A Triply Nested-Grid Modeling System of the MBRS

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Outline

- A 3-level nested-grid modelling system using the semi-prognostic method
- Two applications of the nested-grid system
  - Circulation and connectivity associated with climatological forcing (under the normal condition)
  - Circulation and river plumes during Hurricane Mitch (under extreme conditions)
- Summary and future work

Connectivity over coral reefs of the MBRS

- Connectivity of dense matrices of reefs in the Meso-American Barrier Reef System (MBRS) of the western Caribbean Sea (WCS) is strongly affected by hydrodynamics in the region, particularly the through-flow Caribbean Current.
- Connectivity of the MBRS reefs under extreme weather conditions could be ecologically significant (Cowen et al., 2006).
- Connectivity studies in the region call for the state-of-the-art hydrodynamic models with fine horizontal and vertical resolutions (~500 m in the horizontal and ~5 m in the vertical).

ECONAR -- Ecological Connections Among Reefs

- A 3-year (2002-2004) NSERC research project to support a a Canadian research team led by Dr. Peter Sale to study ECONAR in the MBRS with five sub-components (hydrodynamic modeling, field ecology, age and growth, microchemistry of otoliths, and molecular genetics).

- A single-domain model of the western Caribbean Sea was developed based on CANDIE. The model has the horizontal resolution of 18 km, and 31 z-levels in the vertical.

- The model was used in the study of 3D circulation and hydrographic distributions under the climatological conditions (Sheng and Tang, 2003).

2. A Nested-Grid Model of the MBRS

Main Features:

- The nested model is relocatable and has three sub-components: an outer model (~20 km), a middle model (~6 km) and an inner model (~2 km).
- The model was constructed from CANDIE using the 4th order numerics and flux limiter for advection terms.
- The nested mode uses the new two-way nesting technique based on the semi-prognostic method (Sheng et al., 2001, Sheng et. al., 2005).

CANDIE

- CANDIE stands for CANadian version of Diecast.

- It is a 3D, primitive-equation, z-level ocean circulation model developed by Sheng et al. (1998).

- It uses the fourth-order numerics and flux limiter.

- CANDIE has been applied to various shelf circulation modeling problems (e.g., Sheng et al., Jtech, 1998; Lu et al. CFAS, 2001; Sheng, JPO, 2001; Sheng et al., JGR, 2001; Sheng and Tang, JPO, 2003 and OD, 2004; Sheng and Wang, JGR, 2004; Wang et al., JPO, 2007; Sheng et al., PiO, 2006; Sheng and Rao, CSR, 2006; Tang et. al., JGR, 2006, Sheng et al., JGR, 2007).

- **Website: www.phys.ocean.dal.ca/programs/CANDIE**

Governing Equations

$$\frac{\partial u}{\partial t} + \mathcal{L}u - f\,v = -\frac{1}{\rho_o}\frac{\partial p}{\partial x} + \mathcal{F}_m u$$

$$\frac{\partial v}{\partial t} + \mathcal{L}v + f\,u = -\frac{1}{\rho_o}\frac{\partial p}{\partial y} + \mathcal{F}_m v$$

$$\frac{\partial p}{\partial z} = -[\alpha\rho_m + (1-\alpha)\rho_c]g$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

$$\frac{\partial(T,S)}{\partial t} + \mathcal{L}(T,S) = \mathcal{F}_h(T,S)$$

$$\mathcal{L}Q = \frac{\partial uQ}{\partial x} + \frac{\partial vQ}{\partial y} + \frac{\partial wQ}{\partial z}$$

$$\mathcal{F}_{(m,h)}Q = \mathcal{D}_{(m,h)}Q + \frac{\partial}{\partial z}(K_{(m,h)}\frac{\partial Q}{\partial z})$$

$$\mathcal{D}_{(m,h)}Q = \frac{\partial}{\partial x}(A_{(m,h)}\frac{\partial Q}{\partial x}) + \frac{\partial}{\partial y}(A_{(m,h)}\frac{\partial Q}{\partial y})$$

Diagnostic, Prognostic and Semi-Prognostic Methods

1. Pure-Diagnostic Method:

Calculates ocean currents from given temperature and salinity fields.

Relatively easy to run and robust in multi-year simulations.

Incapable of simulating the interaction of temperature/salinity with the flow field (e.g. fronts, eddies, etc).

2. Pure-Prognostic Method:

Calculates ocean currents, together with temperature and salinity fields.

Capable of simulating baroclinic instability and convective mixing.

Model performance deteriorates in longer simulations.

3. Semi-Prognostic Method (Sheng, Greatbatch, and Wright, 2001) :

Replace the conventional hydrostatic equation by:

$$\frac{\partial p}{\partial z} = -[\alpha\rho + (1-\alpha)\rho_c]g$$

Model performance better in the multi-year simulations of currents, and temperature/salinity fields.

Physical Interpretation:

$$p = p^* + \hat{p}$$

- $p^* \Longleftarrow$ traditional pressure variable
- $\hat{p} \Longleftarrow$ additional pressure variable

$$\begin{aligned} \frac{\partial p^*}{\partial z} &= -g\rho_m \\ \frac{\partial \hat{p}}{\partial z} &= -g\beta(\rho_c - \rho_m) \end{aligned}$$

with $\beta = (1 - \alpha)$. Horizontal momentum equations are expressed as

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho_o}\frac{\partial p^*}{\partial x} - \frac{1}{\rho_o}\frac{\partial \hat{p}}{\partial x} + \ldots..$$

$$\frac{\partial v}{\partial t} = -\frac{1}{\rho_o}\frac{\partial p^*}{\partial y} - \frac{1}{\rho_o}\frac{\partial \hat{p}}{\partial y} + \ldots..$$

Therefore, the additional forcing terms are used to correct for model errors and unresolved processes.

New two-way nesting technique

For the inner model:

$$\frac{\partial p}{\partial z} = -g\left[\beta_i \rho_{inner} + (1-\beta_i)\rho_{outer}\right]$$

For the outer model:

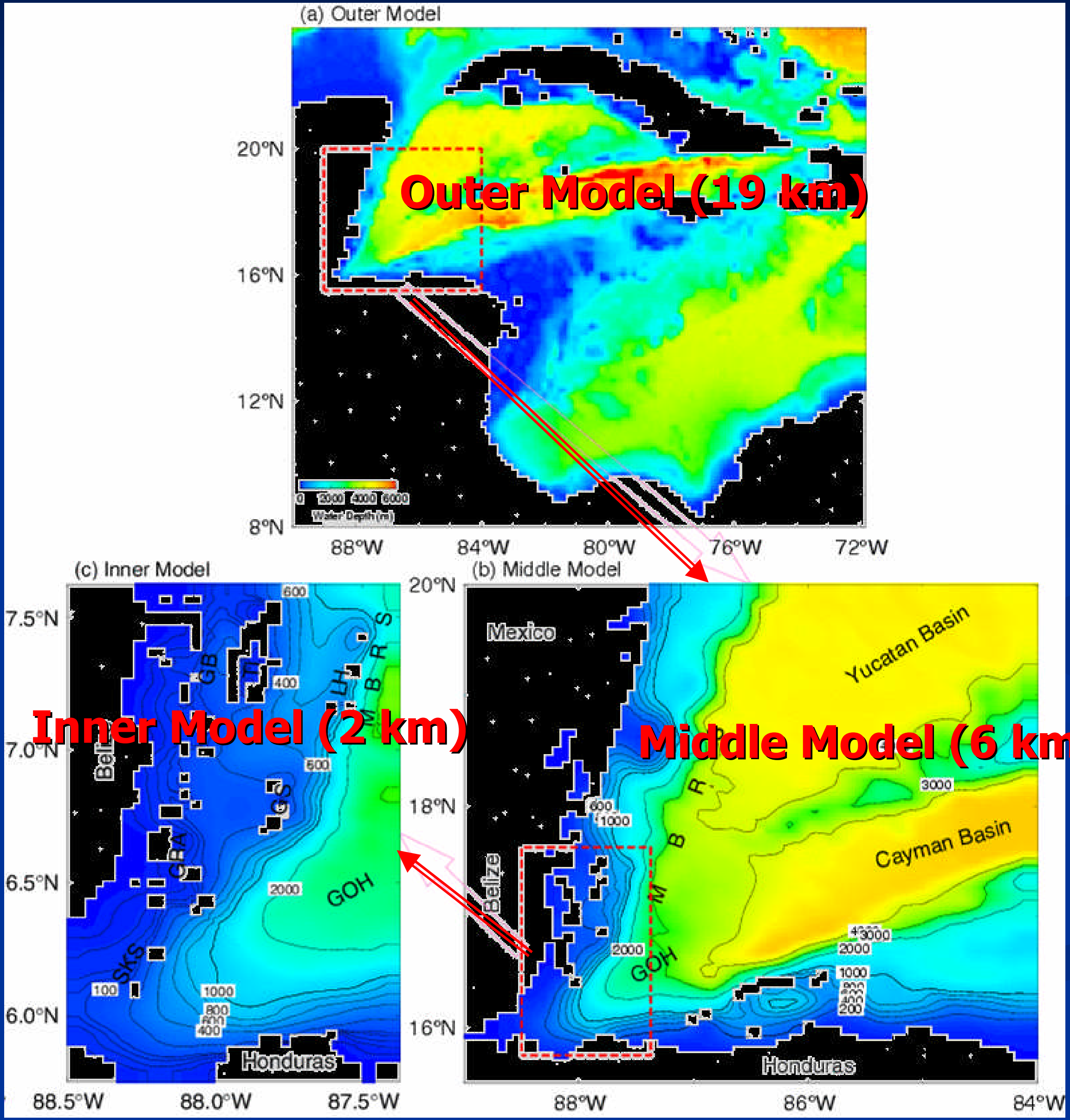
$$\frac{\partial p}{\partial z} = -g\left[\beta_0 \rho_{outer} + (1-\beta_0)\rho_{inner}\right]$$

β_o and β_i are set to 0.5

Lateral boundary conditions for the inner model:

- Sommerfield radiation condition (U,V,T,S)
- Restoring to outer model values

3. Application 1: Circulation and connectivity on the Belize shelf under the normal condition (Tang, Sheng, Hatcher and Sale, JGR, 2006)



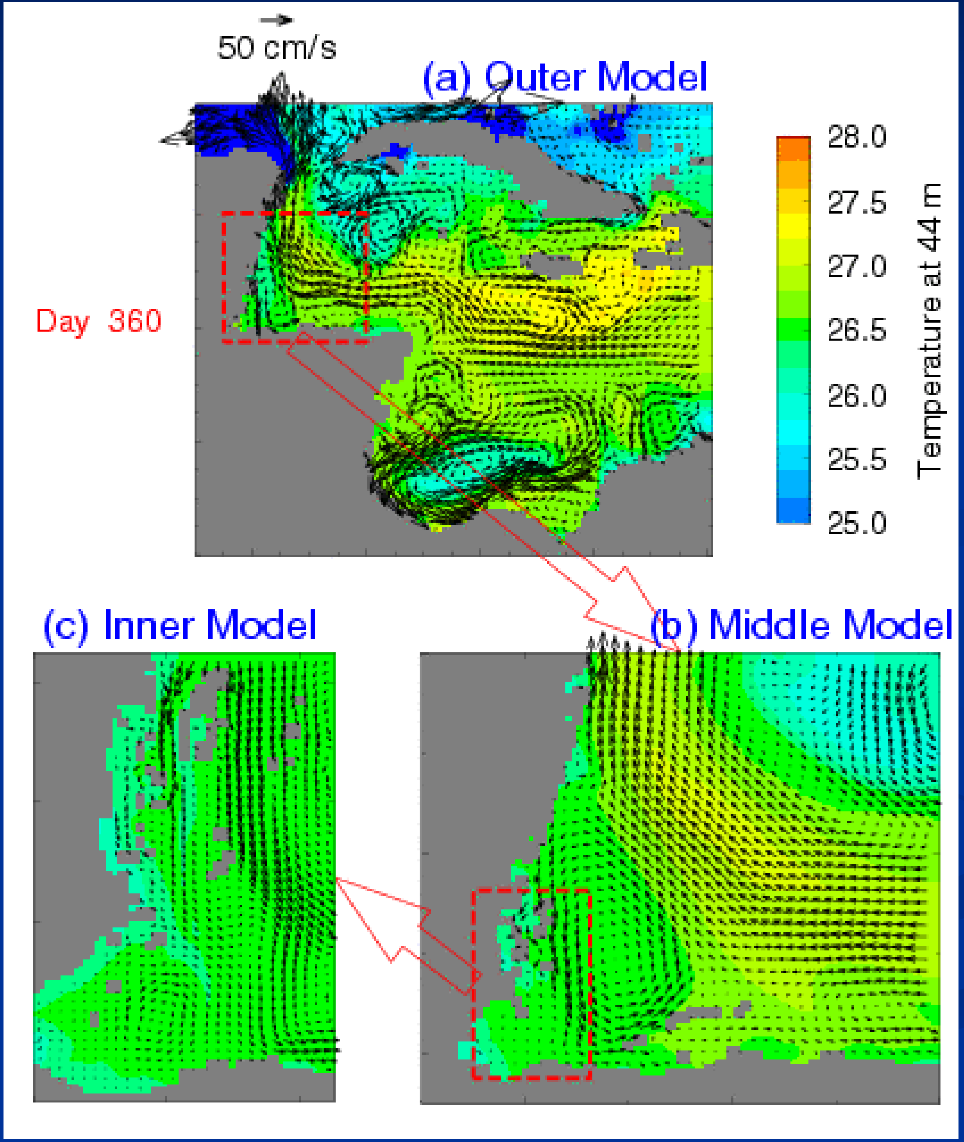
Model external forcing (normal condition):

- Monthly mean surface wind stress (0.5-by-0.5 climatology of da Silva et al., 1994).
- Monthly mean surface heat flux (0.5-by-0.5 climatology of da Silva et al., 1994).
- Monthly mean sea surface temperature and salinity (Sheng and Tang, 2003).
- Monthly depth-mean currents through the open boundaries calculated by a coarse resolution Atlantic Ocean circulation model (FLAME, Eden, 2003).

Model sub-gridscale mixing parameterizations:

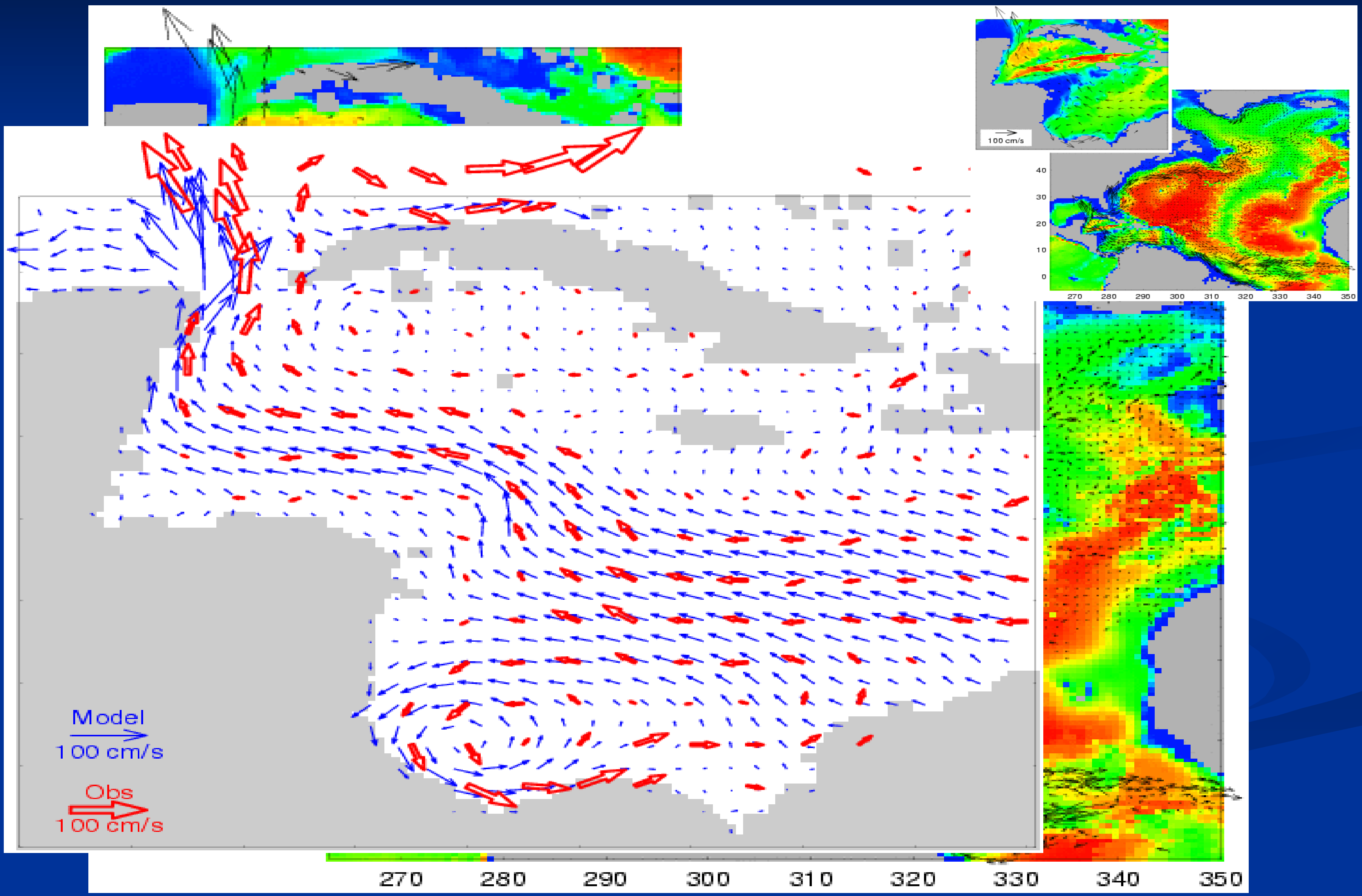
- Smagorinsky (1963) scheme for horizontal mixing.
- Large et al. (1994) and Csanady (1982) for vertical mixing.

