A Two-Way Nested-Grid Ocean Circulation Model

with Application to the Caribbean Sea and Scotian Shelf

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1. Introduction

List of Research Projects involved:

a) **ECONAR** -- **E**cological **Con**nectivity **A**mong **R**eefs in the Caribbean Sea

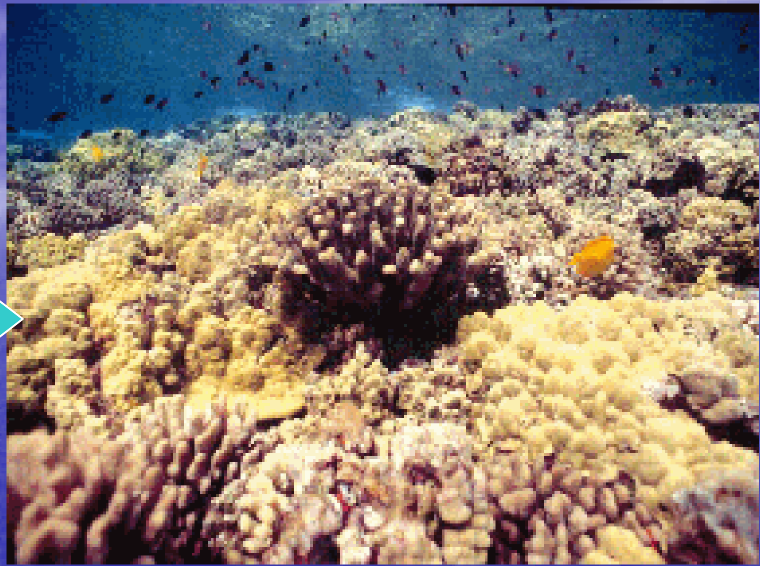
b) **Nested-grid model development** for the Scotian Shelf

c) Research Chair program funded by NSERC/MARTEC/MSC

d) High-resolution coastal modelling project as part of CMEP (Center for Marine Environmental Prediction)

e) Environmental Assessments of Carol Reef Ecosystems: Interdisciplinary Research Using EOS Platforms and Numerical models funded by NASA.

a) ECONAR project:



Coral reefs contain about one-quarter of the marine fish species. Coral reefs are however in serious danger due to both natural and man-made causes:

- Population growth and development have altered the coral reef environment.
- Destructive fishing practices, land-based sources of pollution such as agricultural runoff have detrimental effects on delicate reefs.
- Global warming also has the potential to be destructive to corals (sea-level rise and higher ocean temperature).

- US$24.2 million grant to protect the Meso-American Barrier Reef System (MBRS) provided by

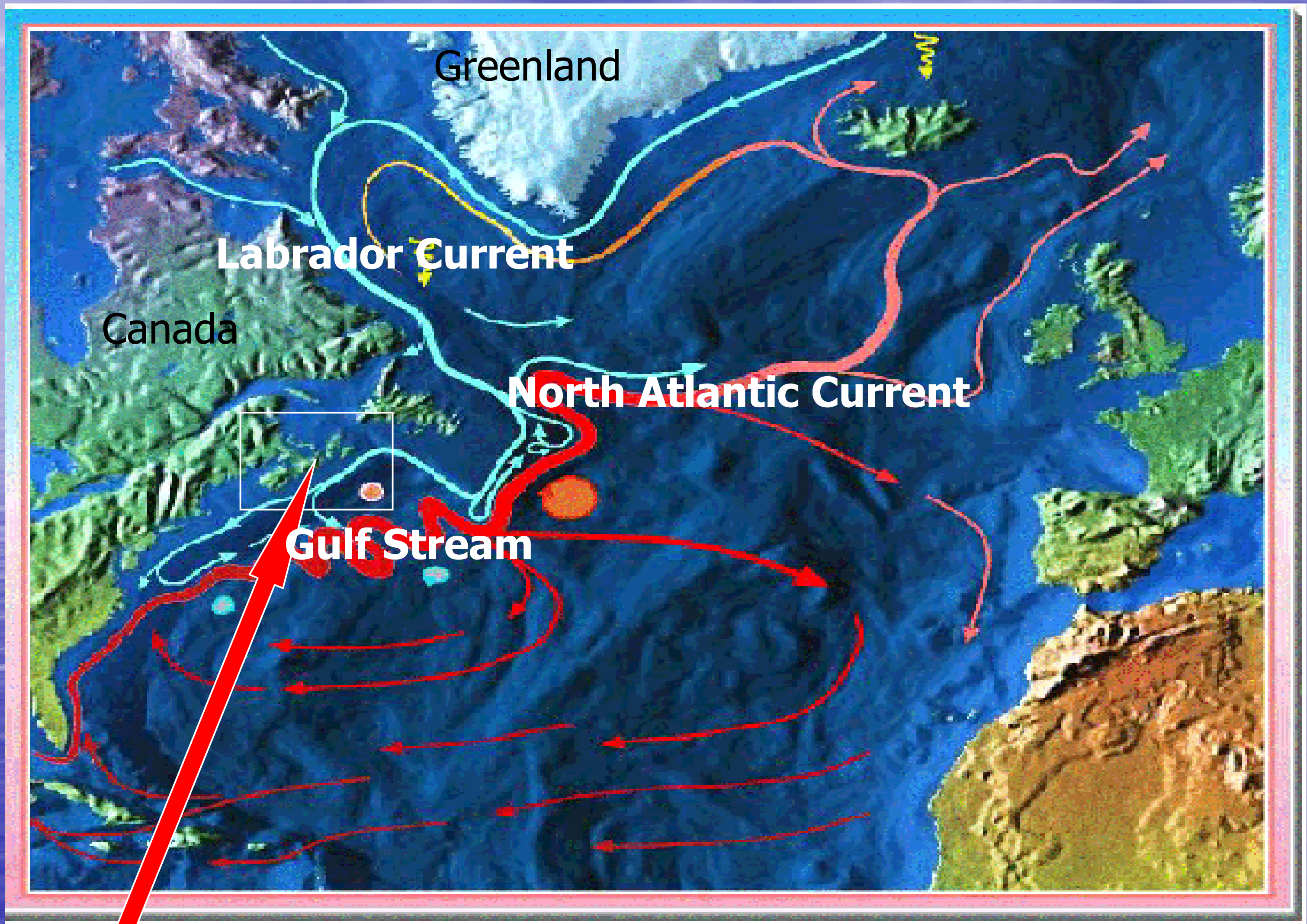
  Global Environment Facility (World Bank), World Wildlife Fund
  Belize, Canada, Guatemala, Honduras, Mexico
  University of Miami, Oak Foundation

- CDN$0.5 million grant to study ECONAR in the Caribbean Sea provided by NSERC (Natural Sciences and Engineering Research Council, Canada). My research team was responsible for:

  - Developing a three-dimensional ocean circulation models for the Caribbean Sea (two-way nested-grid model);

  - Determining particle dispersion and retention among reefs in the region (Markov Chains approach).

b) Nested Model Development for the Scotian Shelf:



Scotian Shelf

2. CANDIE: Primitive Equation Ocean Model

- CANDIE stands for CANadian version of Diecast.

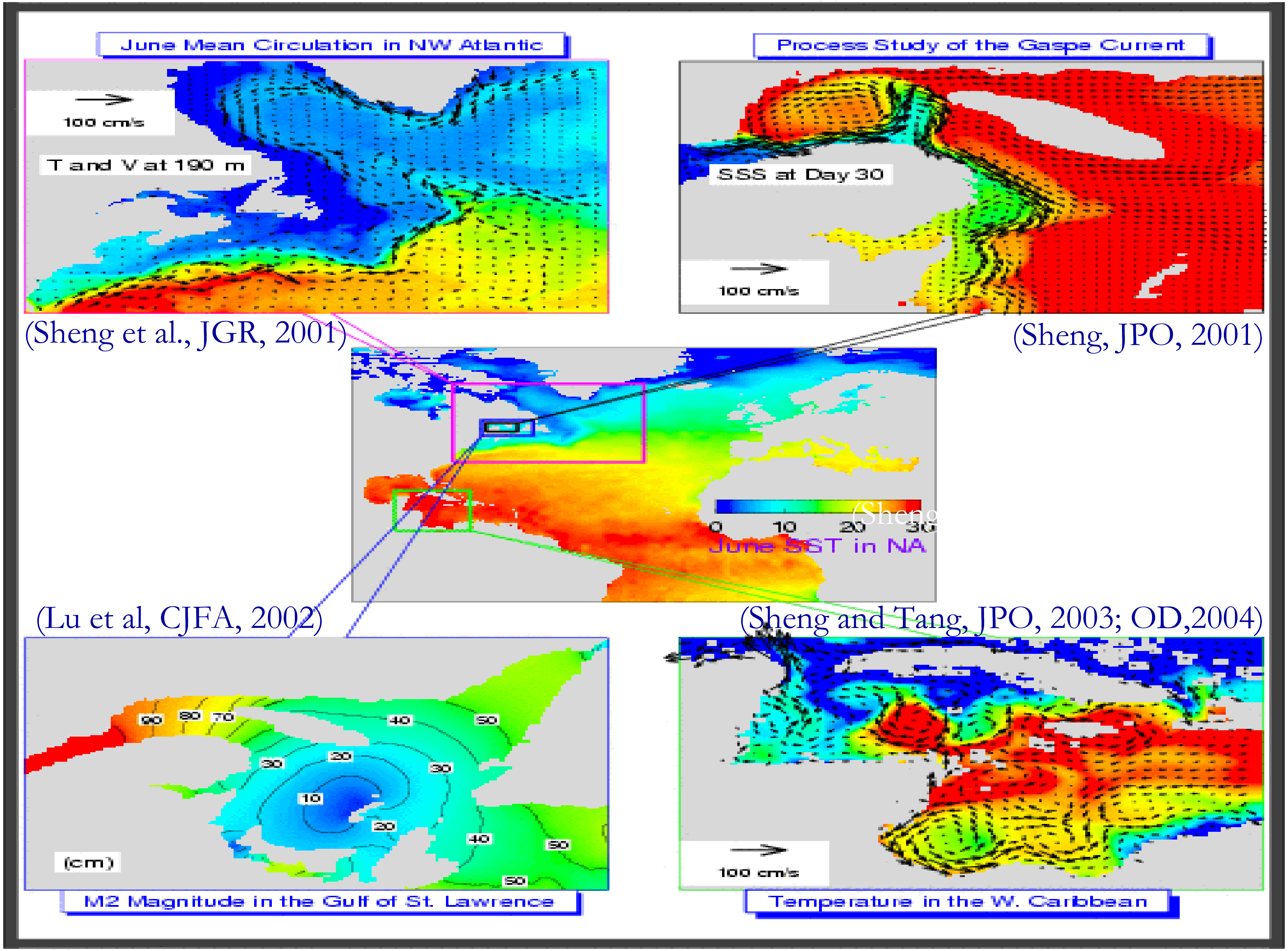
- Developed by Sheng, Wright, Greatbatch, and Dietrich (1998).

- A three-dimensional (3D), fully non-linear, primitive equation, finite-difference, z-level model.

- Numerical scheme: 4th-order of accuracy with a flux limiter for advection terms

- CANDIE has been subjected to several rigorous tests, using test problems with known solutions, an important process for building confidence in a numerical model.

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


June Mean Circulation in NW Atlantic
100 cm/s
T and V at 190 m
(Sheng et al., JGR, 2001)
Process Study of the Gaspe Current
SSS at Day 30
100 cm/s
(Sheng, JPO, 2001)
0 10 20 30
June SST in NA
(Lu et al, CJFA, 2002)
(Sheng and Tang, JPO, 2003; OD,2004)
90 80 70 40 50 30 20 30 10 20 40 50 50
(cm)
M2 Magnitude in the Gulf of St. Lawrence
100 cm/s
Temperature in the W. Caribbean

Major Applications

1. Wind-driven circulation over a coastal canyon (Sheng, Greatbatch, Wright and Dietrich, JAOT, 1998).
2. Process studies of the density-driven Gaspe Current (Sheng, JPO, 2001).
3. Seasonal circulation in the northwest Atlantic Ocean (Sheng, Greatbatch and Wright, JGR, 2001).
4. Internal tide generation over topography (Lu, Wright and Brickman, JAOT, 2001).
5. Tidal circulation and mixing in the Gulf of St. Lawrence (Lu, Thompson and Wright, CJFAS, 2001).
6. General circulation in the western Caribbean Sea (Sheng and Tang, JPO, 2004).
7. Two-way nested-grid ocean model for the MBRS (Sheng and Tang, Ocean Dynamics, 2004).
8. High-resolution tidal simulations in Lunenburg Bay (Sheng and Wang, ECM8, 2004).

Governing Equations

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

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

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

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

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

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

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

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

Diagnostic vs Prognostic Methods

Diagnostic Method:

Calculates ocean currents from specified temperature and salinity fields.

- Relatively easy and straightforward to run.
- Robust in multi-year simulations.
- Wrong model for studying the interaction of temperature/salinity fields with the flow field.
- Wrong model for studying winter convective mixing.

Prognostic Method:

Calculates ocean currents, together with temperature and salinity fields.

- Capable of simulating baroclinic instability.
- Capable of estimating winter convective mixing.
- Sensitive to subgrid-scale mixing parameterizations
- Deteriorating model skill in longer simulations.

The Semi-Prognostic Method

Sheng, Greatbatch and Wright (2001, JGR) recently proposed a semi-prognostic method to improve the utility of the ocean model. The main idea is to replace the hydrostatic equation $\frac{\partial p}{\partial z} = -\rho g$ by

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

with temperature and salinity equations unchanged.

The semi-prognostic method is:

- better than the robust diagnostic approach proposed by Sarmiento and Bryan [1982], since the new method does not constrain the temperature and salinity equations.
- different from the assimilative approach examined by Woodgate and Killworth [1997], since the new method does not add any relaxation terms directly in the momentum equations.

Sheng et al., 2001 (JGR); Greatbatch et al., 2004 (CSR); Eden et al., 2004 (JPO); Zhao et al., 2004 (GRL,submitted)

Physical Interpretation:

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

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

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

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

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

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

A New Two-Way Nesting Technique using the semi-prognostic method

- Conventional nesting techniques:

➡ **Exchange information through the dynamic interfaces (Kurihara et al., 1979).**

➡ **Replace the outer model variables with the inner model variables over the common subregion (Oey and Chen, 1992).**

- The new two-way nesting technique:

➡ **Exchange information between nested grids using the semi-prognostic method (Sheng et al., 2001; Eden et al., 2004; Greatbatch et al., 2004; Zhai et al., 2004).**

- 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 in this study

4.2 One-Way and Two-Way Nested Models

One-Way Nested Model:

Coarse-resolution outer model results are used to specify boundary conditions of the fine-resolution inner model.

Two-Way Nested Model:

Outer model results are used to specify boundary conditions of the inner model.

