Evaluating an Ensemble Forecast System for Loop Current Eddy Separation in the Gulf of Mexico

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GOM Extended Range Ensemble Forecast System

Ensemble Forecast System:

- **NCOM**[1] ocean model with 3 km grid / 49 levels.
- **32 ensemble members + control member.**
- 3-DVar assimilation via **NCODA**[2].
- Atmospheric Forcing
  - 17 km COAMPS[3] (< week).
  - Climatology (> week)
- Boundary Conditions:
  - Global HYCOM (< week forecast) Climatology (> week).

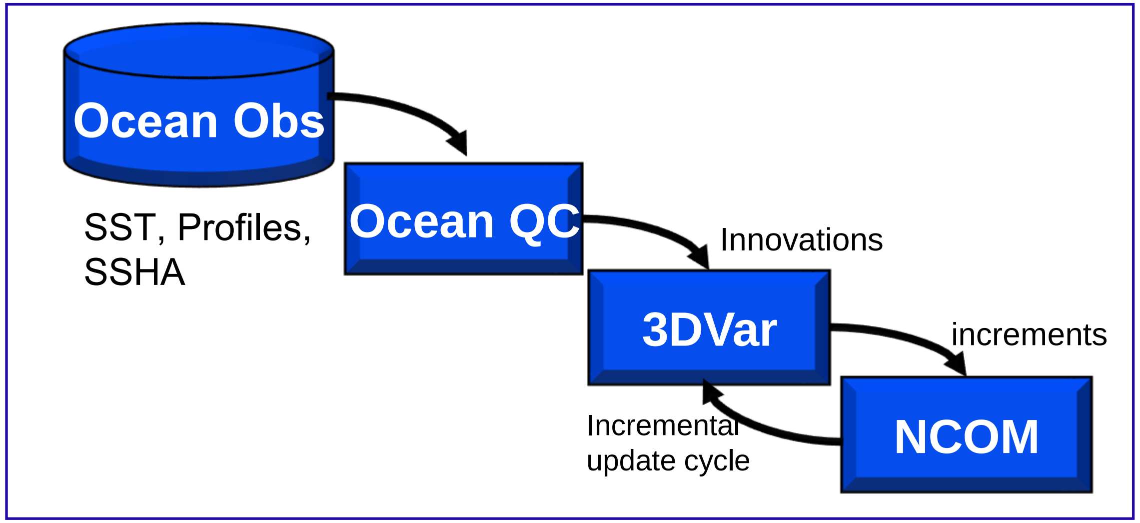
Forecast:

- 4-day forecast – daily.
- **91-day forecast** - once per week.
- Real-time since January 2013.

Ensemble Generation

- The ensemble transform (ET) method is used to generate perturbed initial conditions.
- ET creates a set of initial conditions that represent possible states of the ocean, capturing the uncertainty around the initial state due to errors in observations, model physics, or other factors.

NCODA



[1]NCOM – Navy Coastal Circulation Model
[2]NCODA – Navy Coupled Ocean Data Assimilation
[3]COAMPS – Coupled Ocean Atmosphere Mesoscale Prediction System

Present State of Gulf of Mexico Prediction

- The Loop Current (LC) flows from the Caribbean Sea into the Gulf of Mexico through the Yucatan Channel and exits through the Florida Straits.

- Loop Current Eddy (LCE): Every 6-11 months, a bulge in the current cuts off into a clockwise-rotating eddy.