Currents and temperature at 44 m produced by the nested system (under the normal condition)

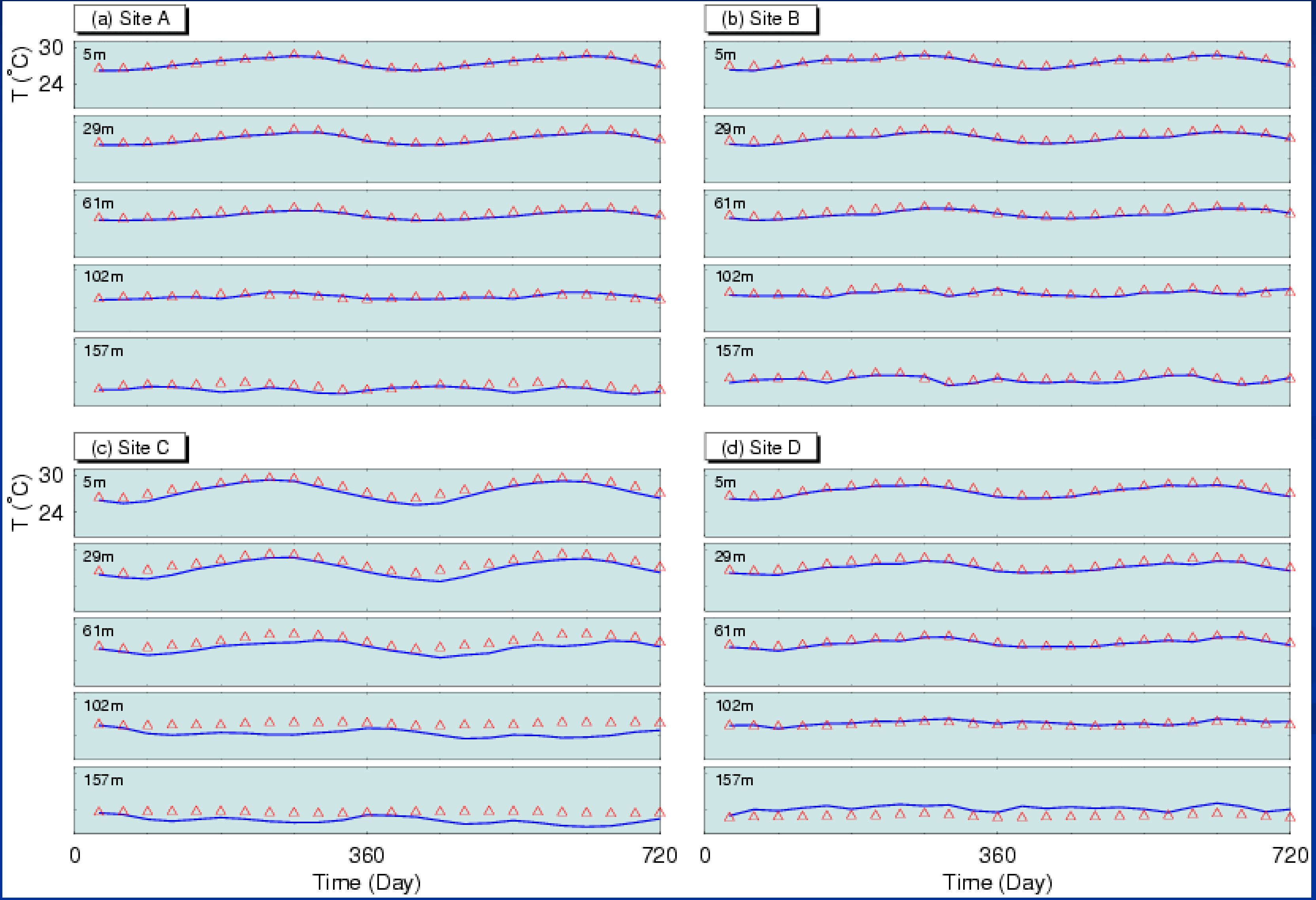


Comparison of calculated and observed near-surface currents

(Data from David Fratantoni, WHOI)



Comparison of calculated and climatological monthly mean temperature

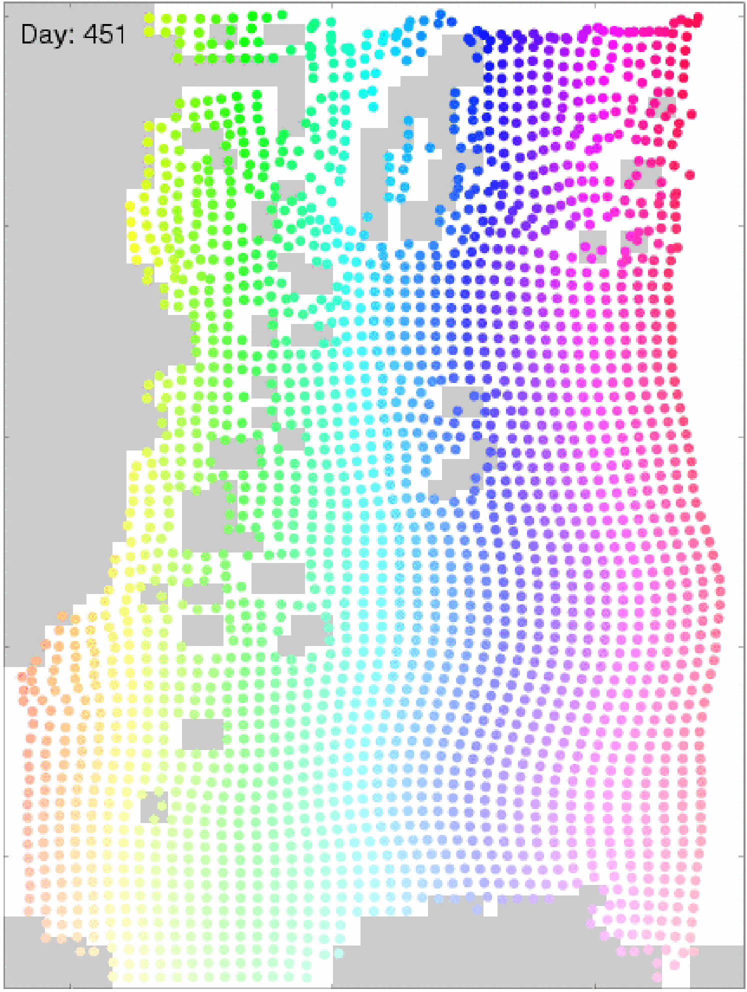


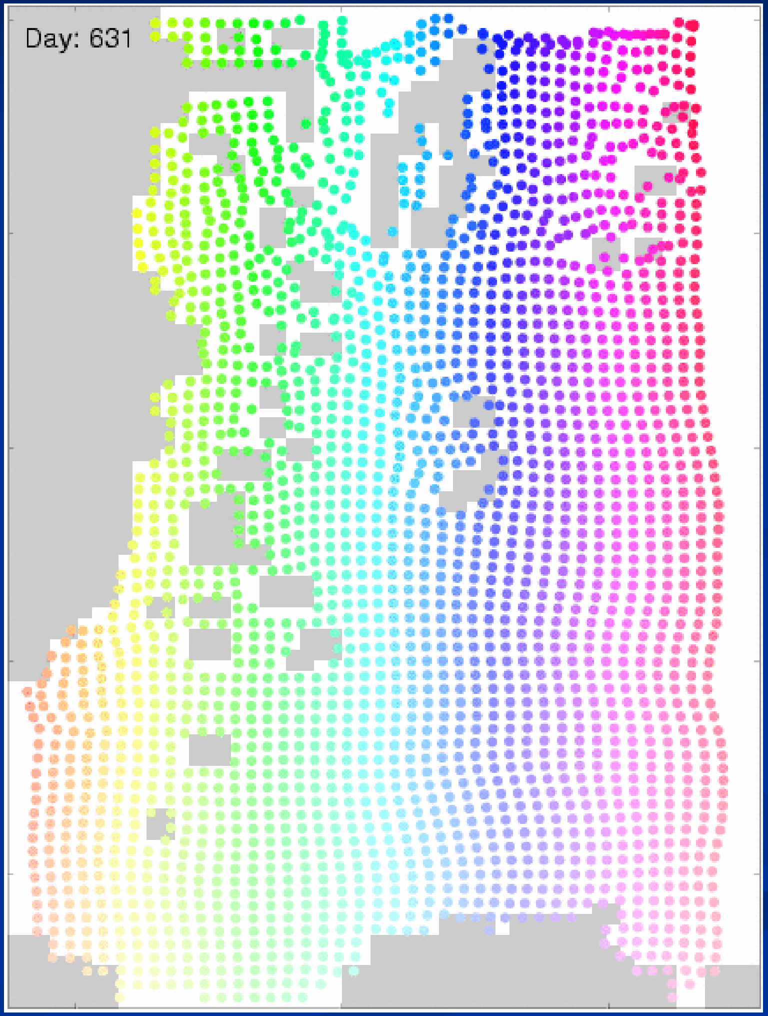
Dispersion and Connectivity in the Belizean Shelf

- An important issue for the ecosystem-based management in the BS is the degree of larval exchange among populations of marine organisms inhabiting specific coral reefs.
- Coral reef species on the MBRS have a pelagic larval stage lasting for weeks to months.
- During this stage, larvae are subjected to transport by ocean currents, as well as being able to modify that transport through vertical and horizontal swimming abilities.
- We examined the dispersion/retention and connectivity of surface waters based on the physical model (Tang, Sheng, Hatcher and Sale, JGR, 2006).

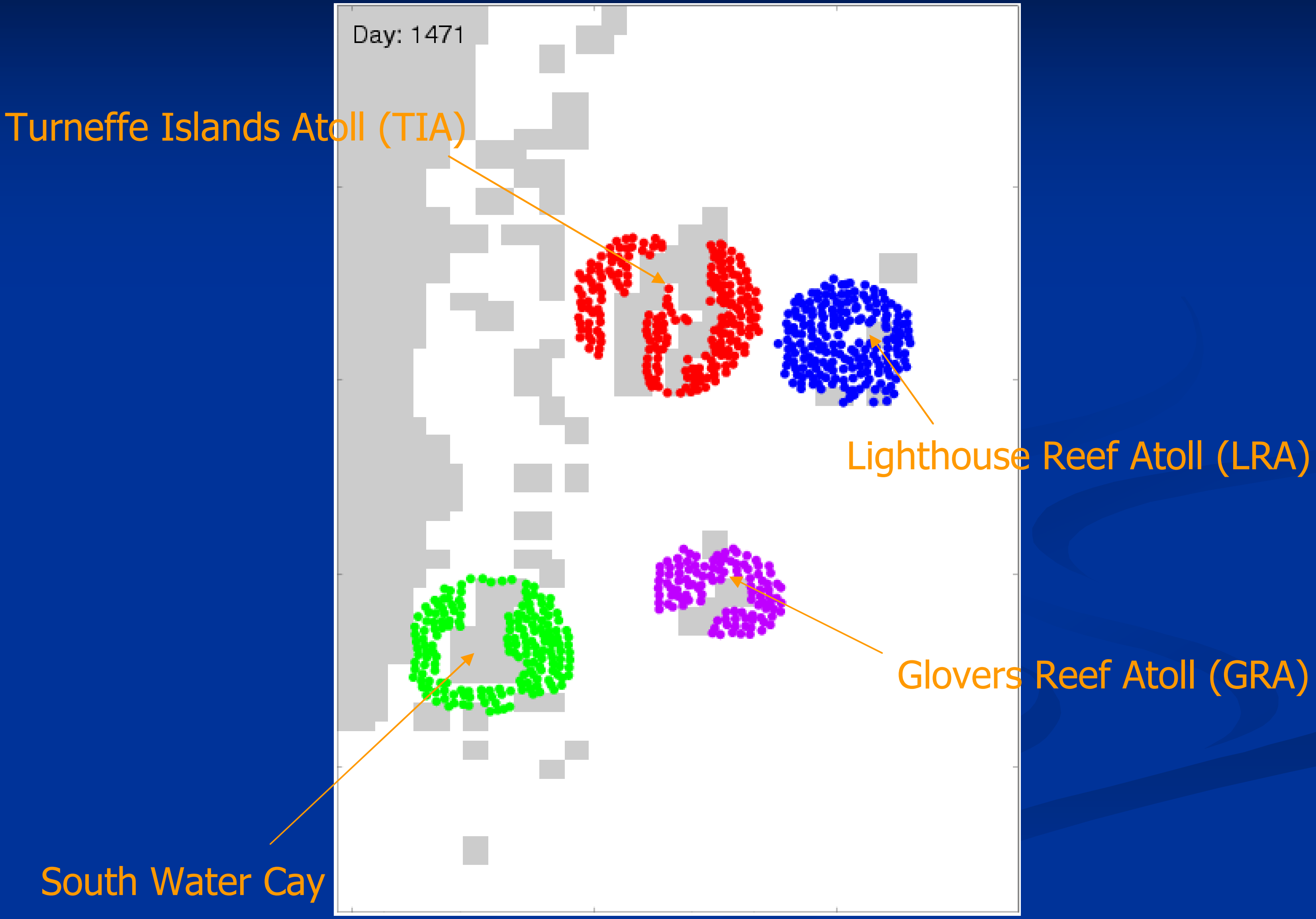
Spring Season

Fall Season

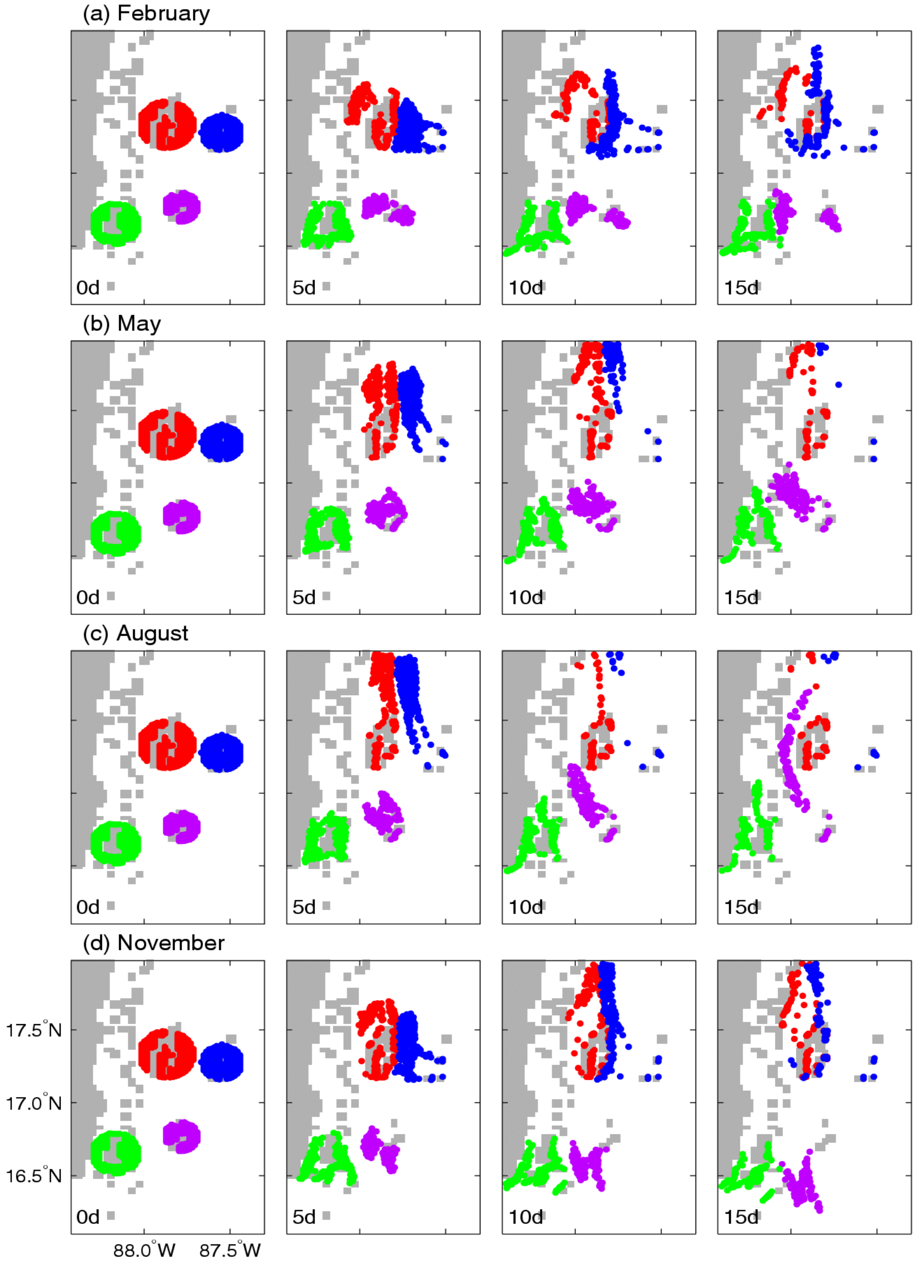




Movements of near-surface (passive) particles in February (under the normal condition)

