\right)\overline{V_n}' \\ &\quad + \cancel{\rho_0 b_0\left(\overline{V_n^2}' - \overline{V_n}^{2'}\right)} + \rho_0 c_0\left(\overline{V_n^3}' - \overline{V_n}^{3'}\right)\end{aligned}$$

$$\boxed{\overline{|\boldsymbol{\tau}|}' \;\approx\; \rho_0\left(a_0 + 2b_0\overline{V_n} + 3c_0\widetilde{\overline{V_n}}\;\overline{V_n}\right)\overline{V_n}' + \rho_0 c_0\left(\overline{V_n^3}' - \overline{V_n}^{3'}\right)}$$

Approximation to less than ~2% relative error

Analytical Relationship Between Time-Averaged Spatially High-Pass Filtered Neutral Wind Speed and Stress Magnitude

$$\overline{|\boldsymbol{\tau}|}' \approx \boxed{\rho_0\left(a_0 + 2b_0\overline{V_n} + 3c_0\widetilde{\overline{V_n}}\;\overline{V_n}\right)\overline{V_n}'} + \rho_0 c_0\left(\overline{V_n^3}' - \overline{V_n}^{3'}\right)$$

$$\overline{V_n}' = \alpha_v \overline{T}'$$

$$\boxed{\Gamma \alpha_{\boldsymbol{v}} \overline{T}'}$$

$$\Gamma = \rho_0\left(a_0 + 2b_0\overline{V_n} + 3c_0\widetilde{\overline{V_n}}\;\overline{V_n}\right)$$

- Stress perturbations are proportional to the neutral wind speed perturbations <u>*and*</u> to the ambient large-scale neutral wind speed

- This term accounts for 80-100% of the SST-induced stress response

SST-induced stress response is larger relative to the wind speed response wherever and whenever the ambient large-scale neutral wind speed is larger

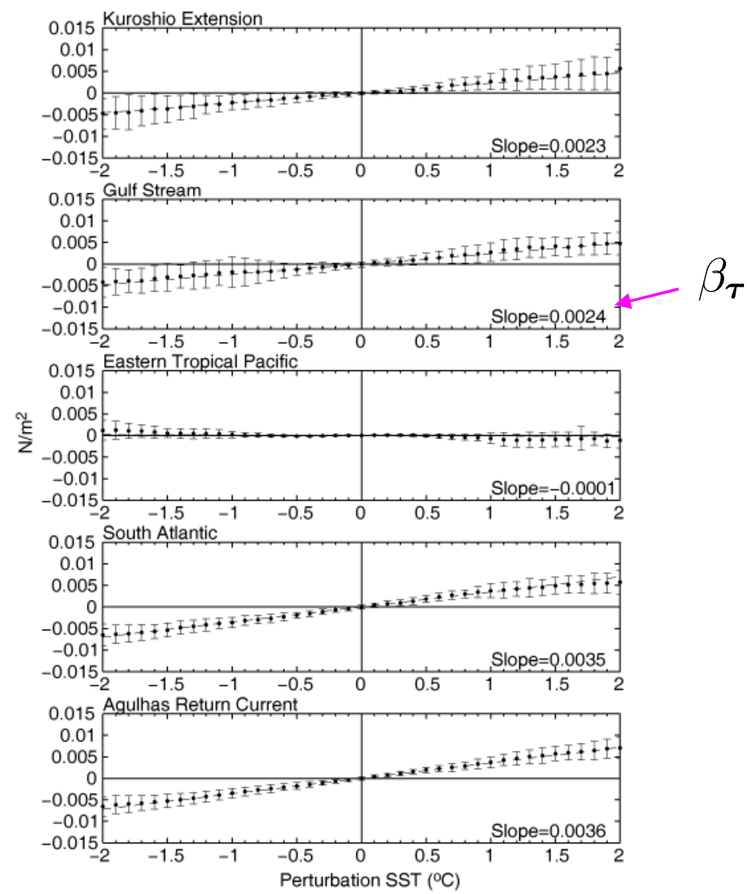
Analytical Relationship Between Time-Averaged Spatially High-Pass Filtered Neutral Wind Speed and Stress Magnitude

$$\overline{|\boldsymbol{\tau}|}' \approx \rho_0 \left(a_0 + 2b_0 \overline{V} + 3c_0 \widetilde{\overline{V}}\, \overline{V} \right) \overline{V}' + \boxed{\rho_0 c_0 \left(\overline{V^3}' - \overline{V}^{3'} \right)}$$

- Arises from temporal neutral wind speed variability on time scales shorter than period of time averaging, which here is one month

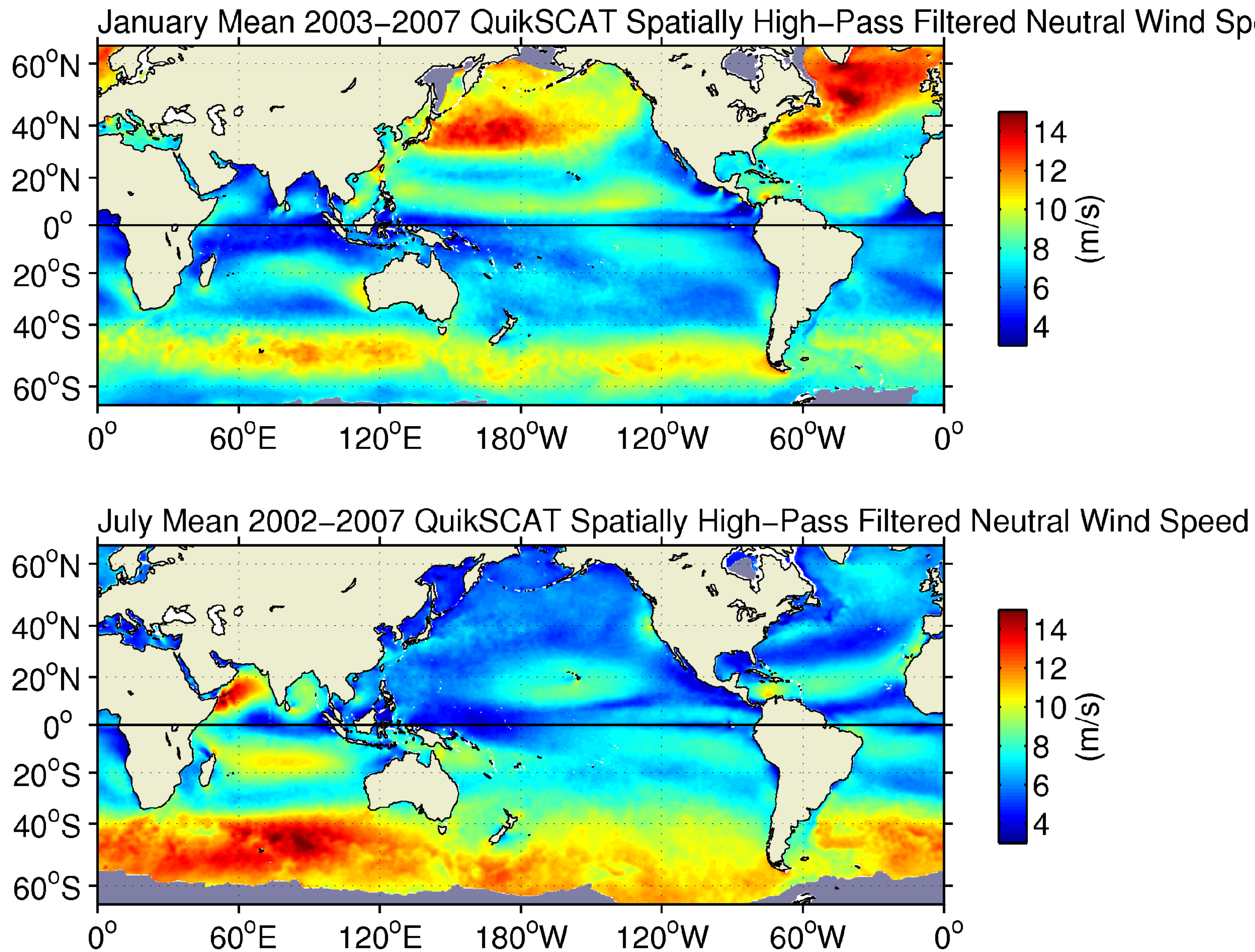
- This term is also related linearly to the perturbation SST in mid-latitudes

