Evaluating the Influence of Assimilating Surface Drifter on Ocean Response During Tropical Cyclones

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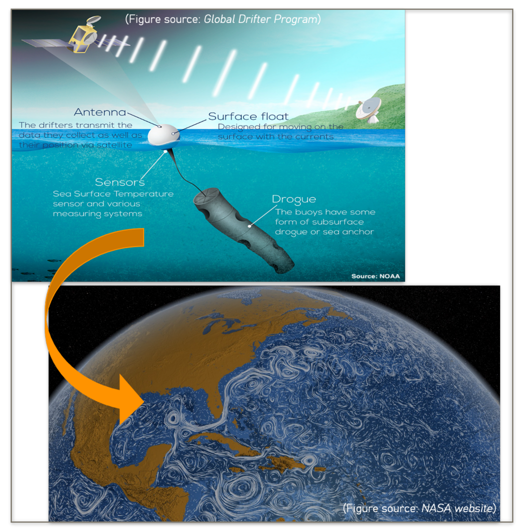
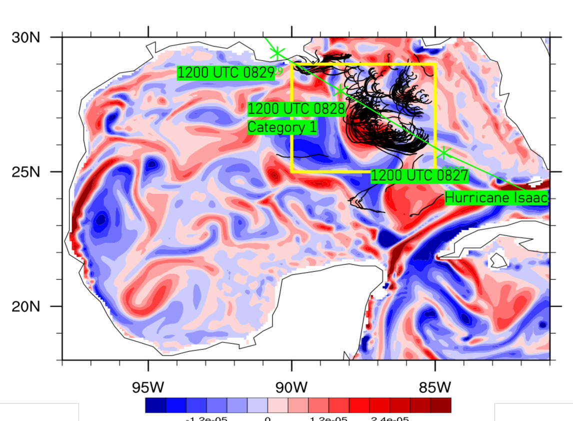
Abstract: Satellite-tracked in situ surface drifters, providing measurements of near-surface ocean quantities, have become increasingly prevalent in the global ocean observation system. However, the position data from these instruments are typically not leveraged in operational ocean data assimilation (DA) systems. In this work, the impact of an augmented-state Lagrangian data assimilation (LaDA) method using the Local Ensemble Kalman Transform Filter is investigated within a realistic regional DA system. Direct positioning data of surface drifters released by the Consortium for Advanced Research on Transport of Hydrocarbon in the Environment during the summer 2012 Grand Lagrangian Deployment experiment are assimilated using a Gulf of Mexico (GoM) configuration of the Modular Ocean Model version 6 of the Geophysical Fluid Dynamics Laboratory. Multiple cases are tested using both 1/4° eddy-permitting and 1/12° eddy-resolving model resolutions: (1) a free running model simulation, (2) a conventional assimilation of temperature and salinity profile observations, (3) an assimilation of profiles and Lagrangian surface drifter positions, and (4) an assimilation of the profiles and derived Eulerian velocities. LaDA generally produces more accurate estimates of all fields compared to the assimilation of derived Eulerian velocities, with estimates of surface currents notably improving, when transitioning to 1/12° model resolution. Further experiments applying a vertical localization while assimilating surface drifter positions improves the estimates of temperature and salinity below the mixed layer depth. Cases including the surface drifter positions in the DA show better Lagrangian predictability than the conventional DA. Additionally, LaDA produces the most accurate estimates of sea surface velocities and improves analysis of the ocean state responding to hurricane conditions when hurricane Isaac (2012) impacted the GoM. These results, which can be applicable to other tropical oceans, open new avenues for estimating ocean initial conditions to improve tropical cyclone forecasting.