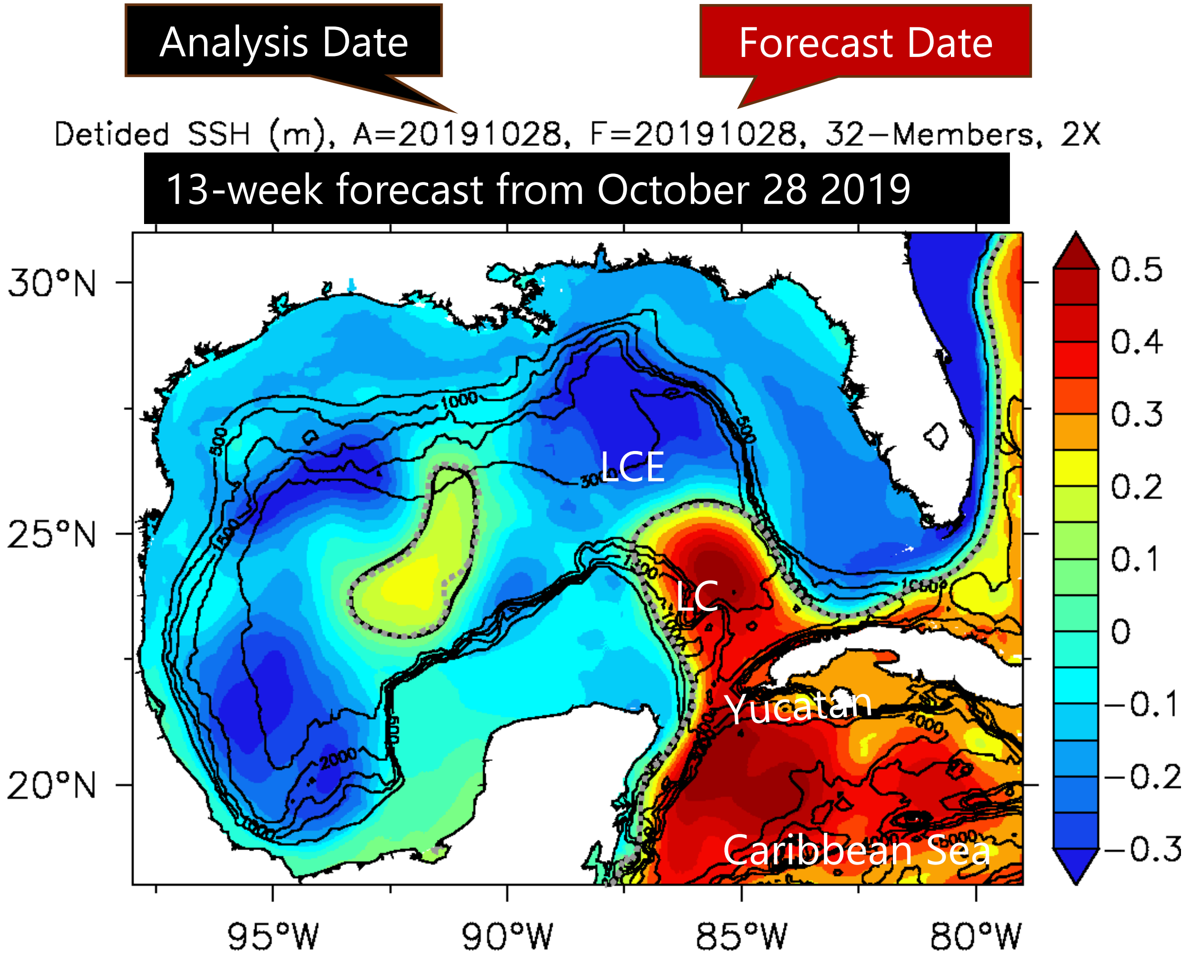
- This shedding process leads to the LC retracting to its original position, while the detached LCE drifts westward into the Gulf.

Forecasting the separation of LCE from the LC is challenging due to several interrelated physical and observational limitations:

- The separation of an LCE is influenced by complex and nonlinear interactions between the LC, mesoscale eddies, and deep ocean features, particularly deep cyclones.

- LCE separation events do not follow a regular pattern and can vary significantly from event to event.

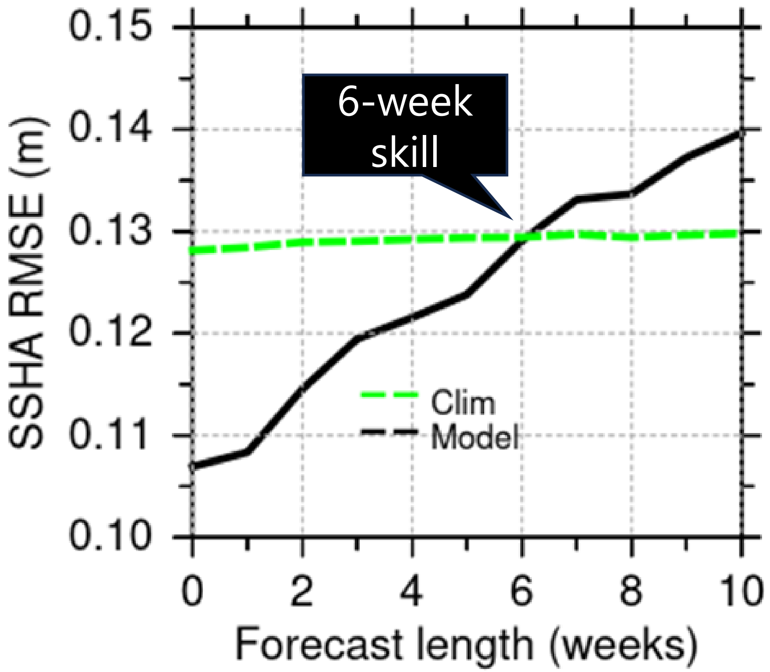
- Forecasting LCE separation is hindered by limited subsurface observations.



