Assimilation of SWOT Observations for Multi-Scale 4DVAR

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Objective:
To find which assimilation system, standard or multi-scale 4DVAR, more accurately captures small-scale phenomenon.

Motivation:
Improving our analysis of sea surface height enhances the predictive accuracy of our forecasts, which positively impacts the efficiency and effectiveness of naval operations (i.e. search and rescue, surface drift).

Background:
Data assimilation is the process of correcting model forecasts with observations. Typically, assimilation systems do well with portraying mesoscale features or larger; smaller scale phenomena are more difficult to capture. As observation technologies improve, they provide an increasing amount of data at a higher resolution. This causes assimilation techniques that can handle an increased number of observations to become more appealing. The Surface Water Ocean Topography (SWOT) wide-swath altimeter will capture ocean phenomena with ten times the resolution of current technologies*. The SWOT satellite will be launched in 2021*.

Methodology:
Standard 4DVAR correction:
Correction = $BH^T(HBH^T+R)^{-1}(y-Hx)$

Multi-scale 4DVAR correction:
1st outer loop, larger correction scale
$(\delta x_{Ls}) = K(\tilde{y}-Hx)$
2nd outer loop, smaller correction scale
$(\delta x_{SS}) = K(y-H(x+\delta x_{Ls}))$

The standard 4DVAR assimilation system attempts to correct both large scale and small scale features at once, while the multi-scale 4DVAR assimilation system corrects large scale phenomena in the first outer loop, and then corrects small scale phenomena in the second outer loop.

Experiment Setup:
- Nature run is run, providing the "truth"
- Simulated SWOT observations are drawn from a nature run
- 4DVAR and multi-scale 4DVAR ocean simulations are run using different initial conditions than the nature run
- A free run (no assimilation) is run to provide a control experiment
- Dates: Jan. 5 2016 – Feb. 29 2016
- Resolutions: 3km for multi-scale and 4DVAR, 1km for nature run
- Domain: North Arabian Sea

Results:

Figure 1: The upper left map is of the experiment domain. The bottom left plot shows the observations used in the 4DVAR assimilation system, and the bottom right plot shows the observations used in the multi-scale assimilation system. From this graph, it is evident that the multi-scale 4DVAR assimilation system uses many more observations than the 4DVAR to calculate its corrections to the model ocean state.