Motivation



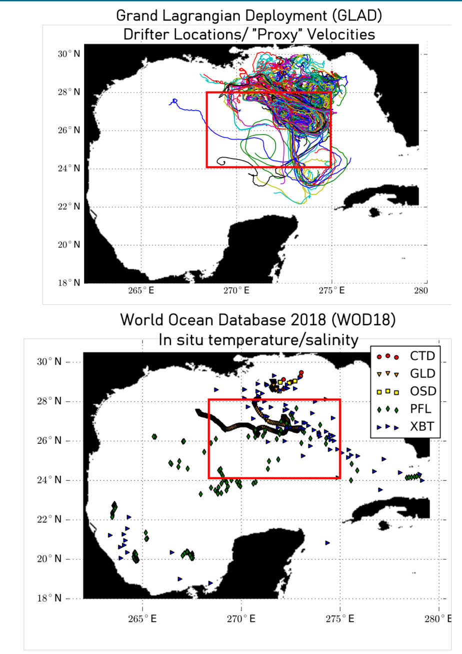
The motivation for assimilating surface drifter data in ocean data assimilation (DA) is to address the challenge of accurately estimating ocean velocities, which has been difficult due to a lack of direct measurements for ocean surface currents on synoptic scales. Despite technological advancements in observing ocean currents, such as satellite-based altimetry and high-frequency radar, the high resolution required by models demands even more precise observations. Surface drifters offer a practical solution by providing spatially distributed, simultaneous measurements of the ocean's surface velocity field across various scales, significantly enhancing the accuracy of DA in capturing smaller scale phenomena.

Hurricane Isaac (2012)



At 1800 UTC on 21 August, Isaac formed east of the Lesser Antilles at 15.2N 53.1W. Isaac moved toward the northwest and entered the southeastern Gulf of Mexico early on 27 August, then became a hurricane while centered about 975 mb at 1200 UTC 28 August. Slowly strengthening, it reached a minimum central pressure of 965 mb on 29 August at 0300 UTC as it moved northwest and then began to weaken upon moving inland at 1800 UTC 29 August.

Data Assimilation (DA) and Experiments



Observations for surface drifter: In the summer of 2012, the Consortium for Advanced Research on Transport of Hydrocarbon in the Environment (CARTHE) carried out the Grand Lagrangian Deployment (GLAD) experiments by deploying 297 CODE-type surface drifters, tracked using SPOT GPS units and centered at a depth of one meter. These drifters, without temperature or salinity sensors, were launched over several days starting 20 July and drifted with surface ocean currents until 22 October 2012. In this work, the instantaneous drifter position entries are assimilated using the augmented-state Lagrangian DA (LaDA).

Observations for temperature and salinity: During the examination period in the Gulf of Mexico (GoM), in situ temperature and salinity profile observations were sourced from the World Ocean Database 2018 (WOD18). Data entries in WOD18 are subject to quality control checks, and any observations marked with a negative quality control flag were excluded from this study's analysis to prevent the adverse effects of outlier measurements.

Forecast model: We use a regional model with the Gulf of Mexico (GoM) configuration of the Modular Ocean Model, version 6 (MOM6). The model domain is defined in a region extending 18°–30.5°N and 262°–279.5°E using spherical coordinates. Two primary horizontal resolutions are tested: an eddy-permitting configuration of 1/4° (roughly 24 km) and an eddy-resolving configuration of 1/12° (roughly 8 km). A total of 75 levels defined with z coordinates are used in the vertical with 2–3-m resolution in the top 50 m. The ocean model integration step is chosen as 150 s. Ensemble surface atmospheric forcing is provided by the twentieth century Reanalysis version 3 (20CRv3).

DA method: The Local Ensemble Transform Kalman Filter (LETKF; Hunt et al. 2007) and LETKF-LaDA algorithms (reference [2] and [3]) were employed for all data assimilation (DA) runs, using an ensemble size of 30 members. DA experiments used 6-hour assimilation windows. The horizontal localization radius was set at twice the Rossby radius of deformation for both profile and surface drifter measurements. Each observation had a static estimated error assigned: 2.0°C for temperature, 1.0 psu for salinity, 0.08 for longitude/latitude of surface drifter position.

Experiments: Multiple cases are tested using both 1/4° eddy-permitting and 1/12° eddy-resolving model resolutions: (1) a free model run (baseline); (2) an assimilation of only in situ T/S (PROF); (3) an assimilation of in situ T/S + surface drifter locations (BOTH); (4) an assimilation of in situ T/S + 'proxy' velocity from surface drifters (BOTHvel; not shown in poster, the results are shown in section 3b of reference [2]); and (5) an assimilation of in situ T/S + surface drifter locations w/ vertical localization (VLOC).

