Numerical Study of the Upper Ocean Response of the Scotian Shelf to Hurricane Juan

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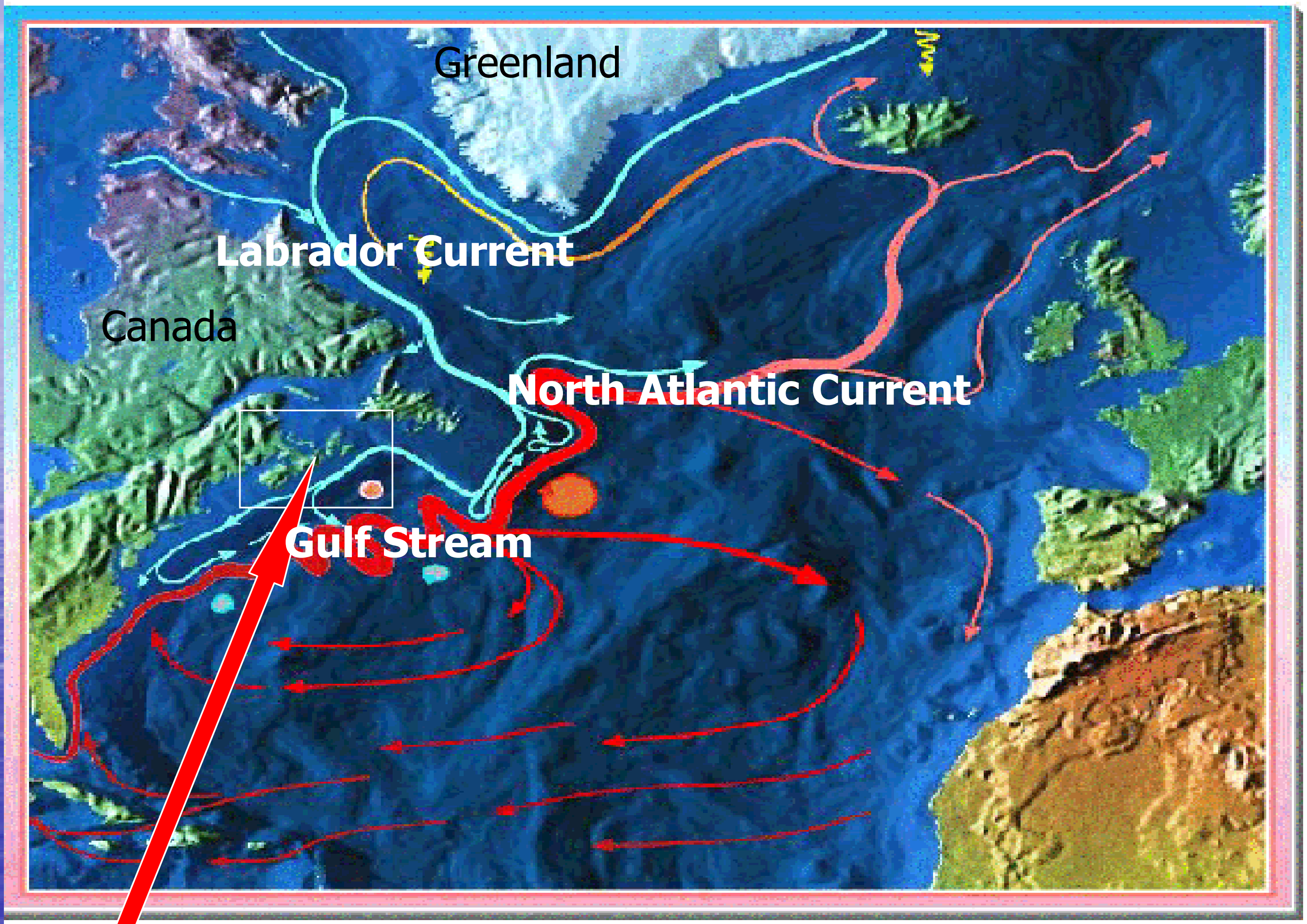
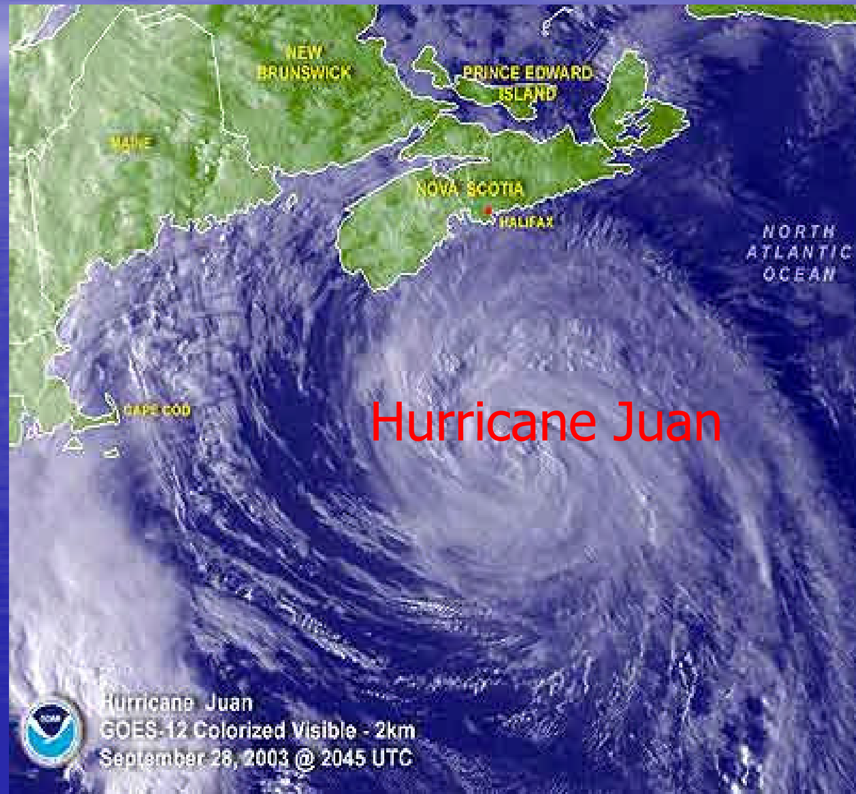


(By courtesy of Dr. Igor Yashayaev)

Scotian Shelf

Numerical Study of Storm-induced circulation During Hurricane Juan

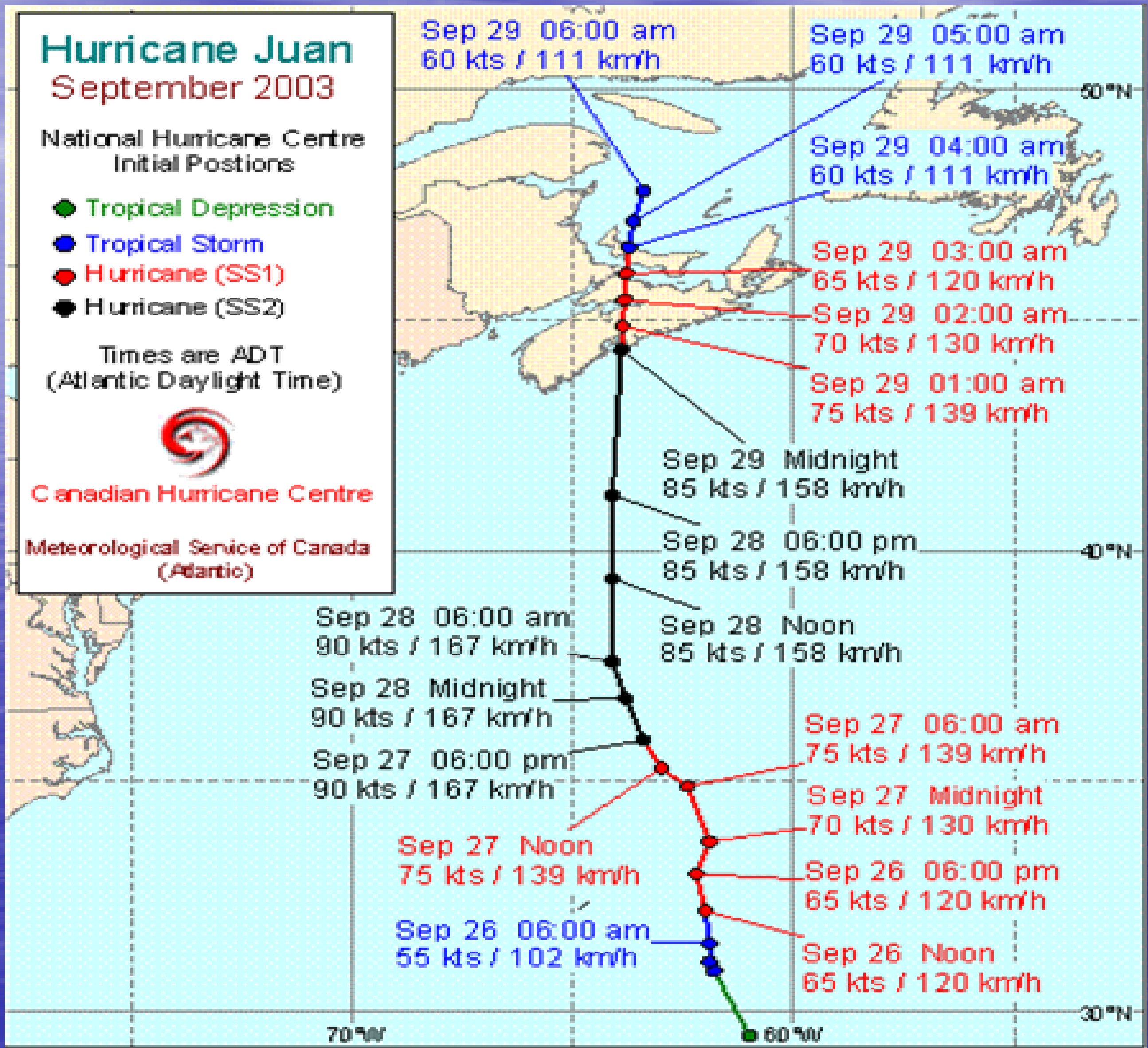
- Hurricane Juan was a category-2 hurricane when it made landfall in Nova Scotia, and is one of the most powerful and damaging hurricanes to ever affect Canada.
- The nested-grid model is used to simulate the storm-induced circulation on the Scotian Shelf associated with Hurricane Juan on September 28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

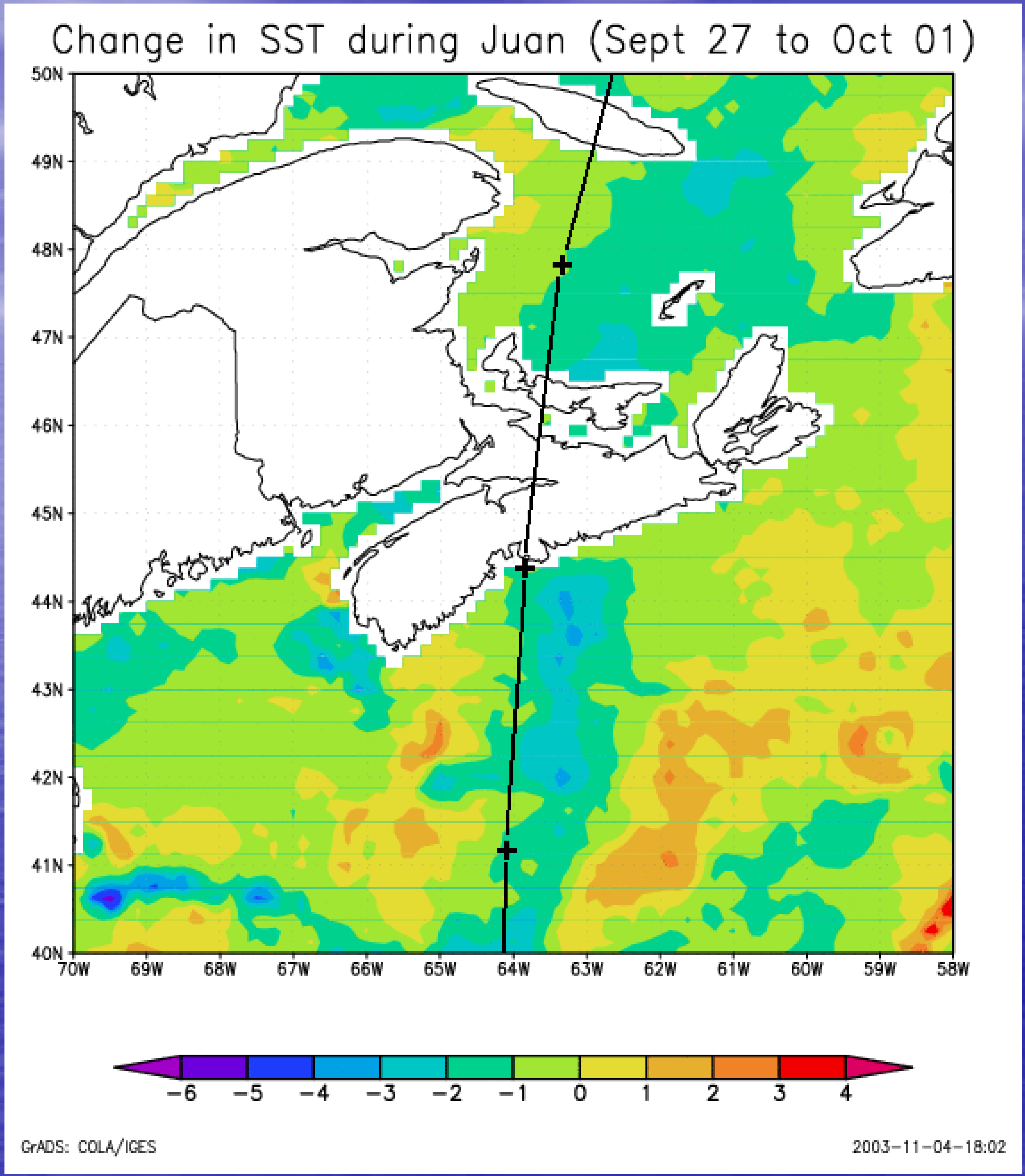


Damages Made by Juan (Sept. 29, 2003)

(Adopted from MSC webpage)

Storm track of Hurricane Juan





(by courtesy of Chris Fogarty)

Objectives:

- Determine the upper ocean response to Hurricane Juan using a two-way nested ocean circulation model
- Examine the advective spreading of the inertial energy produced by the storm in the deep ocean

References:

Zhai, X., 2004: Studying storm-induced circulation on the Scotian Shelf and slope using a two-way nested-grid model, M. Sc. Thesis, Department of Oceanography, Dalhousie University.

