Submesoscale and Mesoscale Ekman Pumping on Smaller than 100 km

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Scientific Question:

How large is the vertical velocity of Ekman pumping from air-sea interaction on mesoscale-to-submesoscale length scales <100 km?

Four sources of upwelling on submesoscales and mesoscales:

1. Submesoscale variability from intrinsic ocean dynamics unrelated to the wind.
2. Ekman pumping from SST influence on surface winds (high wind speed over warm water, low wind speed over cold water).
3. Ekman pumping from surface current effects on the relative wind, and hence on the surface stress.
4. Ekman pumping from the gradient of the relative vorticity of surface ocean currents.
   - This can be thought of as a modification of the planetary vorticity gradient β from the effects of surface currents.

The Total Vertical Velocity Near the Sea Surface

The continuity equation for mass conservation is

$$\nabla \cdot \vec{u} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0.$$

Assuming $w(0) = 0$ and the horizontal velocity components u and v are constant between the surface and $z = -D$, the vertical velocity at a depth D found by integrating vertically is

$$w(-D) = D \left(\frac{\partial u_o}{\partial x} + \frac{\partial v_o}{\partial y} \right).$$

where u_0 and v_0 are the horizontal components of velocity at the sea surface.

Note that geostrophic velocity is horizontally non-divergent. The total vertical velocity therefore cannot be estimated geostrophically from SSH (e.g., from SWOT).

Diagnosis of Submesoscale Ekman Pumping

From Stern (1965, *Deep-Sea Res.*), the Ekman pumping velocity is

$$w_{tot} = \frac{1}{\rho_0} \nabla \times \left(\frac{\vec{\tau}}{f + \zeta} \right) \approx \frac{\nabla \times \vec{\tau}}{\rho_0 f} + \underbrace{\frac{1}{\rho_0 f^2} \left(\tau_x \frac{\partial \zeta}{\partial y} - \tau_y \frac{\partial \zeta}{\partial x} \right)}_{w_\zeta}$$

The above formalism is sufficient to determine the total wind-driven Ekman pumping.

It is of further interest to investigate the physical mechanisms that contribute to $\nabla \times \vec{\tau}$.

Assuming that estimates of surface ocean velocity $\vec{u}_o$ are available with sufficient accuracy from SWOT or Doppler scatterometry, the various contributions to $\nabla \times \vec{\tau}$ can be determined independently if high-resolution measurements of SST are also available (e.g., from AVHRR).

Diagnosis of Submesoscale Ekman Pumping

The total surface stress can be partitioned into 4 contributions:

$$\vec{\tau} = \vec{\tau}_{bg} + \vec{\tau}_c + \vec{\tau}_{SST} + \vec{\tau}_{noise},$$

where

$\vec{\tau}_{bg}$ is the stress from the large-scale background wind.

$\vec{\tau}_c$ is the stress from the effects of surface ocean currents on the relative wind.

$\vec{\tau}_{SST}$ is the perturbation of the stress field from the effects of SST on surface winds.

$\vec{\tau}_{noise}$ is the small-scale variability in the surface wind field from atmospheric mesoscale and synoptic variability, which can be considered noise in the present context.

Since $\nabla \times \vec{\tau}_{bg}$ is small compared with the curls of the other contributions to $\vec{\tau}$, the Ekman pumping from the curl of the total surface stress $\vec{\tau}$ can be approximated as

$$\boxed{\frac{\nabla \times \vec{\tau}}{\rho_0 f} \approx \frac{1}{\rho_0 f}\left(\nabla \times \vec{\tau}_c + \nabla \times \vec{\tau}_{SST} + \nabla \times \vec{\tau}_{noise}\right)}$$

$$= \qquad w_c \quad + \quad w_{SST} \quad + \quad w_{noise}$$

Summary of Submesoscale Ekman Pumping

From the preceding analysis, the total Ekman pumping can be decomposed as

$$w_{tot} \approx w_\zeta + w_c + w_{SST} + w_{noise}$$

where the four components of submesoscale Ekman pumping are:

$$w_\zeta = \frac{1}{\rho_0 f^2}\left(\tau_x \frac{\partial \zeta}{\partial y} - \tau_y \frac{\partial \zeta}{\partial x}\right)$$

$$w_c = \frac{\rho_a C_D}{\rho_0 f} \nabla \times \left[\left(\vec{u}_{bg} - \vec{u}_o\right)\left|\vec{u}_{bg} - \vec{u}_o\right|\right]$$

$$w_{SST} = -\frac{\alpha}{\rho_0 f}\frac{\partial T}{\partial n}$$

$$w_{noise} = \frac{1}{\rho_0 f} \nabla \times \vec{\tau}_{noise}$$

Calculations of Ekman Pumping from the Effects of SST and Surface Currents from Models of Submesoscale Variability

(from model output courtesy of Jeroen Molemaker)

Case 2: The Northern CCS

Assumptions:

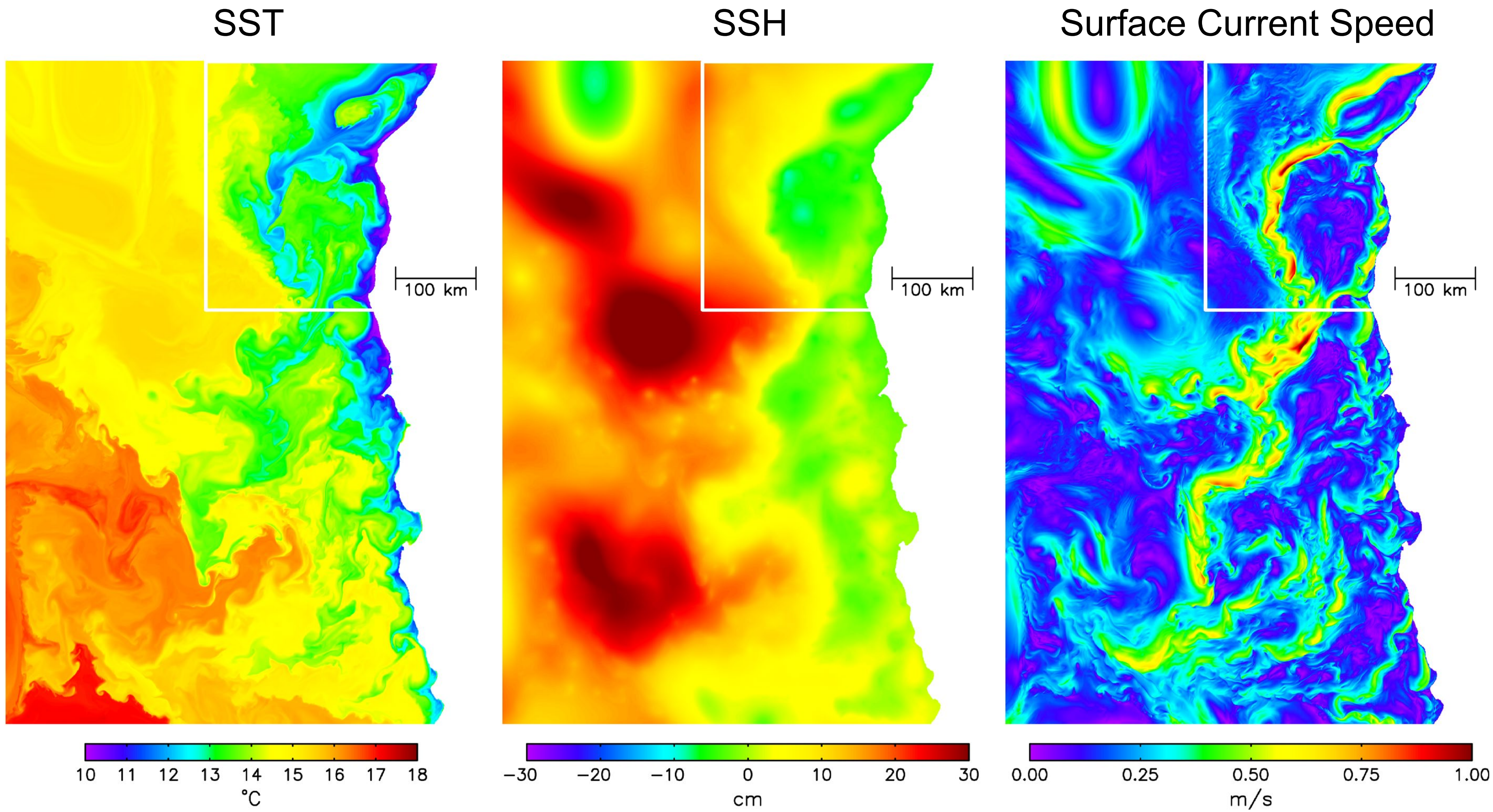
1) QuikSCAT climatological winds for June (from SCOW).

