Observational and Numerical Study of Ocean Dynamics over Canadian Atlantic Coastal Waters

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Liang Wang

DALHOUSIE UNIVERSITY *Inspiring Minds*

cmep Centre for Marine Environmental Prediction

NSERC CRSNG

Canadian Foundation for Climate and Atmospheric Sciences (CFCAS)
Fondation canadienne pour les sciences du climat et de l'atmosphère (FCSCA)

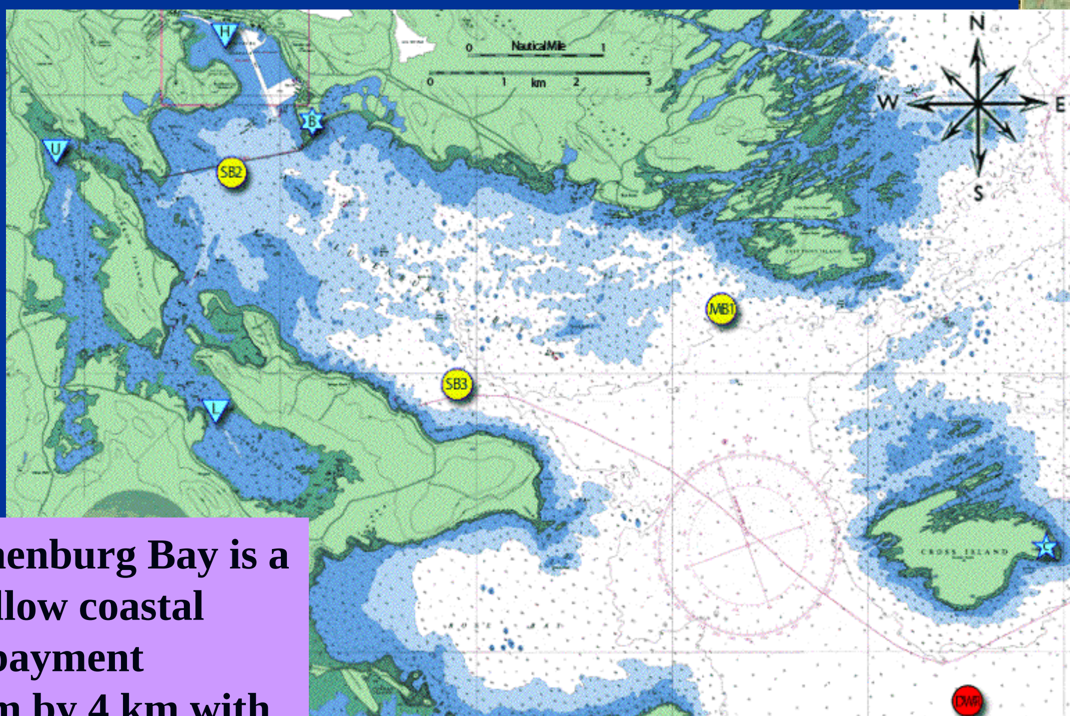
Contents

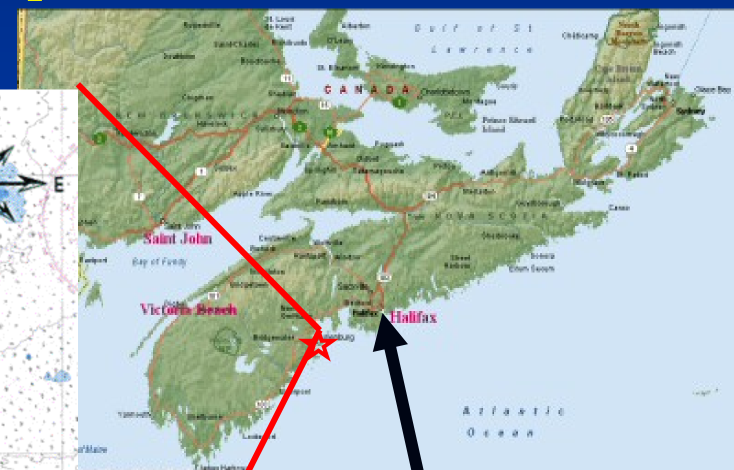
1.1 Canadian Coastal Ocean Observatory

- The coastal ocean observatory (CMEP-Bay) was established in summer of 2002.
- It provides continuous real-time observations of marine environmental variables in spring to fall of last 6 years.
- The observatory was operational when Hurricane Juan made land fall within 50 km of the site in September, 2003 and tropical storm Alberto in June 2006.

Centre of Marine Environmental Prediction (CMEP)

- Canadian scientists established a coastal ocean observatory in Lunenburg Bay, Nova Scotia, as part of a research project of marine environmental observation and prediction in the Atlantic Ocean of Canada.





- **Lunenburg Bay is a shallow coastal embayment**
- **8 km by 4 km with water depth less than 30 m**

Halifax, Nova Scotia

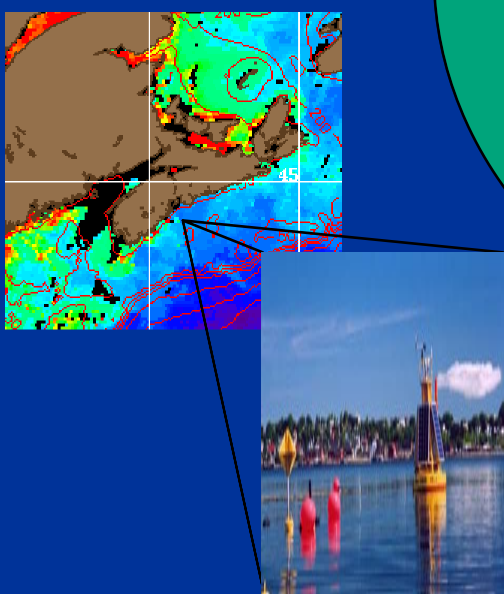
Ocean Observing System in Lunenburg Bay, Nova Scotia as part of CMEP-Bay

CMEP-Bay: Forecast System Using Measurements from Land and Sea

Atmospheric Model

Pressure, Winds, Fluxes,…

Remote Sensing &
Ocean Observatories

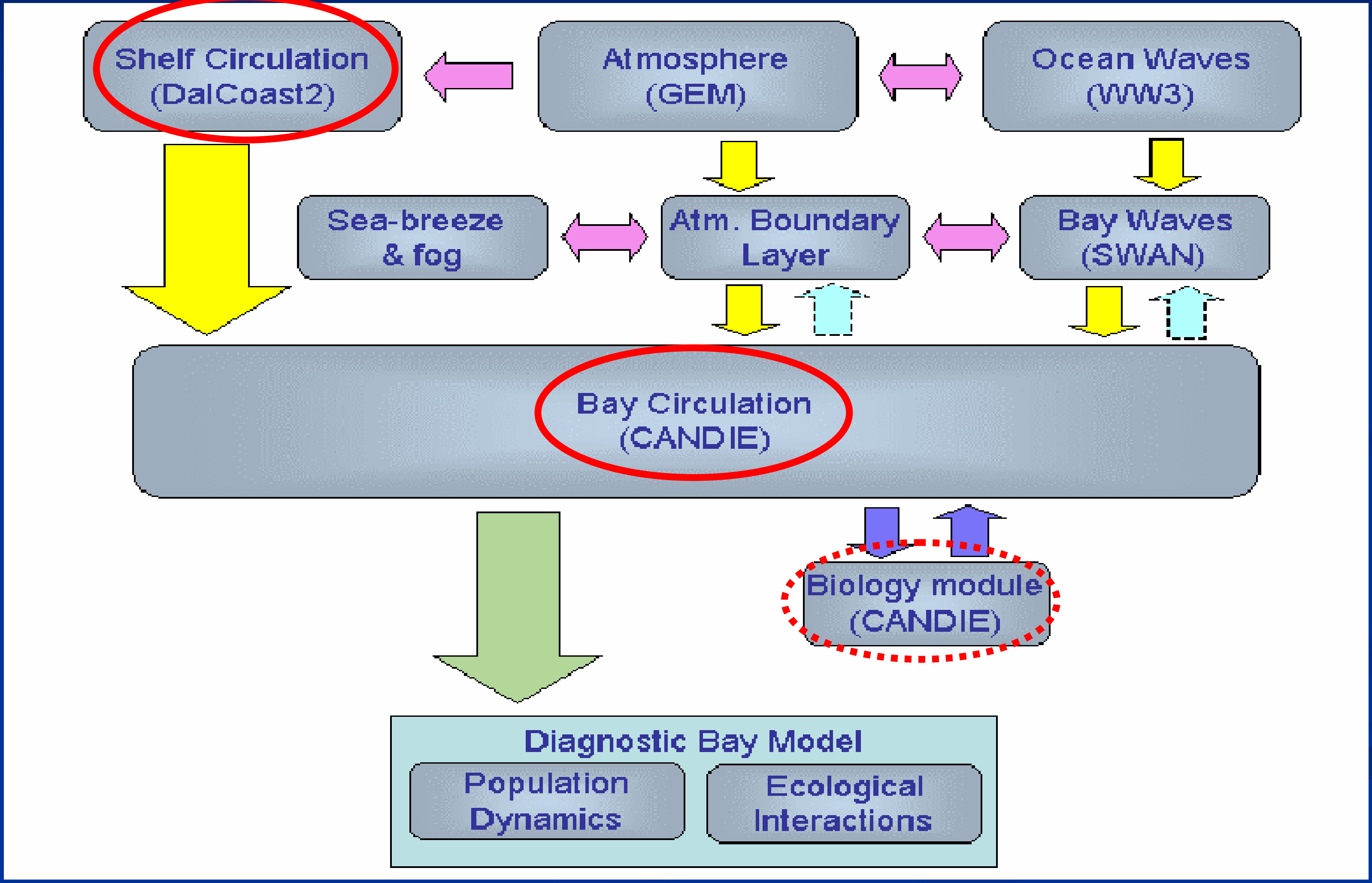


Circulation Model

Sea Level, Currents
Temp, Salinity

Biology & Sediment Models

An interdisciplinary coupled modeling system

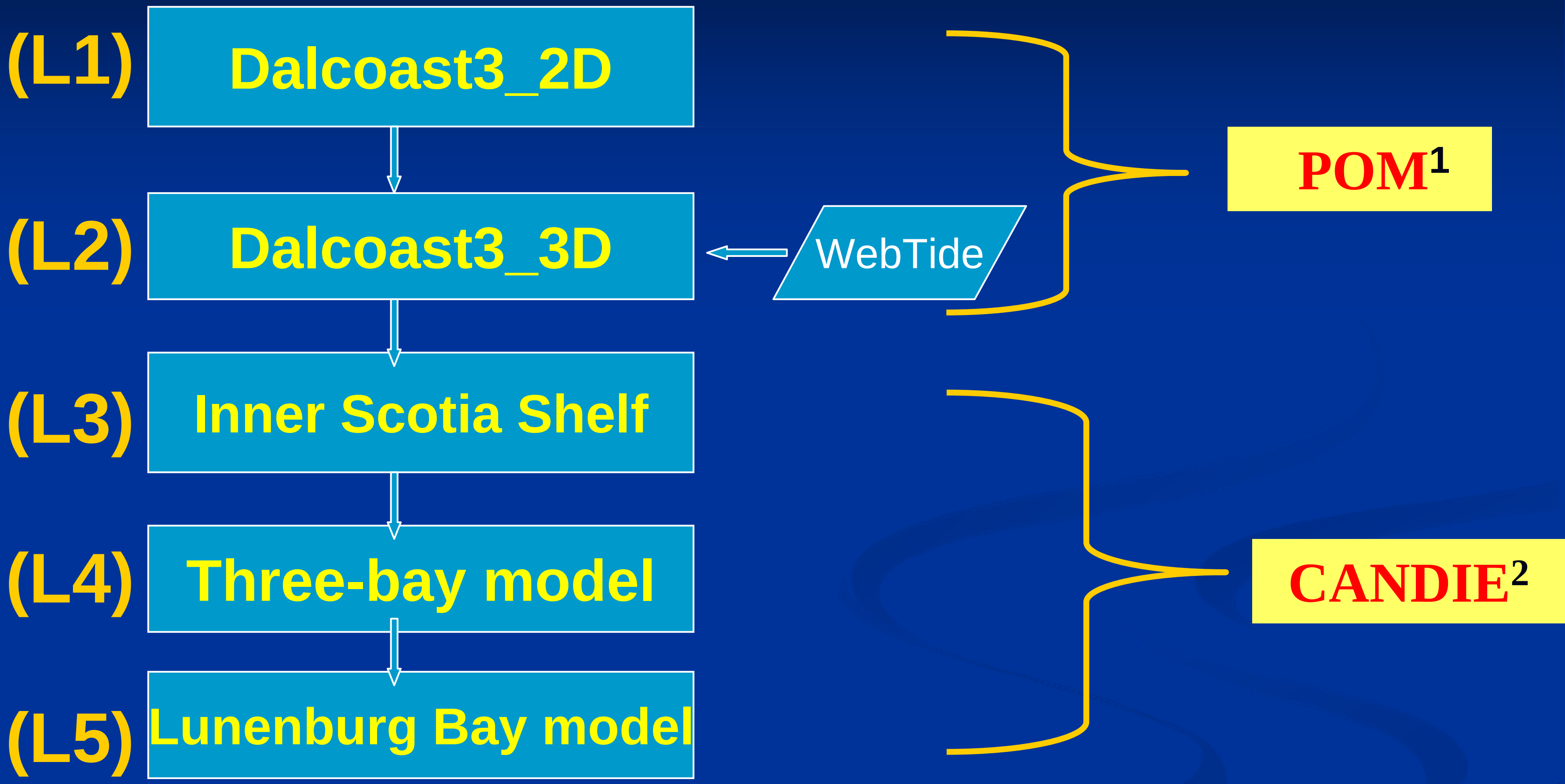


1.2 Nested-Grid Coastal Ocean Circulation Prediction System (NCOPS-LB)

Main Features:

- Five sub-models with different horizontal resolutions
- Based on Dalcoast3 (POM) and CANDIE.
- One-way nesting (two-way nesting based on SPM will be implemented)
- Driven by astronomical forcing (WebTide) and meteorological forcing (forecast products produced by Meteorological Service of Canada, MSC)

NCOPS-LB

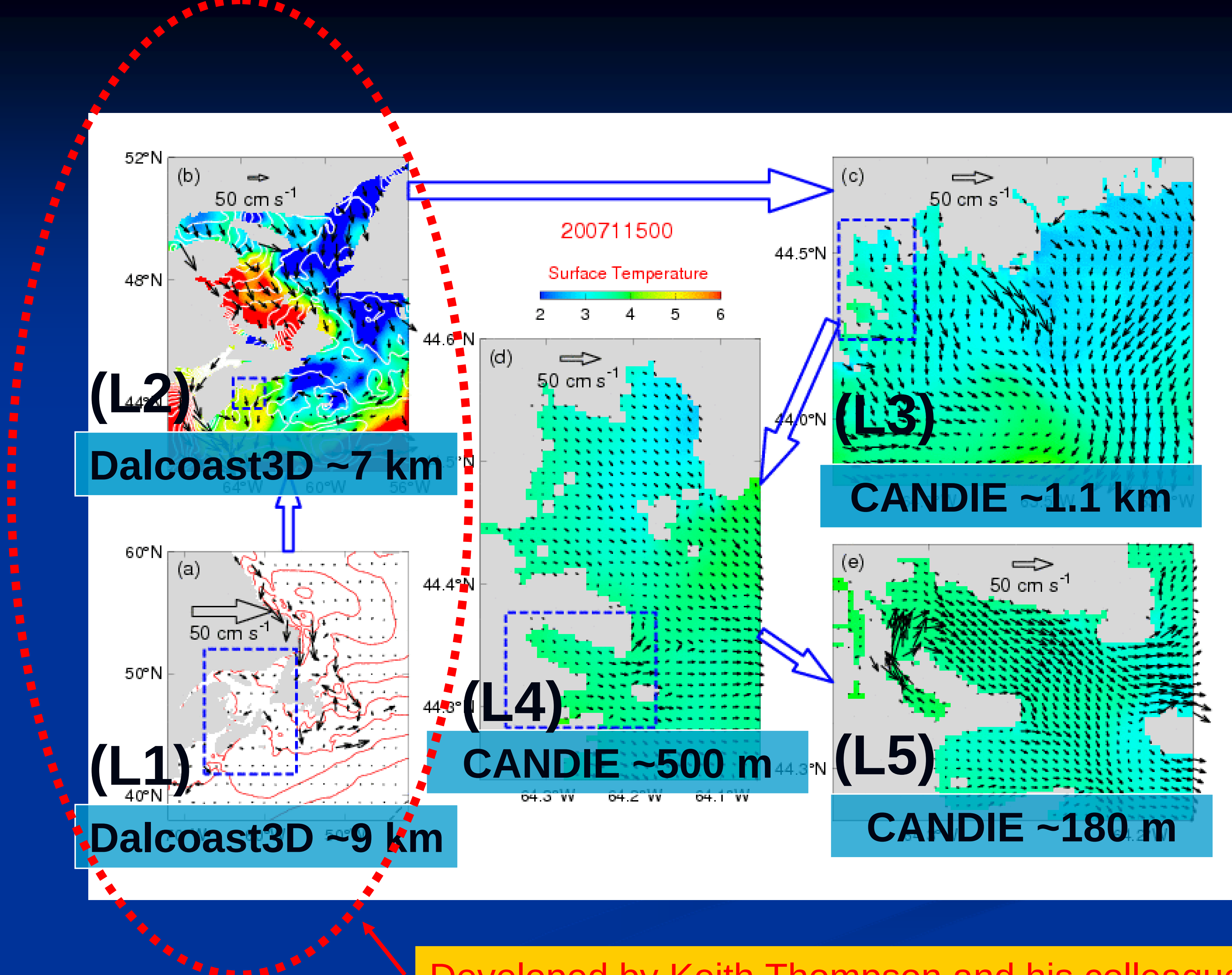


[1]Thompson et al., CRS, 2007; Ohashi et al., JGR, 2008

[2]Wang et al., JPO, 2007; Zhai et al., CRS, 2007; Zhai et al., JGR, 2008

CANDIE

- CANDIE stands for CANadian version of Diecast.
- A primitive-equation, z-level ocean circulation model developed by Sheng, Wright, Greatbatch and Dietrich (1998) from Diecast.
- The fourth-order numerics, flux limiter and implicit free surface.
- 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 & Tang, JPO, 2003; Sheng & Tang, OD, 2004; Sheng & Wang, JGR, 2004; Wang et al., JPO, 2007; Sheng et al., PiO, 2006; Sheng & Rao, CSR, 2006; Tang et. al., JGR, 2006, Sheng et al., JGR, 2007; Yang et al., OD, 2007; Wang et al., JPO, 2007; Zhai et al., CRS, 2007, Zhai et al., JGR, 2008; Zhai et al., CRS, 2008; Sheng et al., JMS, 2008).
- **Website: www.phys.ocean.dal.ca/programs/CANDIE**