Forecast Skills of Ocean States Since 1 Aug., 2012

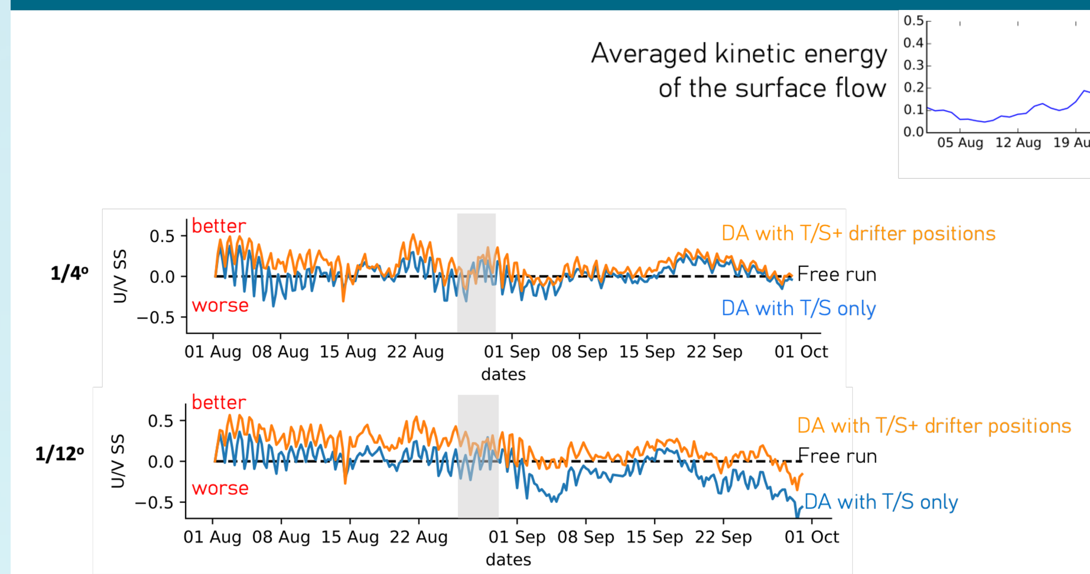


Fig 1. Time variation of the forecast skill score measured against free run solution (black dashed line) for kinetic energy in (a) 1/4-degree system; and (b) 1/12-degree system. Valid from 1 Aug to 29 Sep 2012. The gray shadows in all panels represent the time region for Hurricane Isaac (26–30 Aug 2012).

Assimilation of the drifter locations improves the forecast of surface velocity:

As shown in **Fig. 1**, the velocity skill score is constantly larger during the entire examination period when assimilating both drifter positions and profiles (BOTH) than when assimilating only profiles (PROF). The average velocity skill score of PROF is -0.07 due to its poor performance after 31 days, while adding the assimilation of surface drifter positions provides an average 0.17 velocity skill score. This improvement of BOTH in estimating the velocity over PROF in the eddy-resolving configuration is more significant than in the eddy-permitting system (see Table 1 and Table 2 in reference [2]). This is probably because the 1/12-degree forecast model can resolve currents of eddy scale and provide more reasonable ensemble uncertainty in all the fluid states for the DA. The negative velocity skill scores of BOTH and PROF at the end of September may be caused by the dynamic change of the surface flow after Hurricane Isaac. The analysis generated by DA at 1/12 degree possibly introduces energy at smaller scales (than the 1/4-degree analysis) that somehow becomes the problematic to the forecast as the hurricane passes over the area.

Assimilation of the drifter locations with vertical localization improves the forecast of T/S:

Assimilating surface drifter positions in addition to temperature and salinity profiles can degrade estimates of temperature and salinity below the mix layer depth (MLD) and even some levels above the MLD. Therefore, we add a cutoff vertical localization to the assimilation of drifter positions (denoted as VLOC), which restricts the influence of surface drifter position observations to remain above the MLD, instead of the entire water column. The cutoff MLD at each time step is determined by using the ensemble mean

$$f(\Delta h)=\begin{cases}1, & \text{if } \Delta h<\overline{\mathrm{MLD}}\\ 0, & \text{if } \Delta h\geq\overline{\mathrm{MLD}}\end{cases},$$

where Δh is the height difference between the forecast ocean fluid states and the surface drifter observations. The $\overline{\mathrm{MLD}}$ is the mean MLD of all the forecast ensemble members. We note that this vertical localization is only applied to the surface drifter position observations, while the conventional in situ temperature and salinity profiles still influence the ocean state estimates for the entire water column.