   This affects every component of Ekman pumping (W_{SST}, W_c and W_ζ)

2) A wind stress curl coupling coefficient of 0.013 N m^{-2} per °C.

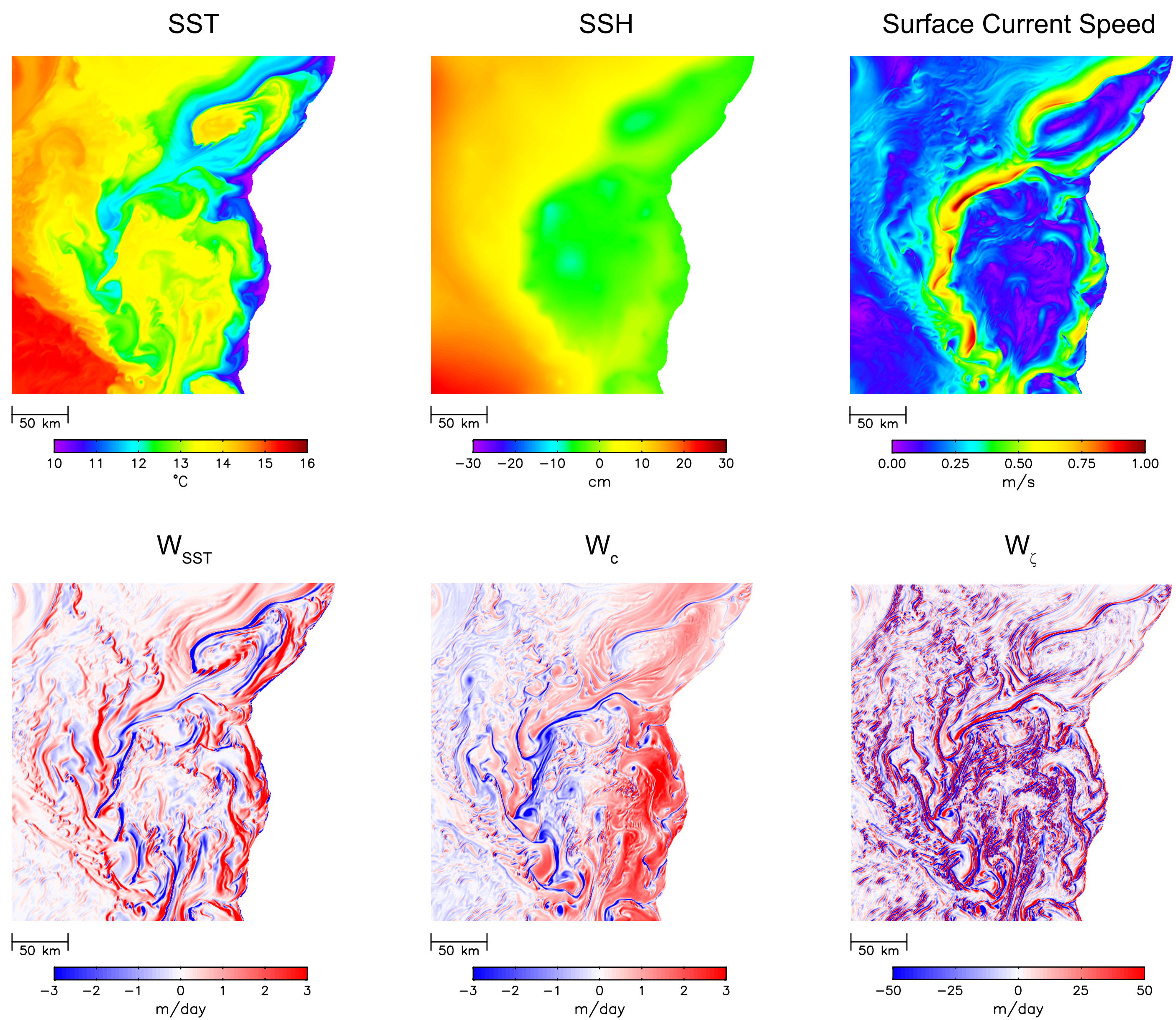
   This affects only W_{SST}

High-Resolution Model (0.5 km grid) of the California Current (Courtesy of Jeroen Molemaker, UCLA)