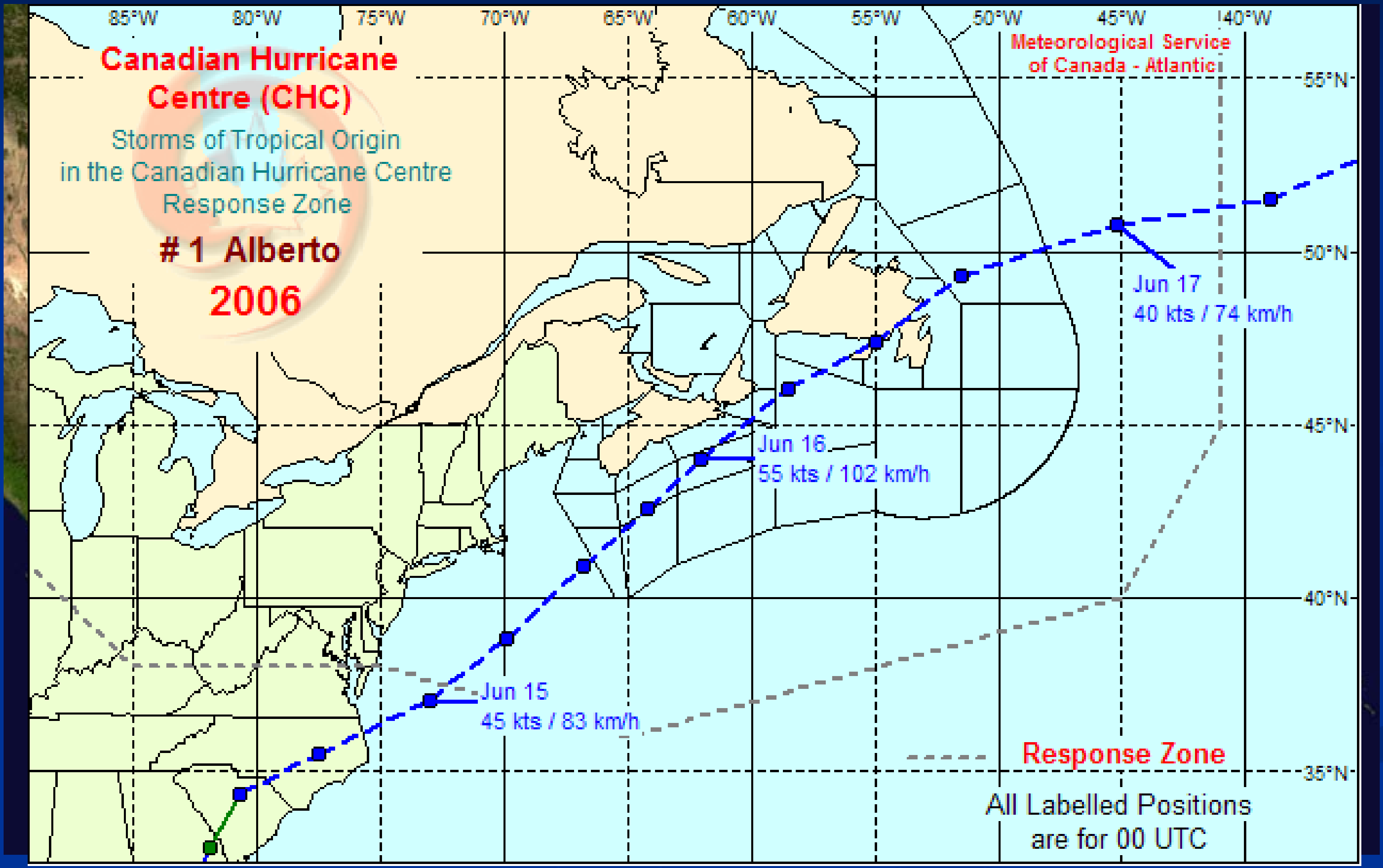
Developed by Keith Thompson and his colleagues

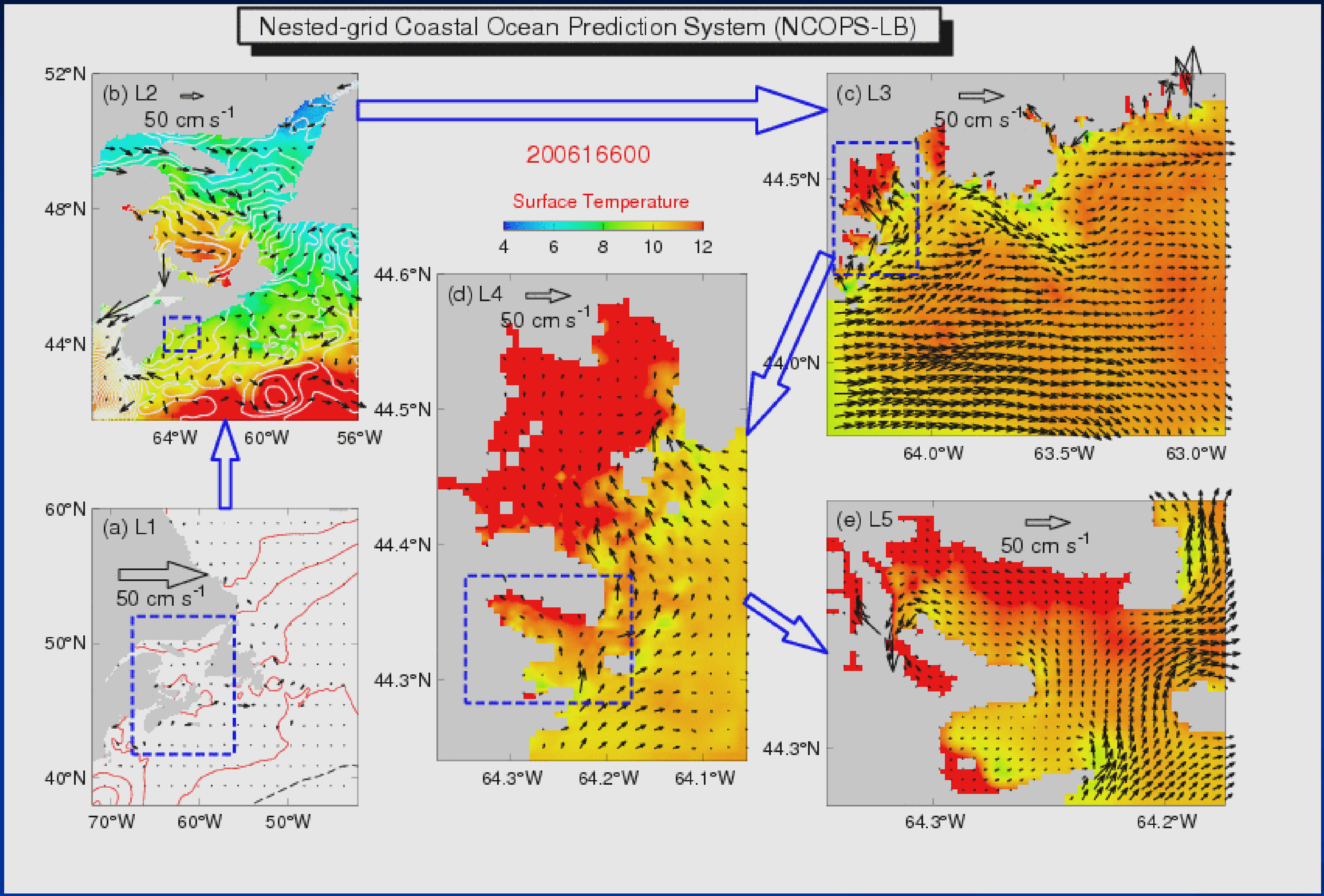
1.3 Storm-Induced Circulation during Alberto

Tropical Storm Alberto in June 2006:

- The first tropical storm of the 2006 Atlantic hurricane season.
- Formed on June 10 in the northwestern Caribbean Sea, and moved northward and then northeastward with a peak intensity of 110 km/h.
- Moved through eastern Georgia, North Caroline and Virginia as a tropical depression before becoming an extra-tropical storm on June 14.
- The remnants of Alberto produced strong winds and left four people missing in Atlantic Canada.

Storm Track of Tropical Storm Alberto

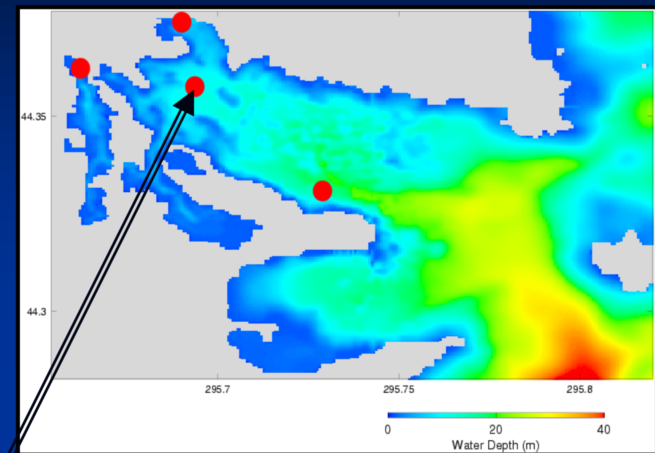


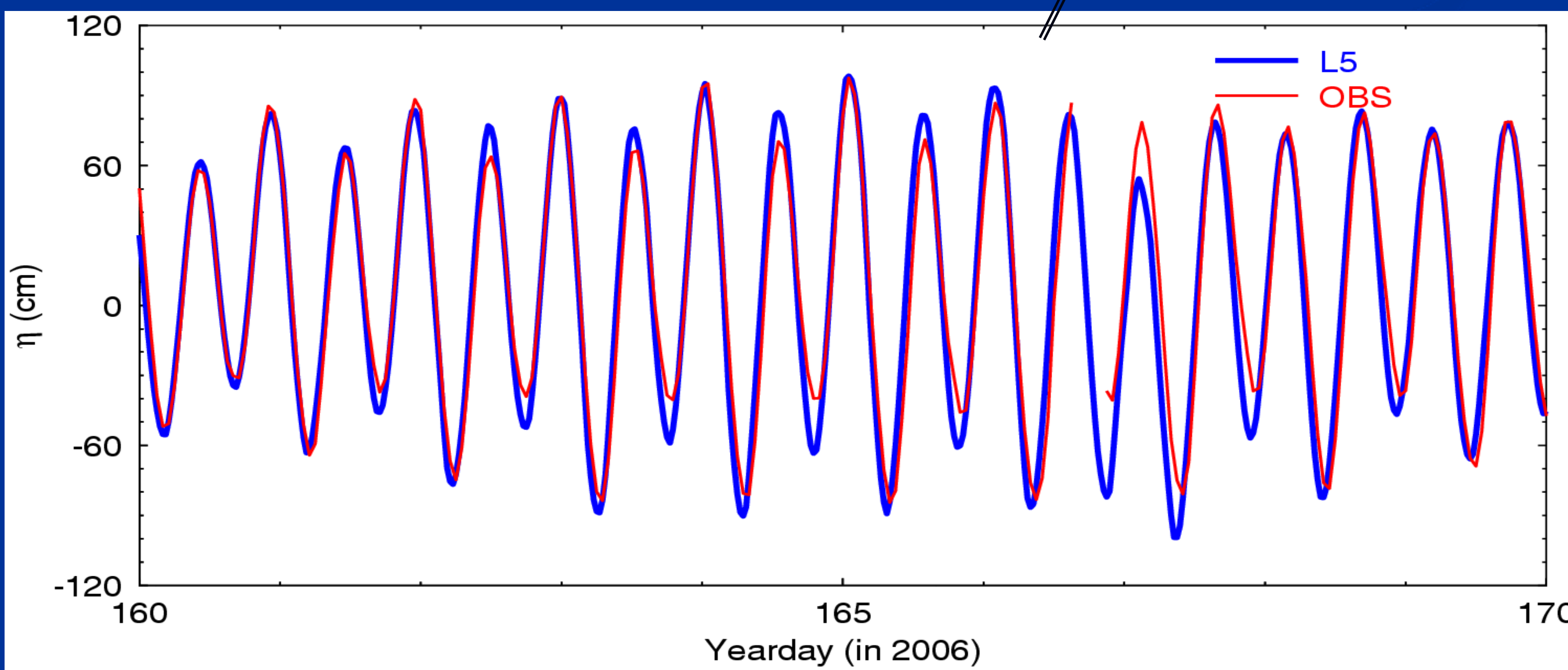


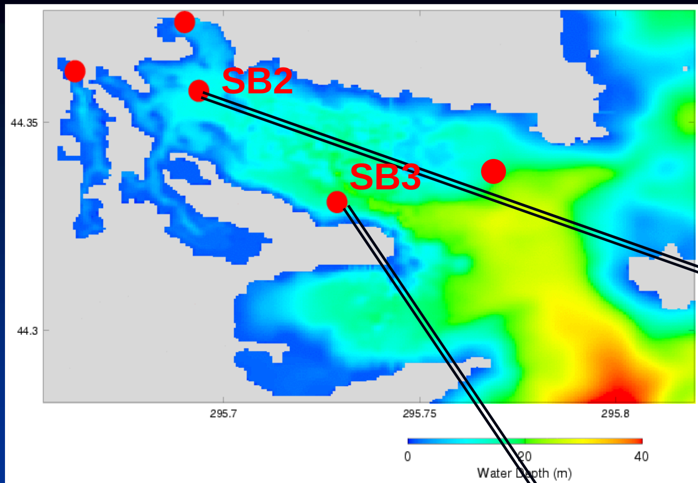
(June 15 - 18, 2006)