- Consistent with the findings of Sampe and Xie (BAMS, 2007) – transient high wind events found more frequently over warm SST perturbations in mid-latitudes and are likely a dominant contributor to this term



Summary

- Both neutral wind speed and wind stress magnitude are stronger over warm SST perturbations and weaker over cool SST perturbations
- Three perplexing observations that at first were difficult to explain
  - The neutral wind speed and wind stress magnitude are observed to be related linearly to the perturbation SST despite the nonlinear relationship between neutral winds and stress
  - Stress coupling coefficients not well related to neutral wind speed coupling coefficients
  - There is a large seasonal pulsing in the SST-induced wind stress magnitude field that is not mirrored in the SST-induced neutral wind speed field
- Ambient large-scale neutral wind speed modulates the SST-induced wind stress response relative to that of the neutral wind speed
  - SST-induced wind stress perturbations are stronger relative to those of neutral wind speed wherever and whenever the ambient large-scale neutral wind speed is stronger
  - This accounts for seasonal and geographical variability of the SST-induced wind stress response relative to that of wind speed


January Mean 2003−2007 QuikSCAT Spatially High−Pass Filtered Neutral Wind Spe
July Mean 2002−2007 QuikSCAT Spatially High−Pass Filtered Neutral Wind Speed
(m/s)

Temporal Variability of QuikSCAT Wind Stress Magnitude Response to SST

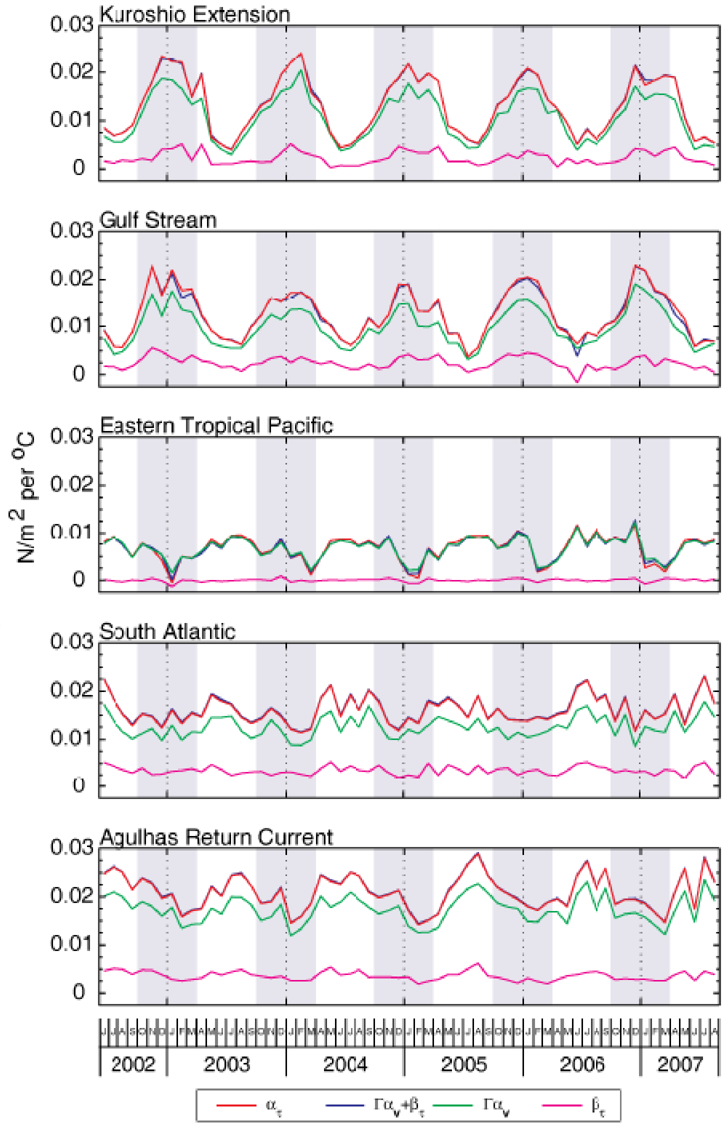
$$\overline{|\boldsymbol{\tau}|}' \approx (\Gamma\alpha_{\boldsymbol{v}} + \beta_{\boldsymbol{\tau}})\,\overline{T}'$$

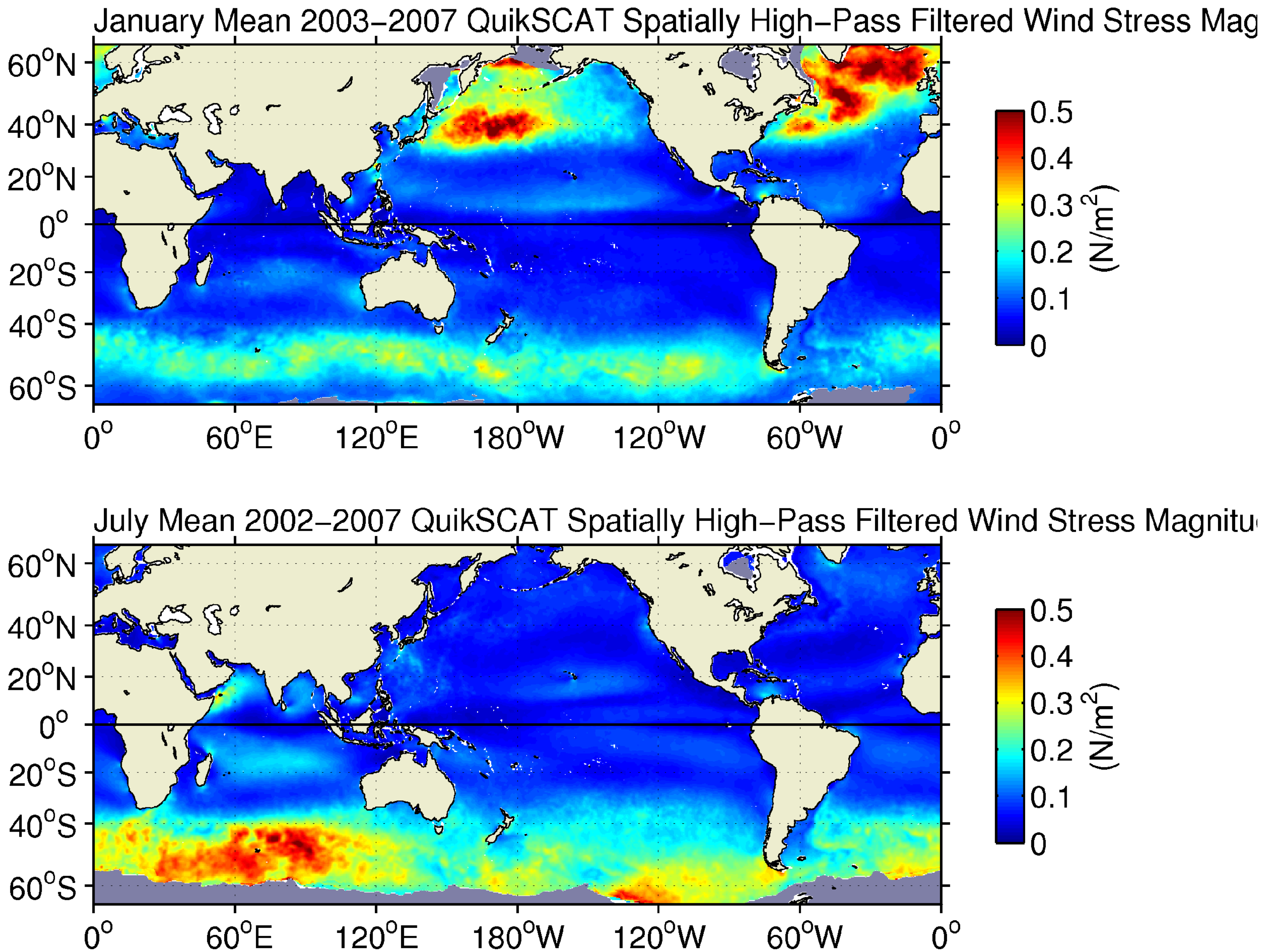
$$\boxed{\alpha_{\boldsymbol{\tau}}} \approx \boxed{\Gamma\alpha_{\boldsymbol{v}}} + \boxed{\beta_{\boldsymbol{\tau}}}$$

