Observations and Modeling of SST Influence on Surface Winds and the Troposphere

by Dudley Chelton, Qingtao Song and Larry O'Neill

Oregon State University
Corvallis, Oregon, USA

Overview:

- *Satellite observations of SST influence on surface winds*
- *SST influence on surface winds in the ECMWF global forecast model*
- *Mesoscale model sensitivity studies to investigate surface wind response to SST*
    - *SST specification*
    - *grid resolution*
    - *horizontal mixing*
    - *vertical mixing*
- *Evidence for SST influence on tropospheric winds from observations and model simulations*

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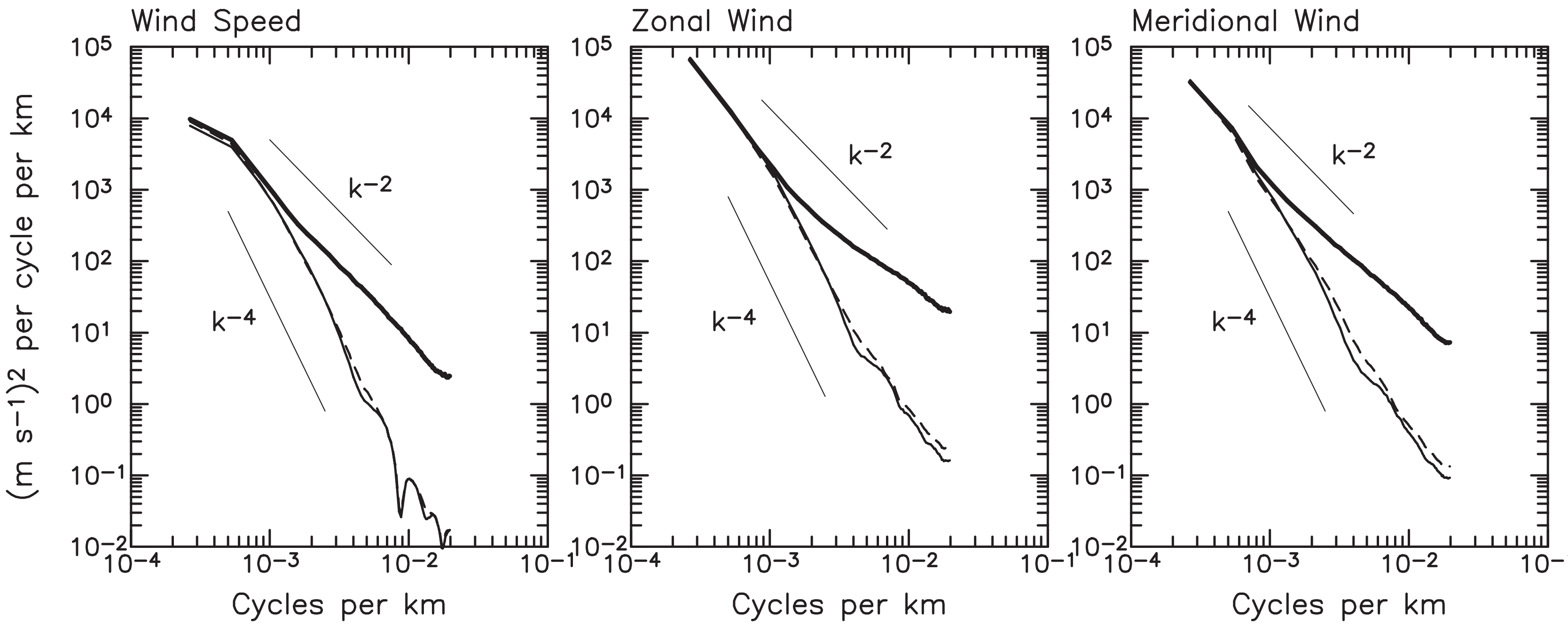
Resolution Inferred from Wavenumber Spectral Analysis of 10-m Winds



heavy solid line: QuikSCAT with 60 km smoothing
dashed line: ECMWF operational analyses with 39 km grid
thin solid line: NCEP operational analyses with 53 km grid

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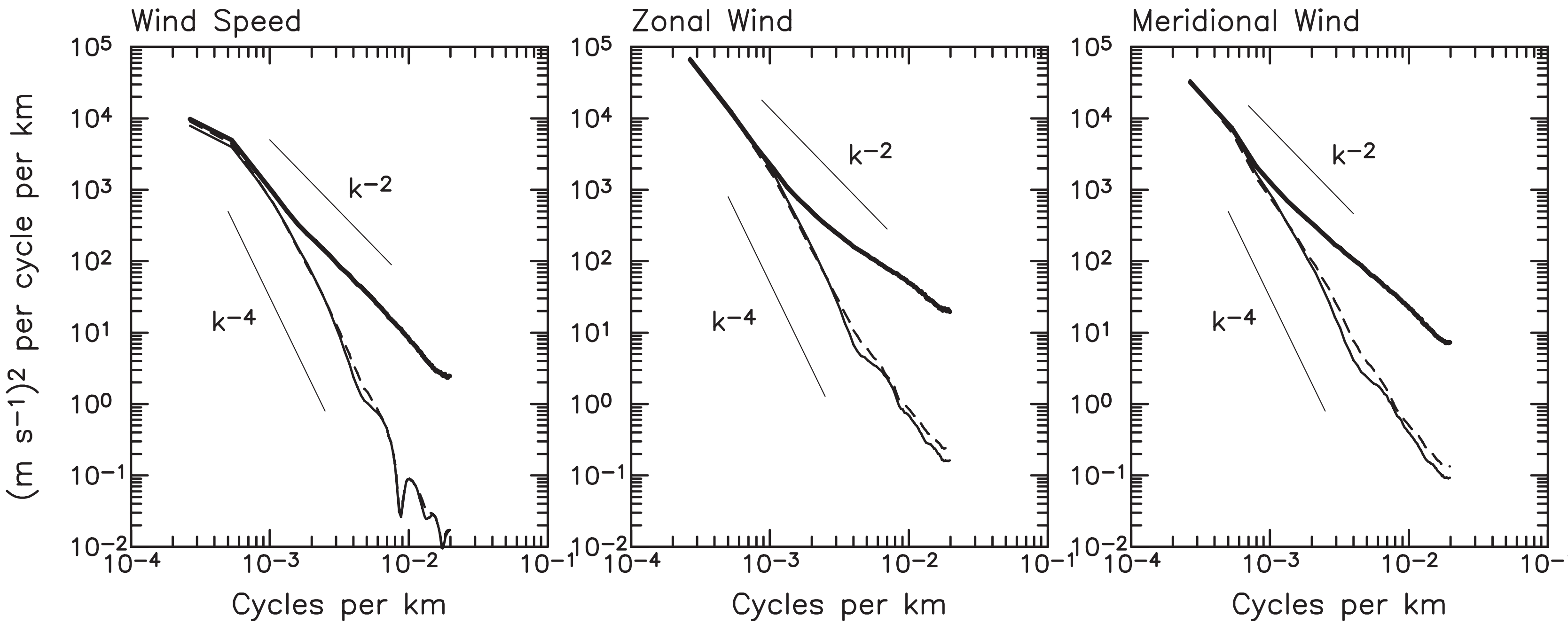

heavy solid line: QuikSCAT with 60 km smoothing
dashed line: ECMWF operational analyses with 39 km grid
thin solid line: NCEP operational analyses with 53 km grid

- *QuikSCAT resolution is ~60 km in wavelength, based on the amount of smoothing that must be applied to eliminate "white noise" flattening at high wavenumbers*
  - *- this is analogous to the filtering characteristics of ~35-km block averages*

- *ECMWF and NCEP spectra deviate from QuikSCAT at wavelengths shorter than ~1000 km*
  - *- the energy levels are about a factor of 15 too small at a wavelength of 200 km, for example*

Results from the Spectral Analysis:

1) *The claimed 25-km resolution of QuikSCAT winds is somewhat overstated*

   - *the actual resolution is ~35 km*

2) *The grid resolution of NWP models is not a good measure of the feature resolution of the models*

   - *the intensity of mesoscale features with scales shorter than ~1000 km are underestimated by the NWP models*

   - *Note that this is true despite the fact that QuikSCAT data are assimilated into both NWP models*

     => *the information content of QuikSCAT data is considerably underutilized by the NWP models*

Objective of this Seminar

To show that the reasons for the underestimation of high wavenumber variability in the NWP models are, in approximate order of importance:

1) *Under-representation of vertical mixing sensitivity to atmospheric stability*

2a) *Resolution limitations of the SST boundary condition*

2b) *Model grid resolution*

2c) *Horizontal mixing*

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To show that the reasons for the underestimation of high wavenumber variability in the NWP models are, in approximate order of importance:

1) *Under-representation of vertical mixing sensitivity to atmospheric stability*

2a) *Resolution limitations of the SST boundary condition*

2b) *Model grid resolution*

2c) *Horizontal mixing*

Items 2a,b,c only affect the model simulations only on scales shorter than ~250 km

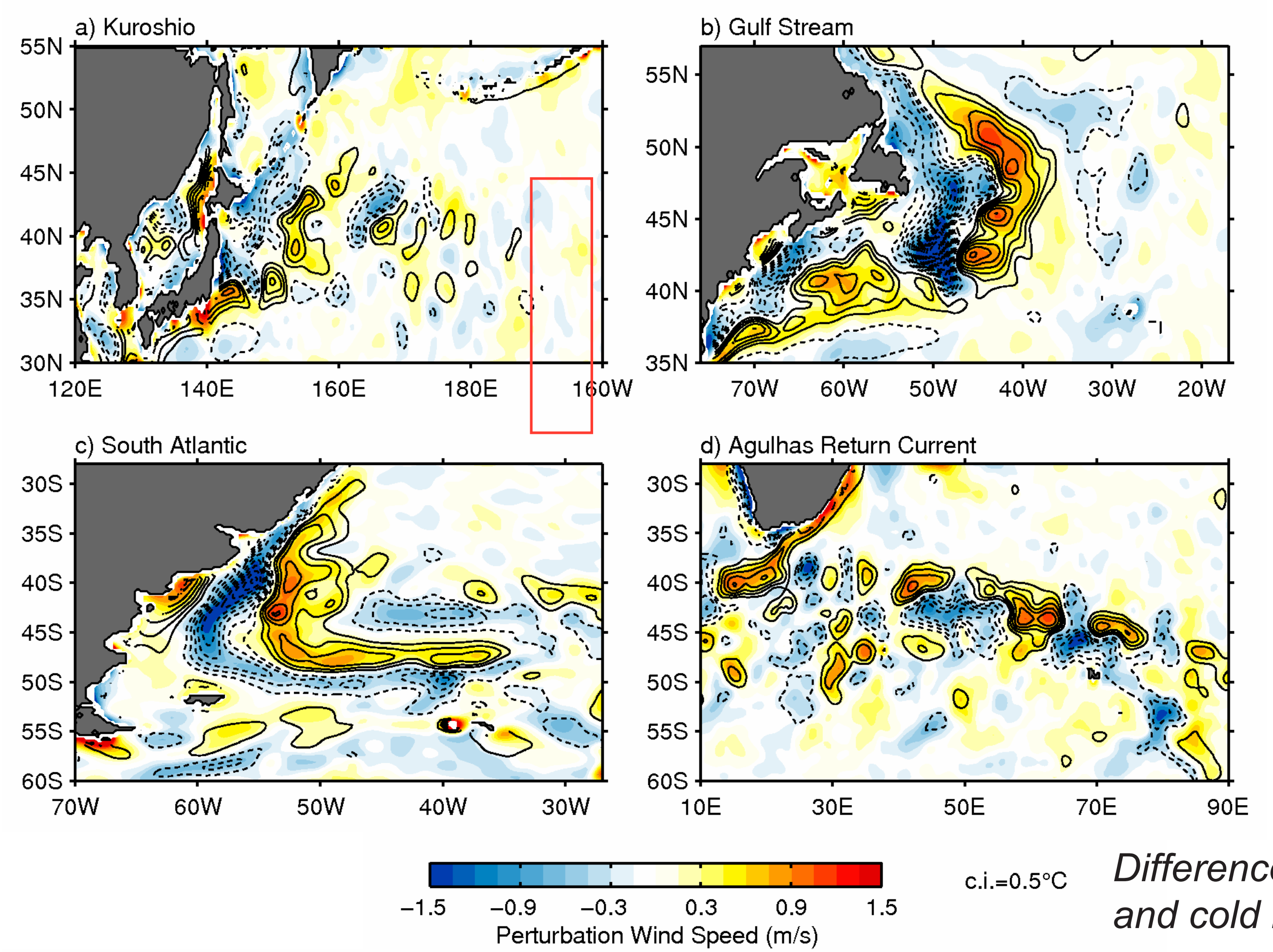
Item 1 affects the model simulations on all scales

1. Satellite Observations of SST Influence on Surface winds

Based on QuikSCAT observations of surface wind speed and AMSR observations of SST

Spatially High-Pass Filtered Wind Speed from QuikSCAT and SST from AMSR

January - December 2003



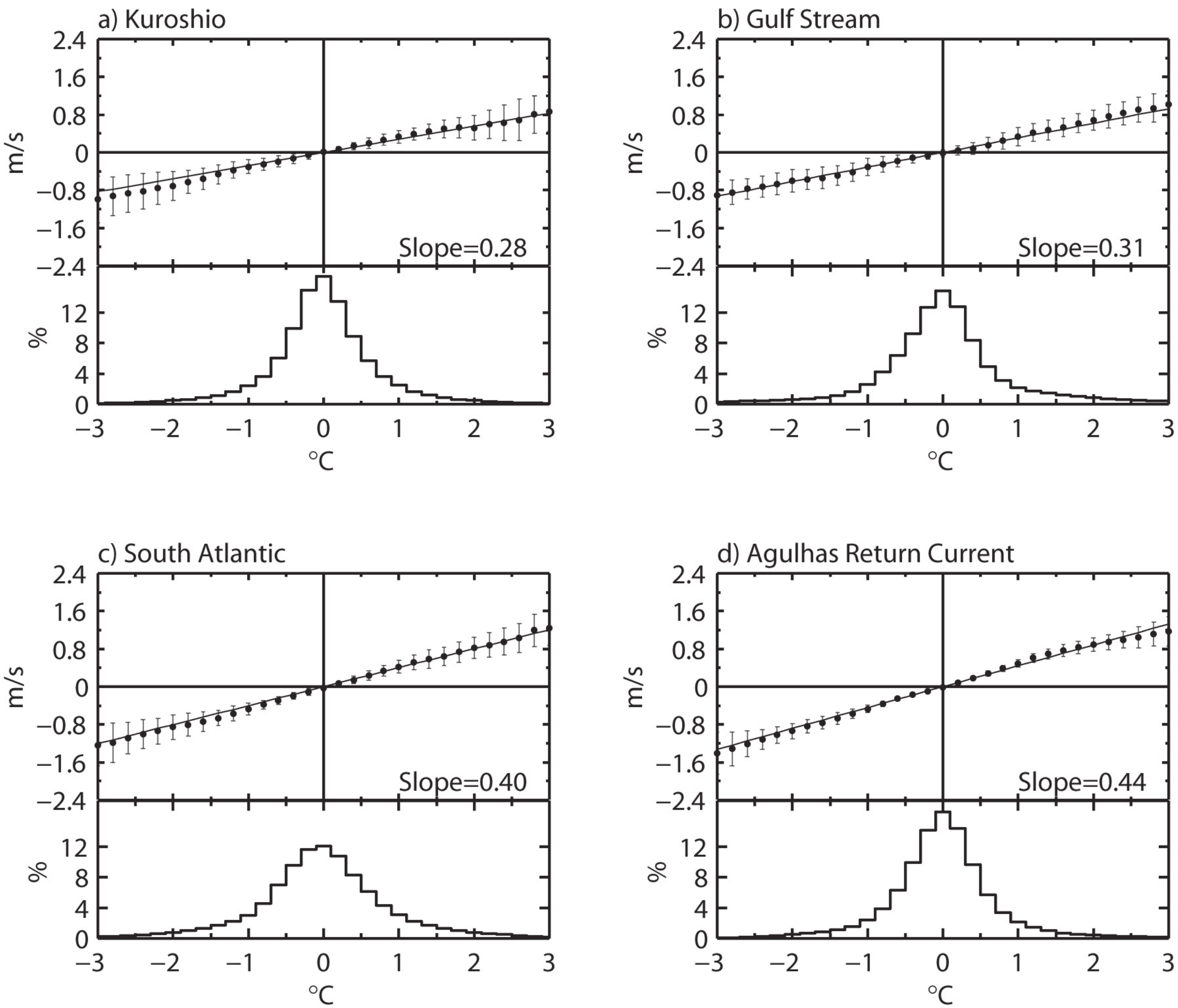
Differences between warm and cold regions are ~3-5ºC and ~2-3 m/s

Solid contours = warm SST perturbations
Dashed contours = cool SST perturbations

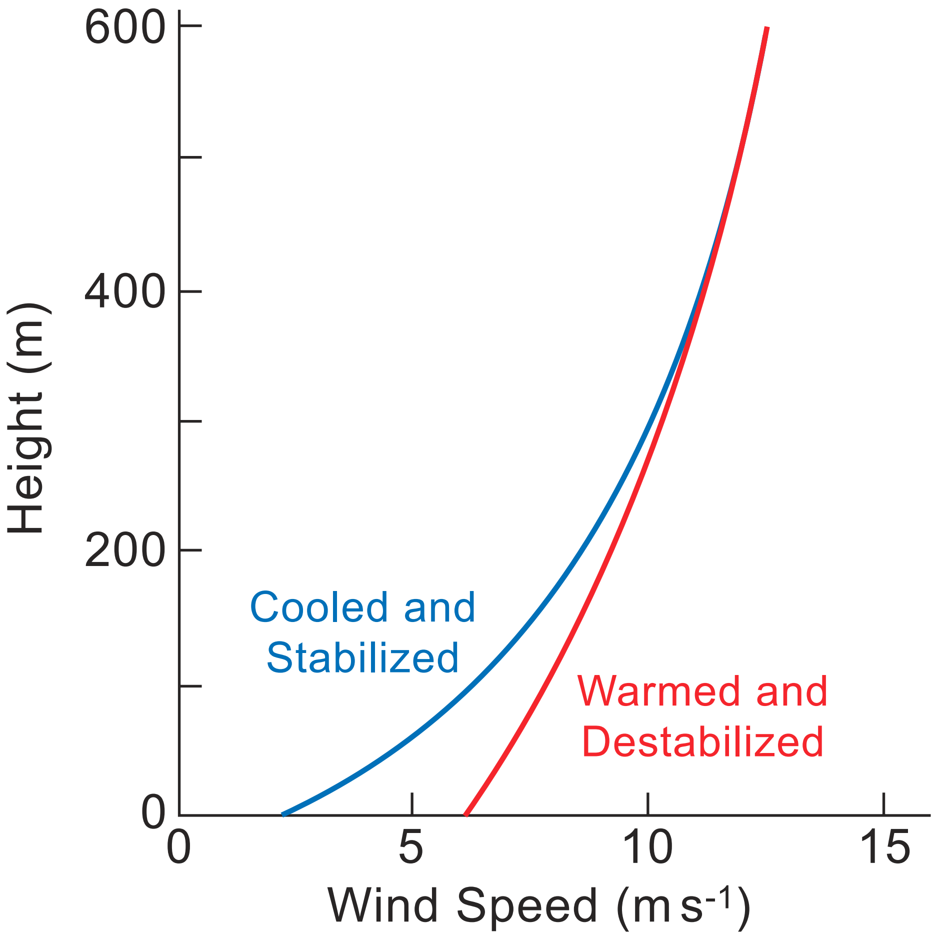
SST Influence on Wind Speed

Winds are locally stronger over warm water and weaker over cold water.