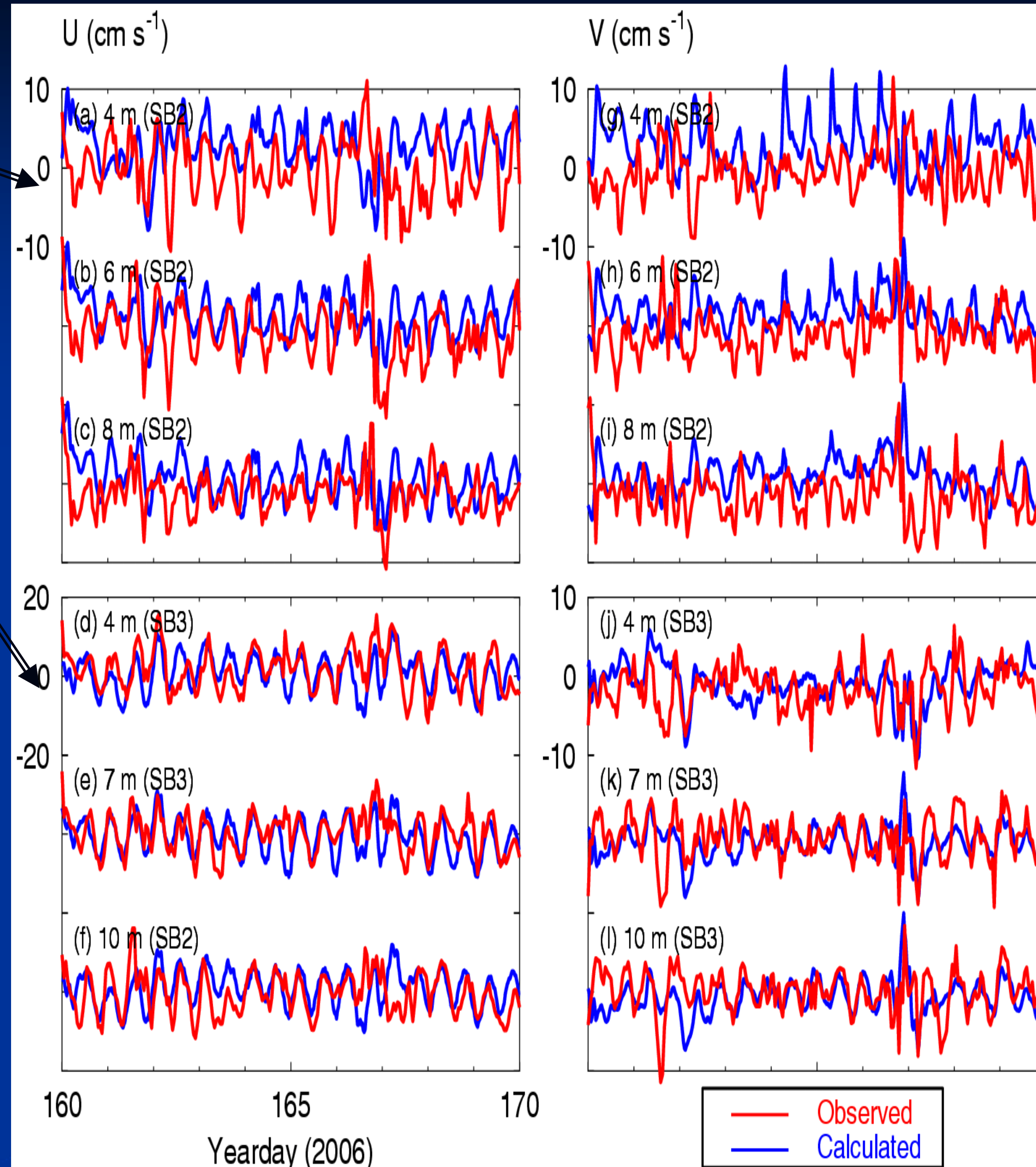
Model performance of NCOPS-LB

Comparison of observed and simulated surface elevations

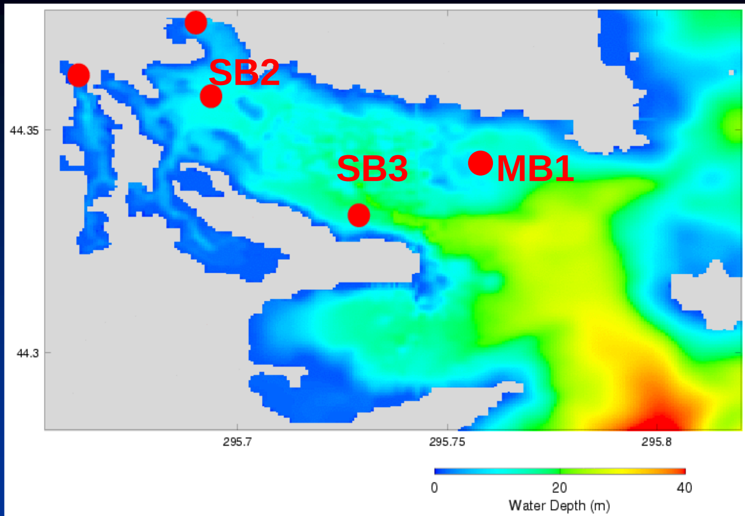




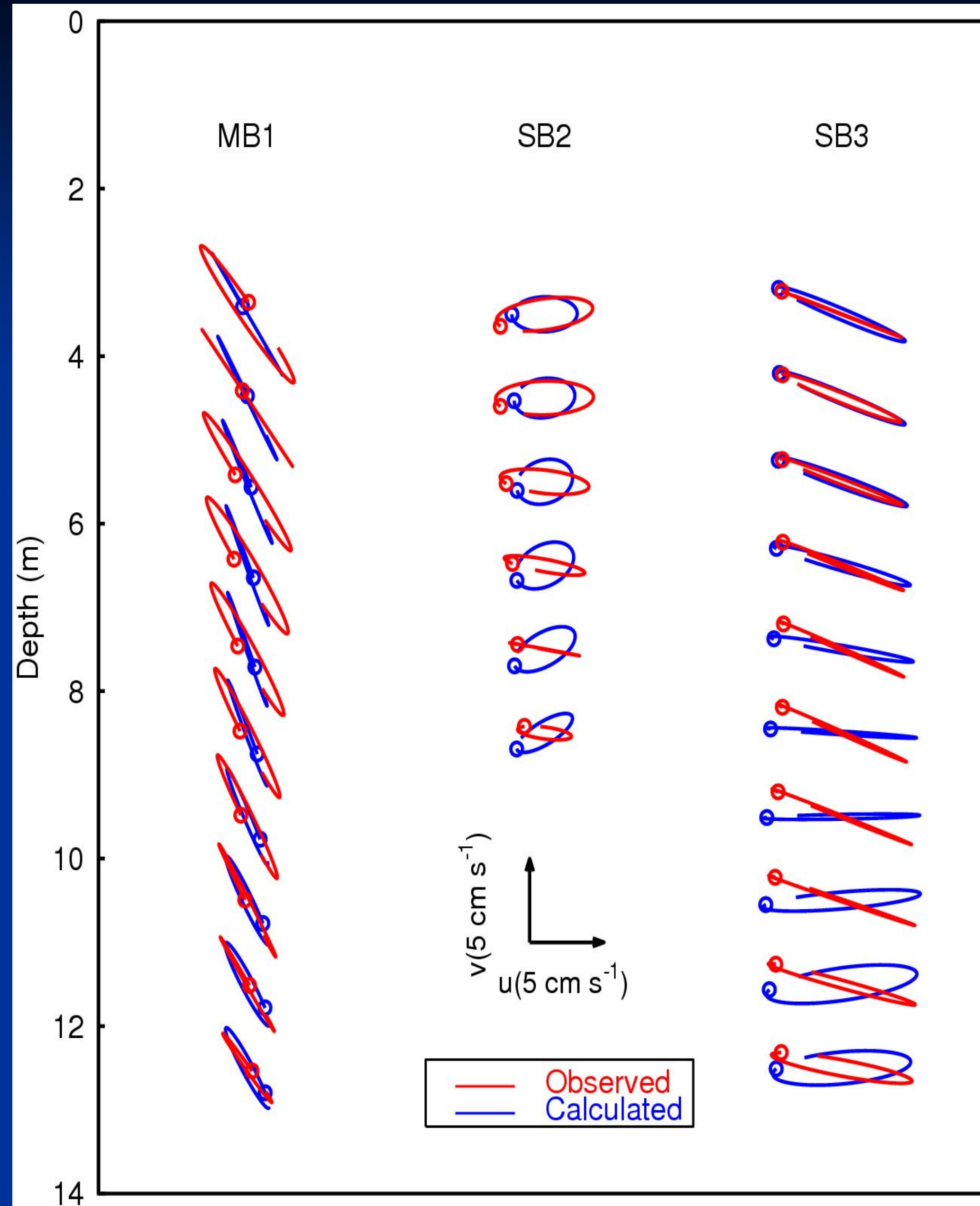




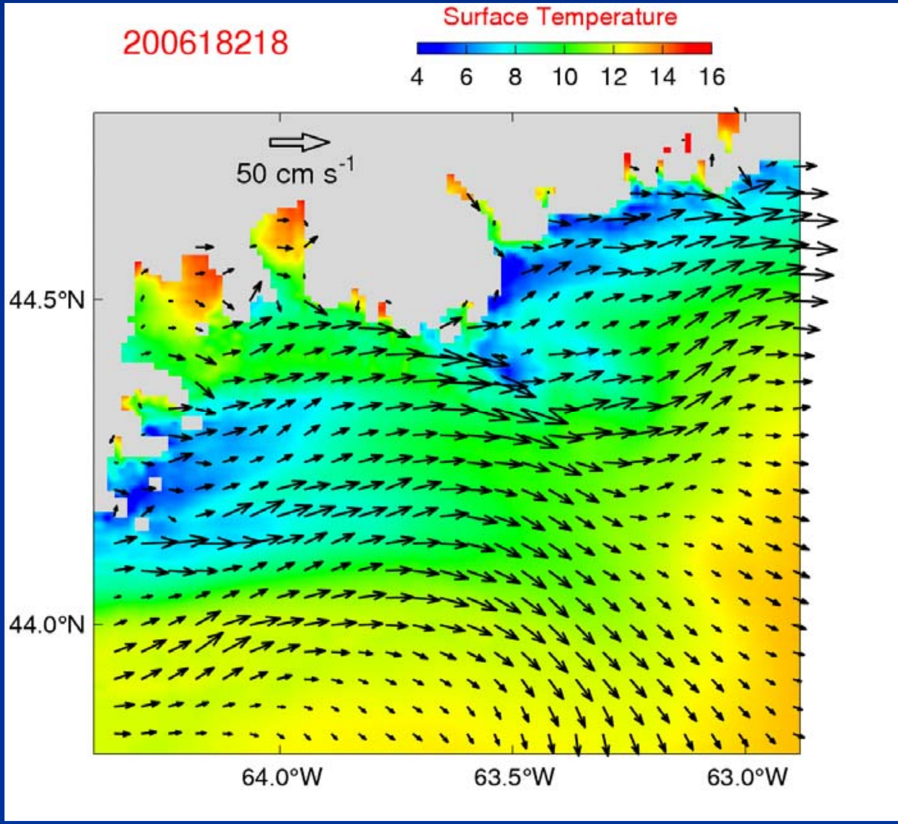
Comparison of observed and simulated currents at SB2 and SB3

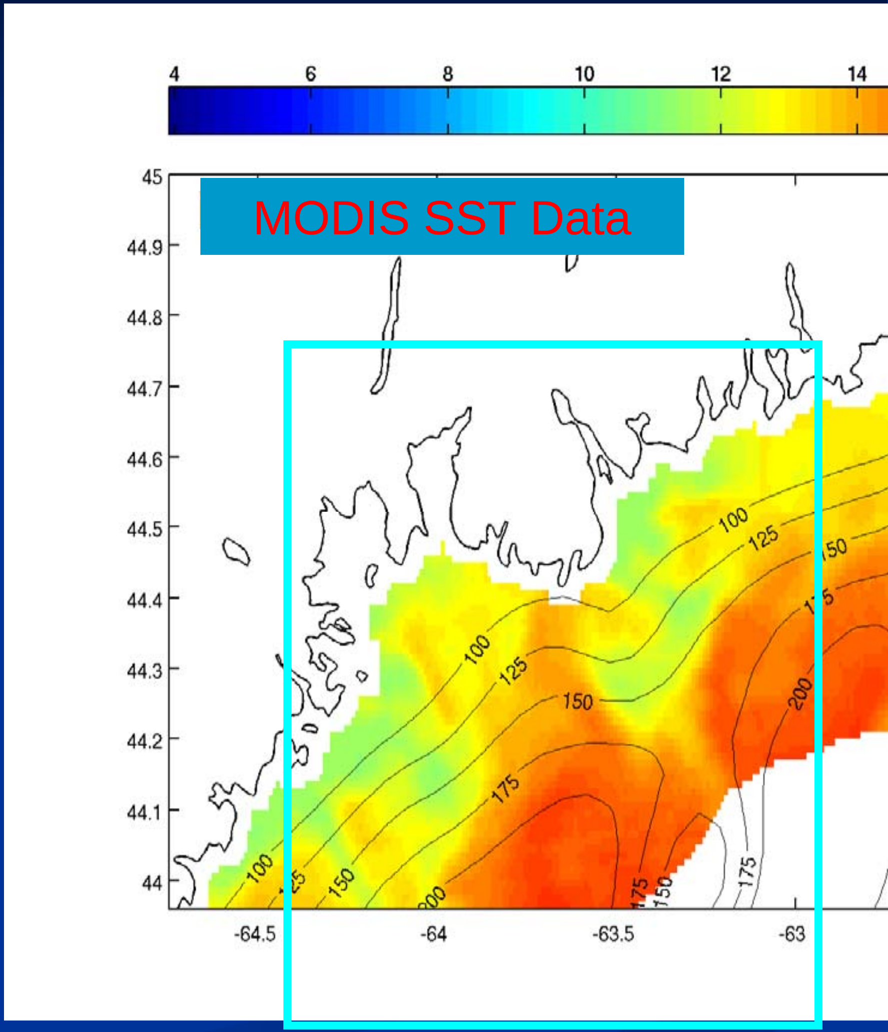


Comparison of observed and simulated M_2 tidal current ellipses at SB2, SB3 and MB1



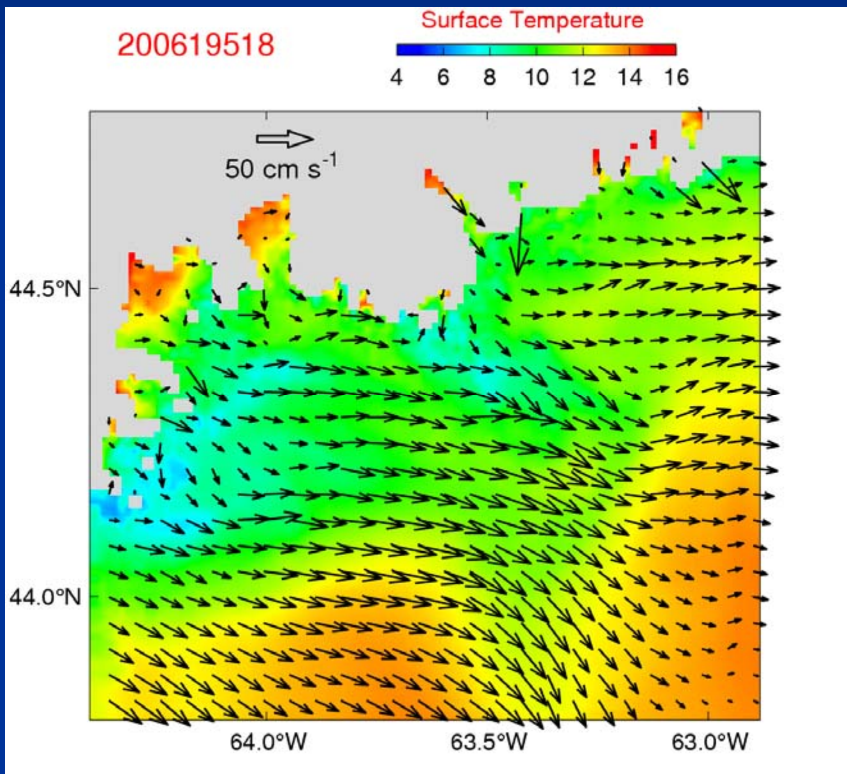
Model SST and near-surface currents (18:00 July 1 2006)

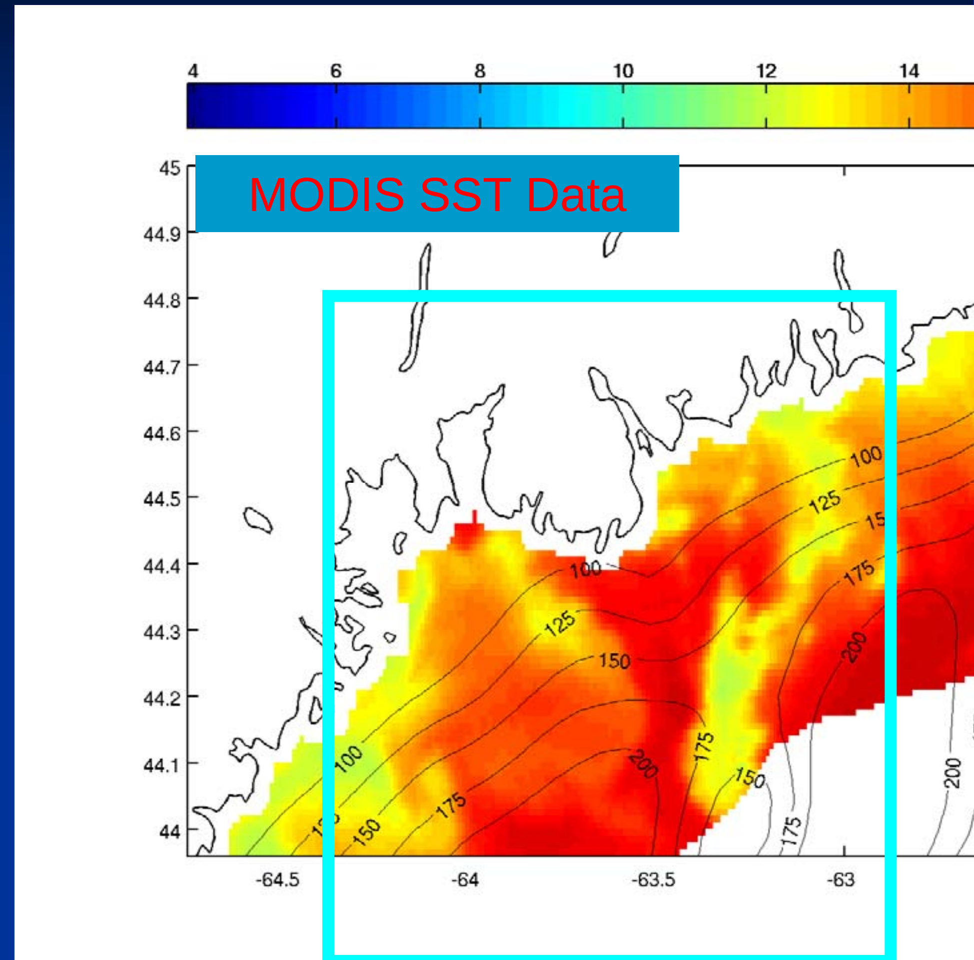




(by courtesy of Chris Jones)

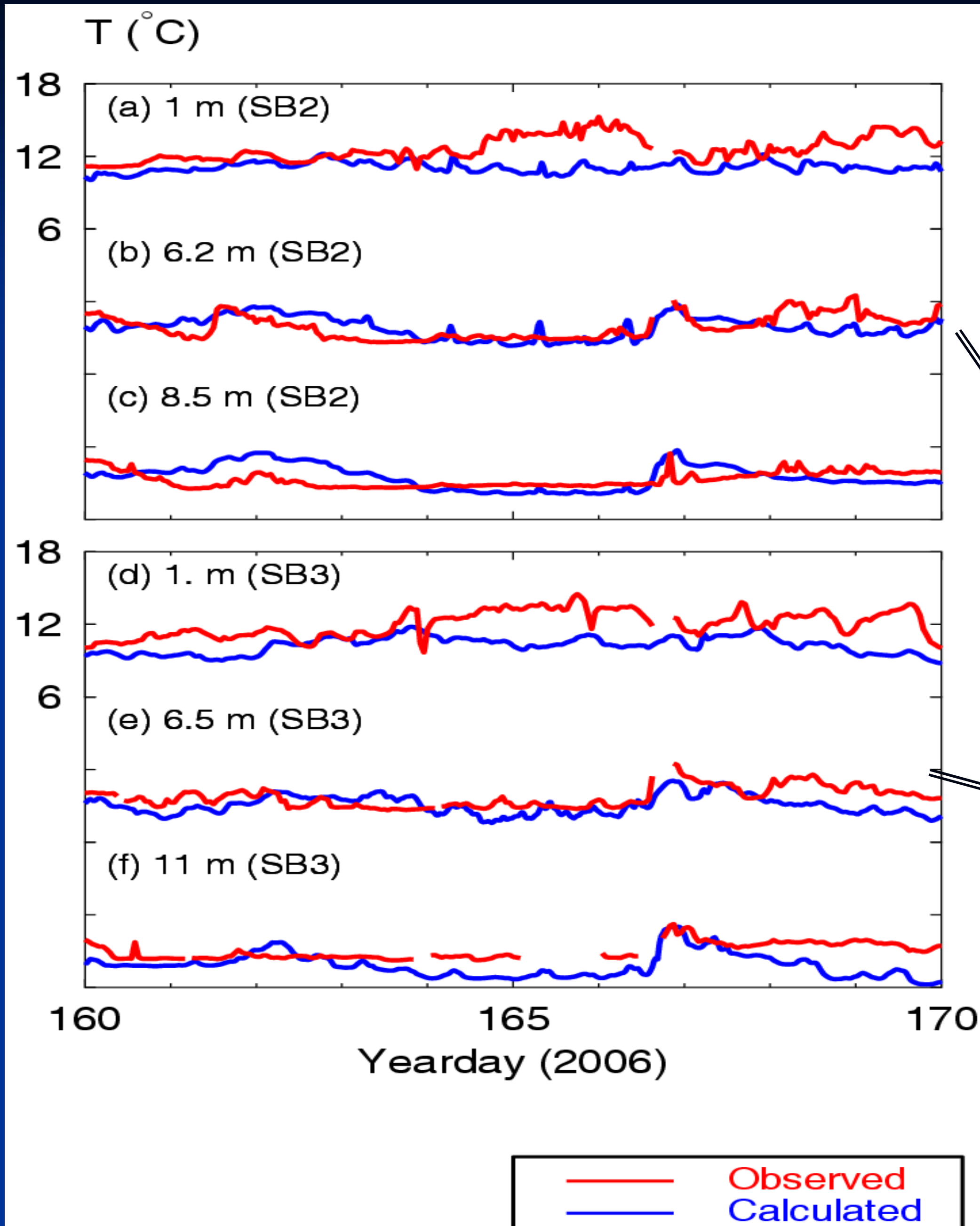
Model SST and near-surface currents (18:00 July 1 2006)