Zhai, X., R.J. Greatbatch, and J. Sheng, 2004: Advective spreading of storm-induced Inertial oscillations in a model of the northwest Atlantic Ocean, Geophys. Res. Lett., 2004.

Sheng, J., X. Zhai, and R.J. Greatbatch, 2004: Numerical study of the storm-induced circulation on the Scotian Shelf during Hurricane Juan using a nested-grid model, Progress in Oceanography (submitted).

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 applied to many shelf modeling problems, including recent applications of the coupled ice-ocean modeling over the eastern Canadian shelf (Zhang et al., JGR, 2004), nonlinear tidal circulation in LB (Sheng and Wang, JGR, 2004), and seasonal circulation in the Caribbean Sea (Sheng and Tang, JPO, 2003).

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

A New Two-Way Nesting Technique using the smoothed semi-prognostic (SSP) 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 smoothed semi-prognostic (SSP) method (Eden et al., 2004; Greatbatch et al., 2004; Zhai et al., 2004). The SSP method is modifed from the original semi-prognostic (OSP) method suggested by Sheng et al. (2001).**

- For the inner model:

$$\frac{\partial p}{\partial z}\Big|_{inner} = -g\rho_{inner} - g(1-\alpha_i)\,\langle \hat{\rho}_{outer} - \rho_{inner} \rangle$$

- For the outer model:

$$\frac{\partial p}{\partial z}\Big|_{outer} = -g\rho_{outer} - g(1-\alpha_o)\,\langle \hat{\rho}_{inner} - \rho_{outer} \rangle$$

(α_i and α_o are set to 0.5 in this study)

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

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

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.

Physical Interpretation:

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

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

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

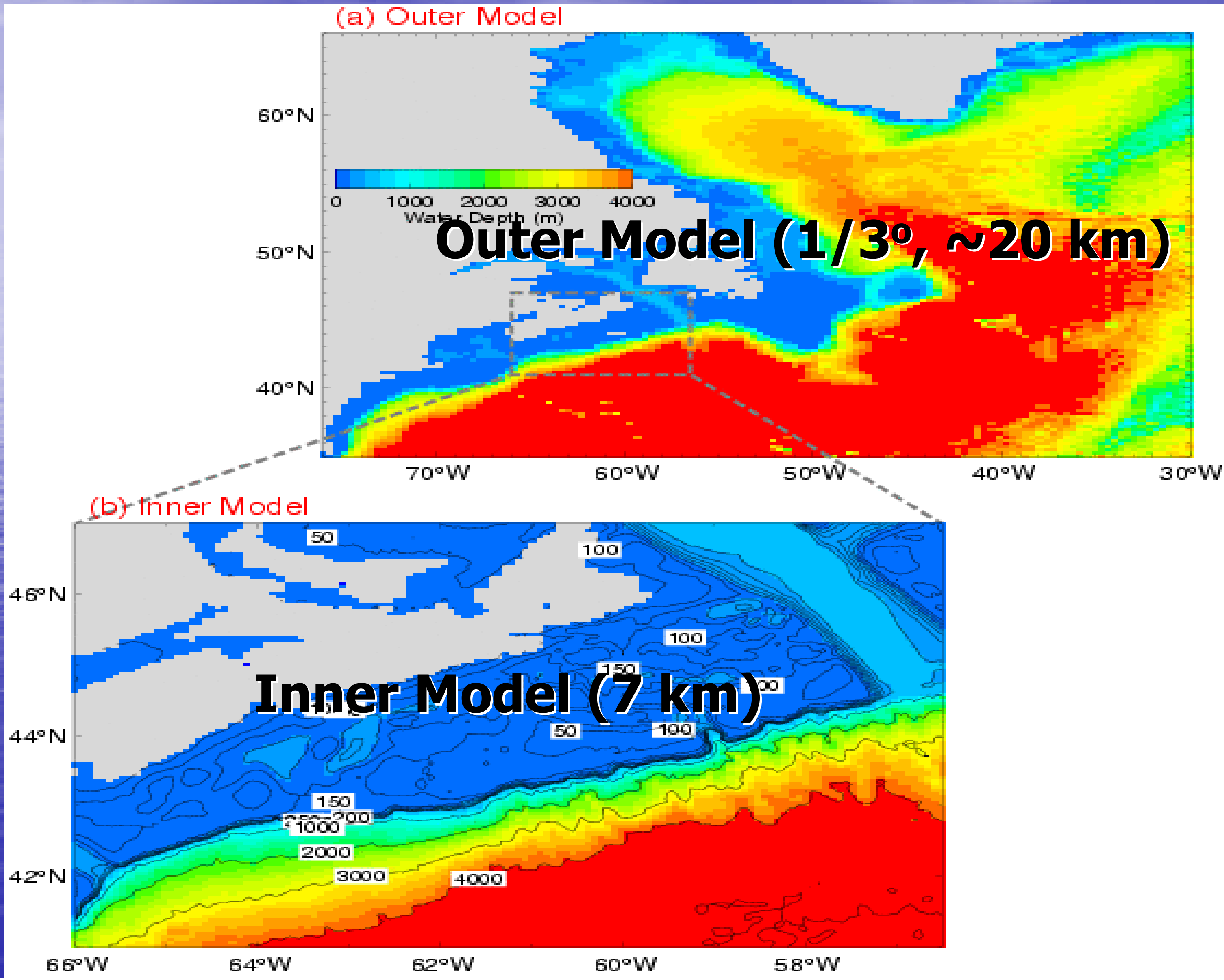
with $\beta = (1 - \alpha)$. Horizontal momentum equations are expressed as

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

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

A Nested-grid modelling System for the Scotian Shelf

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



Two numerical experiments were conducted:

1. The nested system is forced by climatological monthly mean forcing (Exp CLIM).

2. The nested system is forced by the combination of the climatological monthly mean forcing and idealized (symmetric) wind stress associated with Juan (Exp CLIM+STORM).

We use the differences in model results between Exp CLIM+STORM and Exp CLIM to represent the ocean response to Hurricane Juan.

Experiment CLIM

• CANDIE was driven by monthly COADS wind and annual depth-mean boundary flow calculated by Greatbatch et al. (1991).

• Sea surface salinity was restored to the monthly mean climatology generated by Geshelin, Sheng and Greatbatch (1999).

• The net heat flux through the Sea surface Q_{net} is approximated by :

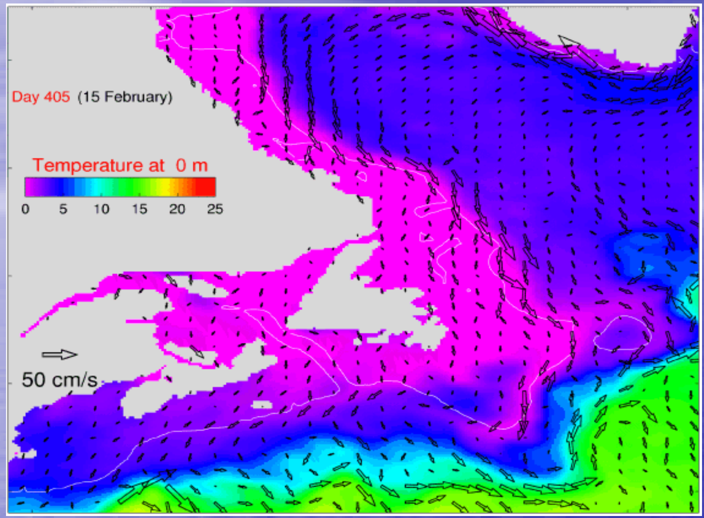
$$Q_{net} \approx Q_{net}^{clim} + \alpha \left(SST^{clim} - SST^{model} \right) \qquad (2)$$

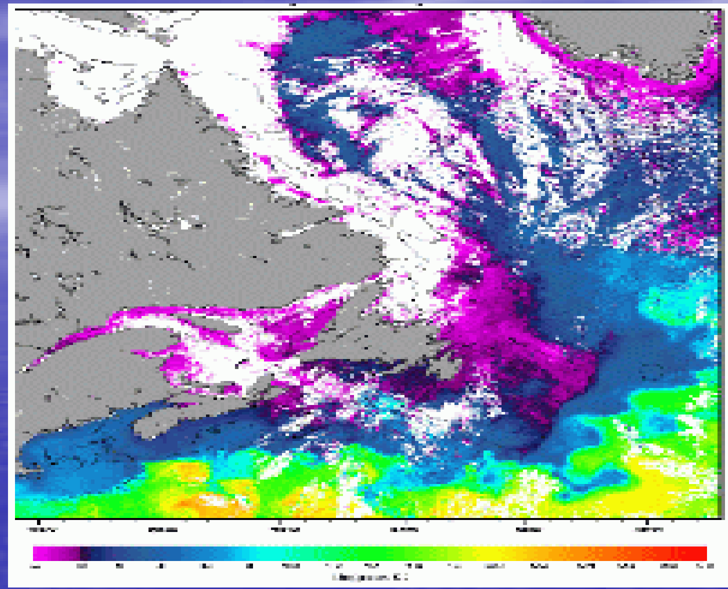
Where $\alpha = \frac{\partial Q}{\partial T}$, Q_{net}^{clim} and SST^{clim} are respectively monthly mean COADS net heat flux and Geshelin et al.'s SST.

• Sommerfeld radiation conditions were applied to T, S and normal velocity at open boundaries