Coupling Between Wind Speed and SST



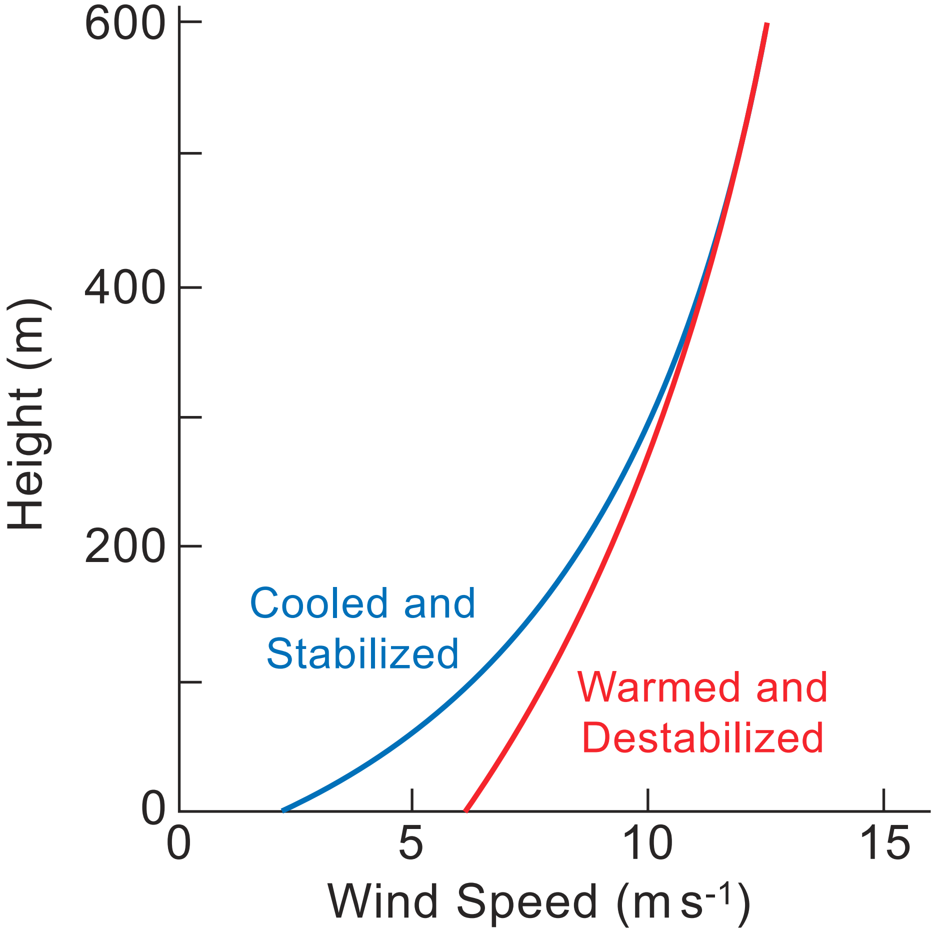
Schematic Summary of SST Influence on the Wind Speed Profile in the Marine Atmospheric Boundary Layer



This is similar to diurnal variation of the atmospheric boundary layer over land:

- *nocturnal stable boundary layer from radiative cooling*
- *daytime unstable boundary layer from solar heating of the land*

Schematic Summary of SST Influence on the Wind Speed Profile in the Marine Atmospheric Boundary Layer

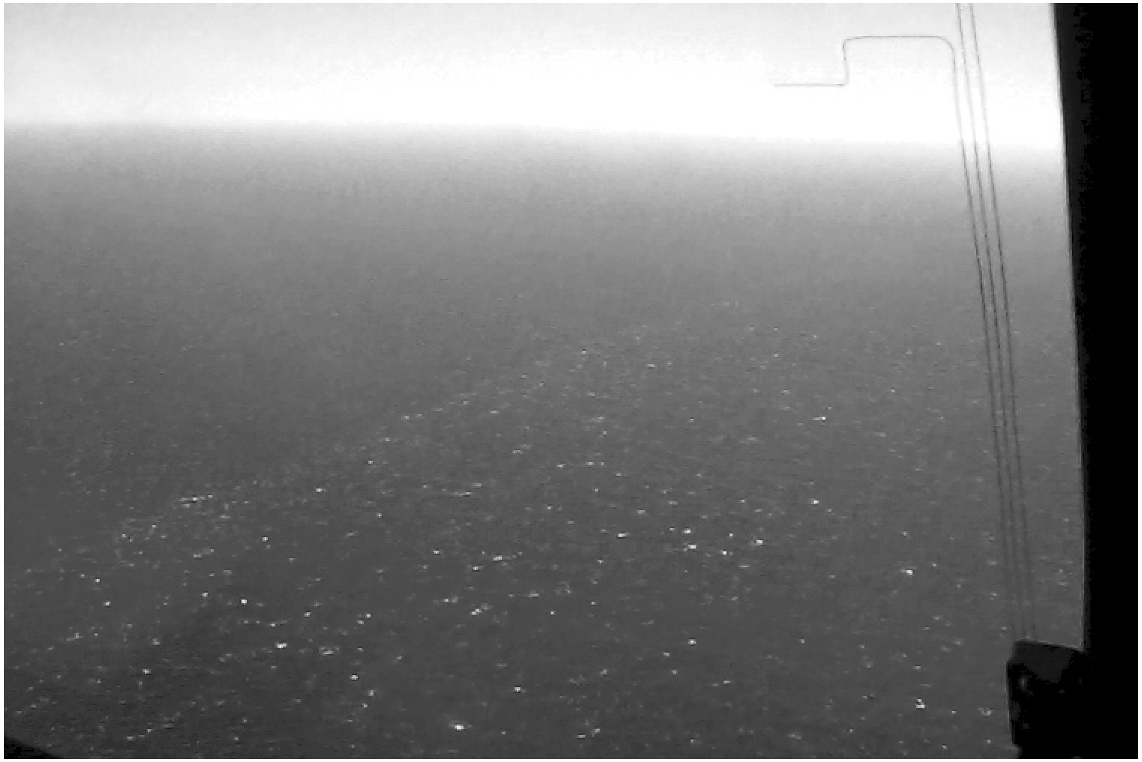


This is similar to diurnal variation of the atmospheric boundary layer over land:

- *nocturnal stable boundary layer from radiative cooling*
- *daytime unstable boundary layer from solar heating of the land*

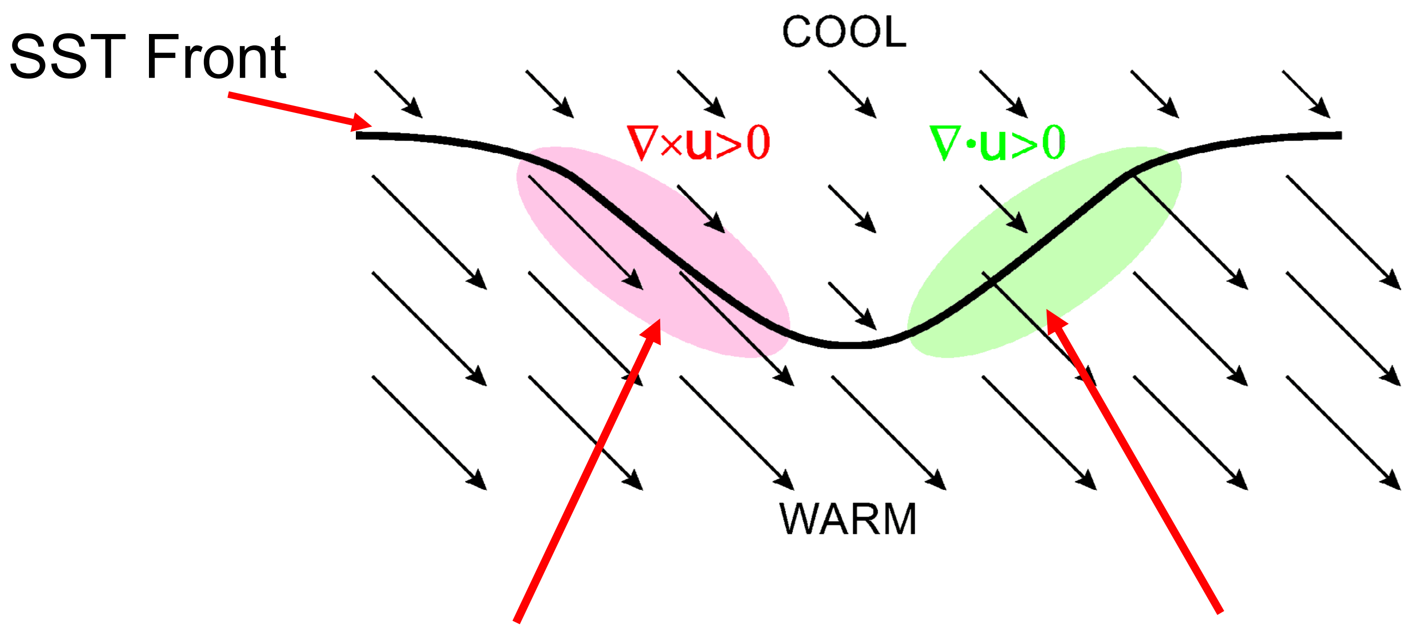
Note that vertical turbulent mixing is not the only term that is important in the momentum balance. The nonlinear advection and pressure gradient terms are also important, especially the latter.

- *see later discussion of wind direction changes across SST fronts*



Photograph taken from the NOAA P-3 aircraft looking northeast across the North Wall of the Gulf Stream. The winds were blowing from the northeast at the time of the photograph. The seas were calm over the colder slope waters to the northwest of the Gulf Stream (the upper left area of the photo) and white caps covered the warmer water to the southeast. (Courtesy of Paul Chang, NOAA.)

SST-Induced Perturbations of Vorticity and Divergence Near SST Fronts



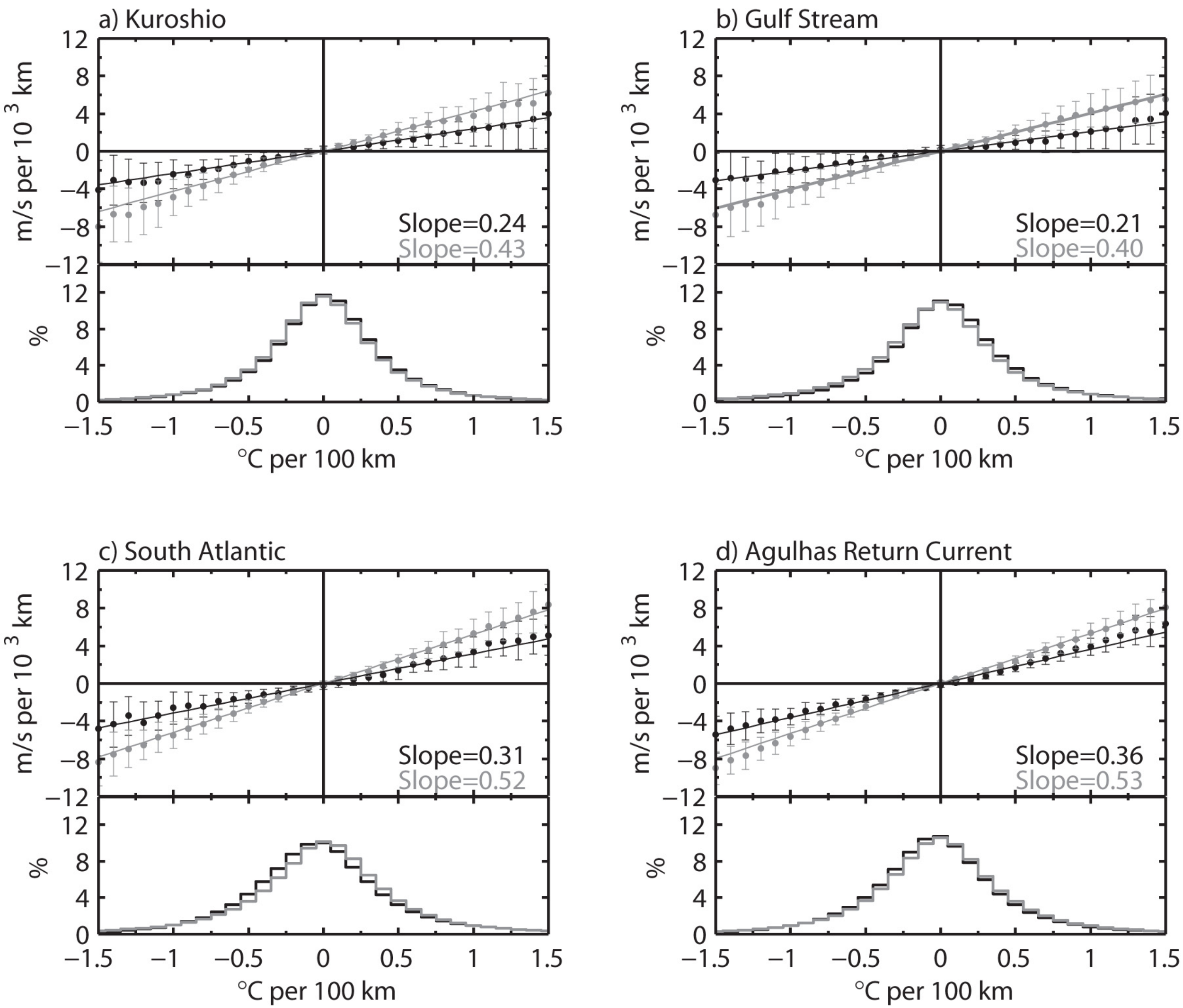
Vorticity associated with crosswind SST gradient as winds blow along SST fronts

Divergence associated with downwind SST gradient as winds blow across SST fronts

Wind Vorticity and Divergence Responses to SST Gradients

Coupling Between Vorticity and Crosswind SST Gradient (black)
and Between Divergence and Downwind SST Gradient (gray)

Note that divergence response is consistently stronger than vorticity response.



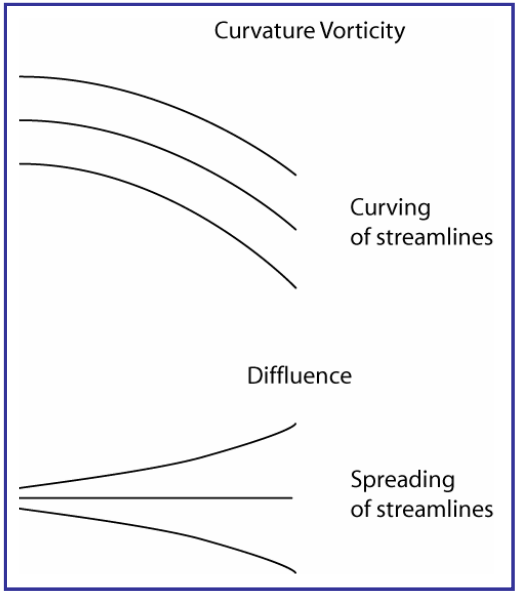
Vorticity and Divergence in Natural Coordinates

$$\underbrace{\nabla \times \boldsymbol{u}}_{\text{Vorticity}} = \underbrace{-\frac{\partial V}{\partial n}}_{\substack{\text{Crosswind}\\\text{Speed Gradient}}} + \underbrace{V\frac{\partial \psi}{\partial s}}_{\substack{\text{Curvature}\\\text{Vorticity}}}$$

$$\underbrace{\nabla \cdot \boldsymbol{u}}_{\text{Divergence}} = \underbrace{\frac{\partial V}{\partial s}}_{\substack{\text{Downwind}\\\text{Speed Gradient}}} + \underbrace{V\frac{\partial \psi}{\partial n}}_{\text{Diffluence}}$$

where

$$\begin{aligned} \boldsymbol{u} &= \text{Surface Wind Vector } (u, v) \\ V &= \text{Surface Wind Speed} \\ \psi &= \text{Surface Wind Direction} \\ (s, n) &= \text{Local Downwind and Crosswind Directions} \end{aligned}$$



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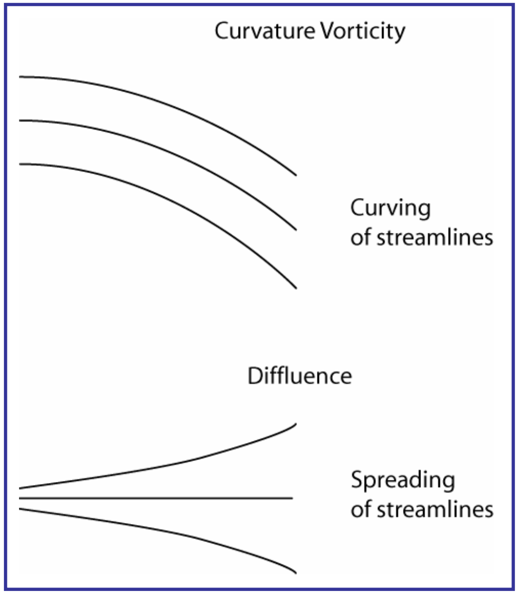
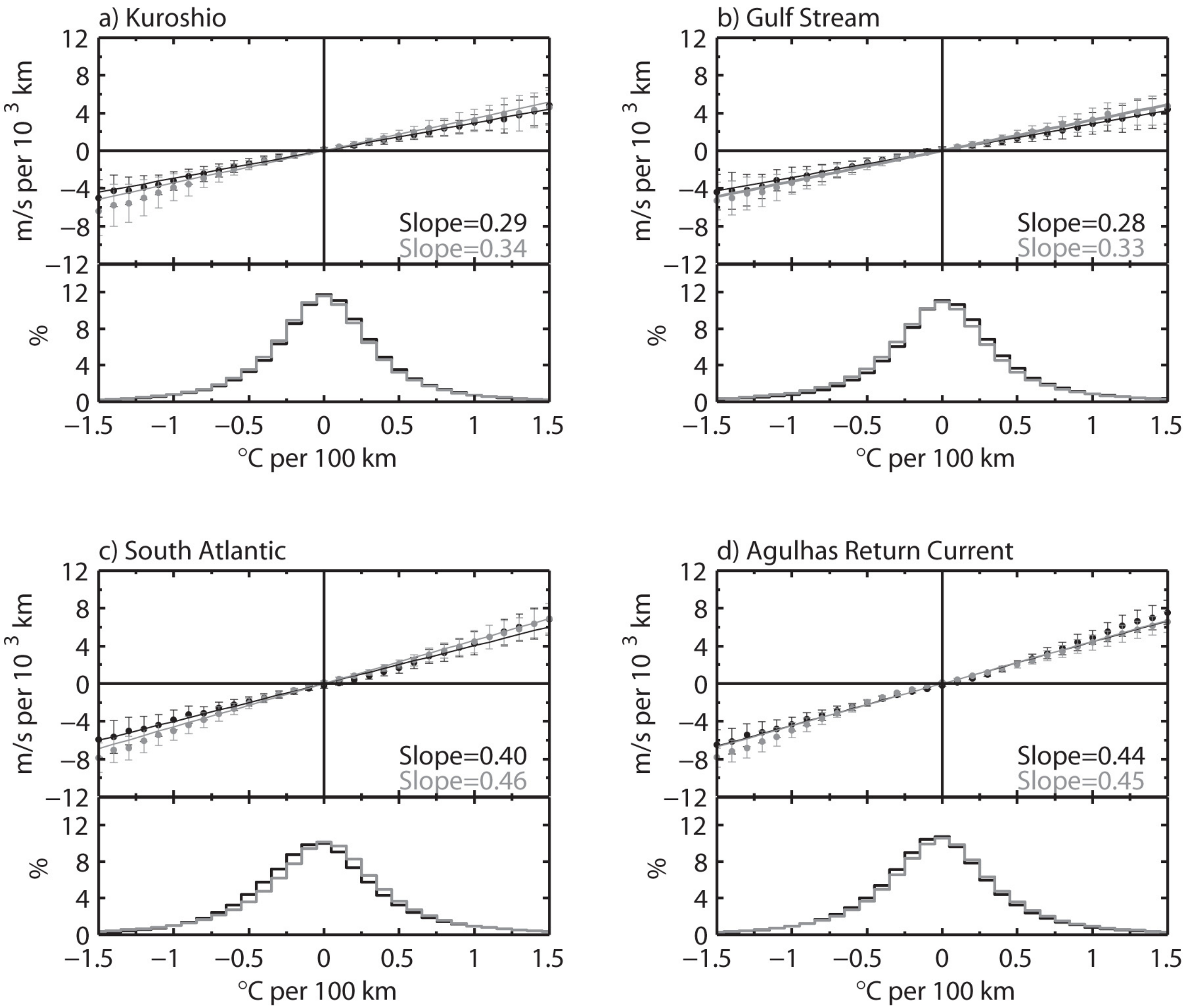


The speed-only contributions should have the same coupling coefficients as that for wind speed dependence on SST:

- *the crosswind speed gradient vs. the crosswind SST gradient*
- *the downwind speed gradient vs. the downwind SST gradient*