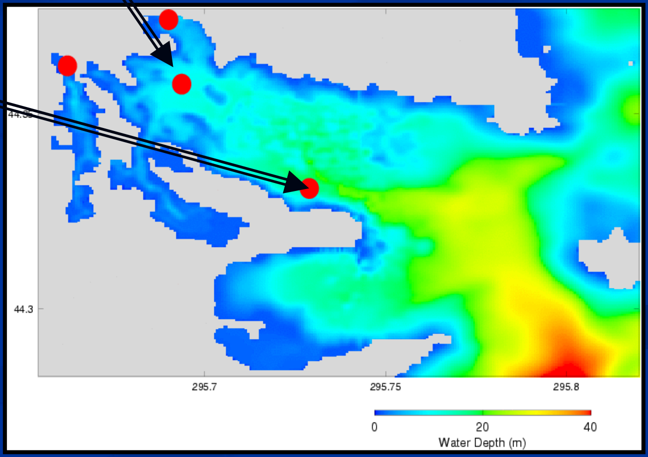


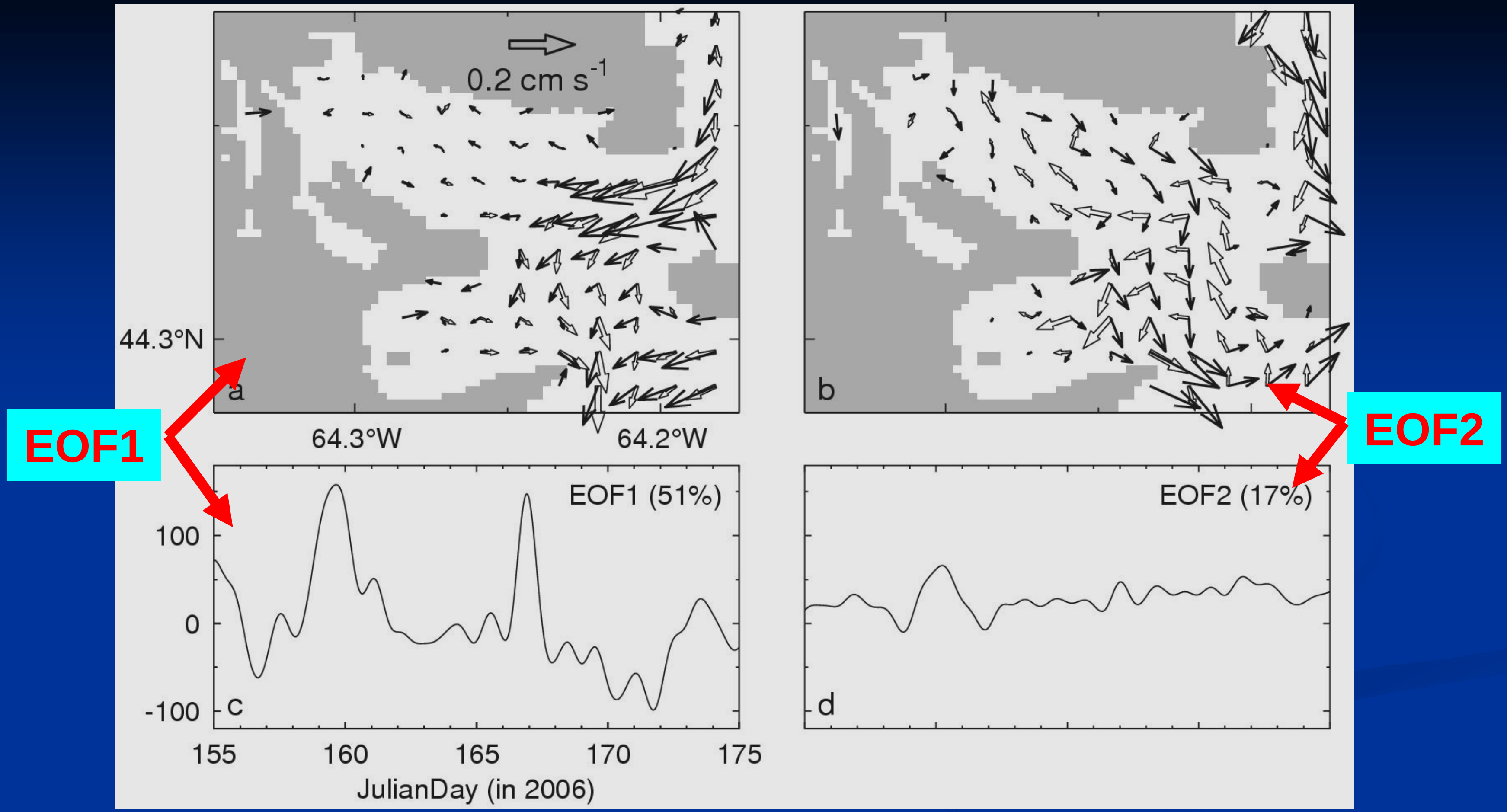


(by courtesy of Chris Jones)

Comparison of observed and simulated SST







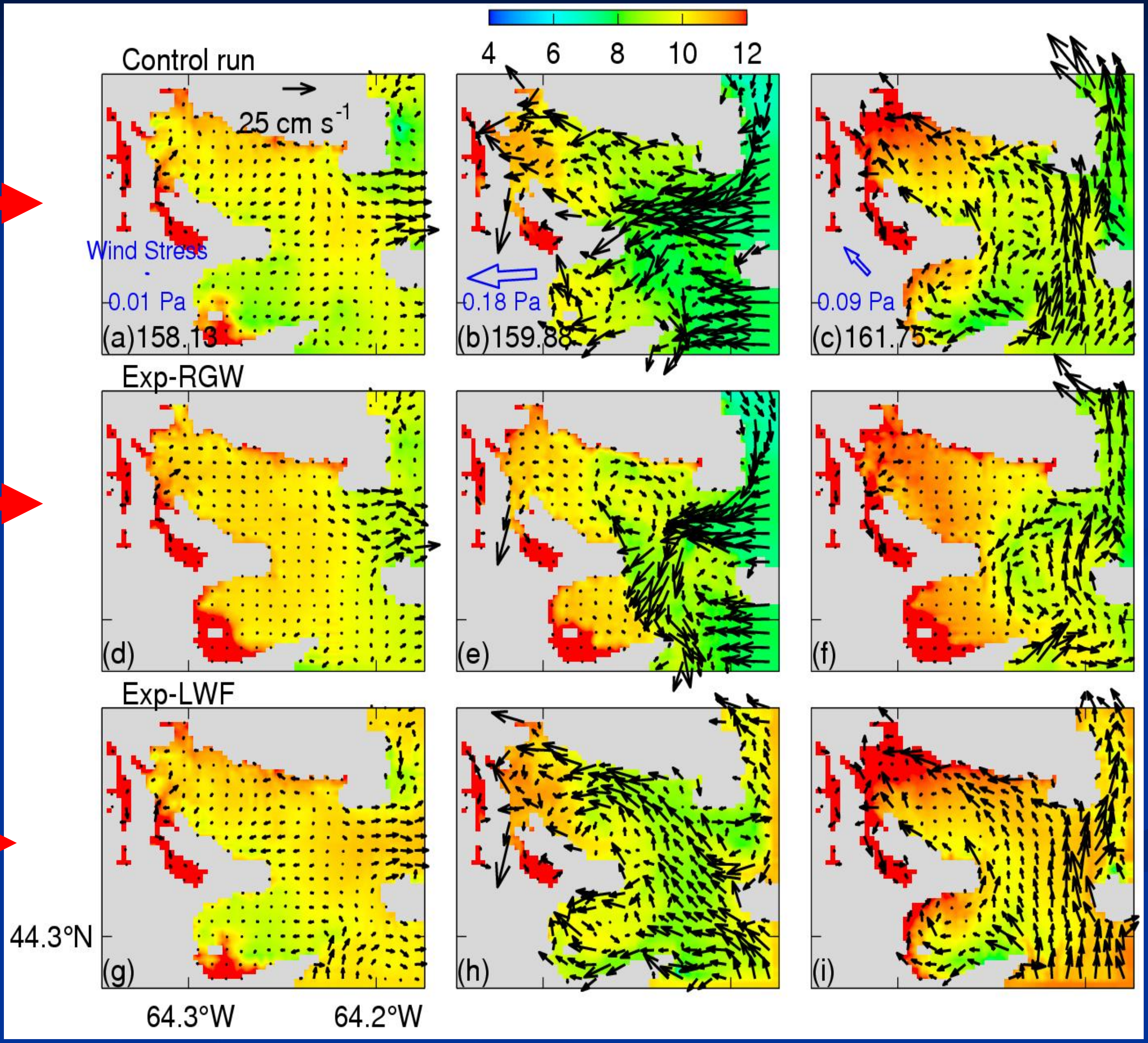
Eigenvectors and mode coefficients of at 3.5 m (solid arrow) and 8.5 m (open arrow) from day 155 to 175. Velocity vectors are plotted at every 5th grid point.

Model Sensitivity Study

Control Run

Exp-RGW

Exp-LWF



Outline of Part 2

2.1 Data analysis of observations

2.2 Process study of baroclinic dynamics

2.3 Numerical simulation of 3D circulation

2.4 Data assimilation using the pressure-correction method

2.5 Summary

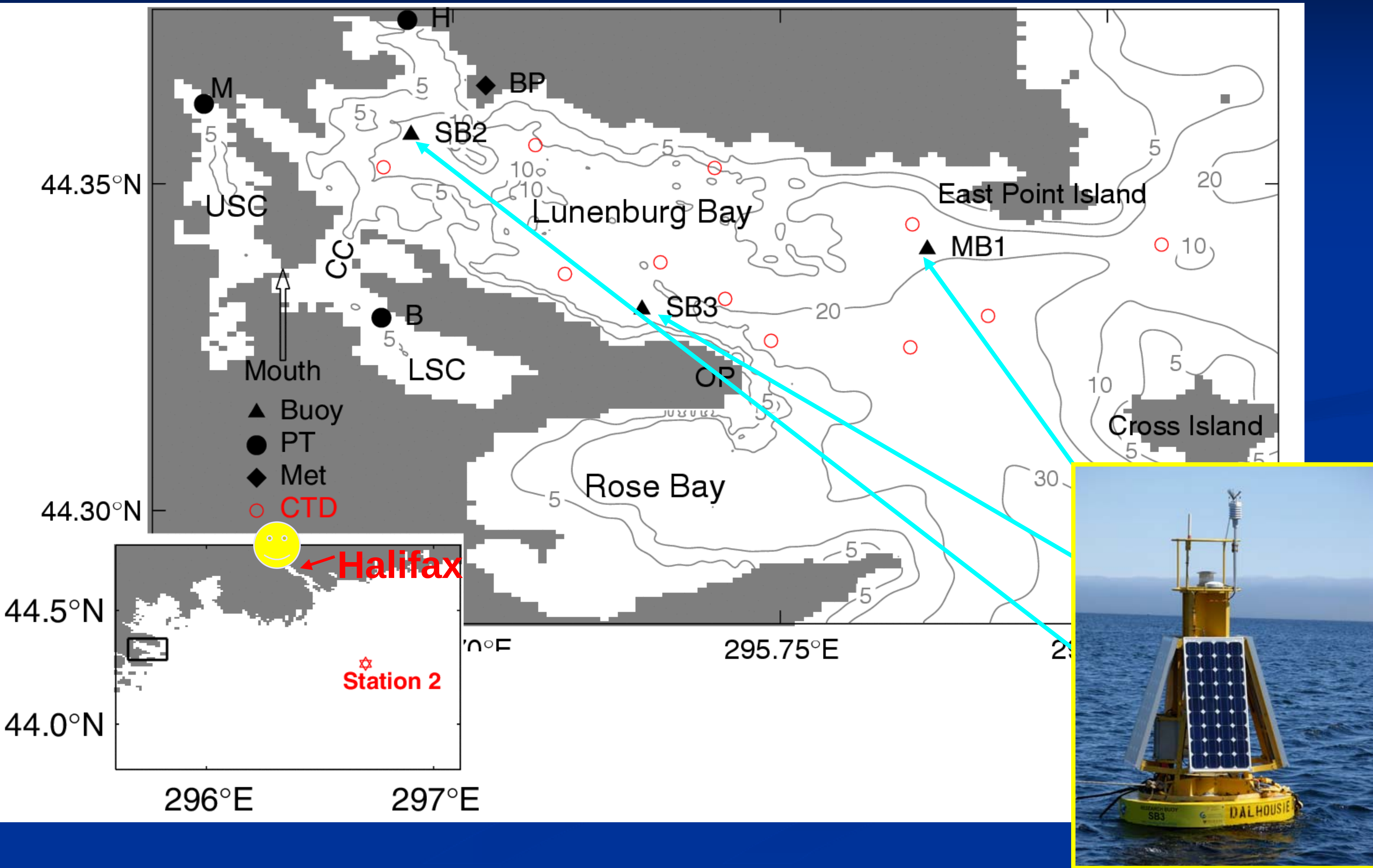
References:

(a) Zhai, Ph.D thesis, 2008; (b) Zhai et al., CSR, 2007; (c) Zhai et al., CSR, 2008 (in press); (d) Zhai et al., JGR-Oceans, 2008.

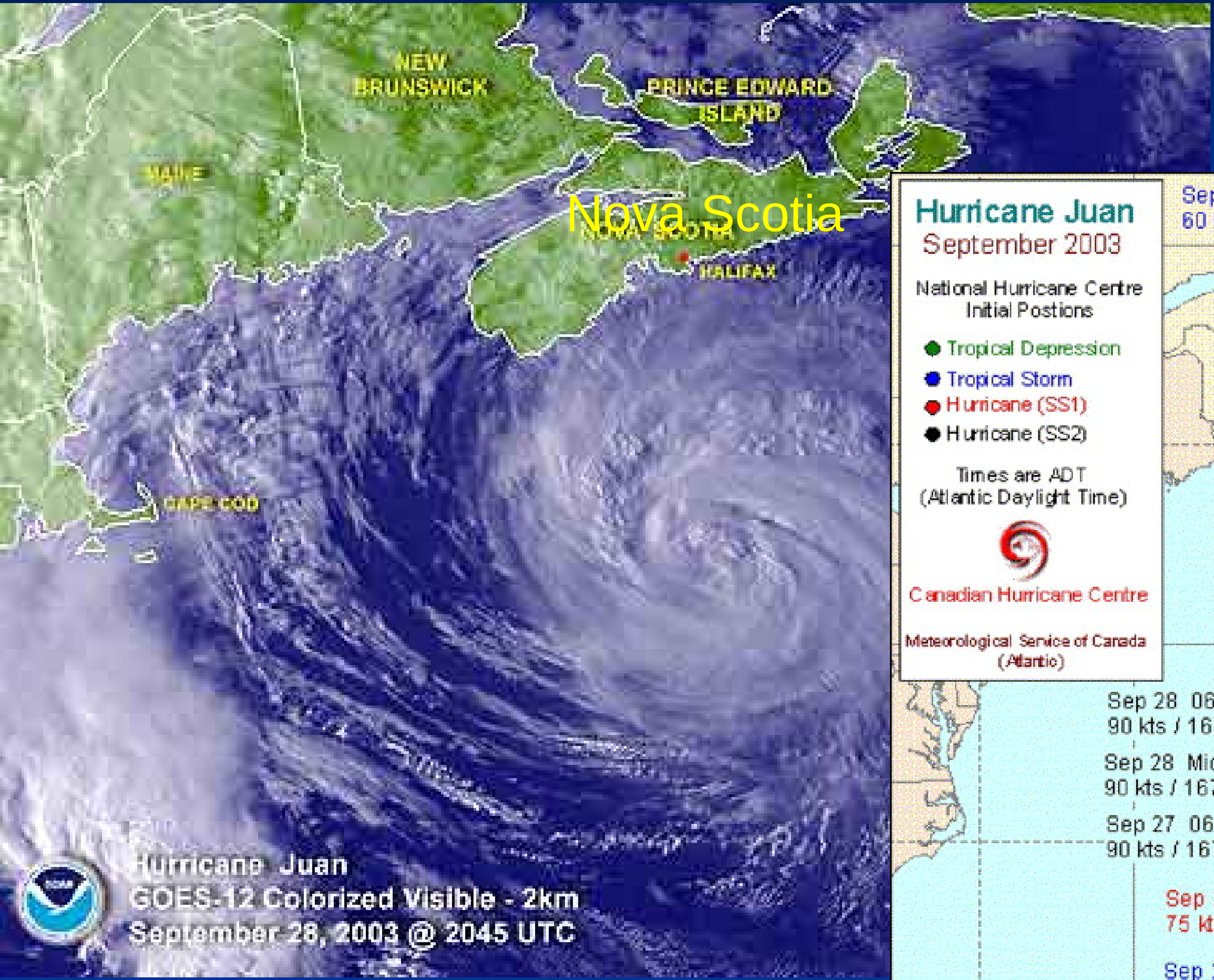
The Main Objective of Part 2:

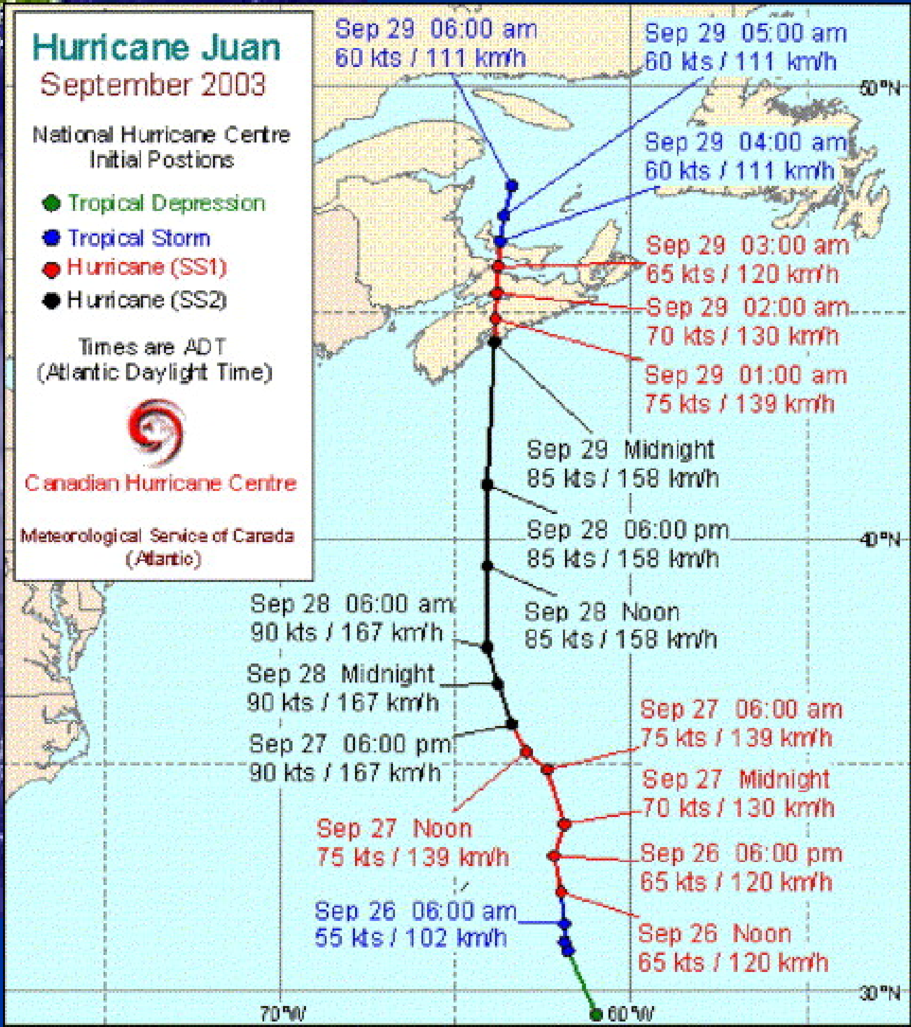
To have better understanding of baroclinic dynamics, water mass distributions, and associated variability over coastal waters using observations and three-dimensional ocean circulation models.