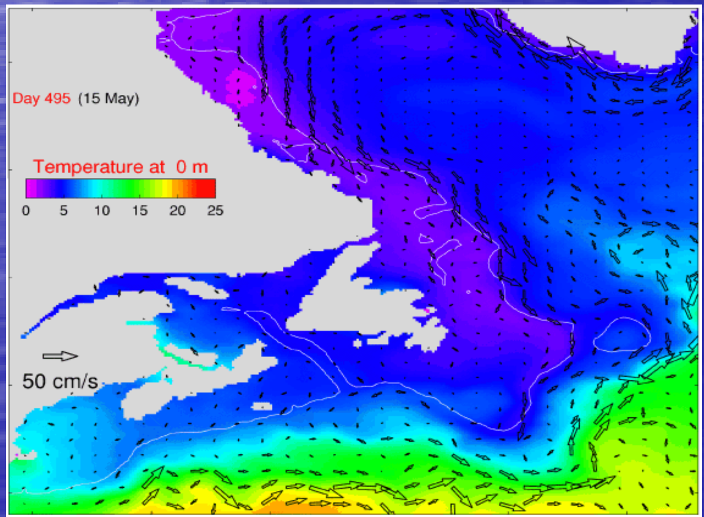
Simulated Observed

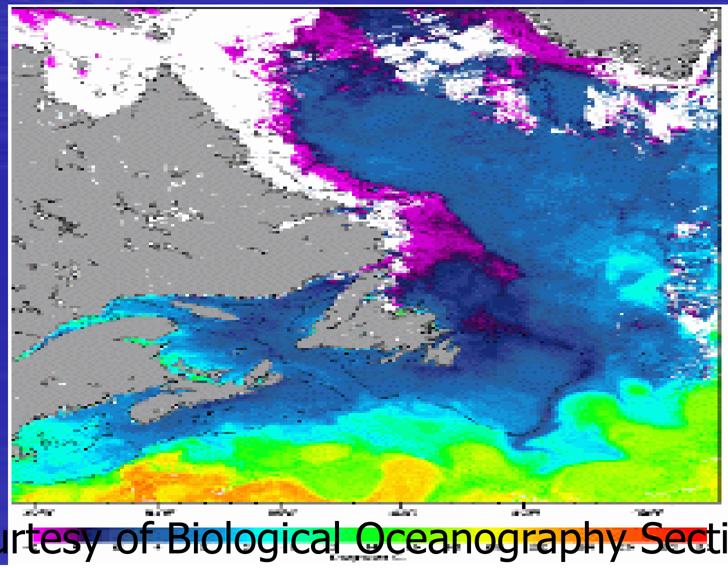
Sea Surface Fields in February





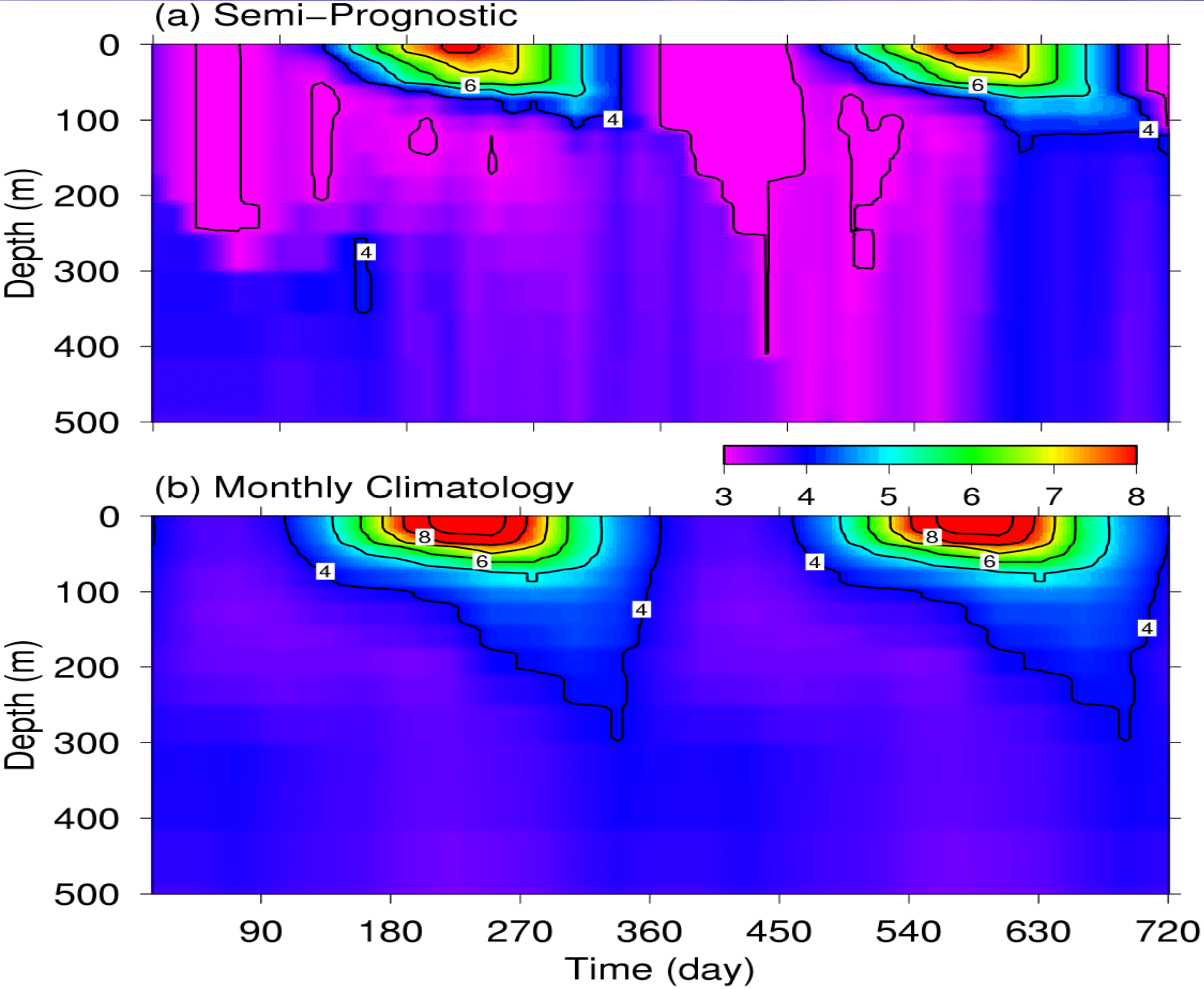
Sea Surface Fields in May

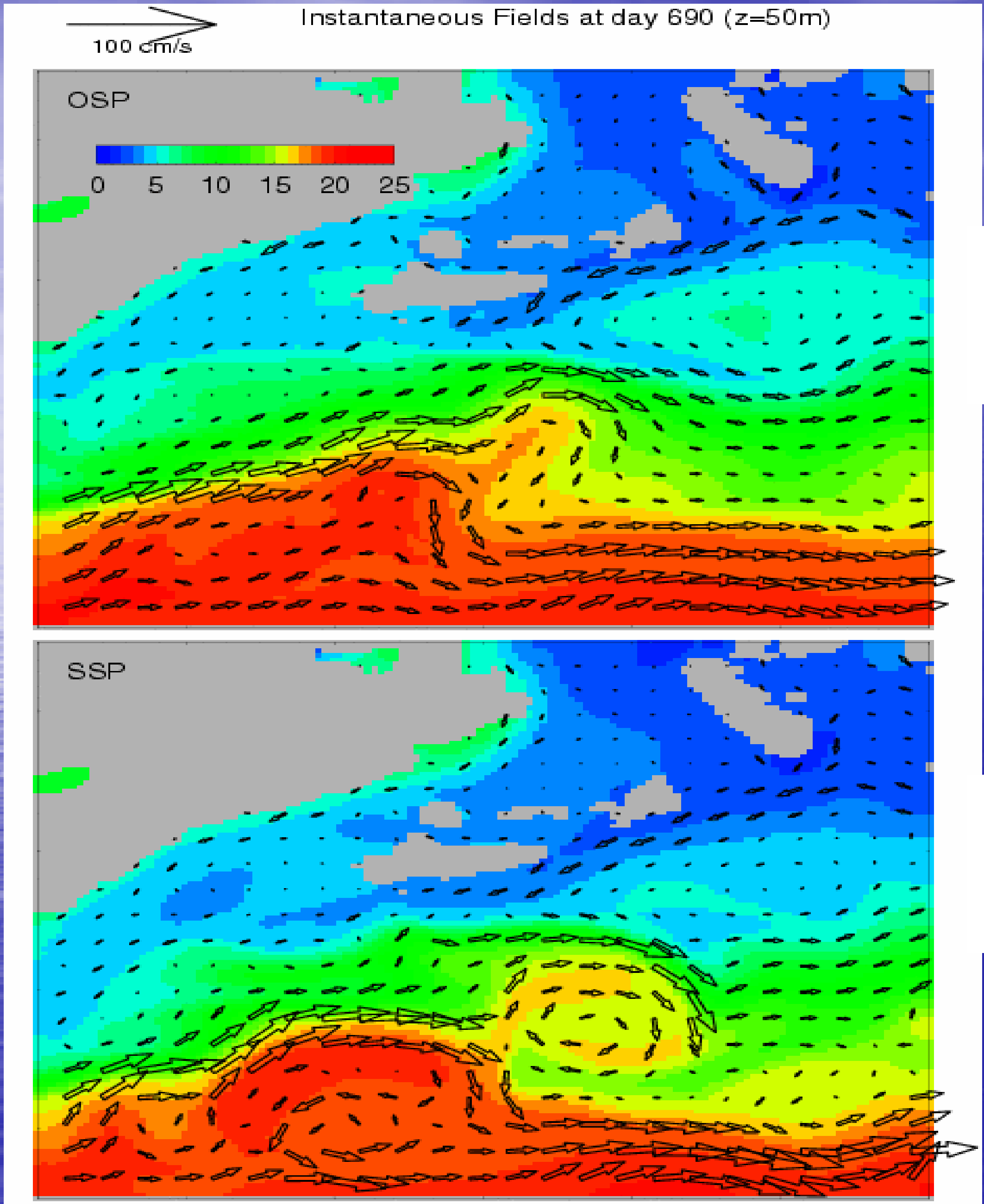




(By courtesy of Biological Oceanography Section, BIO)