SST Influence on Speed-Only Contributions to Divergence and Vorticity



Speed-Only Contributions to Divergence and Vorticity

$$\nabla \times \boldsymbol{u} = -\frac{\partial V}{\partial n}$$

lateral shear

$$\nabla \cdot \boldsymbol{u} = \frac{\partial V}{\partial s}$$

along-wind acceleration

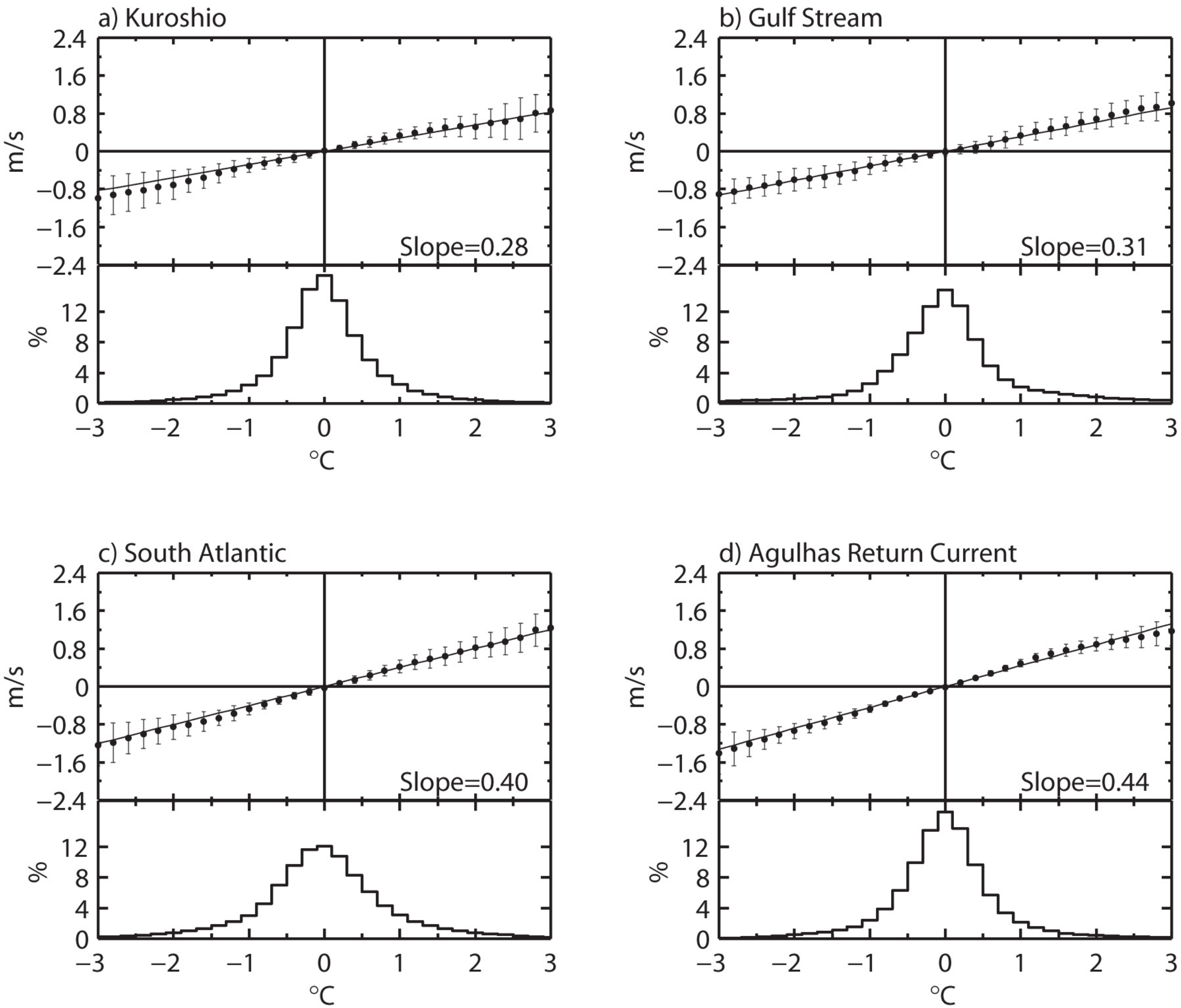
where

$\boldsymbol{u}$ = Surface Wind Vector (u, v)

V = Surface Wind Speed

(s, n) = Local Downwind and Crosswind Directions

SST Influence on Wind Speed



$$
\begin{aligned}
\nabla \times \boldsymbol{u} &= \boxed{-\frac{\partial V}{\partial n}} + V\frac{\partial \psi}{\partial s} \\
\nabla \cdot \boldsymbol{u} &= \boxed{\frac{\partial V}{\partial s}} + V\frac{\partial \psi}{\partial n}
\end{aligned}
$$

Result:

The slopes of the *speed-only contributions* to vorticity and divergence in response to SST gradients are the same as the slope the wind speed response to SST.

$$\nabla \times \boldsymbol{u} = \boxed{-\frac{\partial V}{\partial n}} + V\frac{\partial \psi}{\partial s}$$

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The slopes of the *speed-only contributions* to vorticity and divergence in response to SST gradients are the same as the slope the wind speed response to SST.

Implication:

The larger slopes of the *total* vorticity and divergence in response to SST gradients are evidently due to effects of SST on wind *direction* that enhance divergence while diminishing vorticity.

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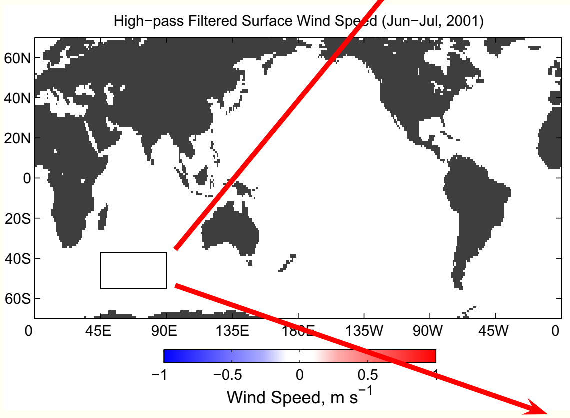
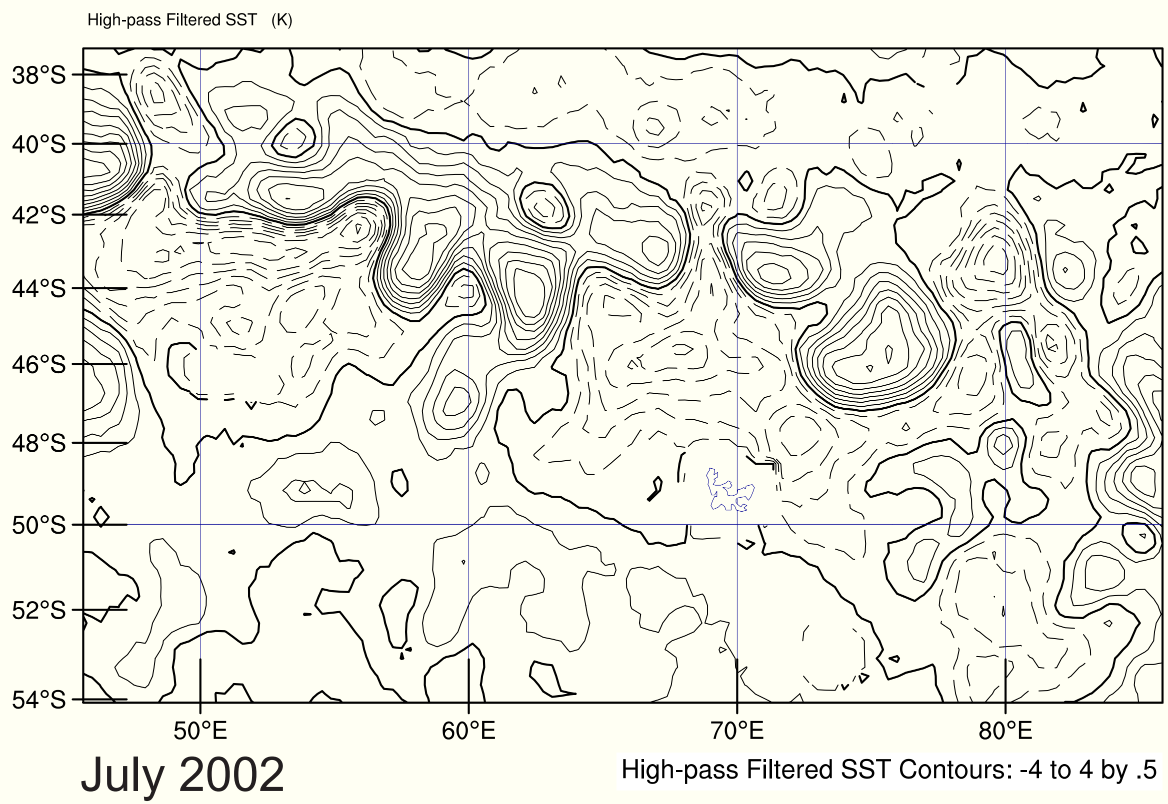
Question:

What is the mechanism for SST influence on wind direction?

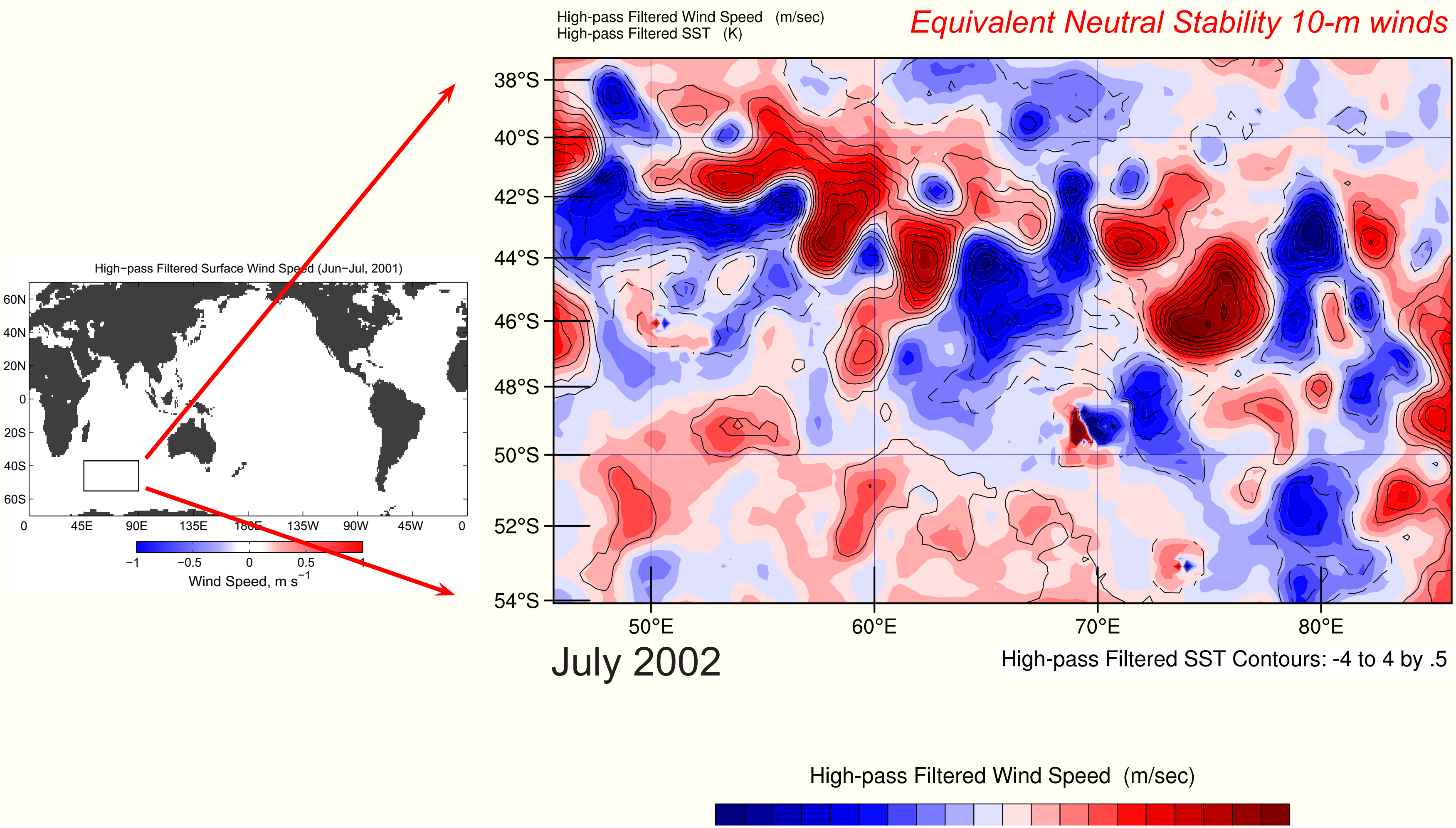
- *This was investigated from simulations with the Weather Research & Forecasting (WRF) model (successor to the MM5 model)*

AMSR SST (spatially high-pass filtered)

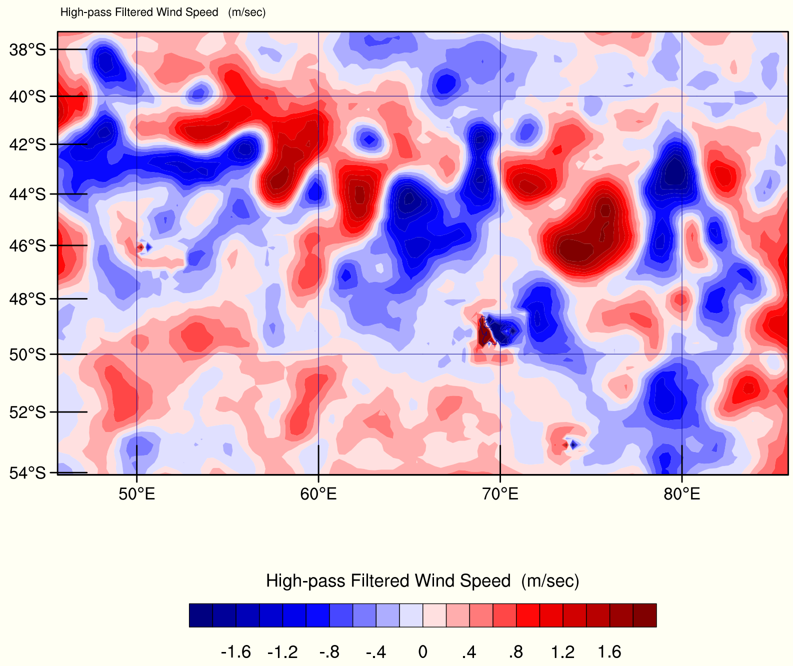


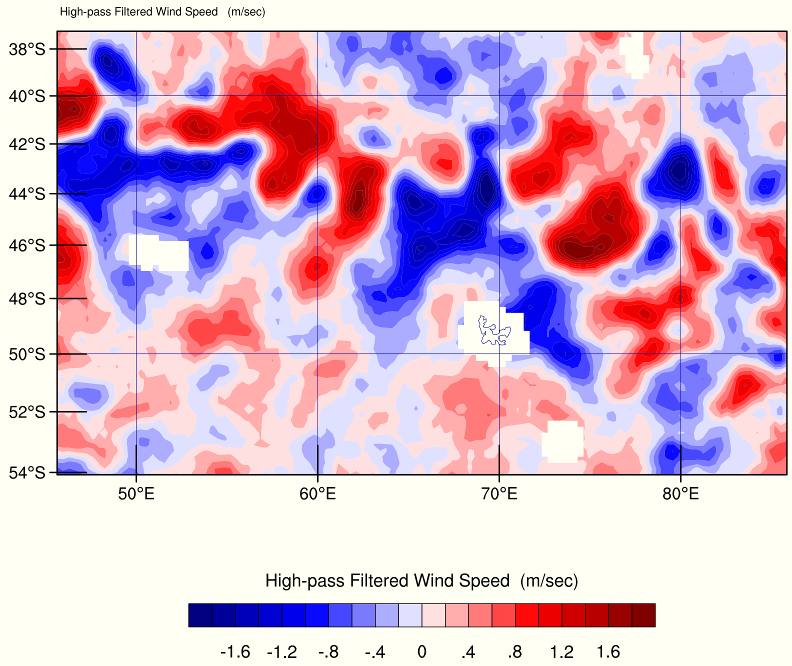


AMSR SST + WRF Wind Speed (color)



WRF wind speed (U_{10}^{N})   *QuikSCAT observation*





(July 2002, spatially high-pass filtered)

The close agreement between surface winds from the WRF model and from the QuikSCAT observations lends confidence that the WRF model can be used to investigate the dynamics of SST influence on the atmosphere.

Summary of the Momentum Budget from the WRF Model

- Vertical turbulent mixing generated by air-sea heat flux increases the wind speed over warm water and decreases it over cold water.
- Spatial variability of the SST field leads to vorticity and divergence of the winds over SST fronts
- Pressure perturbations develop just downstream of SST anomalies.
  - *Other terms in the momentum budget besides the pressure gradient are also important, e.g., the Coriolis term and advection*
- Geostrophic adjustment in response to the pressure gradient rotates the winds cyclonically downwind of warm SST anomalies and anticyclonically downwind of cold SST anomalies.
- The divergence response to downwind SST gradients is stronger than the vorticity response to crosswind SST gradients because of these changes in wind direction that:
  - *enhance the divergence response to downwind SST gradients through difluence*
  - *diminish the vorticity response to crosswind SST gradients through curvature vorticity.*

2. SST Influence on Surface winds in the ECMWF Global Forecast Model

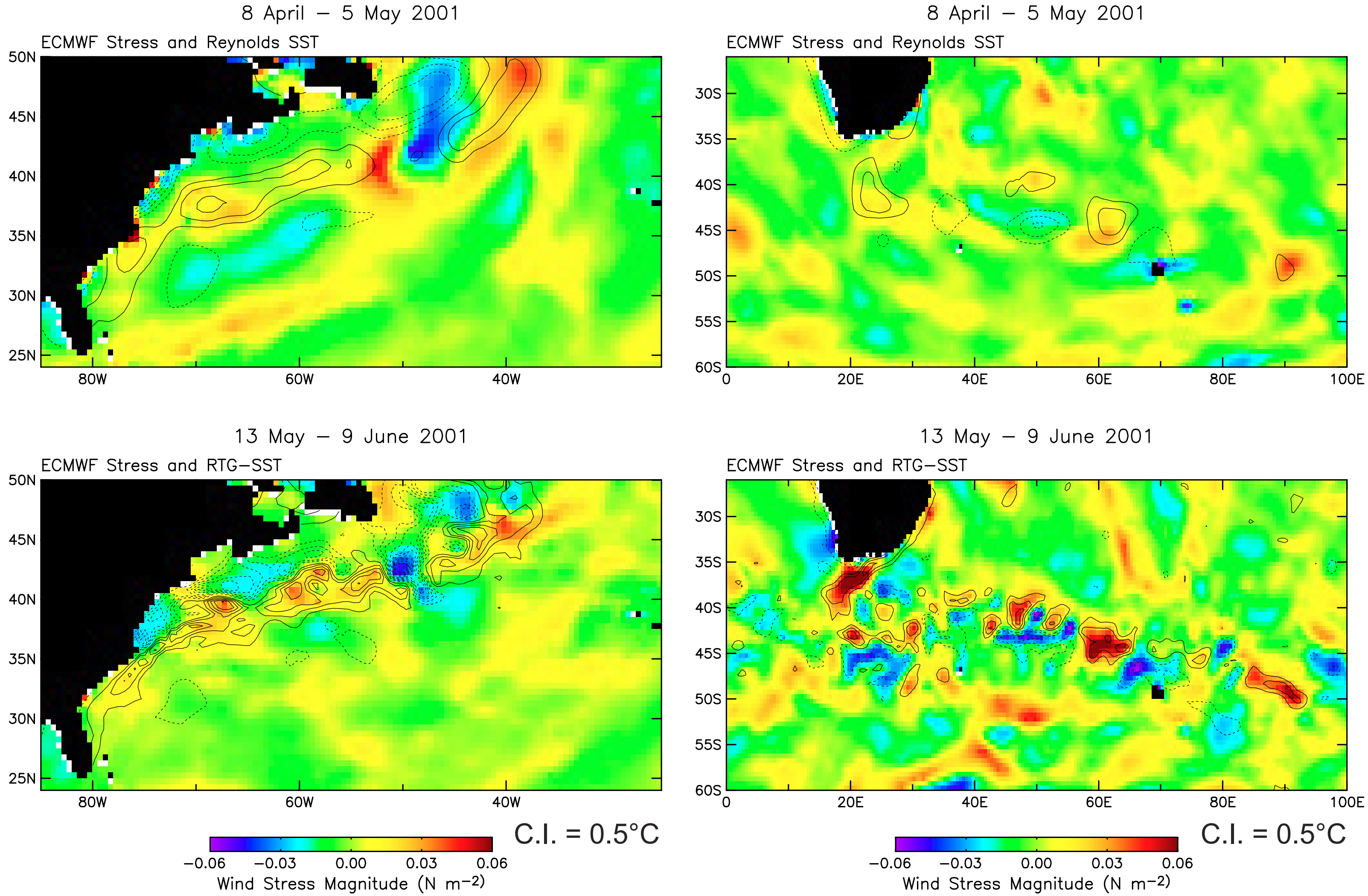
Based on surface wind analyses from the operational ECMWF global forecast model

The importance of SST specification is evident from comparisons of ECMWF winds before and after 9 May 2001:

The ocean surface boundary condition was changed from the low-resolution Reynolds SST analyses to the higher resolution Real-Time Global (RTG) SST analyses on this date.