In addition, the semi-prognostic method is used to exchange information between the inner and outer models

$$\partial \hat{p}/\partial z = -g\beta(\rho_{\text{outer}} - \rho_m) \quad \text{for the inner model}$$

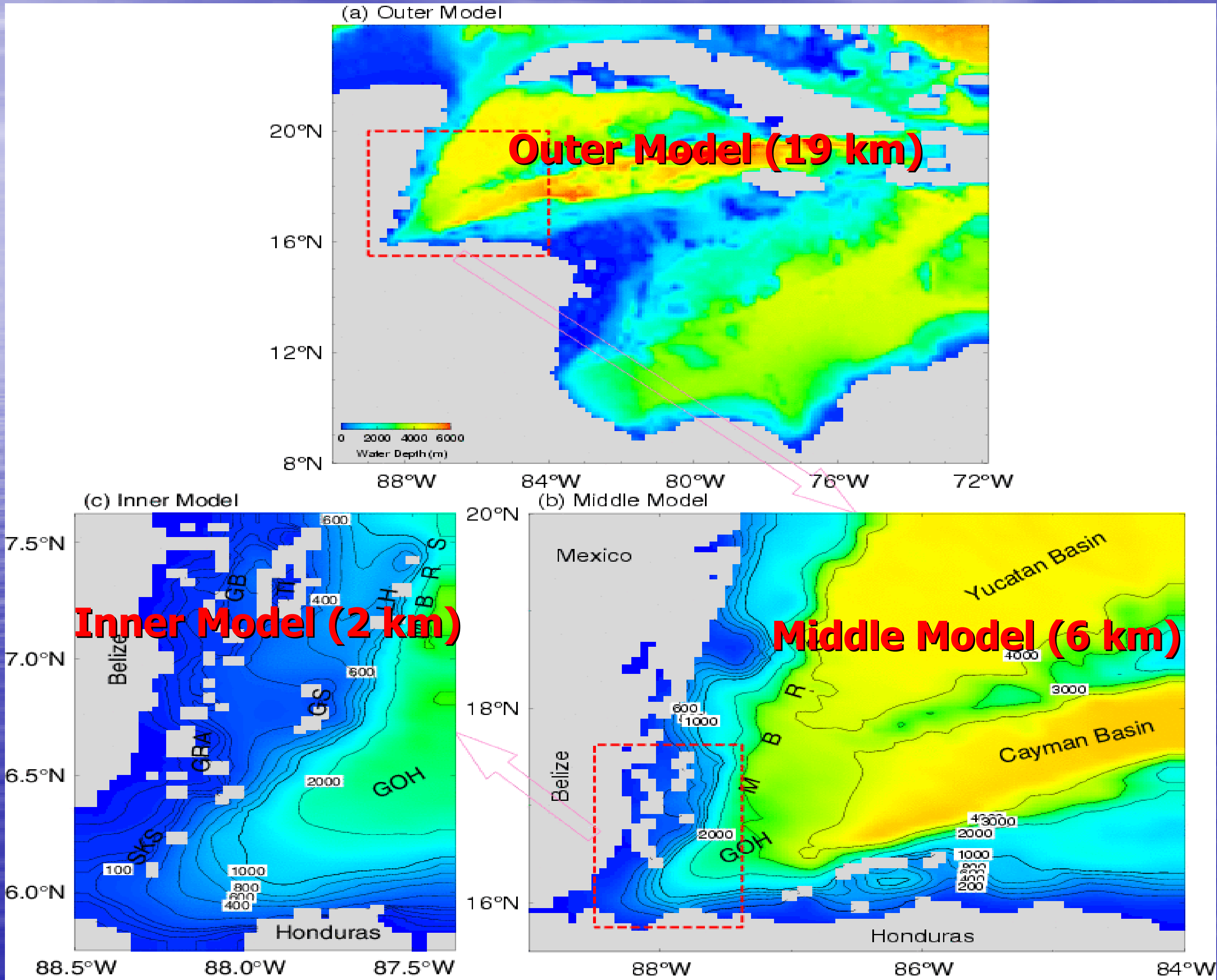
$$\partial \hat{p}/\partial z = -g\beta(\rho_{\text{inner}} - \rho_m) \quad \text{for the outer model}$$

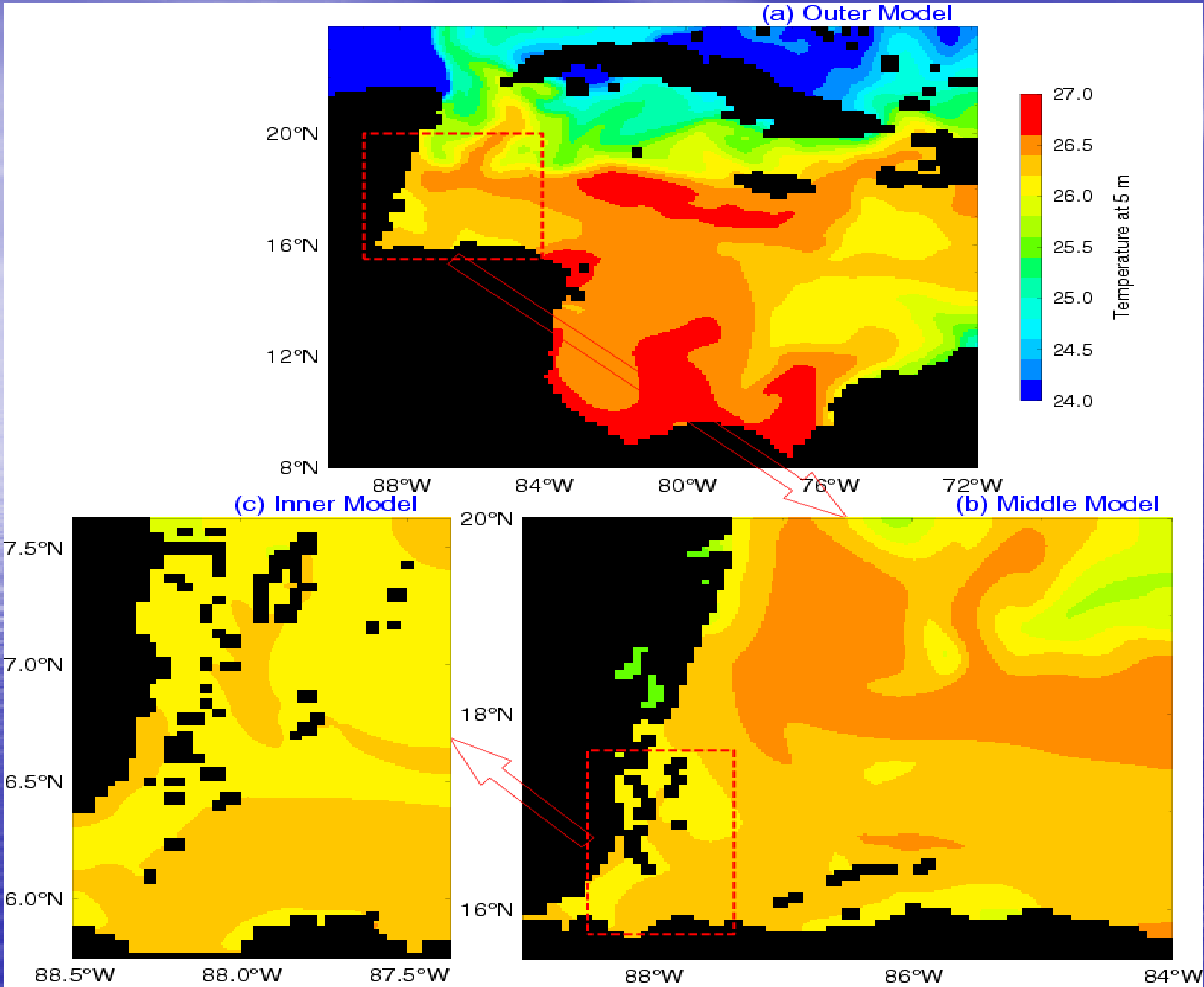
$$\frac{\partial u}{\partial t} = -\frac{1}{\rho_o}\frac{\partial p}{\partial x} - \frac{1}{\rho_o}\frac{\partial \hat{p}}{\partial x} + \cdots\cdots$$

$$\frac{\partial v}{\partial t} = -\frac{1}{\rho_o}\frac{\partial p}{\partial y} - \frac{1}{\rho_o}\frac{\partial \hat{p}}{\partial y} + \cdots\cdots$$

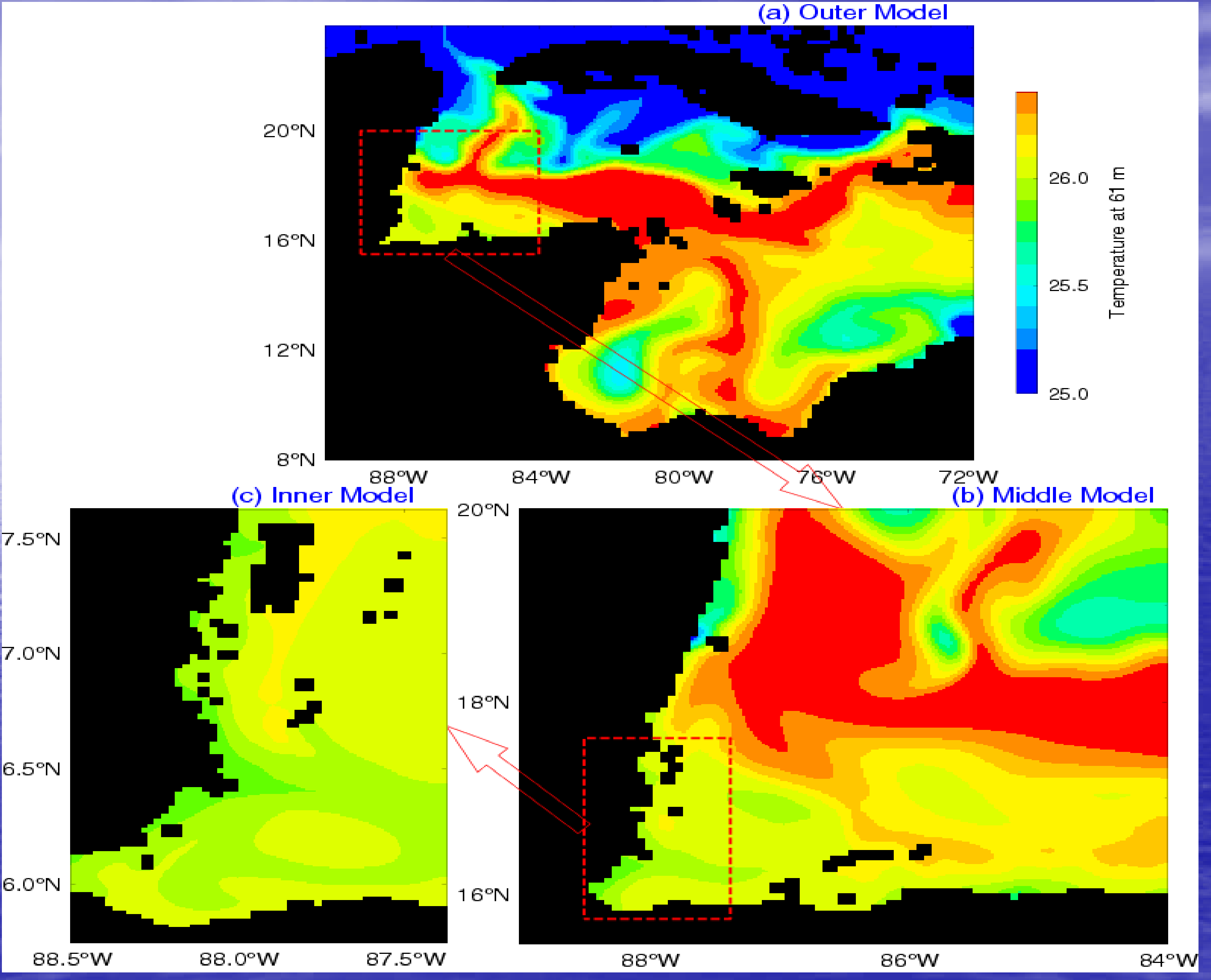
4. Application to the Caribbean Sea

(Sheng and Tang, Ocean Dynamics, 2004)