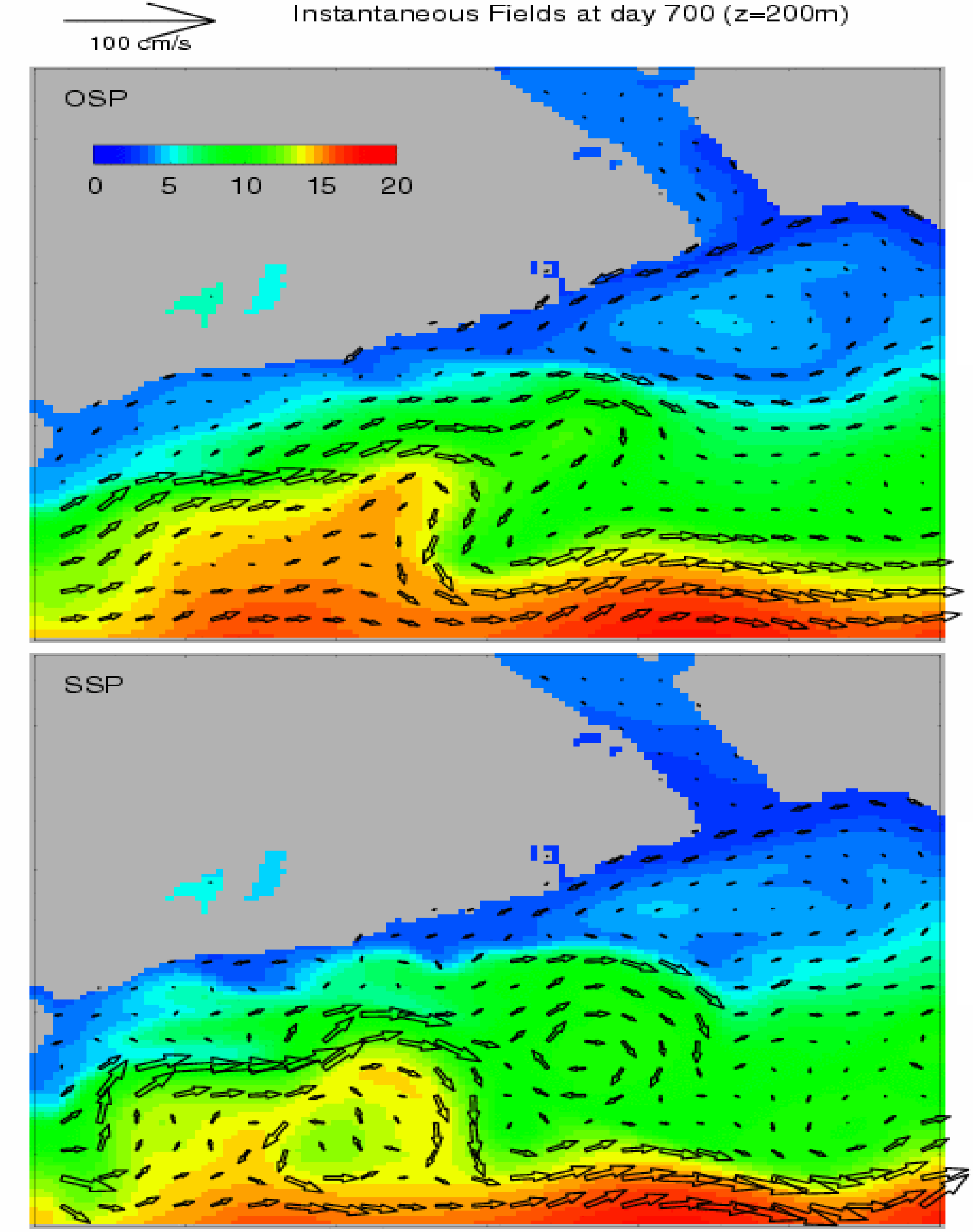
Time-Depth Distribution of Temperature





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

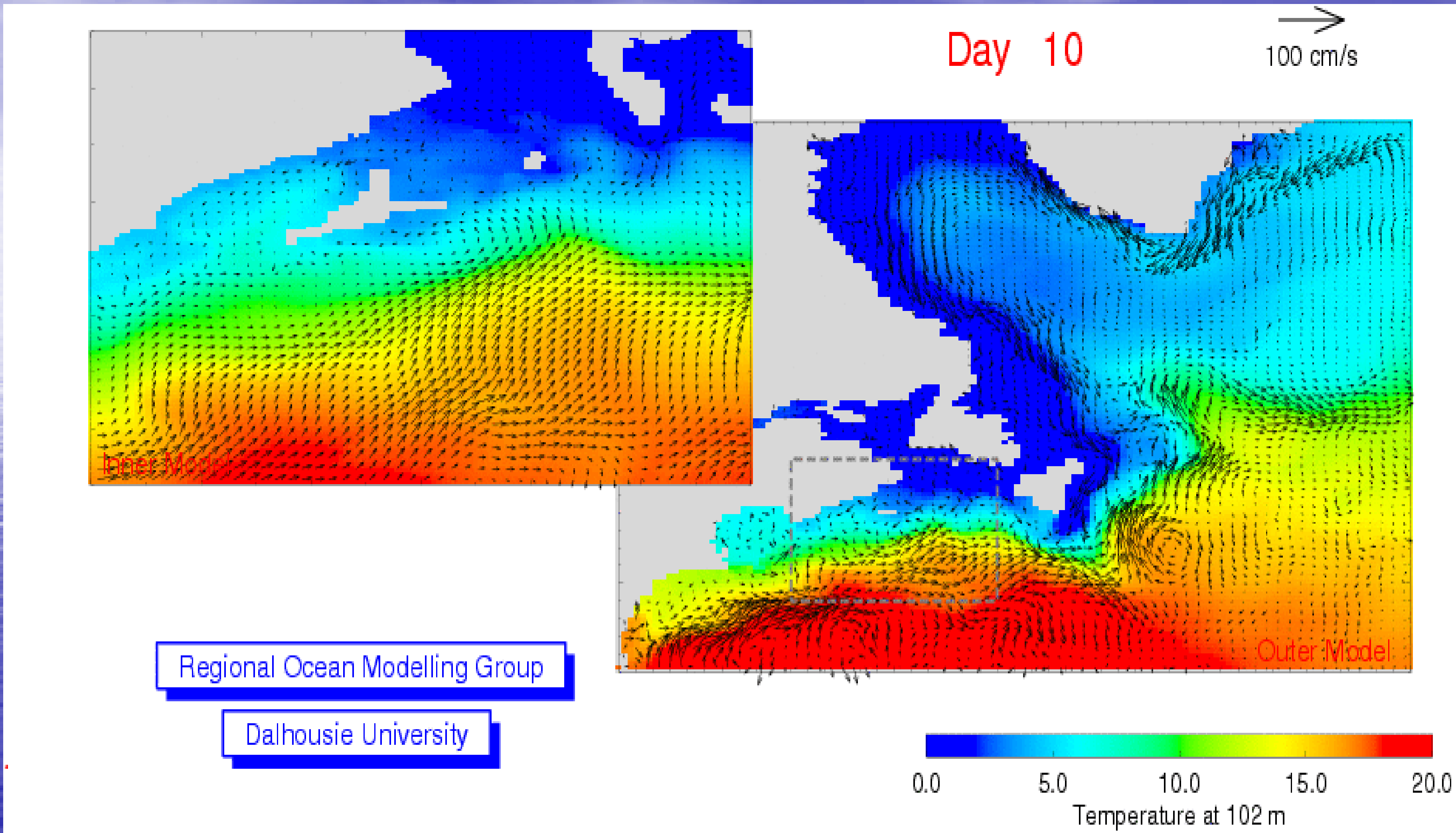
SSP: two-way nesting using the smoothed semi-prognostic method



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

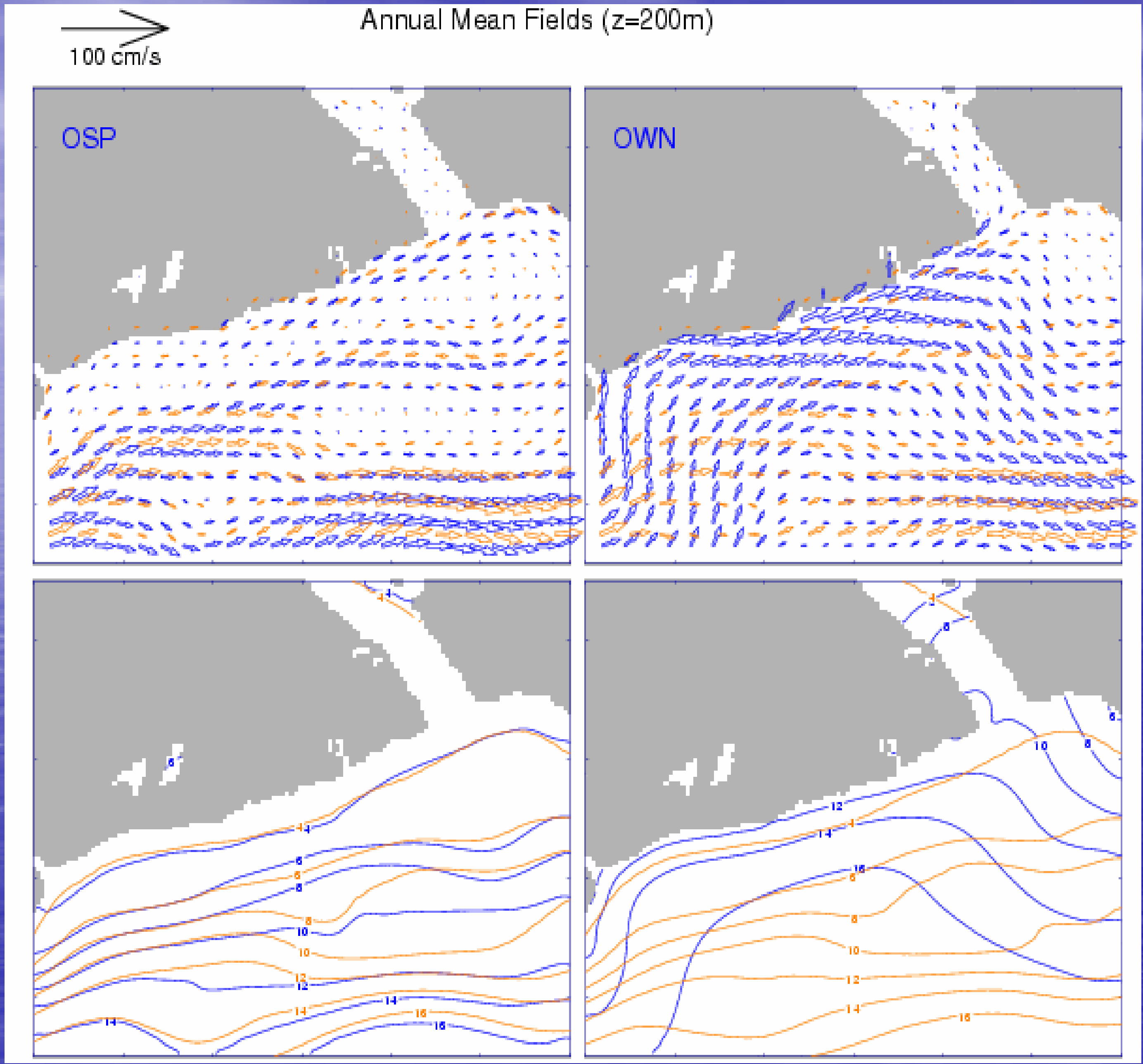
SSP: two-way nesting using the smoothed semi-prognostic method

Model Results in Exp CLIM



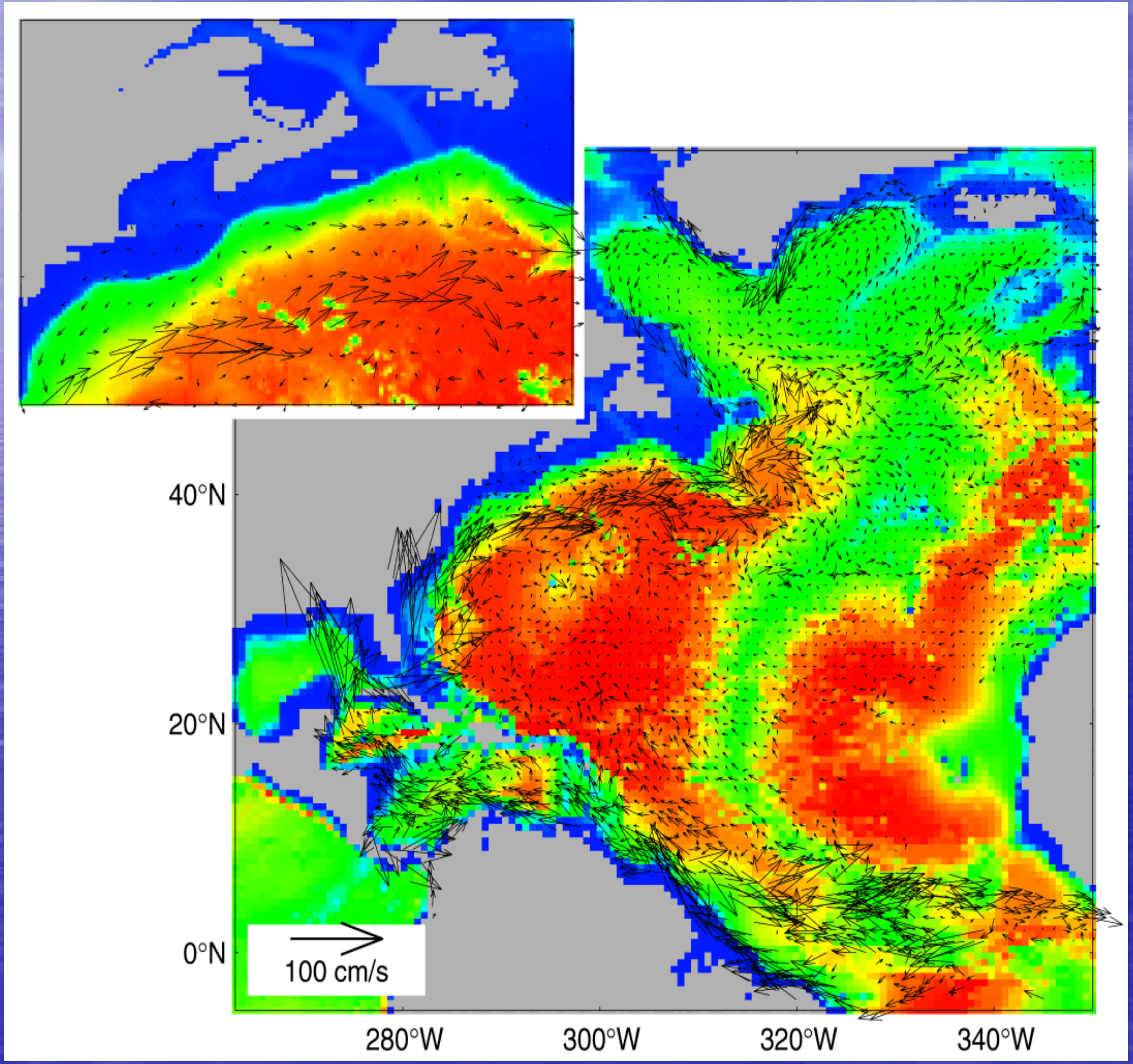
Orange: outer model

Blue: inner model

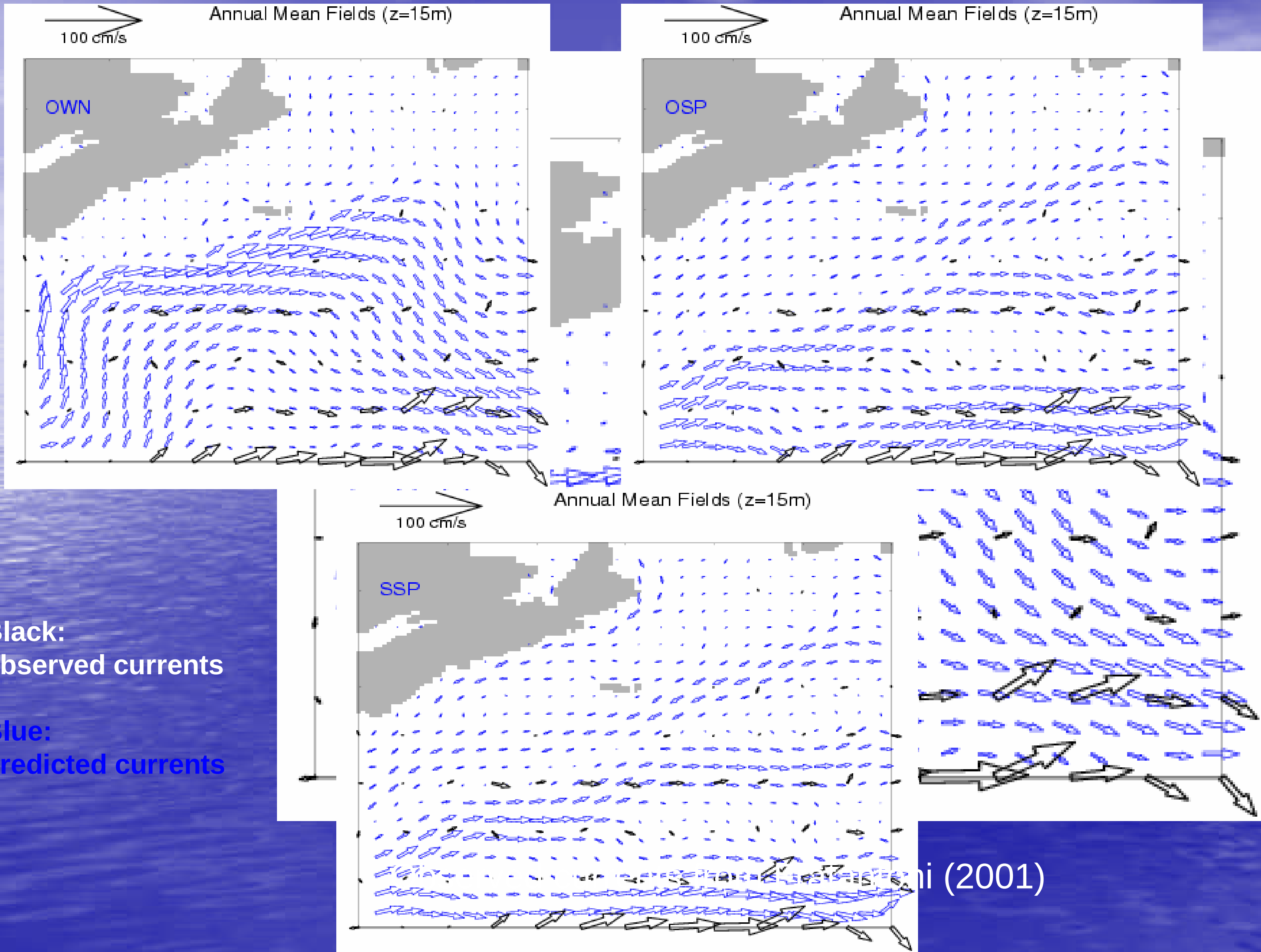


OSP-Original Semi-Prognostic Method, OWN – Conventional One-Way Nesting

Decadal mean currents at 15 m determined from trajectories of near-surface drafters (Fratantoni, 2001)