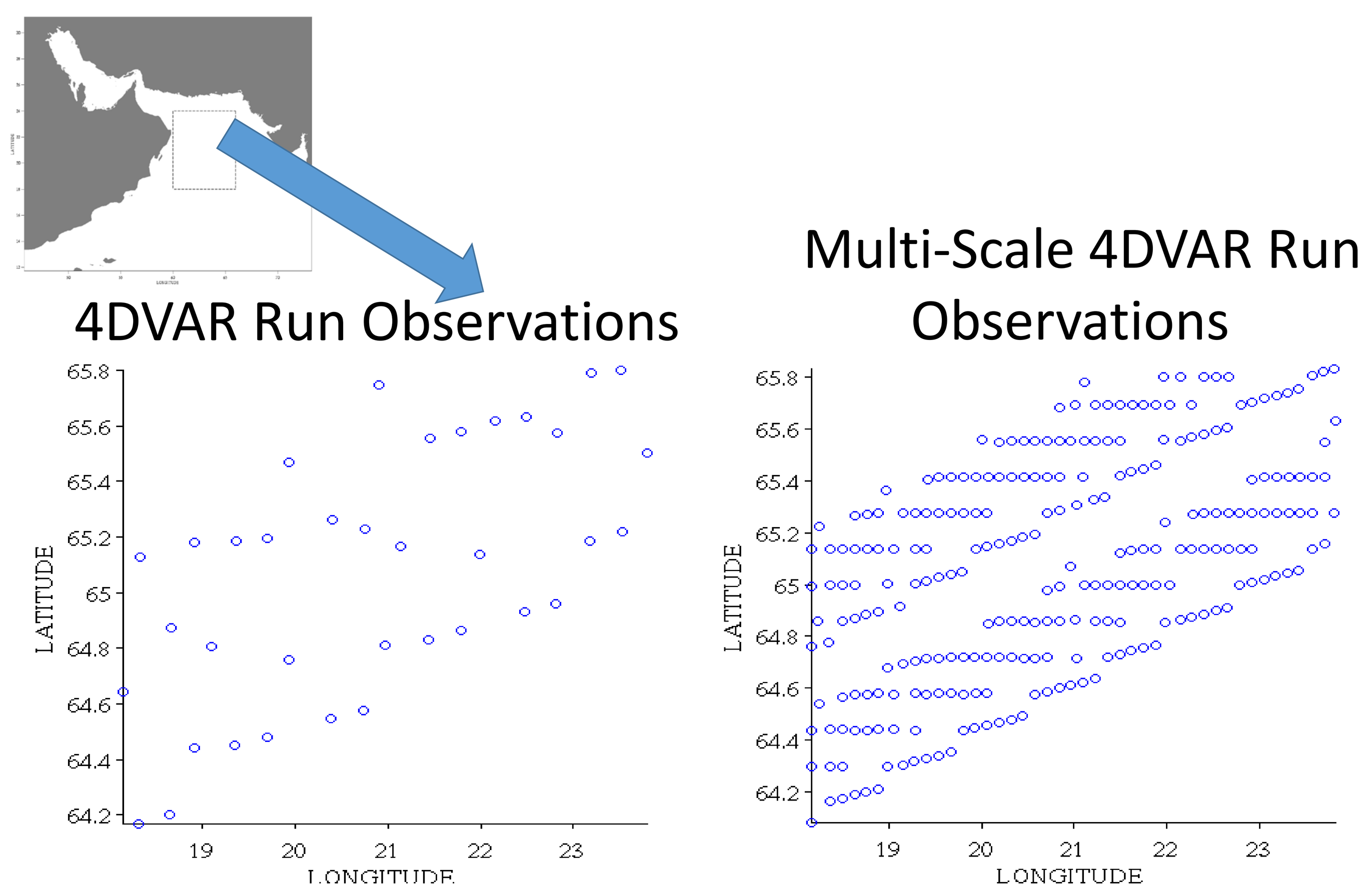


Figure 2: These plots show various runs for sea surface height. The 4DVAR run captured the sea surface height the most accurately; multi-scale 4DVAR captured the sea surface height less accurately than 4DVAR, and the free run did the worst.