4-Week Averages of ECMWF Wind Stress Magnitude

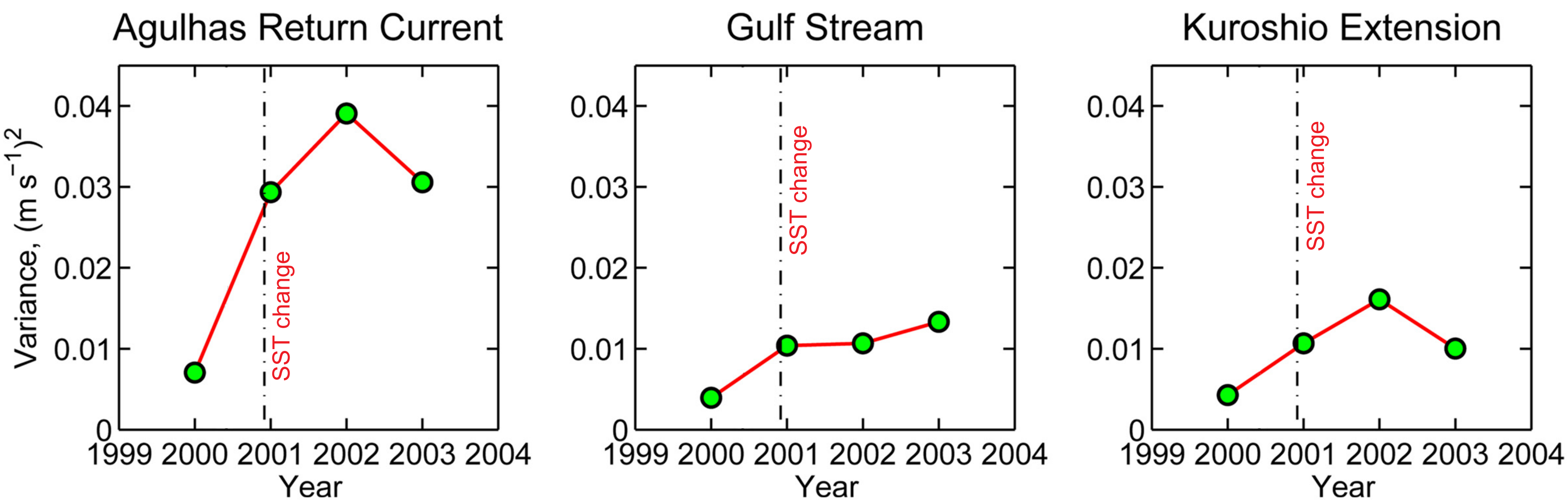
Before and After the 9 May 2001 Change of the SST Boundary Condition



Small-scale variability in the surface wind field increased abruptly after the 9 May 2001 change to a higher resolution SST boundary condition.

Small-Scale Variance in ECMWF 10-m Wind Speed

June-July Averages 2000, 2001, 2002 and 2003



9 May 2001: Change from Reynolds to RTG SST boundary condition

Figure courtesy of Qingtao Song

Small-Scale Variance in ECMWF 10-m Wind Speed

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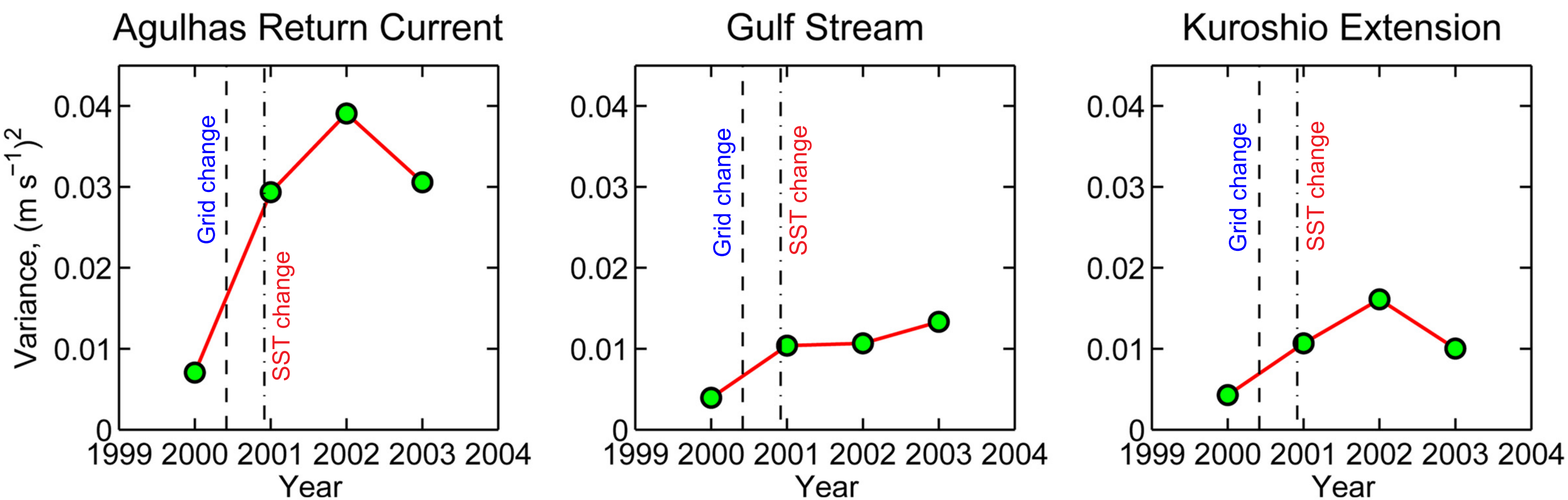
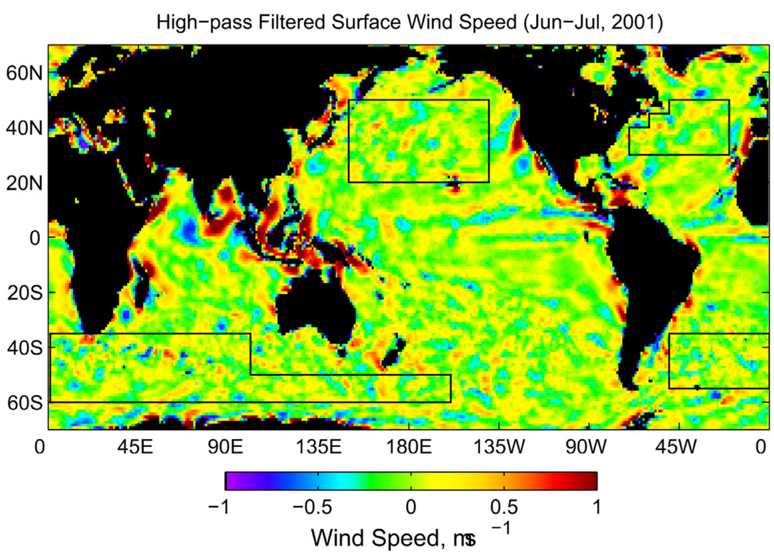


21 November 2000: Change of model grid from TL319 to TL511 (~60 km to ~40 km)

9 May 2001: Change from Reynolds to RTG SST boundary condition

Figure courtesy of Qingtao Song

Small-Scale Spatial Variance in ECMWF 10-m Wind Speed Over Land and Over Open Ocean



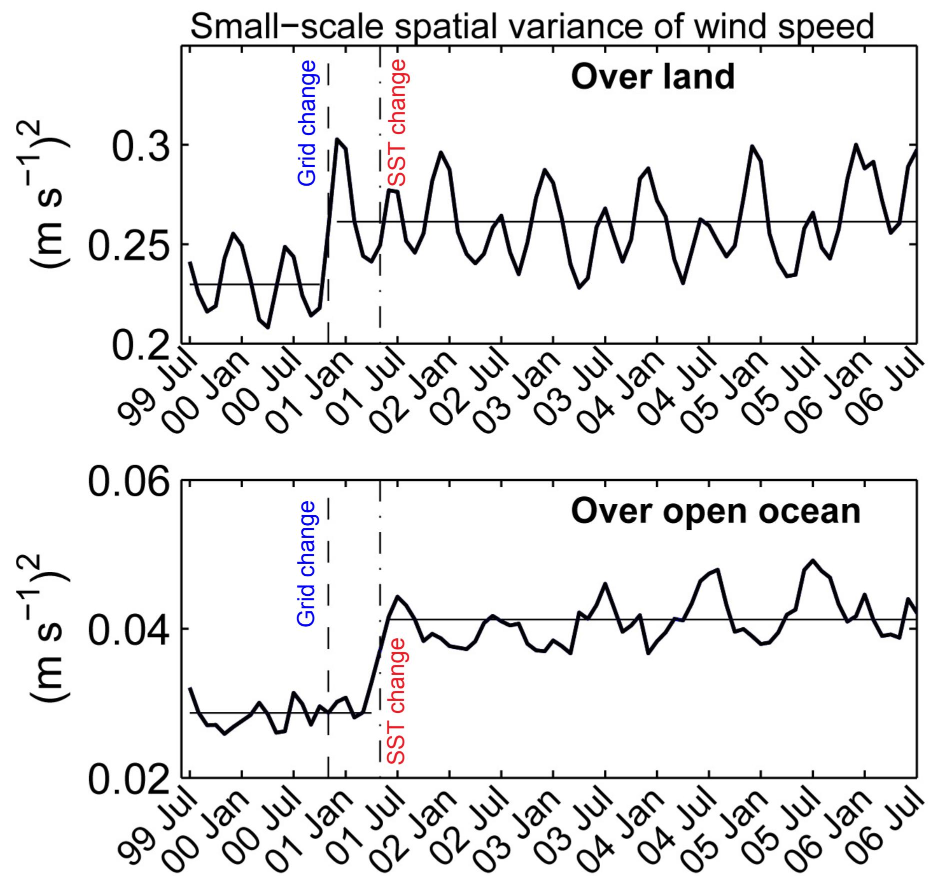


Figure courtesy of Qingtao Song

Result from analysis of ECMWF model sensitivity to SST specification:

Improving the accuracy and resolution of the SST boundary condition in NWP models does indeed improve the accuracy of surface wind fields over the ocean.

Result from analysis of ECMWF model sensitivity to SST specification:

Improving the accuracy and resolution of the SST boundary condition in NWP models does indeed improve the accuracy of surface wind fields over the ocean.

Question:

How well would the observed air-sea interaction be represented in the NWP models if the SST boundary condition were "perfect"?

In other words, how well does the coupling coefficient between surface winds and SST in the NWP models compare with the coupling coefficient inferred from QuikSCAT and AMSR data?

Spatially High-Pass Filtered Wind Speed versus SST

September 2002 - August 2004

The coupling between surface wind speed and SST is underestimated in the ECMWF model by about a factor of 2 in all three regions.

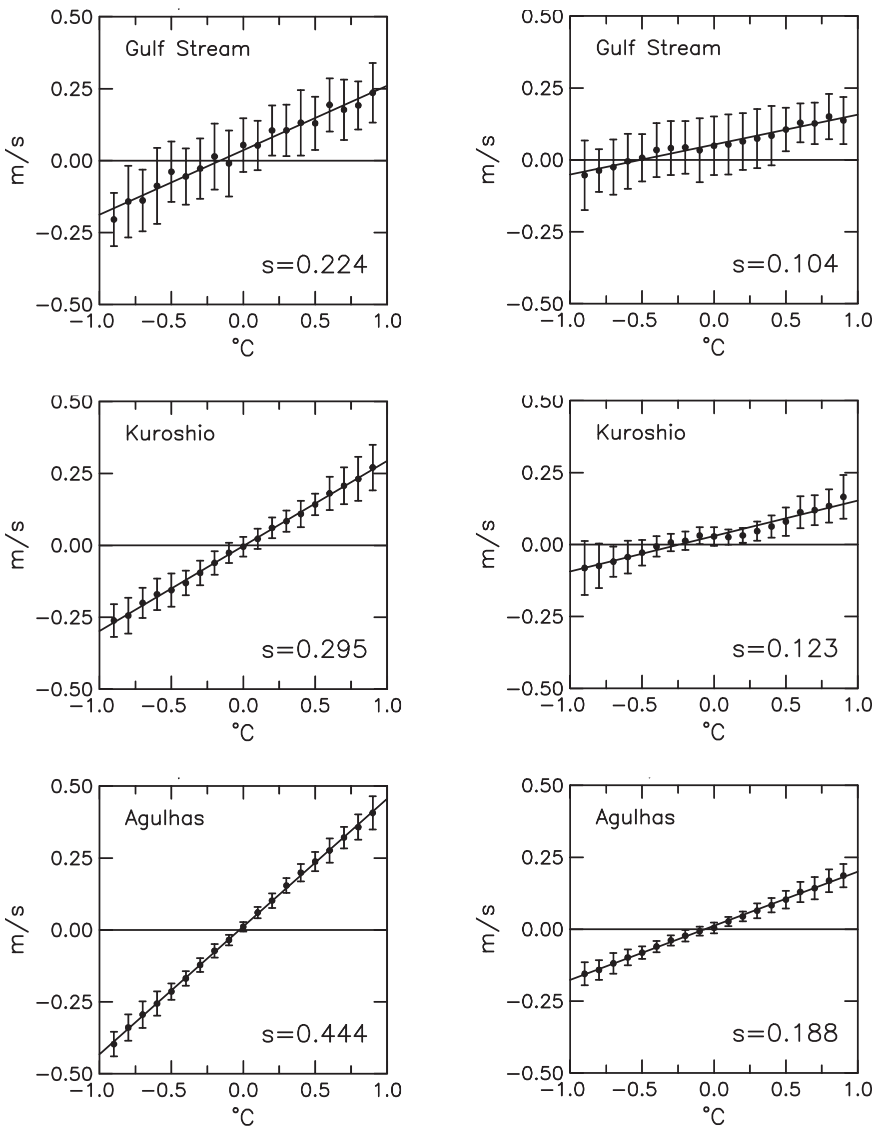
QuikSCAT and AMSR

ECMWF and RTG

Gulf Stream

Kuroshio

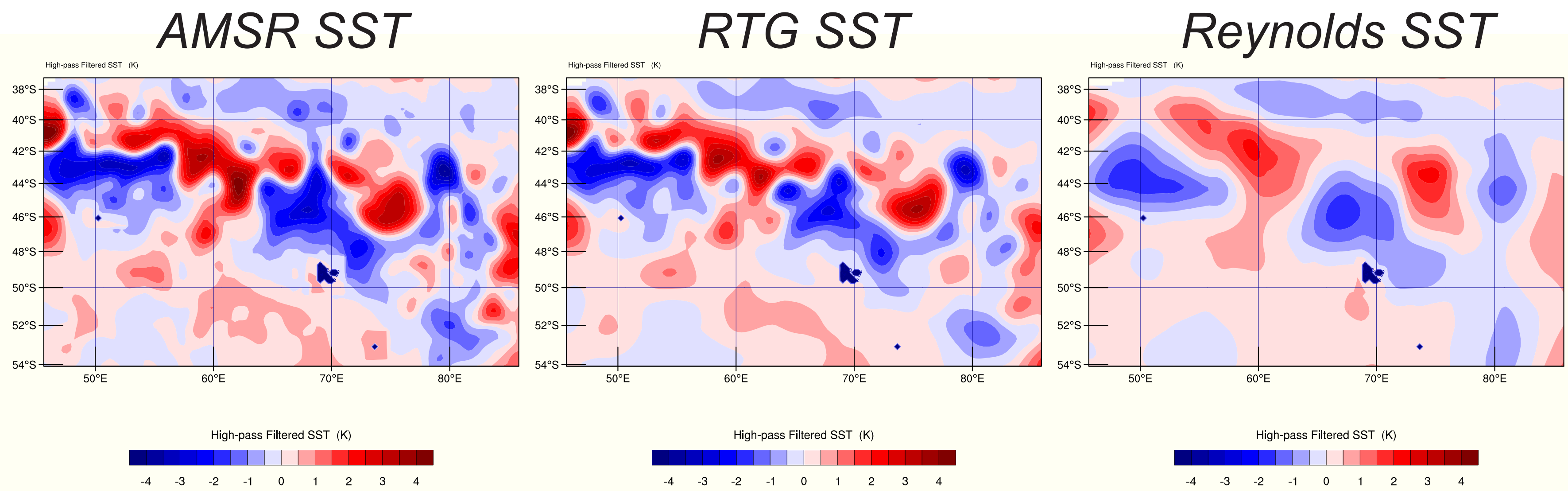
Agulhas

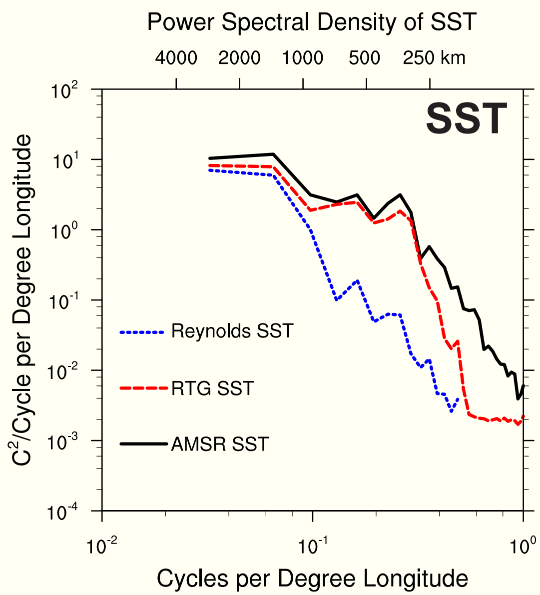


3. Mesoscale model sensitivity studies to investigate surface wind response to SST

Based on wavenumber spectral analysis of simulations with the Weather Research & Forecasting (WRF) model

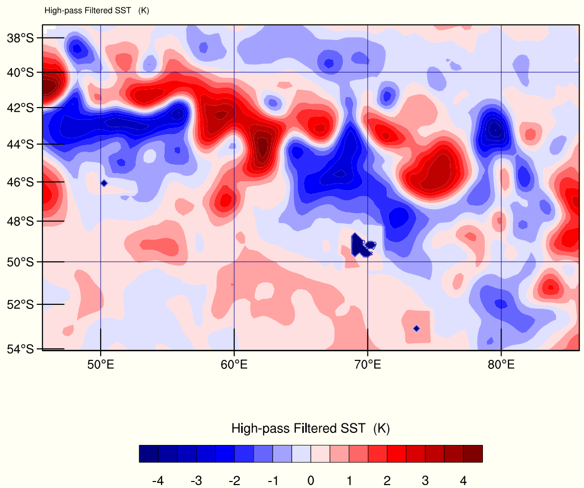
Sensitivity to Specification of the SST Boundary Condition