SST-induced response of wind speed accounts for 80-100% of SST-induced stress response

Accounts for 0-20% of time-averaged wind stress response

Since α_v varies little seasonally over mid-latitudes, most of the seasonality in α_τ occurs because of seasonality in Γ, and hence the ambient large-scale wind speed

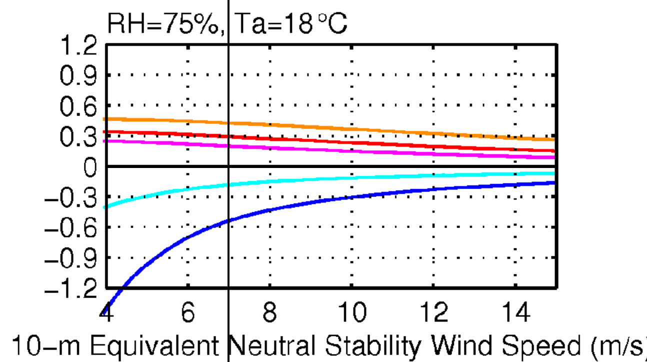




January Mean 2003−2007 QuikSCAT Spatially High−Pass Filtered Wind Stress Mag
60°N
40°N
20°N
0°
20°S
40°S
60°S
0°
60°E
120°E
180°W
120°W
60°W
0°
0.5
0.4
0.3
0.2
0.1
0
(N/m²)
July Mean 2002−2007 QuikSCAT Spatially High−Pass Filtered Wind Stress Magnitu
60°N
40°N
20°N
0°
20°S
40°S
60°S
0°
60°E
120°E
180°W
120°W
60°W
0°
0.5
0.4
0.3
0.2
0.1
0
(N/m²)

Comparing 10-m Neutral and Actual Wind Speed Relative to Surface Ocean Currents

V_n-V
(m/s)



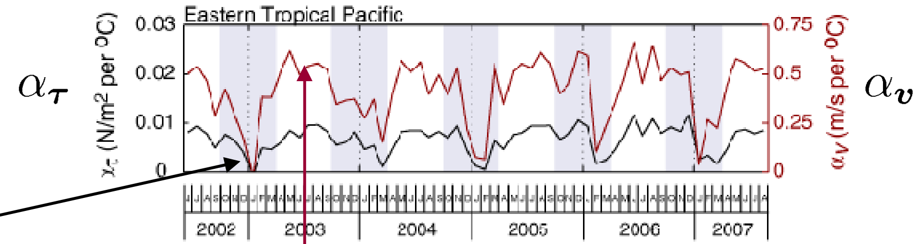
- Computed using similarity theory-based state-of-the-art COARE 3.0 bulk flux algorithm (Fairall et al. 2003) using methodology of Liu and Tang (1996)
- According to similarity theory, difference between 10-m neutral and actual wind speed:
  - Is very significant in extremely stable and low neutral wind speed conditions
  - Decreases very rapidly for increasing wind speed in both stable and unstable conditions
  - Is relatively small in unstable conditions for all neutral wind speeds
  - Differences are very sensitive to addition of wave parameterization in

Time Series of Coupling Coefficients Eastern Tropical Pacific

$$\overline{|\boldsymbol{\tau}|}' = \alpha_{\boldsymbol{\tau}} \overline{T}' \qquad \boxed{\overline{V}' = \alpha_{\boldsymbol{v}} \overline{T}'}$$

- Minima in α_τ and α_v over the eastern tropical Pacific during January-March coincides with the annual collapse of the cold tongue

- During these times, SST gradients are insufficient to drive significant surface wind perturbations



Maxima in α_v occur during late boreal summertime when TIWs are well developed

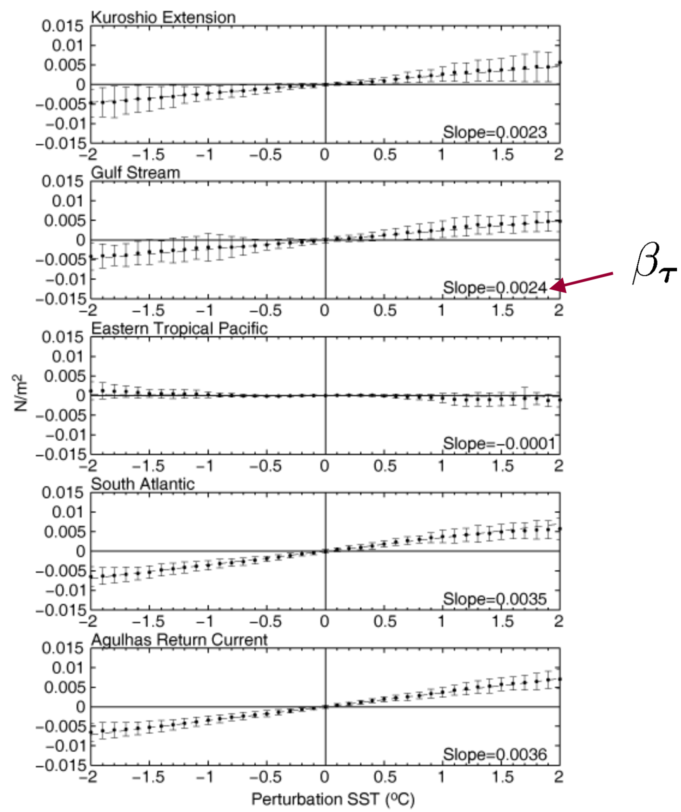
Analytical Relationship Between Time-Averaged Spatially High-Pass Filtered Surface Wind Speed and Stress Magnitude