Compared to experiments assimilating surface drifter positions and in situ profiles without vertical localization (BOTH), the use of vertical localization (VLOC) significantly improves temperature and salinity estimates below the Mixed Layer Depth (MLD) across all forecast model resolutions. While the 1/4-degree model resolution didn't consistently show lower errors with VLOC compared to only assimilating profile observations (PROF) below the MLD, the 1/12-degree model resolution combined with vertically localized LaDA and conventional profile assimilation (VLOC) resulted in the lowest root mean square errors (RMSEs) for temperature and salinity below the MLD. However, for temperature and salinity above the MLD, the errors of VLOC are comparable with PROF.

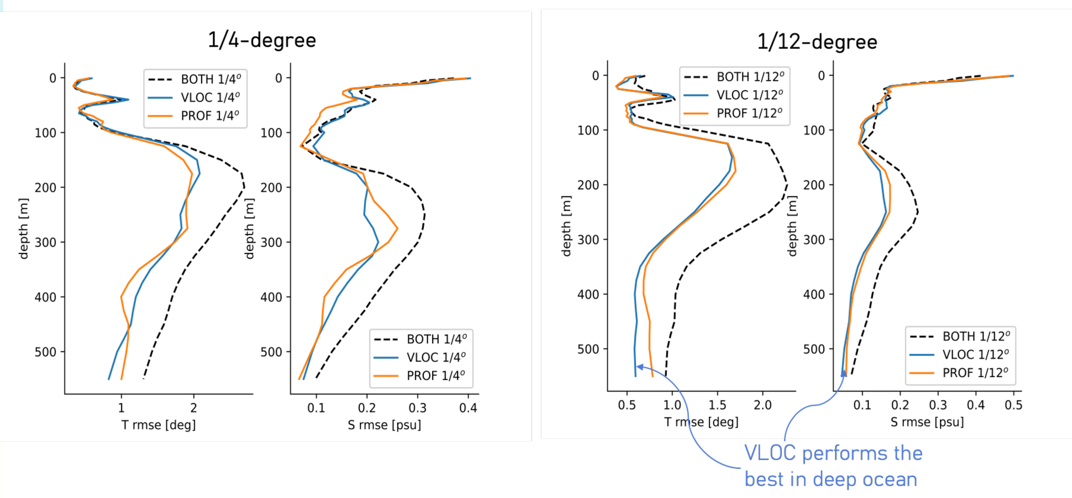


Fig 2. Vertical RMSEs averaged through the whole time period (i.e., 60 days or DA cycles from 1 Aug to 29 Sep 2012) comparing experiments using vertical localization (VLOC; blue line) and without using vertical localization (BOTH; black dashed line). Assimilation of profiles (PROF; orange line) is shown as a reference. (a) Temperature RMSEs in the 1/4-degree system, (b) salinity RMSEs in the 1/4-degree system, (c) temperature RMSEs in the 1/12-degree system, and (d) salinity RMSEs in the 1/12-degree system.

Analysis on Surface Currents During Hurricane Isaac (1200 UTC 28 Aug.)