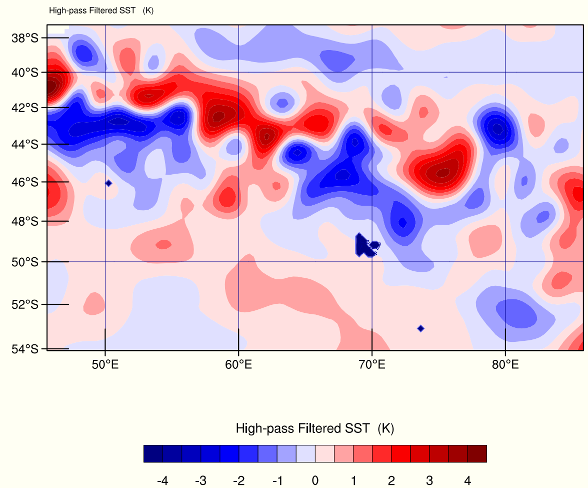


Sensitivity to Specification of the SST Boundary Condition

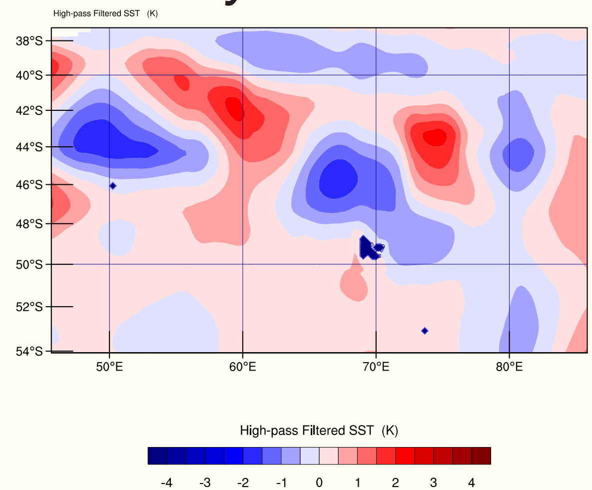
AMSR SST

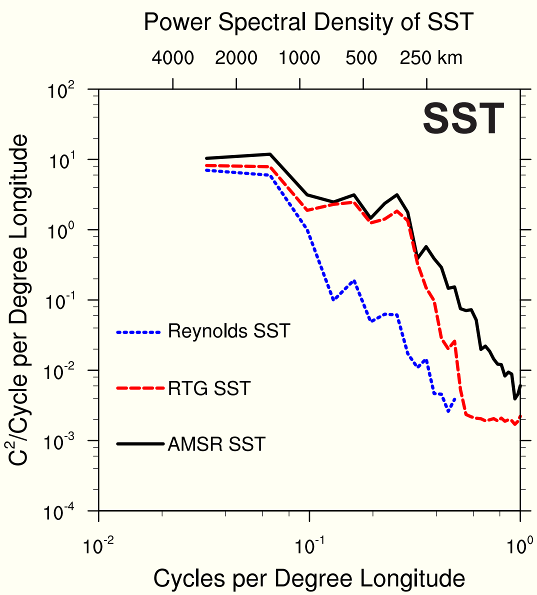


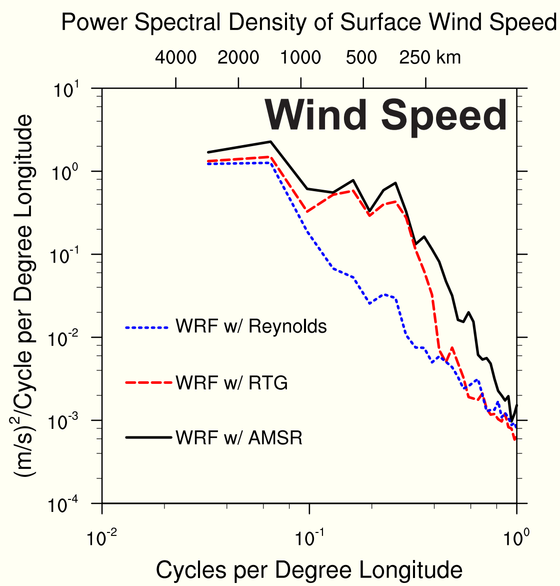
RTG SST



Reynolds SST



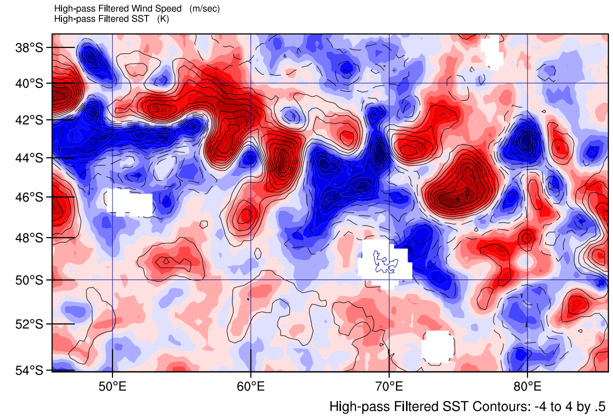


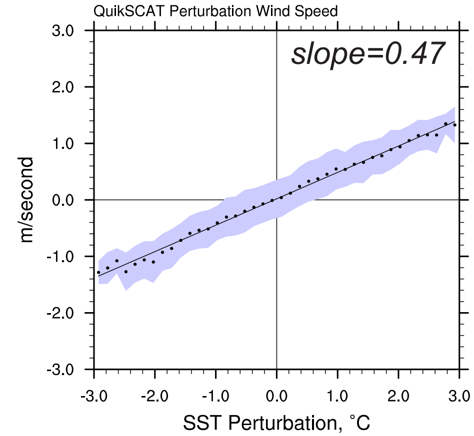


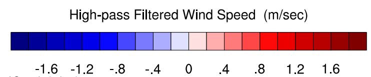
- *Forcing by Reynolds SST underestimates the energy on all scales shorter than ~1000 km.*
- ***Forcing by RTG SST underestimates the energy only on scales shorter than ~250 km***

Coupling Coefficients for Equivalent Neutral Stability 10-m Wind Speed from QuikSCAT and WRF

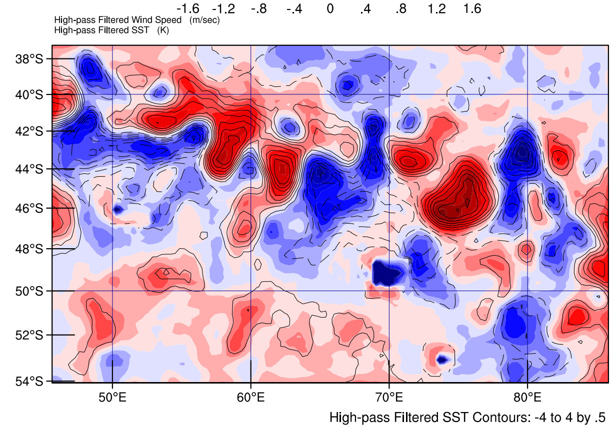
QuikSCAT

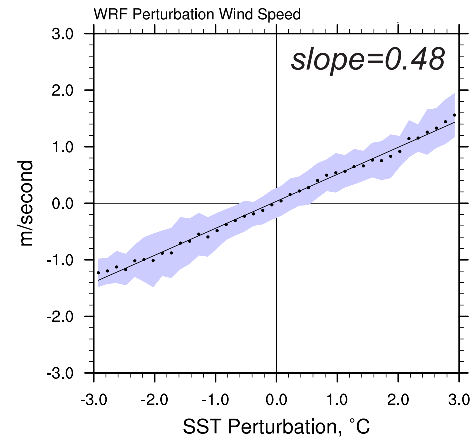


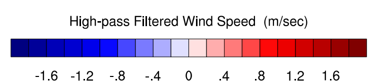




WRF



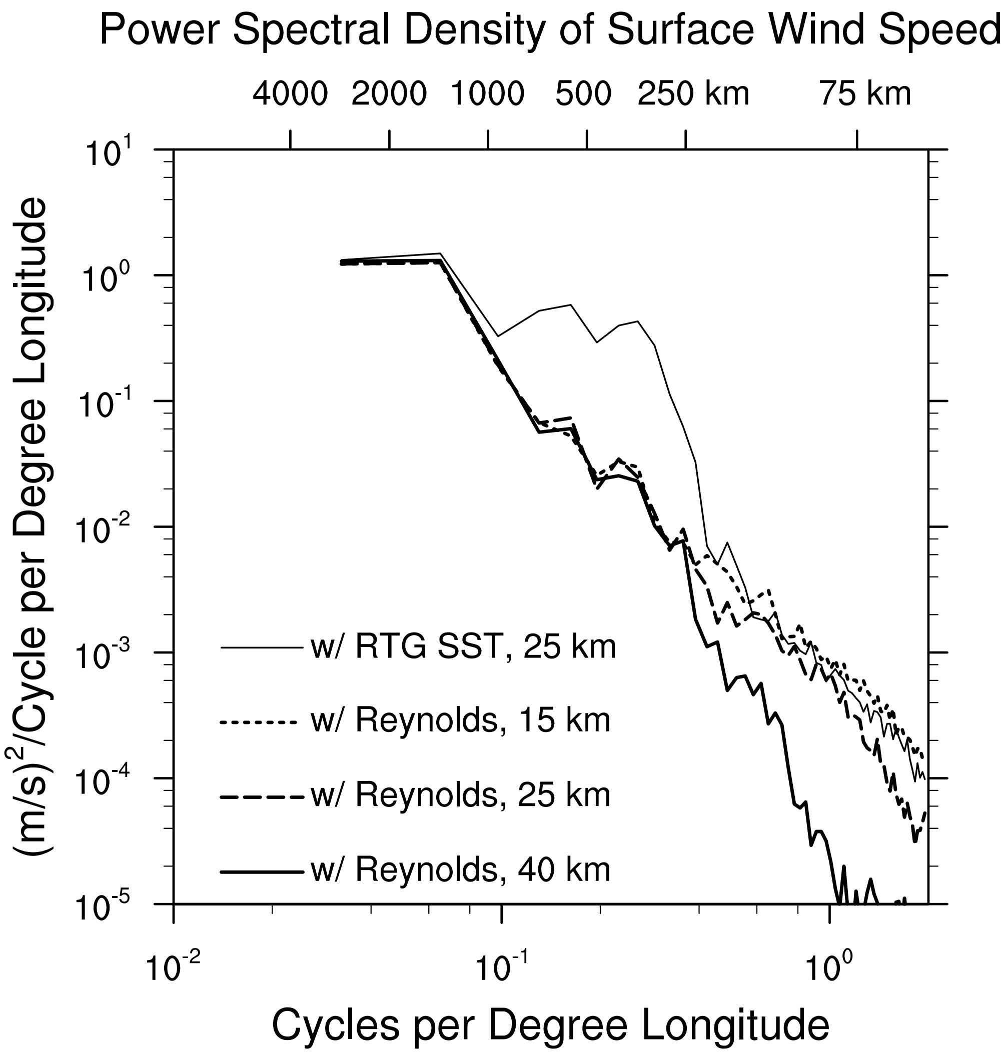




The agreement between QuikSCAT and the WRF simulation forced by AMSR SST is remarkably good.

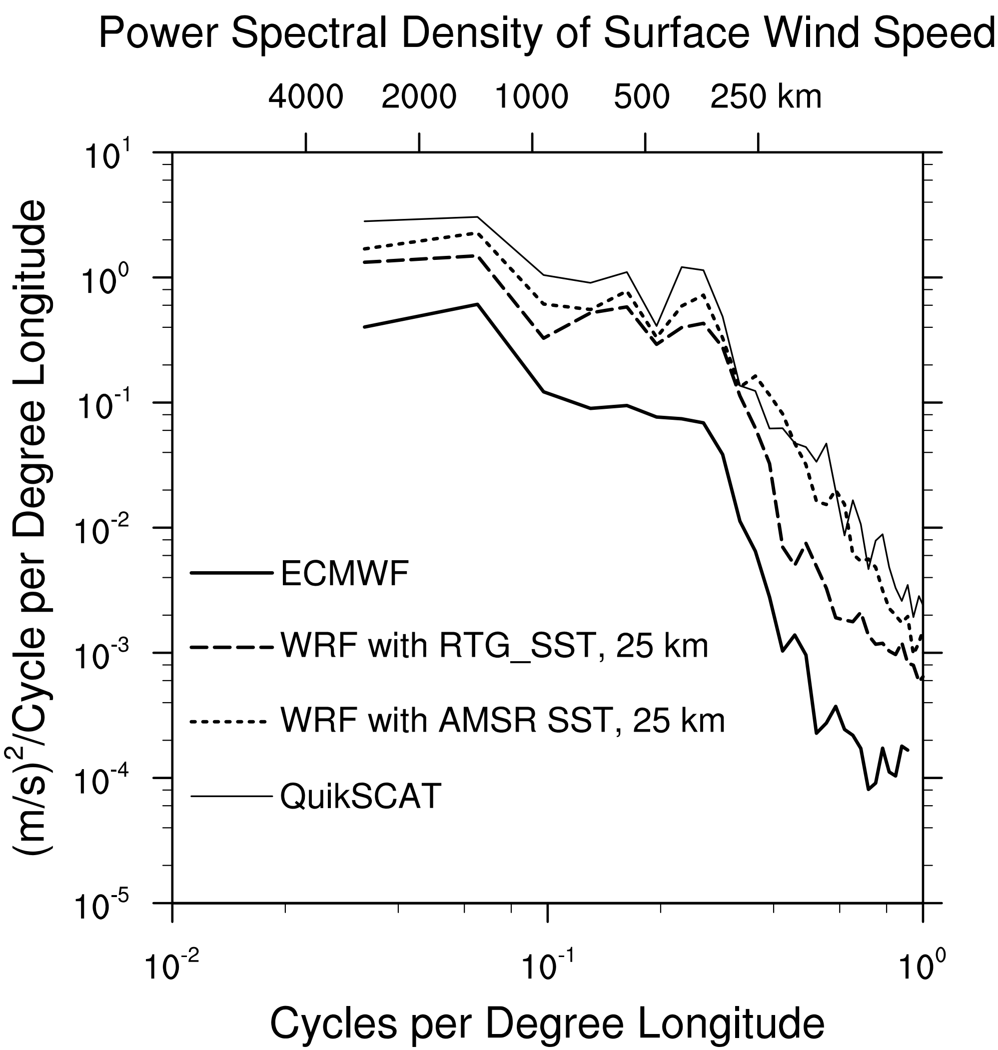
- *Note that the slope is 0.42 for 10-m winds in the WRF model forced by AMSR SST.*

Sensitivity to Grid Resolution



- ***The nominal grid resolution for our WRF experiments is 25 km.***
- *Increasing the grid resolution to 15 km had a minor effect only on scales shorter than ~100 km.*
- ***Decreasing the grid resolution to 40 km degraded the surface wind fields on scales shorter than ~250 km.***
  - *Note that the ECMWF grid resolution was 39 km during the time considered here.*
- *Replacing the Reynolds SST boundary condition with RTG SST had no discernable effect on scales shorter than ~250 km, but increased the energy of the surface winds on scales longer than ~250 km.*
  - *This is because there is little energy in the RTG SST fields on scales shorter than ~250 km, as shown previously.*

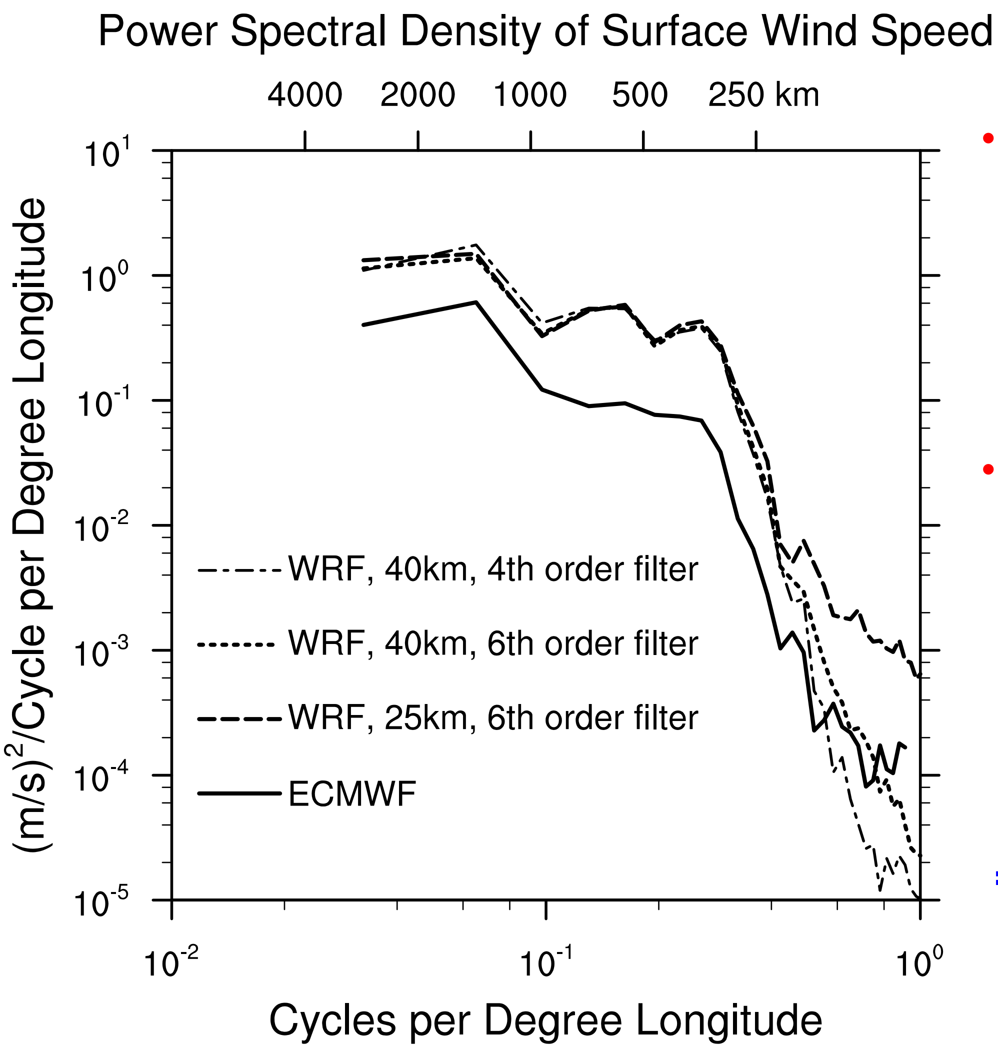
Comparisons between ECMWF, WRF and QuikSCAT



- *The WRF simulation with AMSR SST forcing agrees well with QuikSCAT.*
- *Replacing AMSR SST with RTG SST degrades the surface wind fields on scales shorter than ~250 km, as shown previously.*
- ***The ECMWF model underestimates the wind speed variability on all scales by a factor of 2-3 compared with WRF forced by RTG SST.***
  - *From the previous analysis of sensitivity to grid resolution, only the variability on scales shorter than ~250 km can be accounted for by the difference between the 39 km ECMWF grid resolution and the 25 km grid resolution for our nominal WRF simulation.*

=> The underestimation of wind speed response to SST in the ECMWF model on scales longer than ~250 km is evidently due to something besides grid resolution.

Sensitivity to Horizontal Mixing



- *To control small-scale noise and to avoid numerical instabilities, the WRF model uses implicit horizontal diffusion (filtering) in its integration and advection schemes, in addition to explicit horizontal diffusion.*
- *Changing the nominal 6th-order horizontal filter to 4th-order degraded the surface wind fields moderately on scales shorter than ~250 km.*
  - *This degradation was less than that from decreasing the grid resolution from 25 km to 40 km.*

=> The underestimation of wind speed response to SST in the ECMWF model on scales longer than ~250 km is evidently due to something besides horizontal mixing.

Vertical Mixing in the WRF Model

The WRF model uses the Mellor and Yamada (1982) stability-based parameterization of vertical turbulent mixing, with an option to use the Grenier and Bretherton (2001) enhancement of vertical mixing.

The Mellor and Yamada (1982) parameterization of vertical eddy diffusivity for horizontal velocity can be written as

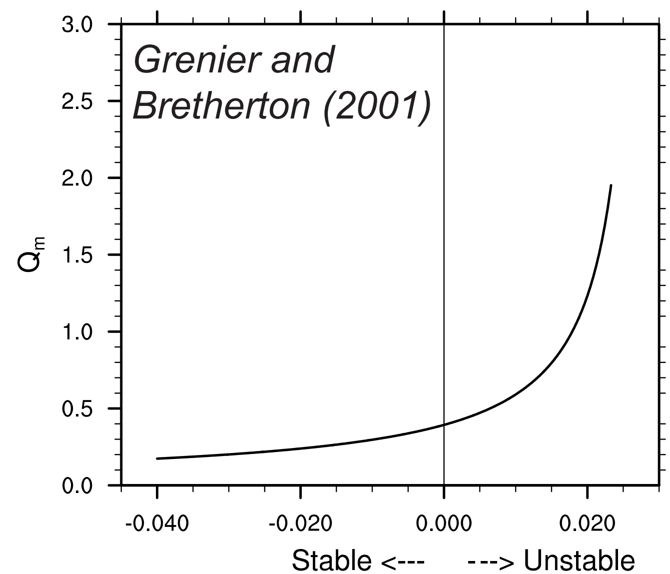
$$K_m = S_m l \sqrt{e}\,,$$

where e is the turbulent kinetic energy (TKE), l is a turbulent length scale and S_m is a stability function.

The Grenier and Bretherton (2001) parameterization enhances the vertical transport of TKE to match the TKE profile obtained from large-eddy simulations by formulating the vertical eddy diffusivity as

$$K_m = Q_m l \sqrt{e}$$

where $Q_m = 5S_m$.



Modification of the Grenier and Bretherton (2001) Parameterization of Vertical Mixing for these Sensitivity Studies

The Grenier and Bretherton (2001) parameterization enhances the vertical transport of TKE to match the TKE profile obtained from large-eddy simulations by formulating the vertical eddy diffusivity as

$$K_m = Q_m l \sqrt{e}$$

where $Q_m = 5S_m$.