Comparison with observed near-surface currents



Black:
observed currents

Blue:
predicted currents

ni (2001)

Comparison with Data

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

Model run	γ^2
OWN	1.01
OSP	0.65
SSP	0.62

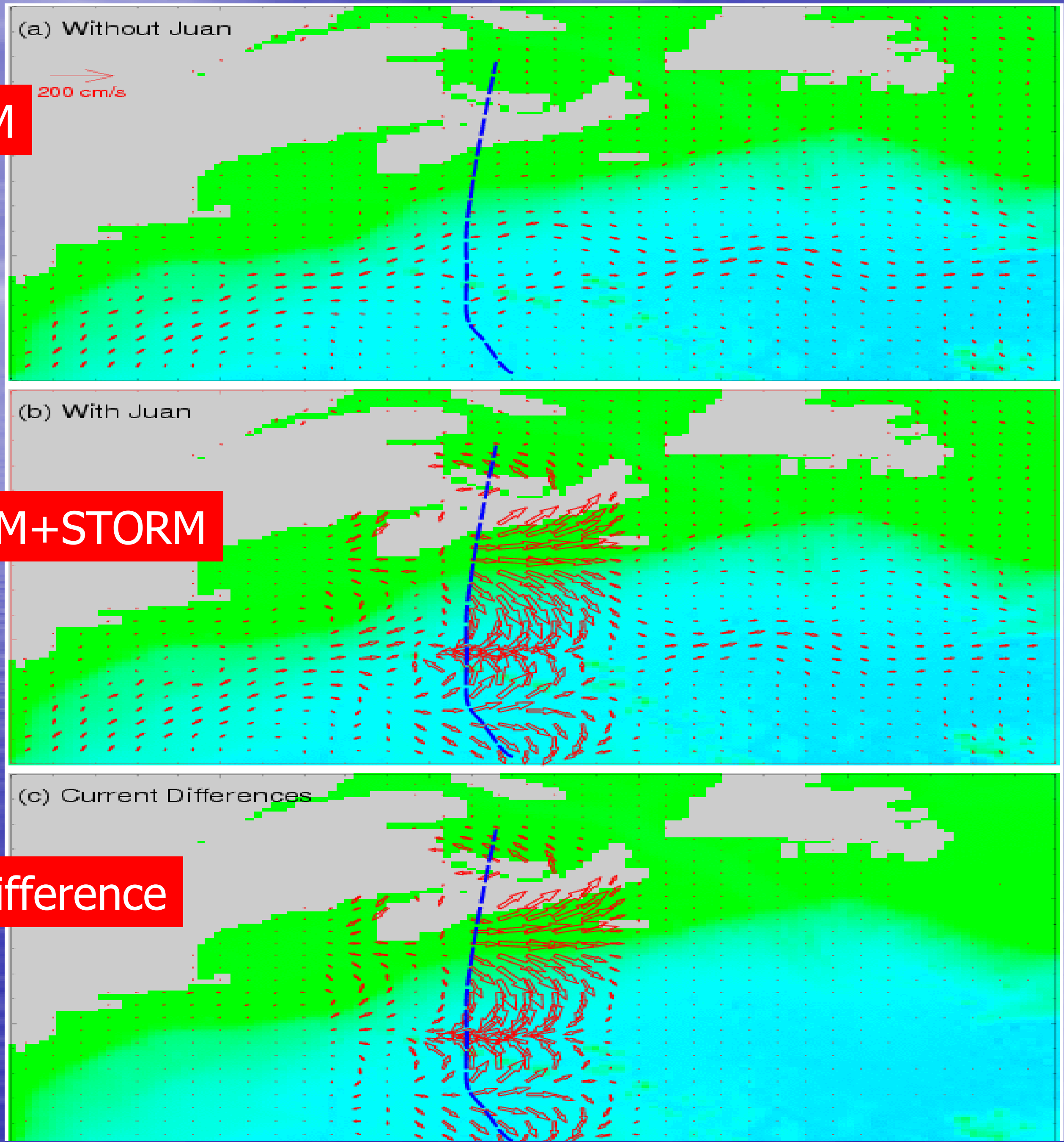
Experiment CLIM+STORM

CANDIE is forced by the combination of climatological forcing and idealized wind stress associated with Hurricane Juan.

Storm parameterization (Chang and Anthes, 1978):

$$\tau = \tau_{max} \times \begin{cases} r / r_{max} & 0 \le r \le r_{min} \\ (r_{max} - r)/(r_{max} - r_{min}) & r_{min} \le r \le r_{max} \\ 0 & r_{max} \le r \end{cases}$$

$$r_{min} = 30 \text{ km}$$
$$r_{max} = 300 \text{ km}$$
$$\tau_{max} = 3 \text{ N m}^{-2}$$
$$U_h = 8.5 \text{ m s}^{-1}$$