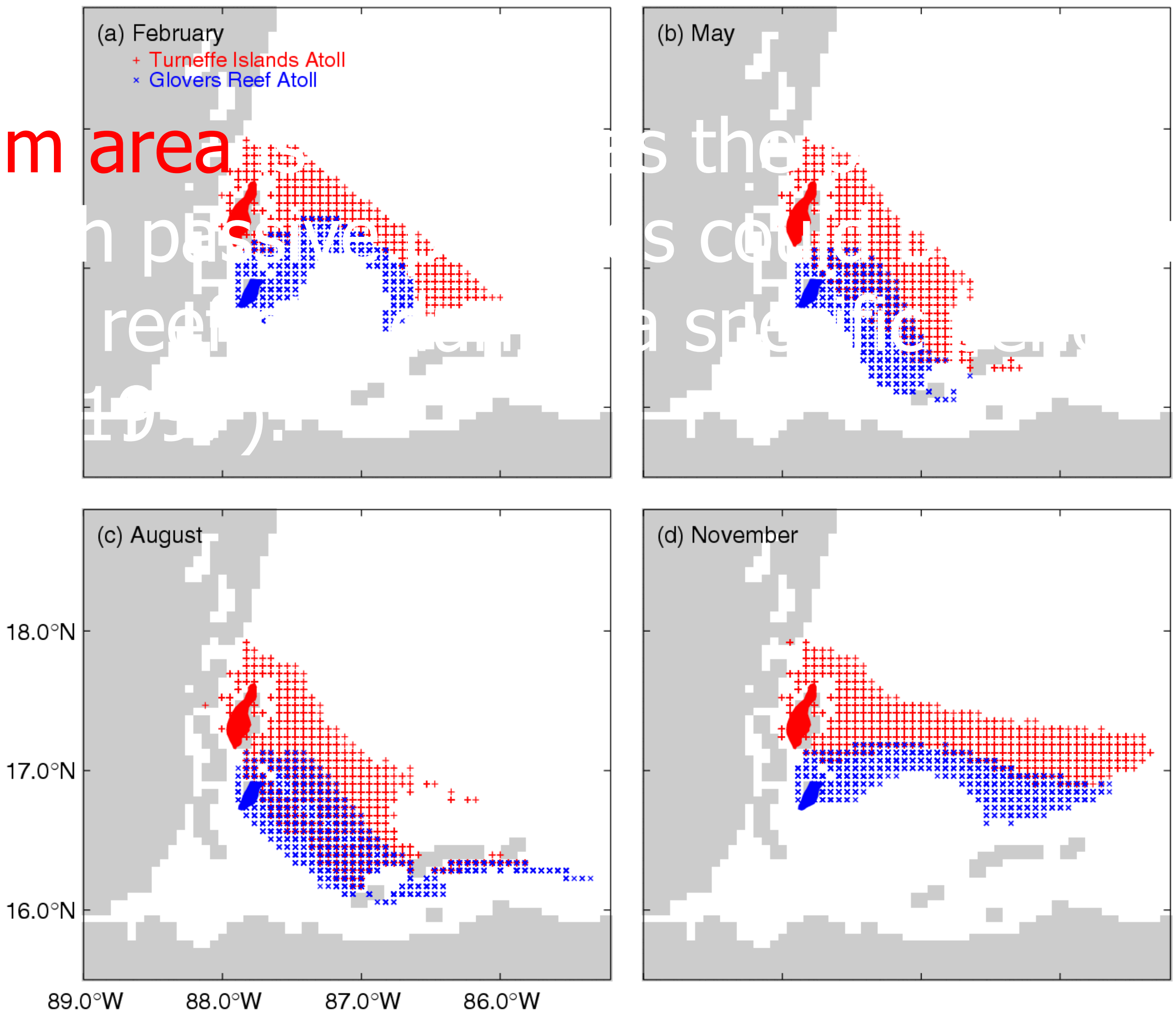


Movements of near-surface (passive) particles in four months



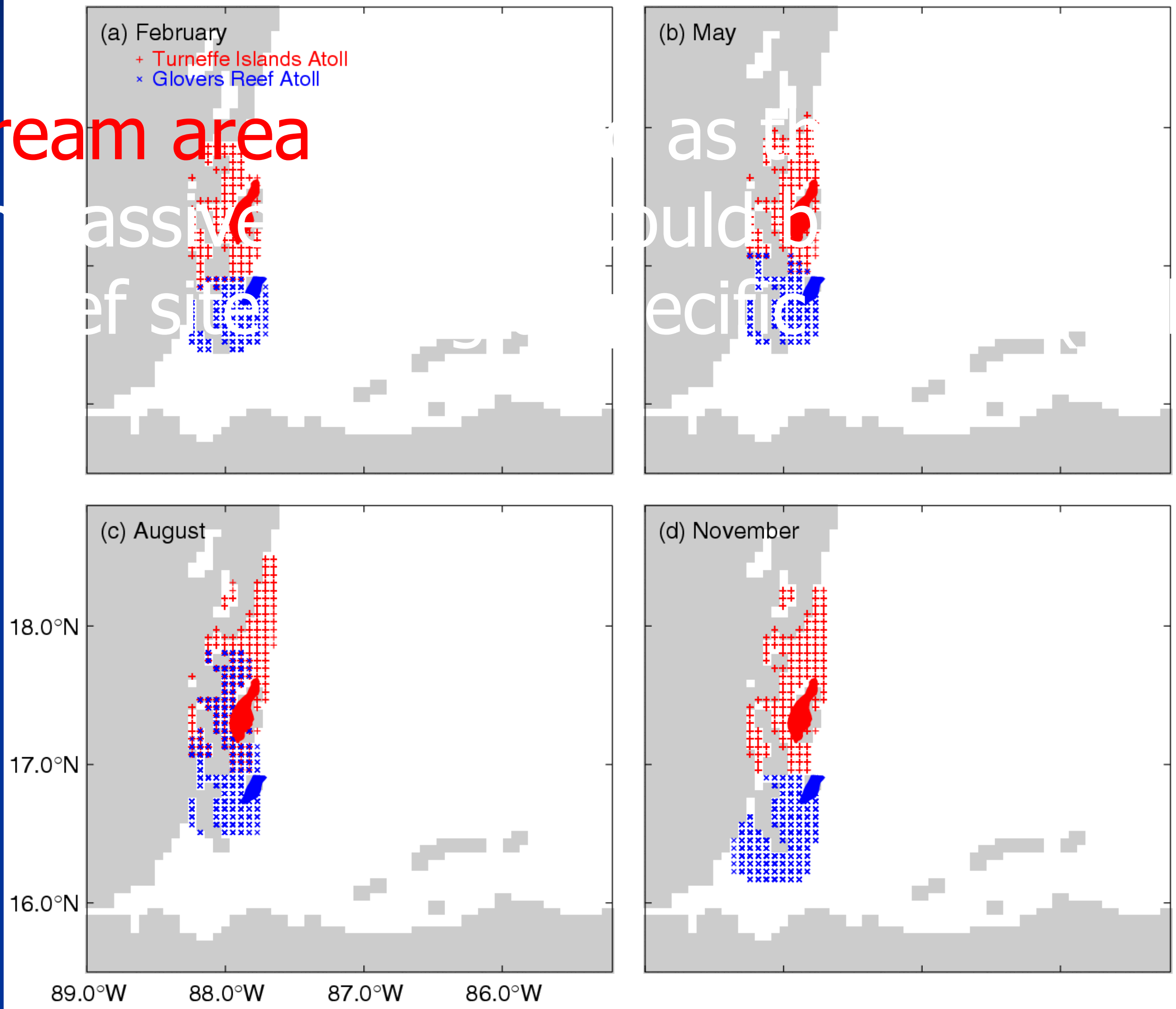
Upstream areas for Turneffe Islands and Glovers Reef Atolls during 30 days

Upstream area s the rea
from wh n pa s co rted
to a giv reef a spe
(Robert 199).



Downstream areas for Turneffe Islands and Glovers Reef Atolls during 30 days

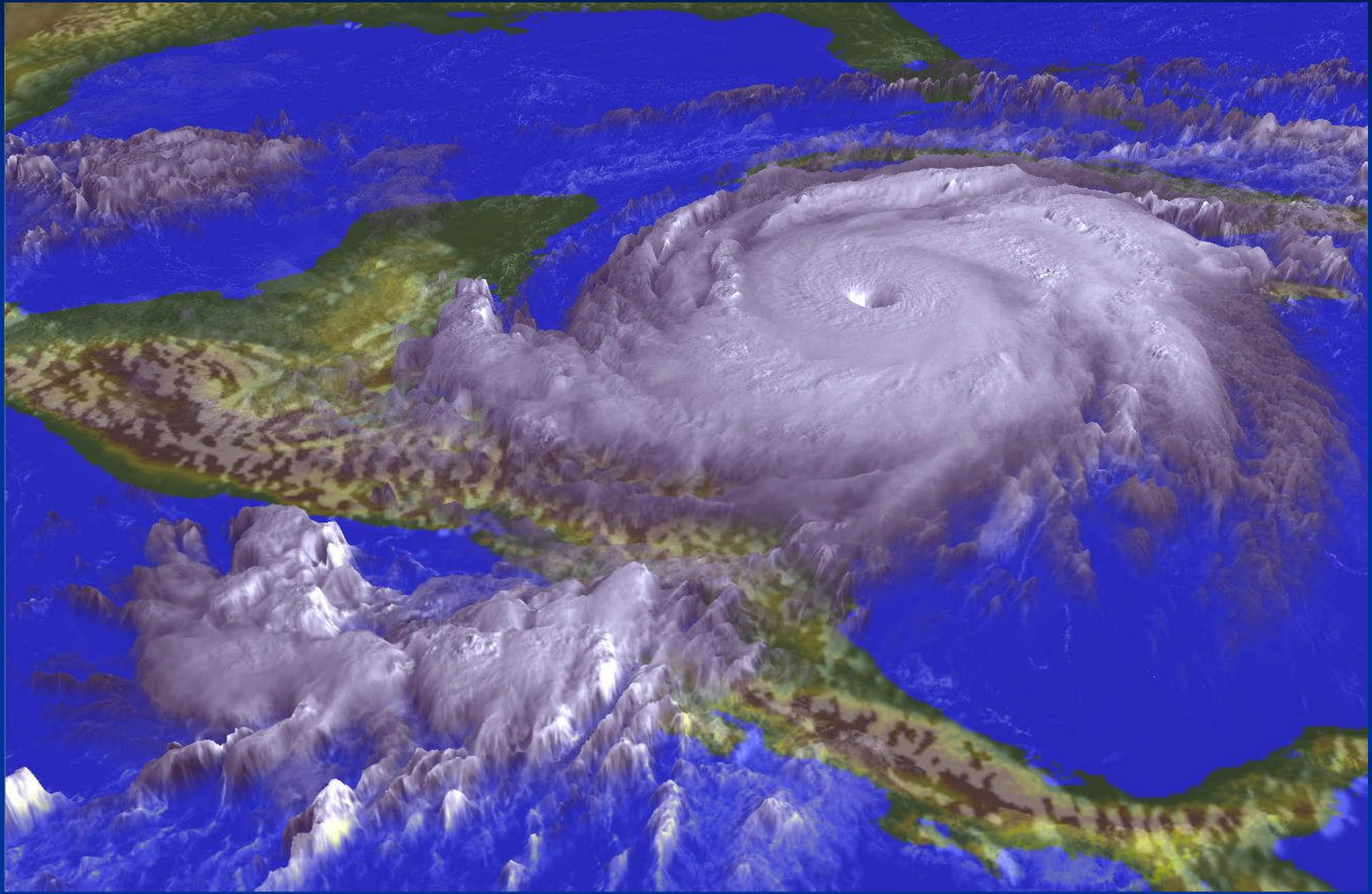
Downstream area as th area to which assive ould b from a given ef site ecific berts, 1997).



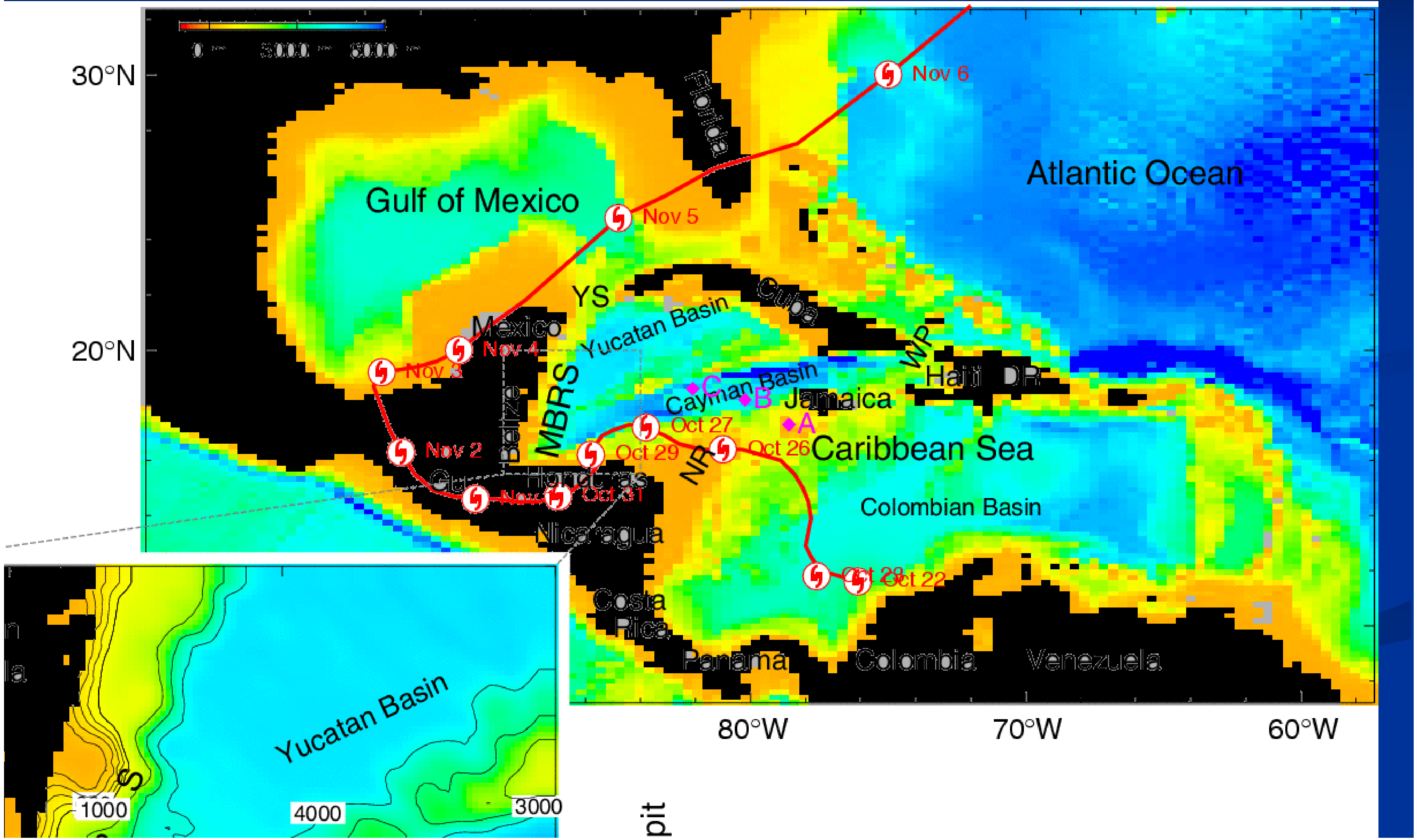
Application 2: Storm-induced circulation during Hurricane Mitch

- Hurricane Mitch was one of most disastrous storms hitting the Central American countries, and generated significant coastal flooding and landslides and caused more than 9000 death.
- Mitch started from a tropic depression to a tropical storm in the southern Caribbean Sea on Oct. 22, 1998 and strengthened to a Category-5 storm by Oct. 26 with maximum sustained wind speeds of ~285 km/h.
- Mitch swept the Honduras and Nicaragua coasts and made landfall on Oct. 29, 1998.
- Mitch generated about a meter of precipitation over Honduras, Nicaragua and Guatemala on its passage, causing massive flood and land slides.