2.1 Data Analysis of Observations (Aug-Oct, 2003)

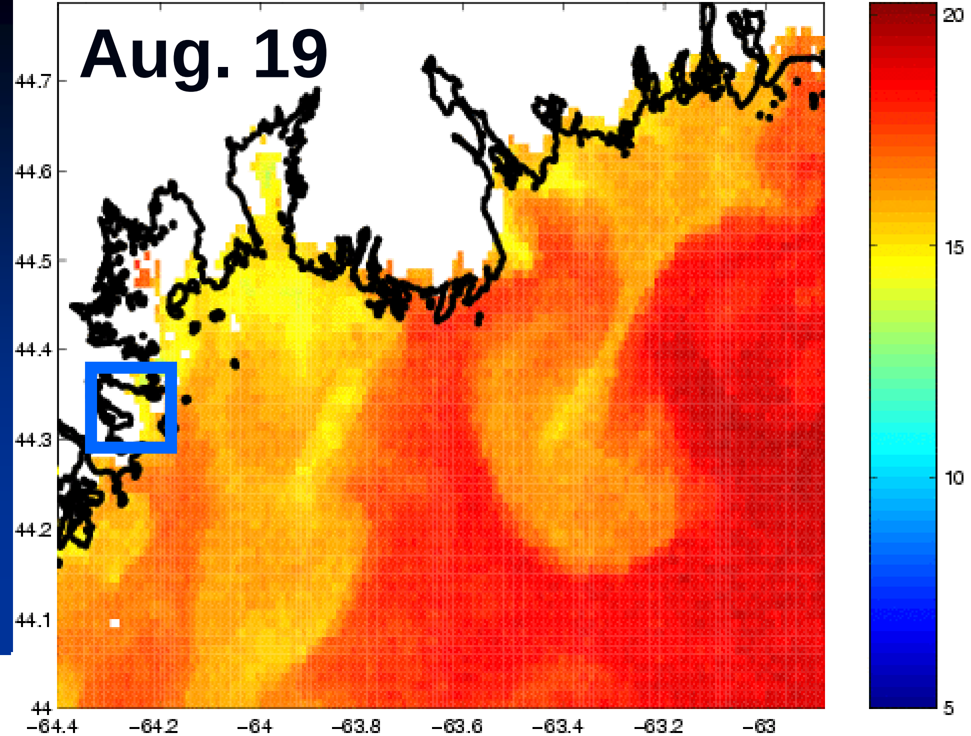


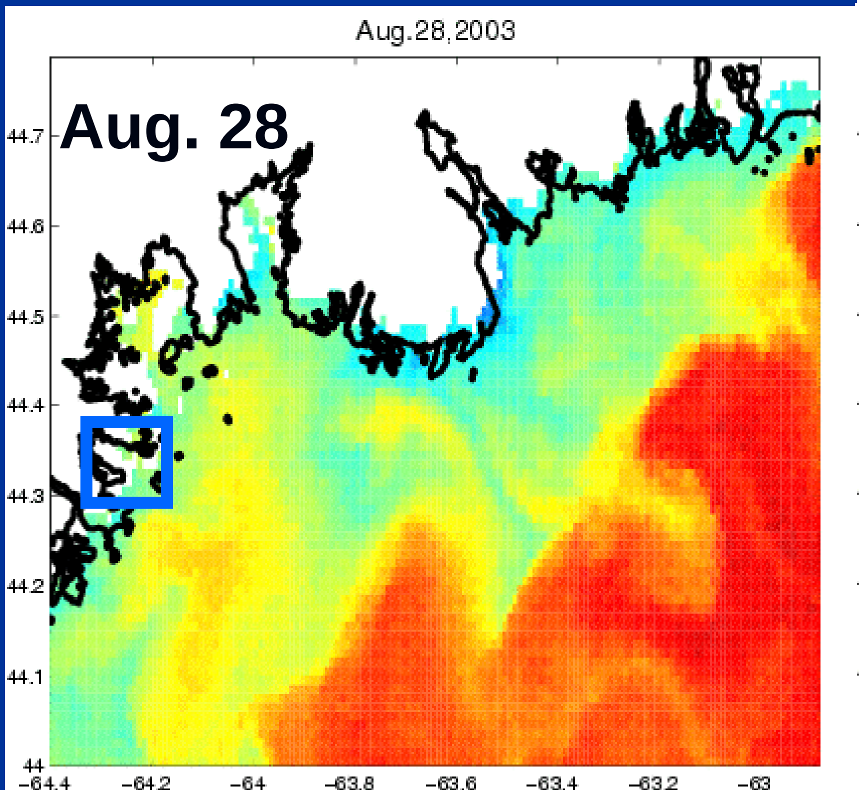
Hurricane Juan (Sep. 29, 2003)

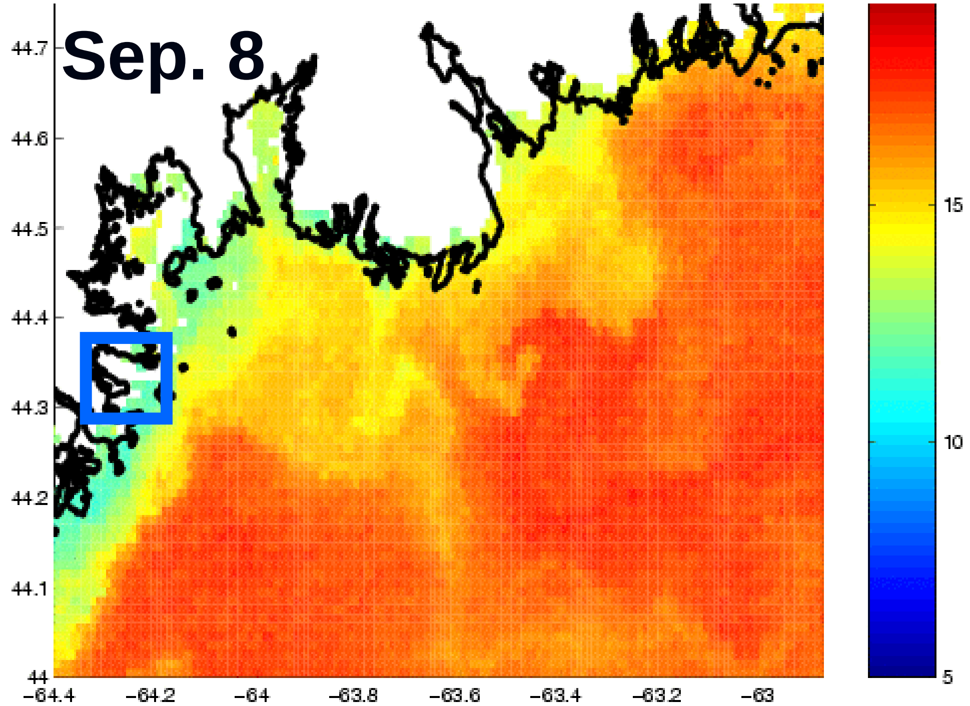




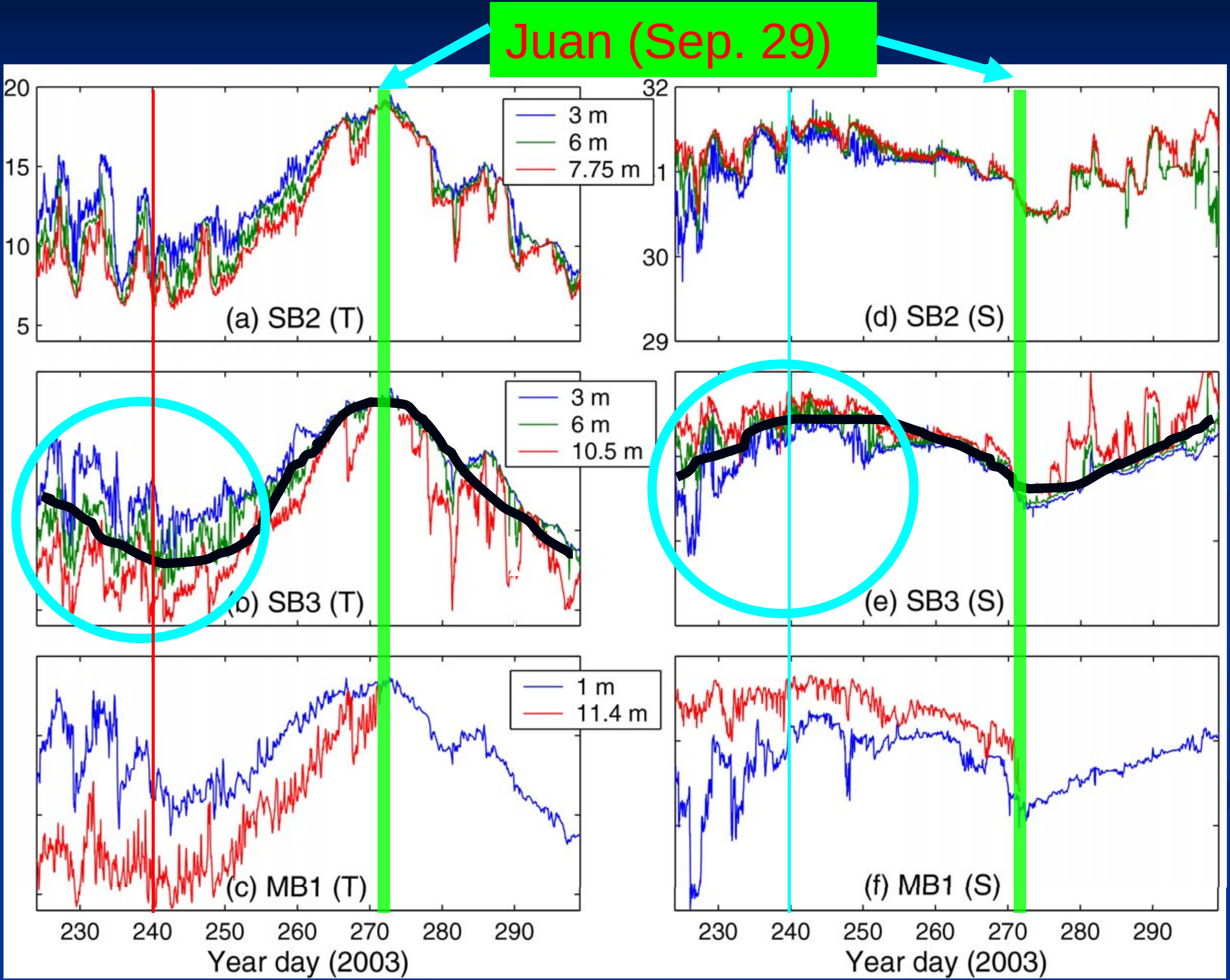
Coastal Upwelling (2003)
(Satellite MODIS SST)



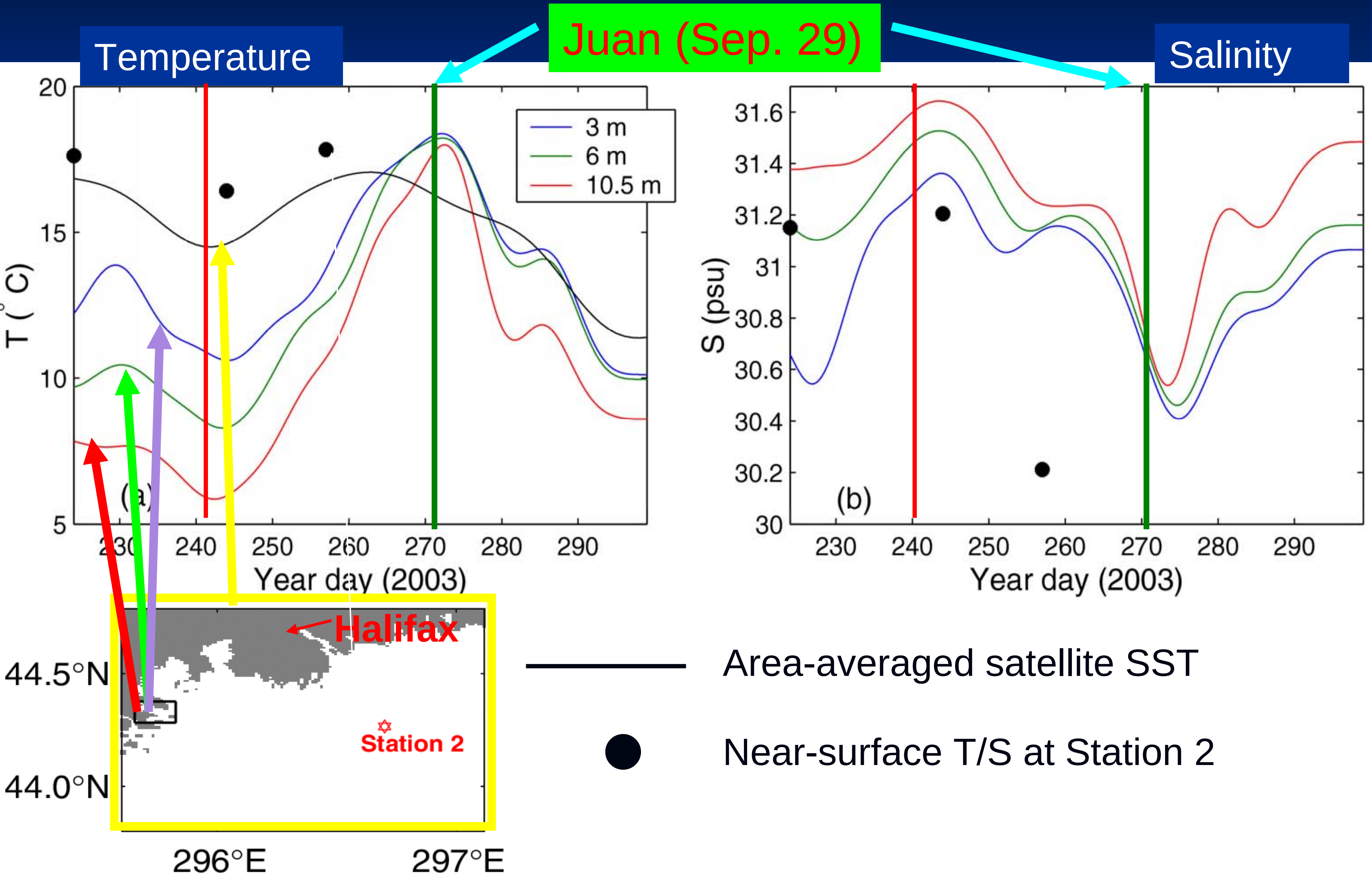




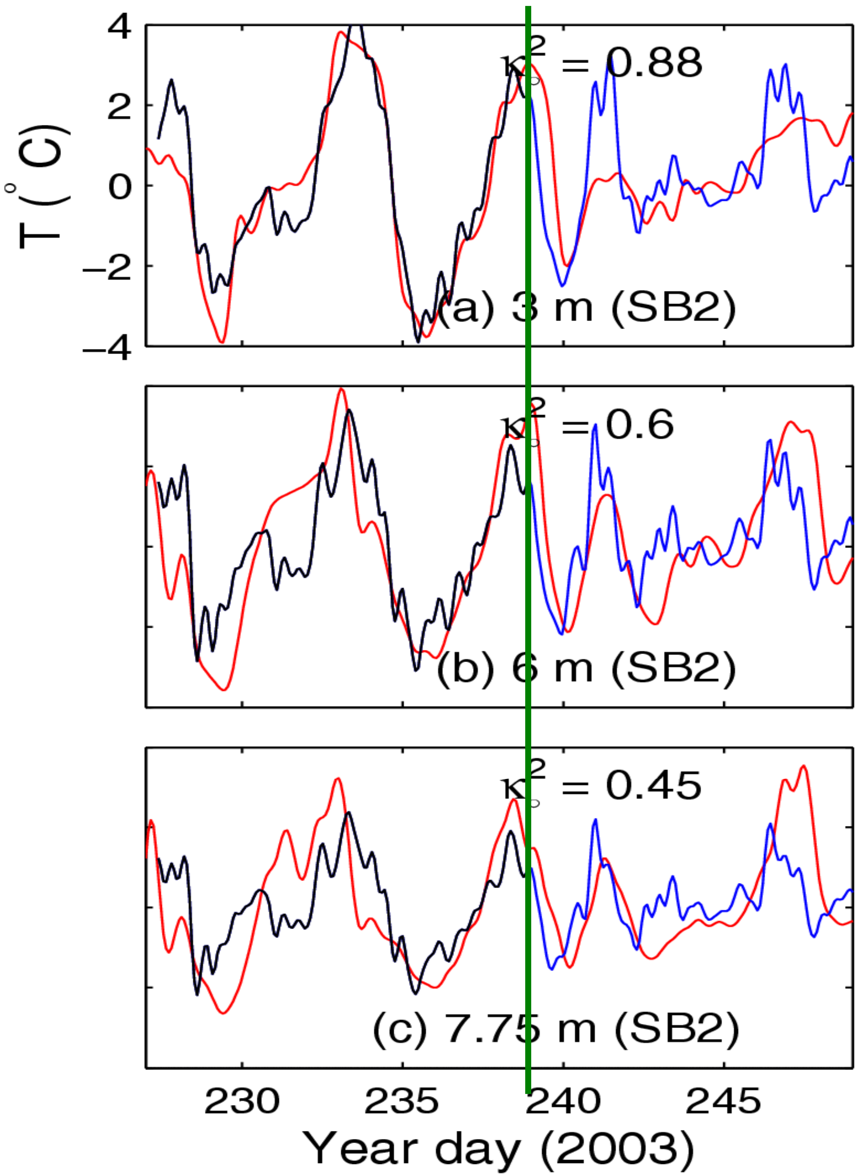
Observed Temperature/Salinity in Lunenburg Bay
(August 13-October 27, 2003)