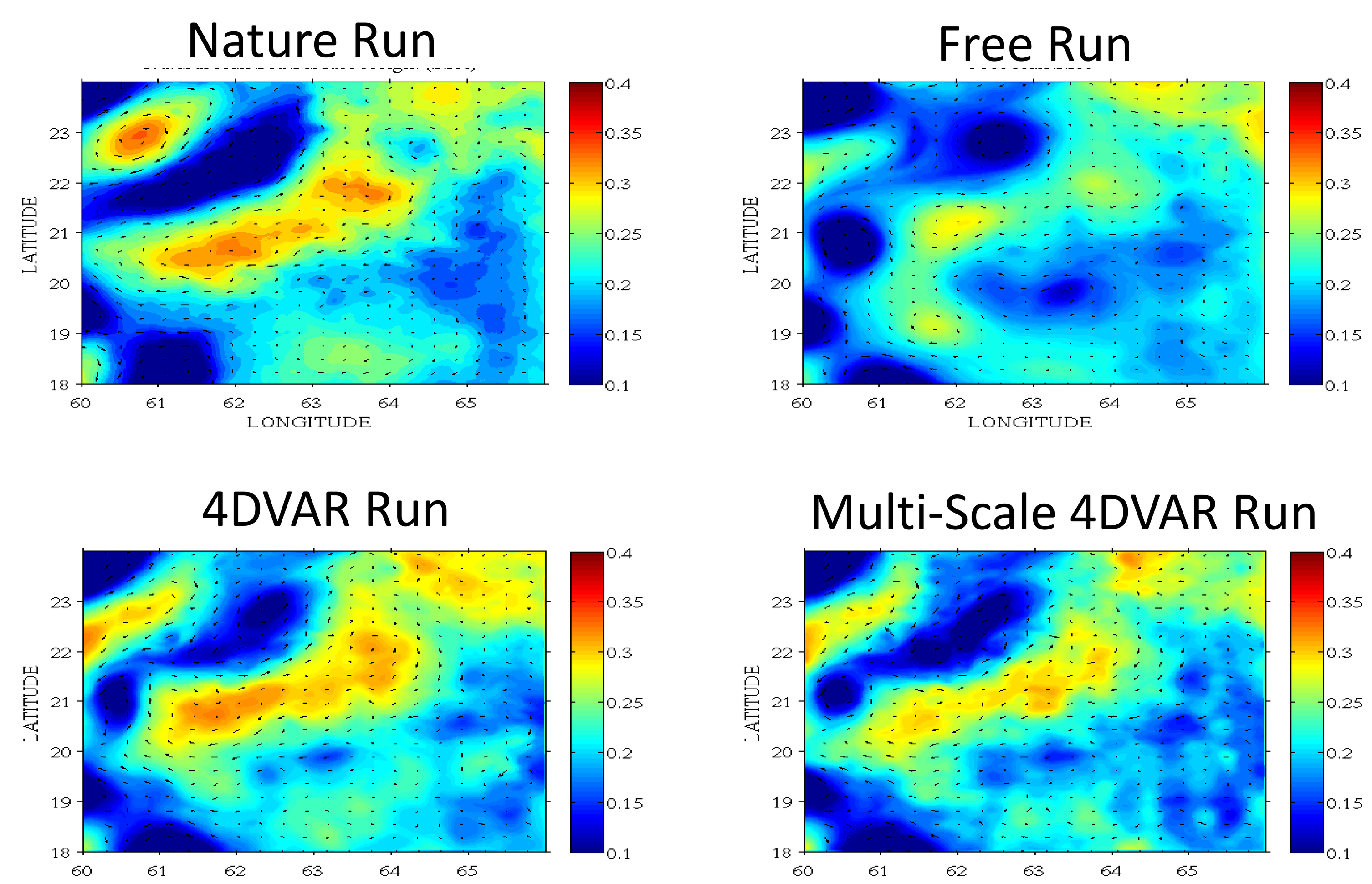


Figure 3: This figure shows plots of sea surface height difference in the various runs and demonstrates how the free run has the most amount of deviation from the true ocean state and is more erroneous than 4DVAR and multi-scale 4DVAR. 4DVAR generally captures features more accurately than multi-scale 4DVAR based upon the lighter colors in the figure.