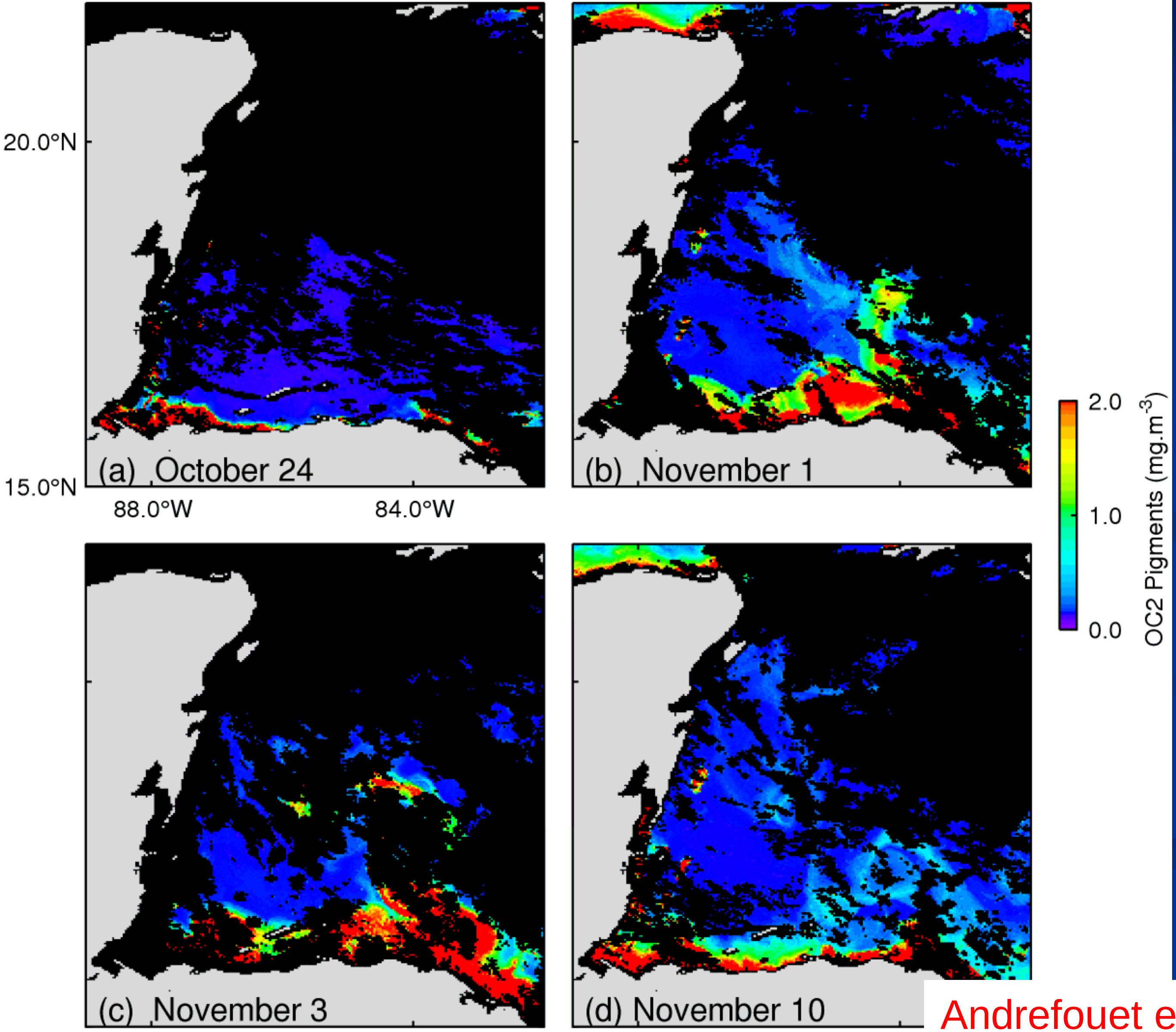
Hurricane Mitch



Storm Track of Hurricane Mitch

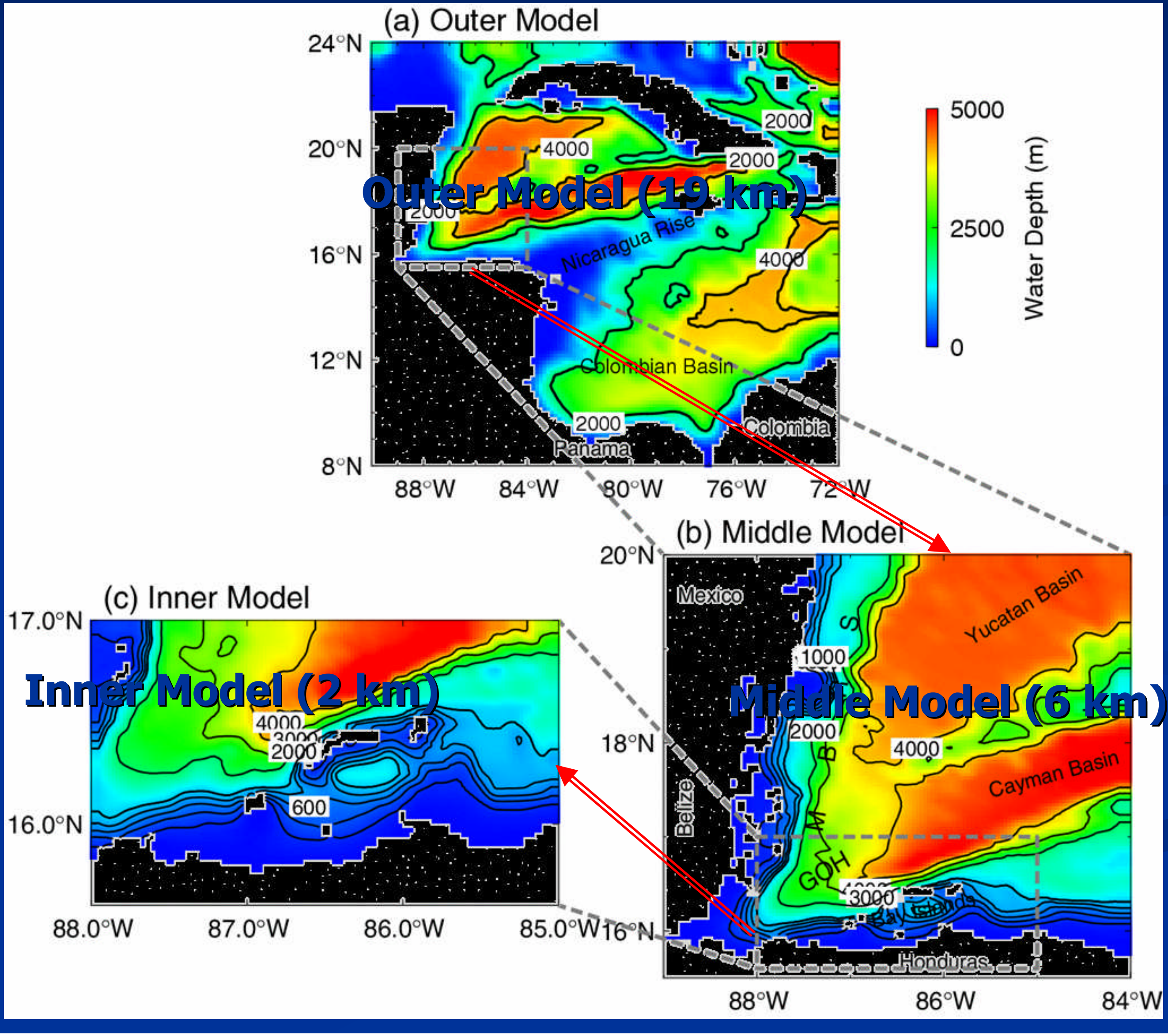


Chlorophyll-a concentrations estimated from SeaWiFS remote sensing data (SeaWiFS : Sea viewing Wide Field-of-view Sensor)



Andrefouet et al., 2002)

3 Application 2: Circulation and river plumes during Hurricane Mitch (Sheng, Wang, Yang and 6 others, submitted to JGR, 2007)



Model Setup and Forcing

The nested-grid model is integrated for 294 days from January 1 to October 21, 1998 forced by

- 6 hourly NCEP/NCAR forcing (Kalnay et al., 1996)
- Monthly mean surface heat flux (da Silva et al., 1994)
- Monthly mean sea surface temperature and salinity
- Time-mean freshwater discharges from 11 major rivers
- Monthly mean currents through outer model open boundaries

The model is integrated for another 20 days from October 22 to November 10 with the following additional forcing:

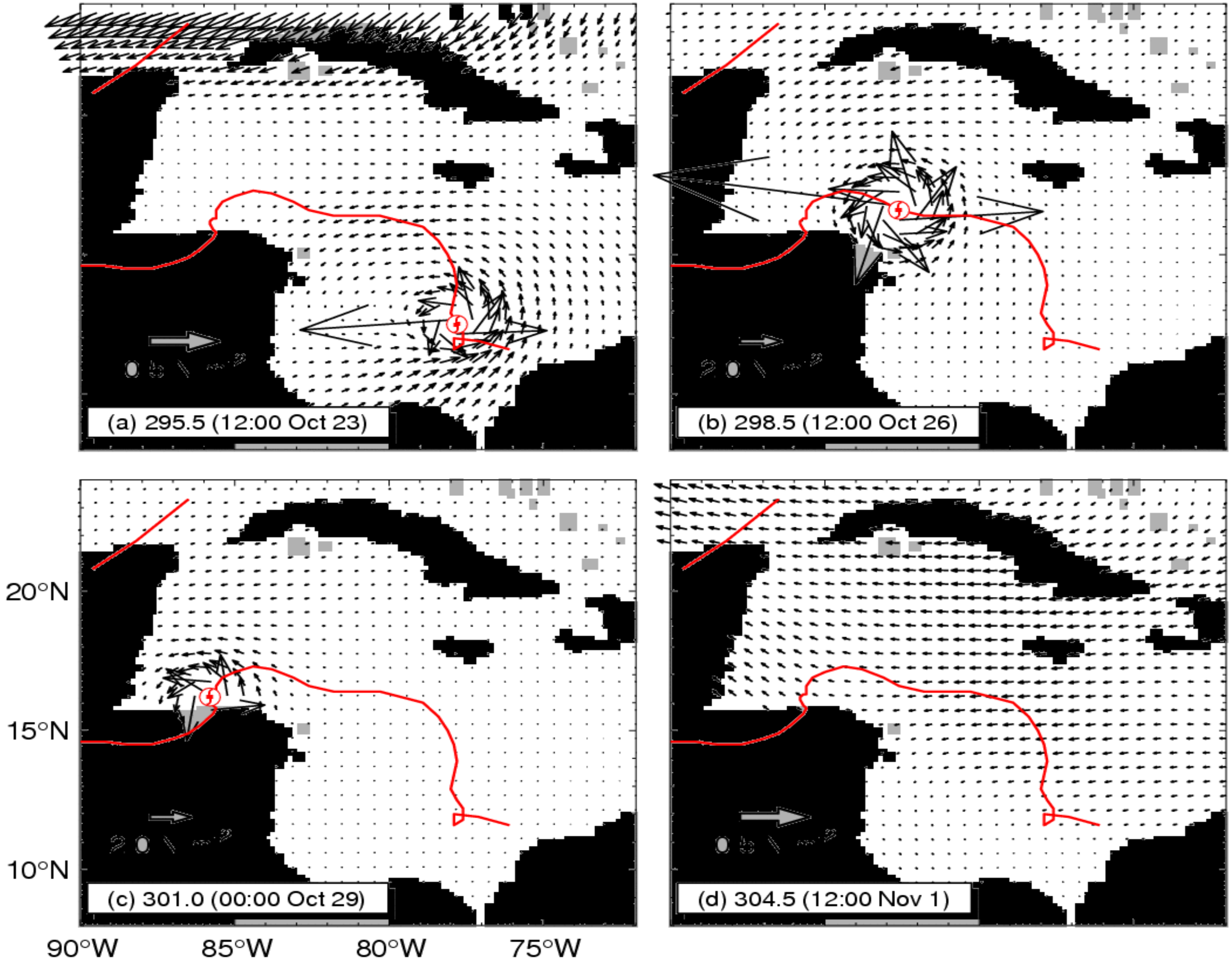
- A simple vortex associated with a moving storm (Fogarty, 2006)
- Storm-induced precipitation (Huffman et al., 2001)
- Storm-induced river runoff (Thattai et al., 2003; Burke and Sugg, 2006; Mastin and Olsen, 2002; Smith et al., 2002; UNCEP/GEF, 2002)

Wind forcing during Mitch is the combination of the 6-hourly NCEP/NCAR wind and a simple vortex for a moving storm given by (Chris Fogarty,2006):

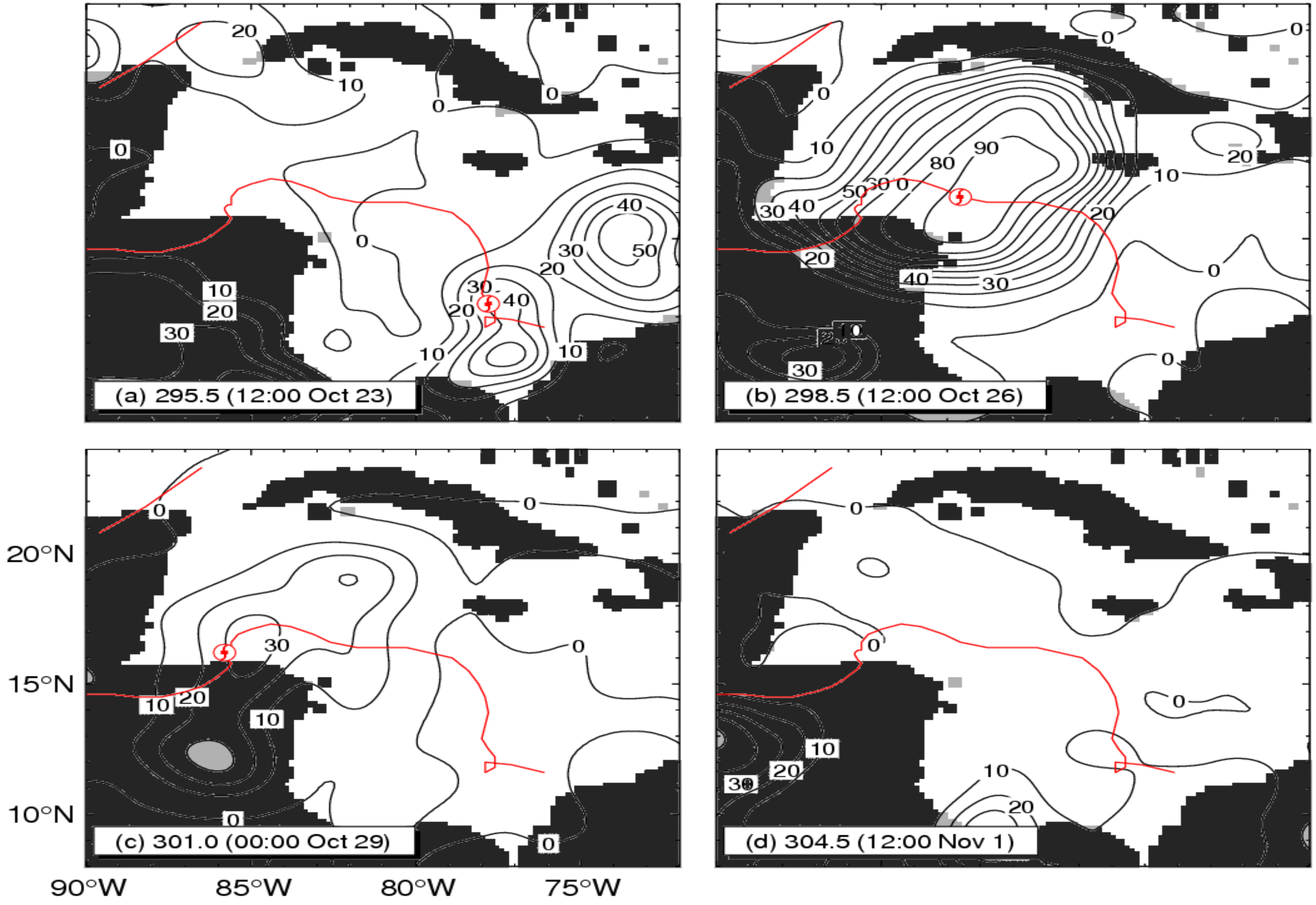
$$\tau(r) = \begin{cases} \tau_{\max} \dfrac{r}{r_{\min}} & r < r_{\min} \\ \tau_{\max} \dfrac{r_{\max} r_{\min}}{r_{\max} - r_{\min}} \left(\dfrac{1}{r} - \dfrac{1}{r_{\max}}\right) & r_{\min} \le r \le r_{\max} \\ 0 & r > r_{\max} \end{cases}$$

All parameters are estimated from satellite images of Mitch and observations.