Low Frequency (>10 days) Variability of Observed T/S at SB3 (August 13-October 27, 2003)



High-frequency (1-10 days) Variability of Temperature at SB2 (August 13 - September 7, 2003)



$$T(t) = \sum_{i=0}^{n} [a_i \tau_x (t - i\Delta t) + b_i \tau_y (t - i\Delta t)] + \epsilon_t$$

Δt = 2 hours
n = 6

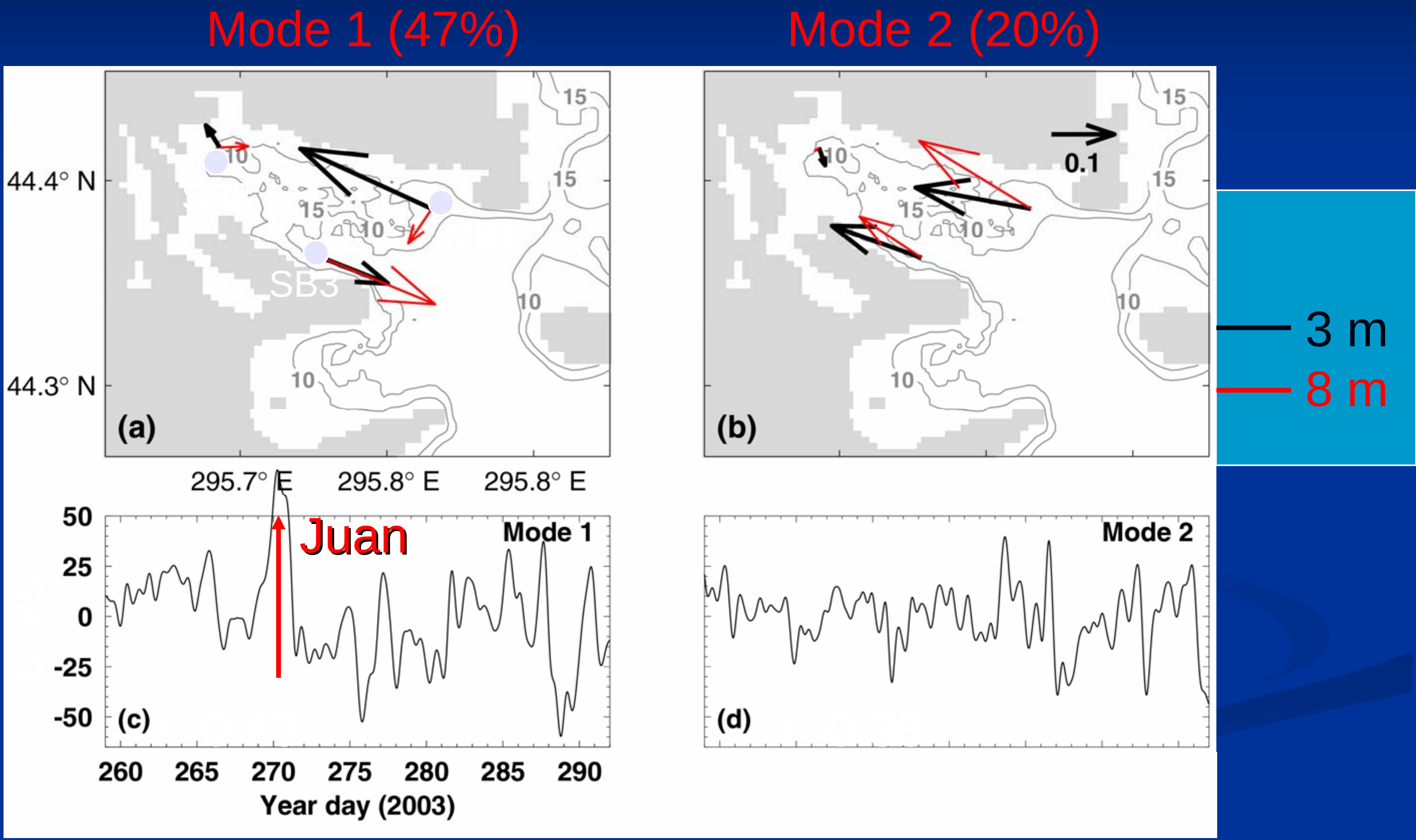
Observed

Fitted

Predicted

K^2: proportion of the observed T accounted for by statistical model

Variability of Observed Non-Tidal Currents (Empirical Orthogonal Function Analysis)

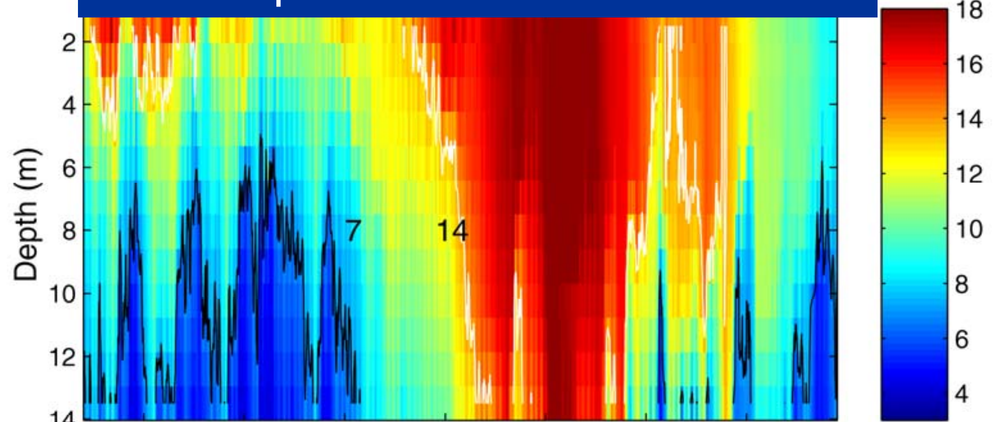


Heat Budget Analysis (August 13-October 27, 2003)

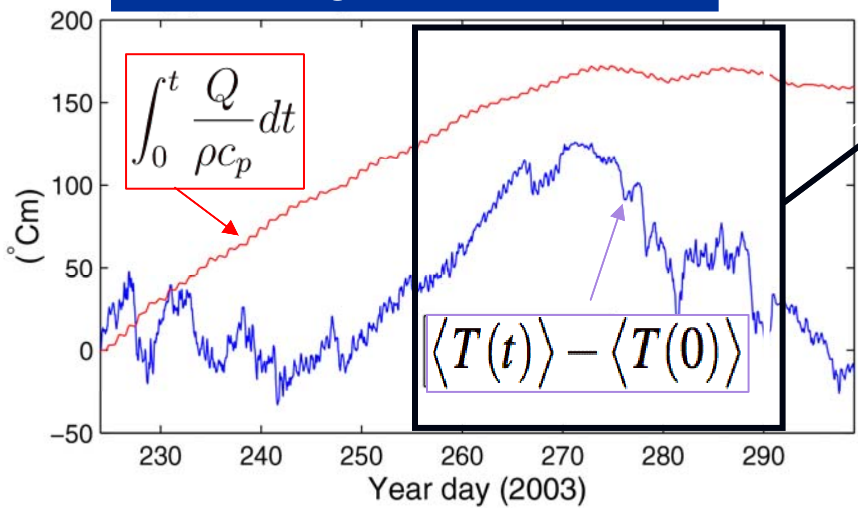
$$\langle T(t)\rangle - \langle T(0)\rangle = \int_0^t \frac{Q}{\rho c_p}dt + \int_0^t \Gamma dt$$

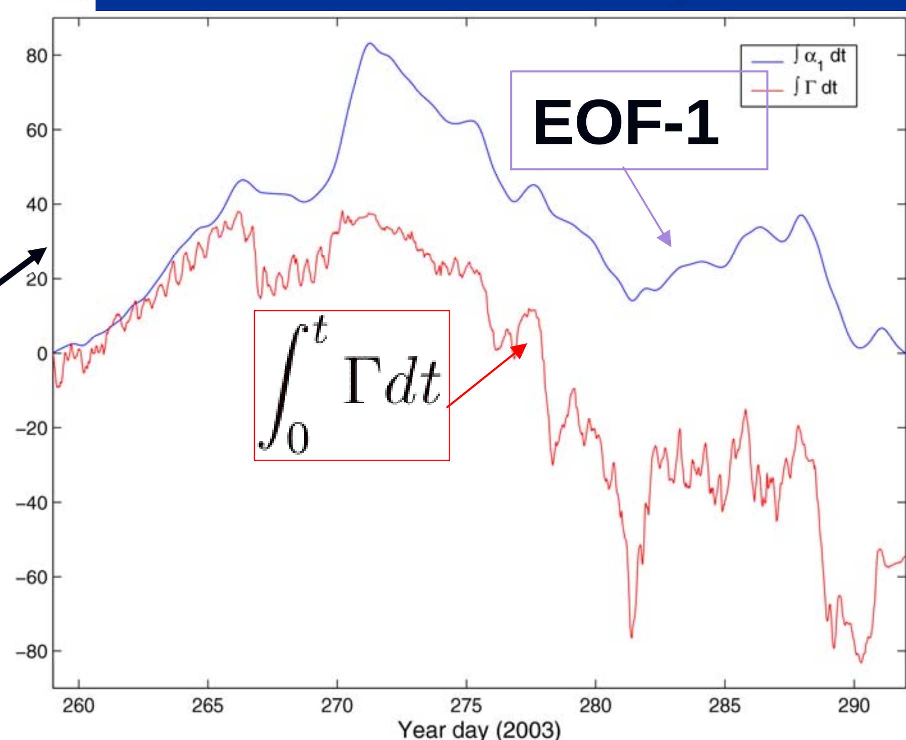
$$\langle\rangle = \int_{-h}^{0} dz$$

Time-depth distribution of T at SB3



Heat budget at SB3





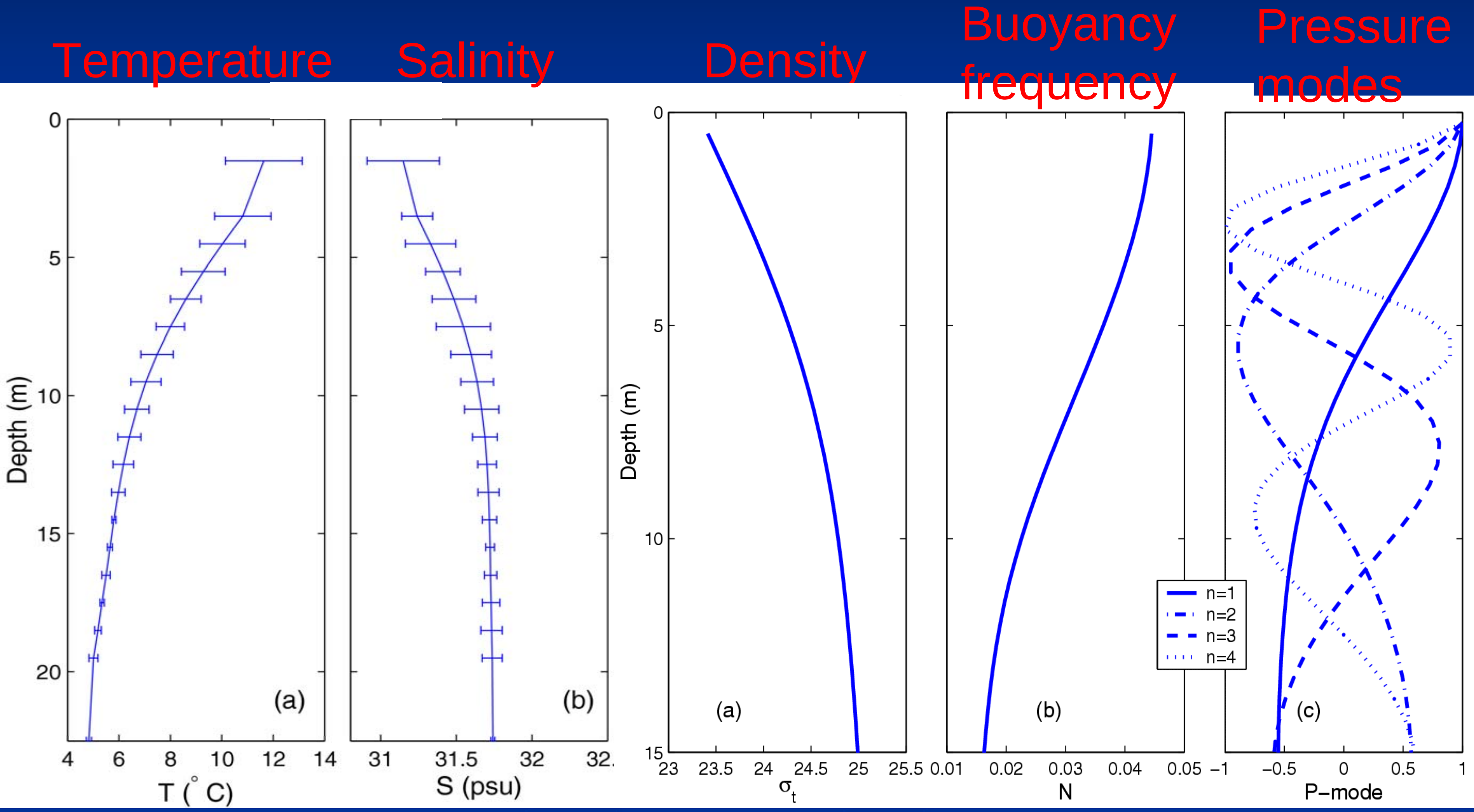
2.2 Process Study of Baroclinic Dynamics Using a Linear Multi-mode Model

Main Features and Model Setup:

- ❖ Model equation is solved by the normal mode approach.
- ❖ Ten dynamic modes are used for the calculation.
- ❖ Density anomaly and baroclinic currents are calculated.
- ❖ Driven by wind forcing only.
- ❖ Realistic coastline with uniform water depth of 15 m.

References:
Gill and Clarke, 1974; McCreary, 1981; Davidson et al, 2001; Heaps, 1971

Hydrographic Measurements
(September 6, 2003)

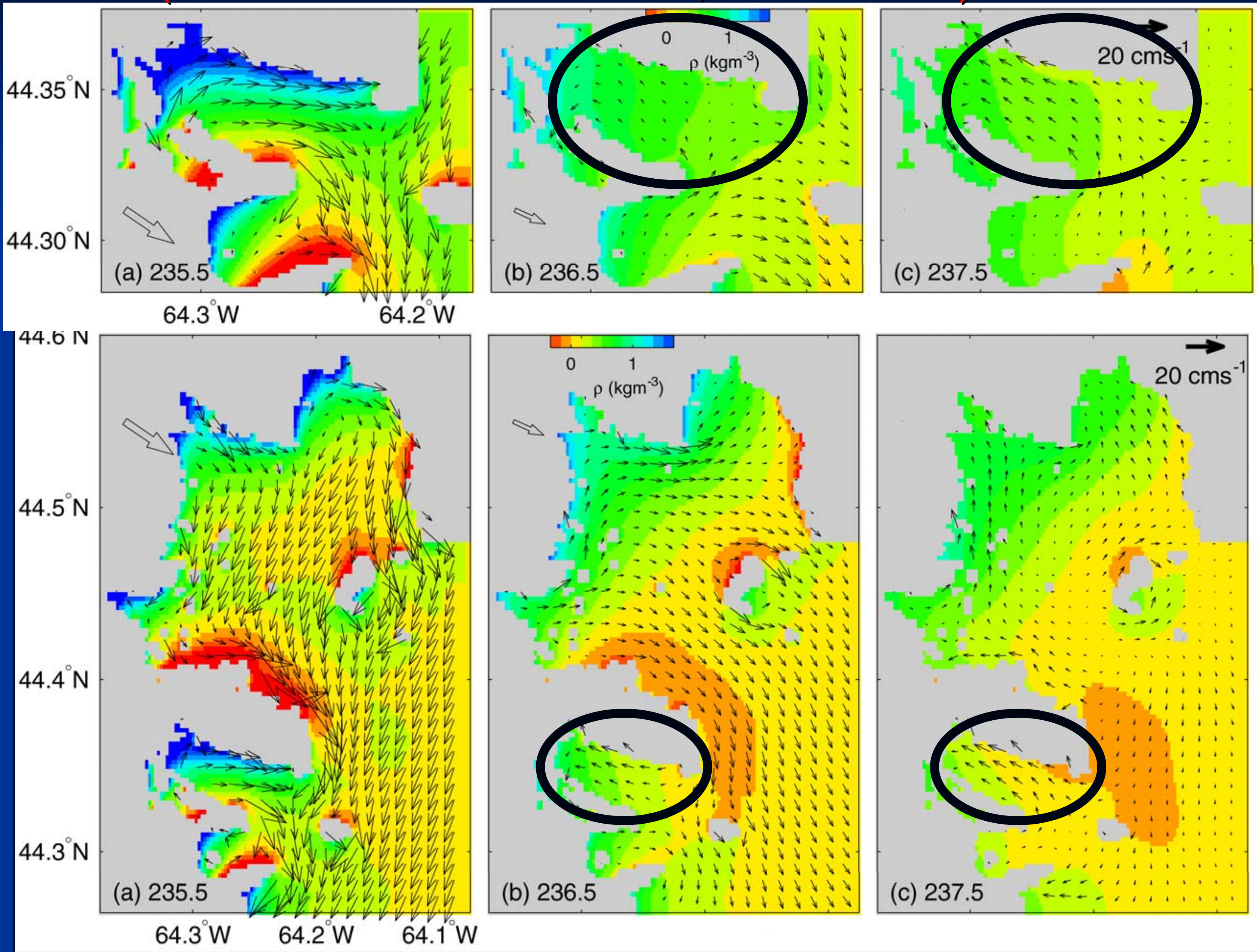


Near-surface Currents and Density Anomaly

(Linear Multi-mode Model, Flat bottom)