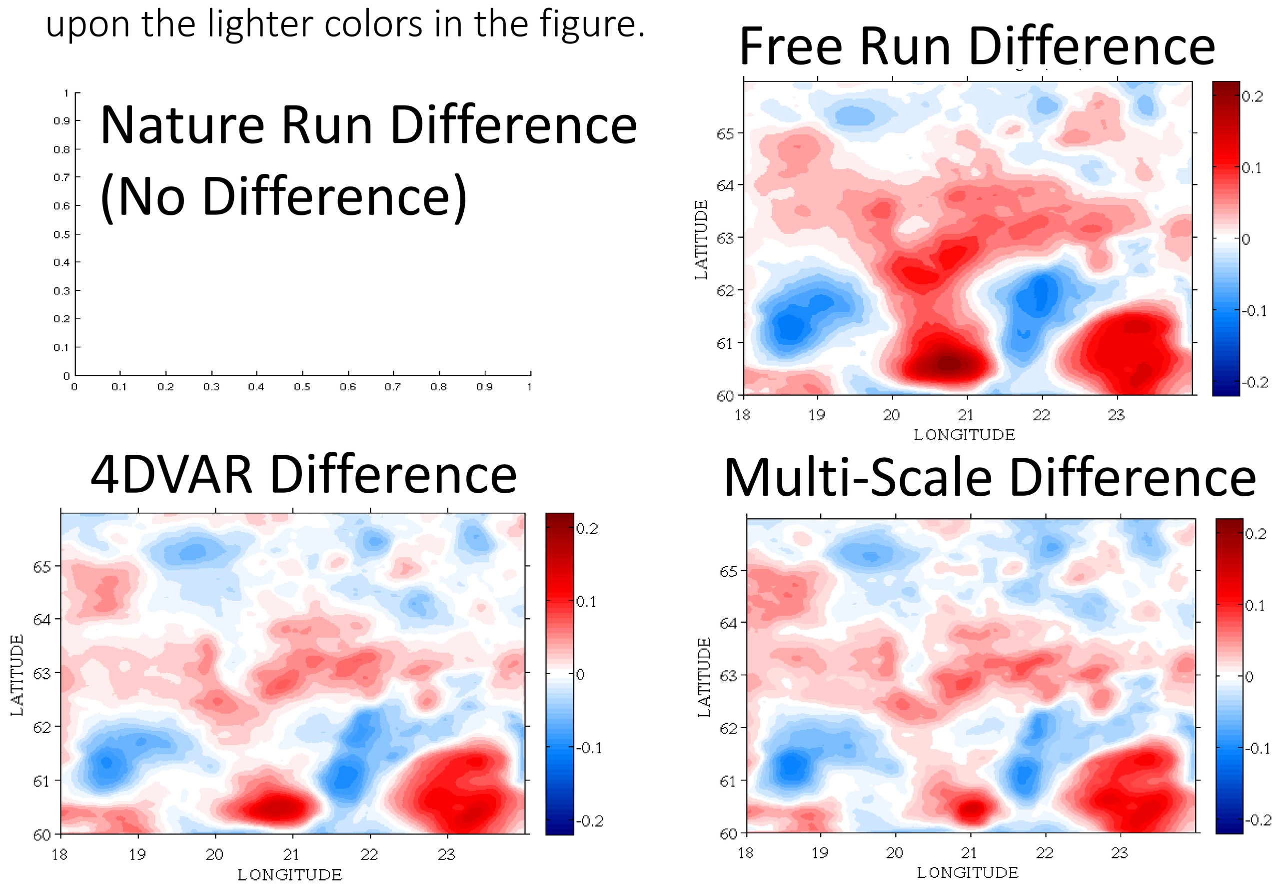


Figure 4: This graph depicts a plot of Root Mean Square Error for the free run, 4DVAR, and multi-scale assimilation system for the entire experiment time period. Root Mean Square is an error measurement form. This figure demonstrates how 4DVAR and multi-scale 4DVAR tend to have similar root mean square error values, while the free run is much more incorrect.