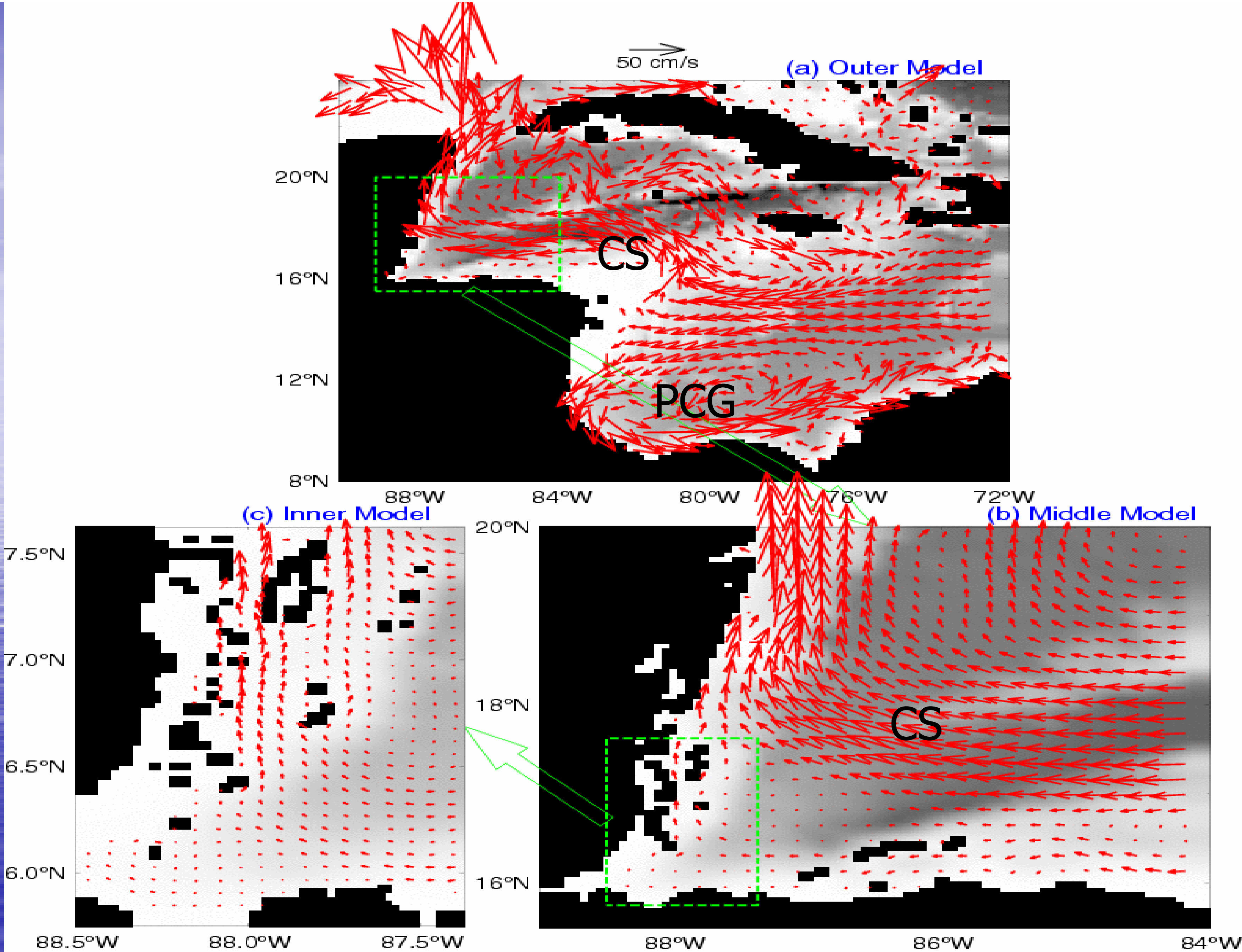




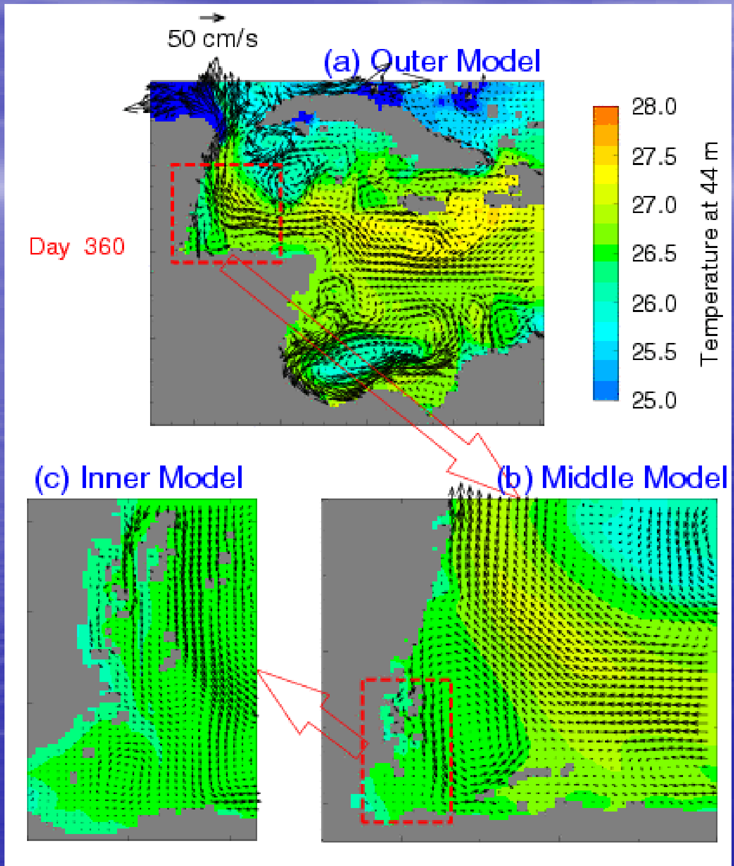
February Mean Near-Surface Temperature



February Mean Sub-Surface (61 m) Temperature

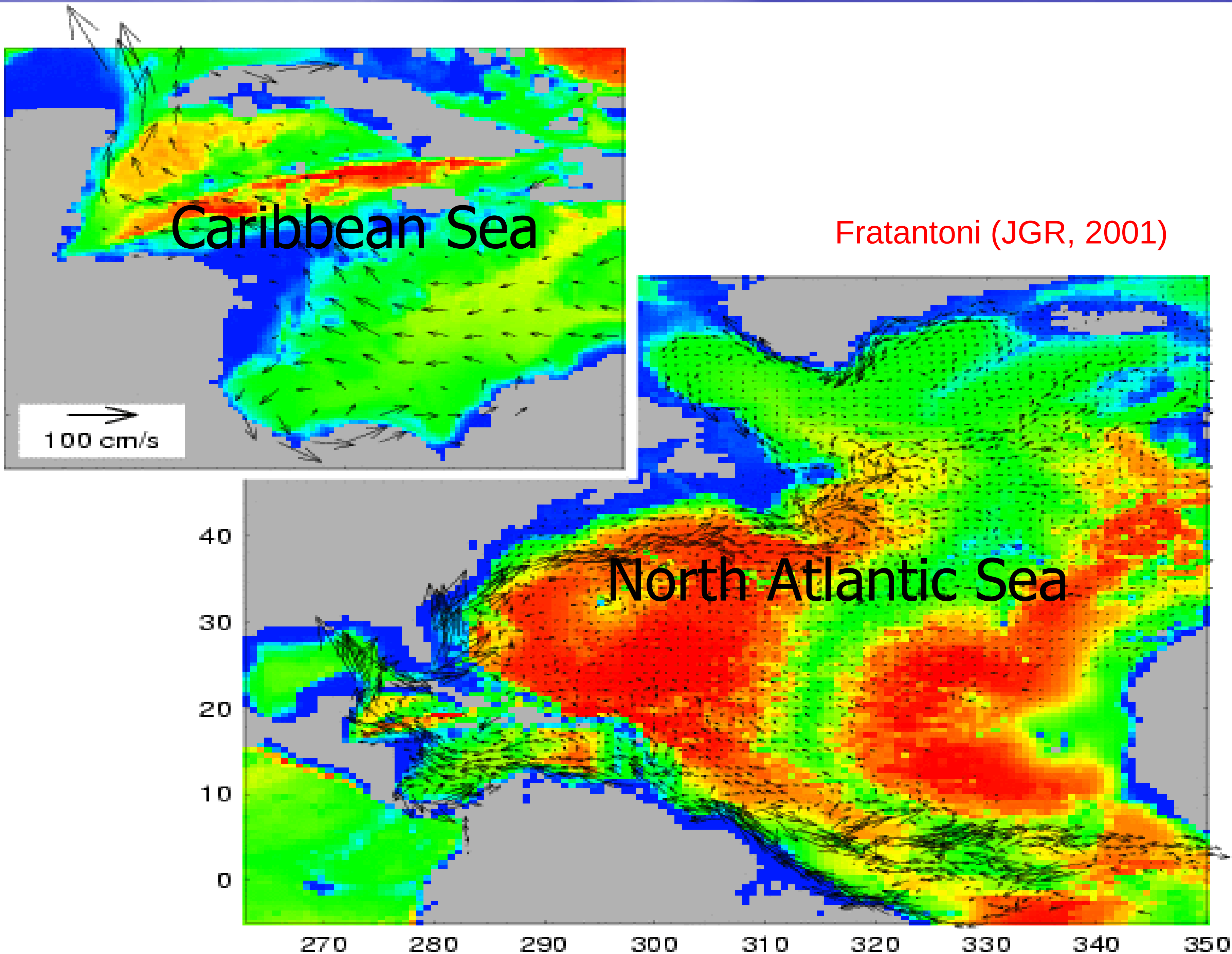


February Mean Near-Surface Circulation



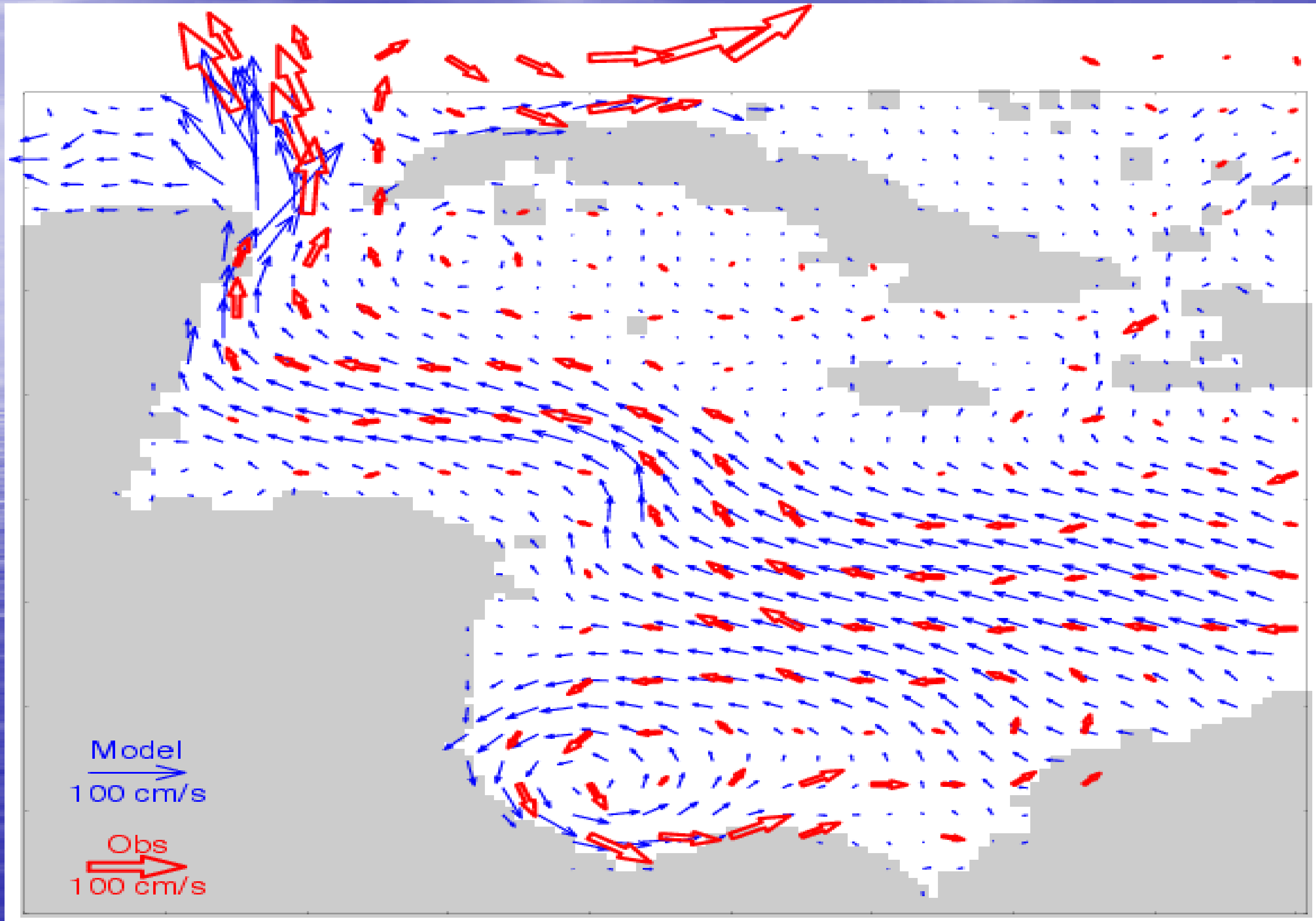
50 cm/s
(a) Outer Model
Day 360
28.0
27.5
27.0
26.5
26.0
25.5
25.0
Temperature at 44 m
(c) Inner Model
(b) Middle Model

Fratantoni (JGR, 2001)



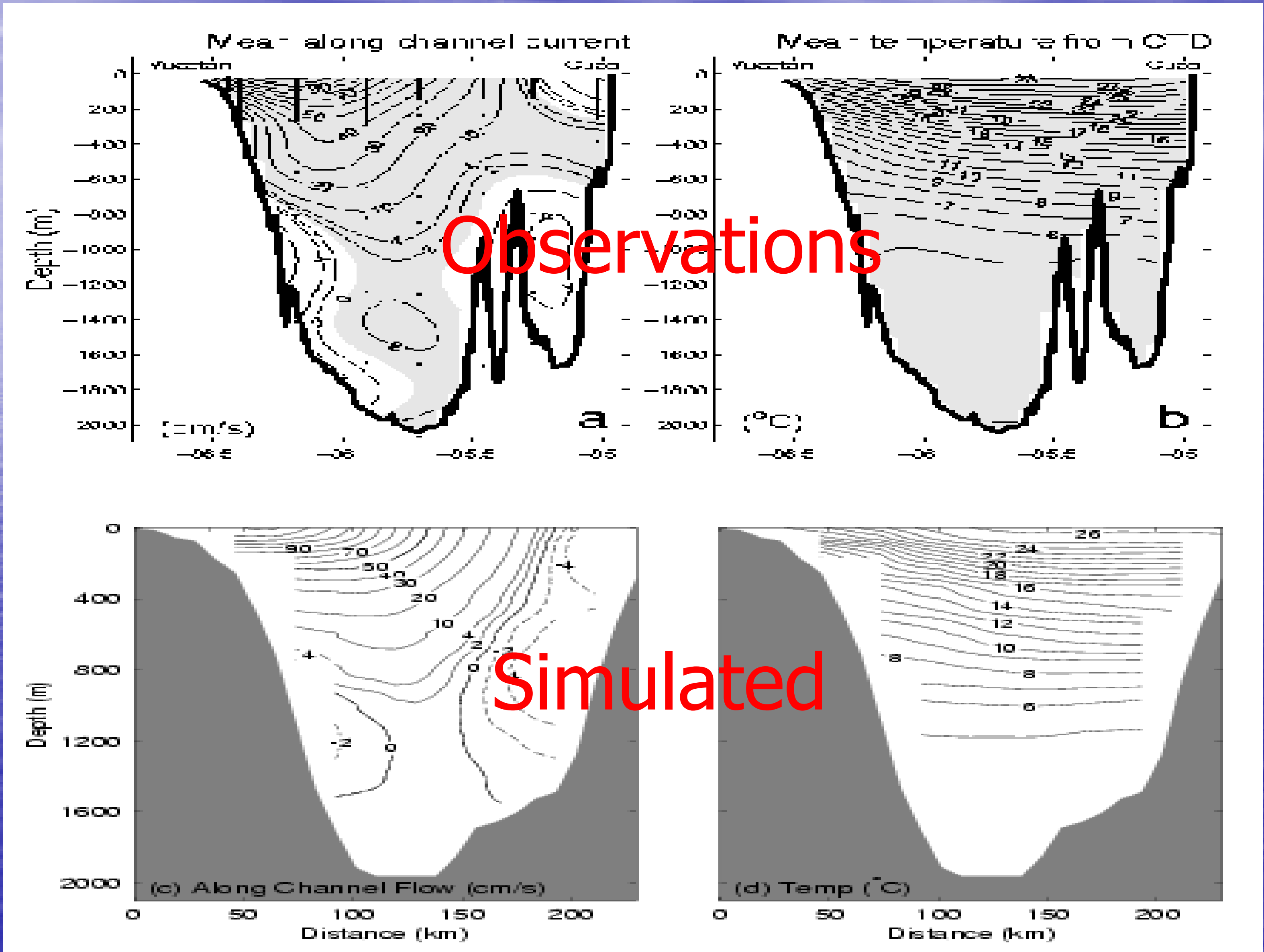
Calculated and Observed Near-Surface Currents

(Data from David Fratantoni, WIO)

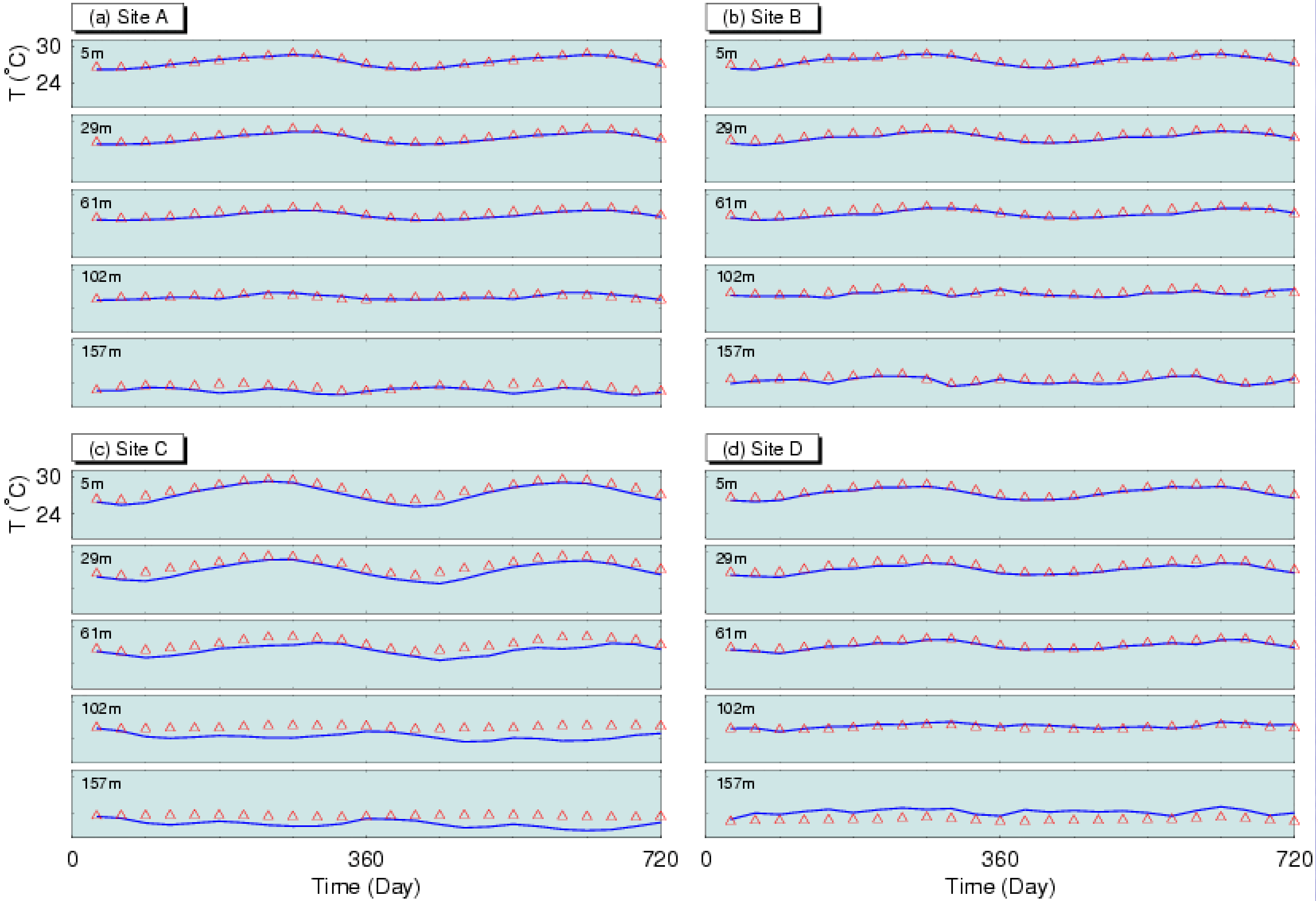


Observed and calculated along-channel Currents

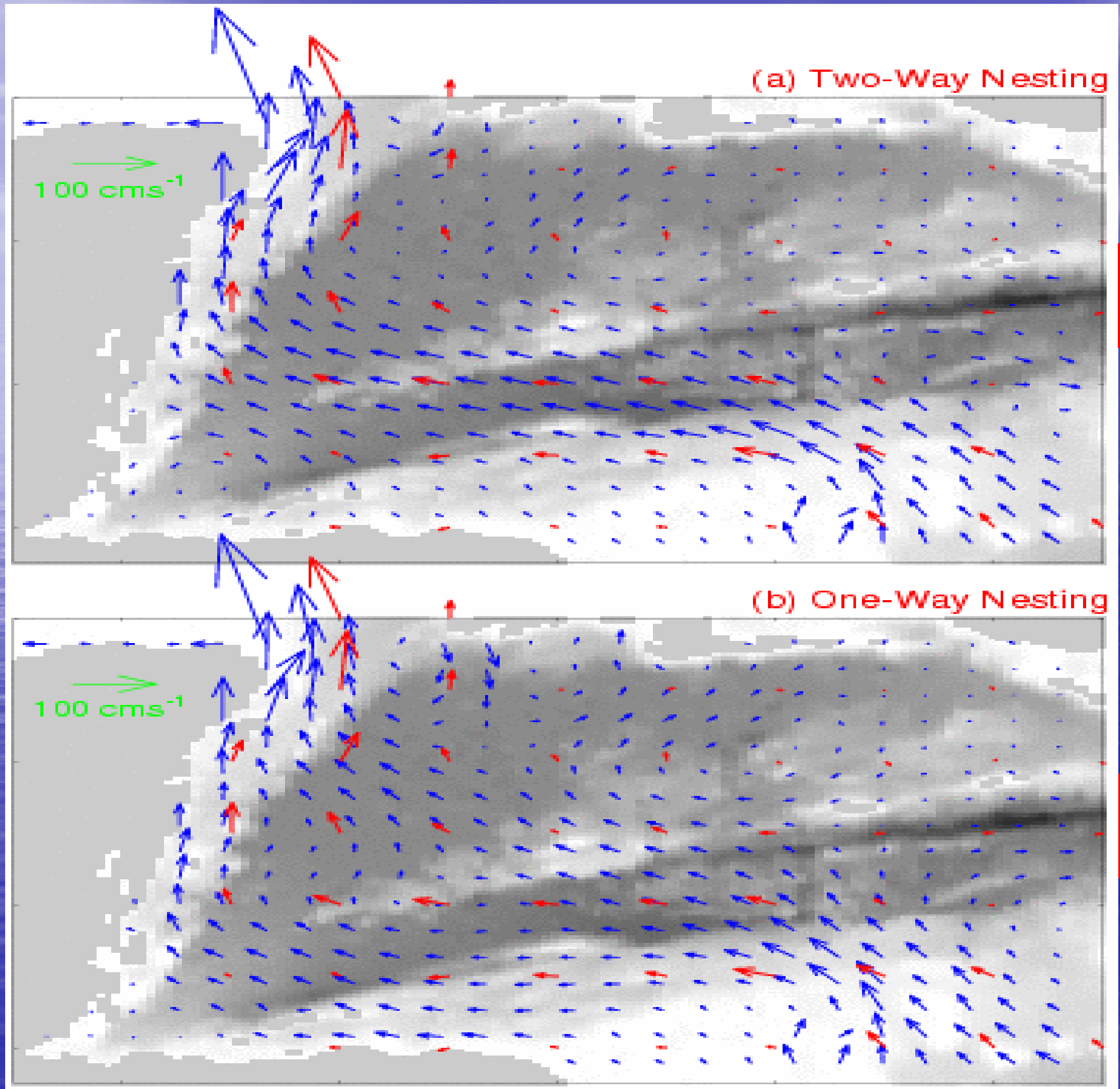
(Data from Sheinbaum et al., 2002)