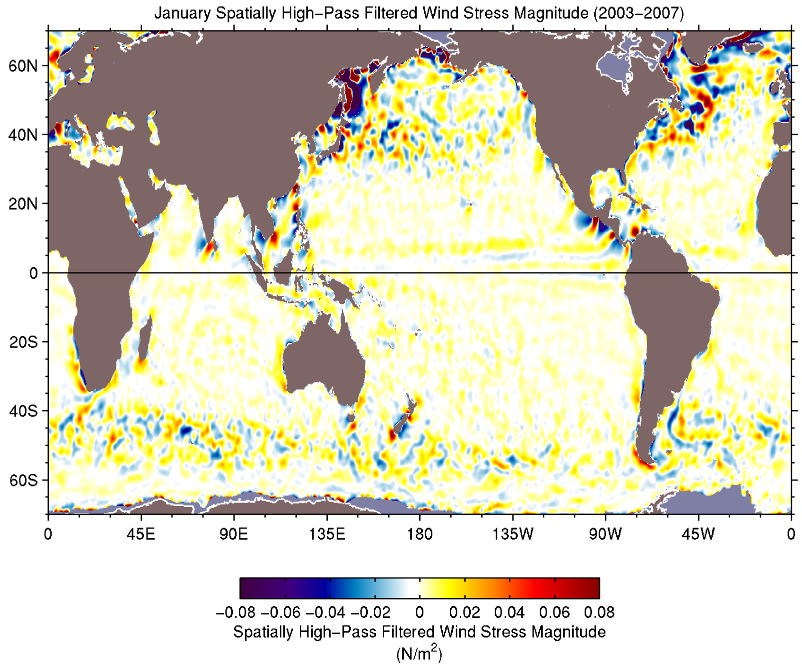
$$\overline{|\boldsymbol{\tau}|}' \approx \rho_0 \left(a_0 + 2b_0 \overline{V} + 3c_0 \widetilde{\overline{V}}\,\overline{V} \right) \overline{V}' + \boxed{\rho_0 c_0 \left(\overline{V^3}' - \overline{V}^{3'} \right)}$$

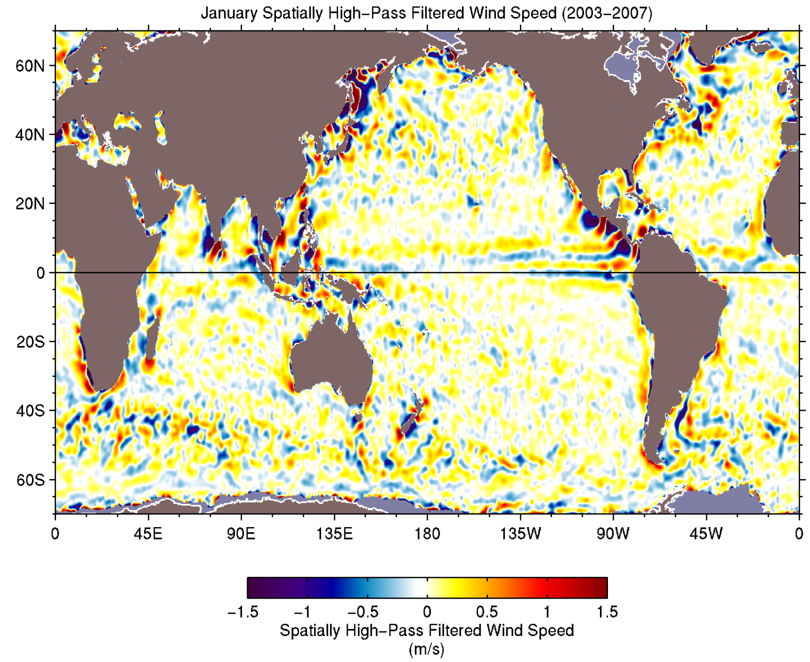
- Arises from temporal variability of wind speed with time scales shorter than the period of time-averaging

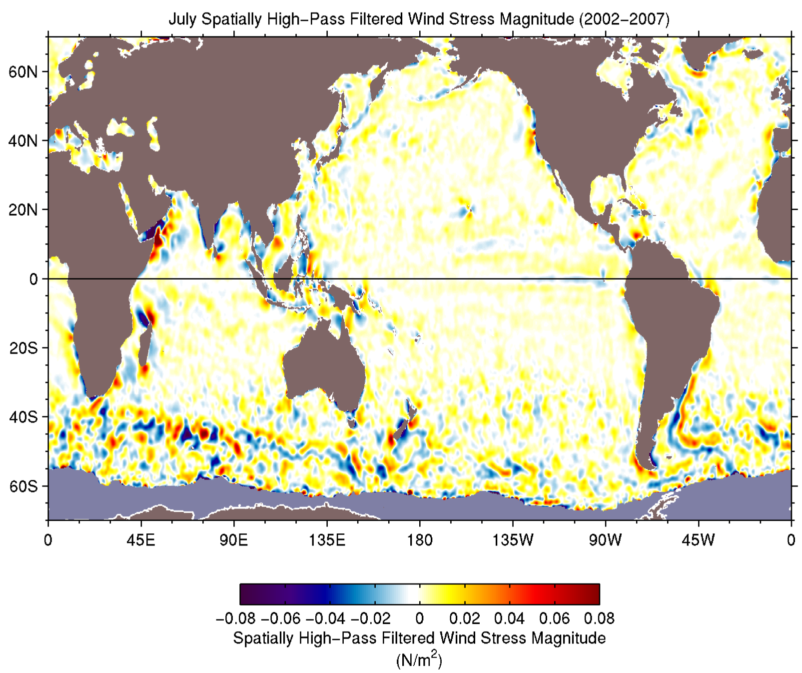
- Transient high wind events occur much more frequently over warm SST perturbations in mid-latitudes (Sampe and Xie, BAMS 2007) and is likely a dominant contributor to this term

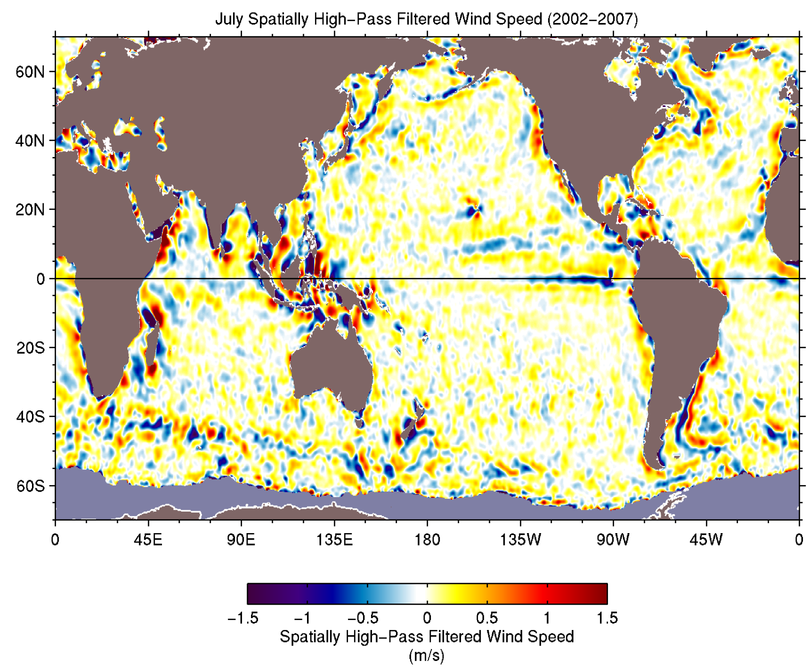
- This term is also related linearly to the spatially high-pass filtered SST in mid-latitudes




January Spatially High−Pass Filtered Wind Stress Magnitude (2003−2007)
60N 40N 20N 0 20S 40S 60S
0 45E 90E 135E 180 135W 90W 45W 0
−0.08 −0.06 −0.04 −0.02 0 0.02 0.04 0.06 0.08
Spatially High−Pass Filtered Wind Stress Magnitude
(N/m2)


January Spatially High−Pass Filtered Wind Speed (2003−2007)
60N 40N 20N 0 20S 40S 60S
0 45E 90E 135E 180 135W 90W 45W 0
−1.5 −1 −0.5 0 0.5 1 1.5
Spatially High−Pass Filtered Wind Speed
(m/s)