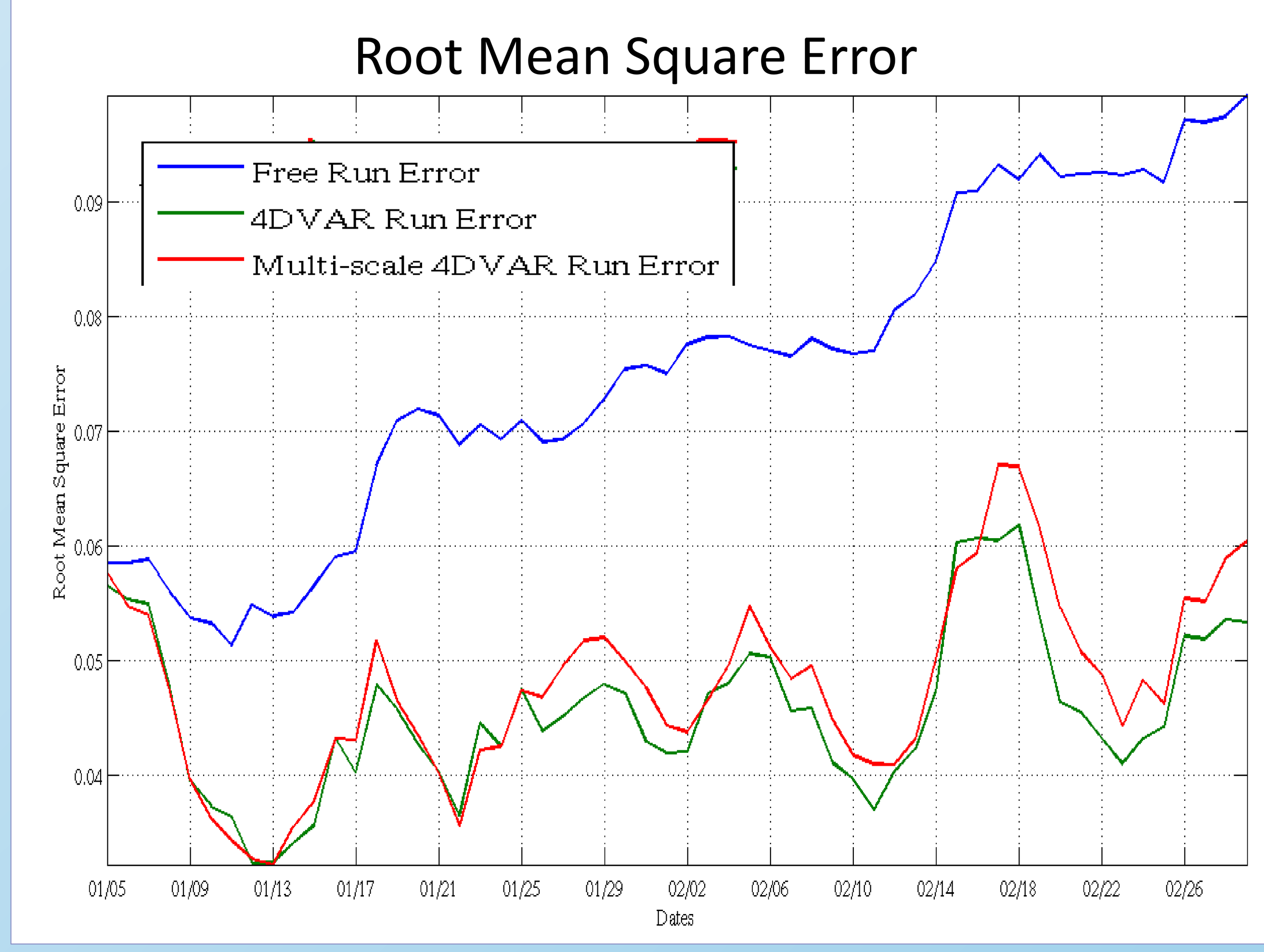


Figure 5: This graph portrays the Power Spectral Density at different wavelengths for the free run, 4DVAR run, and multi-scale 4DVAR run. Both 4DVAR assimilation systems capture too much energy from features that have diameters from 10km to 100km.