LB

MB +LB



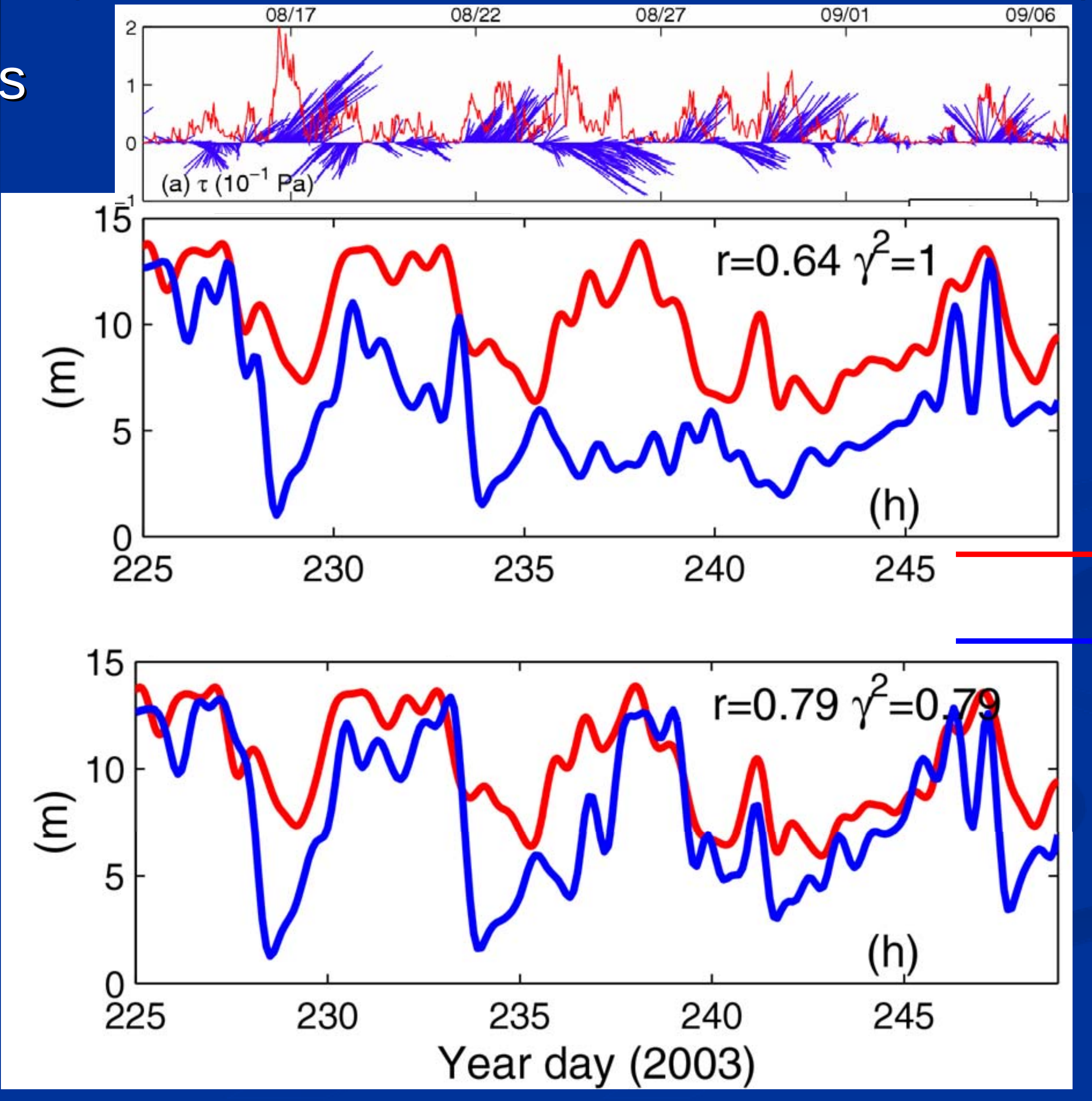
Comparison of Isopycnal Depths at SB3

Aug.13 Sep.7

Wind Stress

LB

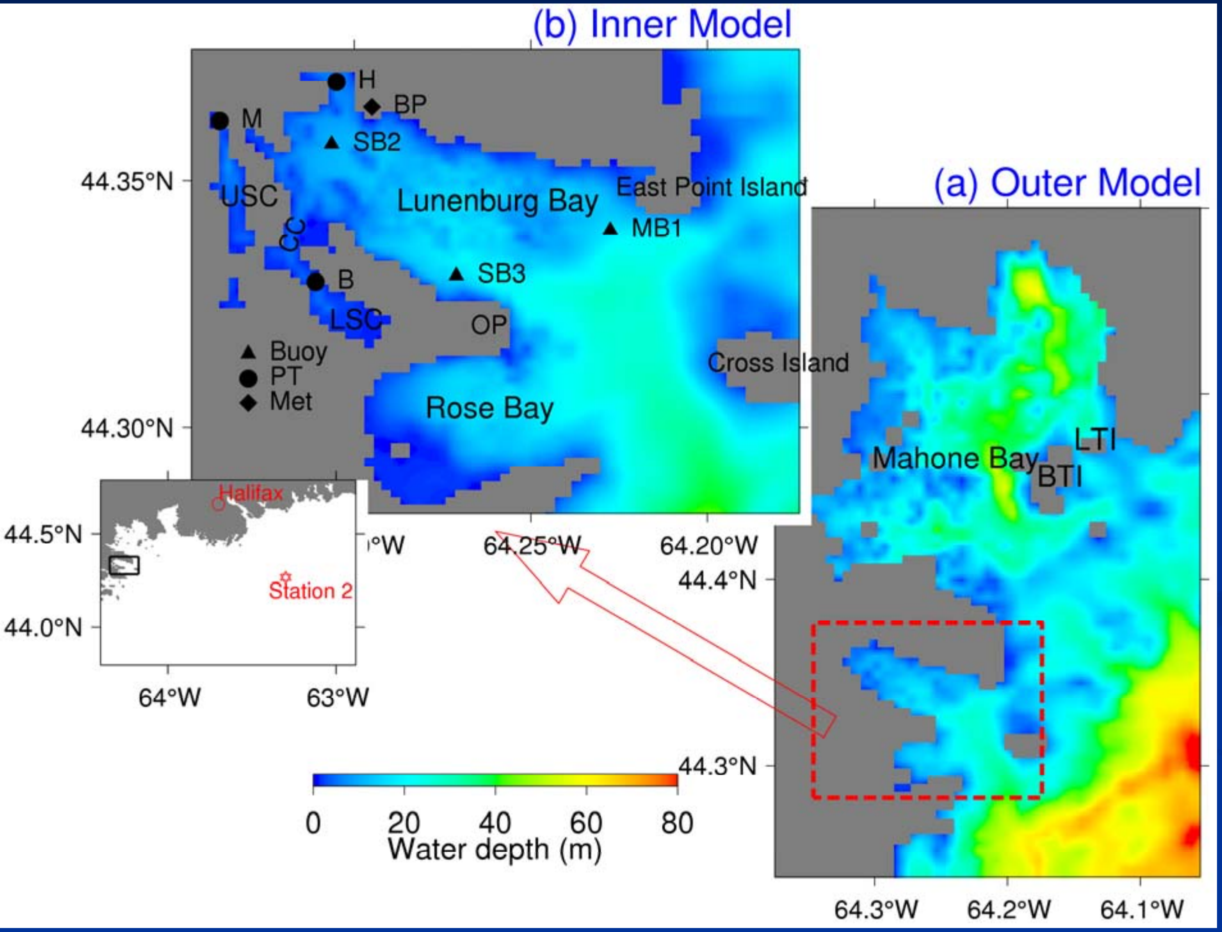
LB+MB



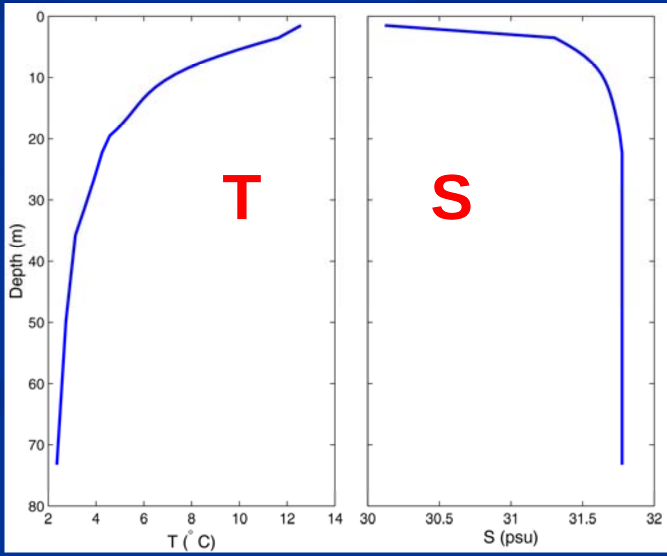
Obs.

Model

2.3 Simulation using a 2-Level Nested-Grid System



- CANDIE
- Resolution
  - Inner: ~200 m
  - Outer: ~500 m
  - 24 z-levels
- OBCs
- Initial T/S



References:

Sheng, Wright, Greatbatch, Dietrich,1998; Lu et al., 2001; Sheng and Wang, 2004

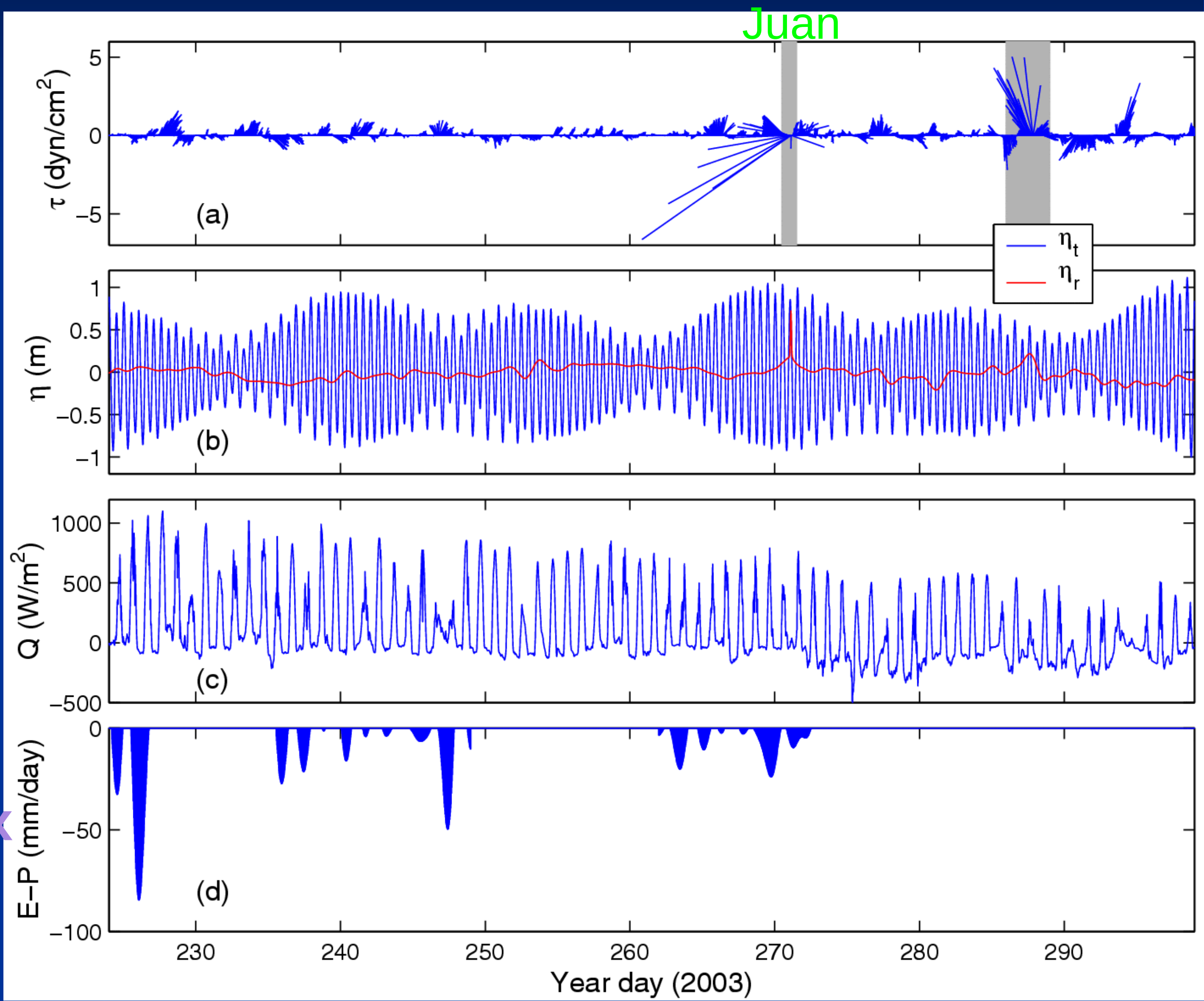
Model Forcing (August-October, 2003)

Wind Stress

Tides and RGWs

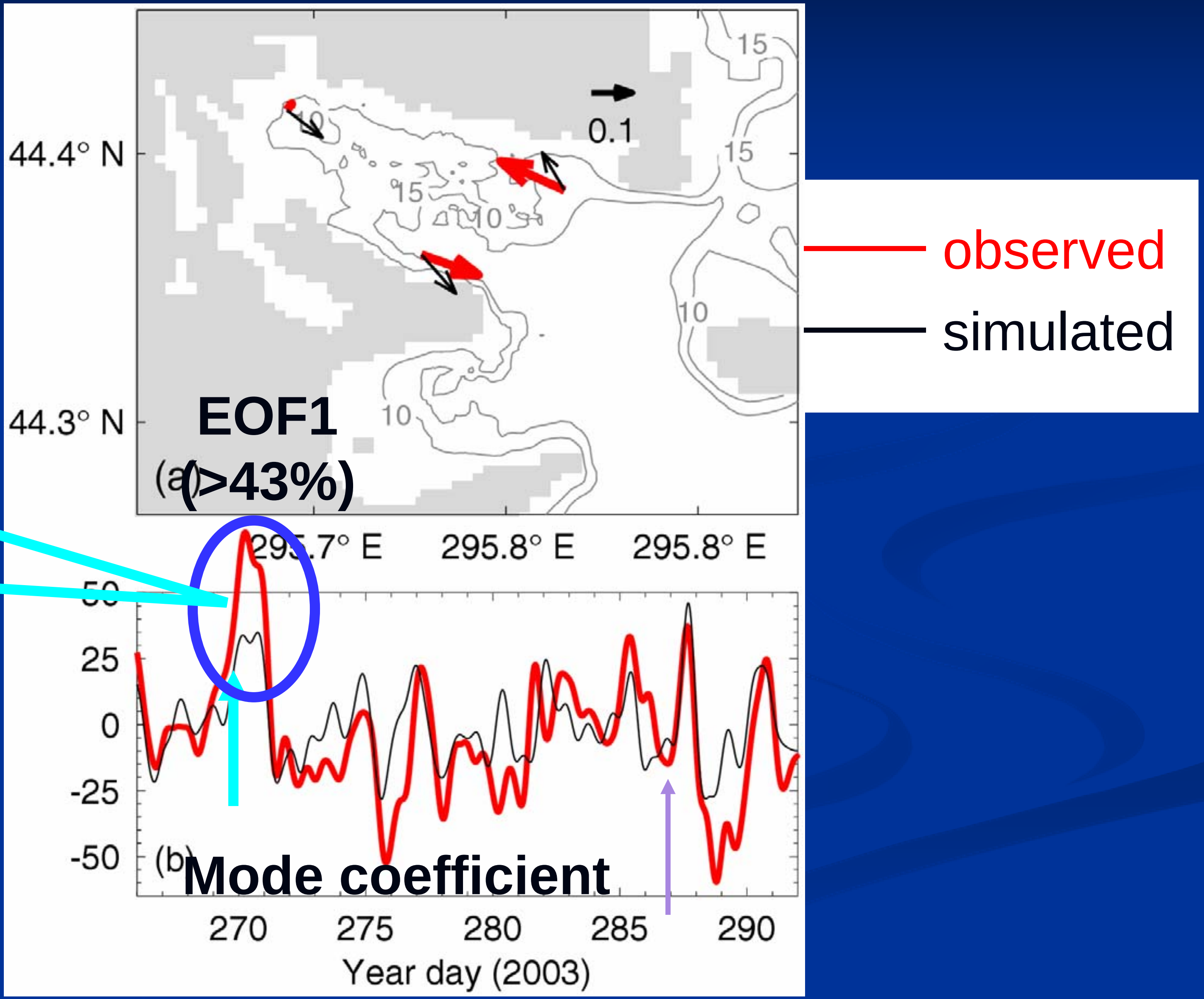
Surface Heat Flux

Surface Freshwater Flux (Diagnosed)



Near-surface Non-tidal Currents

(September 17-October 20, 2003)



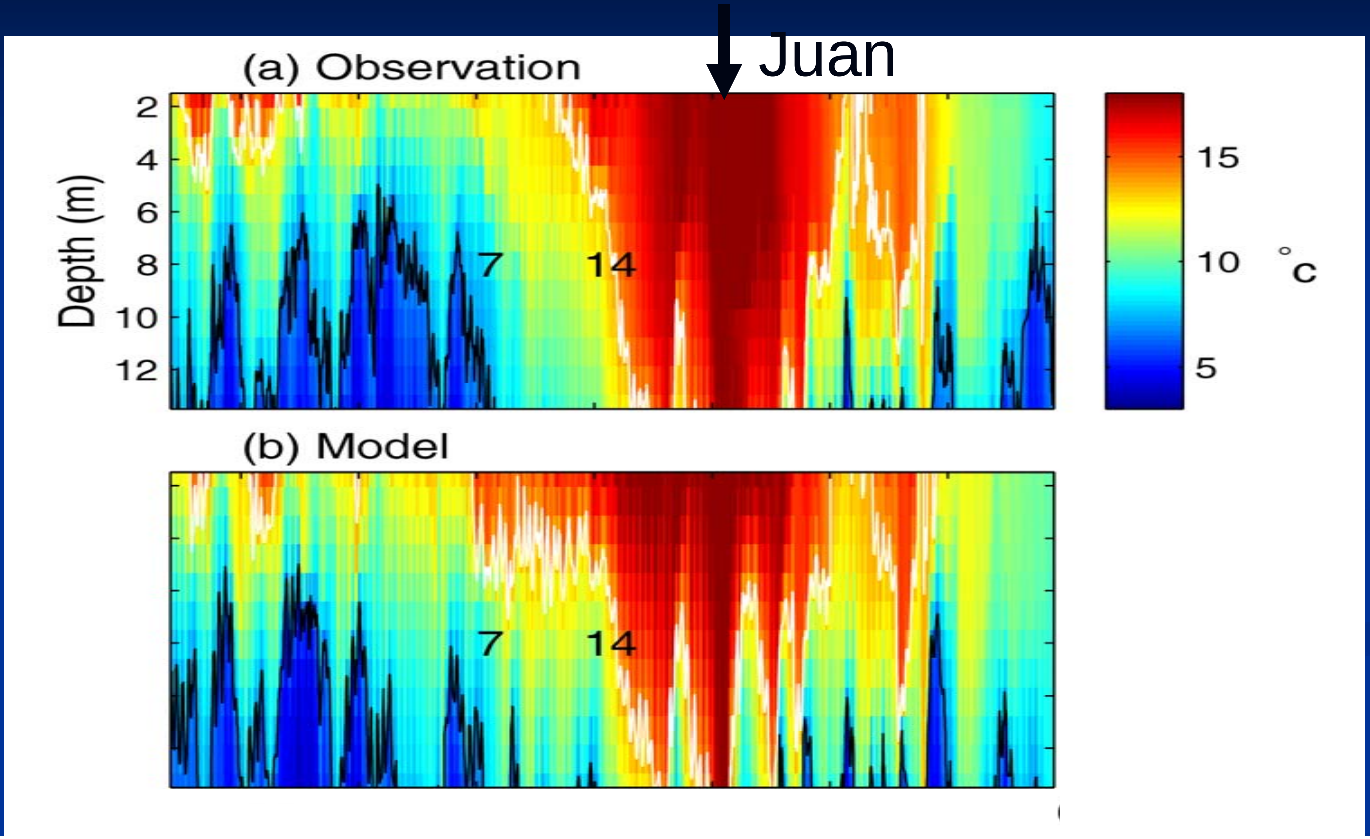
Wave-induced currents play an important role!!