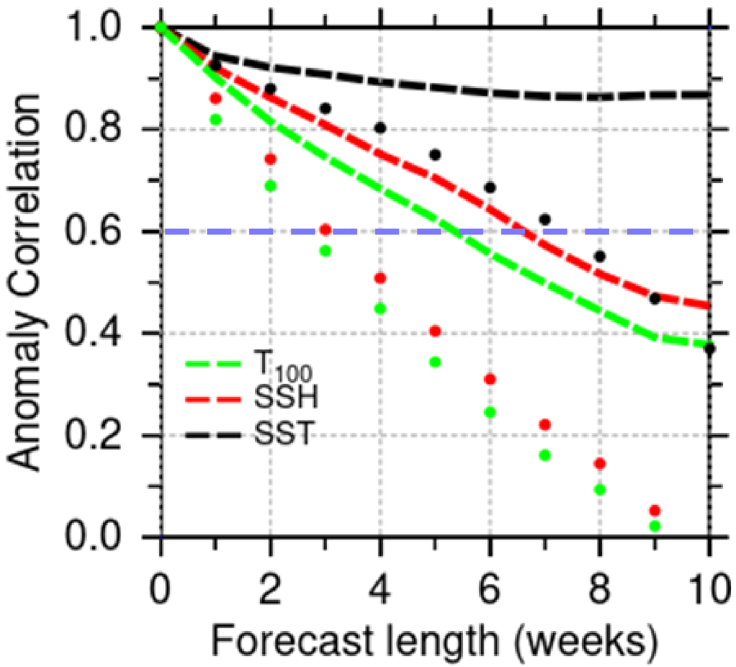
Ensemble mean Sea Surface Height

Predictability of the Mesoscale Variability

RMSE between along-track satellite altimetry SSHA observations and ensemble mean compared to climatology.



AC of SST, SSH and 100 Temp of ensemble mean compared to verifying analyses.

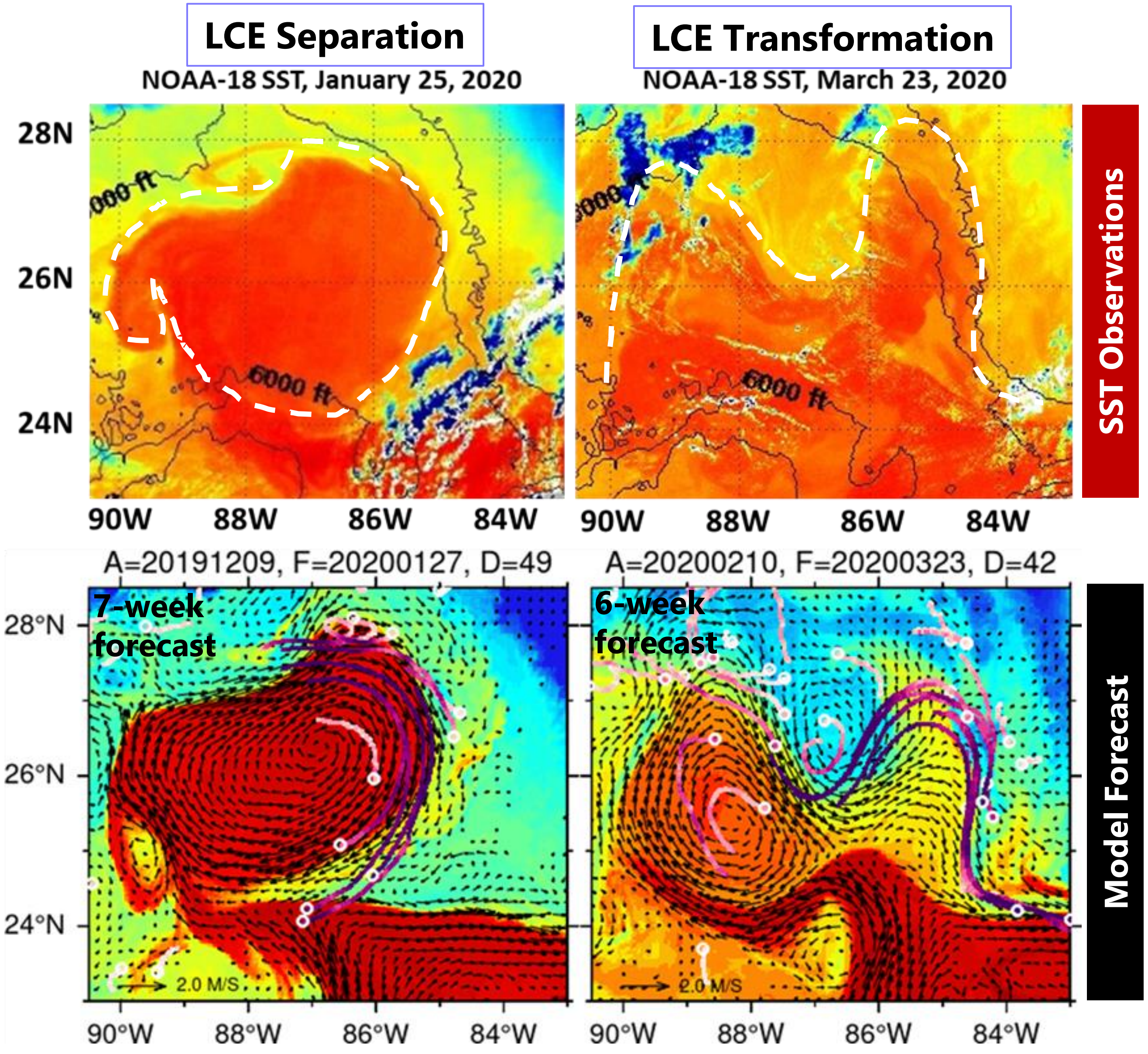


Forecast Skill for SSSHA: Using SSHA observations, the model shows lower RMSE than climatology out to 6 weeks.