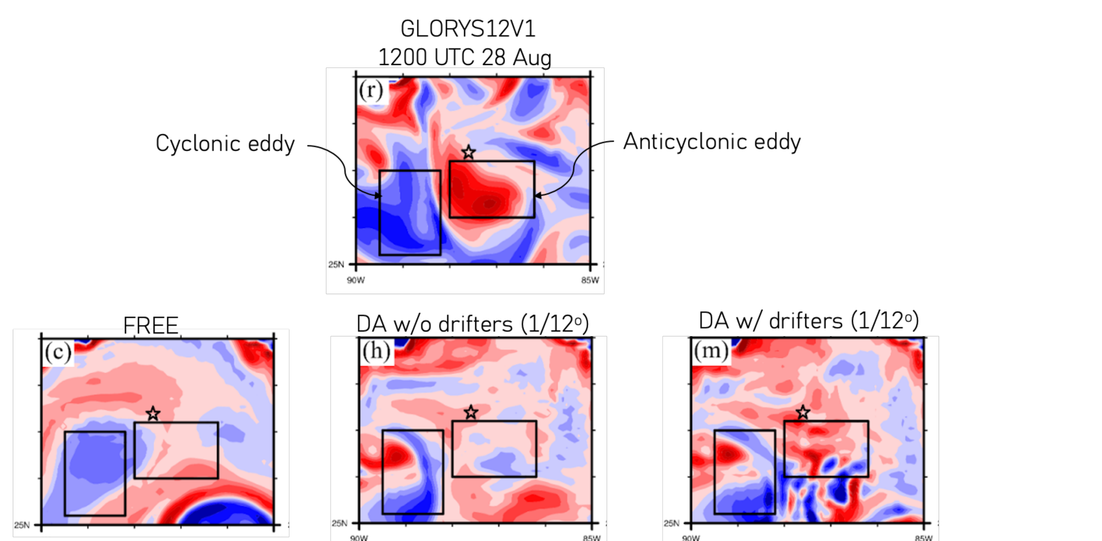


Fig 3. Daily surface vorticity at 1/12 degree in the research area from 26 to 30 Aug: (r) GLORYS12V1 reanalysis; (c) a FREE run; (h) experiment PROF; and (m) experiment VLOC assimilating drifter location with the vertical localization.

Assimilation of drifter positions allows for more accurate mesoscale details:

As Isaac passes through the study focus area on 28 August, the GLORYS12V1 reanalysis reveals a stationary pair of cyclonic (cold core) and anticyclonic (warm core) eddies, indicated by boxes A and B. The experiment FREE, likewise, shows these stationary eddies but with increased spatial extent and intensity of the cyclonic eddy located near the hurricane center on 28 August (**Fig. 3c**).

Assimilating the temperature and salinity profiles (experiment PROF, **Fig. 3h**) shows that a large area of anticyclonic rotation (negative vorticity) in box B near the center of the hurricane on 28 August becomes cyclonic and, as in experiment FREE, the strength of the vorticity center increases by about 4×10^{-6} s^{-1}. In contrast to the GLORYS12V1 reanalysis, even hough the assimilation of hydrographic profiles alone is successful in improving the fine detail of the vorticity field, PROF fails in maintaining the stationary pair of eddies.

When we additionally assimilate drifter positions (experiment VLOC), not only does the vorticity field have fine-scale details but also the position and strength of cyclonic eddies are also more consistent with the GLORYS12V1 reanalysis than experiment PROF. As Isaac enters the study area (**Fig. 3m**), a wide region of anticyclonic (positive) vorticity appears near the box B and near the hurricane center, with a central vorticity exceeding 3.2×10^{-5} s^{-1}. The intensity of the vorticity center is consistent with that of the center of the GLORYS12V1 data in box B (**Fig. 3r**).