July Spatially High−Pass Filtered Wind Stress Magnitude (2002−2007)
60N 40N 20N 0 20S 40S 60S
0 45E 90E 135E 180 135W 90W 45W 0
−0.08 −0.06 −0.04 −0.02 0 0.02 0.04 0.06 0.08
Spatially High−Pass Filtered Wind Stress Magnitude
(N/m2)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60N 40N 20N 0 20S 40S 60S
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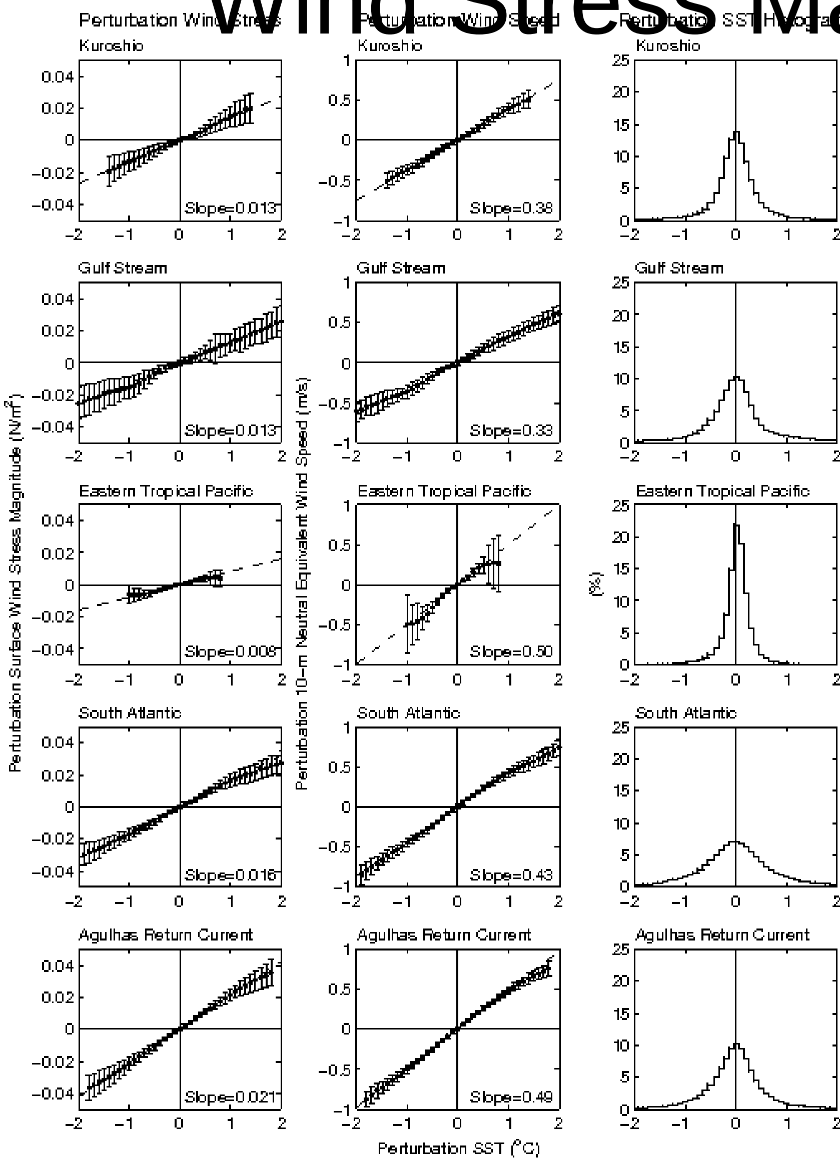
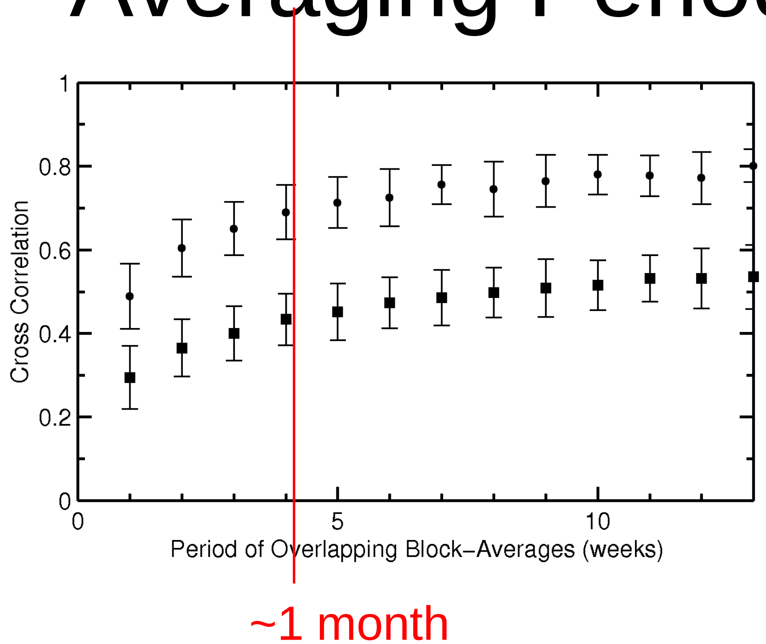
Spatially High−Pass Filtered Wind Speed
(m/s)

Statistical Relationships Between Perturbations of Neutral Wind Speed, Wind Stress Magnitude and SST



- Neutral wind speed perturbations are linearly related to SST perturbations
- Wind stress magnitude perturbations are also related linearly to SST perturbations
- Leads to perplexing conclusion that the neutral wind speed and wind stress magnitude are related linearly to each other despite the nonlinear relationship

Perturbation Neutral Wind Speed-SST Cross-Correlation as a Function of Averaging Period



- Cross-correlation between perturbation neutral wind speed and SST increases as period of averaging increases, up to about 6 weeks.

$$|\boldsymbol{\tau}| = \rho_0 C_{d10n} V_n^2$$

$$C_{d10n} = \frac{a_0}{V_n} + b_0 + c_0 V_n$$

$$\Gamma \alpha_{vn} \overline{T}'$$

$$\frac{|\boldsymbol{\tau}|}{\rho_0} = a_0 V_n + b_0 V_n^2 + c_0 V_n^3$$

$$\Gamma = \rho_0 \left(a_0 + 2 b_0 \overline{V_n} + 3 c_0 \widetilde{\overline{V_n}}\ \overline{V_n} \right)$$