High Skill in SST: The highest prediction skill is observed for SST in the Loop Current region, with predictive skill extending beyond 10 weeks. This is due to the abundance of SST observations that help constrain the initial conditions in the model.

Skill for Other Variables: For SSH and temperature at 100 m depth, the forecast skill extends up to 5–6 weeks, showing variable-specific predictability based on the availability of observational data for initial condition constraints.

Loop Current Eddy (LCE) Separation and its Transformation



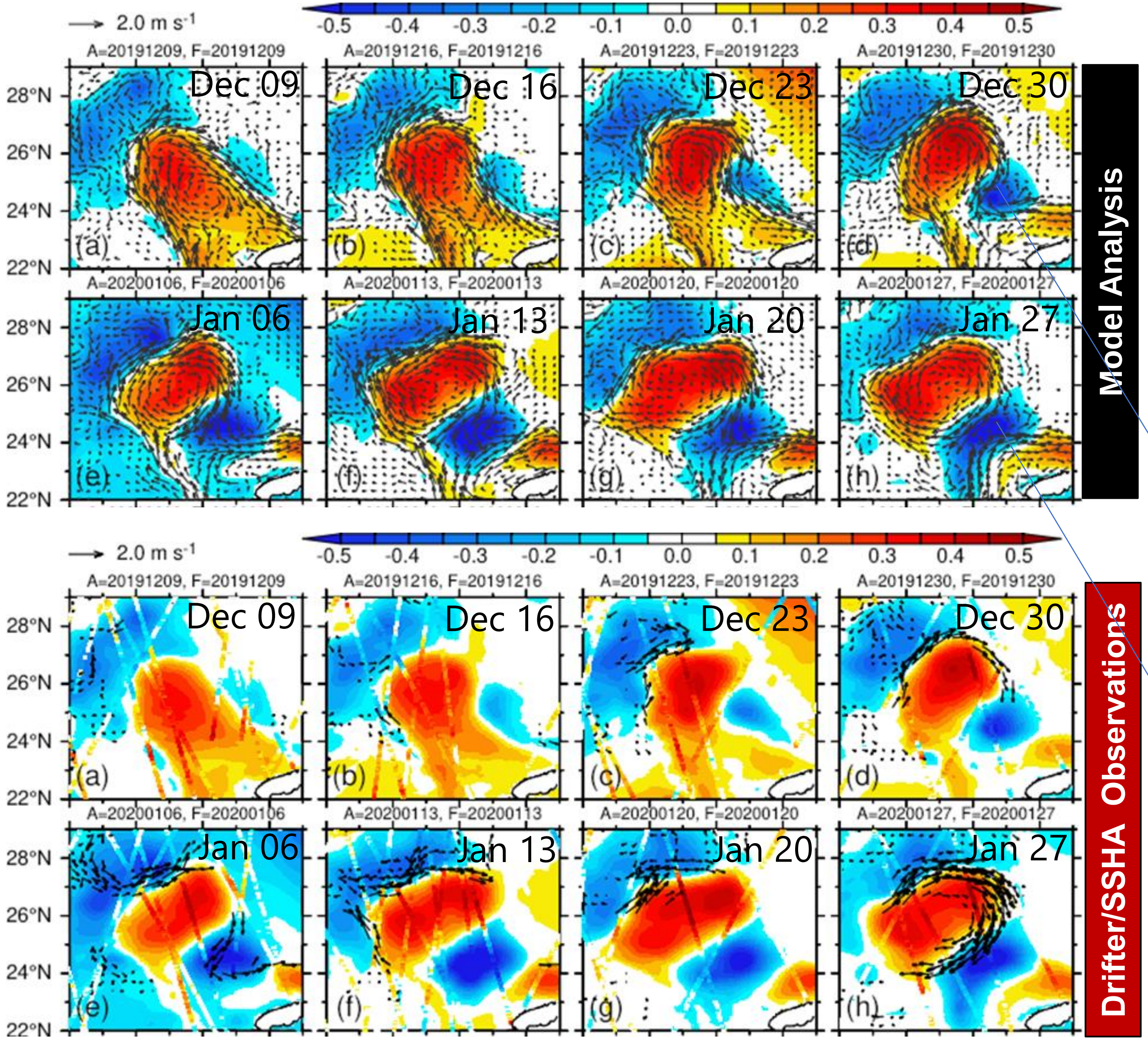
Comparative Analysis: Satellite-derived SST vs. model forecast SST and surface currents, illustrating the Loop Current Eddy (LCE) transformation over time.

Forecast Skill: Model predictions with 6-7 week lead times, demonstrating capability to capture LCE evolution and predict separation events.

Validation with Drifter Tracks: Observed drifter paths superimposed on model output to assess alignment and validate forecast accuracy.

