Comparison of surface wind-SST interactions using satellite observations and numerical simulations

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- Satellite observations of wind speed and direction influenced by SST
- Numerical simulation to determine SST-induced adjustment of boundary layer momentum balances, focusing on the vertical structure
- Relate SST-induced adjustment of momentum budgets to the wind speed and direction perturbations

1-yr averaged spatially high-pass filtered QuikSCAT surface wind speed (colors) and AMSR-E SST (contours) for 2003
Stress much greater in the winter hemisphere

Over Southern Indian Ocean, stress perturbations generally peak in July of each year

In mid-latitudes, seasonal cycle in wind stress perturbations caused by seasonal cycle of the large-scale wind speed through its effect on the drag coefficient
QuikSCAT Wind Speed and AMSR-E SST over the South Indian Ocean

July 2002

Agulhas Current

Agulhas Return Current

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

SST contour interval is 2°C
QuikSCAT Wind Speed and AMSR-E SST over the South Indian Ocean

July 2002

1-month averaged and spatially high-pass filtered wind speed (colors) and SST (contours) are highly correlated with each other.

SST contour interval is 0.25°C
Numerical Simulation

- Do not have observations of momentum budget => use models to infer dynamics of wind-SST interactions in the boundary layer
- Simulations made using the Weather Research and Forecasting (WRF) mesoscale atmospheric model
- Time period of July 2002 where SST-induced wind stress perturbations are at their annual maximum
- Steady 1-month average SST field from AMSR-E
- Triply-nested domain; inner nest has nominal 8 km horizontal resolution, 69 vertical levels with 20 levels below 1 km
- NCEP lateral boundary conditions at boundary of outer nest updated 4 times per simulation day
Modeled surface wind speed agrees very well with those observed from QuikSCAT.

- Wind speed and SST are linearly related in both the satellite observations and the WRF model.
- Slope from WRF closely matches that from the satellite observations.

\[ V' = \alpha_v T' \]
SST-induced adjustment of boundary layer vertical structure

- To easily visualize 3-dimensional wind fields from WRF model, they are split into separate vertical and horizontal functions using EOFs:

\[ d(x, y, z) = \sum_{k=1}^{M} a_k(z) G_k(x, y). \]

- Vertical EOFs are computed for each 1-month averaged term in the momentum balance
First mode shows that wind direction turns cyclonically downwind of warm SST and anticyclonically downwind of cool SST.

First mode of wind speed is more complicated than the surface wind speed; SST affects the vertical structure of wind speed differently than at the surface.
Effect of SST on hydrostatic pressure …

- Low pressure forms downwind of warm SST and high pressure forms downwind of cool SST.
- SST-induced pressure perturbations are felt throughout the depth of the boundary layer, diminishing with height.
- Dynamic range of pressure perturbations is on the order of 1 mb.
… and turbulent stress

- Downwind stress perturbations well correlated with SST
- Crosswind stress perturbations well correlated with SST gradients
Crosswind and downwind momentum budget representation

\[-V \frac{\partial V}{\partial s} - \frac{1}{\rho} \frac{\partial p}{\partial s} - \mathbf{F} \cdot \hat{s} = 0 \quad \text{Downwind budget}\]

\[-V^2 \frac{\partial \psi}{\partial s} - fV - \frac{1}{\rho} \frac{\partial p}{\partial n} - \mathbf{F} \cdot \hat{n} = 0 \quad \text{Crosswind budget}\]

- $s$ is the downwind coordinate and $n$ is the crosswind coordinate
- Downwind budget describes evolution of wind speed and crosswind budget describes evolution of wind direction
Downwind Momentum Budget – First Mode

- First mode amplitude vertical profiles show that the unbalanced pressure gradient below 200 m mainly accelerates near-surface winds.
- Above 200 m, pressure gradient and turbulent stress divergence are more closely in balance.
- Note the large variation in the turbulent stress divergence below 200 m.
First horizontal mode of pressure gradient is spatially shifted ~40km to the west (i.e., upwind) relative to turbulent stress divergence.

Spatially-lagged cross-correlation between first horizontal modes of downwind pressure gradient and downwind turbulent stress divergence; max cross-correlation of -0.84 occurs ~40km to the east.
Second mode shows that near-surface intensification of turbulent stress divergence is important but does not oppose the first mode pressure gradient.
First mode shows that imbalances between the turbulent stress divergence, pressure gradient, and Coriolis forces result in significant centrifugal (i.e., cross-stream) accelerations.
Crosswind Momentum Budget – Mode 2

- Second mode shows that wind direction changes result from an imbalance between the turbulent stress divergence and the Coriolis forces
Baroclinic modification of the crosswind vertical shear and turbulent stress profiles

- The crosswind vertical shear is nearly in thermal wind balance with air temperature gradients caused by SST gradients.
- Crosswind turbulent stress is closely related to crosswind vertical shear.
- SST-induced baroclinic pressure gradients contributes to changes in wind direction within the boundary layer by altering the boundary layer turbulent stress profile.
- The resulting crosswind momentum balance is called a “baroclinic advectively-modified Ekman balance.”
Spatially-Filtered Surface Zonal and Meridional Wind Components

- Zonal wind is faster over warm SST and slower over cool SST
- Meridional wind is northward over warm SST and southward over cool SST
Conclusions

- SST affects both surface wind speed and direction
- Near-surface wind speed response is governed by separate adjustments of the pressure gradient and vertical turbulent stress divergence
  - First mode of downwind momentum budget shows that near-surface pressure gradient is unbalanced by the turbulent stress divergence
  - Second mode shows that an unbalanced turbulent stress divergence accelerates the near-surface flow
- Near-surface wind direction response is governed by a baroclinic advectively-modified Ekman balance
  - Imbalances between the baroclinically-modified crosswind pressure gradient and turbulent stress divergence and the Coriolis force cause wind direction changes linked to SST perturbations
Numerical Simulation

1-yr average QuikSCAT wind and AMSR-E SST

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