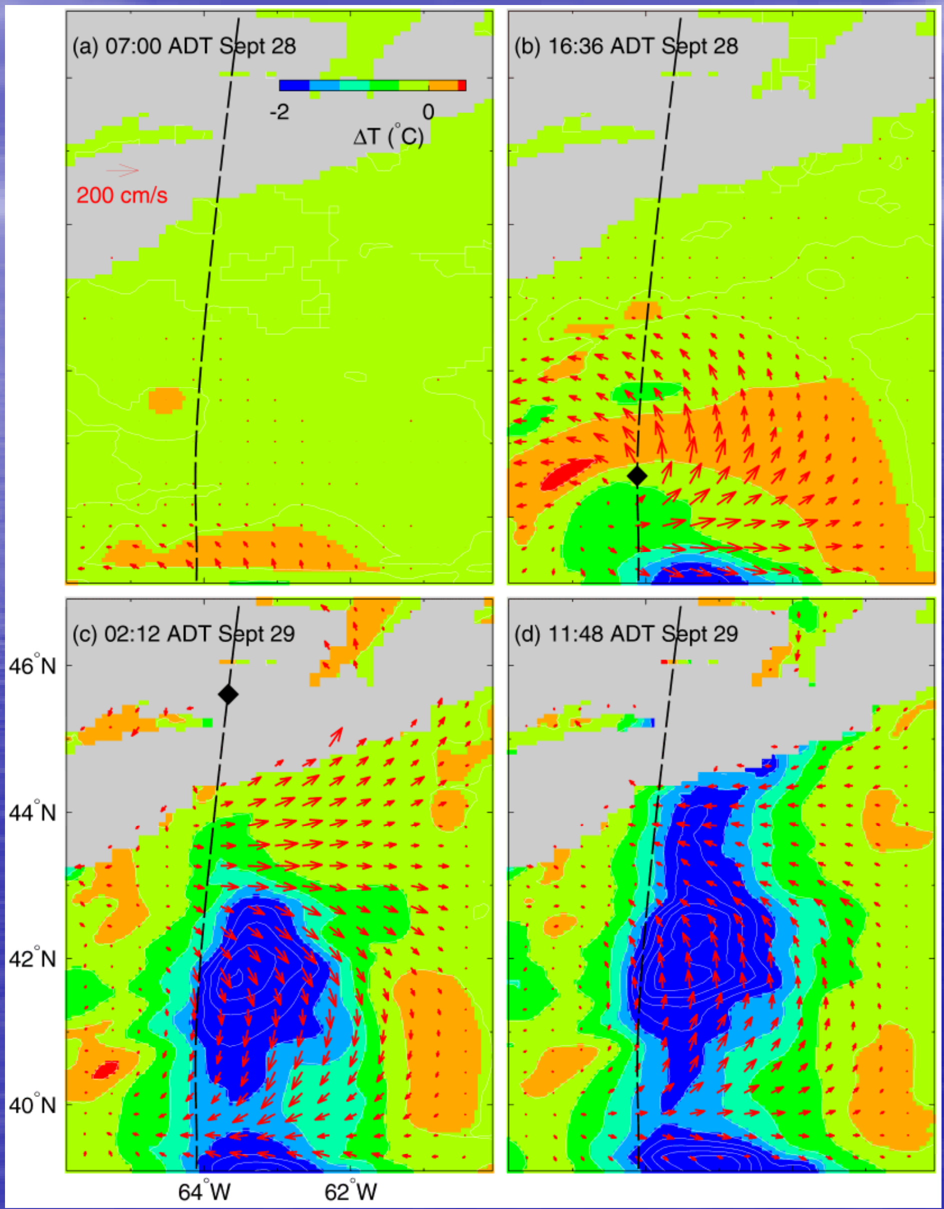


(a) Exp: CLIM

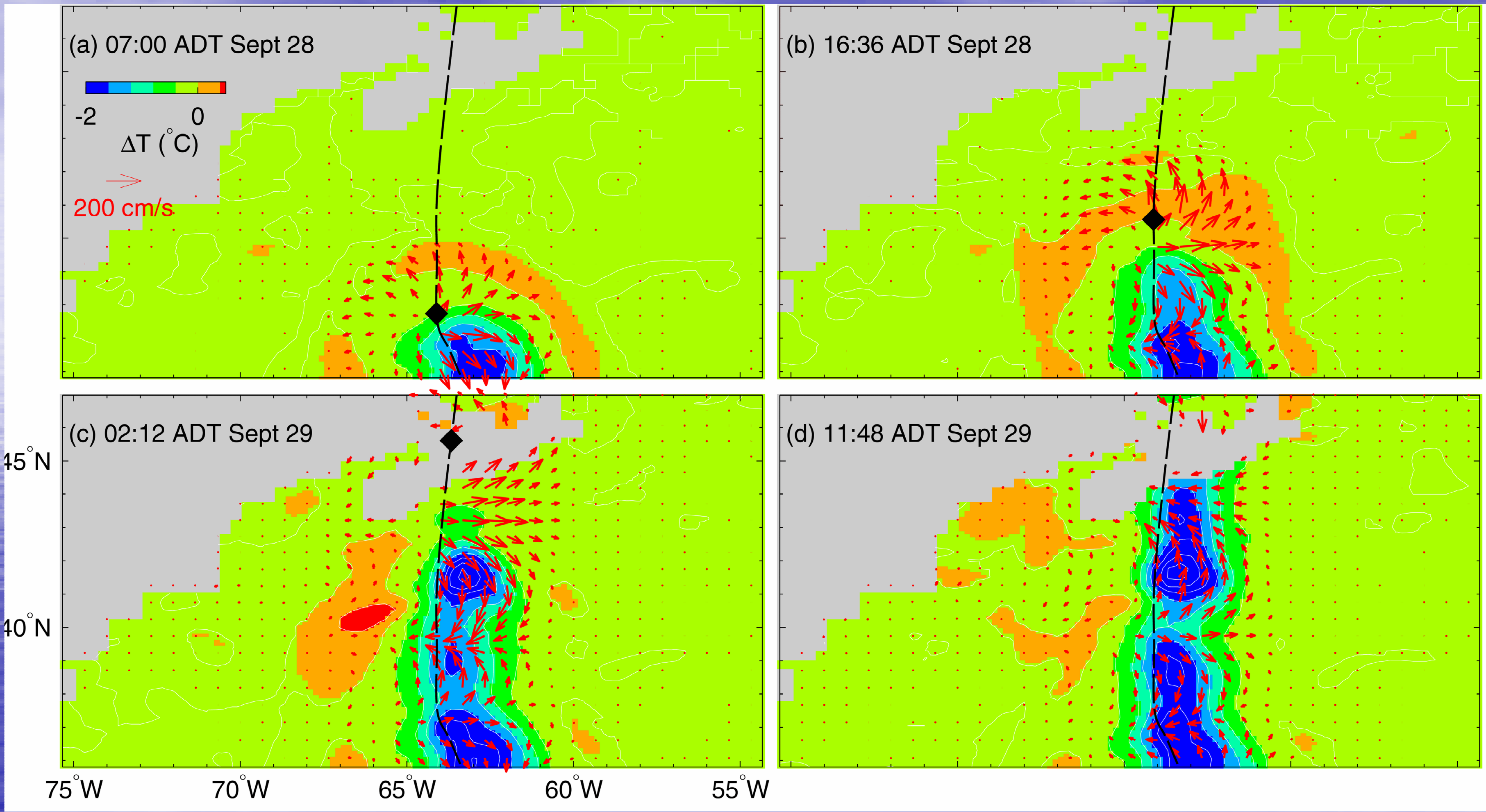
(b) Exp: CLIM+STORM

(c) Current difference

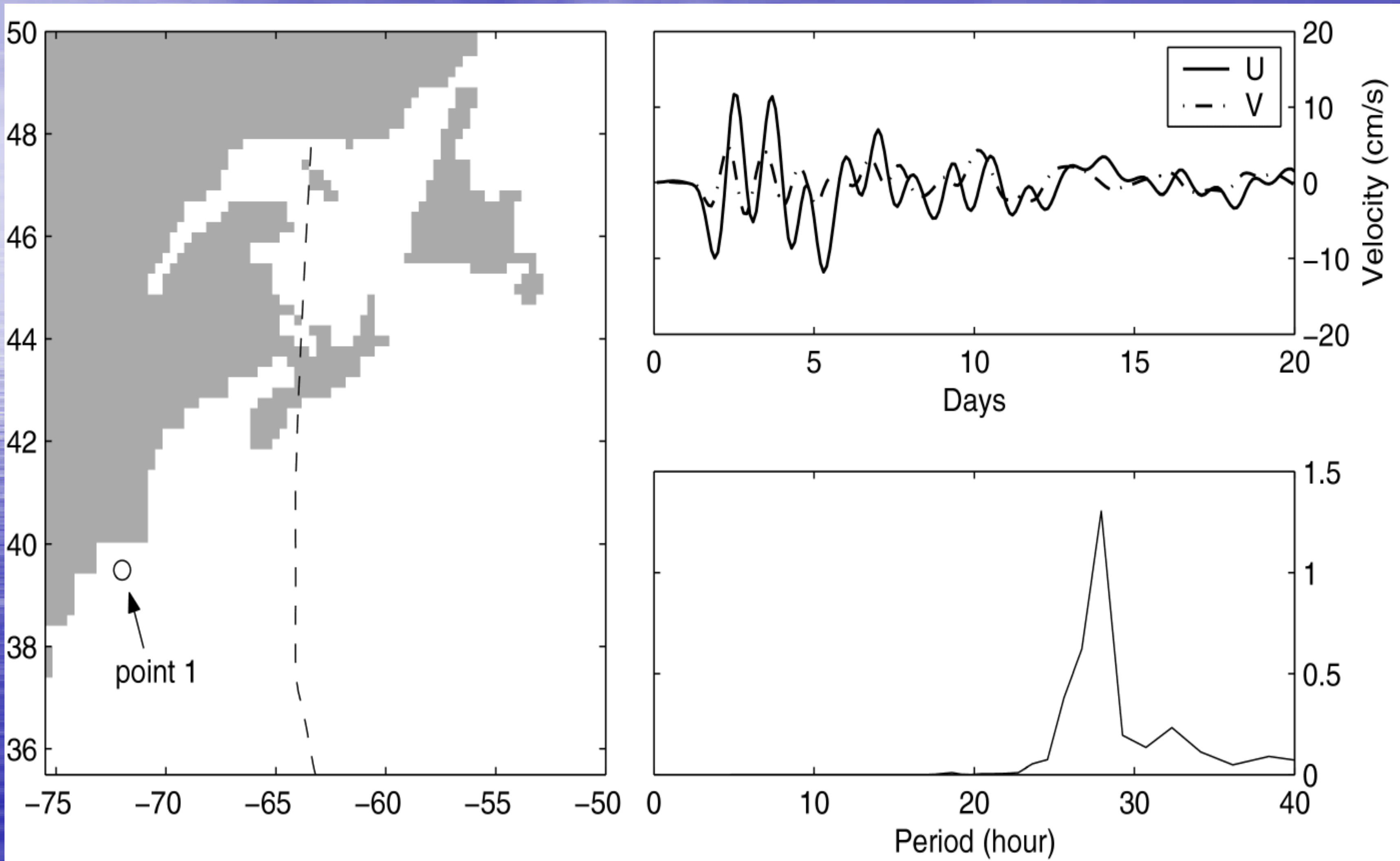
Differences in Near-Surface Currents and SST (inner model)



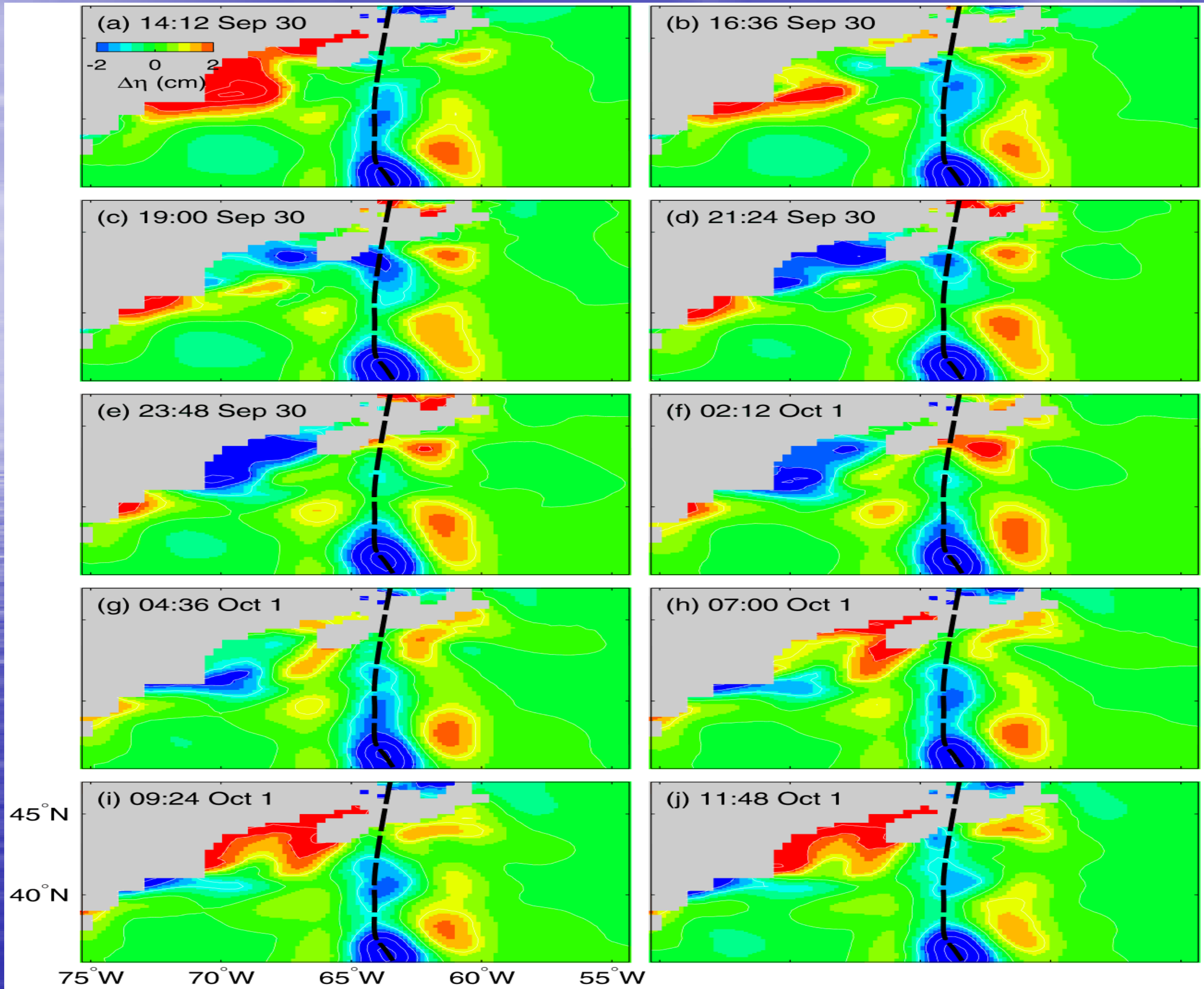
Differences in Near-Surface Currents and SST (outer model)