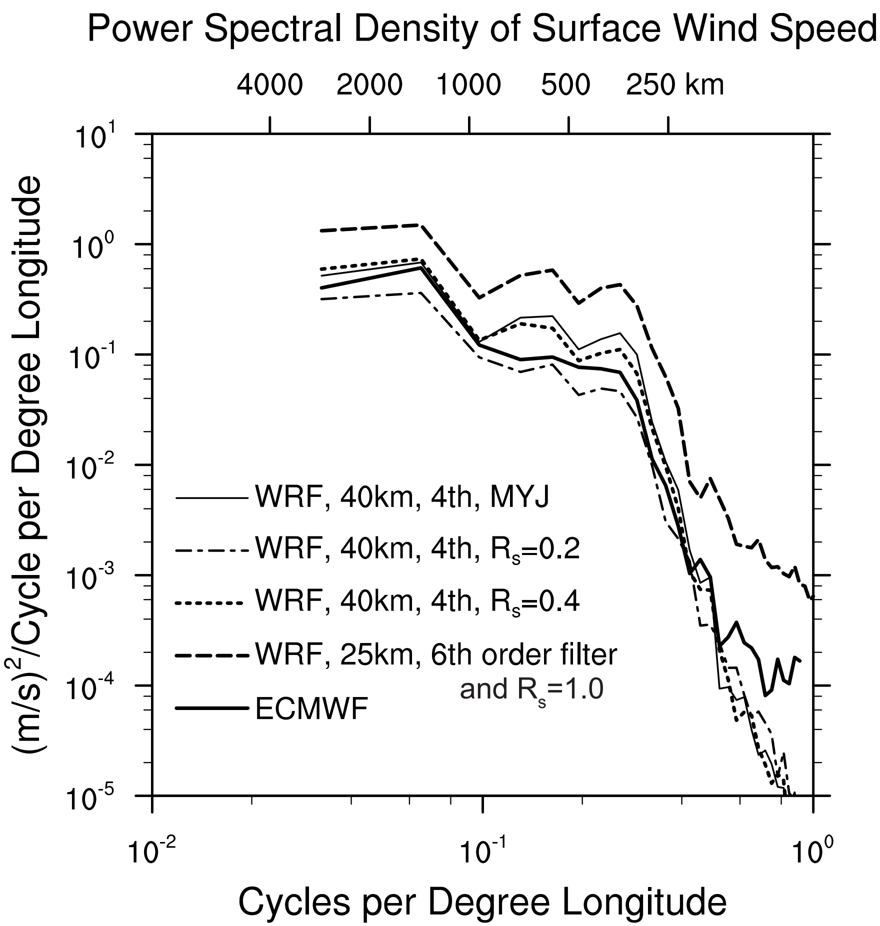
This stability dependence is modified here to have the form

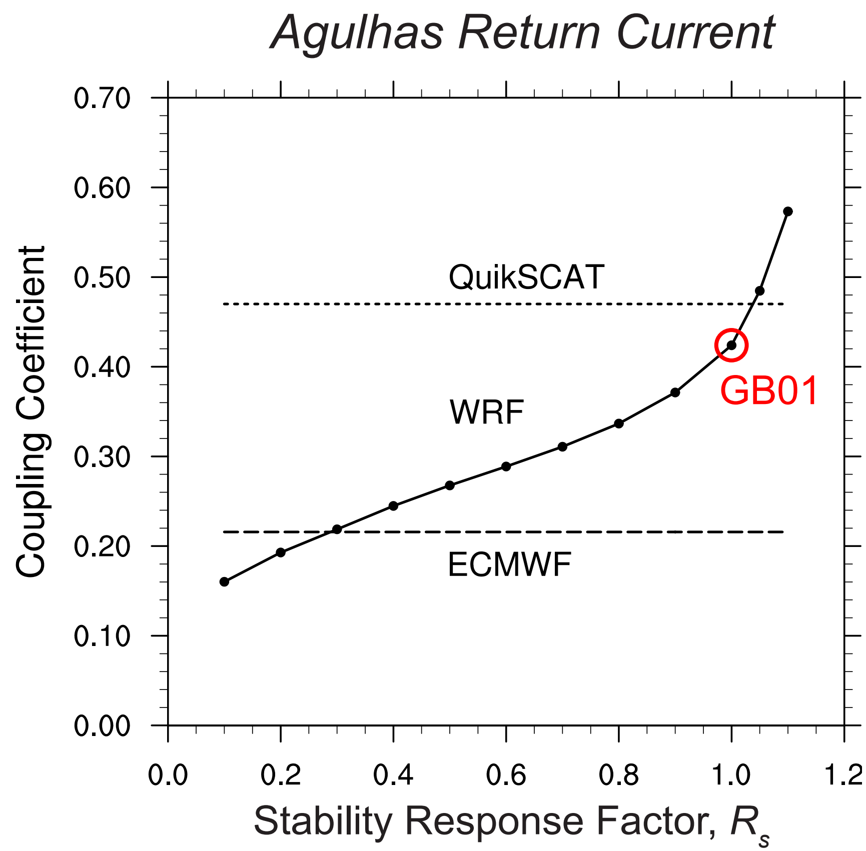
$$Q_m = S_m^N + R_s \left(5S_m - S_m^N\right),$$

where S_m^N is the stability function for neutrally static conditions and the stability response factor R_s modulates the dependence of vertical diffusion on stability.

A value of $R_s = 1$ corresponds to the Grenier and Bretherton (2001) scheme. Values of $R_s < 1$ correspond to reduced dependence of vertical mixing on stability.

Sensitivity to Vertical Turbulent Mixing

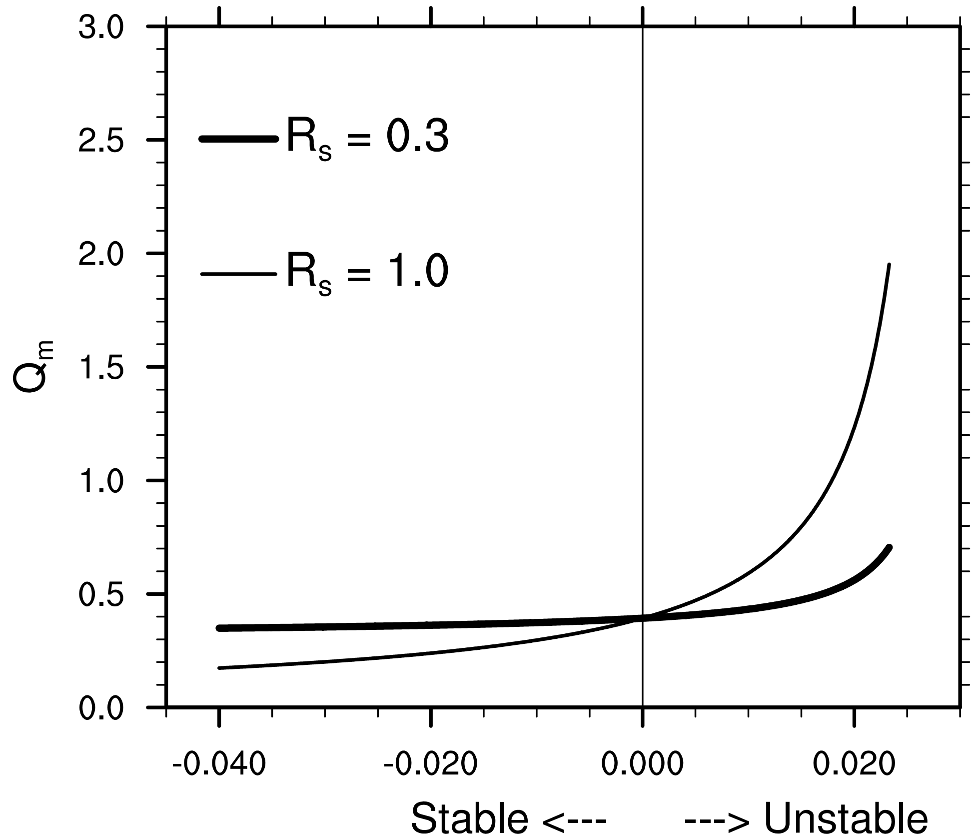




Spectral analysis and the coupling coefficient between surface wind speed and SST in the WRF experiments both suggest that vertical mixing in the ECMWF model is comparable to a value of $R_s \approx 0.3$ for the stability response coefficient.

A value of $R_s \approx 1.0$ yields a WRF response to SST almost identical to QuikSCAT observations, when converted to equivalent neutral stability 10-m winds.

Relevance to the ECMWF Model ??



To the extent that these sensitivity studies have relevance to the ECMWF model, these WRF experiments suggest that the ECMWF model:

- *overestimates vertical mixing in stable conditions*
- *underestimates vertical mixing in unstable conditions*

Conclusions

- *SST exerts a strong influence on surface winds.*
- *This air-sea interaction is evident in the ECMWF model, but is too weak by about a factor of 2.*
- *Inadequacies in the SST boundary condition, grid resolution and horizontal mixing can account for at least some of the underestimation of SST influence on surface winds on scales shorter than ~250 km.*
- *The underestimation of SST influence on surface winds on scales longer than ~250 km can only be accounted for by vertical turbulent mixing. The WRF experiments suggest that the ECMWF model:*
    - *overestimates vertical mixing in stable conditions*
    - *underestimates vertical mixing in unstable conditions*

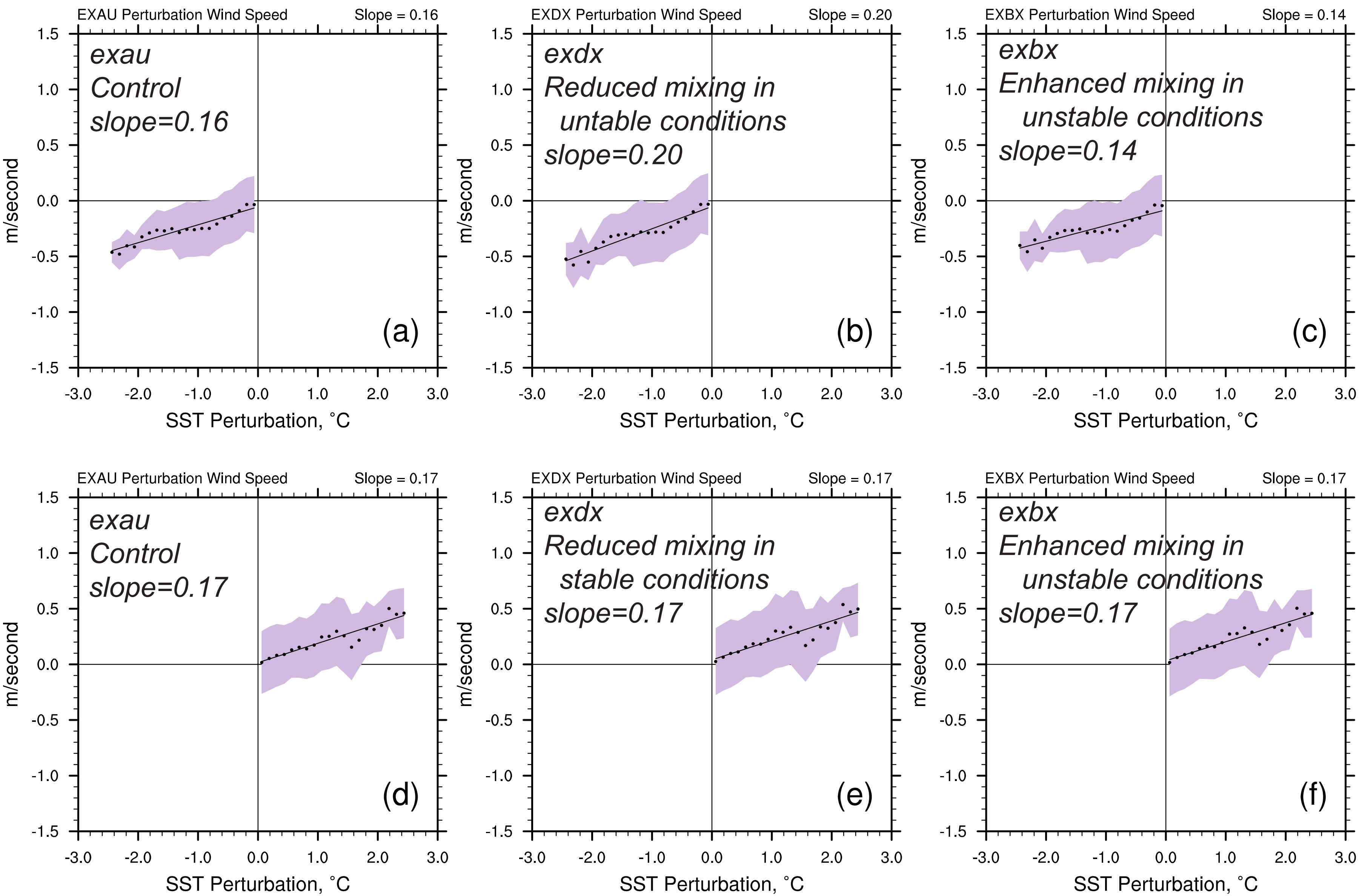
Objectives of My Visit to ECMWF

To analyze experiments conducted with the ECMWF model to investigate the sensitivity of SST influence on surface winds to the parameterization of vertical mixing.

Four ECMWF experiments:

exau	*Control CY32R2*
exdx	*Reduced stable boundary layer diffusion (MO formulation)*
exbx	*Dual mass flux (dry + moist updraught) which has counter-gradient effects in unstable conditions.*
excf	*Diurnal cycle of ocean skin temperature + cold skin effect*

Preliminary Results (from this morning!)



4. Evidence for SST Influence on Tropospheric Winds from Observations and Models

Can an SST influence on the atmosphere be detected above the sea surface?

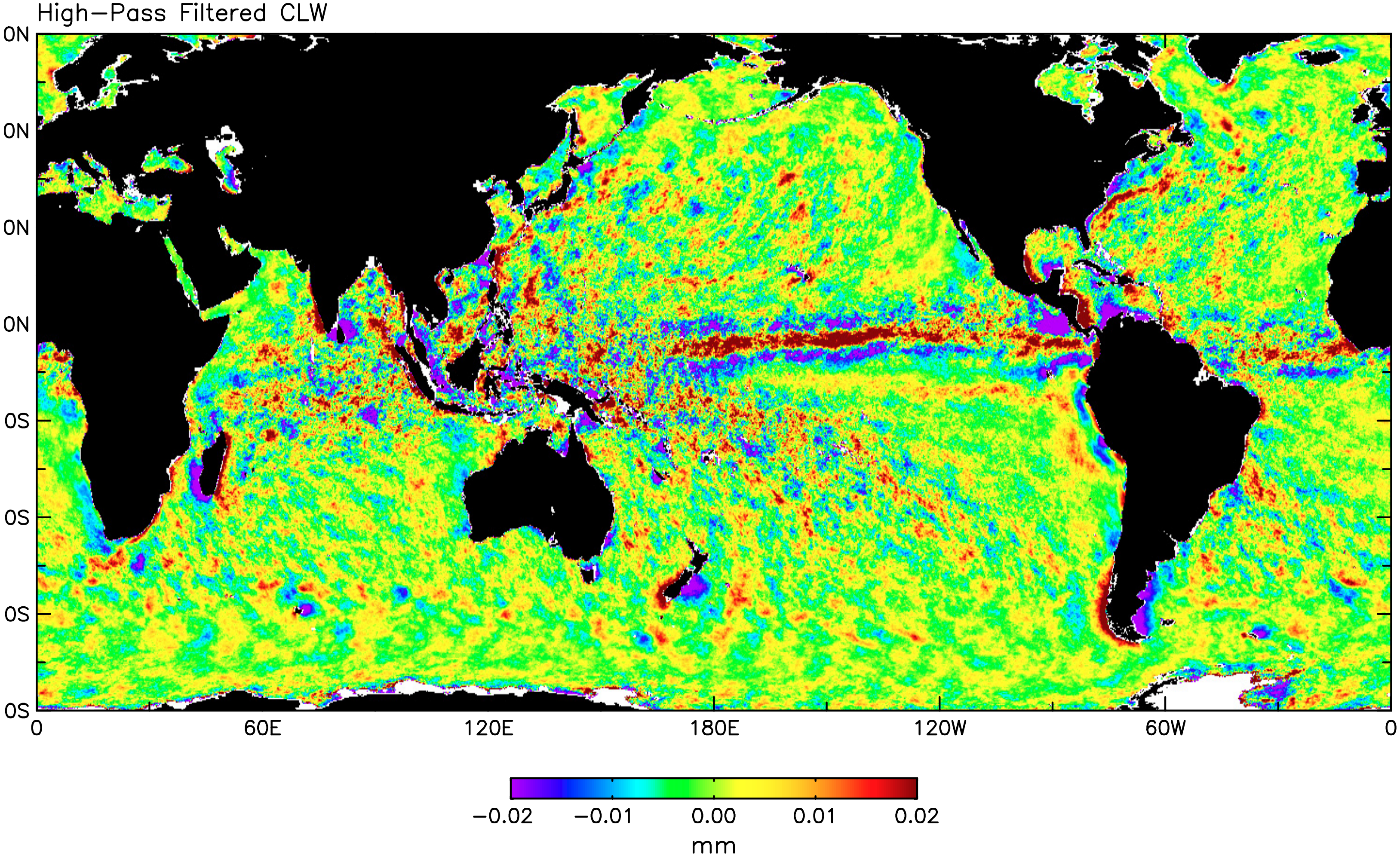
4a. Observed Cloud Liquid Water and Cloud Albedo Responses to SST

Based on AMSR observations of cloud liquid water and SST, and MODIS observations of cloud albedo

AMSR 1-Year Average Cloud Liquid Water

(spatially high-pass filtered)

July 2003 – June 2004

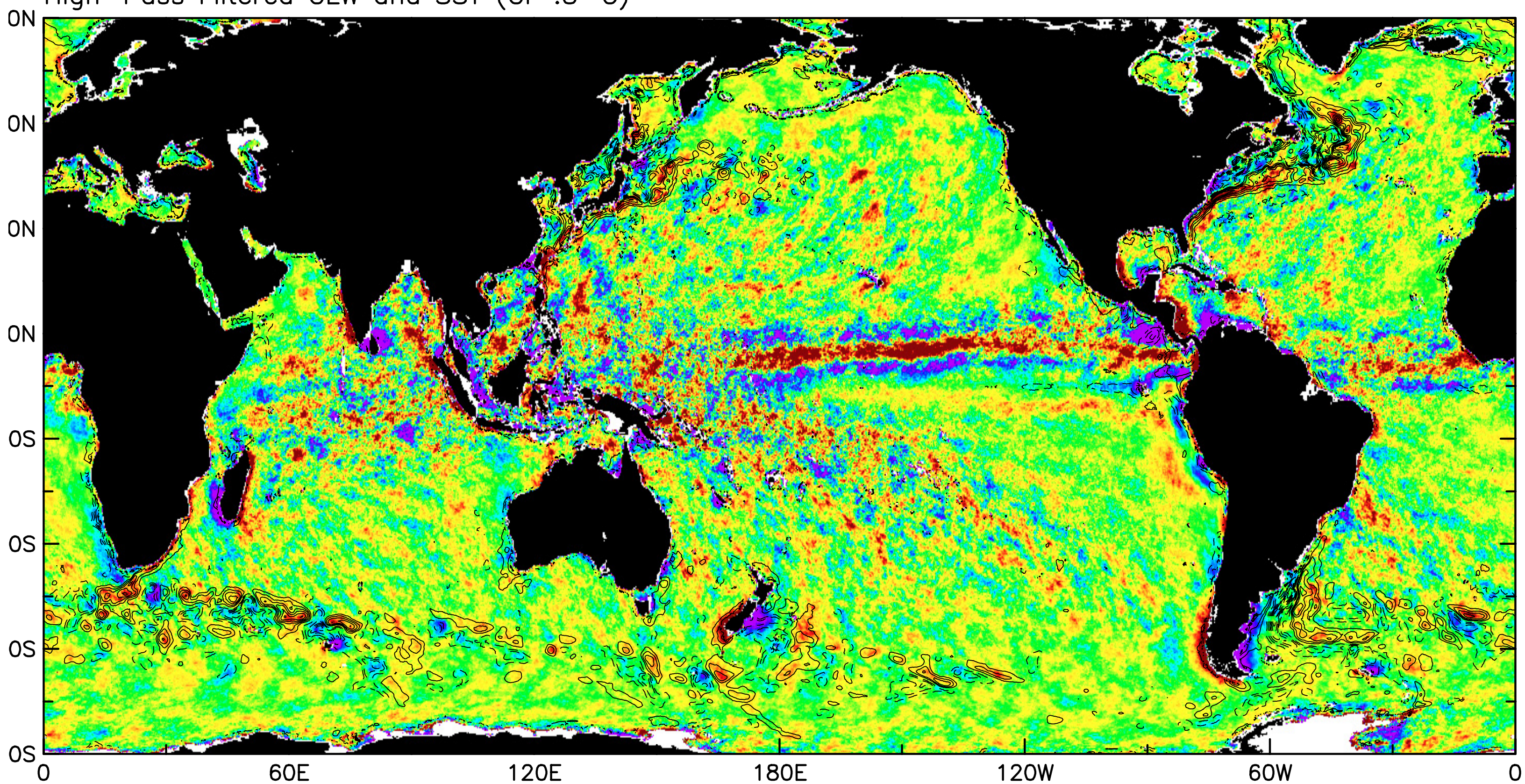


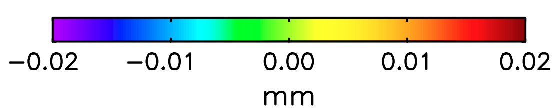
AMSR 1-Year Average Cloud Liquid Water with SST Contours

(spatially high-pass filtered)

July 2003 – June 2004

High–Pass Filtered CLW and SST (CI=.5 °C)