Combination of NCEP/NCAR wind and parameterized vortex



Mitch-induced precipitations estimated from multi-satellite data (Huffman et al. 1991)



$\hat{S}_1^n$

Assuming precipitation was much bigger than evaporation over the WCS. during Mitch and based on the salt balance, the salinity in the top z-level at each time step can be estimated by:

$$S_1^n = \frac{\hat{S}_1^n \cdot \Delta z_1 + S_{00} \cdot \Delta z_p}{\Delta z_1 + \Delta z_p}$$

$\hat{S}_1^n$	model salinity at the top z-level before the modification
S_{00}	salinity of rain waters, which is set to 0
Δz_1	thickness of the top z-level
Δz_p	thickness of the rainfall during one time step

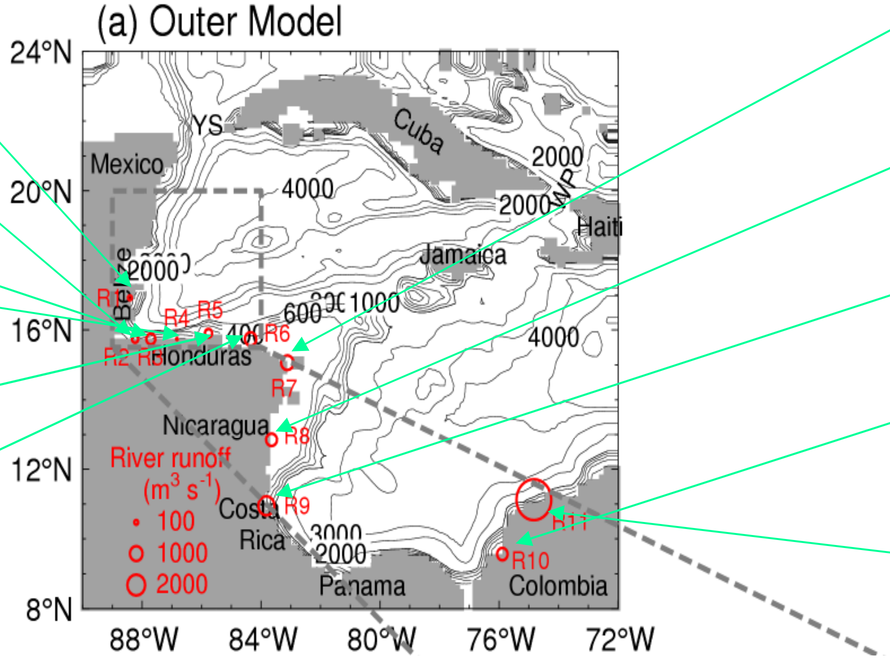
$S^h = \frac{S^m \cdot V_c + S^r \cdot V_r}{V_c + V_r}$

Buoyancy Forcing associated with River Runoff

Totally 11 rivers are considered, with salinity at each river head specified as:

$$S^h = \frac{S^m \cdot V_c + S^r \cdot V_r}{V_c + V_r}$$

(salt balance)

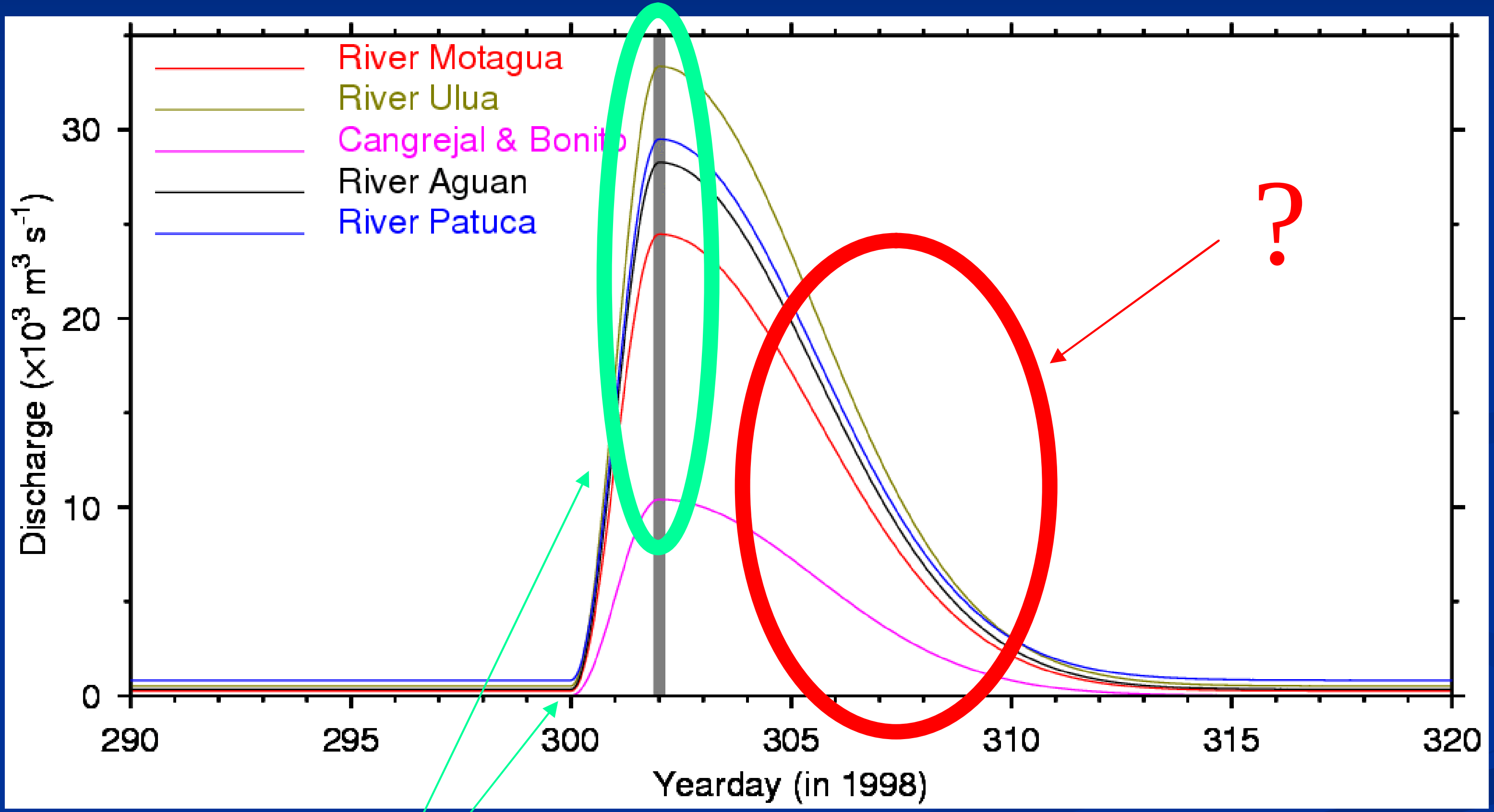


1. Belize
2. Motagua
3. Ulua
4. Cangrejal-Bonito
5. Aguan
6. Patuca
7. Coco
8. GdM
9. San Juan
10. Sinu
11. Magdalena

Estimated drainage areas and average discharges of 11 major rivers in the western Caribbean Sea, and estimated peak discharges of five major rivers in Honduras and Guatemala during Mitch in 1998 (Mastin and Olsen, 2002; Smith et al., 2002; UNCEP/GEF, 2002).

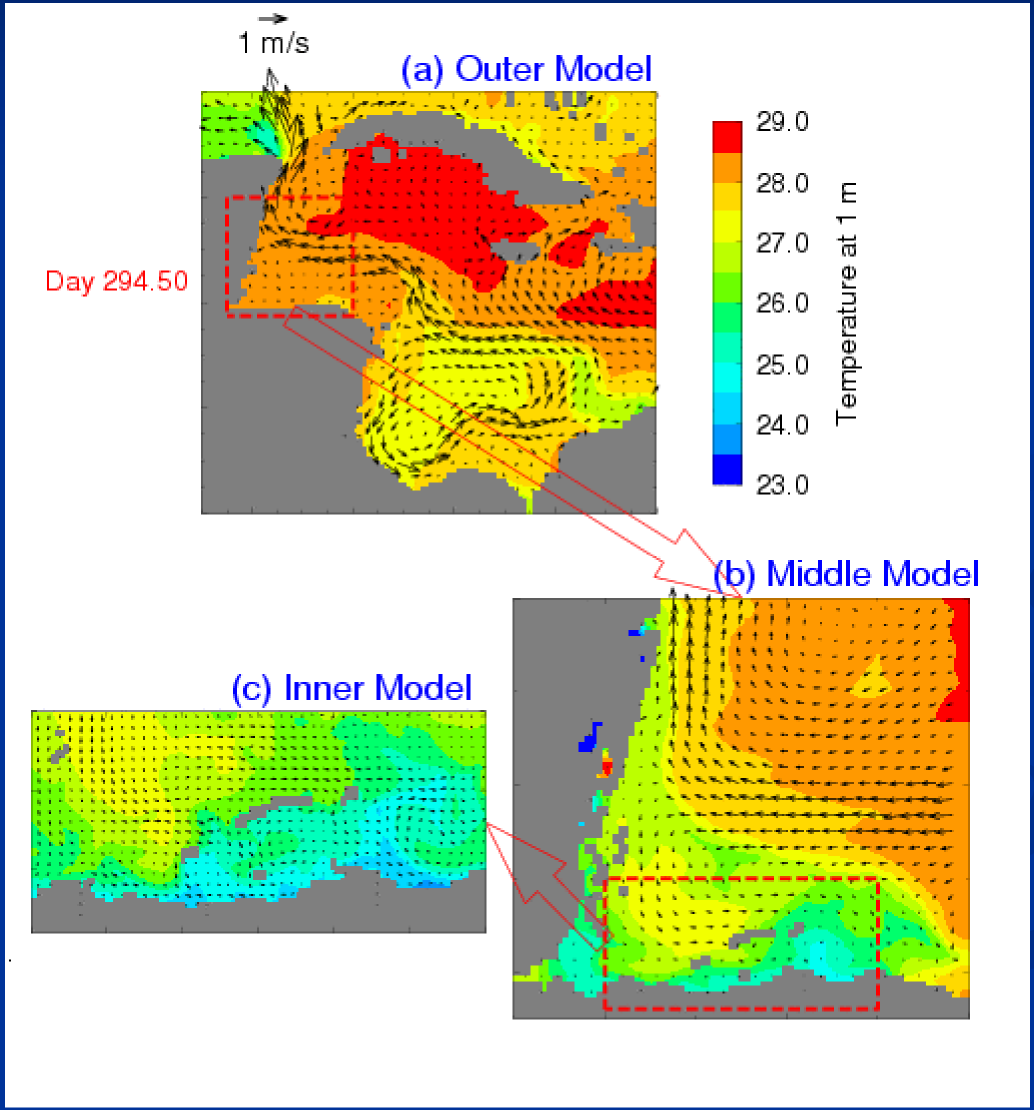
	River / Country	Drainage Area (km^2)	Average Discharge (m^3 s^{-1})	Peak Discharge During Mitch (m^3 s^{-1})
1	Belize / Belize-Guatemala	6,352	96	-
2	Motagua / Guatemala	16,600	252	24,219
3	Ulua / Honduras	22,500	526	32,838
4	Cangrejal-Bonito/Honduras	564	16	10,390
5	Aguan / Honduras	10,580	300	27,939
6	Patuca / Honduras	25,600	825	28,672
7	Coco / Honduras-Nicaragua	26,700	950	-
8	Grande de Matagalpa / Nicaragua	19,700	762	-
9	San Juan /Nicaragua-Costa Rica	38,900	1,620	-
10	Sinu / Colombia	4,200	700	-
11	Magdalena / Colombia	235,000	7,500	-

Parameterized flood processes of 5 major rivers in Guatemala and Honduras

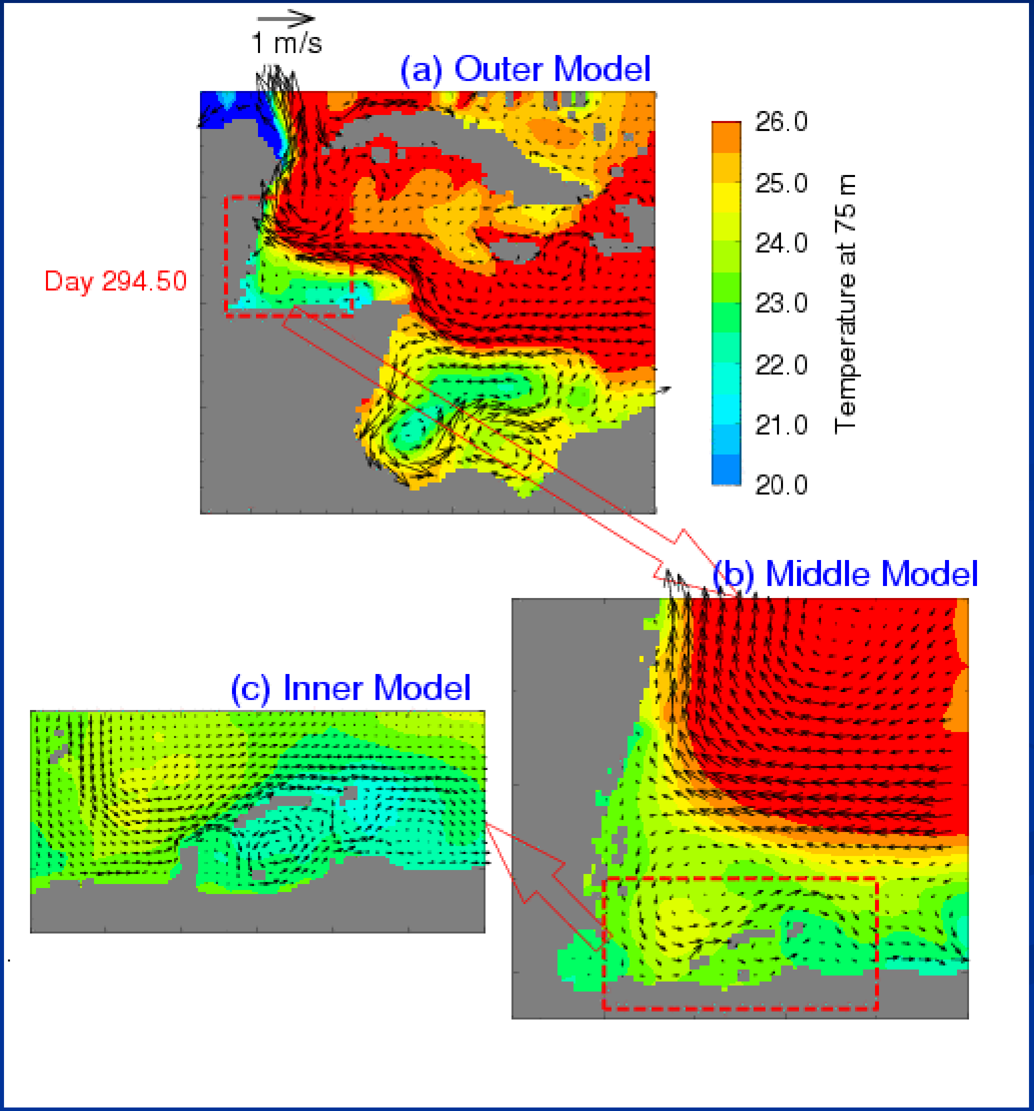


Reasonable estimates

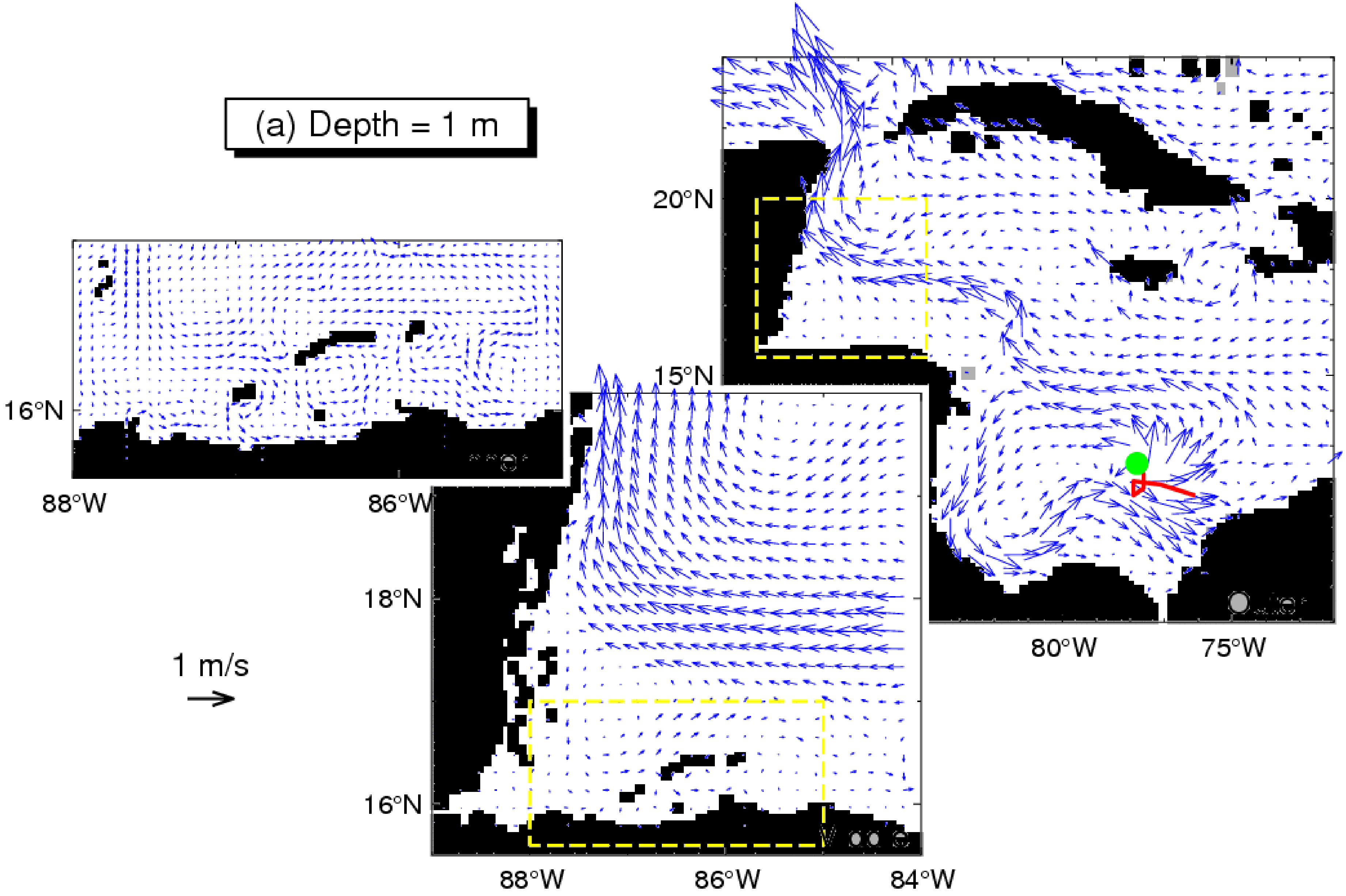
Simulated near-surface currents and temperature during Hurricane Mitch