Calculated and climatological monthly mean T



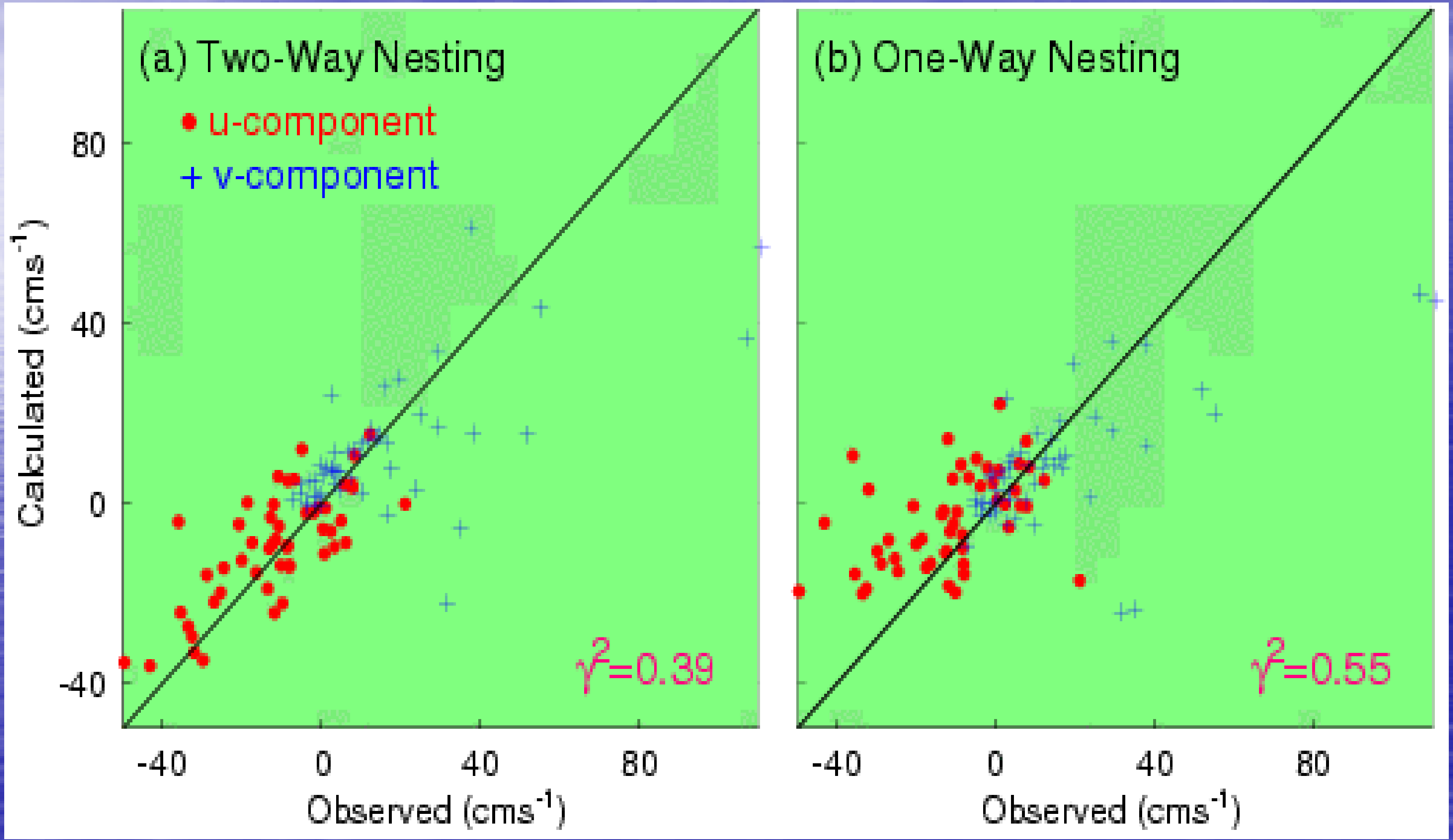
Comparison of Calculated and Observed Surface Currents



Two-Way

One-Way

Scatter-plots of Calculated and Observed Surface Currents



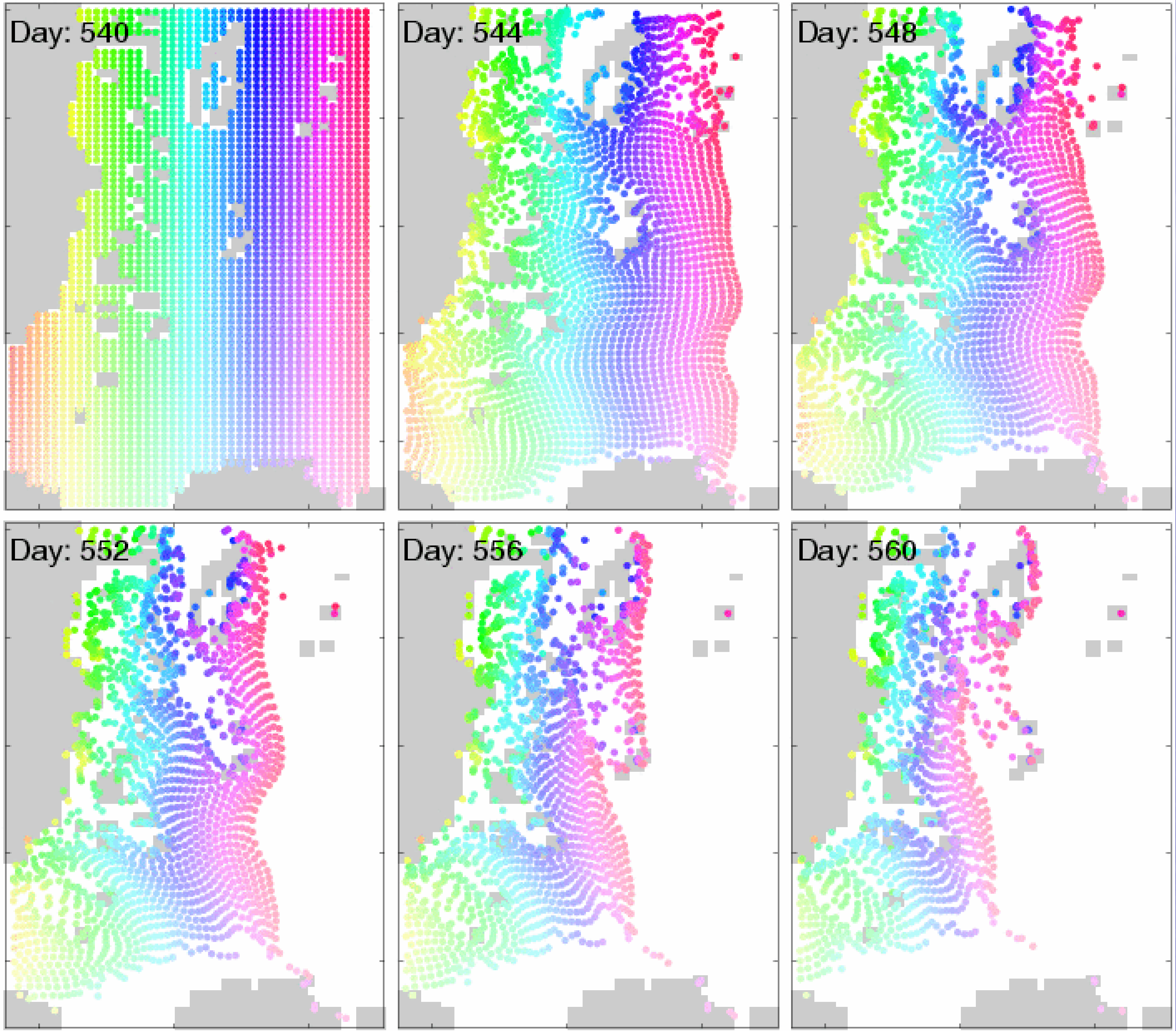
Ecological Connectivity Among Coral Reefs Using a Markov Chain Approach

- The 1st order Markov chain approach is used to develop a coupled physical-biological model to predict retention and dispersion of particles among different coral reefs.
- The probability distribution of particle position at time $t+\Delta t$ is given as (Thompson et al., 2002):

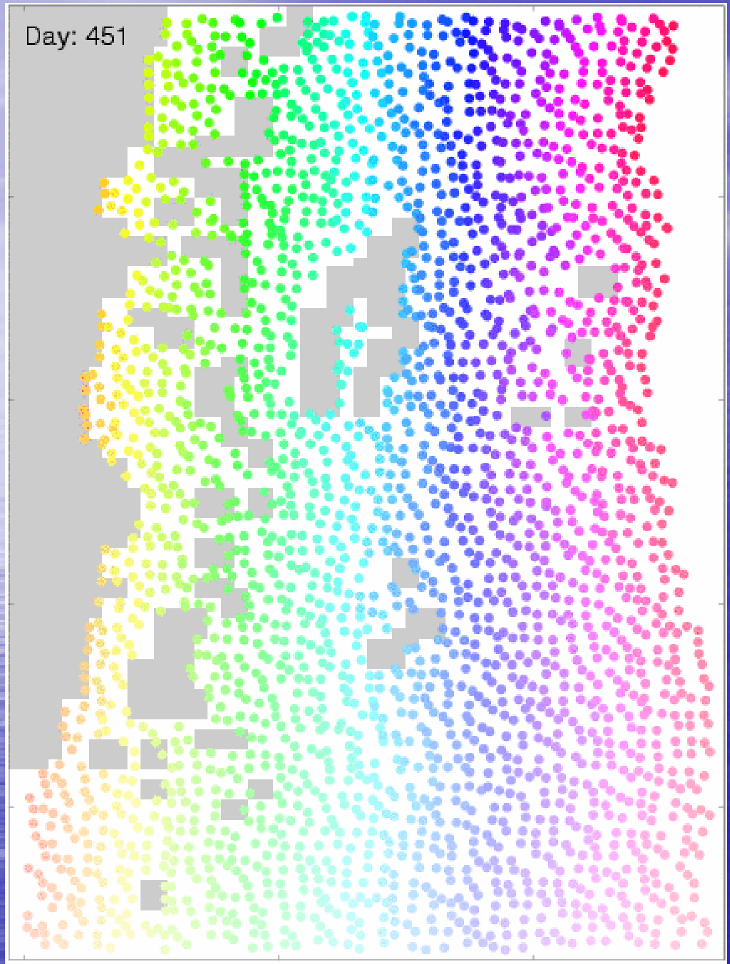
$$\mathbf{X(t+\Delta t) = P * X(t)}$$

$X(t) = [x_1(t), x_2(t), x_3(t), \ldots x_n(t)]$ is a vector describing the probability distribution of particle position at time t;

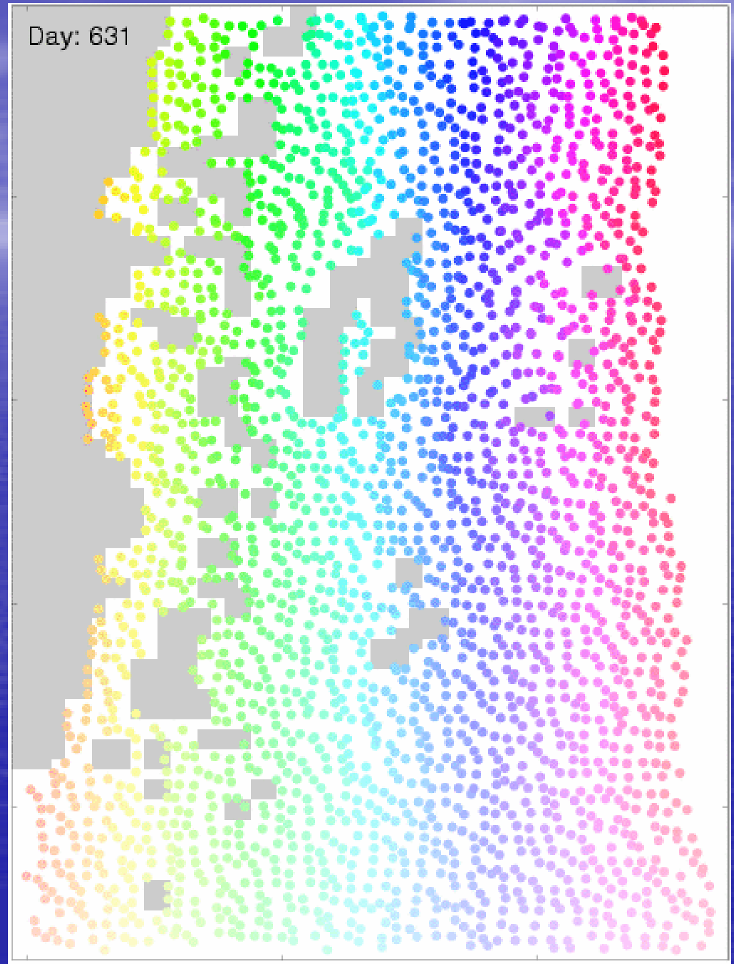
P is a $n \times n$ transition probability matrix describing the probability of any particle from region r_i at time t to region r_j at time t+1.