Storm-induced shelf waves

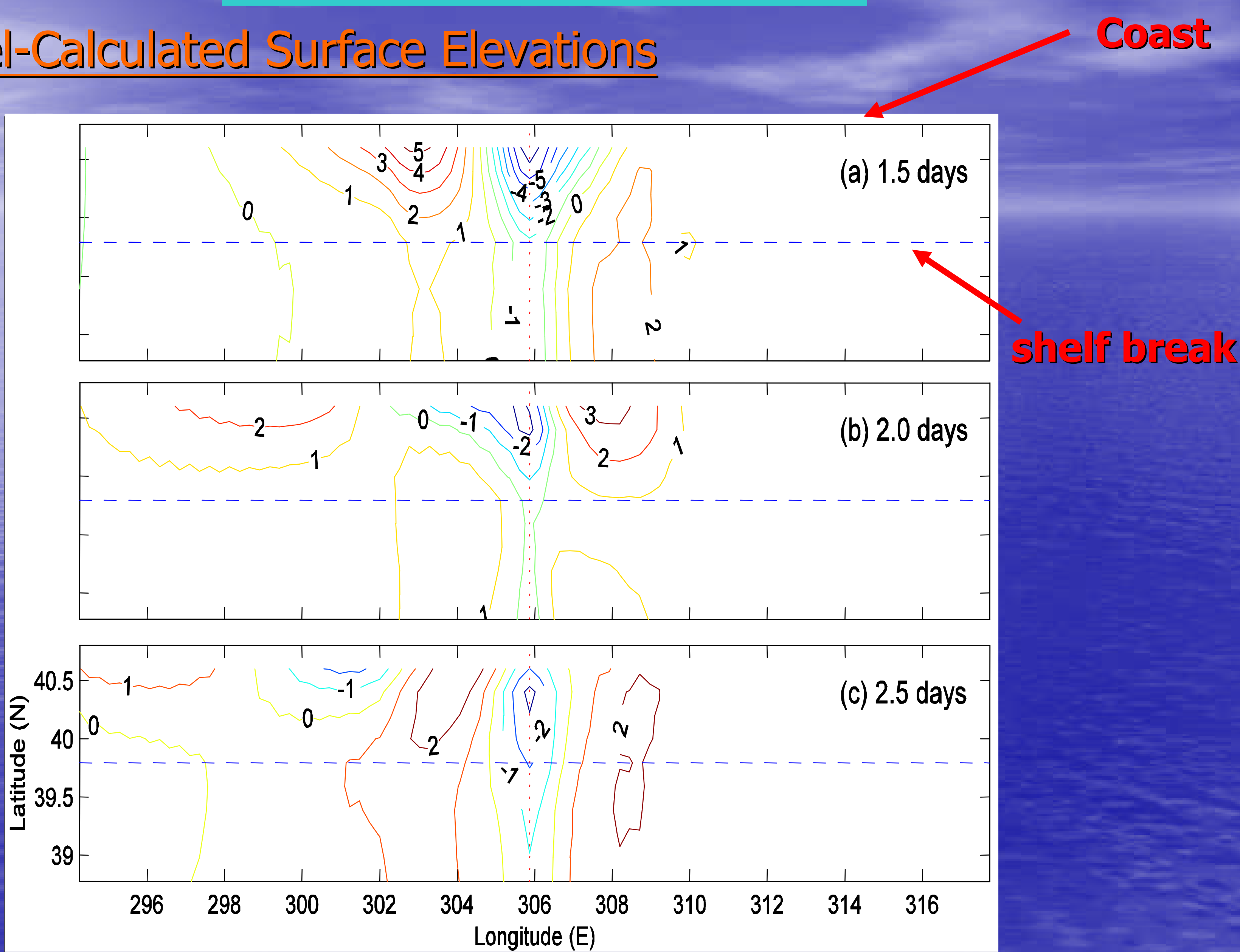


Storm-induced surface elevations during Juan



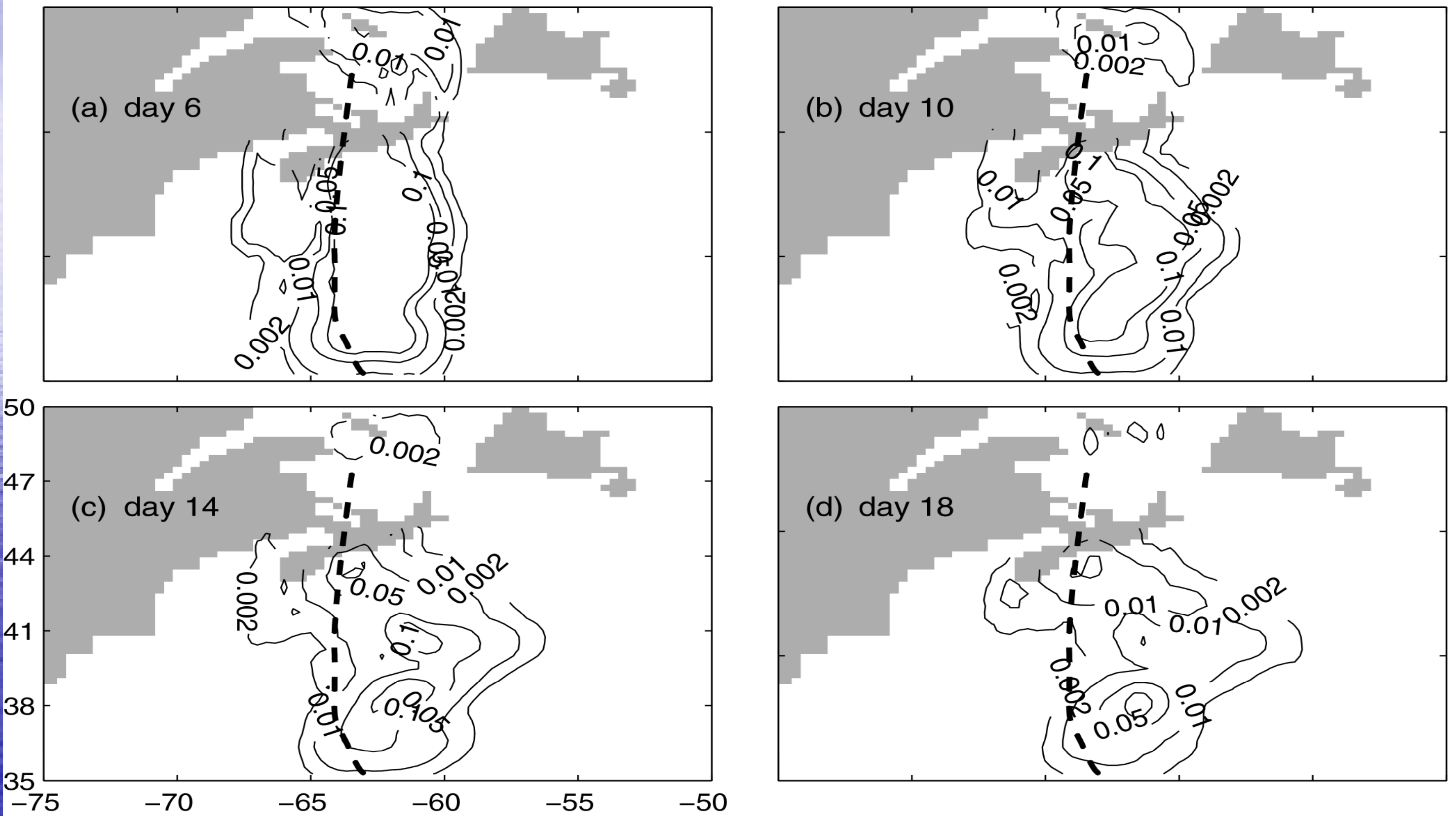
Step-Wise Topography

Model-Calculated Surface Elevations



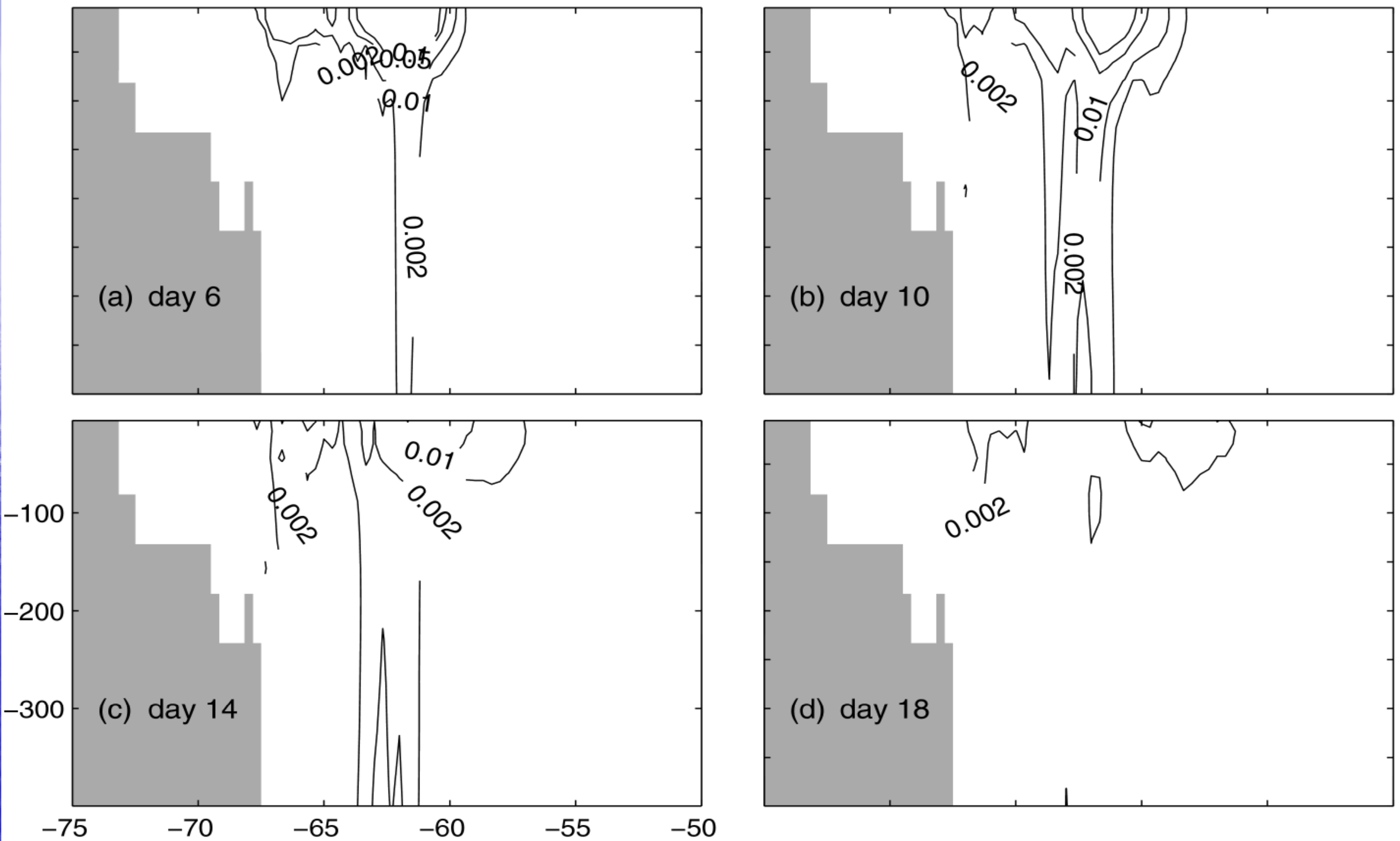
Spreading of Near-Inertial Energy

(Zhai et al., GRL, 2004)



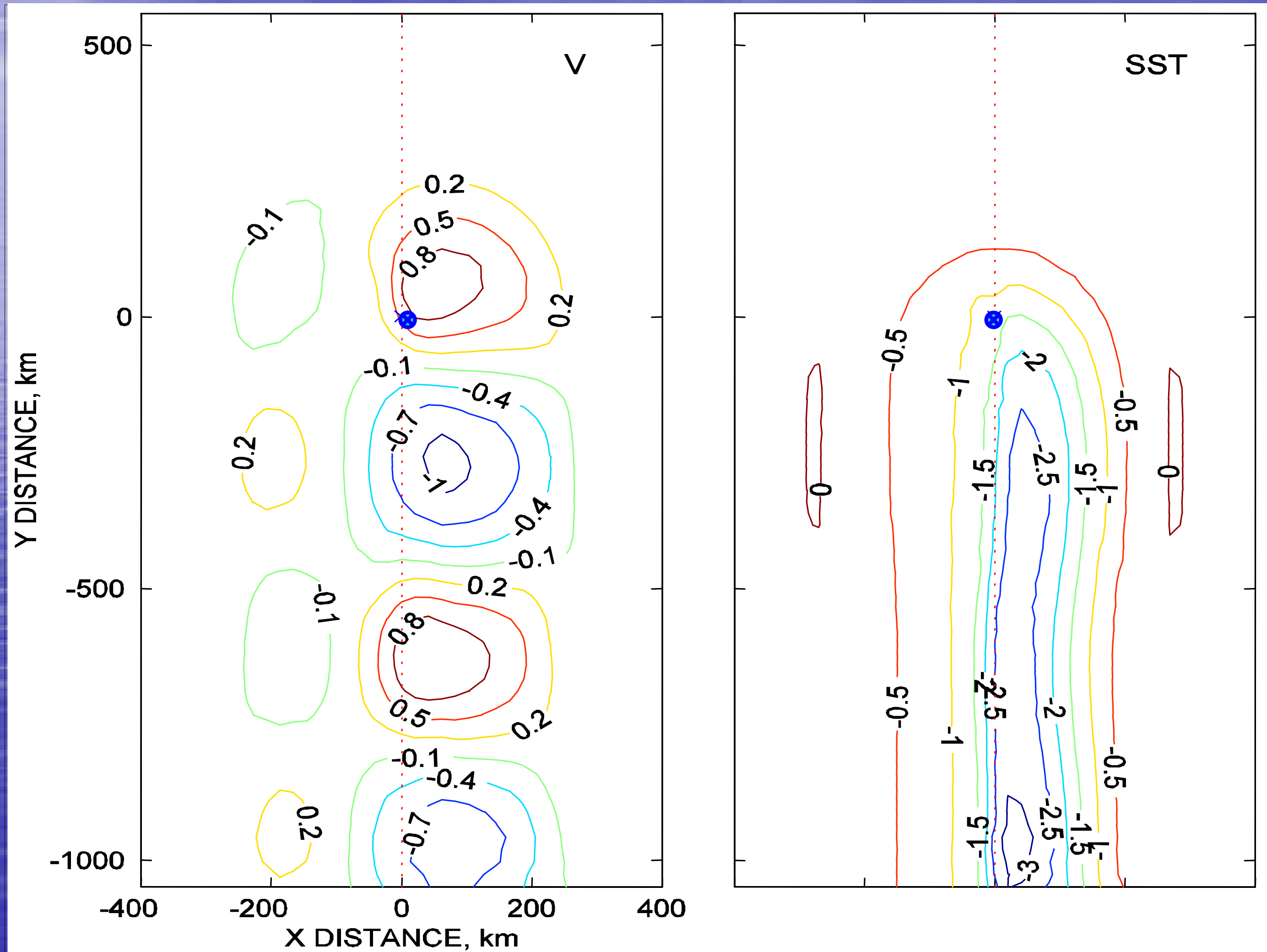
Spreading of Near-Inertial Energy

(Zhai et al., GRL, 2004)