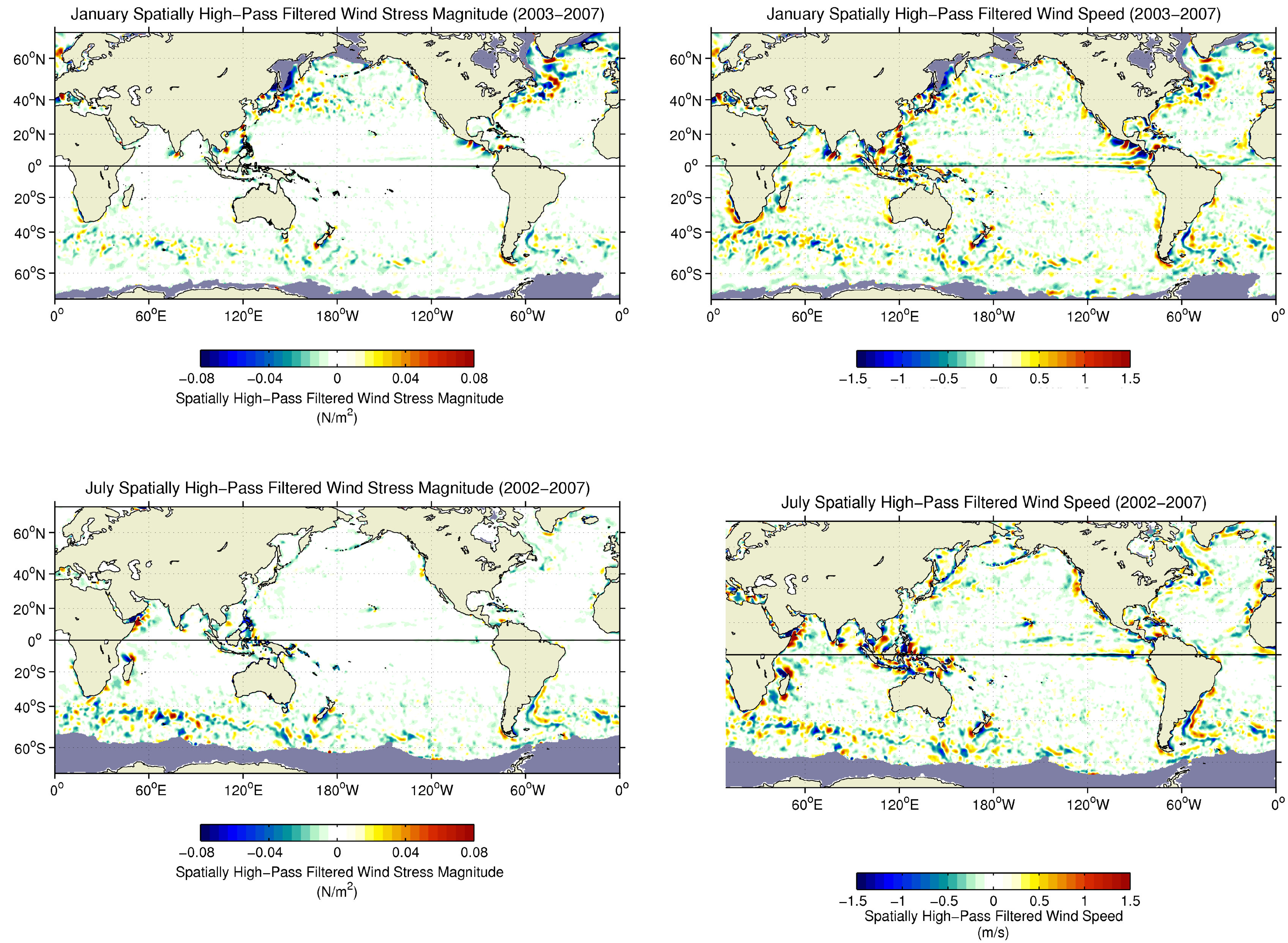
$$\overline{|\boldsymbol{\tau}|}' = \alpha_{\boldsymbol{\tau}} \overline{T}'$$

$$\overline{V}' = \alpha_{vn} \overline{T}'$$

$$\overline{|\boldsymbol{\tau}|}' \approx \left(\Gamma \alpha_{vn} + \beta_{\boldsymbol{\tau}} \right) \overline{T}'$$

$$\alpha_{\boldsymbol{\tau}} \approx \Gamma \alpha_{vn} + \beta_{\boldsymbol{\tau}}$$

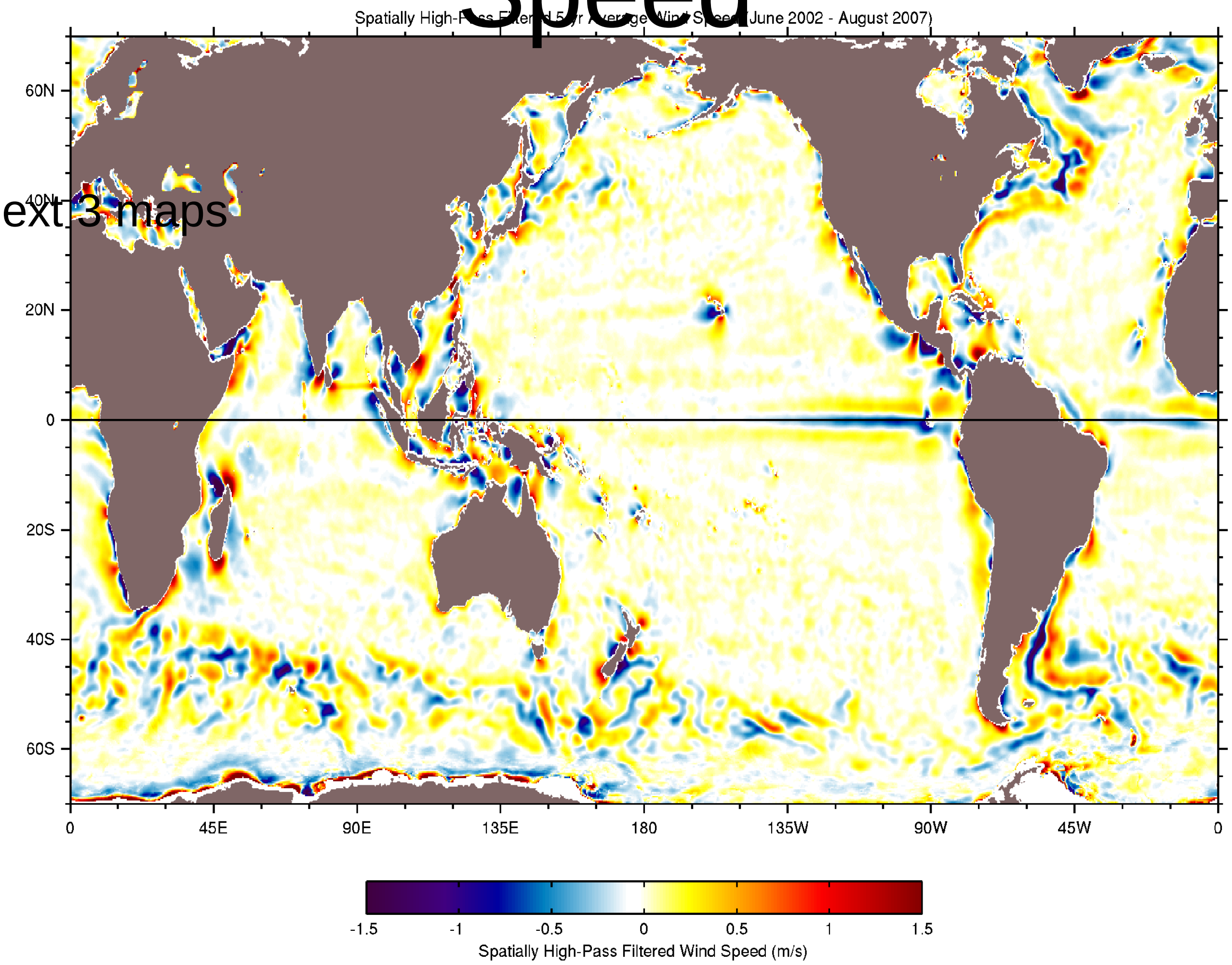
Seasonal Variations of SST-Induced Wind Stress Magnitude and Neutral Wind Speed Perturbations