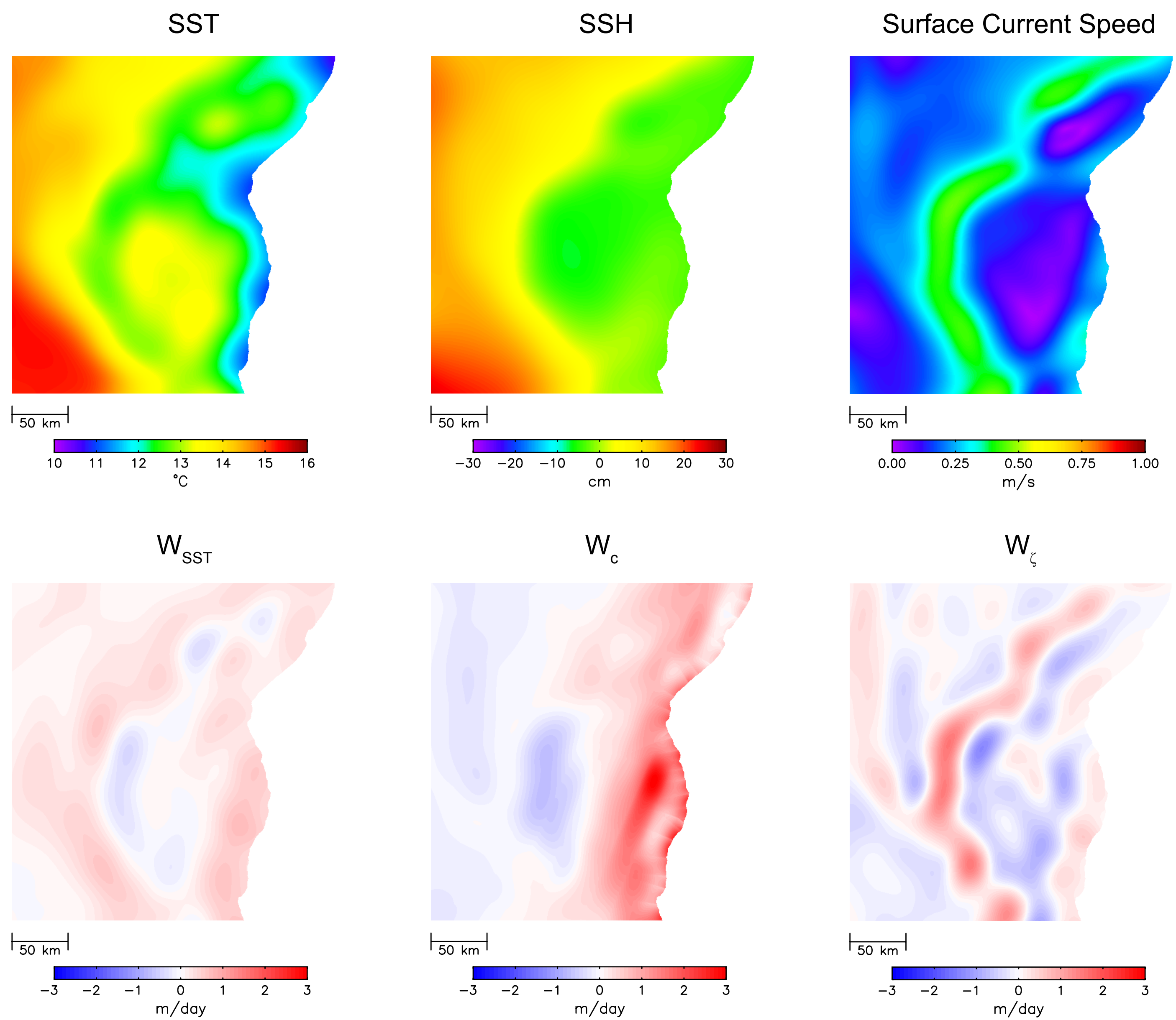


Model grid is rotated 24° relative to latitude-longitude coordinate system

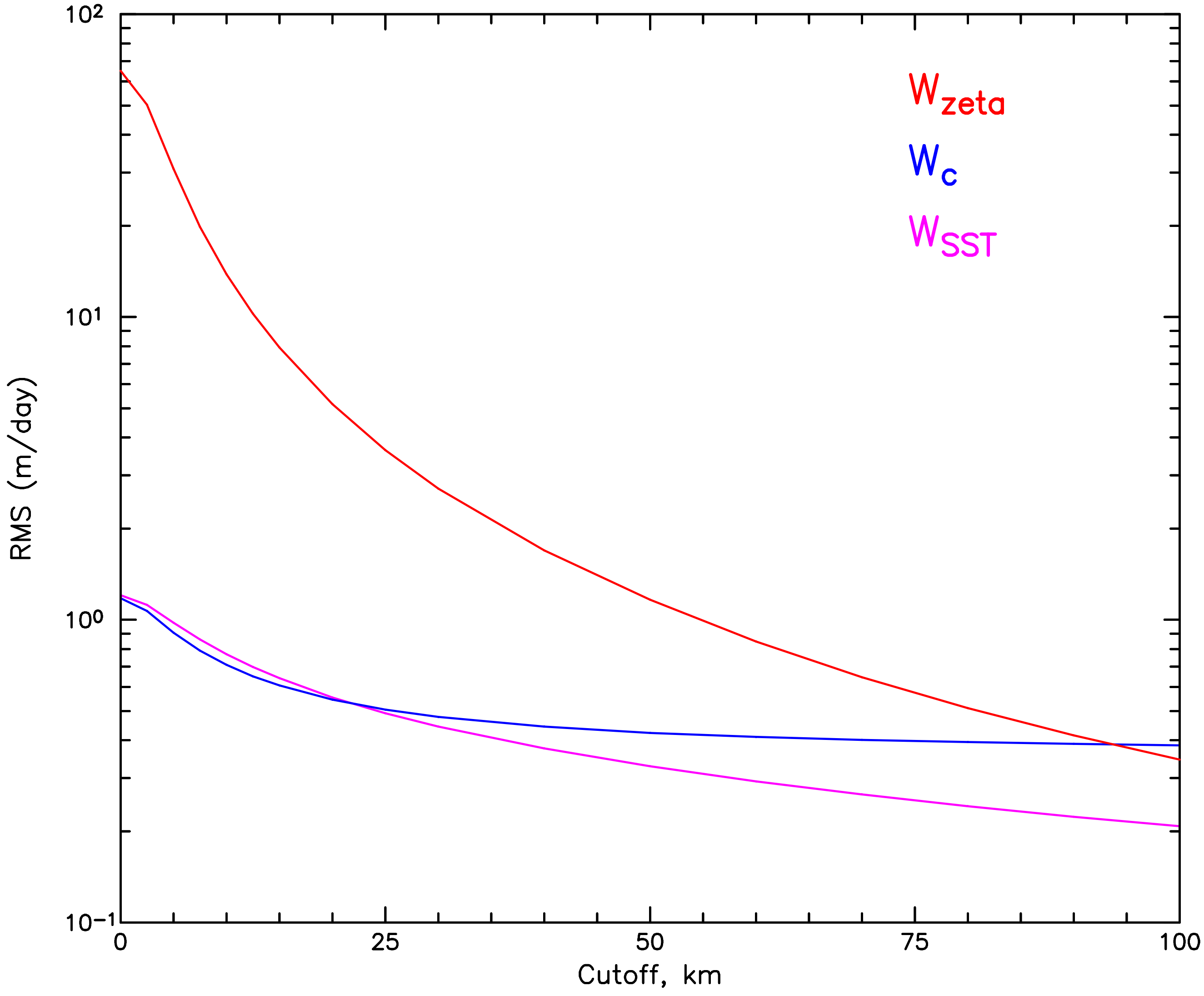
Half-Power Filter Cutoff Wavelength = 1 km



Half-Power Filter Cutoff Wavelength = 100 km



Ekman pumping from w_ζ increases dramatically on scales smaller than ~25 km!