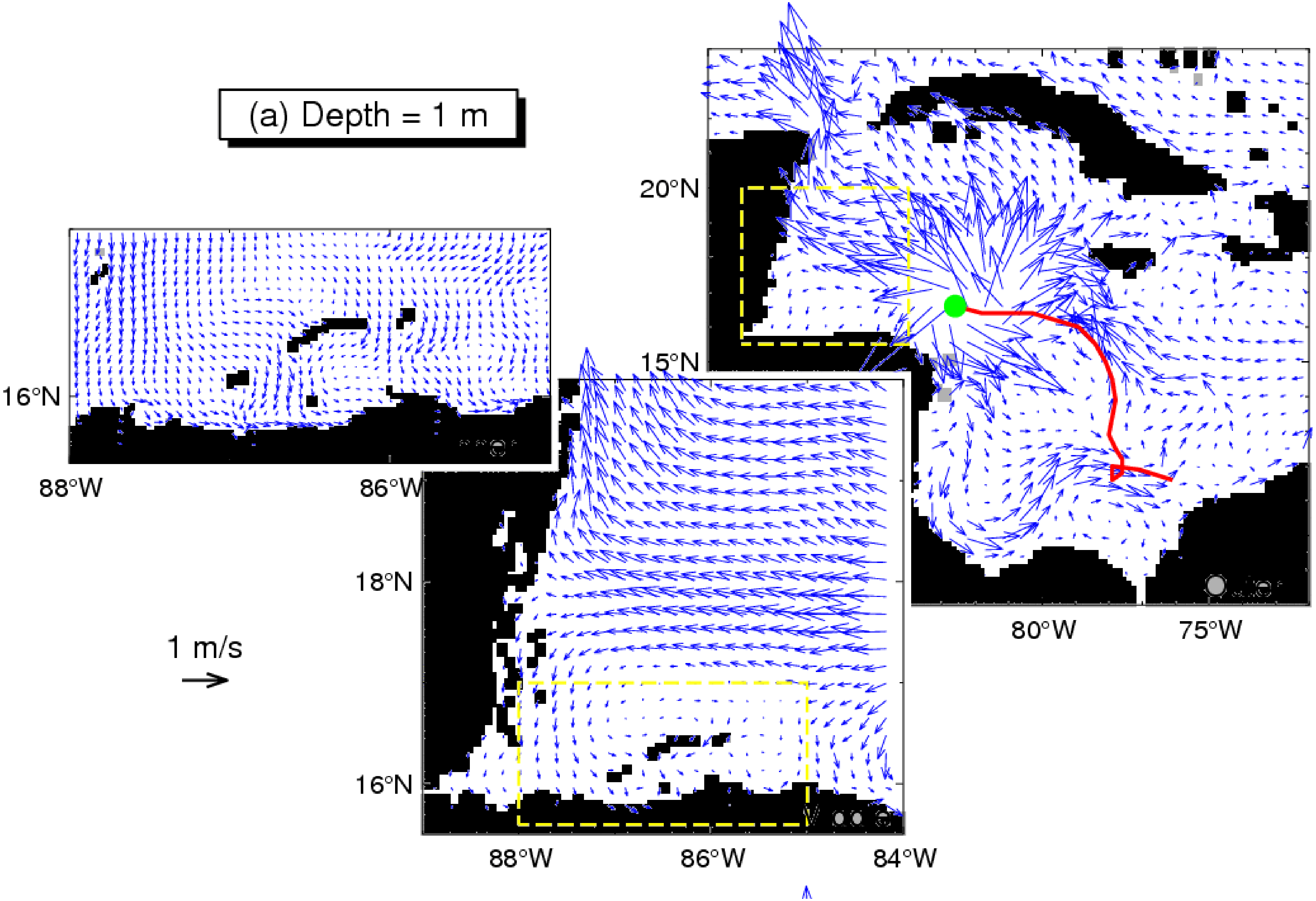
Simulated sub-surface currents and temperature at 75 m during Hurricane Mitch



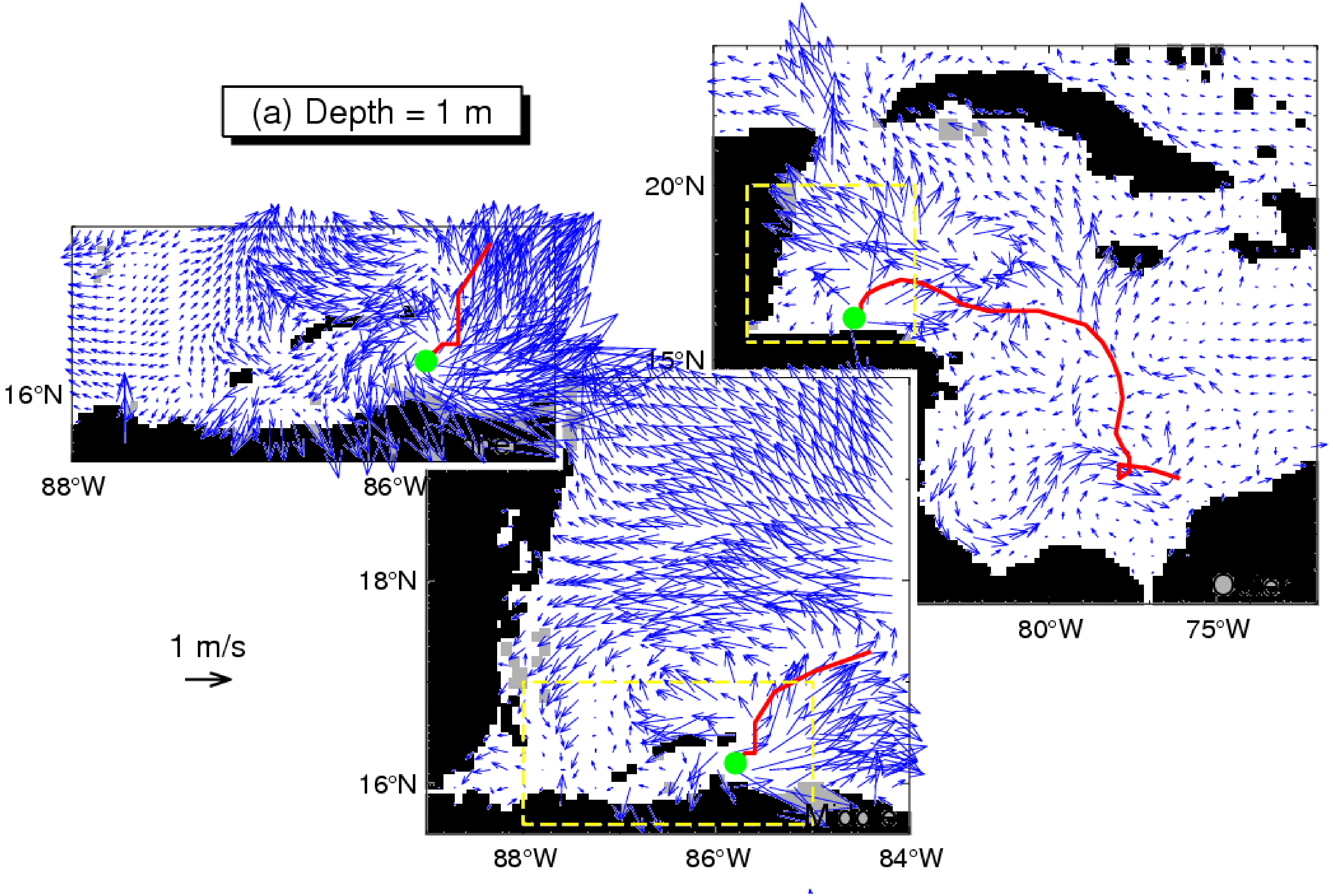
Simulated currents at Day 295.5 (1200 UTC October 23)



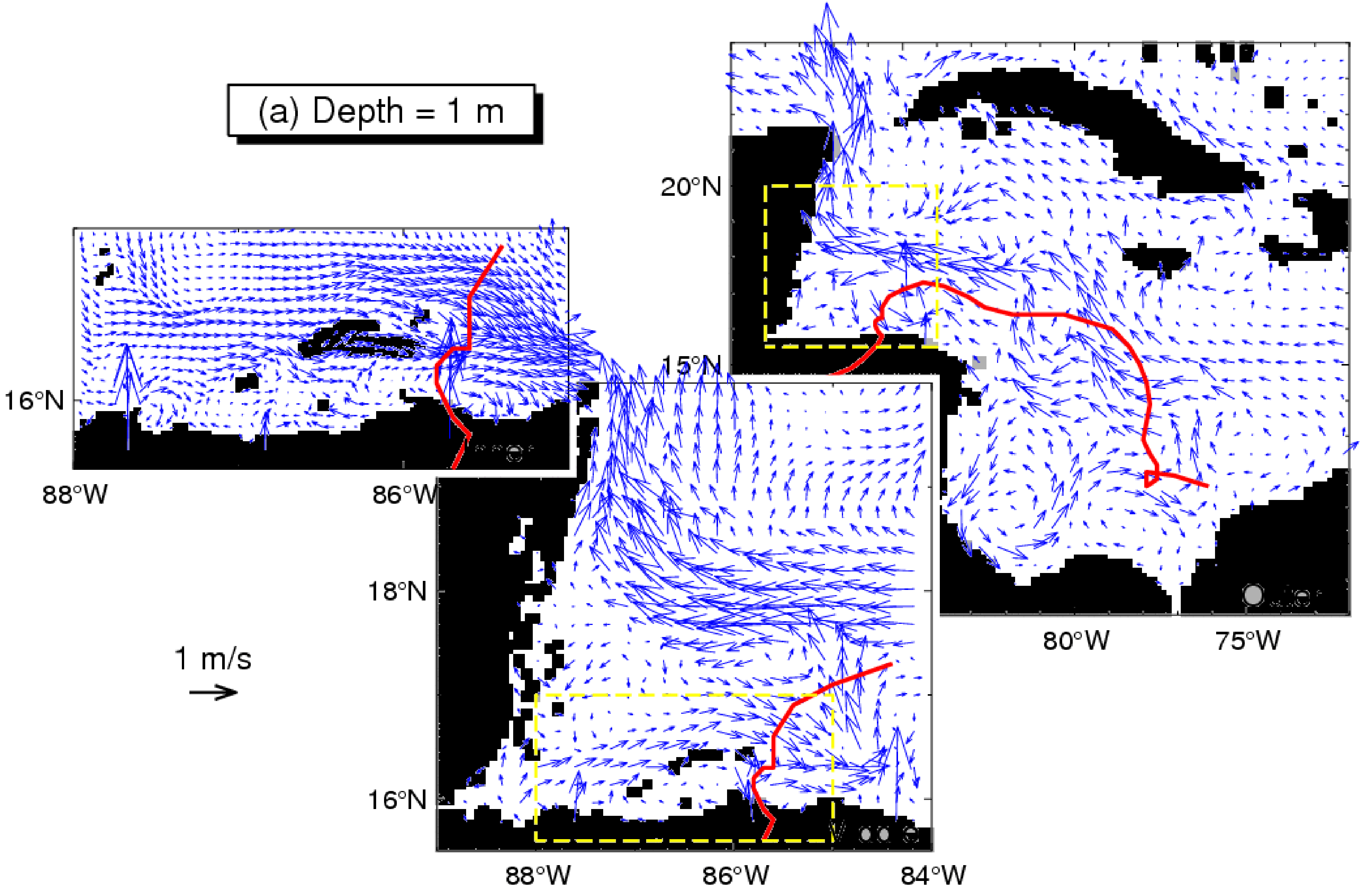
Simulated currents at Day 298.5.0 (1200 UTC October 26)



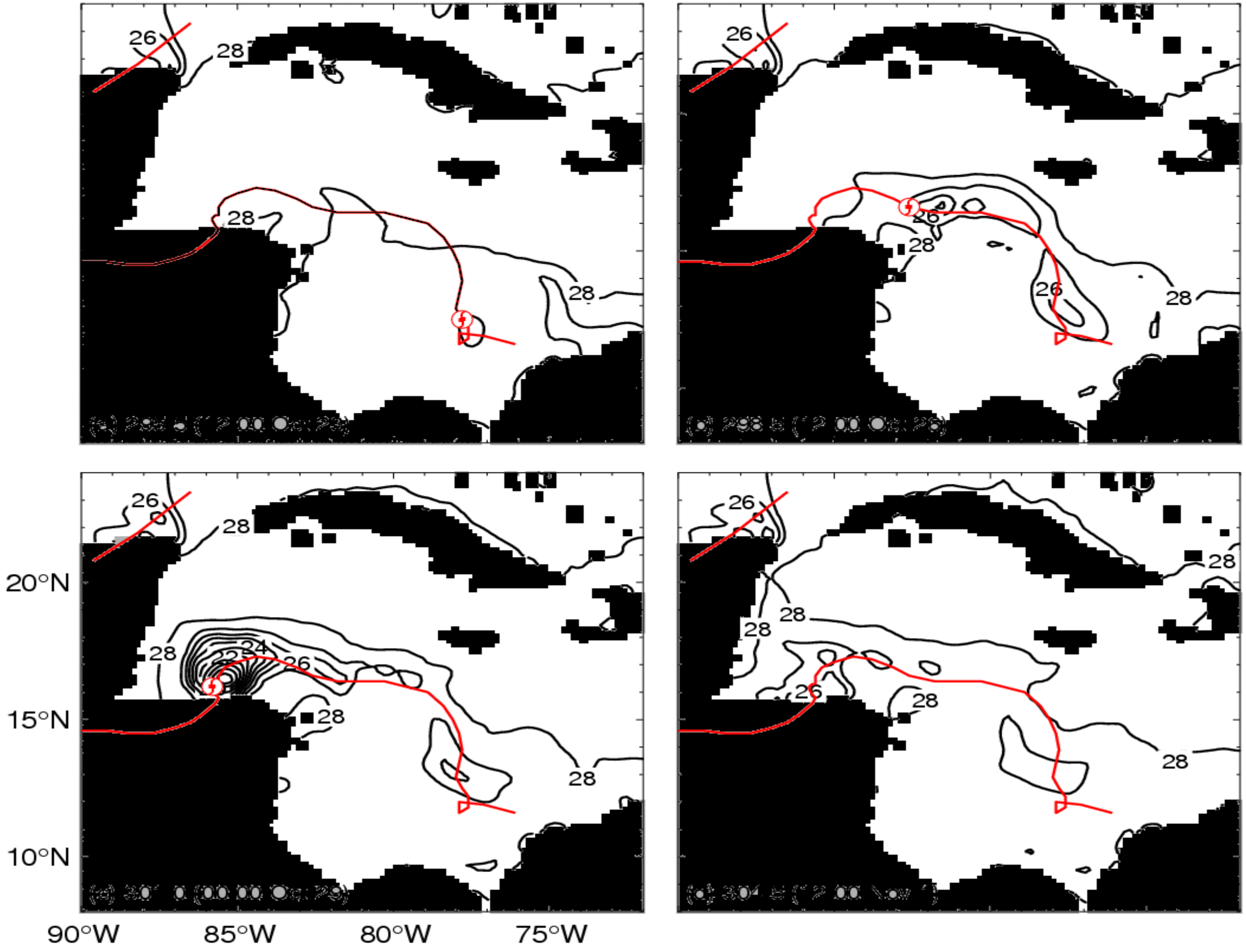
Simulated currents at Day 301.0 (0000 UTC October 29)



Simulated currents at Day 304.5 (1200 UTC November 1)



Simulated SST during Mitch, 1998



Main Features of Mitch-induced Circulations in the western Caribbean Sea

- Strong divergent circulation under the storm and intense near-inertial circulation behind the storm.