Outline
- Analyses Comparisons
- 7-week forecast: LC-LCE separation
- Forecast uncertainty
- 7-week forecast: LCE transformation
- Summary

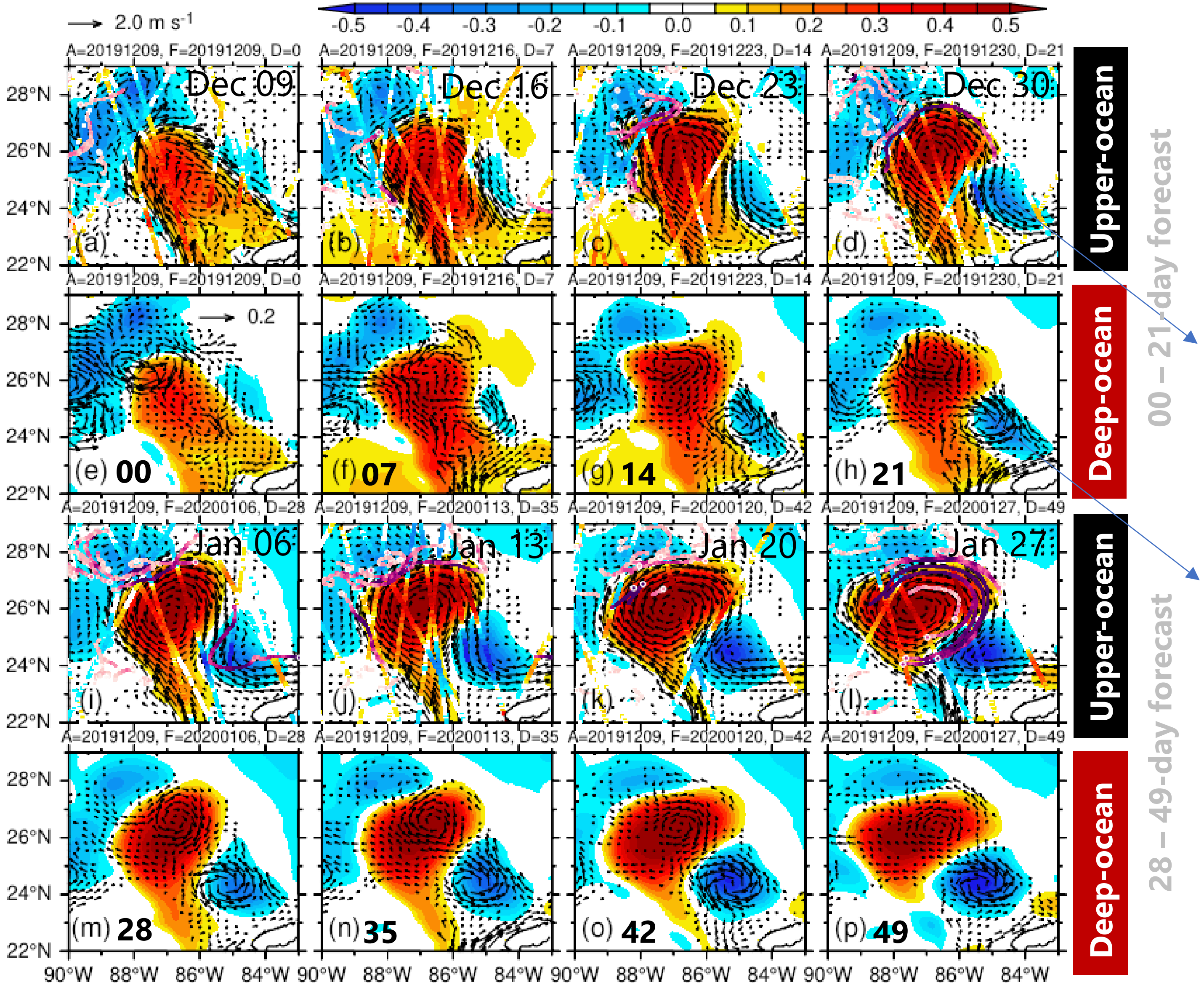
Loop Current (LC) – Loop Current Eddy (LCE) Separation: Analysis



Weekly model analysis SSHA and surface currents from Dec 9, 2019 to January 27, 2020.

- **Northward Extension of the LC**: Between December 9–16, 2019, the LC extended significantly into the Gulf of Mexico, reaching beyond 27°N.
- **Formation of a Cyclone**: A weak cyclone, indicated by a low in SSHA, began developing on the eastern side of the LC, leading to a narrowing or "necking down" of the LC by December 23.
- **Detachment of LCE:** By January 27, 2020, the strengthened cyclone caused the detachment of the LCE from the LC, confirmed through SSHA patterns and drifter observations.

LCE Separation: 7-week Forecast from December 9, 2019 Analysis



Deep cyclone's influence on the LC and the subsequent LCE separation.