Day: 540
Day: 544
Day: 548
Day: 552
Day: 556
Day: 560



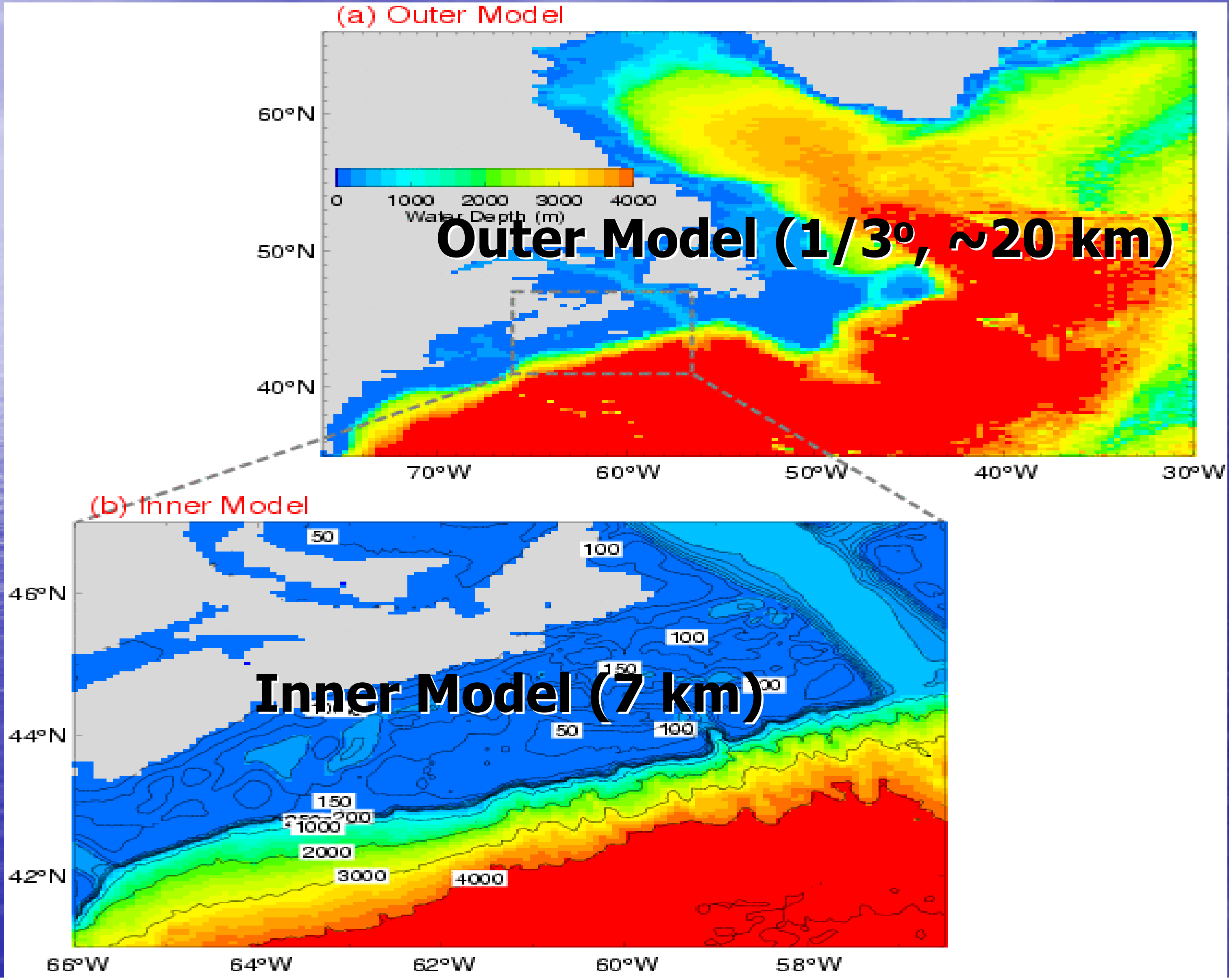
Spring



Fall

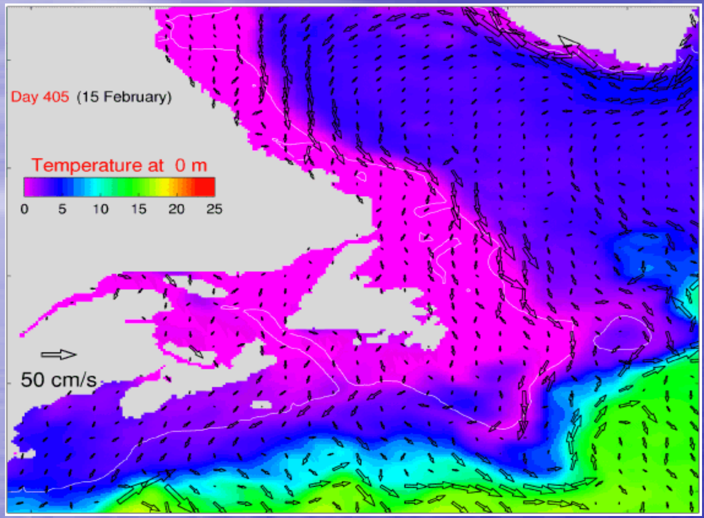
5. Application to the Scotian Shelf

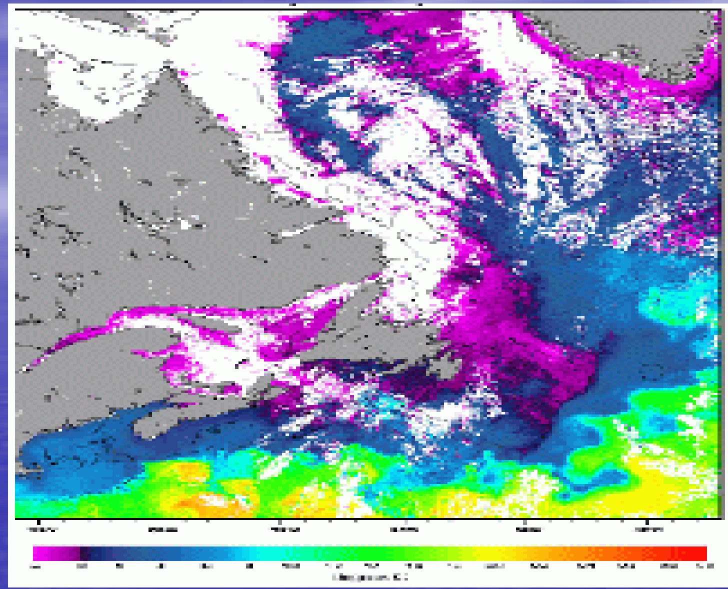
(Zhai's M.Sc. Thesis, 2004, Zhai, Sheng and Greatbatch, ECM8, 2004)