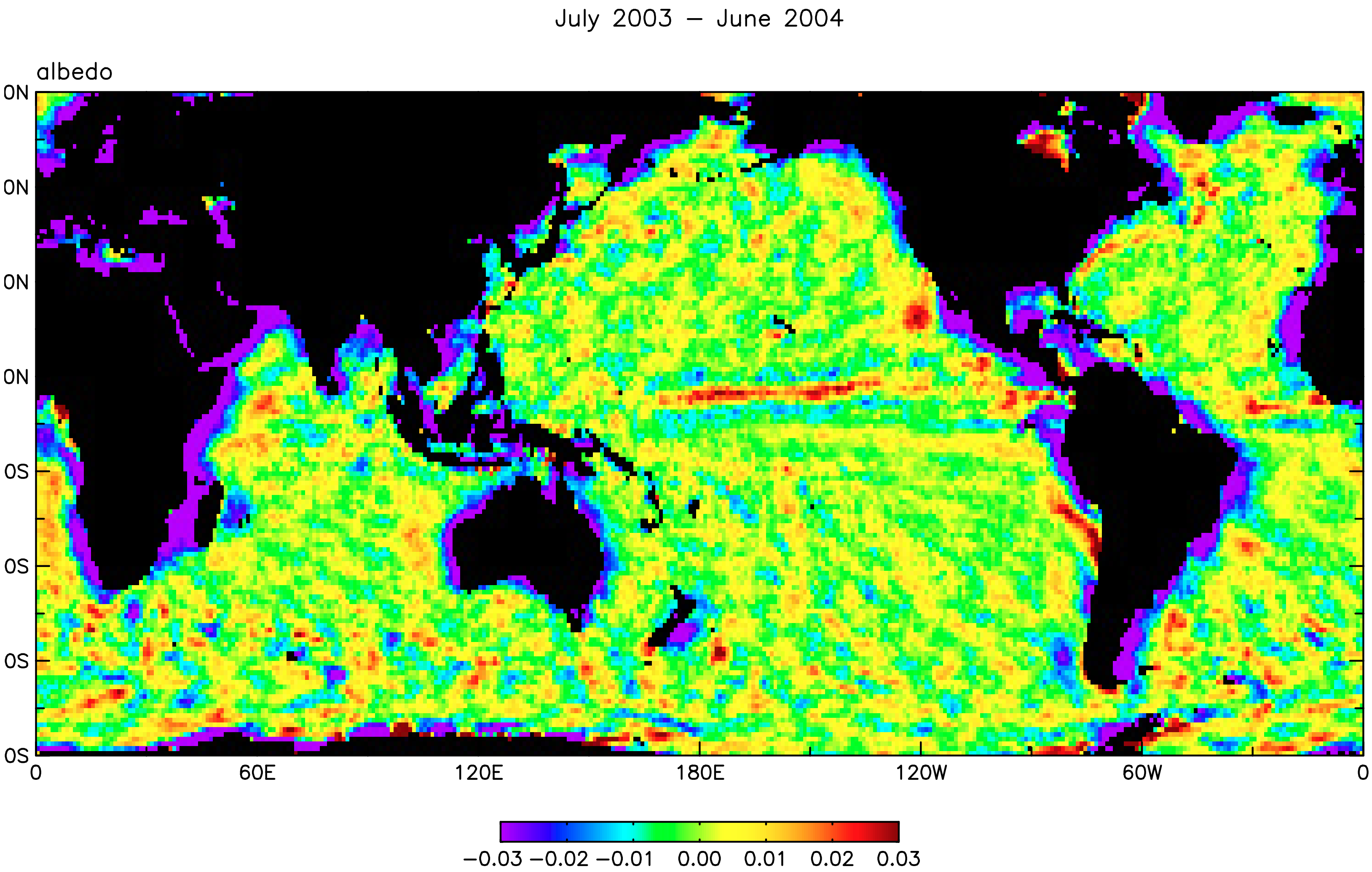


Typical perturbations are ±0.15 mm over SST frontal regions (exclusive of the ITCZ).

For a CLW density of 0.1 g m^{-3} typical of low-level stratocumulus, this corresponds to ~150 m increase in cloud thickness over warm water and ~150 m decrease over cold water.

MODIS 1-Year Average Cloud Albedo

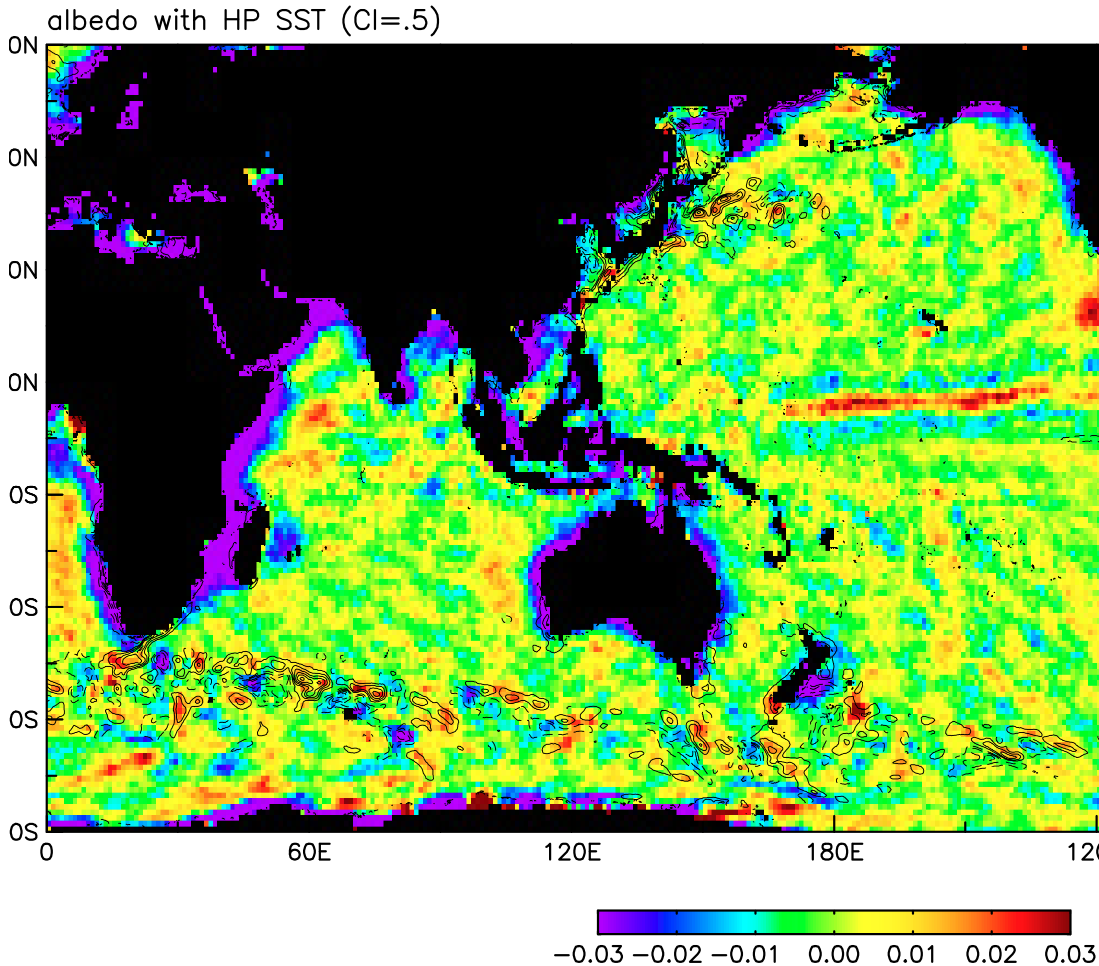
(spatially high-pass filtered)



MODIS 1-Year Average Cloud Albedo with SST Contours

(spatially high-pass filtered)

July 2003 – June 2004



Typical perturbations of albedo are ±0.025 over SST frontal regions (exclusive of the ITCZ).

This is 10-20% of the ambient albedo.

These changes in albedo are probably from enhanced low-level clouds over warm water and reduced low-level clouds over cold water.

Result from analyses of satellite observations of cloud liquid water and albedo:

SST influences clouds at least at the top of the marine atmospheric boundary layer, and perhaps into the troposphere.

Result from analyses of satellite observations of cloud liquid water and albedo:

SST influences clouds at least at the top of the marine atmospheric boundary layer, and perhaps into the troposphere.

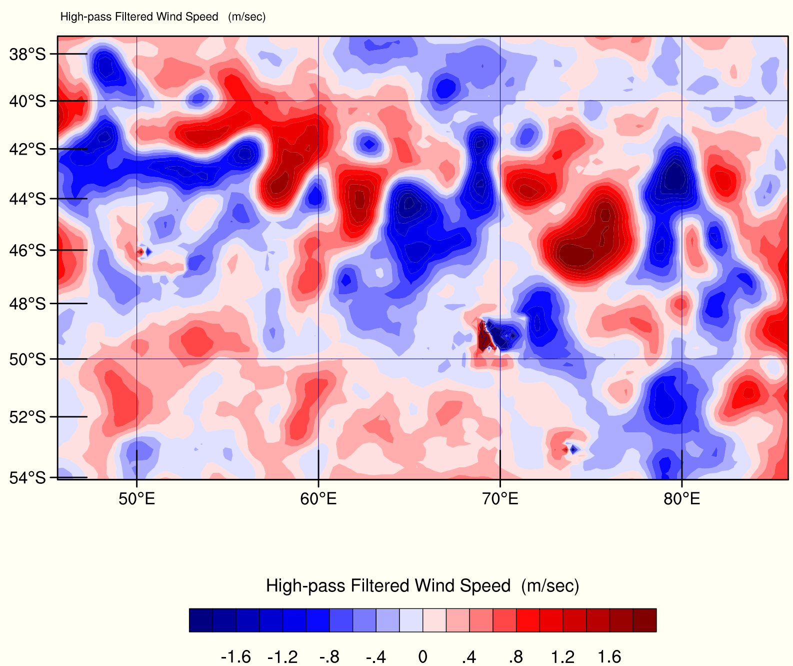
Question:

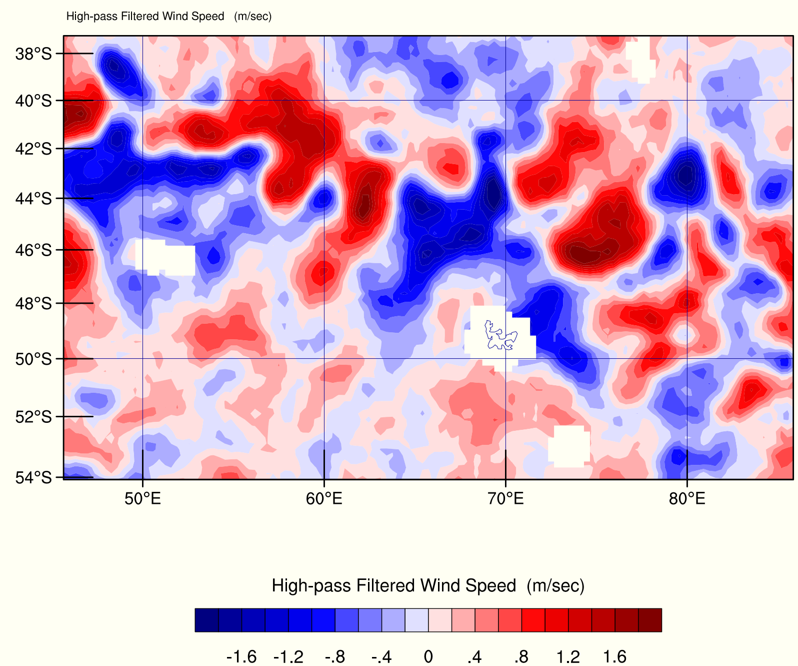
Does SST influence tropospheric winds in the troposphere?

4b. SST Influence on Model Tropospheric Winds

Based on simulations with the Weather Research & Forecasting (WRF) model forced by AMSR-observed SST

WRF wind speed (U_{10}^N) QuikSCAT observation





(July 2002, spatially high-pass filtered)

In addition to investigating the momentum balance for <u>surface winds</u>, the close agreement between surface winds from the WRF model and from the QuikSCAT observations lends confidence that the WRF model can be used to investigate SST influence on <u>tropospheric winds</u>.

Overview of Results:

Unlike at the surface, there is no clear evidence of SST influence on wind speeds above the marine atmospheric boundary layer.

<u>However</u>, there is a clear, though rather confusing, influence of SST on horizontal divergence in the troposphere.

Overview of Results:

Unlike at the surface, there is no clear evidence of SST influence on wind speeds above the marine atmospheric boundary layer.

<u>However</u>, there is a clear, though rather confusing, influence of SST on horizontal divergence in the troposphere.

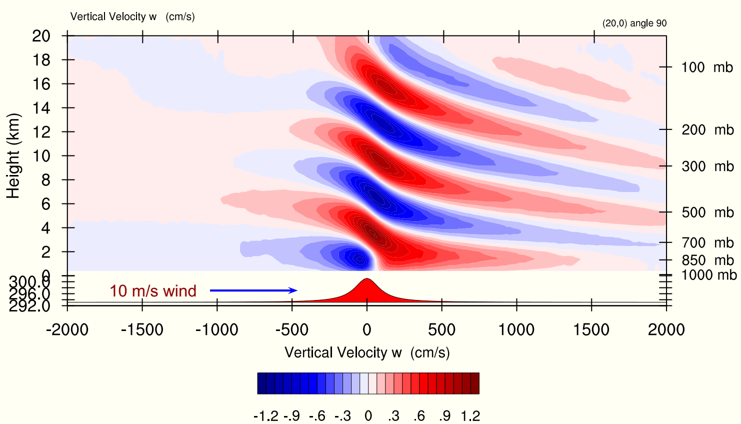
Approach:

WRF experiments were performed with progressively increased spatial smoothing of the AMSR SST fields used as the surface boundary condition.

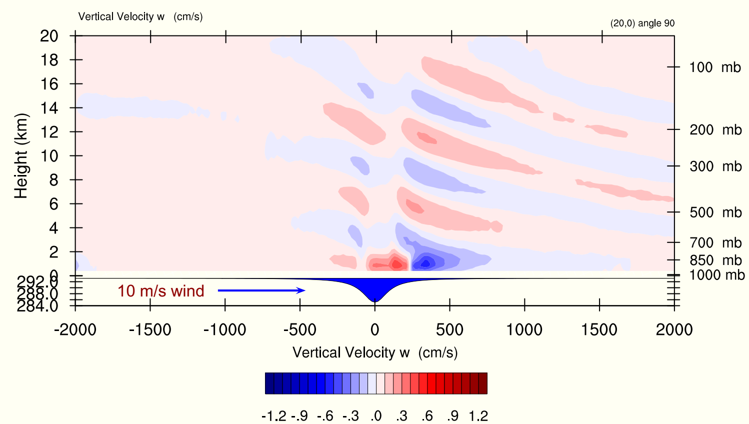
The monthly average of the 3-d fields of horizontal divergence from each simulation was compared with that from a simulation with no smoothing of the AMSR SST boundary condition.

Idealized WRF Model Simulations of Vertical Velocity and Horizontal Divergence to Warm and Cold SST Anomalies

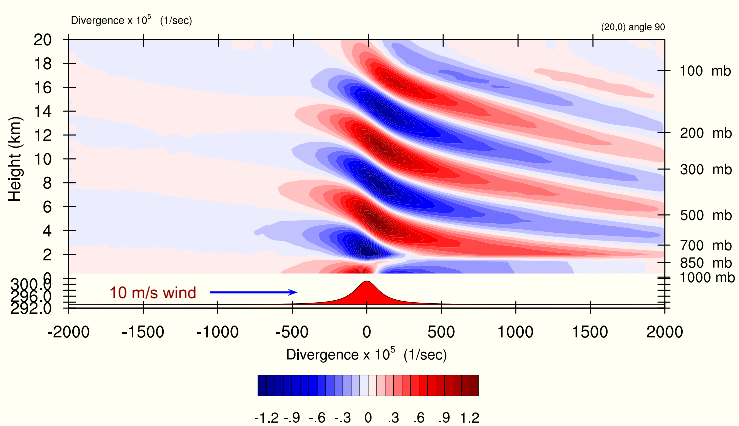
Vertical Motion (2D idealized WRF, SST bump)



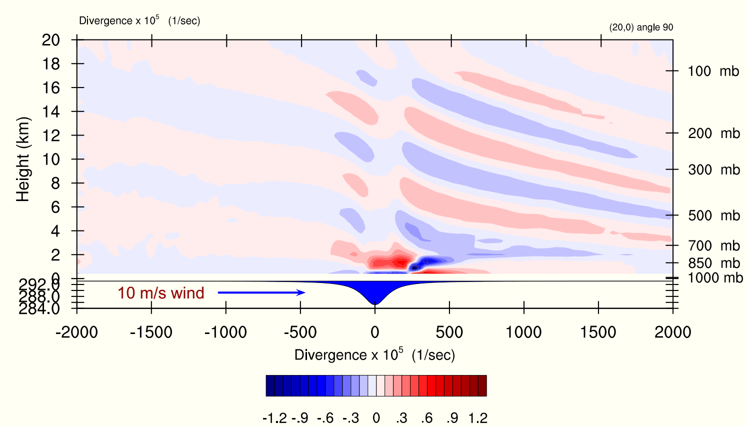
Vertical Motion (2D WRF, SST ⊖)



Horizontal Divergence (2D WRF, SST ⊕)



Horizontal Divergence (2D WRF, SST ⊖)



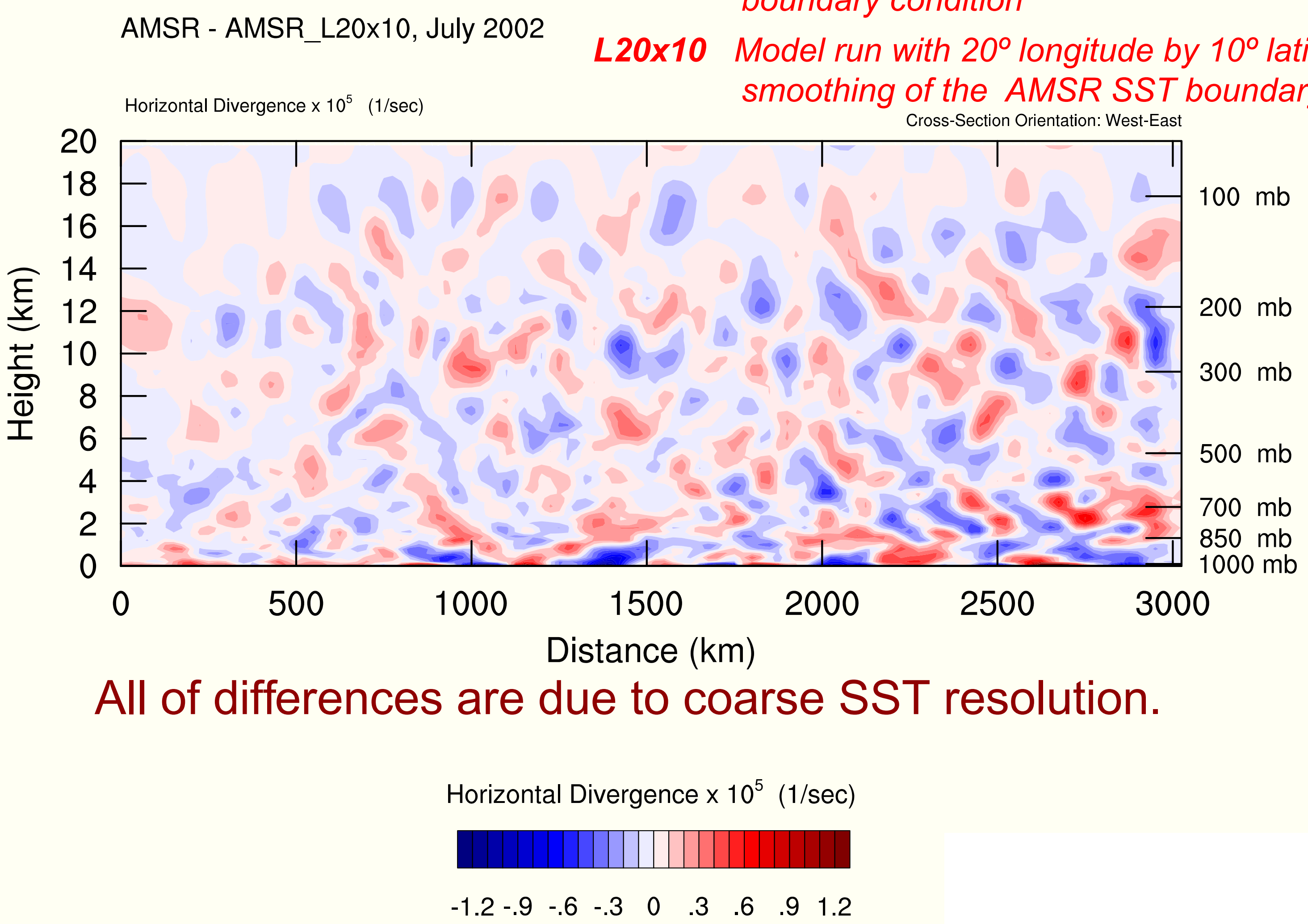
A 3ºC SST anomaly has an effect comparable to a 200 m hill