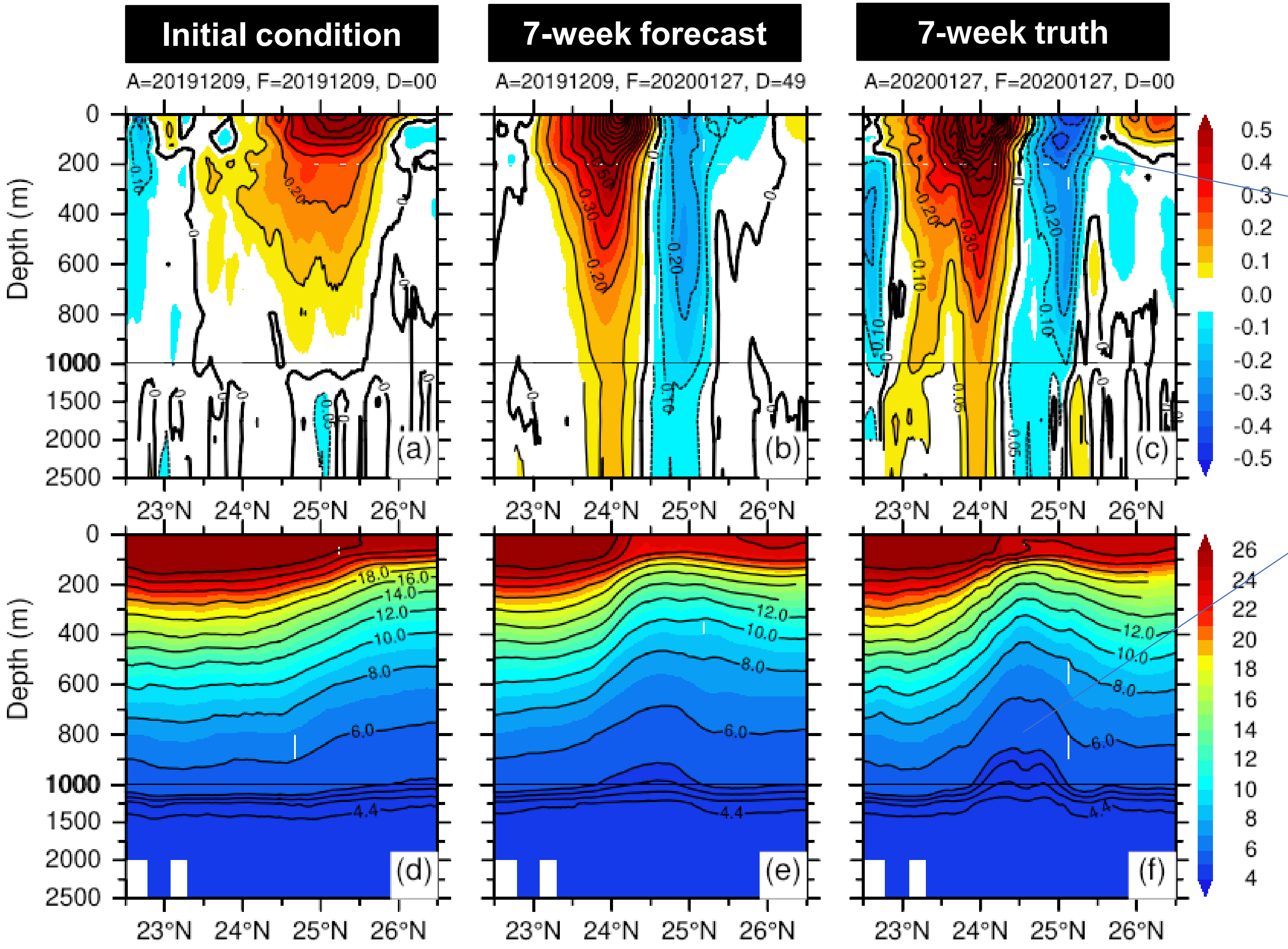
Cyclone Not Constrained in Analysis: The deep cyclone that ultimately triggered the LCE separation was not a feature constrained by the analysis, yet the forecast successfully reproduced the separation event.

Development of Deep Cyclone: A week after the initial forecast (December 16), a deep cyclone began forming at 85°W, 24.5°N. Its development at depth preceded the appearance of a surface cyclone, which became evident around December 30.

Cyclone-Induced Eddy Separation: The deep cyclone continued to strengthen, causing necking along the eastern side of the LC and leading to the LCE separation on January 27, 2020.