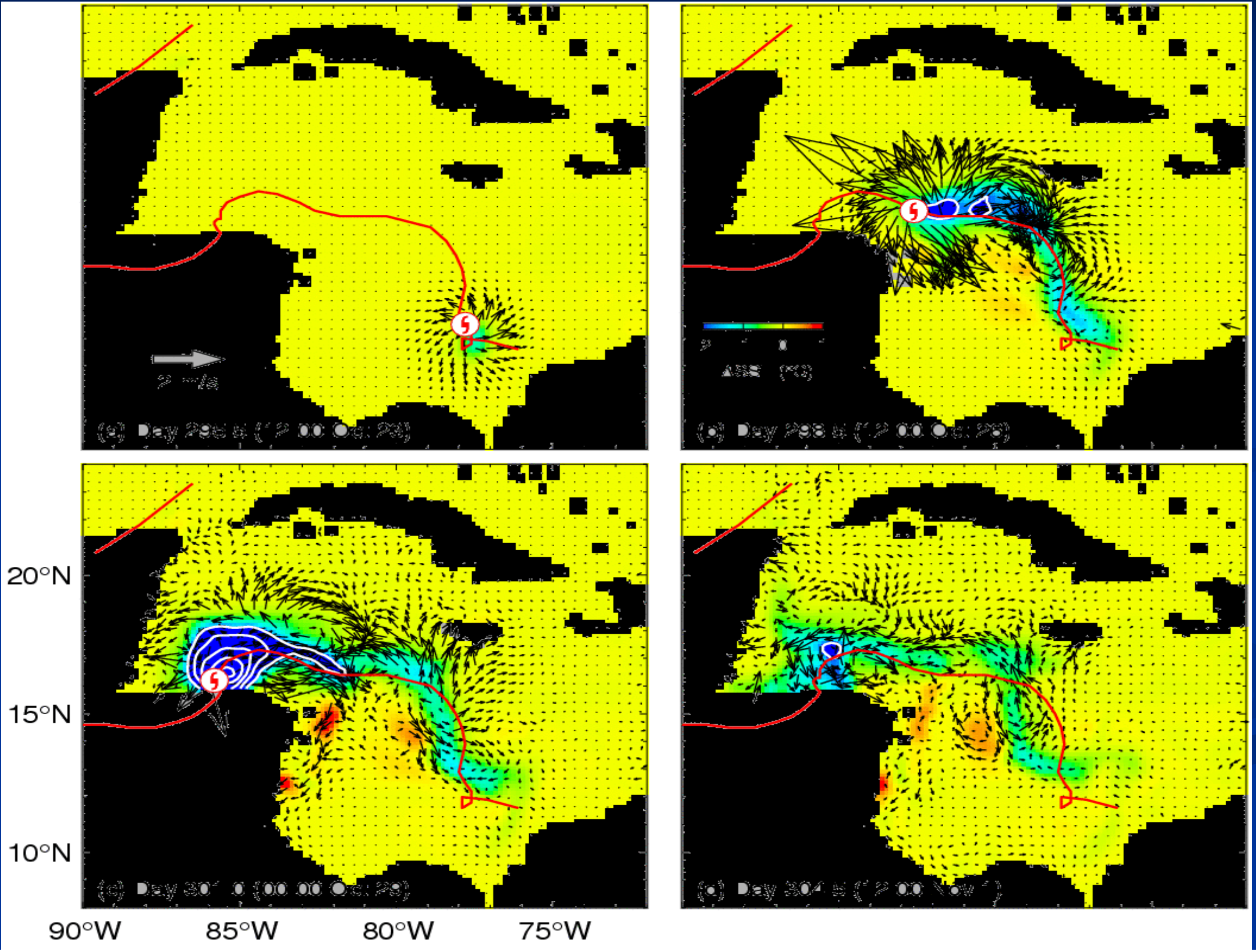
- Intense surface cooling behind the storm.

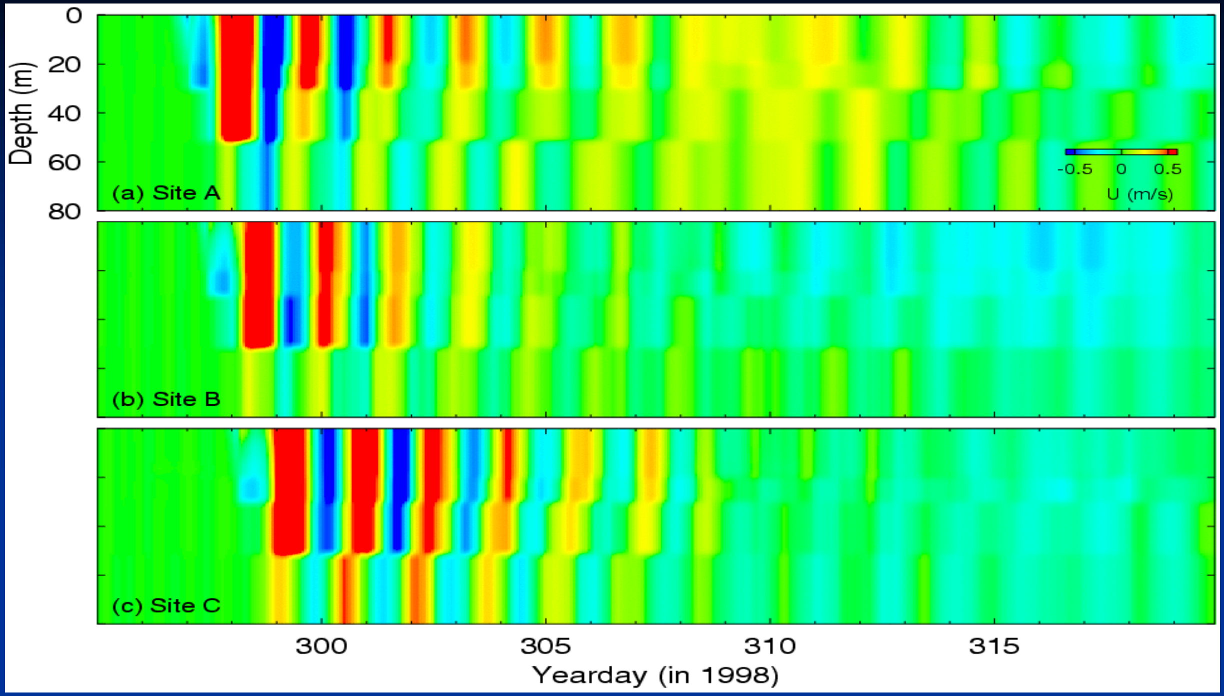
- The SST cooling and near-inertial oscillations are biased to the right side of the storm track.

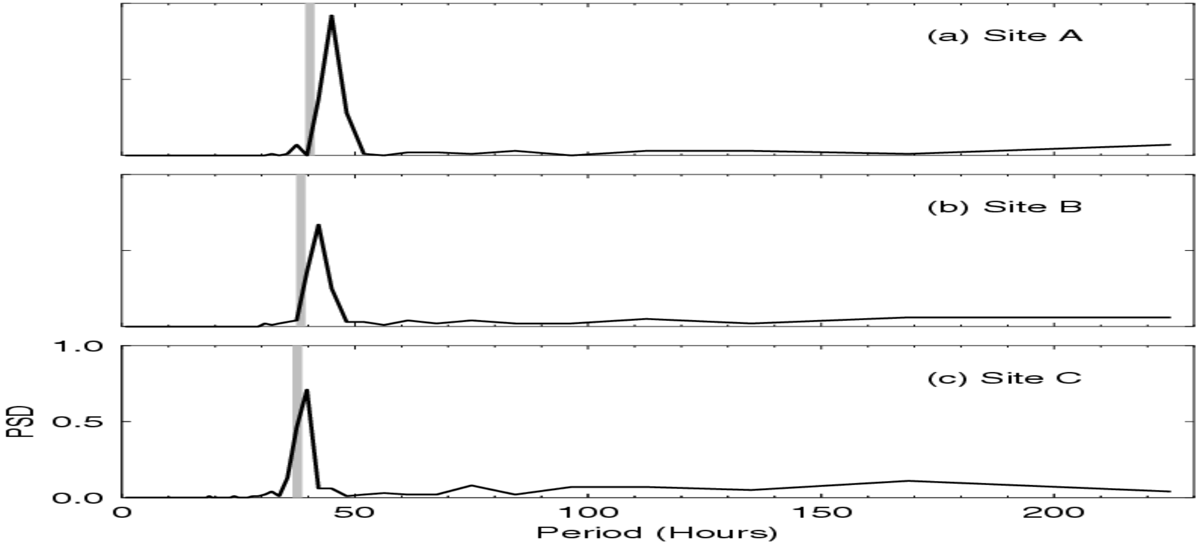
- Consistent with previous studies (Chang and Anthes, 1978; Greatbatch, 1983; Zhai et al., 2005; Sheng et al., 2006).

Difference of Sea Surface Temperature ($\Delta SST = T_{storm+clim} - T_{clim}$)

Day 295 – 304 (October 23-November 1, 1998)




Depth (m)
0
20
40
60
80
(a) Site A
-0.5
0
0.5
U (m/s)
(b) Site B
(c) Site C
300
305
310
315
Yearday (in 1998)


(a) Site A
(b) Site B
(c) Site C
PSD
1.0
0.5
0.0
0
50
100
150
200
Period (Hours)

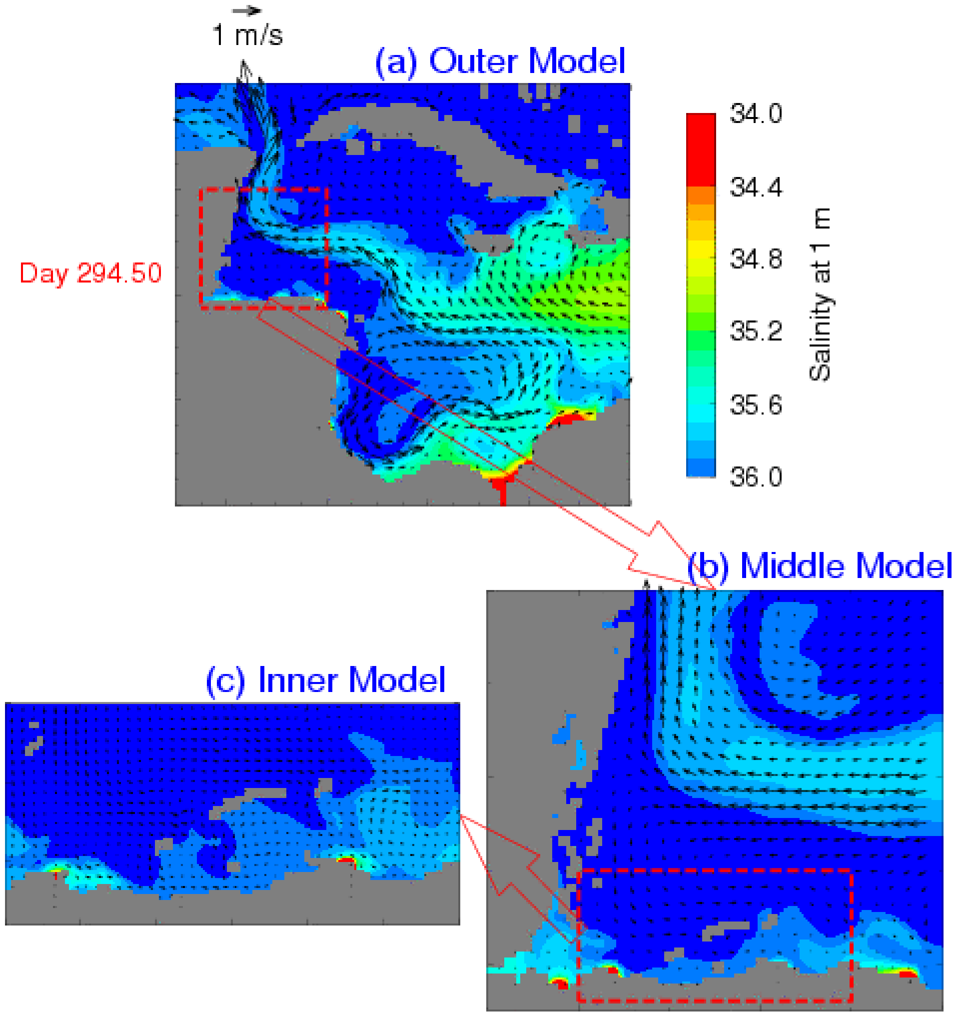
- The main reason for the rightward bias of near-inertial currents and SST cooling behind the storm is that energy transfer from the storm to the ocean is more efficient on the right side of the storm track (Chang and Anthes, 1978, Price, 1981; Greatbatch, 1983; Sheng et al., 2006).

- Wind stress at a fixed point on the right side veers anticyclonically (or clockwise), in the same direction of the inertial oscillation on the northern hemisphere, leading to more efficient energy transfer.

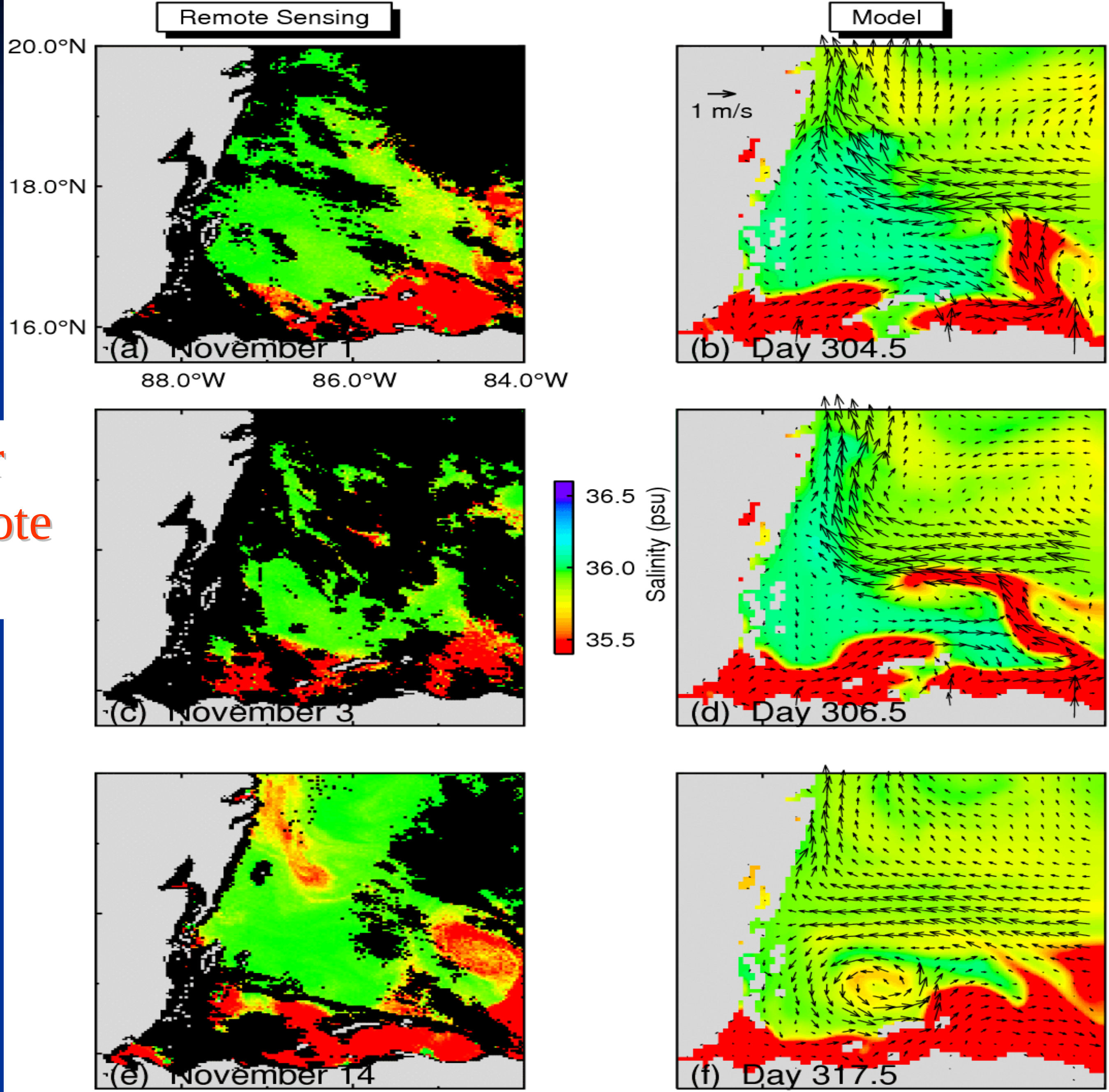
- Wind stress veers cyclonically on the left side of the track in the opposite direction of the inertial currents.