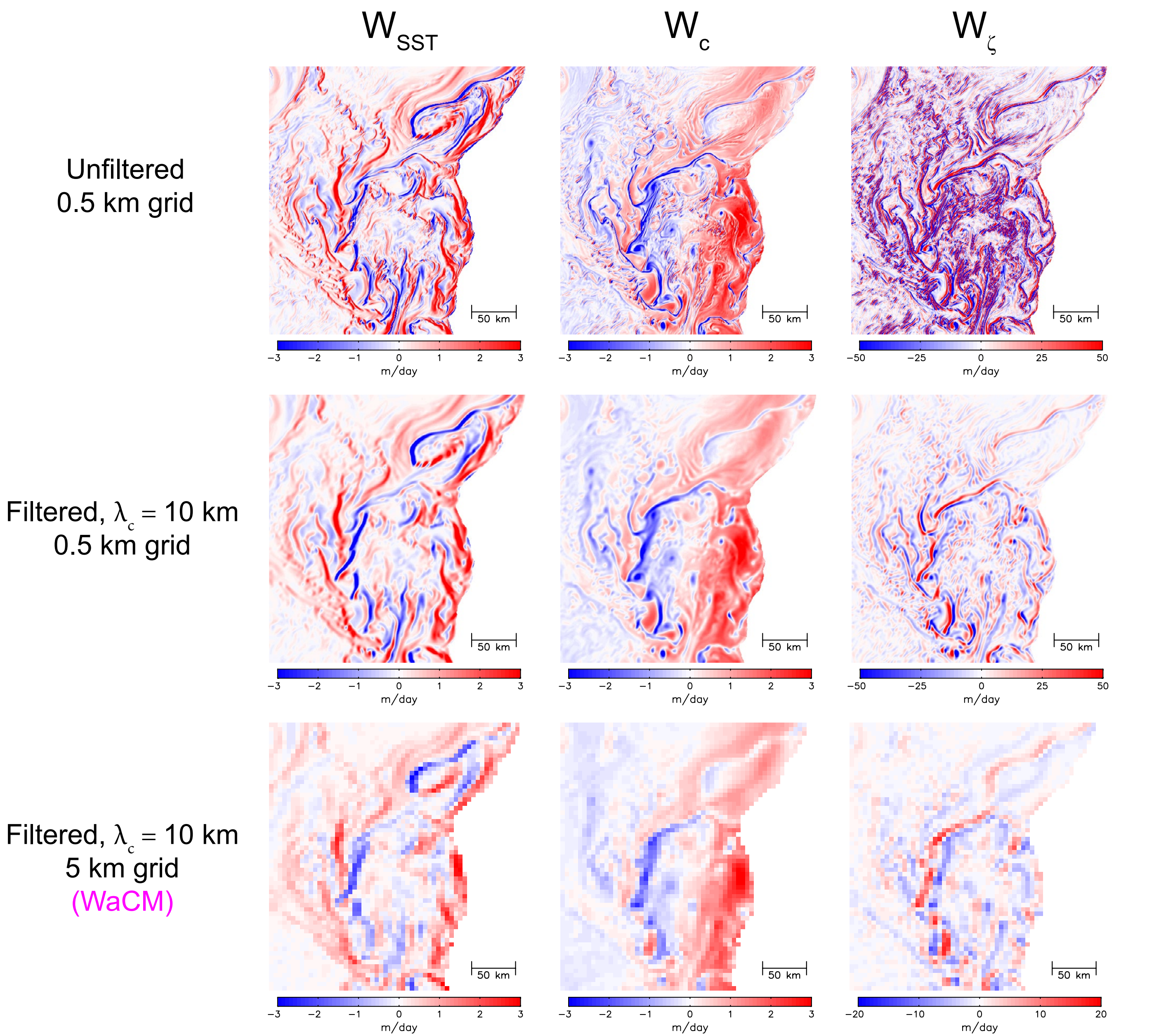
Question

How much smoothing of WaCM data will be necessary to achieve the accuracy required for W_c, W_ζ and W_{div}?

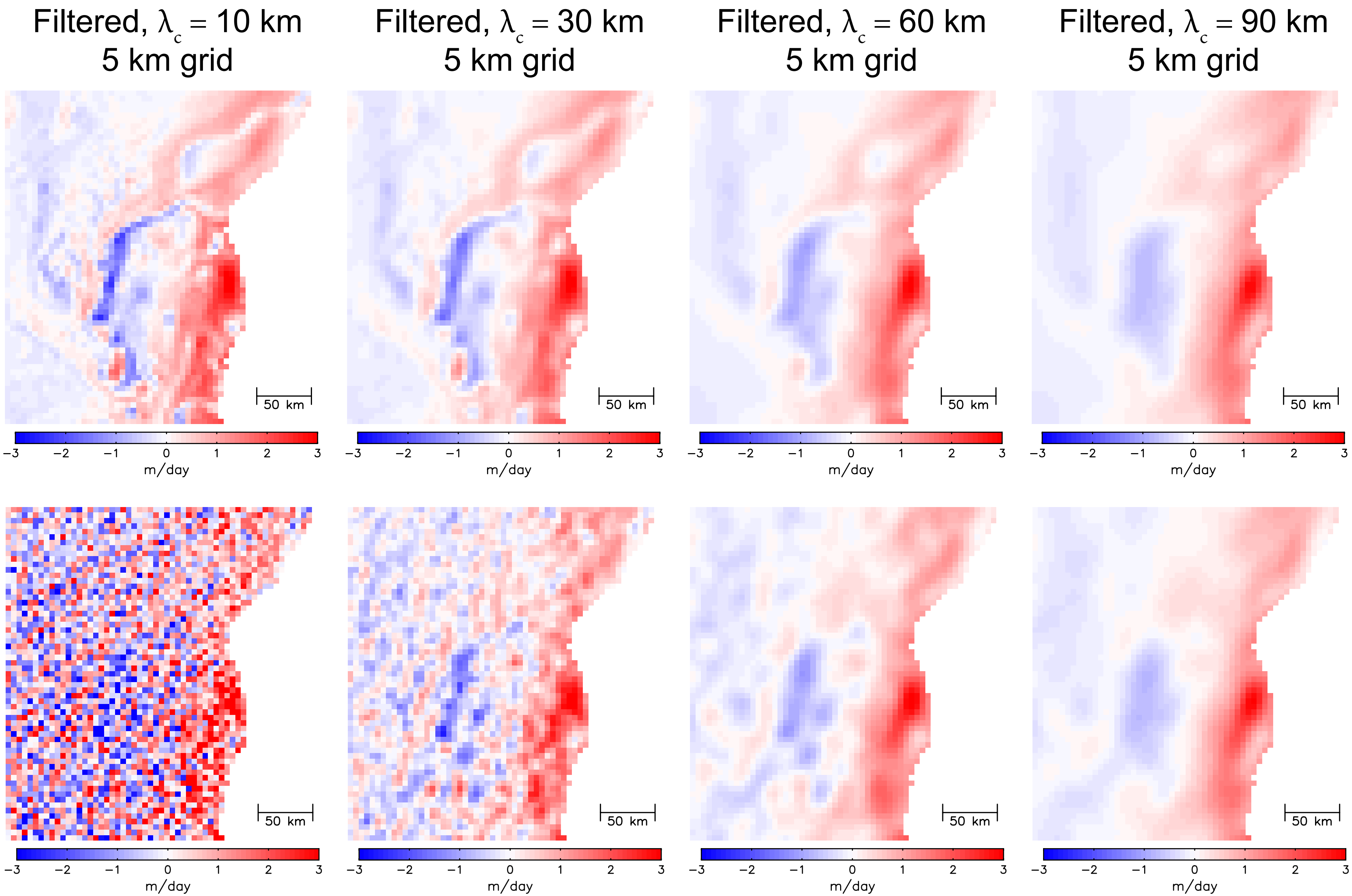
The anticipated accuracy of surface ocean velocity estimates from WaCM is 0.5 m/s with a feature resolution of 5 km (which corresponds to filtering the raw data with a 10-km filter cutoff).

The effects of this noise can be assessed from simulations...