Vertical Structure of Cyclonic Eddy: 7-week forecast

Vertical sections of zonal velocity and temperature: 84.5° - 85.5°W



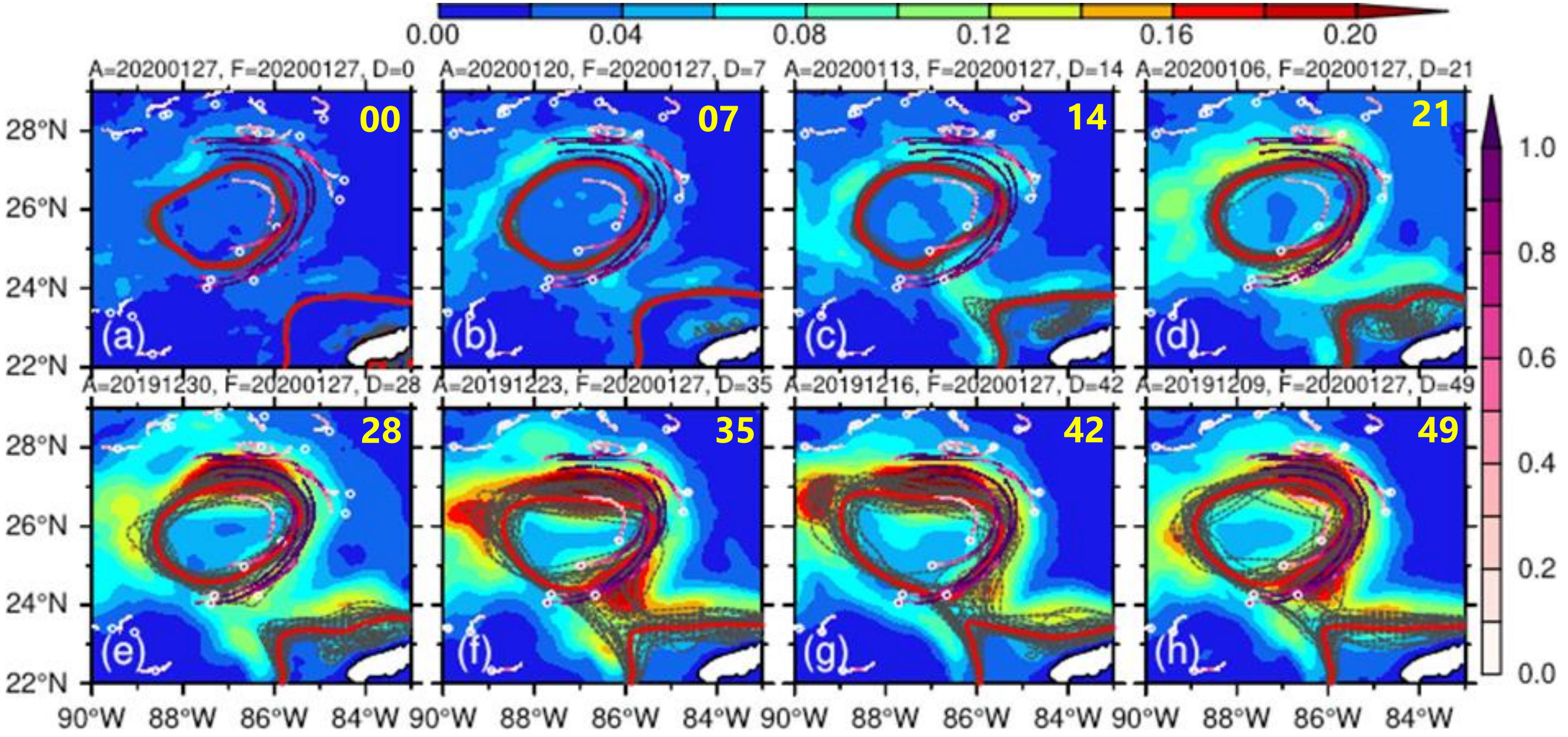
Model Accuracy in Cyclone Representation: The 7-week forecast demonstrates good qualitative agreement with the analysis in representing the vertical structure of the zonal velocity within the cyclone.

Temperature Structure Consistency: The temperature profile across the cyclone in the forecast closely aligns with the analysis, especially the shoaling of 5°C isotherm near 24.5°N.

Cyclone Development Unconstrained by Initial Conditions: The initial conditions on December 9, 2019, did not show a deep cyclone.

Uncertainty in the Predicted Loop Current Eddy Separation

Ensemble spread of forecasts initialized from prior analyses up to 7 weeks in advance and valid on January 27, 2020.