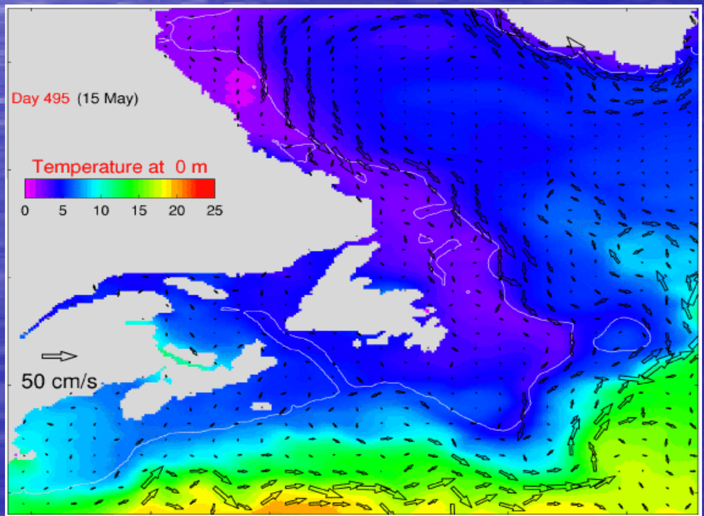
Predicted   Observed

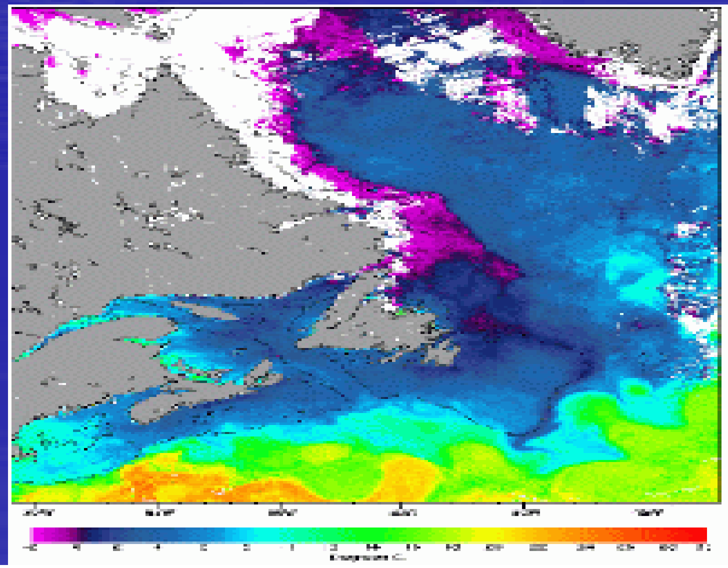
Sea Surface Fields in February



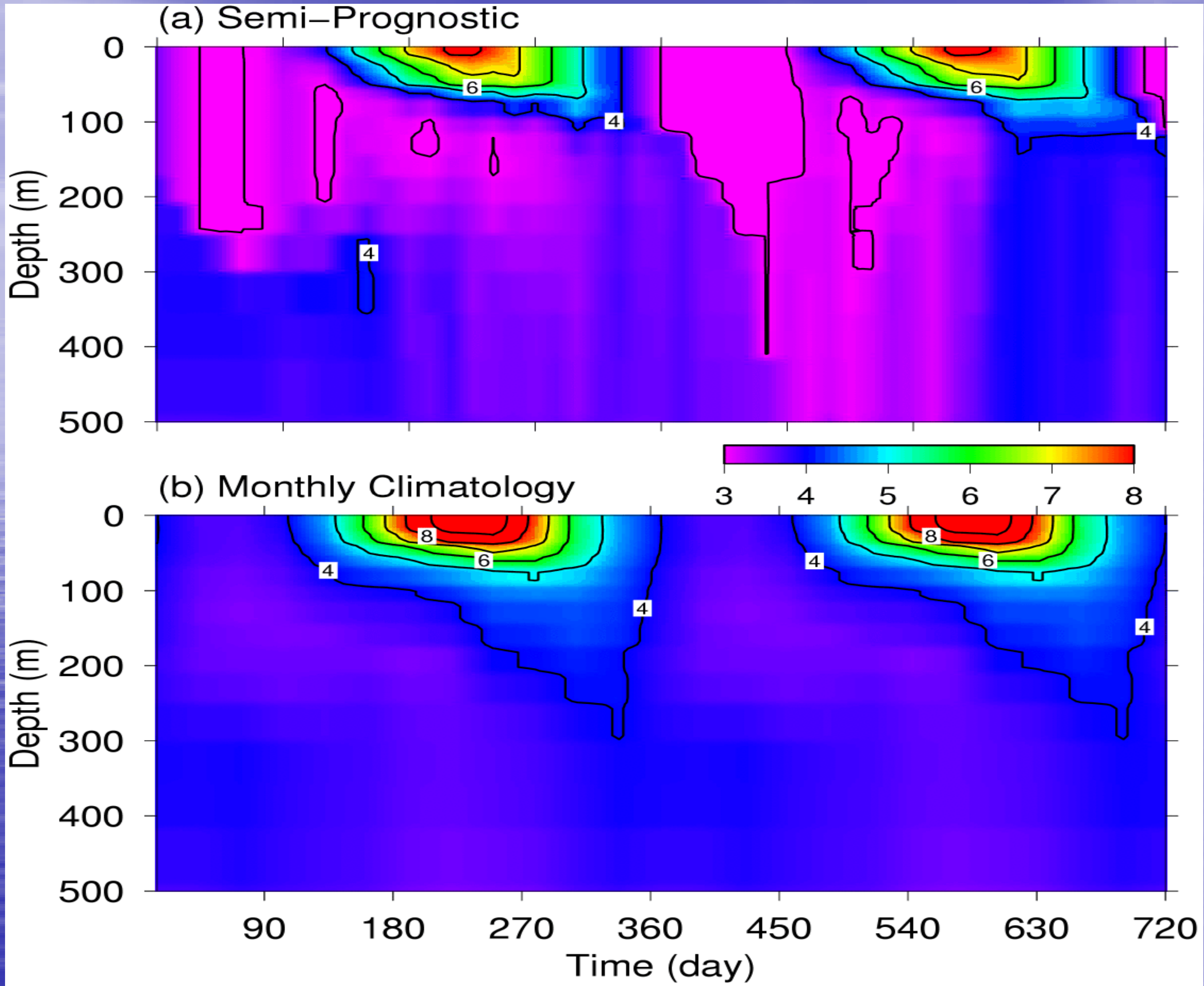


Sea Surface Fields in May



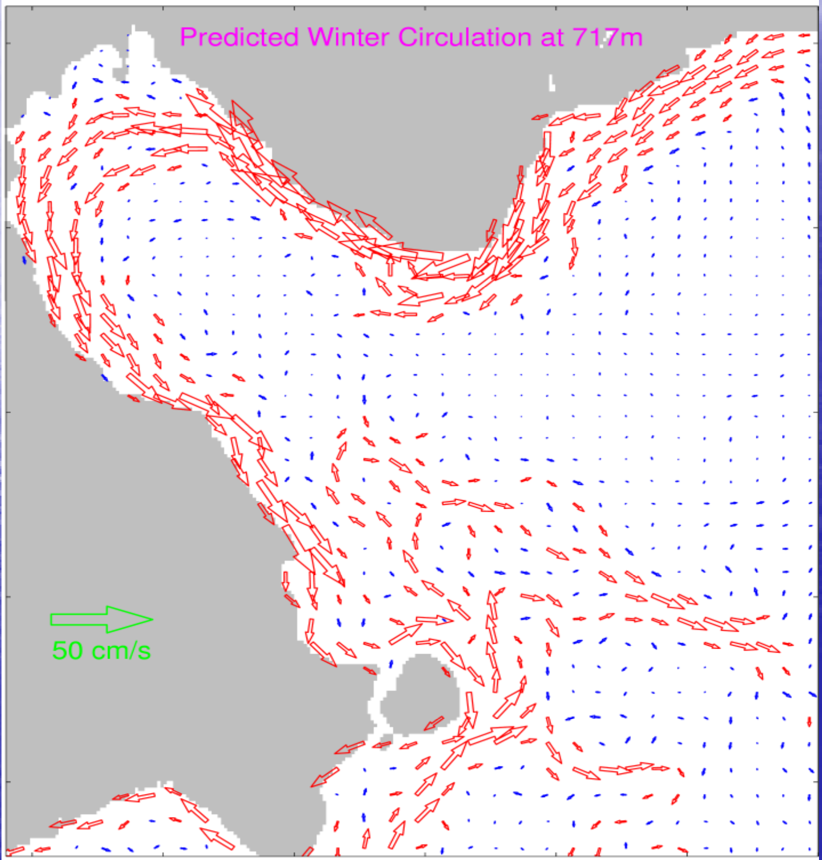


Time-Depth Distribution of Temperature

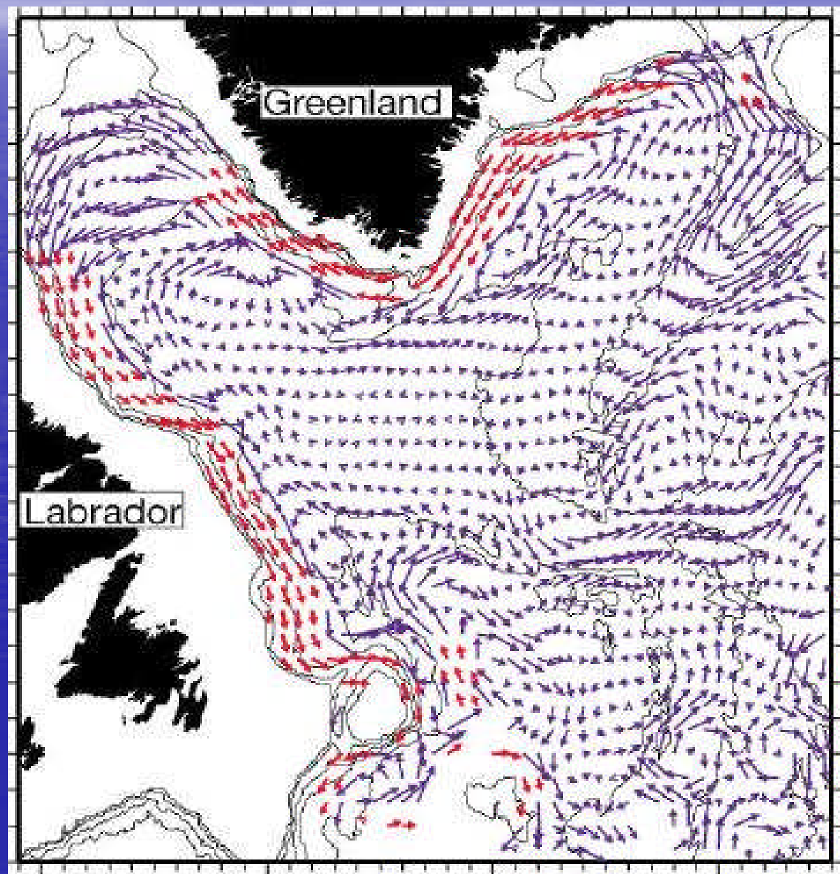


Comparison of Predicted and Observed Sub -Surface Circulation

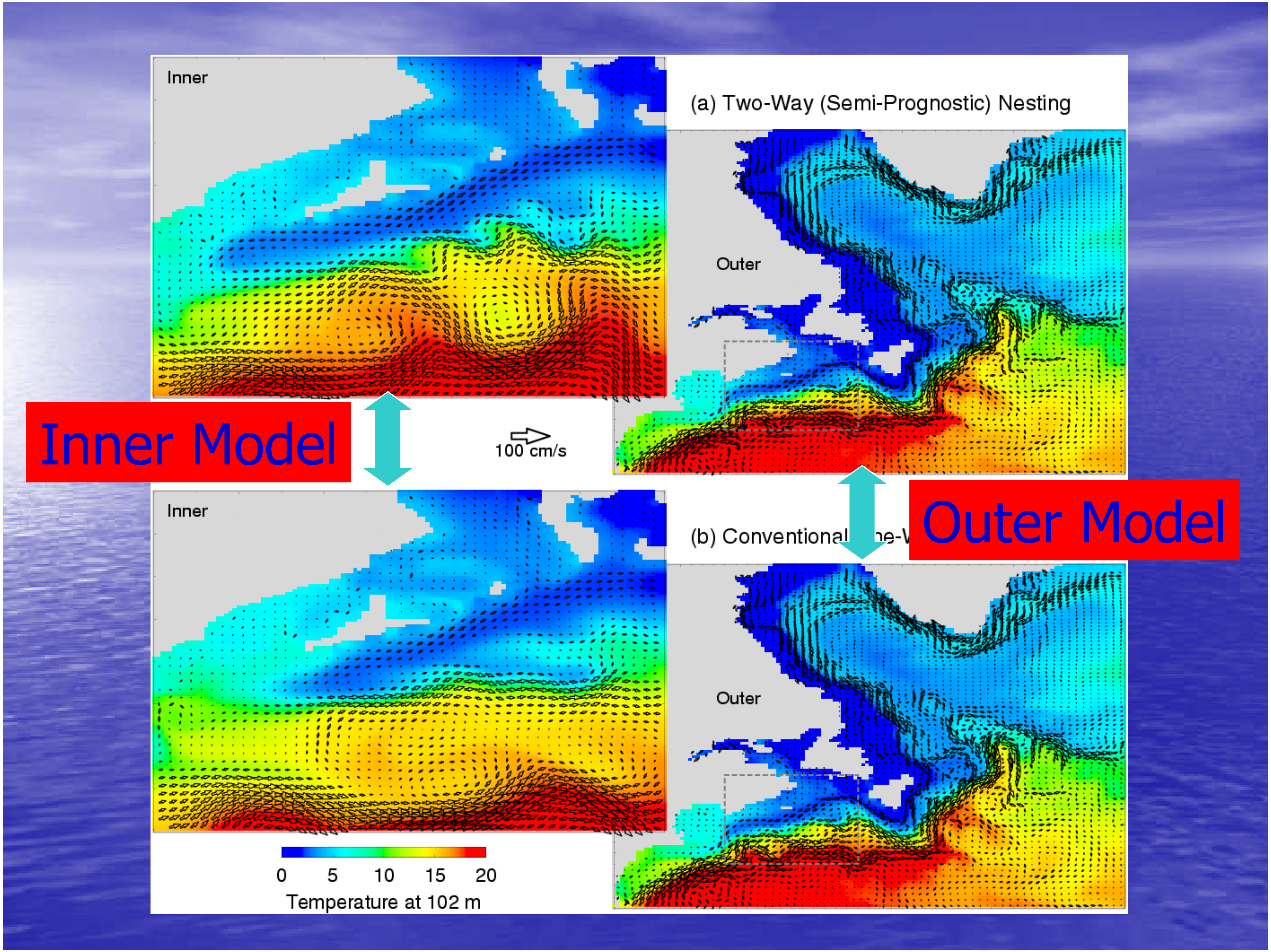
Predicted

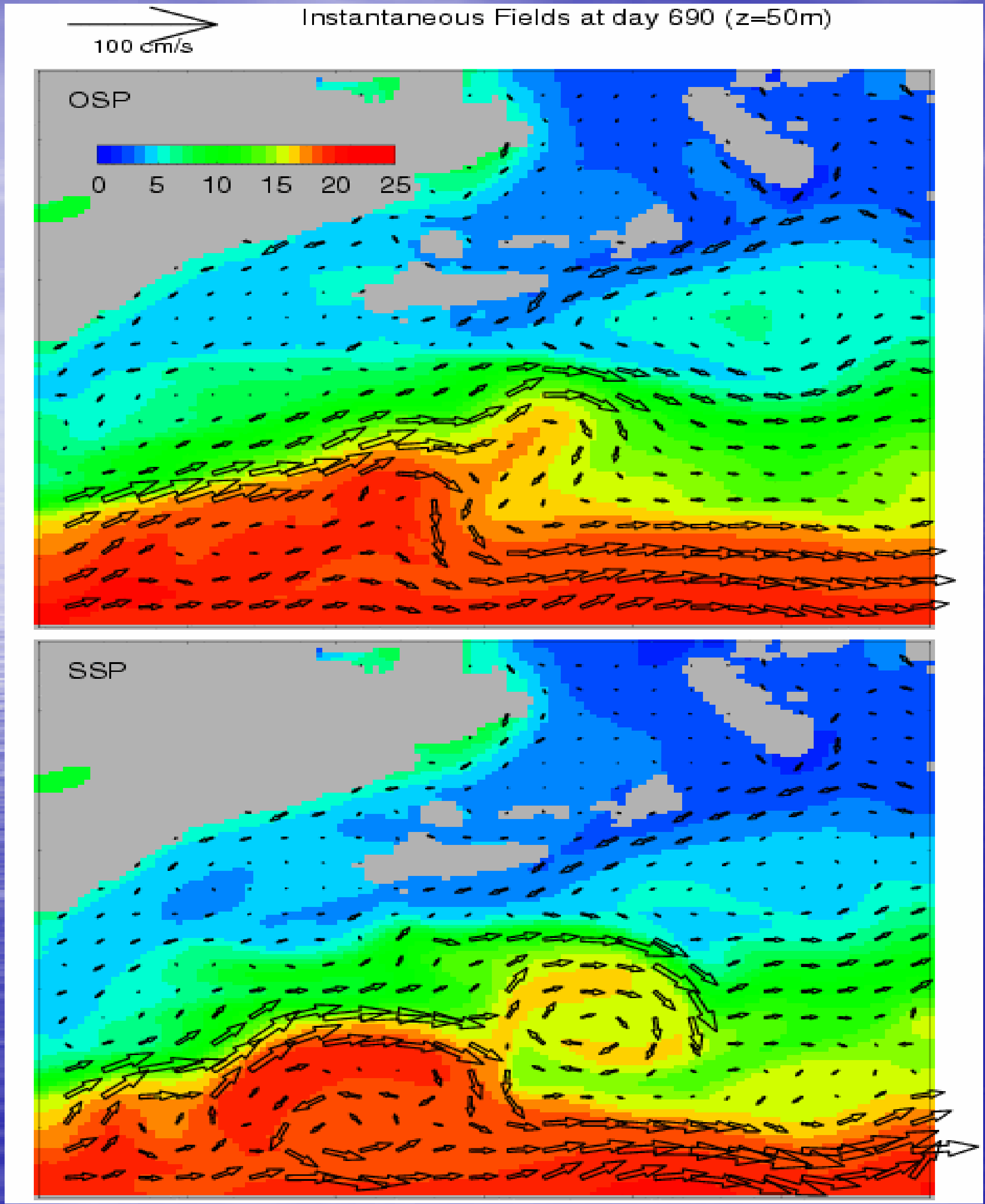


Observed



Blue arrows are speeds of less than 5 cm/s. Red arrows are speeds of greater than 5 cm/s.

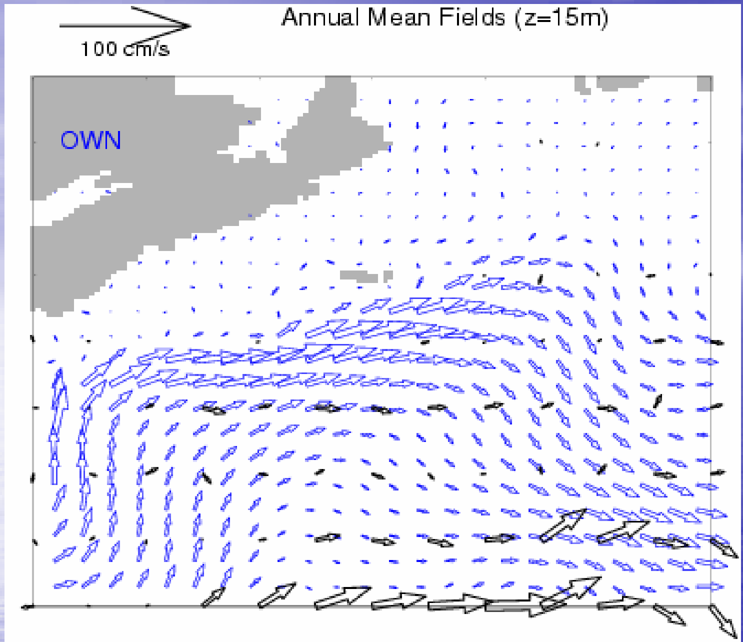

Inner
(a) Two-Way (Semi-Prognostic) Nesting
Outer
Inner Model
100 cm/s
Inner
(b) Conventional
Outer Model
Outer
0 5 10 15 20
Temperature at 102 m

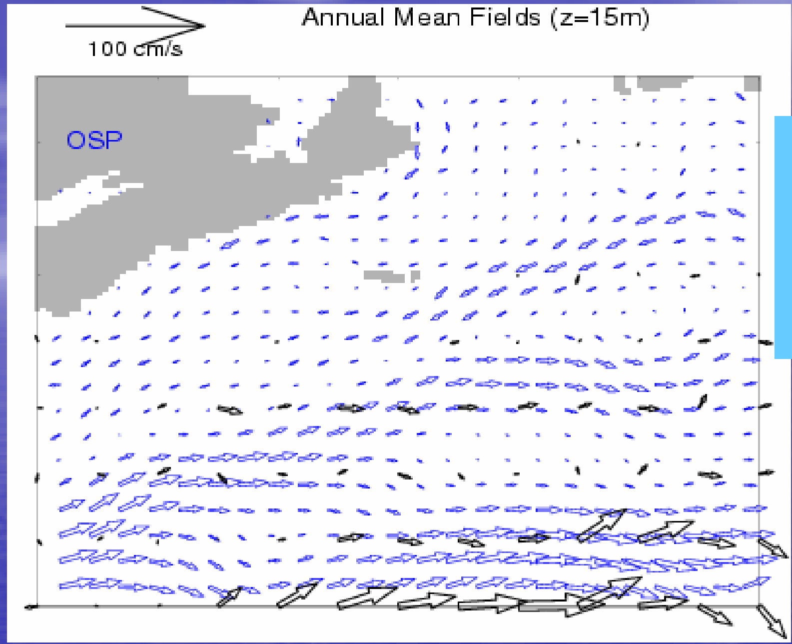


OSP: two-way nesting using the original semi-prognostic method

SSP: two-way nesting using the smoothed semi-prognostic method

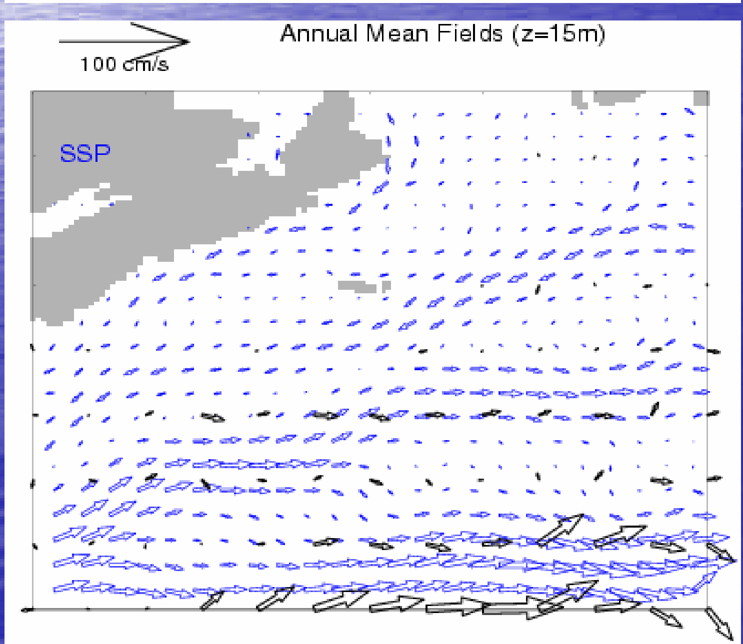
Comparison with Data [Fratantoni (2001)]





Black:
observed currents

Blue:
predicted currents

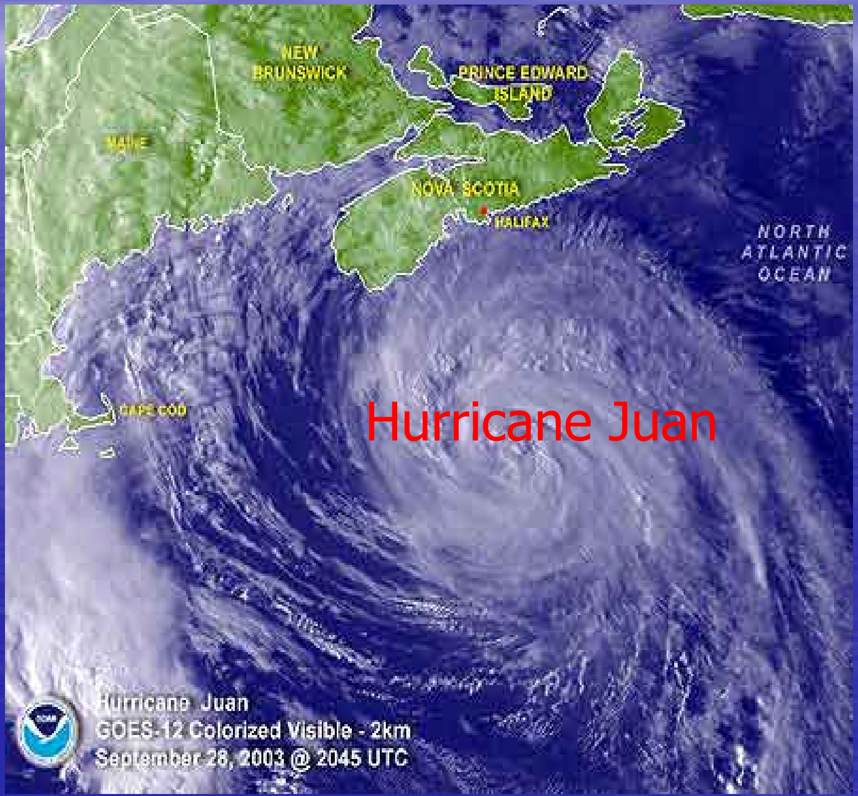


$$\gamma^2 = \frac{\sum \left[(u^o - u^s)^2 + (v^o - v^s)^2 \right]}{\sum \left[(u^o)^2 + (v^o)^2 \right]}$$

Model run	γ^2
OWN	1.01
OSP	0.65
SSP	0.62

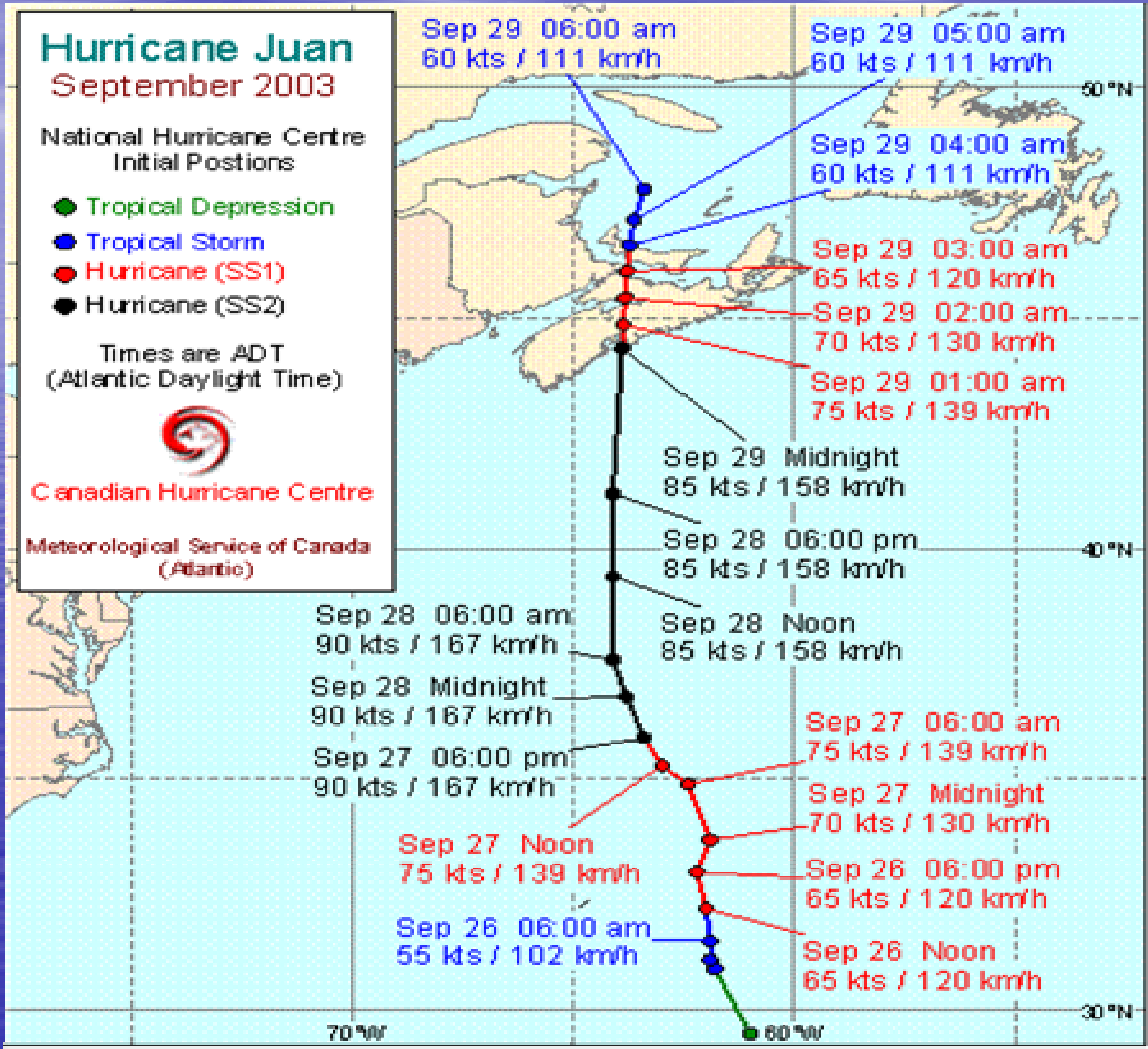
Numerical Study of Storm-induced circulation During Hurricane Juan