Example Comparison

Divergence difference: AMSR Raw minus L20x10

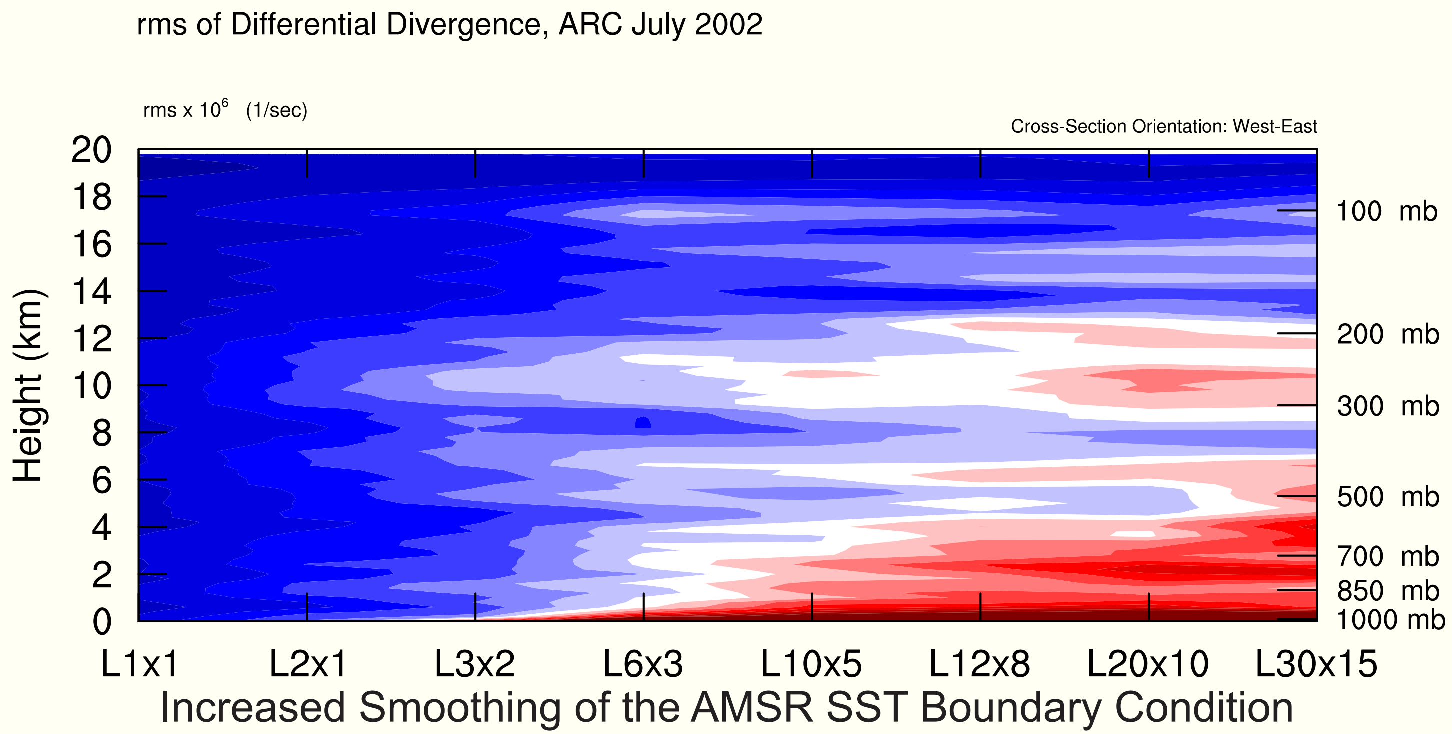
Raw *Model run with no smoothing of the AMSR SST boundary condition*

L20x10 *Model run with 20º longitude by 10º latitude smoothing of the AMSR SST boundary condition*

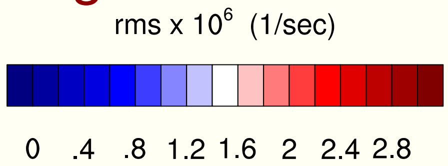


All of differences are due to coarse SST resolution.

x-z: rms of differential divergence along zonal section



Larger Error due to Decreasing SST Influence



Conclusions

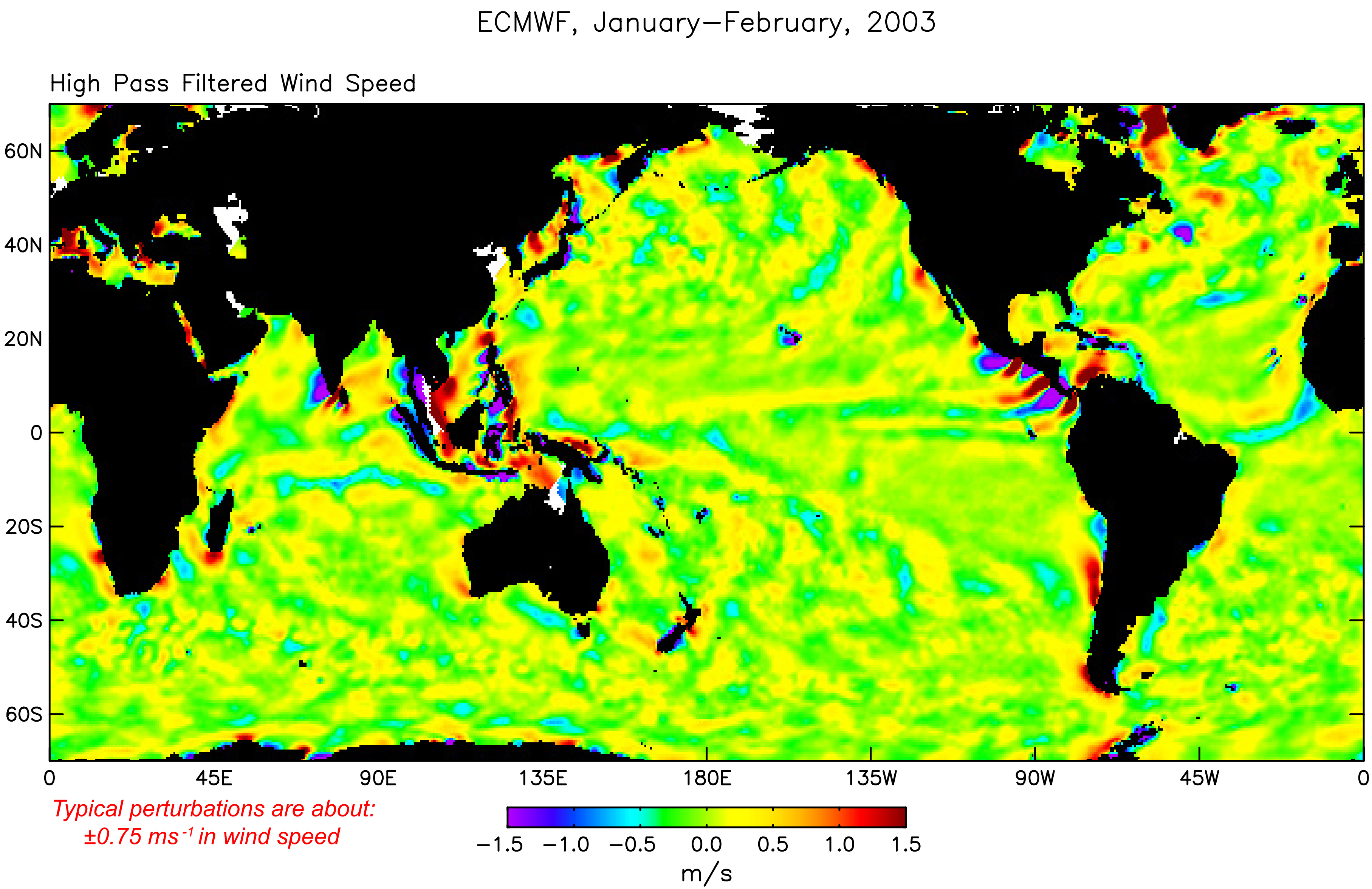
- *SST exerts a strong influence on surface winds.*
- *This air-sea interaction is evident in the ECMWF model, but is too weak by about a factor of 2 due to inadequacies in the SST boundary condition and in the parameterization of vertical mixing.*
- *SST influence on clouds can also be detected. The response is consistent with increases in cloud formation at the top of the boundary layer over warm water and decreases over cold water.*
- *SST influence can be detected as perturbations of the horizontal divergence field up to about 14 km (200 mb) in the troposphere.*
  - *These perturbations appear to propagate vertically as gravity waves.*
  - *An SST anomaly of 3°C has about the same effect as a 200m hill.*

Ongoing Research

Use the WRF model simulations to investigate whether the SST influence on the troposphere modifies horizontal flow in the free atmosphere over the ocean through:

- *vertical eddy fluxes of heat, moisture and momentum,*
- *mass adjustment on large scales.*

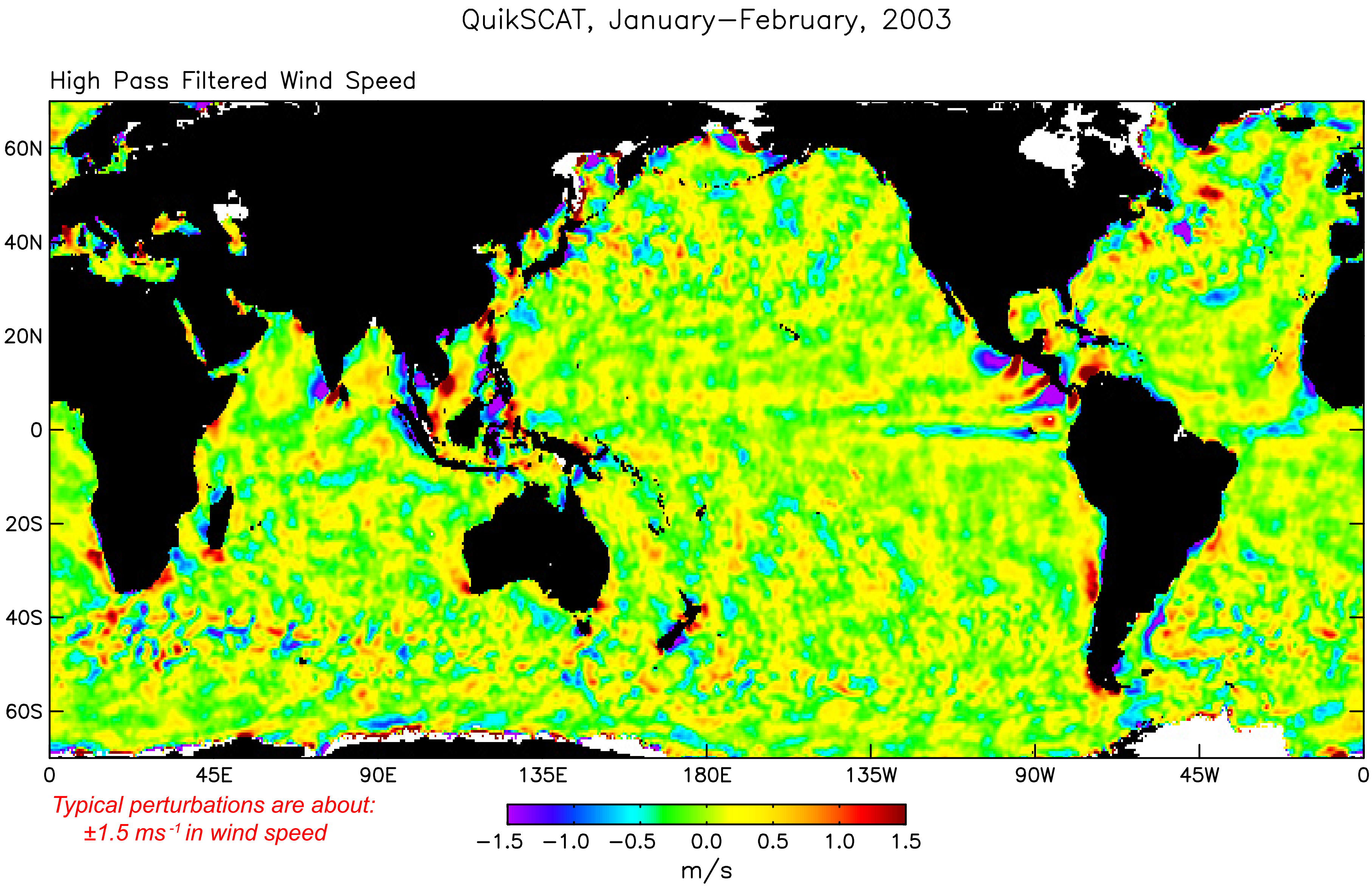
ECMWF 2-Month Average Wind Speed
(spatially high-pass filtered)



Typical perturbations are about: ±0.75 ms^{-1} in wind speed

QuikSCAT 2-Month Average Wind Speed

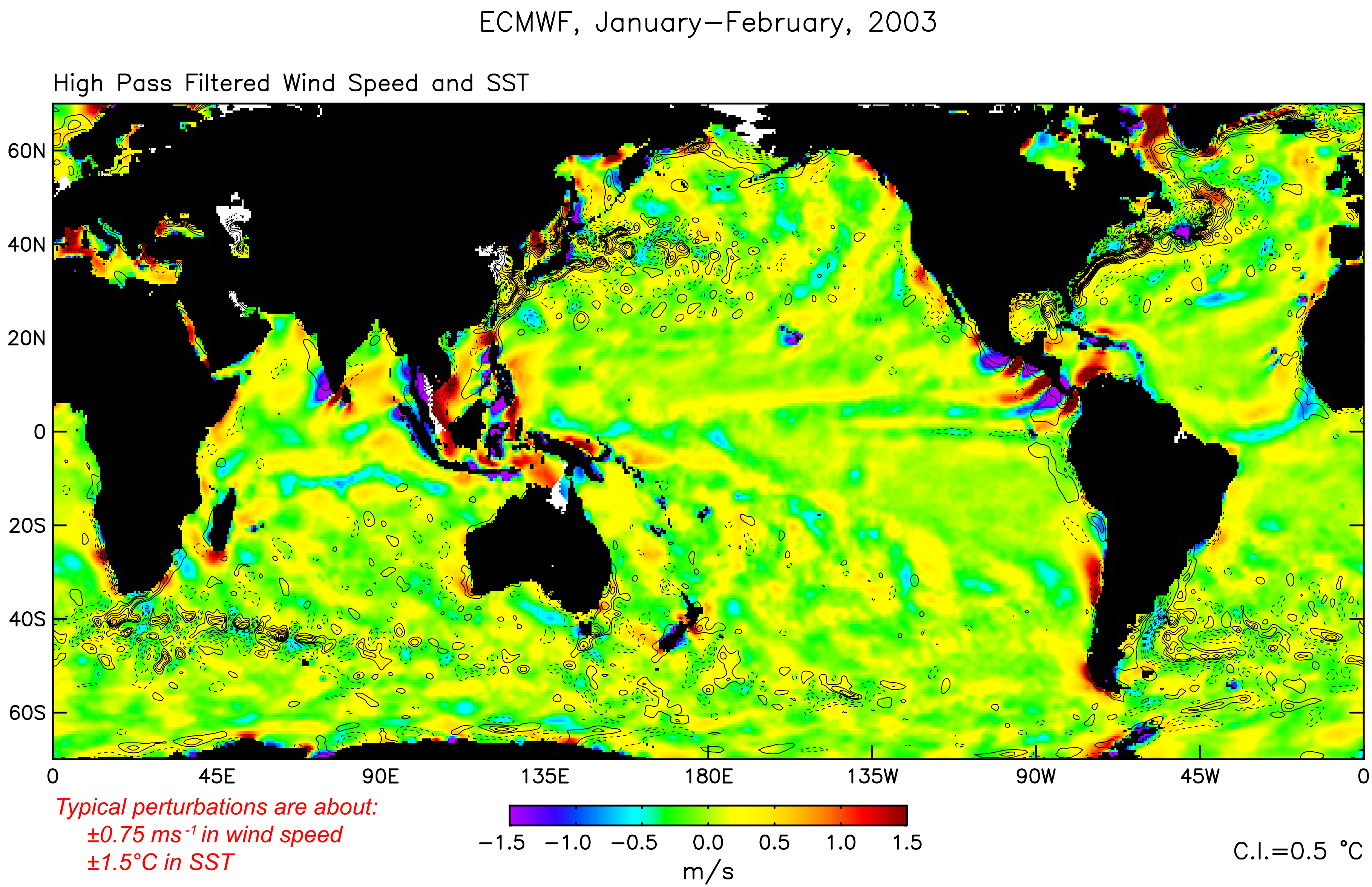
(spatially high-pass filtered)



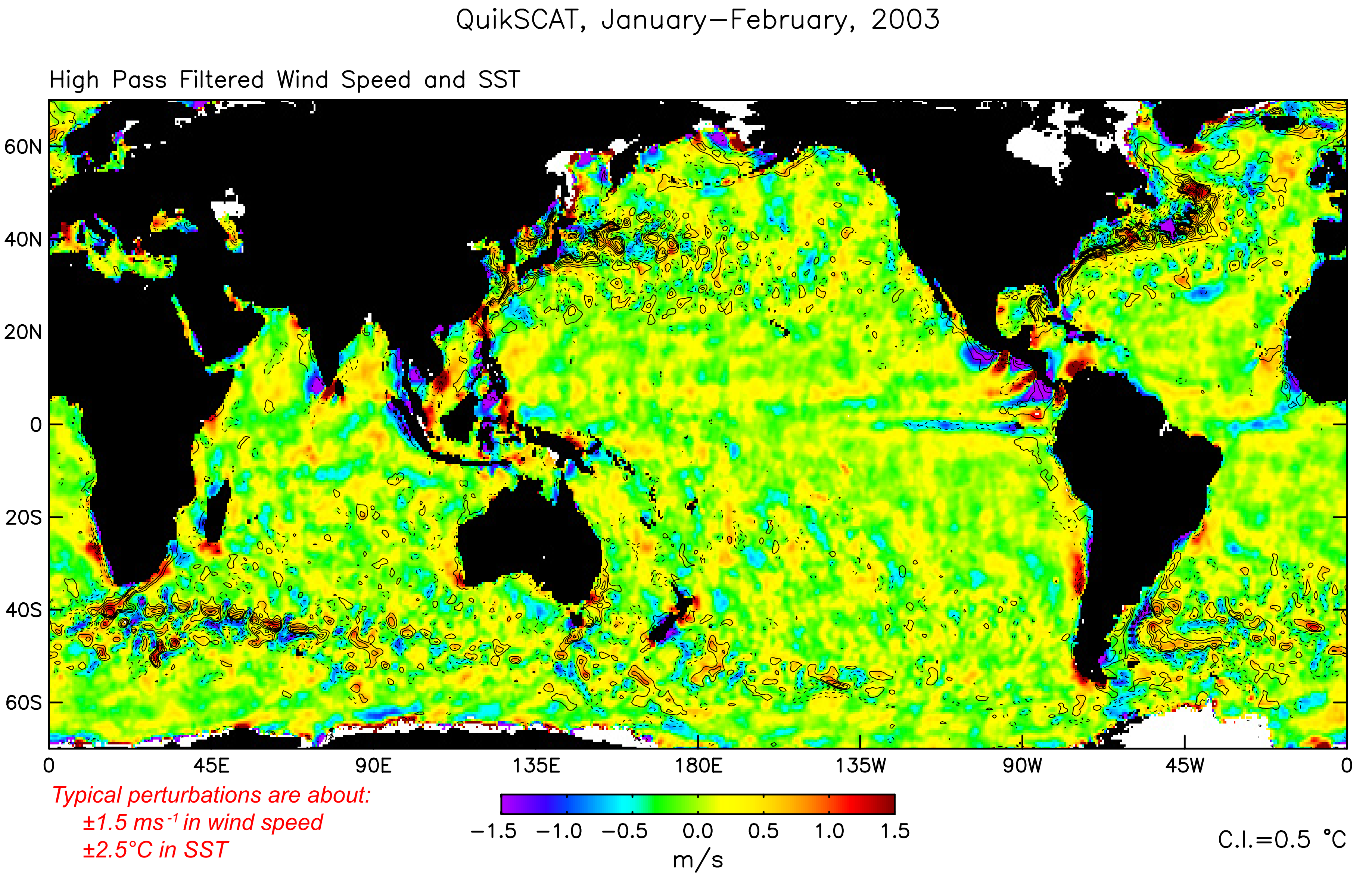
Typical perturbations are about: ±1.5 ms^{-1} in wind speed

ECMWF 2-Month Average Wind Speed with SST Contours

(spatially high-pass filtered)



QuikSCAT 2-Month Average Wind Speed with SST Contours
(spatially high-pass filtered)



Typical perturbations are about:
±1.5 ms^{-1} in wind speed
±2.5°C in SST

Result from comparisons of ECMWF and QuikSCAT global wind fields:

SST influence on surface winds is clearly evident in the ECMWF model, but is underestimated by about a factor of two in intensity.

Detailed analyses that follow will show that there are 2 reasons for this underestimation of ocean-atmosphere coupling:

1) *Resolution limitations in the RTG SST boundary condition and model grid resolution, both of which affect model winds on scales shorter than ~250 km.*

2) *Inadequacies in the model parameterization of vertical mixing*

   - *overestimation in stable conditions*
   - *underestimation in unstable conditions*