- Stronger mixing and entrainment led to stronger SST cooling on the right side of the track.

Simulated River Plumes along the Honduras Coast during Hurricane Mitch



Simulated River Plumes with Remote Sensing Data



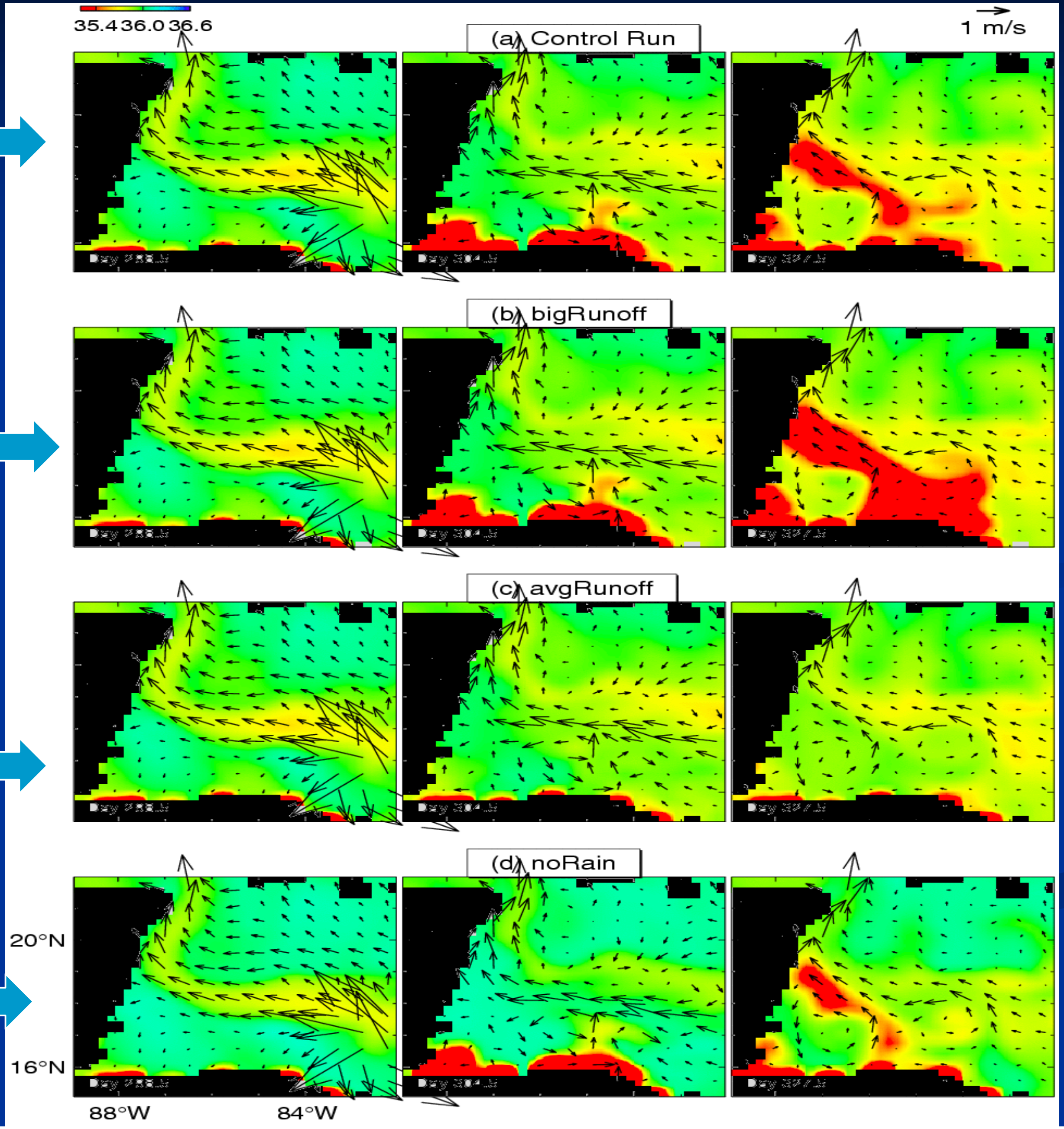
Sensitivity Studies

Control Run:

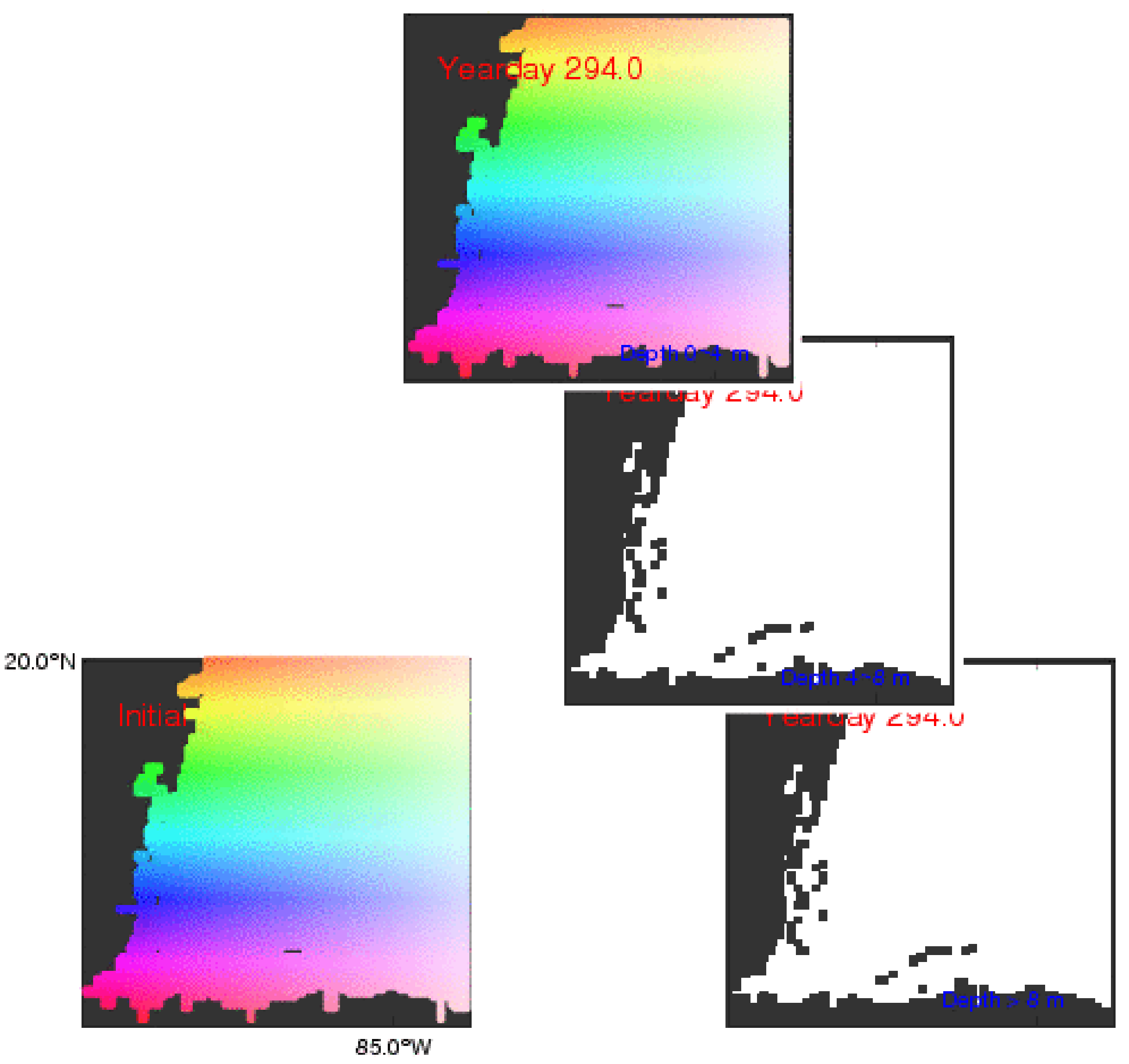
Large Runoff:

Mean Runoff:

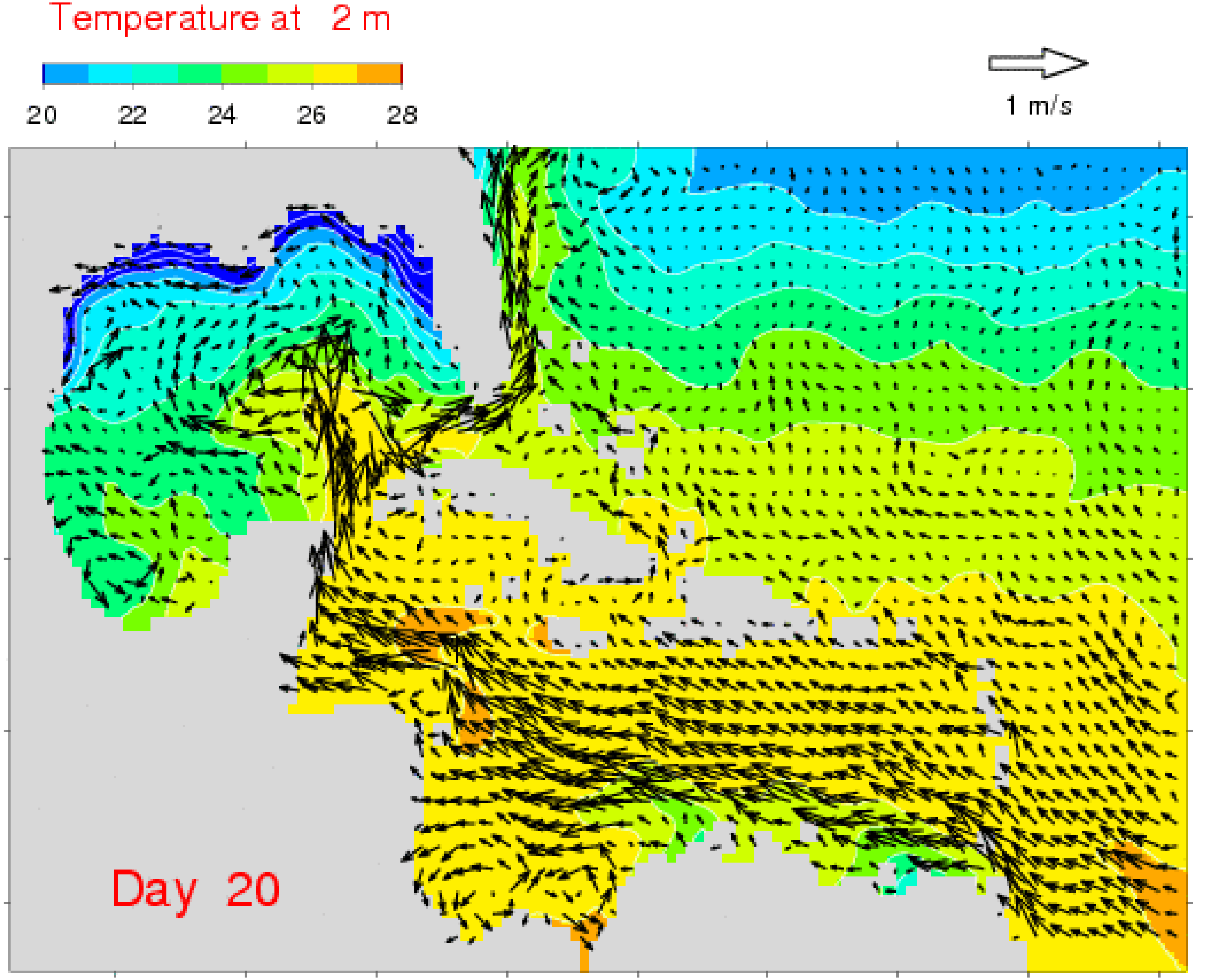
No Rain:



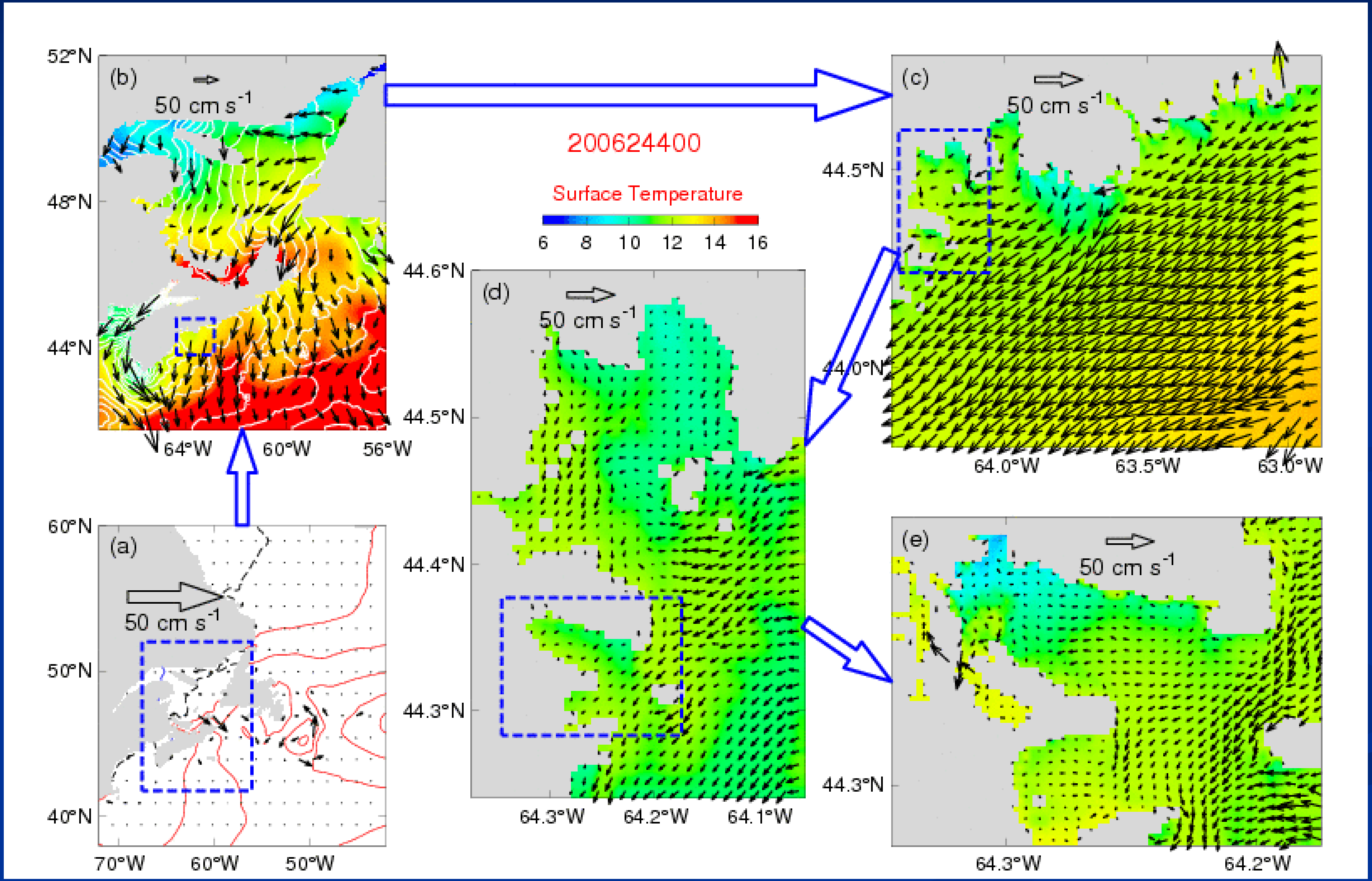
3D particle tracking



Simulation of circulation in the Intra-American Seas



Prototype Forecast System for Lunenburg Bay of Nova Scotia



Summary and Future Work

- Circulation and hydrographic distributions in the western Caribbean Sea under the normal and extreme conditions were studied using a triply nested-grid modelling system.

- Model results were used to examine the upper ocean responses of the MBRS (SST cooling, near-inertial oscillation and rightward bias, coastal estuarine plumes, etc) to Mitch.

- Effects of buoyancy forcing associated with river runoff and precipitation during Mitch on the upper ocean circulation were studied.

- SeaWiFS data were used to validate the model results.

Future Work:

- Simulate the fine-scale 3D circulation and hydrography over selected reefs of the MBRS using a 4-level circulation model.
- Produce high-resolution topography using remote sensing data.
- Calculate particle dispersion and retention during Mitch.
- Quantify hydrodynamic connectivity (transition matrix) over the MBRS reefs during Mitch.

Thank you