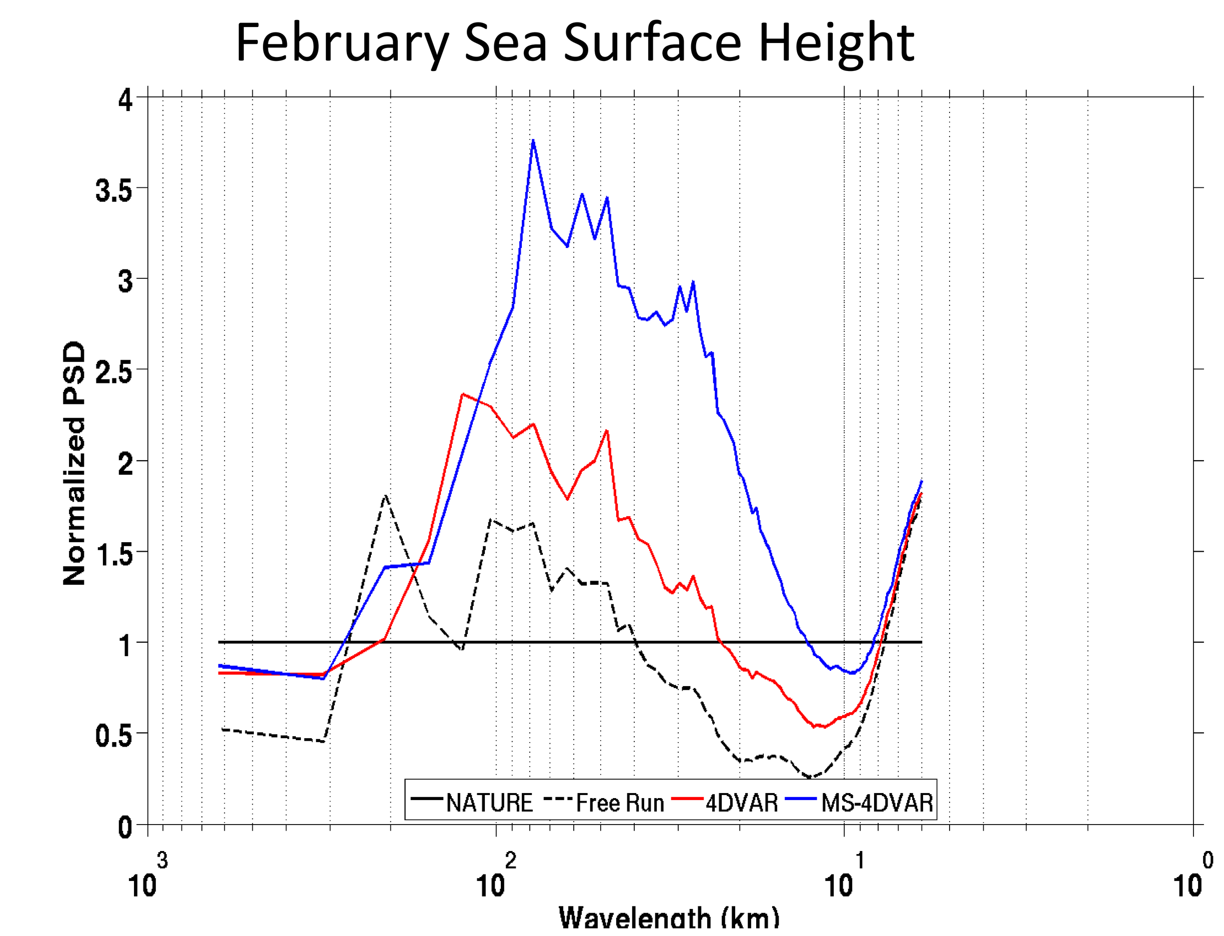
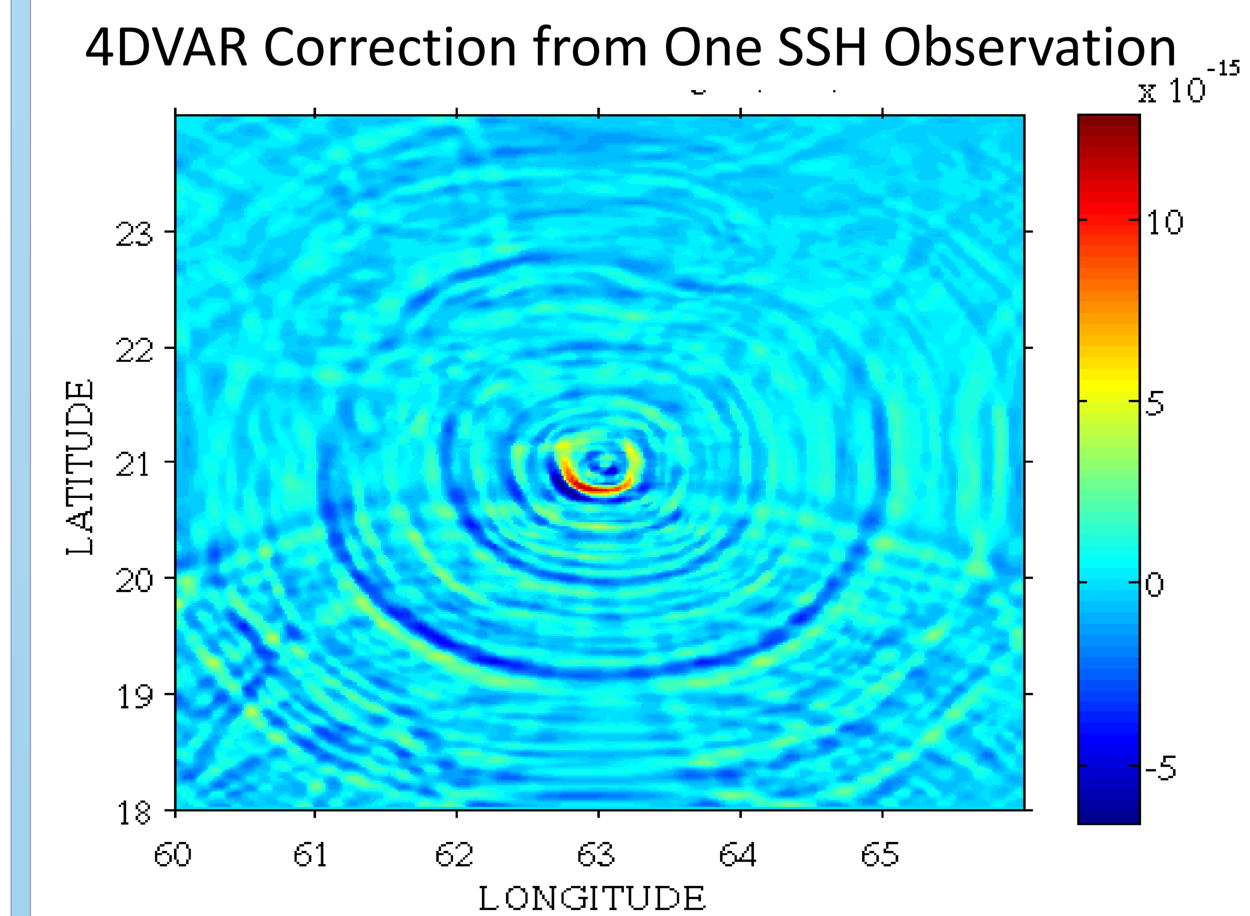


Figure 6: This plot shows the 4DVAR correction from one SSH observation on January 4th, 2016. The ripples on this graph emphasize the contaminating influence of gravity waves on sea surface height corrections.



Conclusion:
We attempted to use multi-scale 4DVAR to see if it could handle SWOT observations better than the standard 4DVAR assimilation system. Figure 2, Figure 3, and Figure 4 exemplify how it does not. The graph of the 4DVAR correction from one sea surface height observation (Figure 6), demonstrates how direct SSH assimilation generates lots of gravity waves. Although both multi-scale 4DVAR and 4DVAR directly assimilate SSH values, multi-scale 4DVAR processes more observations than 4DVAR (Figure 1), causing it to generate many more contaminating gravity waves than 4DVAR. We believe that gravity wave propagation is the reason for multi-scale 4DVAR's worse performance compared to 4DVAR. A possible solution to reduce the contaminating effect of gravity waves is using MODAS profiles rather than direct assimilation; another solution is using a damping term to the 4DVAR to smooth SSH perturbations.

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References:
"The Surface Water and Ocean Topography (SWOT) Mission." *Canadian Space Agency* , Government of Canada, 9 Aug. 2017, www.asc-csa.gc.ca/eng/satellites/swot.asp