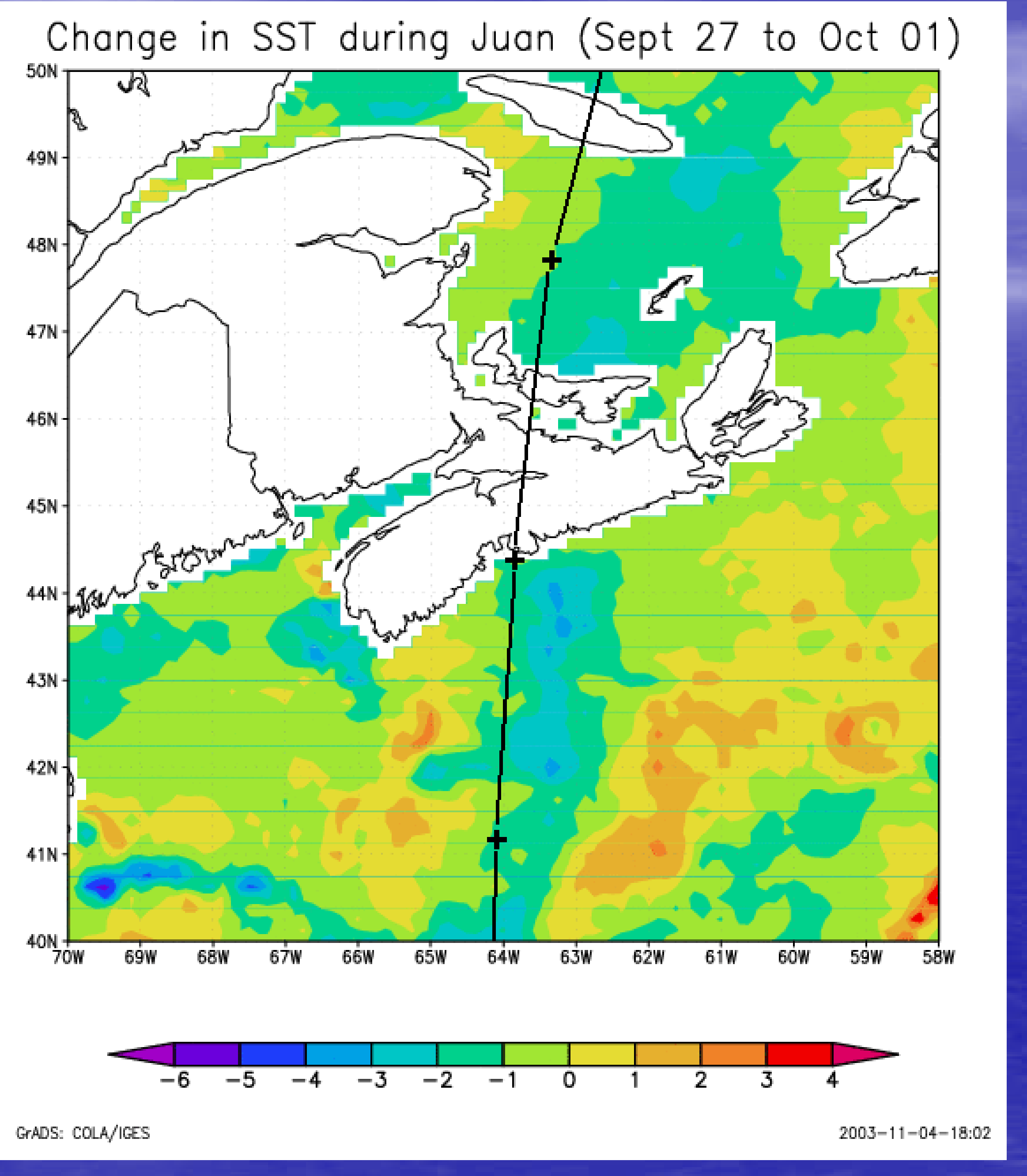
- Hurriane Juan was a category-2 hurricane that made landfall in Nova Scotia, as one of the most powerful and damaging hurricanes to ever affect Canada.
- The nested-grid model is used to simulate the storm-induced circulation on the Scotian Shelf associated with Hurricane Juan on September, 28 and 29, 2003
- M. Sc. thesis research by Xiaoming Zhai.



Damages Made by Juan (Sept. 29. 2003)

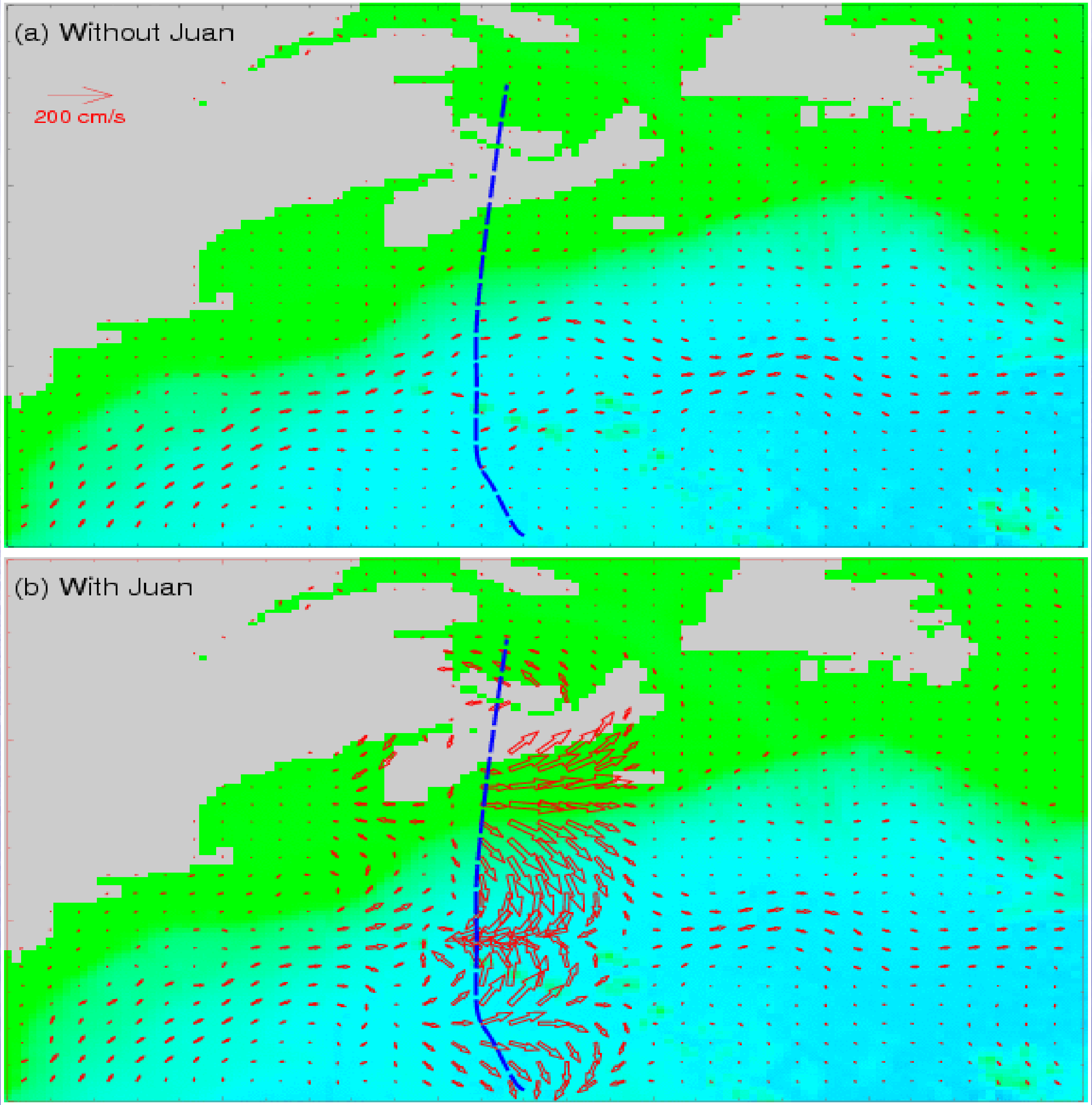
Storm track of Hurricane Juan





Change in SST during Juan (Sept 27 to Oct 01)
50N
49N
48N
47N
46N
45N
44N
43N
42N
41N
40N
70W 69W 68W 67W 66W 65W 64W 63W 62W 61W 60W 59W 58W
−6 −5 −4 −3 −2 −1 0 1 2 3 4
GrADS: COLA/IGES
2003-11-04-18:02

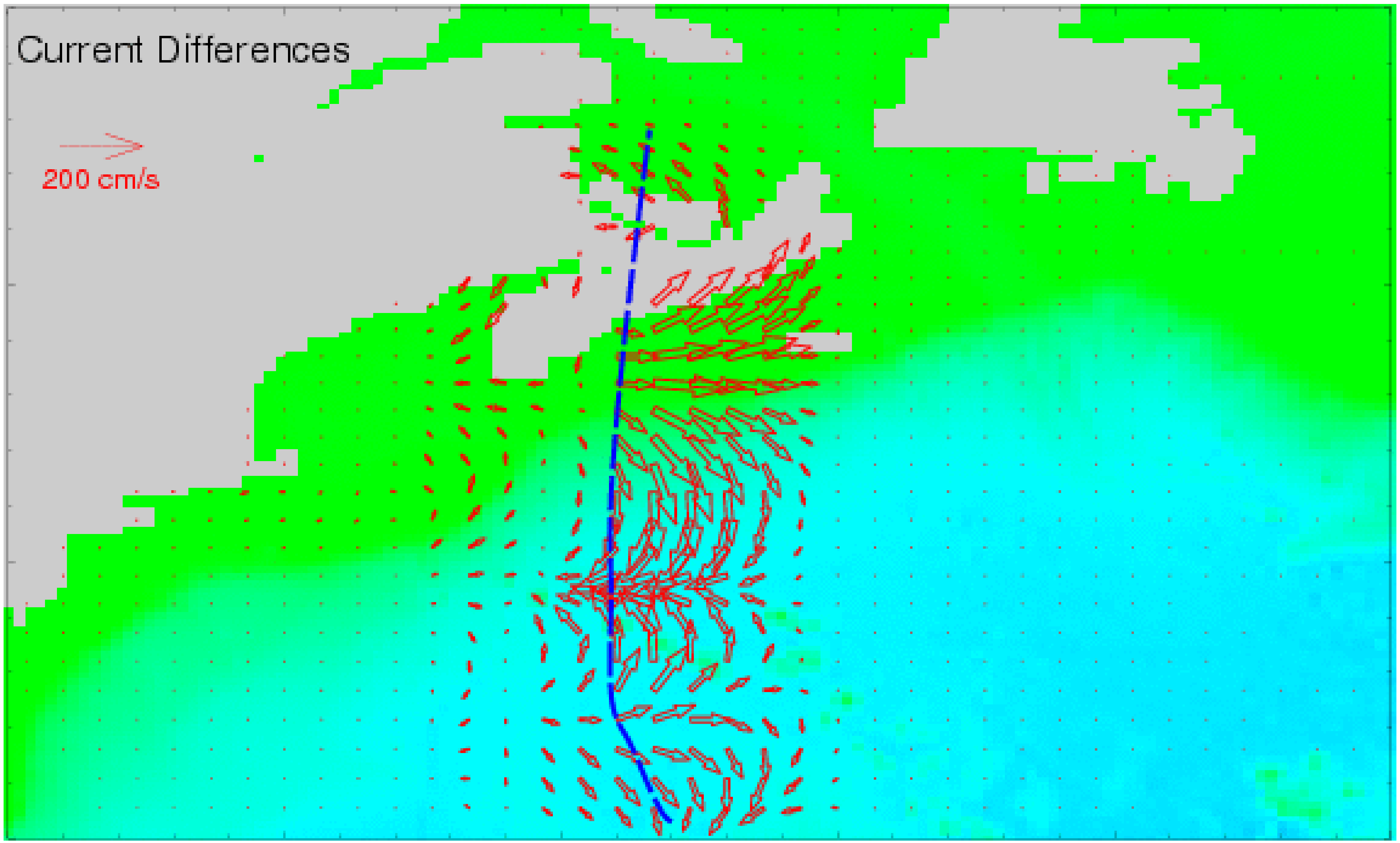
The Oceanic Response to a Moving Storm Using the Two-Way Nested-Grid Model



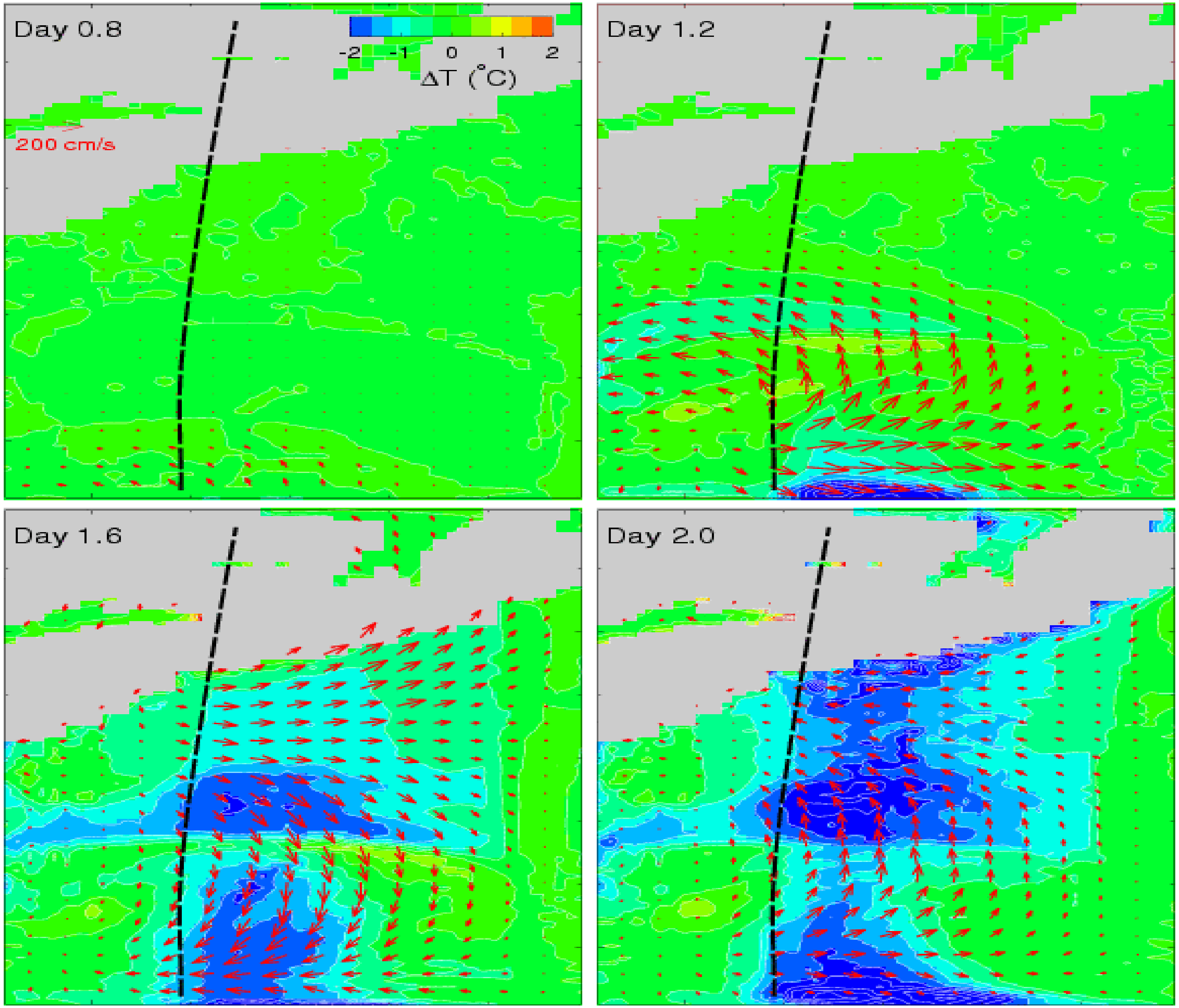
(a) Without Storm

(b) With Storm

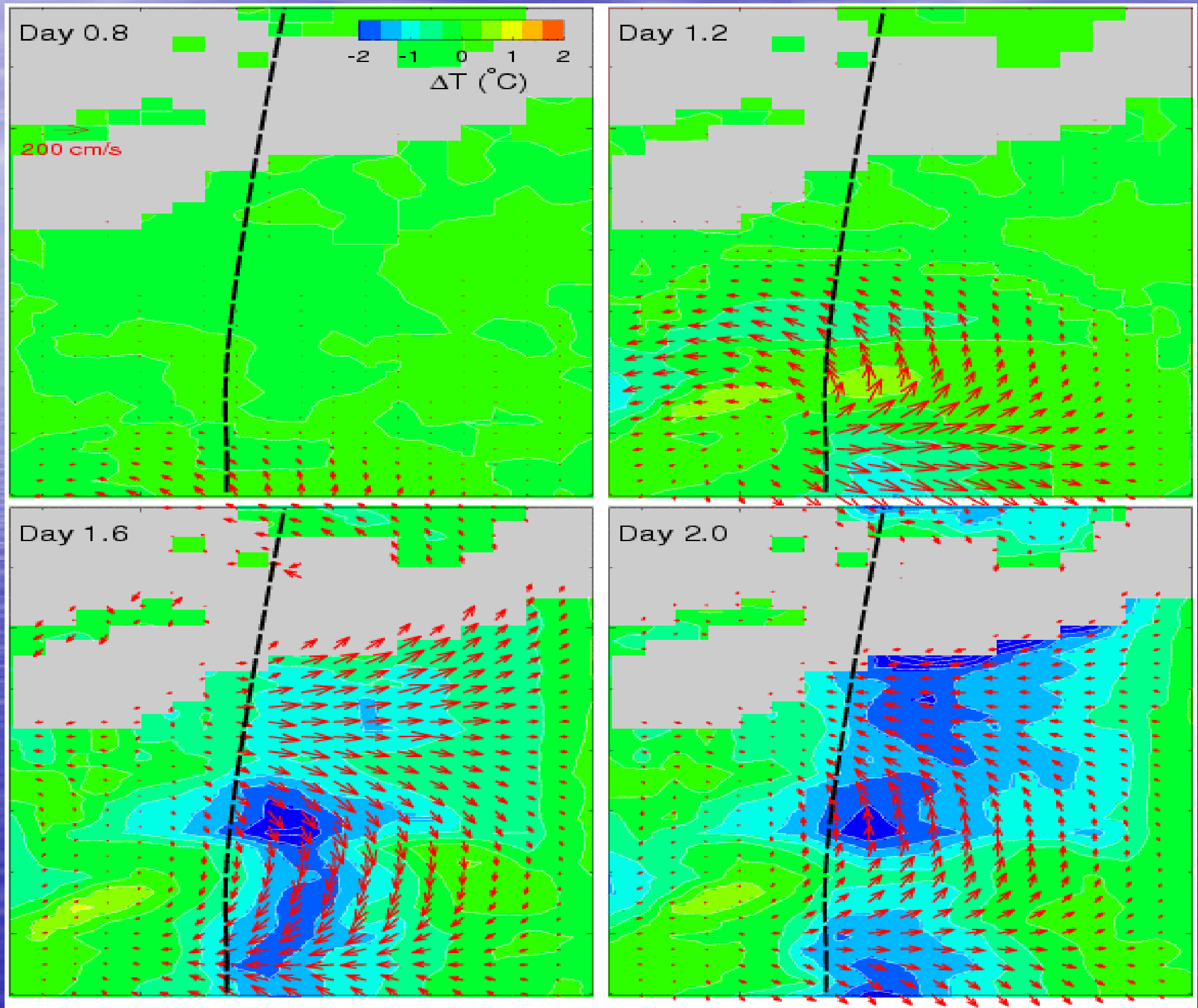
Near-Surface Currents due to Hurricane Juan