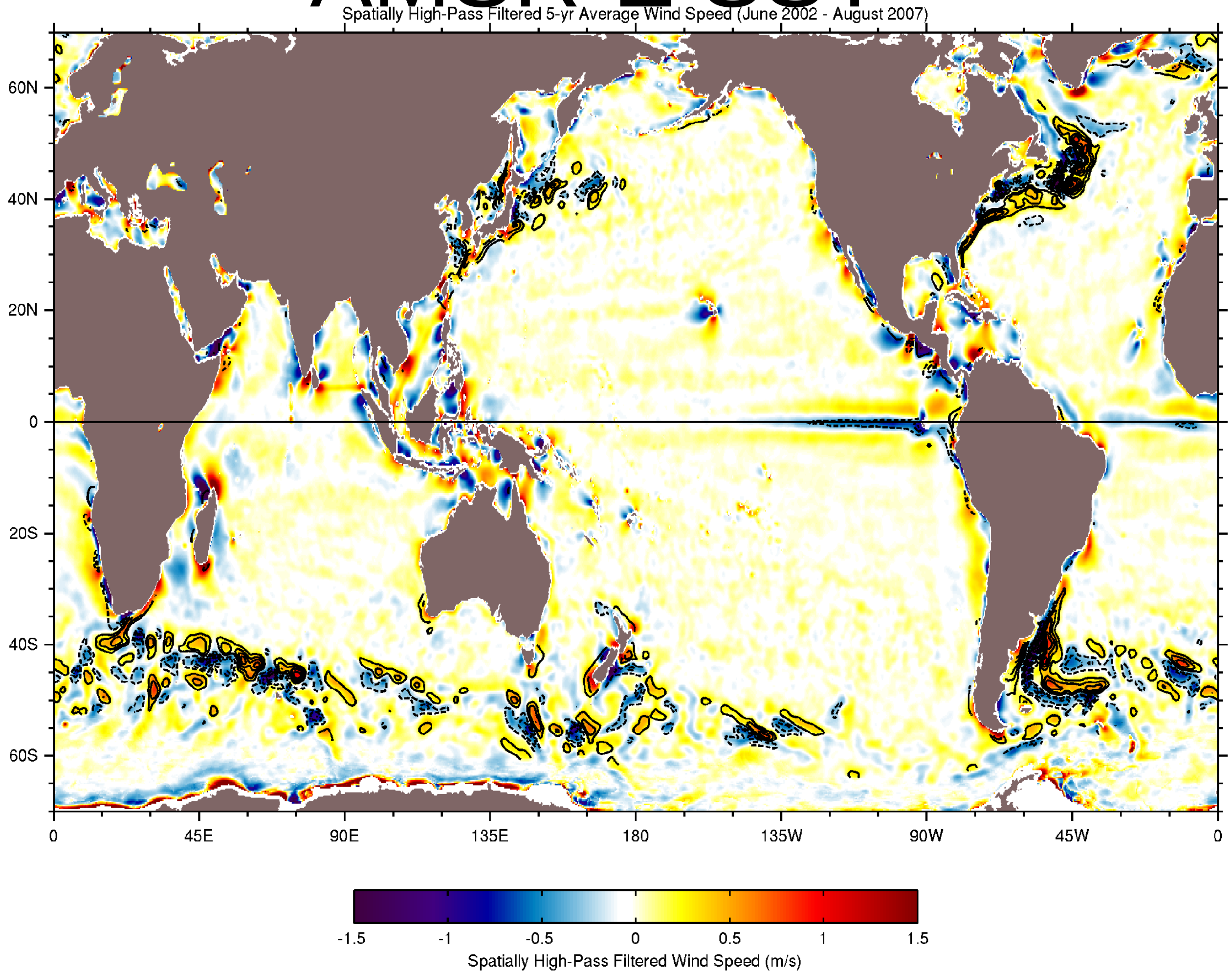
5-yr Average Spatially High-Pass Filtered QuikSCAT 10-m Neutral Wind Speed

Redo the next 3 maps

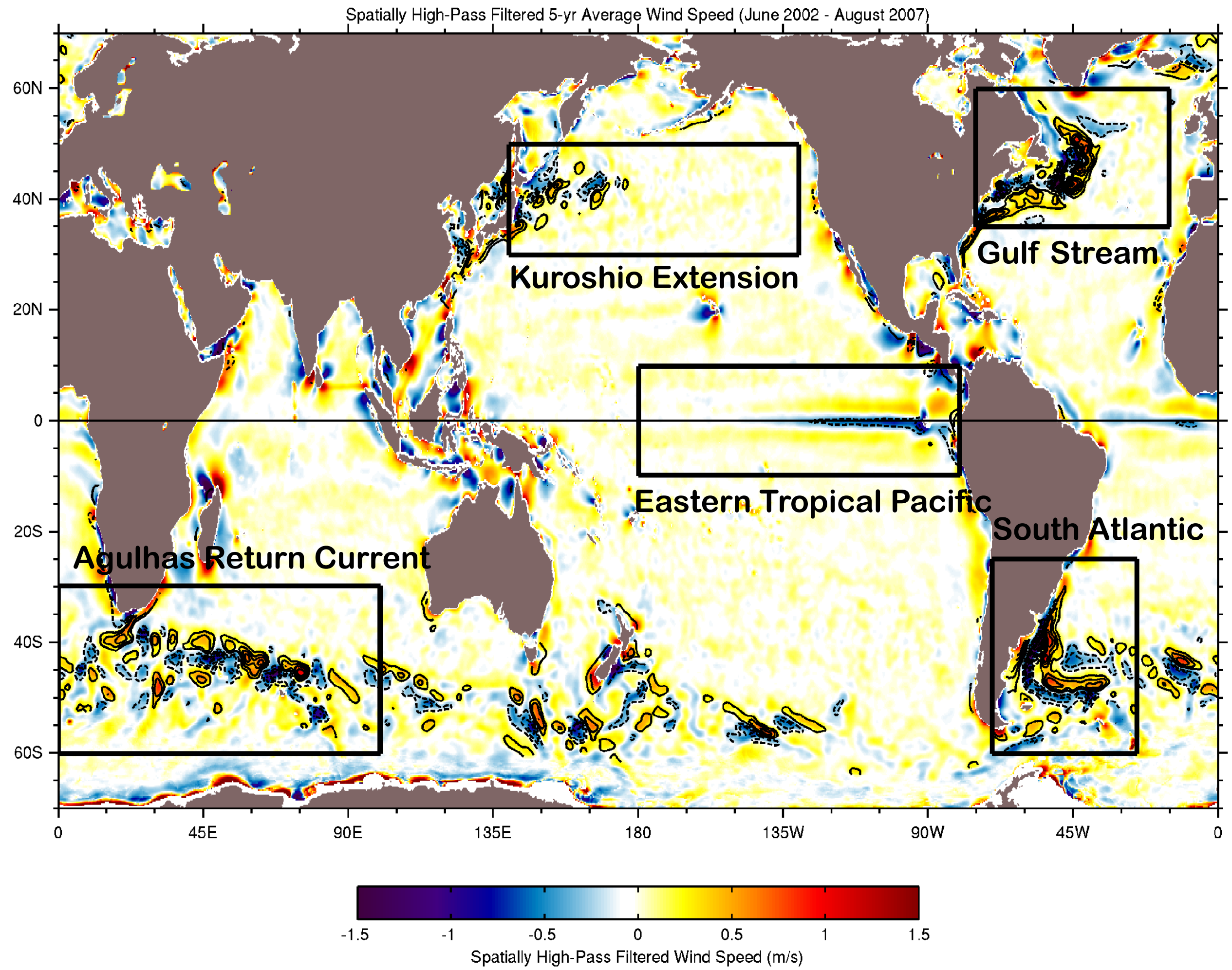
Bigger font



5-yr Average Spatially High-Pass Filtered QuikSCAT 10-m Neutral Wind Speed and AMSR-E SST



5-yr Average QuikSCAT 10-m Neutral Wind Speed



Analytical Relationship Between Time-Averaged Spatially High-Pass Filtered Neutral Wind Speed and Stress