Ekman pumping from noise-free velocity

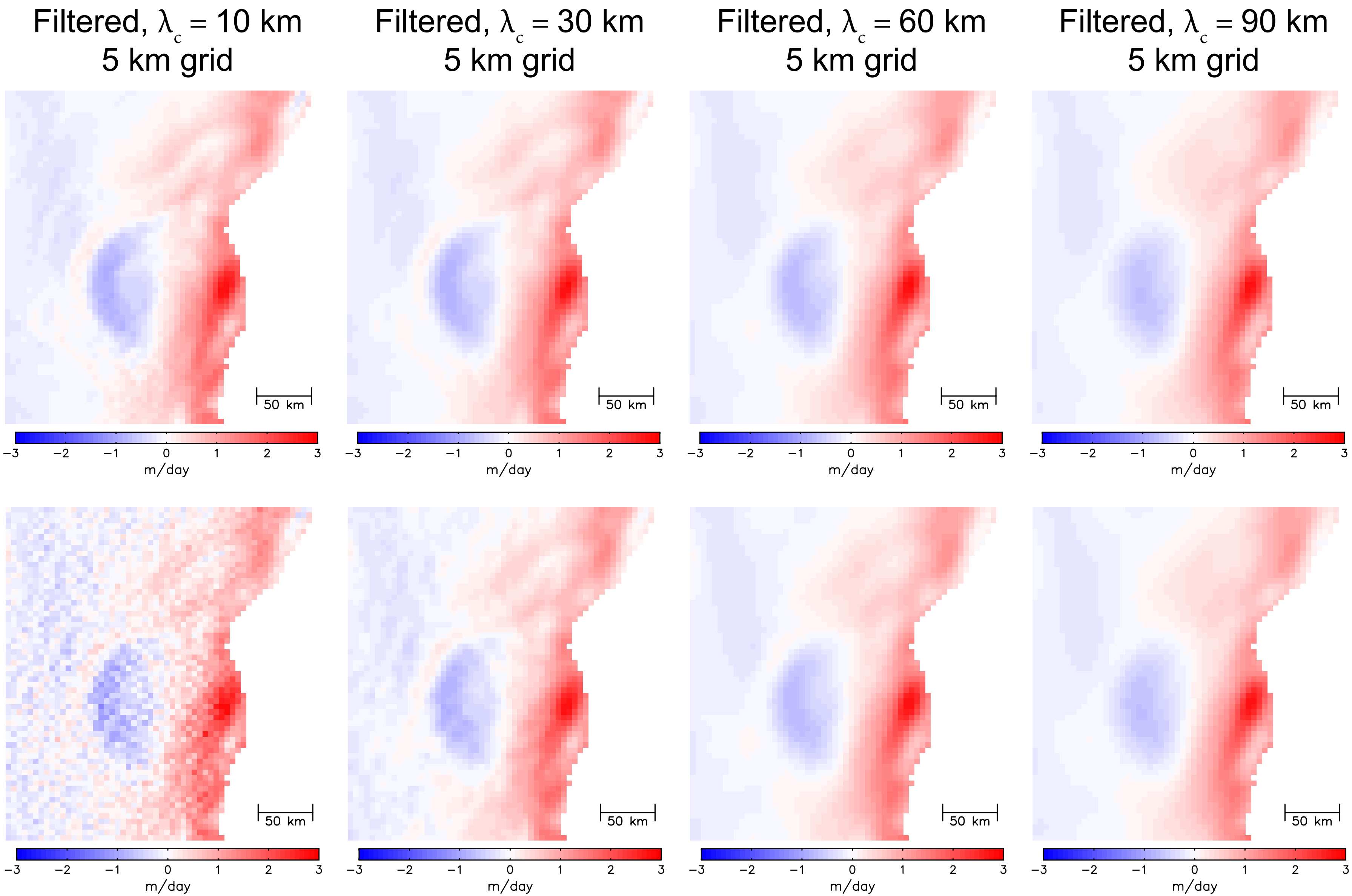


W_c from 5-km Surface Velocity With and Without 0.5 m/s Errors: Spatial Smoothing Only



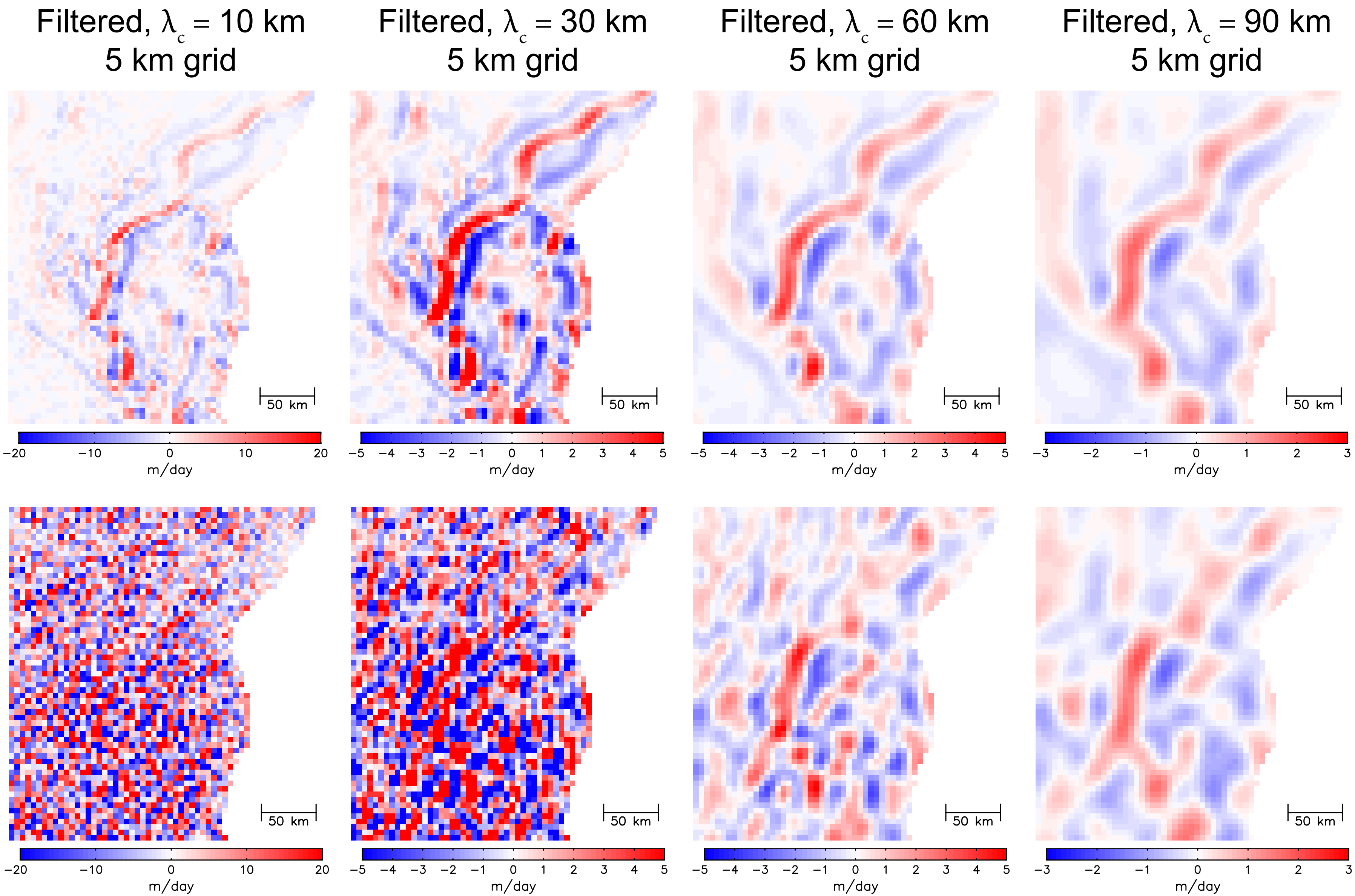
W_c from 5-km Surface Velocity With and Without 0.5 m/s Errors:

Spatial Smoothing and 30-Day Averaging



W_ζ from 5-km Surface Velocity With and Without 0.5 m/s Errors:

Spatial Smoothing Only



W_ζ from 5-km Surface Velocity With and Without 0.5 m/s Errors:

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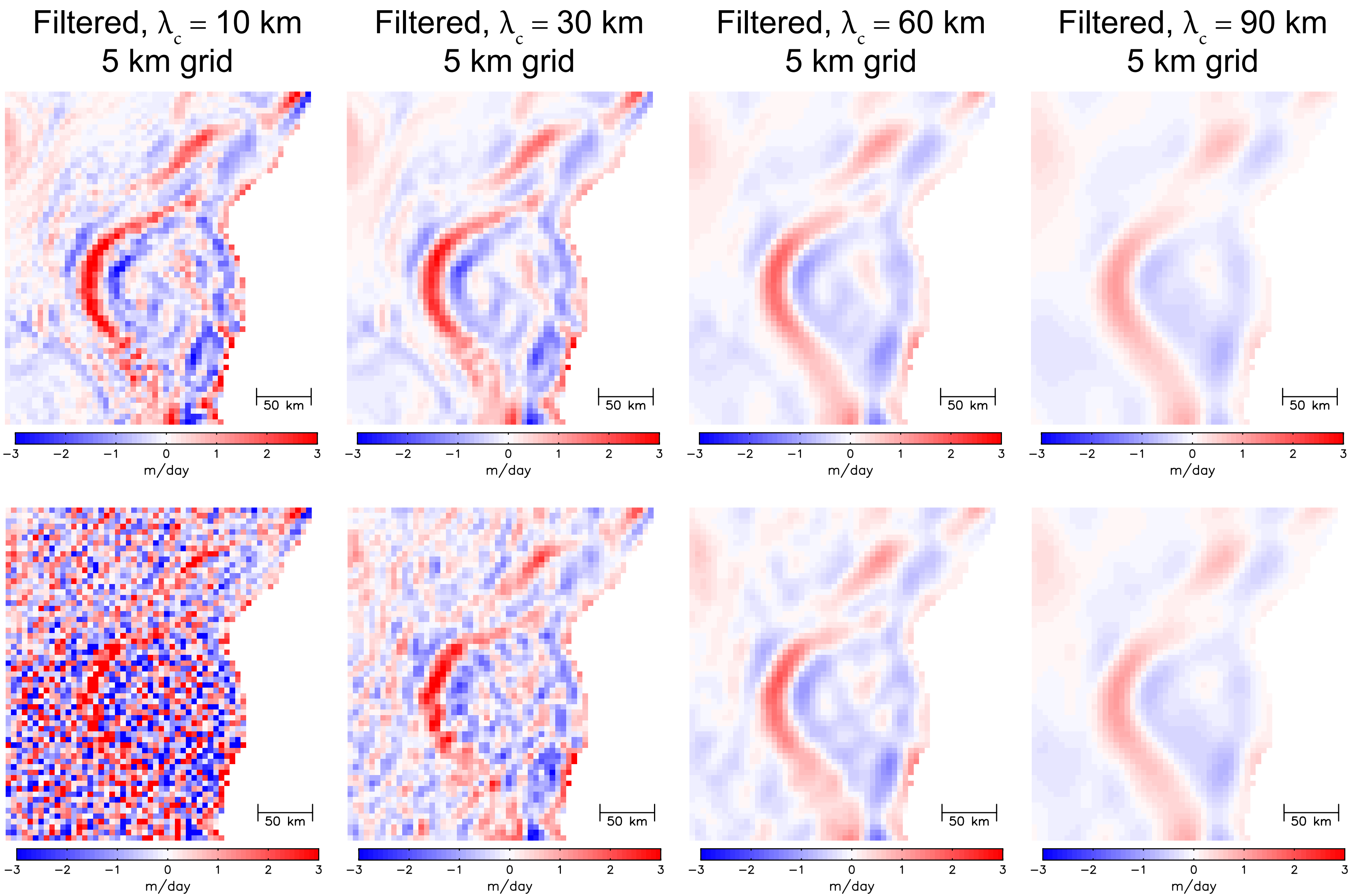


Statistics Over the Full CCS Region

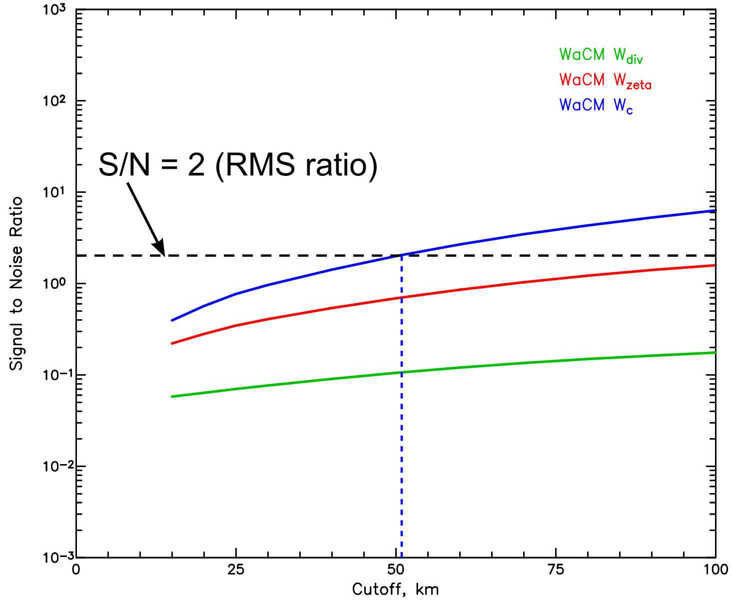
1) Signal-to-Noise Ratio of RMS Values of Upwelling Estimated from WaCM

2) Correlation between Upwelling Estimated with and without WaCM Errors

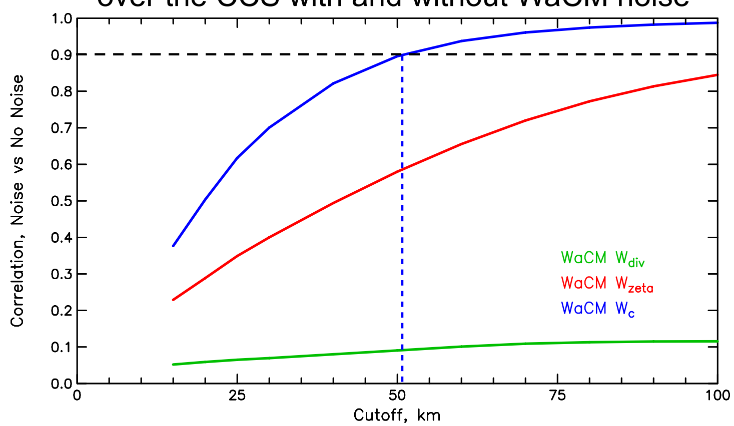
Ekman Pumping W_c, W_ζ and W_{div} From Noisy WaCM Data

Spatial Smoothing Only

Signal-to-Noise RMS Ratio of Ekman pumping fields over the CCS from WaCM



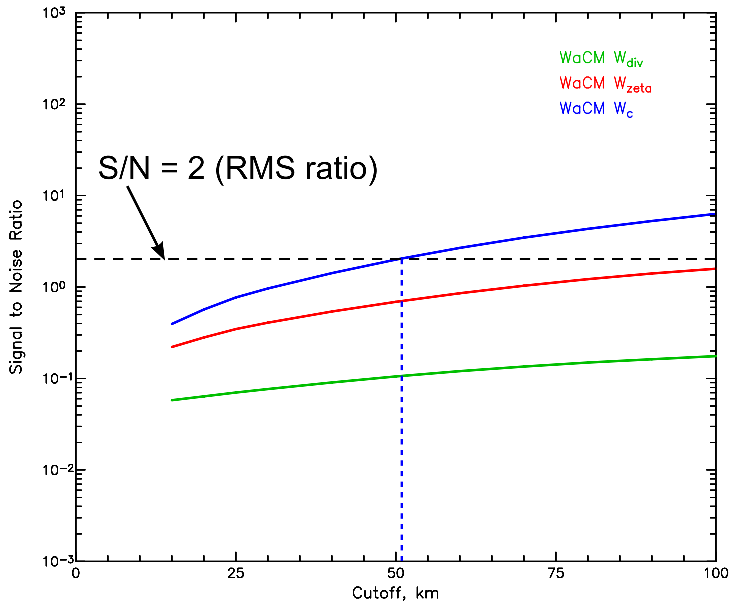
Correlation between Ekman pumping fields over the CCS with and without WaCM noise



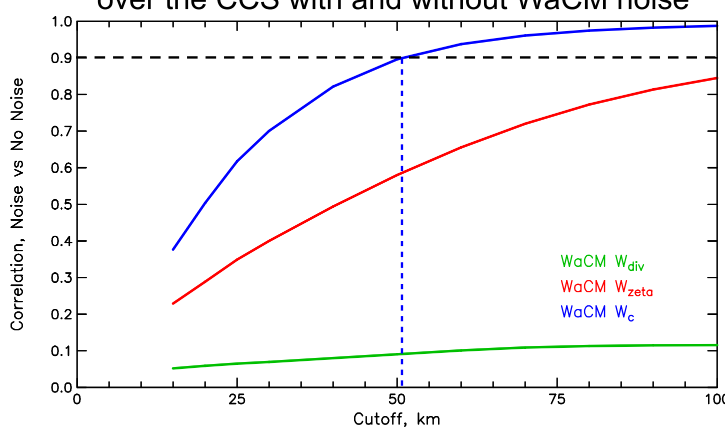
Ekman Pumping W_c, W_ζ and W_{div} From Noisy WaCM Data