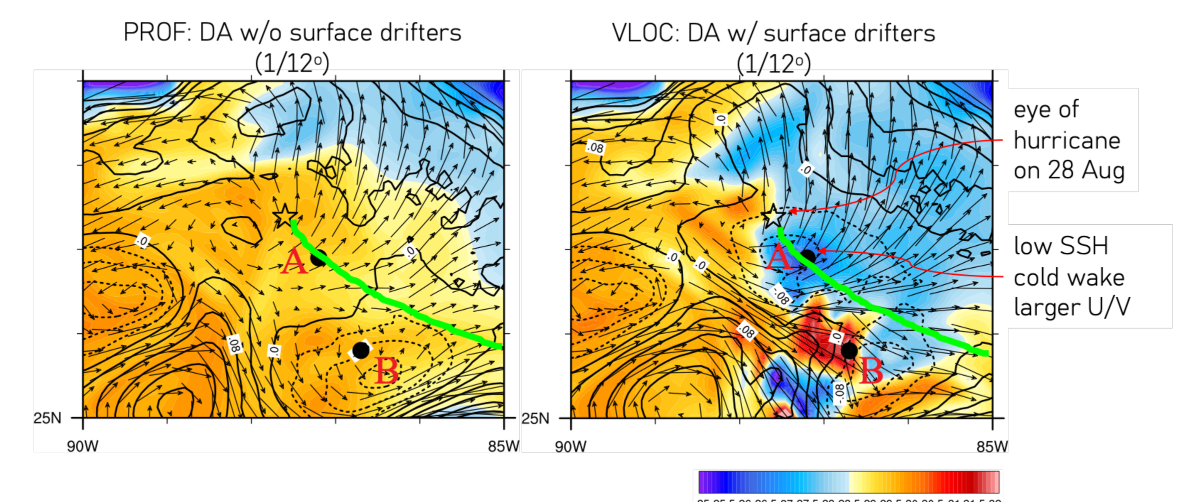


Fig 4. Comparison of surface ocean variables from different experiments on 28 Aug. Colors show SST, black contours show SSH (m; contour interval is 0.04 m; low values are indicated by the dashed lines), and the vectors indicate the surface current velocity (m s21). Black stars indicate the eye of Hurricane Isaac, and solid circles A and B indicate the possible locations of cold and warm wakes. (a) experiment PROF at at 1/12-degree resolution, and (b) experiment BOTH at 1/12-degree resolution.

Assimilation of drifter positions improves surface variables:

The response of the sea surface flow field is mainly the Ekman response of surface cyclonic dispersion. Thus, SST and SSH drop caused by sea surface divergence of Ekman pumping should be mainly located on the right side of the hurricane in the North Hemisphere.

- SST: The VLOC SST response to Isaac is markedly asymmetric (Price 1981), with a clear "cold wake" with a central SST of 25.50C (**Fig. 4b**, point A) appearing in the eastern sector of the hurricane track. This cooling is the result of horizontal divergence at the sea surface in the vicinity of point A and upwelling of cool subthermocline water. In contrast, horizontal divergence near point B simply upwells warm water from within the deeper thermocline at this location (**Fig. 4b**) (leaving a "warm wake"). Additionally, the surface currents forced by Isaac west of point B are constantly transporting warm water eastward. This transport slows near point B (a central SST of 32oC), thus causing the warm water to accumulate and the hurricane heat potential to increase.
- SSH: A difference in SSH is also obvious between the two experiments. A distinct low in SSH (dashed lines) with a central value of -0.08 m in the southeast quadrant is collocated with the cold wake in the experiment VLOC, as expected from the hydrostatic relationship between pressure and density (**Fig. 4b**). However, in the experiment PROF (**Fig. 4a**), no cold wake appears on the southeast quadrant, and there is no corresponding area of low SSH.
- Surface current: the stronger hurricane winds in the eastern sector results in stronger northward-oriented currents. These results are consistent with the surface velocity in the eastern sector in experiment VLOC being stronger than experiment PROF.

Conclusions:

The DA system assimilated the historical dataset with in situ T/S from WOD18 and surface drifter locations from GLAD. The impacts on two types forecast models were assessed: 1) **an eddy-permitting forecast model** with 1/4-degree horizontal resolution; and 2) **an eddy-resolving forecast model** with 1/12-degree horizontal resolution

- BOTHs are capable of improving the synoptic ocean surface U/V for different types of the horizontal resolutions.
- As for the estimation of the synoptic T/S fields, BOTH reduces less RMSE than PROF in fitting the forecast to the in situ T/S observations especially below MLD.
- BOTH outperformed the Eulerian approach (BOTHvel) using the "proxy" velocity in estimating not only for surface velocities, but also for T/S as well.
- We proposed a modification to alleviate the bias in forecasting T/S by employing a vertical localization on BOTH that allows for updating the synoptic ocean states only above MLD as assimilating the surface drifter measurement.
- This modification has shown significant advancements in forecasting the T/S within both of eddy-permitting and eddy-resolving systems in the first 40th days. In addition, VLOC has significant improvements in Lagrangian predictability, as compared with PROF.
- Assimilation of drifter positions allows for more accurate mesoscale detail of ocean surface current fields, and more accurate changes in the ocean surface current in response to the passage of Hurricane Isaac.
- Assimilating the drifter positions also improves simulation of the asymmetric (with respect to track) impact of Hurricane Isaac on SST and SSH.

References:

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3. Sun, Luyu, and Stephen G Penny. "Lagrangian Data Assimilation of Surface Drifters in a Double-Gyre Ocean Model Using the Local Ensemble Transform Kalman Filter." *Monthly Weather Review* 147, no. 12 (2019): 4533–51. https://doi.org/10.1175/MWR-D-18-0406.1.

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