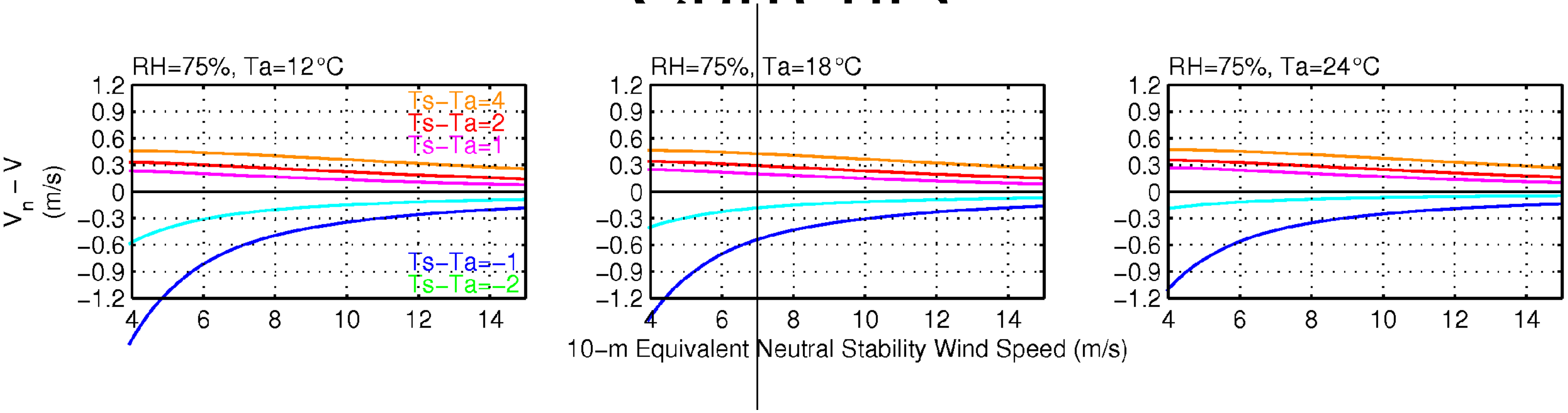
$$\frac{|\boldsymbol{\tau}|}{\rho_0} = a_0 V_n + b_0 V_n^2 + c_0 V_n^3$$

$$V_n = \underbrace{\overline{\widetilde{V_n}}}_{\substack{\text{Time Mean}\\ \text{Low–Pass}}} + \underbrace{\tilde{V}_n^{*}}_{\substack{\text{Time Varying}\\ \text{Low–Pass}}} + \underbrace{\overline{V_n'}}_{\substack{\text{Time Mean}\\ \text{High–Pass}}} + \underbrace{V_n'^{*}}_{\substack{\text{Time Varying}\\ \text{High–Pass}}}$$

$$\begin{aligned}\overline{|\boldsymbol{\tau}|}' &= \rho_0 \left(a_0 + 2b_0\overline{V_n} + 3c_0\overline{\widetilde{V_n}}\;\overline{V_n}\right)\left(1 - \frac{b_0\overline{V_n}' - c_0\overline{V_n}'^2}{a_0 + 2b_0\overline{V_n} + 3c_0\overline{\widetilde{V_n}}\;\overline{V_n}}\right)\overline{V_n}' \\ &+ \rho_0 b_0\left(\overline{V_n^2}' - \overline{V_n}^{2'}\right) + \rho_0 c_0\left(\overline{V_n^3}' - \overline{V_n}^{3'}\right)\end{aligned}$$

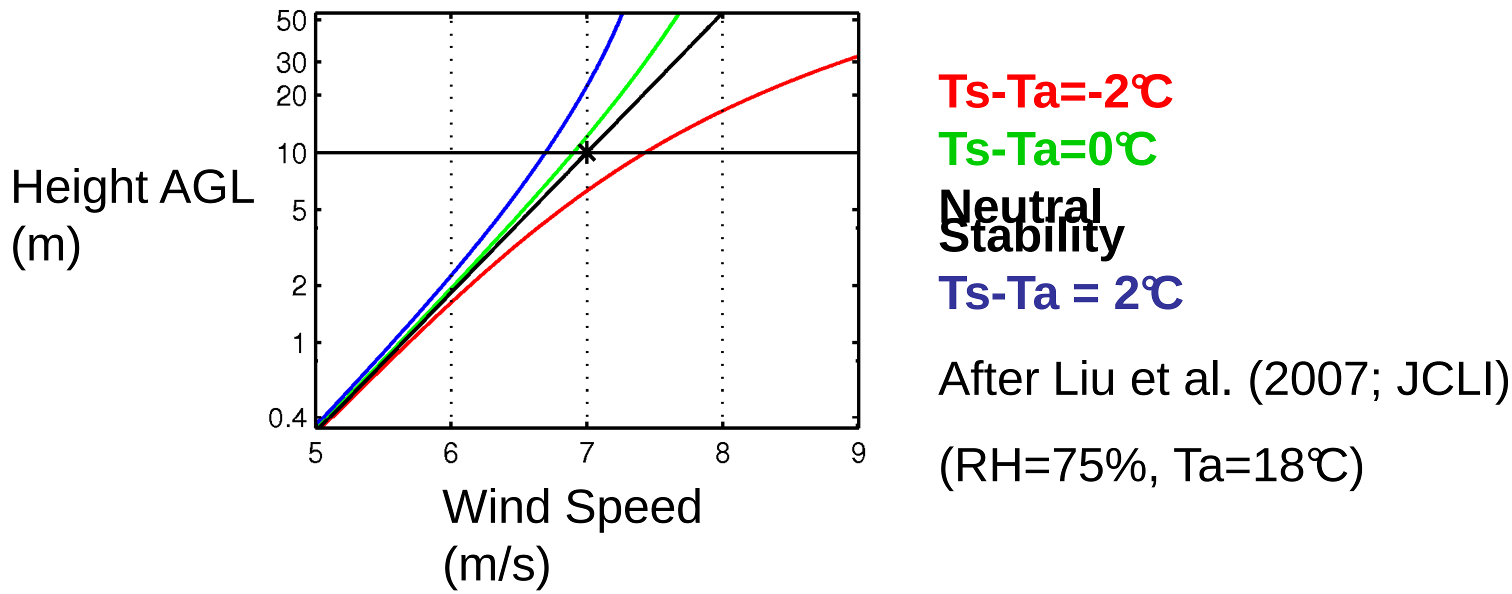
$$\boxed{\overline{|\boldsymbol{\tau}|}' \approx \rho_0\left(a_0 + 2b_0\overline{V_n} + 3c_0\overline{\widetilde{V_n}}\;\overline{V_n}\right)\overline{V_n}' + \rho_0 c_0\left(\overline{V_n^3}' - \overline{V_n}^{3'}\right)}$$

Comparing 10-m Neutral and Actual Wind Speed Relative to Surface Ocean Currents



- Computed using similarity theory-based state-of-the-art COARE 3.0 bulk flux algorithm (Fairall et al. 2003) using methodology of Liu and Tang (1996)
- According to similarity theory, difference between 10-m neutral and actual wind speed:
  - Is very significant in extremely stable and low neutral wind speed conditions
  - Decreases very rapidly for increasing wind speed in both stable and unstable conditions
  - Is relatively small in unstable conditions for all neutral wind speeds
  - Differences are very sensitive to addition of wave parameterization in

Comparing 10-m Neutral and Actual Wind Speed Relative to Surface Ocean



- Computed using similarity theory-based state-of-the-art COARE 3.0 bulk flux algorithm (Fairall et al. 2003) using methodology of Liu and Tang (1996)
- For a 10-m neutral wind speed of 7 m/s, range of actual 10-m wind speed is 6.7-7.4 m/s for an air-sea temperature difference of +/- 2℃