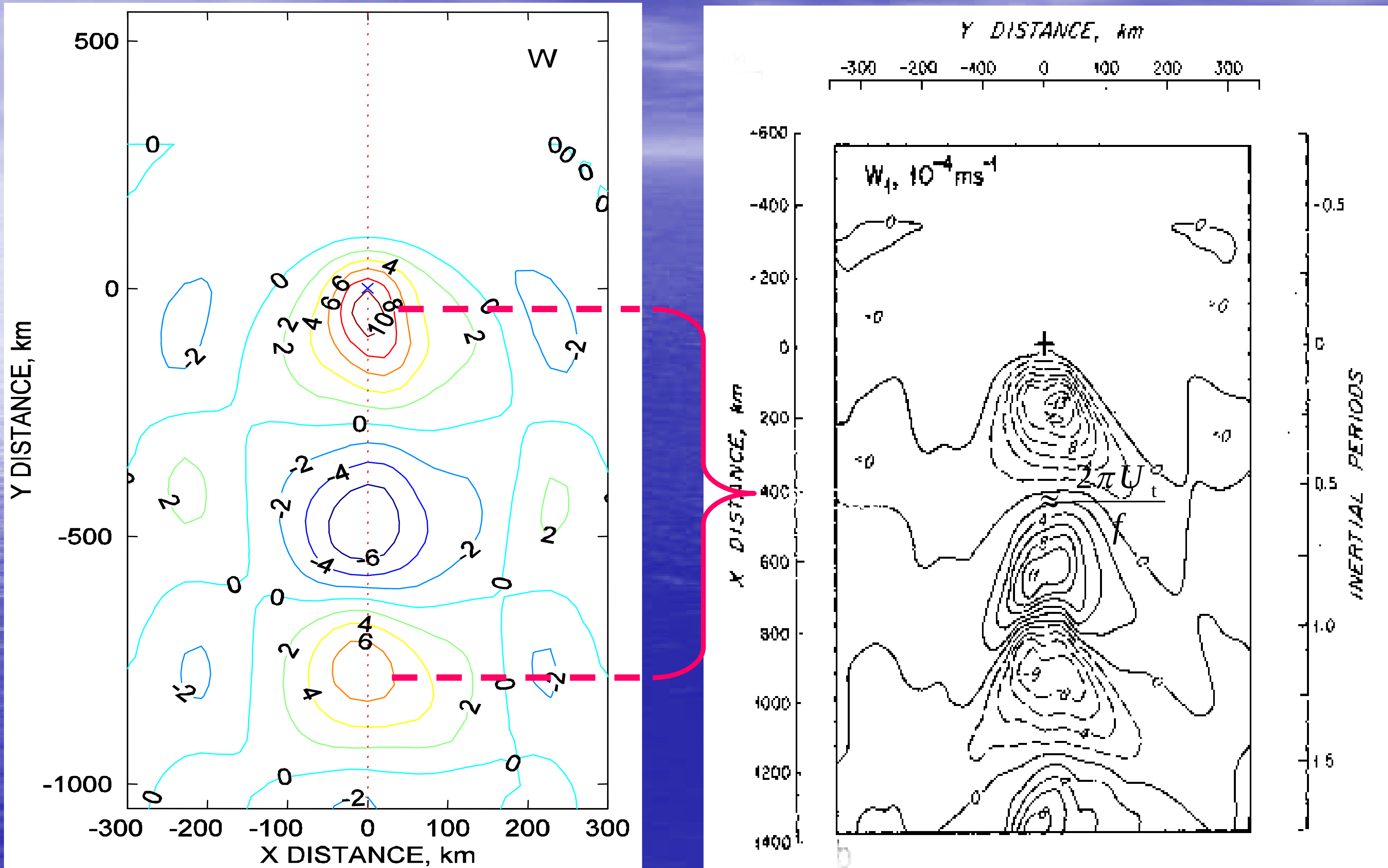


Flat-Bottom Case

Model-Calculated Surface Currents and Temperature



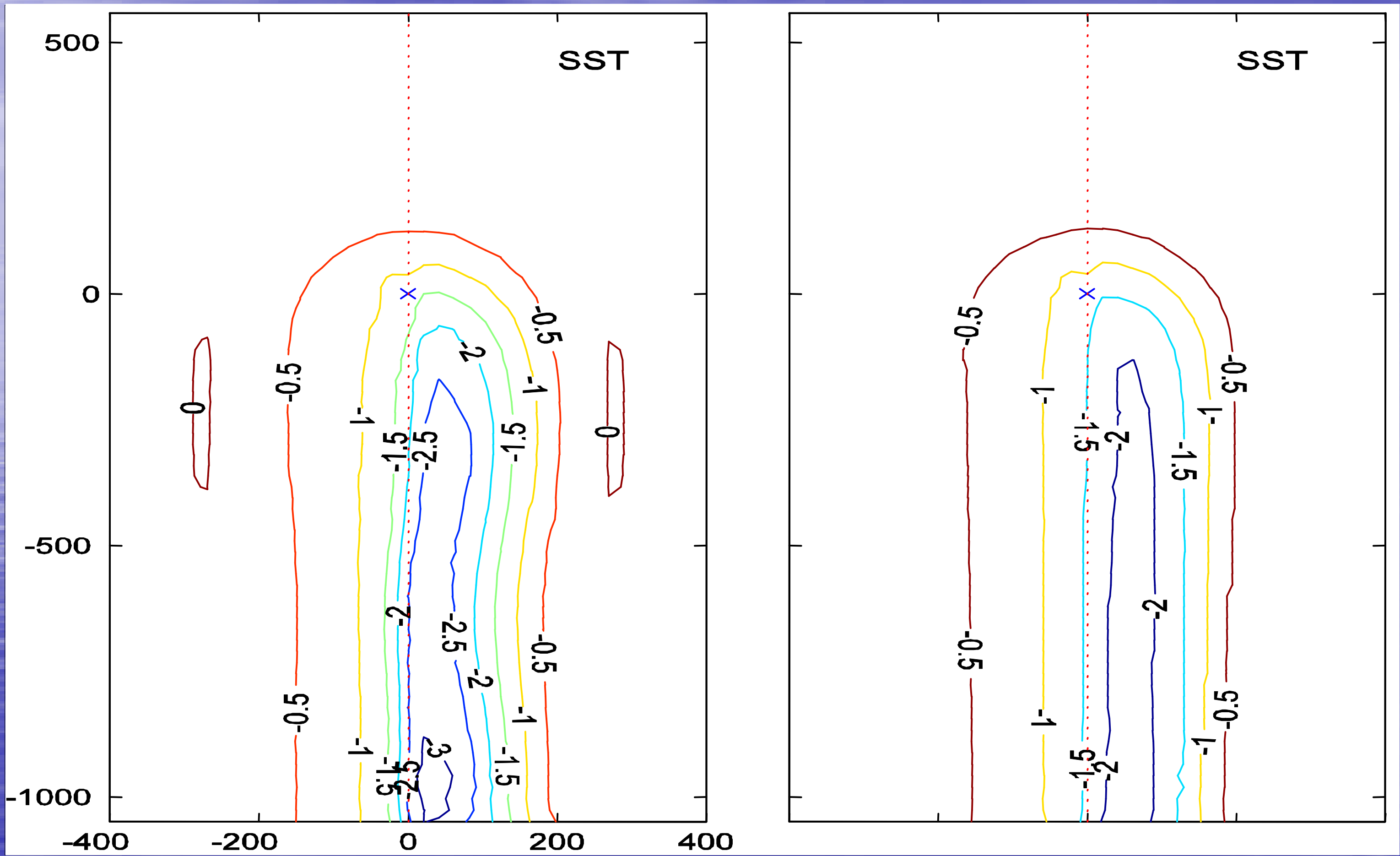
Vertical Velocity



CANDIE

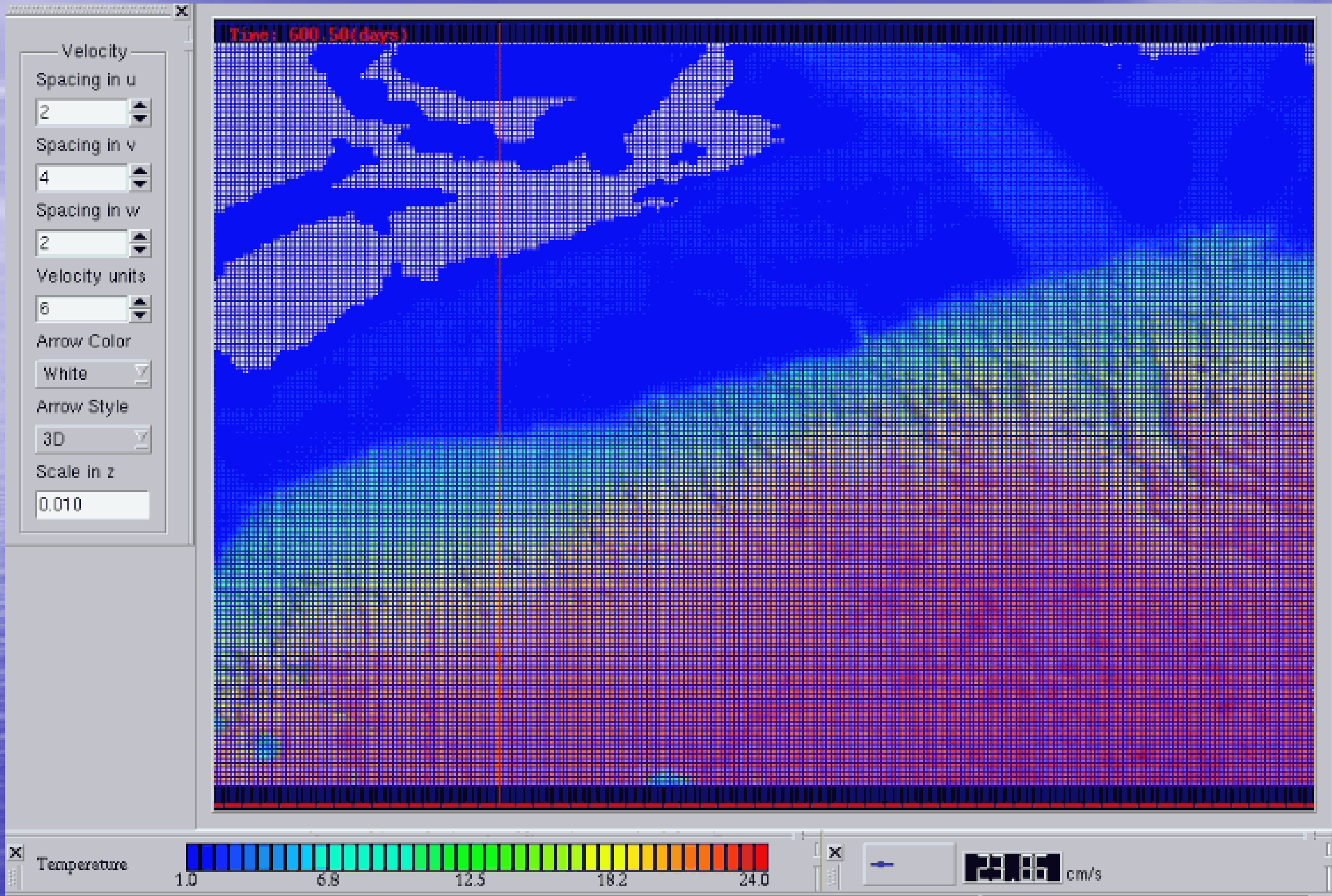
adopted from Price (1981)

Upwelling vs. Vertical mixing

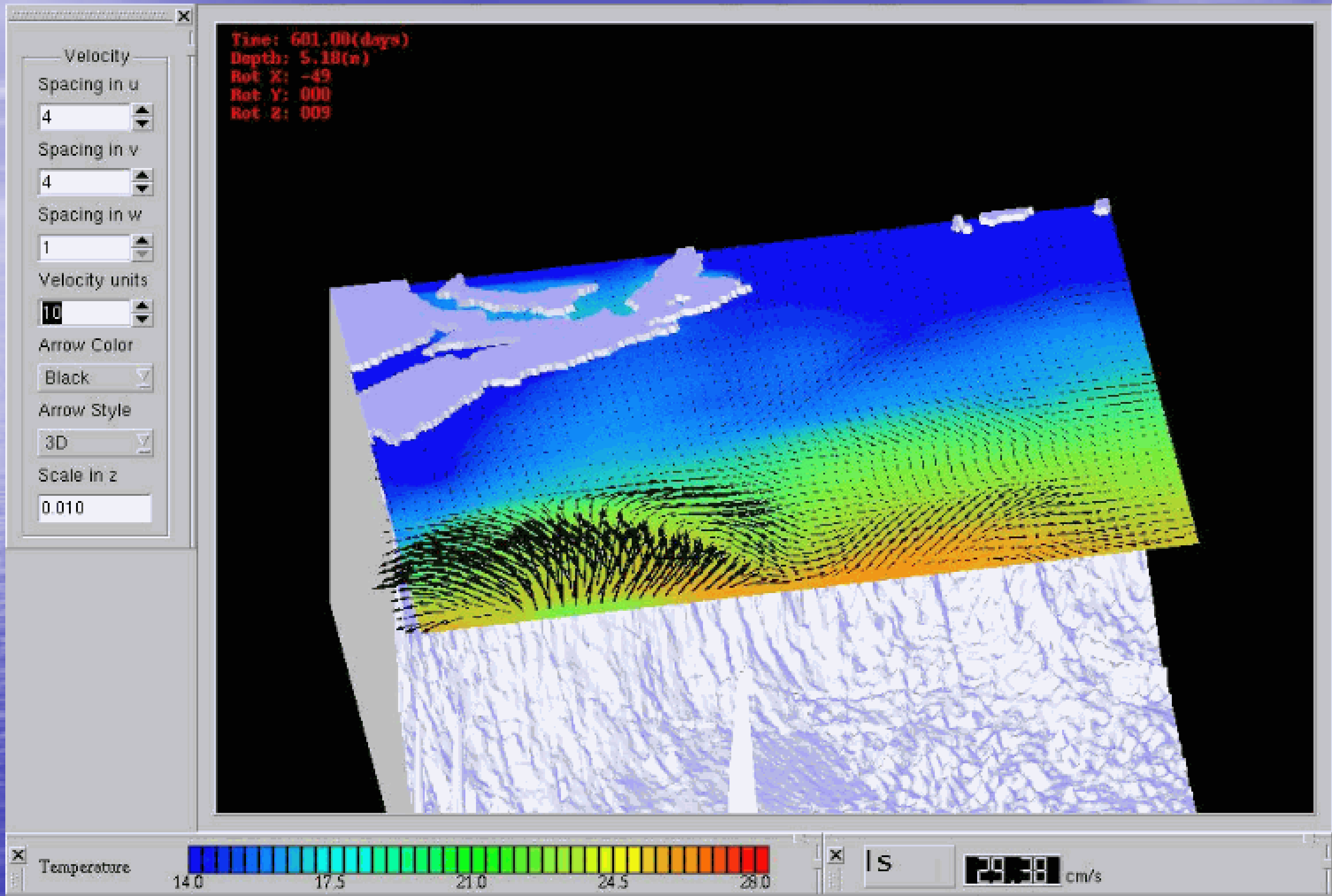


a) Vertical mixing and temperature advection

b) Vertical mixing only



(Dr. Jim Chuang and his students)



(Dr. Jim Chuang and his students)

Summary and Conclusion

- The smoothed semi-prognostic method (Eden et al., 2004; Greatbatch et al., 2004) was used in developing a two-way nested-grid modelling system for the Scotian Shelf and slope.
- The nested system was used to examine the storm-induced circulation associated with Hurricane Juan on the Scotian Shelf (Zhai, 2004; Zhai et al., 2004; Sheng et al., 2004).
- The upper ocean response to Juan is characterized by (a) large divergent currents forced by the storm wind; (b) intense inertial currents in the wake of the storm; (c) rightward bias of SST cooling.
- Juan also generates shelf waves that propagate equatorward.
- Some of near-inertial energy excited by the storm is advected into the ocean interior by the eastward Gulf Stream.


Thank you
NEW BRUNSWICK
PRINCE EDWARD ISLAND
MAINE
NOVA SCOTIA
HALIFAX
NORTH ATLANTIC OCEAN
CAPE COD
Hurricane Juan
GOES-12 Colorized Visible - 2km
September 28, 2003 @ 2045 UTC