Spatial Smoothing Only

Signal-to-Noise RMS Ratio of Ekman pumping fields over the CCS from WaCM

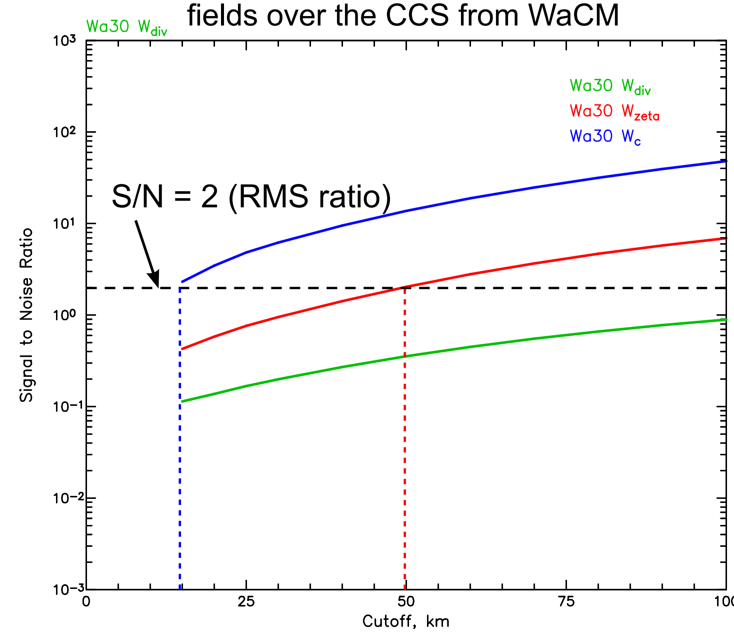


Correlation between Ekman pumping fields over the CCS with and without WaCM noise

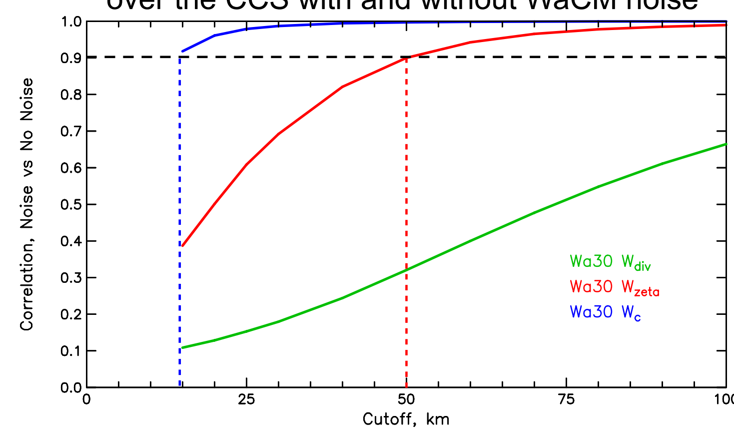


Spatial Smoothing and 30-Day Averaging

Signal-to-Noise RMS Ratio of Ekman pumping fields over the CCS from WaCM



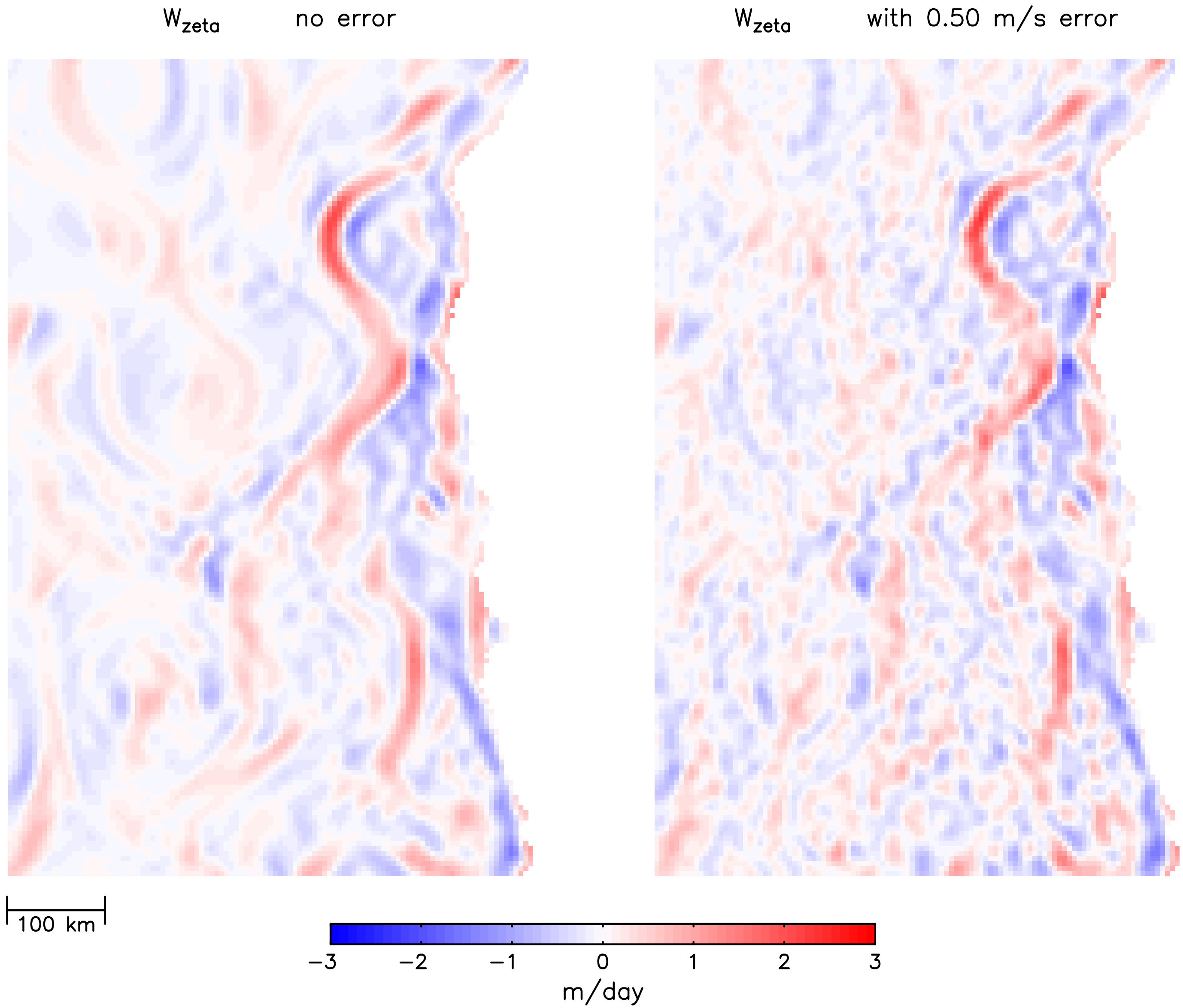
Correlation between Ekman pumping fields over the CCS with and without WaCM noise