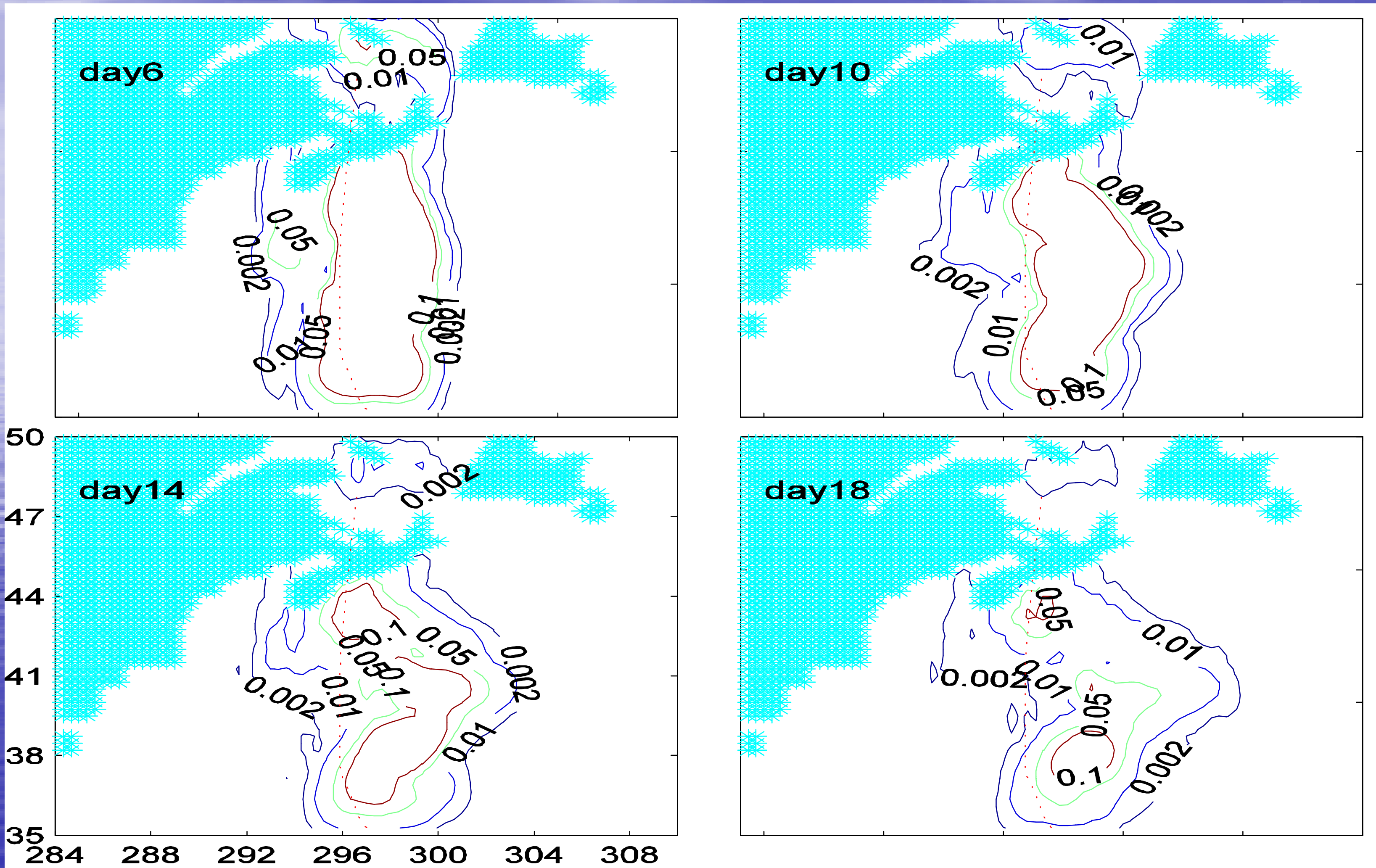
Differences in Near-Surface Currents and SST (inner model)

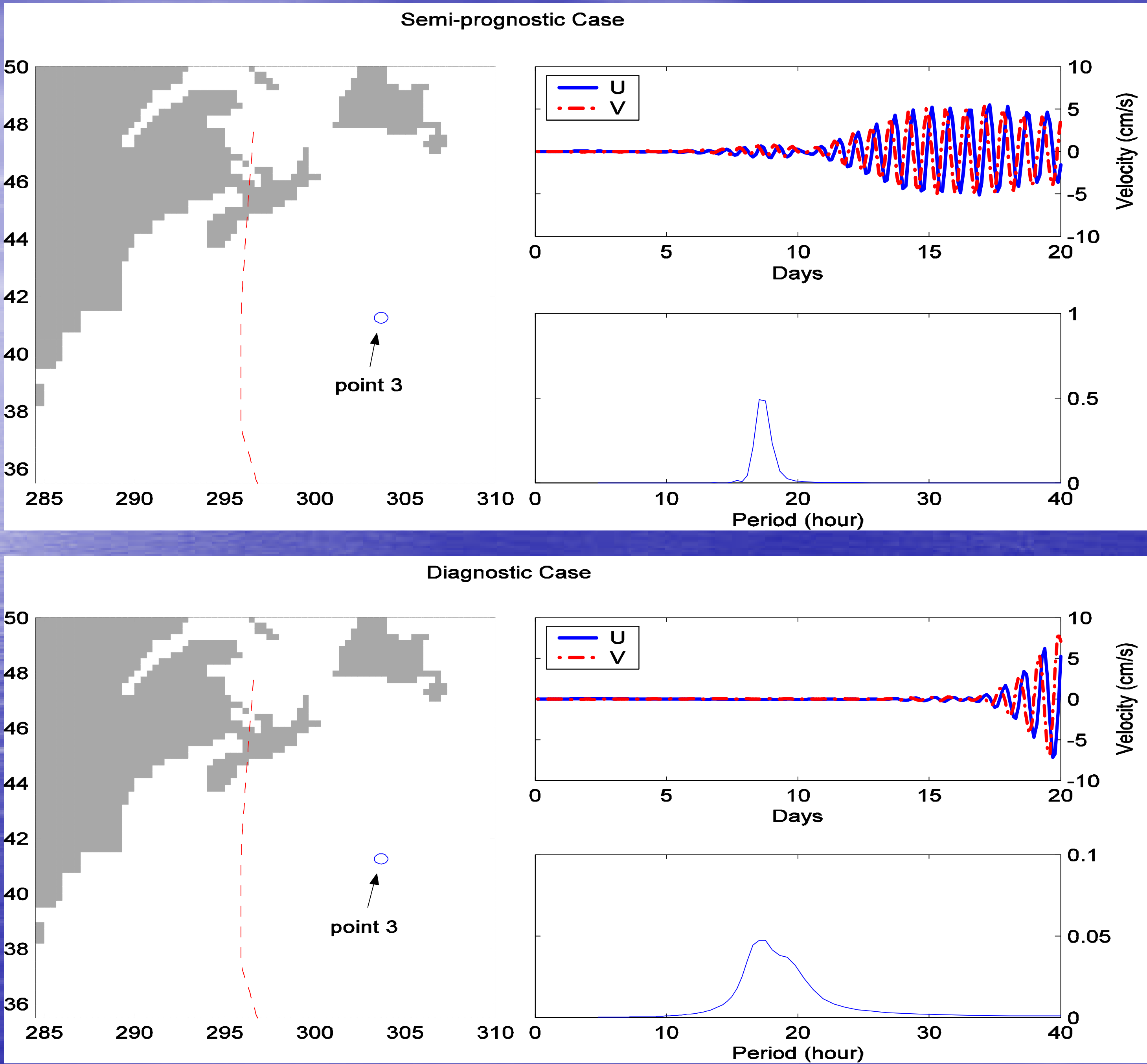


Differences in Near-Surface Currents and SST (outer model)

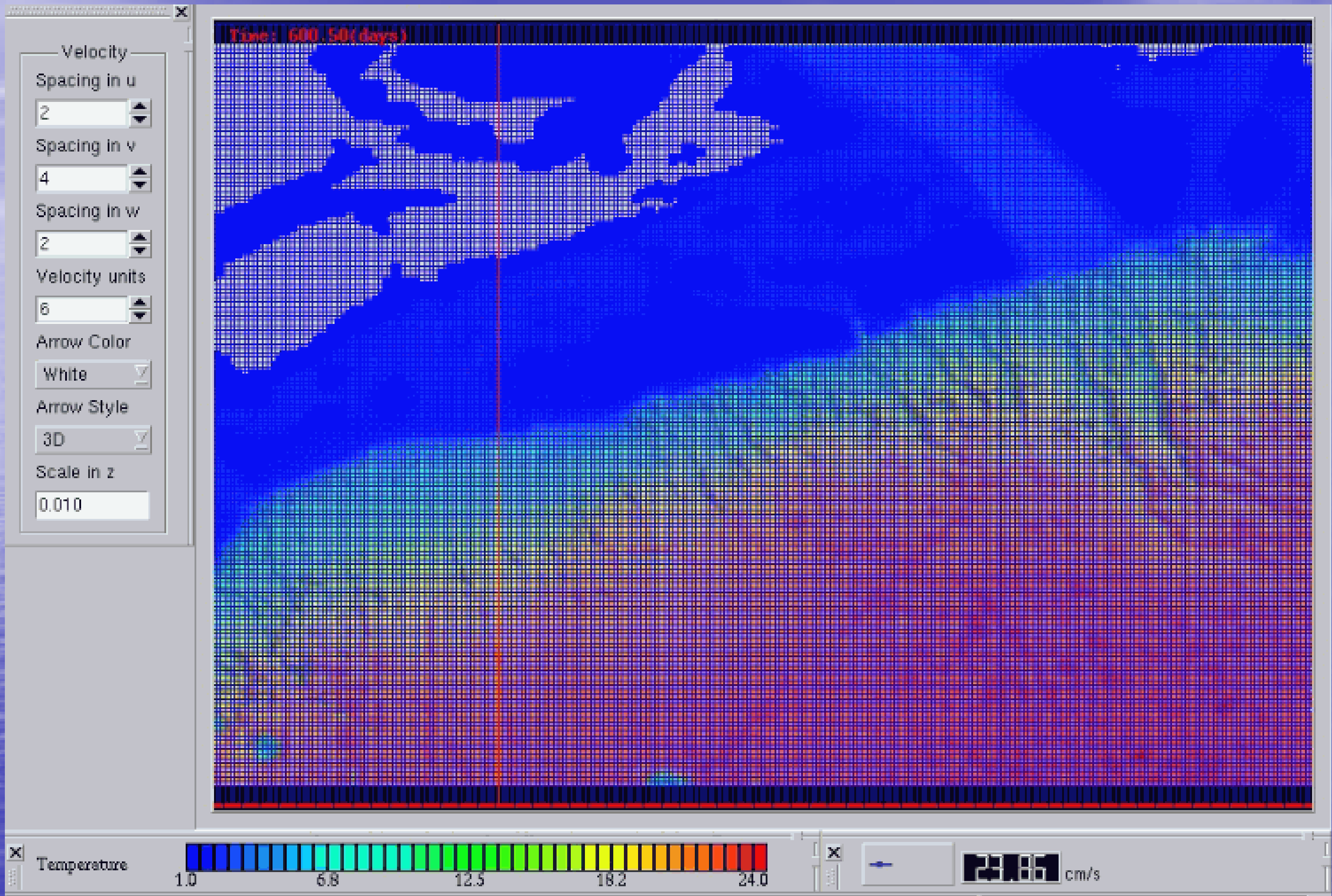


Spreading of Near-Inertial Energy

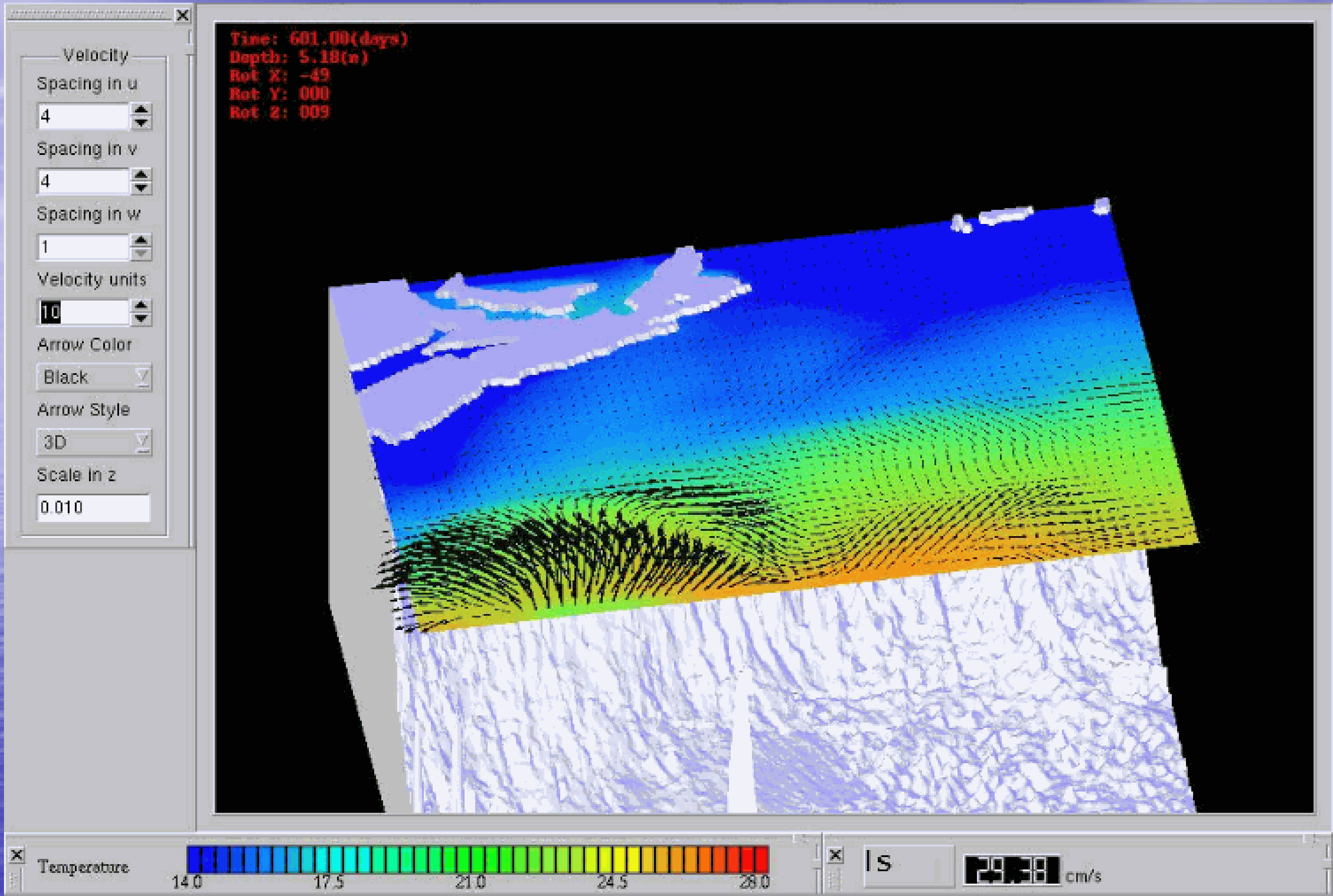




Semi-prognostic Case
U
V
Velocity (cm/s)
Days
Period (hour)
point 3
Diagnostic Case
U
V
Velocity (cm/s)
Days
Period (hour)
point 3



(Dr. Jim Chuang and his students)



(Dr. Jim Chuang and his students)

Summary and Conclusion:

- The semi-prognostic method (Sheng et al., 2001; Eden et al., 2004; Greatbatch et al., 2004) was used to reduce model errors and also used to develop a two-way nested-grid model.
- A 3D primitive-equation ocean model known as CANDIE (Sheng et al., 1998) was used in the development of a two-way nested-grid ocean circulation model for the western Caribbean sea (Sheng and Tang, 2003, 2004).
- Model reproduces many well-known circulation features in the Caribbean Sea, including the main pathway of the Caribbean Current and the Panama-Colombia Gyre.
- The model was also used to simulate the storm-induced circulation associated with Hurricane Juan on the Scotian Shelf (Zhai, 2004; Zhai et al., 2004).