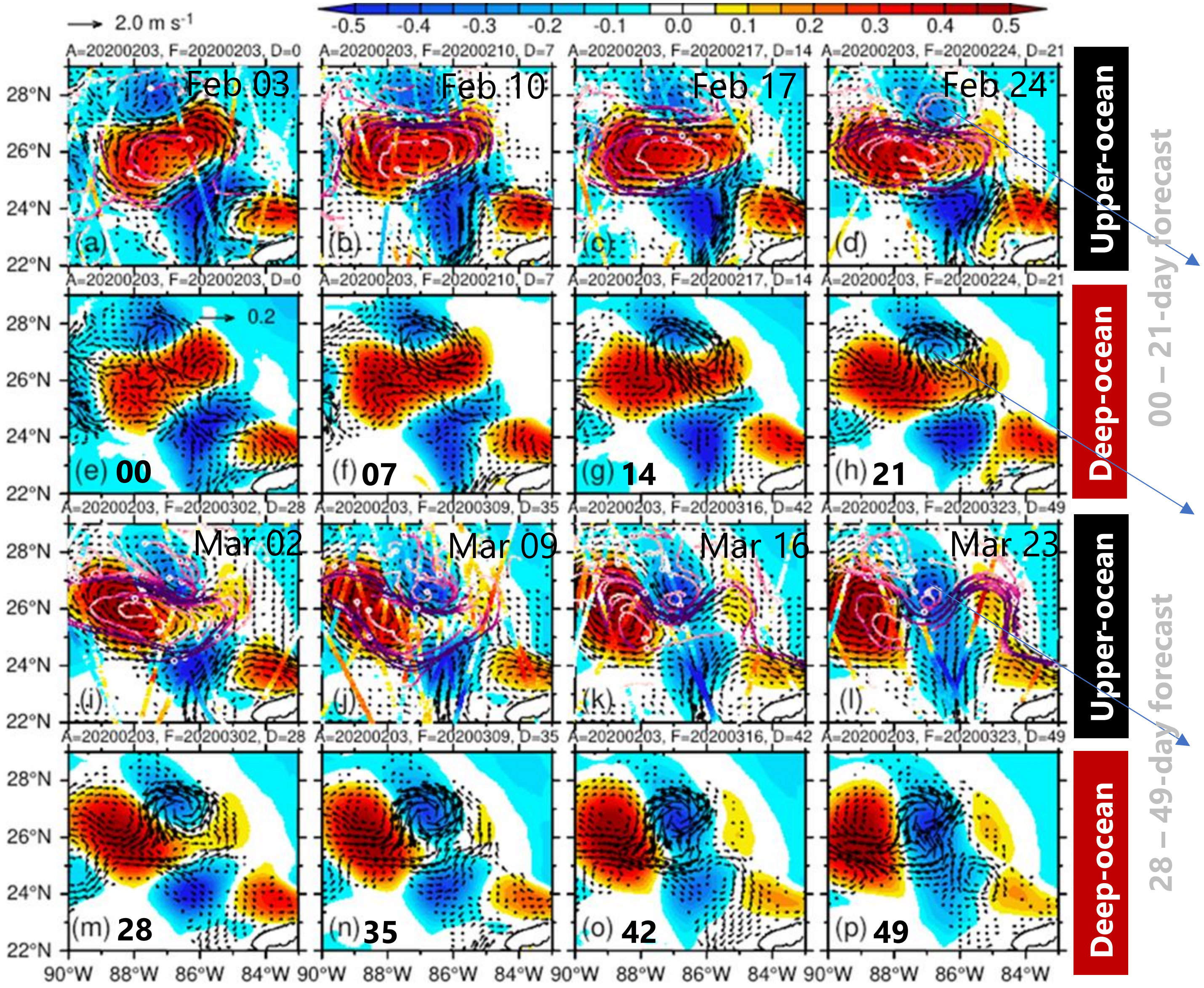
A spaghetti plot of 17 cm SSH contours for ensemble members is used to track the LC and LCE, with the spread indicating the uncertainty in predictions.

Ensemble Spread: In an ensemble forecast, the ensemble mean provides the best estimation, while the ensemble spread quantifies the uncertainty of predictions.

Ensemble Spread and Lead Time: Ensemble spread, which increases with lead time, highlights forecast uncertainty as dynamical instabilities grow. The increasing spread around energetic LCE shows how forecast skill diminishes over time.

Bi-Modal Pattern in Longer Forecasts: By weeks 5–7, some ensemble members show a detached LCE while others indicate an attached LC/LCE, illustrating forecast uncertainty in this period. Despite this, the ensemble mean aligns well with drifter observations.

LCE Transformation: 7-week Forecast from February 3, 2020, Analysis



How cyclonic eddy to the north contribute to the LCE transformation and its eventual splitting and weakening?

The cyclone located along the northern edge of the LCE interacts with the LCE, causing its eastern side to weaken and narrow by week 3 of the forecast.

Initially, the deep cyclone does not align vertically with the surface cyclone.

The cyclone's southeastward movement continues to disrupt the LCE, which eventually leads to its splitting by week 7.

This deep-surface coupling emphasizes the challenges in forecasting LCE behavior.

Summary: Key Findings and Limitations

Accurate Prediction of LCE Separation: The 32-member ensemble forecast system successfully predicted the separation of the Loop Current Eddy (LCE) "Thor" from the Loop Current (LC) **7 weeks in advance**. This prediction closely aligns with observations from January 2020, demonstrating the model's skill.

Role of Deep Cyclone in LCE Shedding: The study emphasizes the critical role of a **deep cyclone along the eastern edge** of the LC in triggering LCE separation. This deep cyclone intensified and expanded westward, leading to LCE detachment by January 27, 2020.

LCE Transformation: After separation, the LCE undergoes significant deformation due to interactions with a **cyclone on its northern edge**. This interaction nearly splits the LCE, with the eastern portion partially reattaching to the LC.

Variability in LCE Predictability: Predictability of LCE separation events since 2013 has varied, suggesting that multiple factors influence LCE formation. This variability indicates that no single mechanism fully explains all LCE shedding events.

- **Limited Deep Ocean Constraints**: Deep ocean circulation in data-assimilative systems is largely unconstrained due to sparse subsurface observations, which limits the accuracy in capturing deep mesoscale features.

- **Weaker Model Representation of Subsurface Currents**: The model forecasts consistently show weaker subsurface currents, aligning with previous studies reporting an underestimation of EKE under the LC region, which may impact forecast skill for Gulf of Mexico circulation.