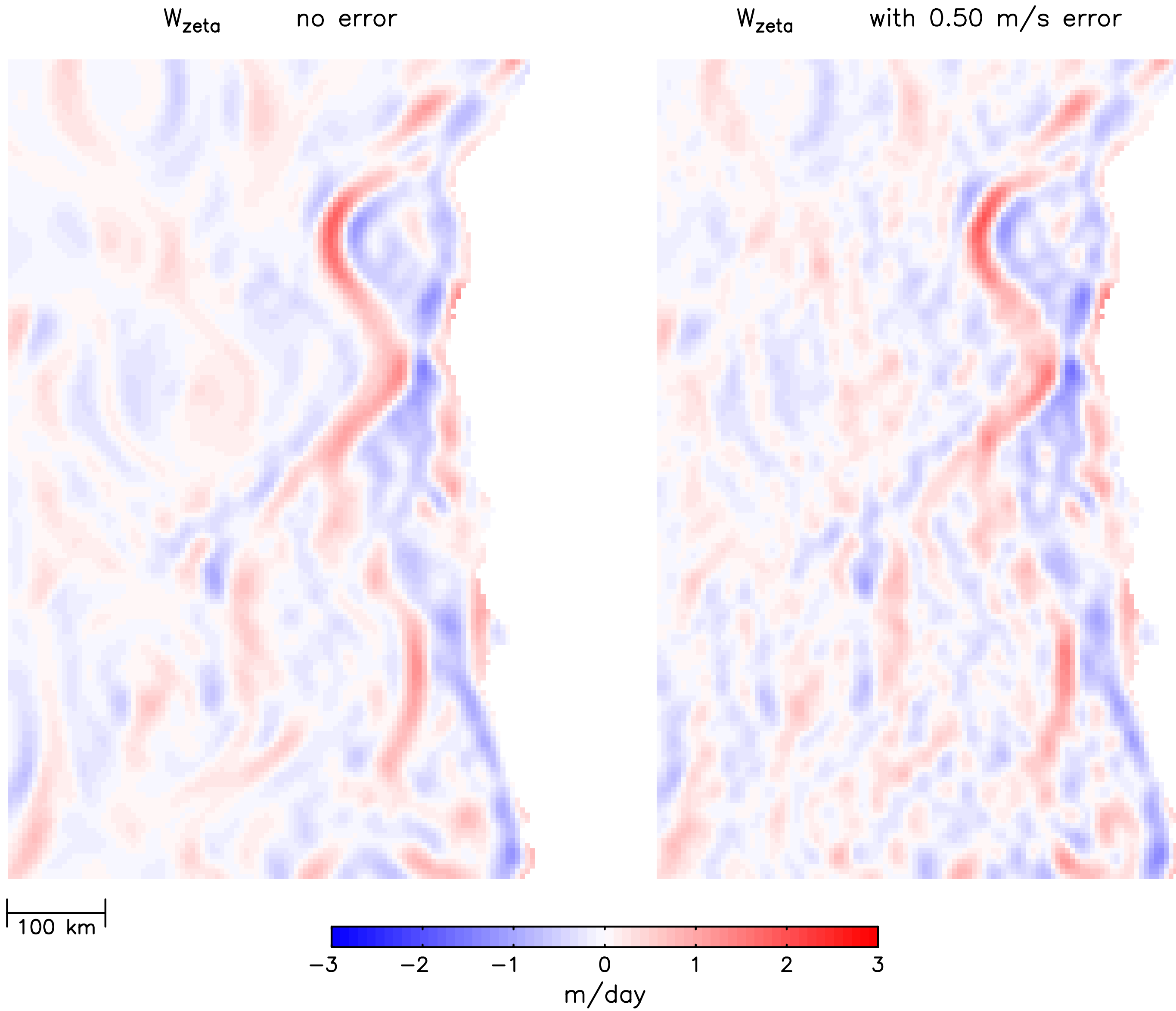
WaCM Estimates of 30-day Averaged W_ζ Over the Full CCS Domain

with 50, 60 and 70 km smoothing

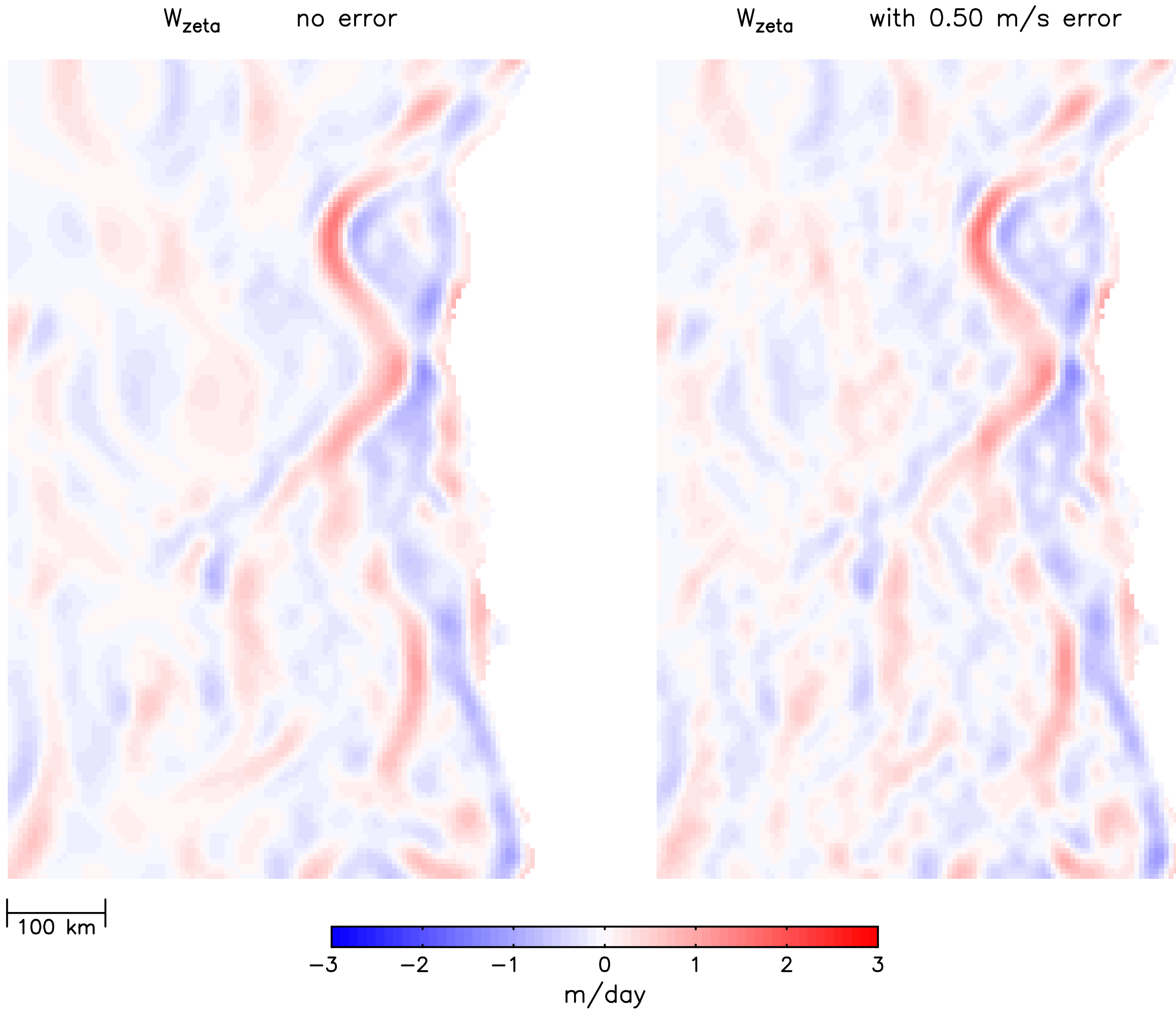
W_ζ from 5-km Surface Velocity With and Without 0.5 m/s Errors: Spatial Smoothing with 50 km Filter Cutoff and 30-Day Averaging



W_ζ from 5-km Surface Velocity With and Without 0.5 m/s Errors: Spatial Smoothing with 60 km Filter Cutoff and 30-Day Averaging



W_ζ from 5-km Surface Velocity With and Without 0.5 m/s Errors: Spatial Smoothing with 70 km Filter Cutoff and 30-Day Averaging



Conclusion

With the anticipated 0.5 m/s noise in WaCM measurements of surface velocity, it appears from this preliminary analysis that:

- Scientifically useful estimates of W_c and W_ζ can be obtained from 30-day averages with a filter cutoff of about 50 km (a feature resolution of ~25 km).
- Estimation of W_{div} will require more smoothing in space and time.