Comparison of Temperatures at SB3

(August-October, 2003)

Observed

Simulated



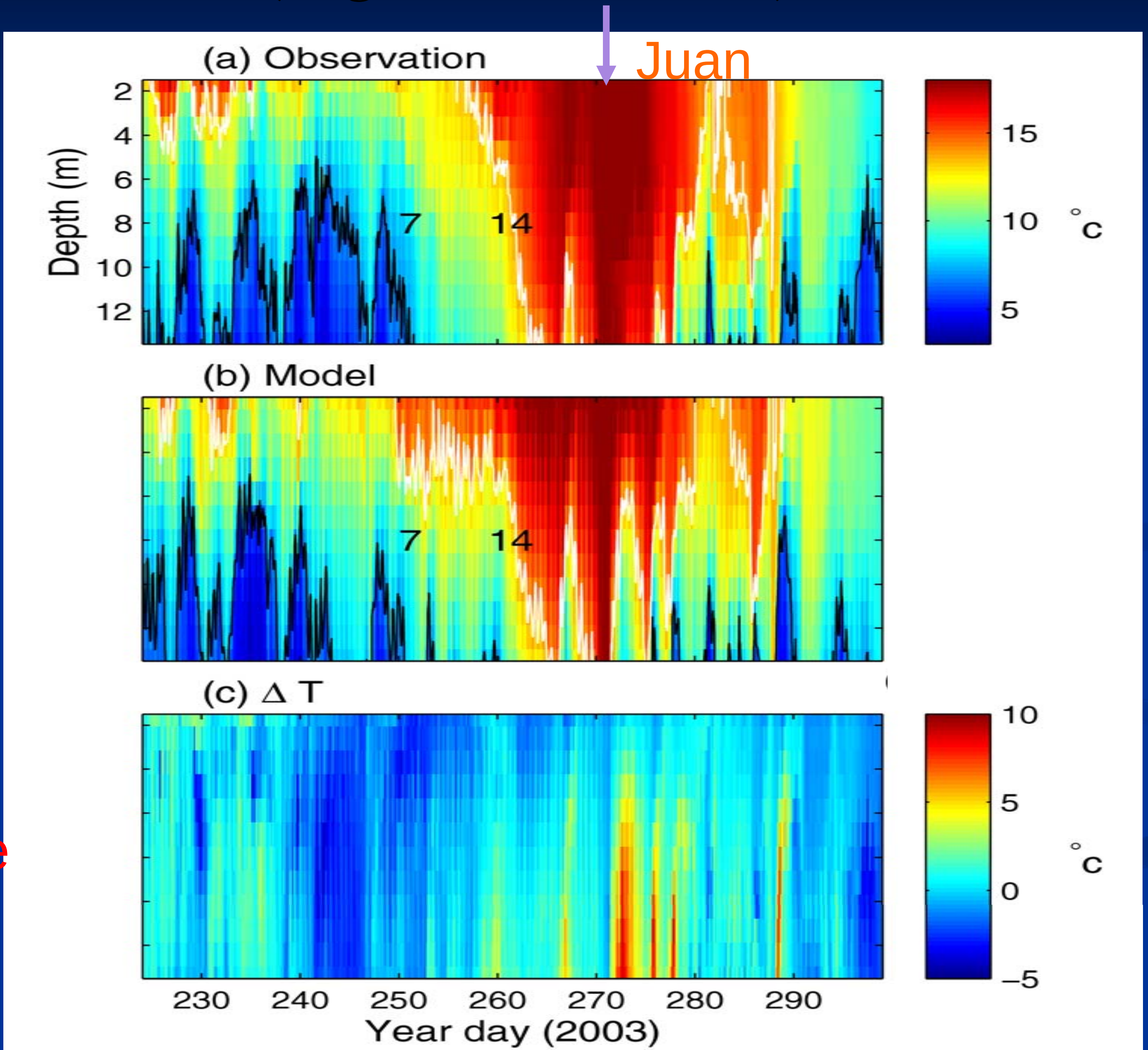
Comparison of Temperatures at SB3

(August-October, 2003)

Observed

Simulated

Difference



2.4 Data Assimilation

Pressure-correction method: correcting the wind stress error in the model through the pressure gradient term in momentum equations, and leaving tracer equations fully prognostic. (Bell et al., 2004; Sheng et al., 2001)

$$\frac{\partial u}{\partial t} + \ldots - fv = -\frac{1}{\rho_0}\frac{\partial p_m}{\partial x} + \frac{\partial \tau_{xz}}{\partial z} + \frac{\partial \tau^c_{xz}}{\partial z} \ldots,$$

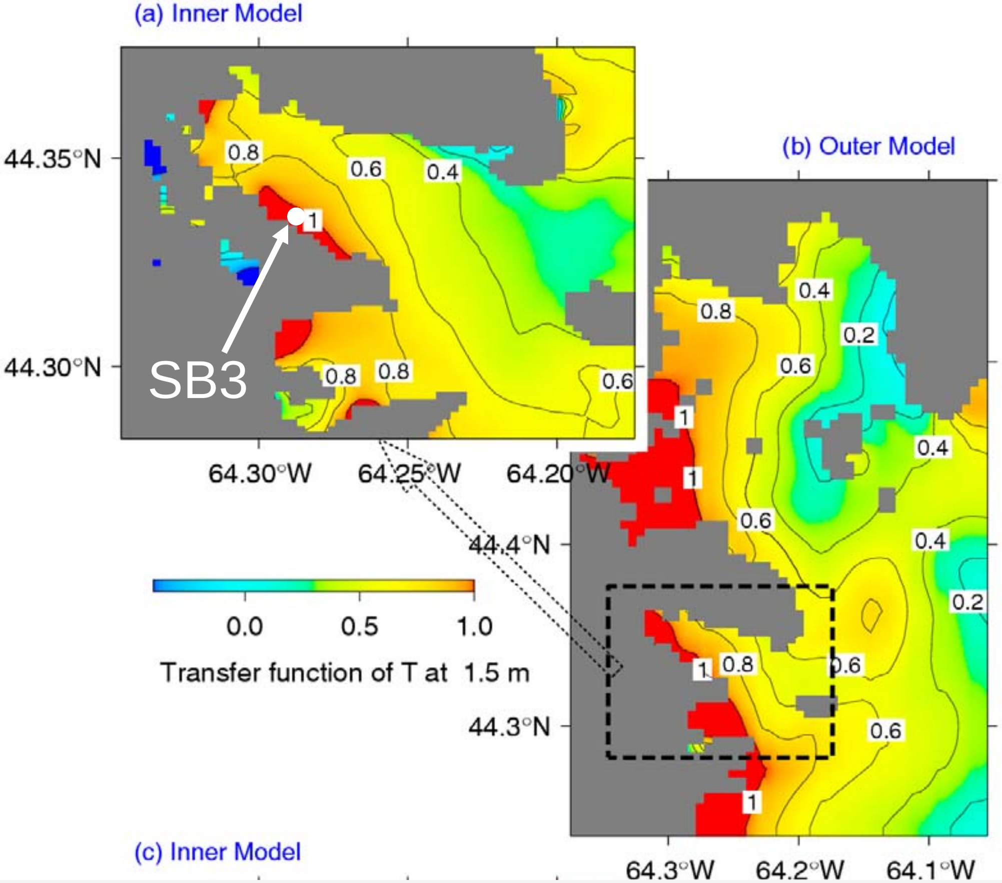
where

$$\frac{\partial \tau^c_{xz}}{\partial z} = -\frac{1}{\rho_0}\frac{\partial}{\partial x}(-\delta p)$$

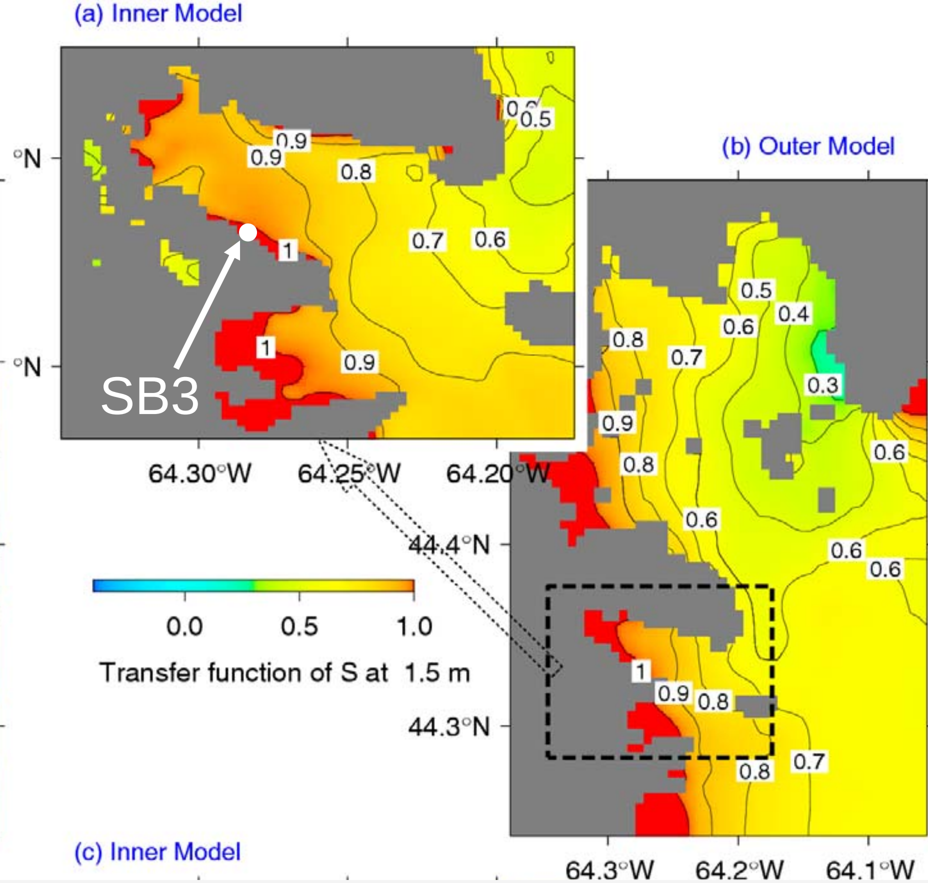
$$\delta p = \int_z^\eta g(\rho(T_o, S_o) - \rho_m) g$$

$$T_o = T_m + K(\hat{T}_o - \hat{T}_m) \qquad K = (\hat{T}_m \hat{T}'_m)^{-1} \hat{T}_m T_m$$

Horizontal Distribution of Transfer Function for T/S (at 1.5 m depth)

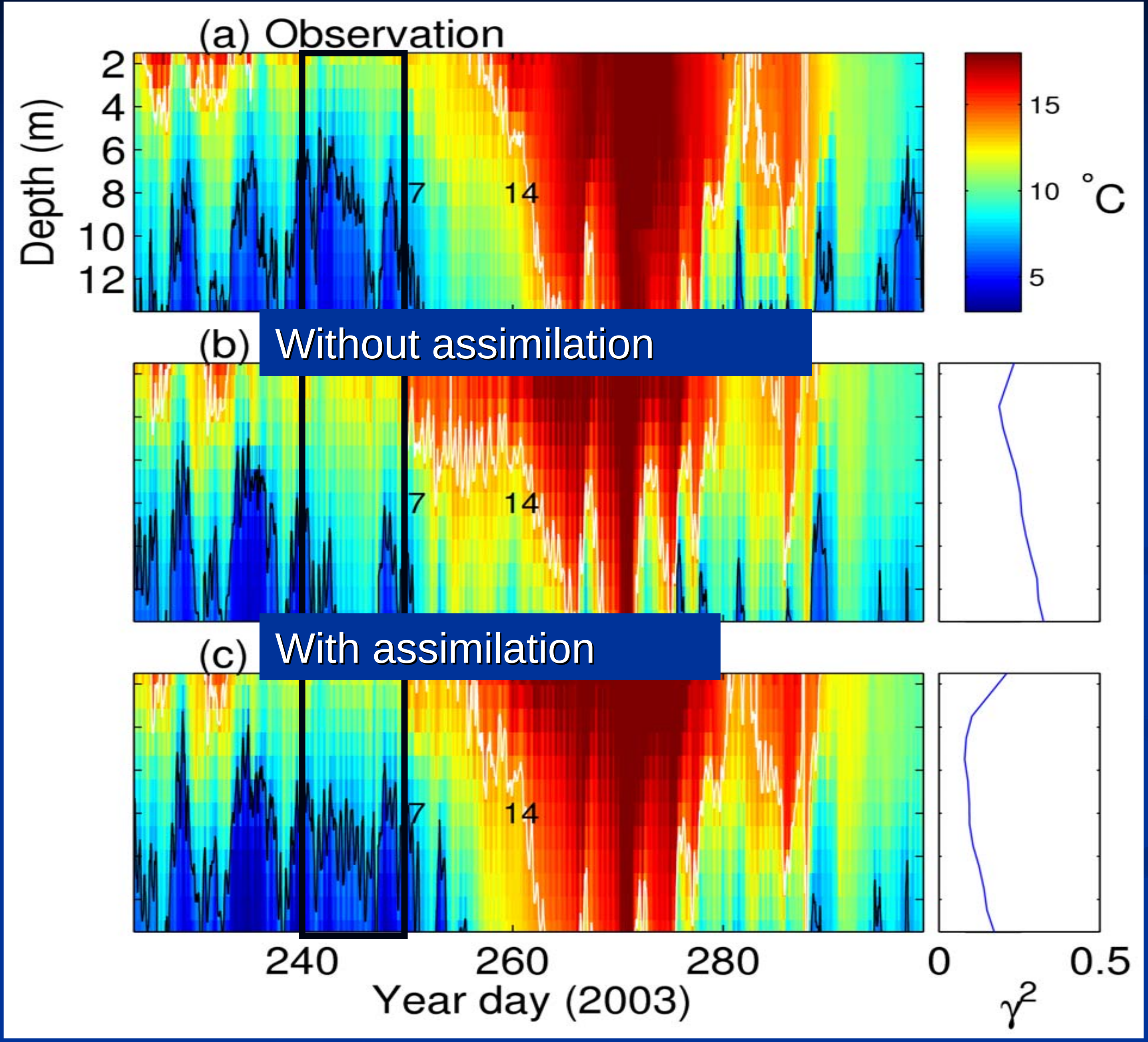


Temperature



Salinity

Comparison of Temperatures at SB3



Summary (Part One)

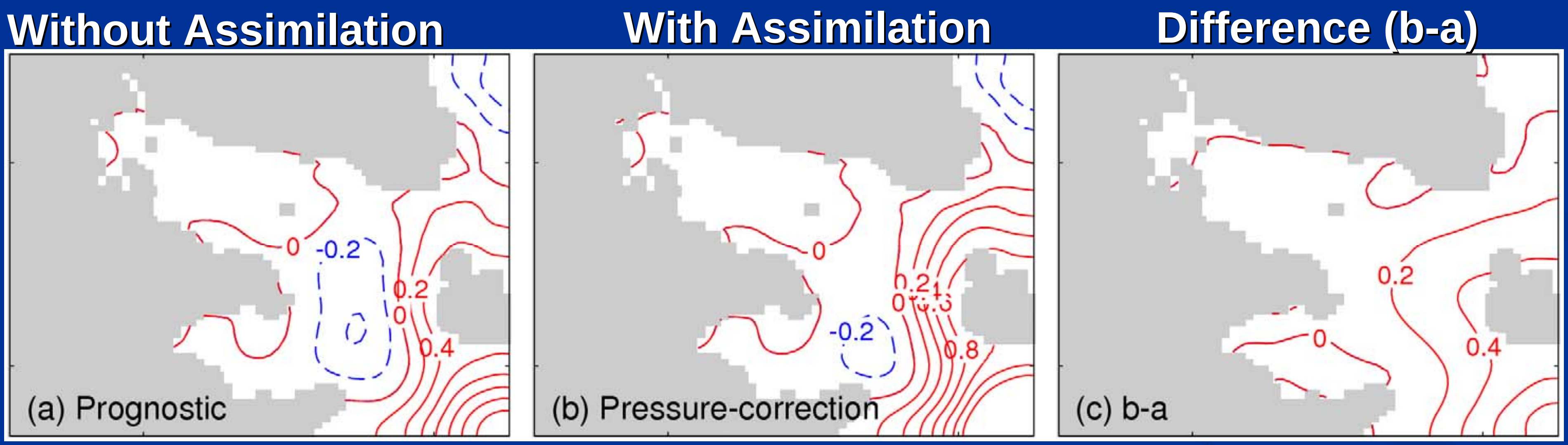
- A 5-level nested-grid coastal circulation prediction system (NCOPS-LB) was developed recently for Canadian Atlantic coastal waters.
- The nested-grid model was used in simulating storm-induced circulations during Hurricane Juan (2003) and tropical storm Alberto (2006).
- Observations made in Lunenburg Bay were used to assess the performance of NCOPS.
- Future work includes better specification of fluxes over the transition zone of outer and inner models and the use of two-way nesting based on the semi-prognostic method.

Summary (Part Two)

- Observations demonstrated that circulation and surface heat flux play important roles in heat budget of Lunenburg Bay.
- The propagation of Kelvin waves plays an important role in generating coastal upwelling/downwelling in the bay.
- The pressure correction method is useful to improve the model performance in simulating water mass distributions in the bay.

Thank You!

Comparison of Horizontal Transport Stream-function (day 240-250)



Model-calculated Near-surface Currents and Temperatures (Inner Model)