Modeling Lake Erie circulation and thermal structure and the potential impact of wind farms

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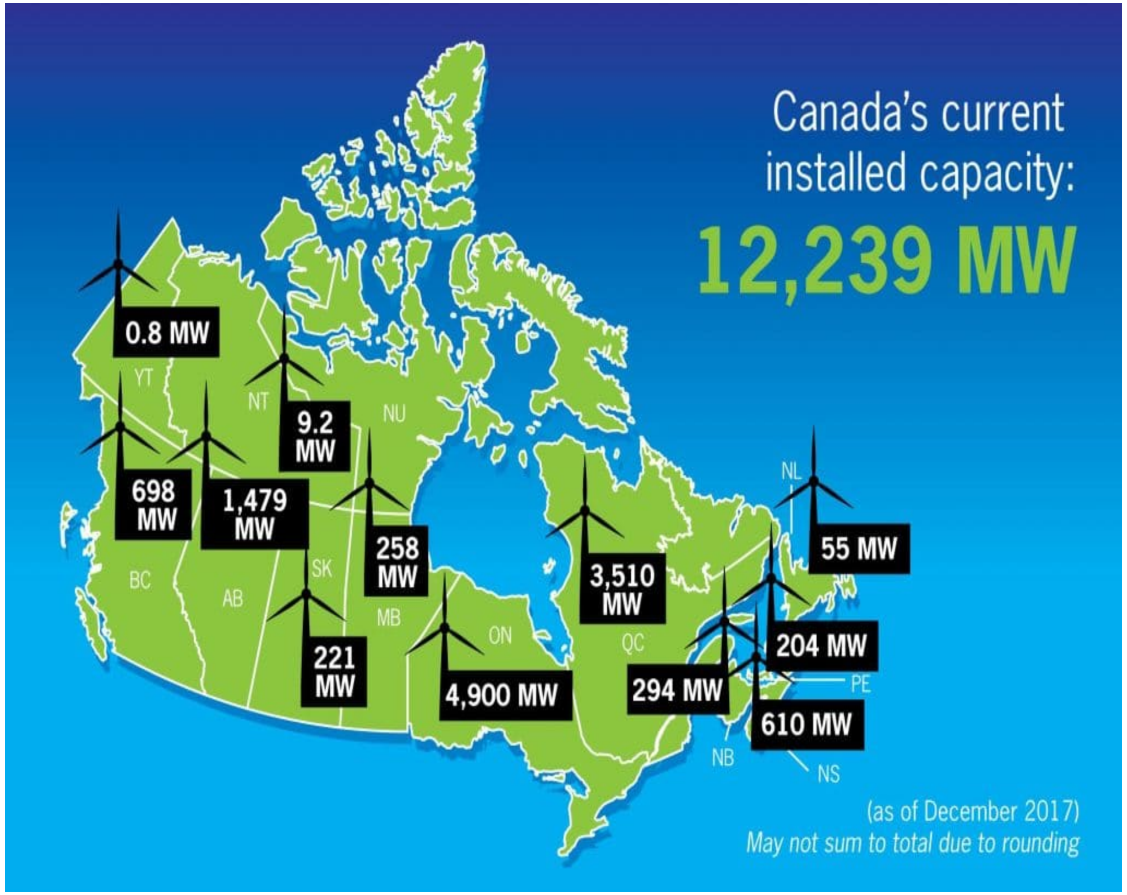
CMOS 2018, June 11-14, Halifax.

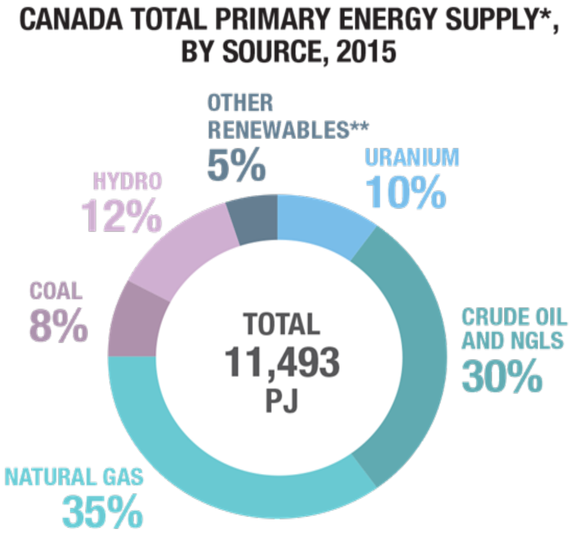
Modeling Lake Erie circulation and thermal structure and the potential impact of wind farms

There will be wind farms in the Great Lakes very soon. The presence of large wind farms could affect the thermal structure of the lake, particularly during summer when a thermocline develops. Temperature increases, caused by lowered wind speeds and reduced mixing in the upper part of the water column, may be small, but could still impact algal bloom development. Algal blooms absorb sunlight, causing added heating so there is a potential positive feedback.

The potential impact of a large wind farm on Lake Erie's hydrodynamic and thermal structure is investigated by using COHERENS (Coupled Hydro-dynamical Ecological model for Regional and Shelf Seas). Using meteorological data (winds, air temperatures, cloud cover) from 2005 the circulation and thermal structure in the open water season (May-October) is modeled and matches previous modeling studies and measurements reasonable well. The effects (reduced wind speeds in turbine wakes) of a large (21.6 GW) wind farm, with 432, 5 MW turbines are then added, in a 12 km x 50 km region offshore from Cleveland, and the model is re-run to investigate potential changes. Surface water temperatures increase by 1 to 2°C in and around the wind farm but the overall impact is relatively small in other parts of the lake.

CANWEA's wind vision 2025: calls for 55000 MW by the end of following decade. By 2025, the wind energy industry is projected to create 52,000 new "Green Collar Jobs" in Canada. According to the government of Canada, wind power has become the second largest renewable power source in Canada 2017.





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Offshore Wind Plans in:

Ontario

- up to 86 GW of offshore projects to be developed by 2050. The Great Lakes can generate about 15 percent of the development
- (Hamilton, 2016, Ontario's love-hate relationship with Great Lakes wind turbines. Retrieved from https://tvo.org/article/current-affairs/climate-watch/ontarios-love-hate-relationship-with-great-lakes-wind-turbines)

Lake Erie

- Lake Erie Energy Development Corporation (LEEDCO)
- $127 million Icebreaker project
- Generates 1 GW of wind energy by 2020
- The potential of electric generation in the U.S. side of the Great Lakes is estimated to be 4,223 GW.
- Lake Erie counts for 50 GW

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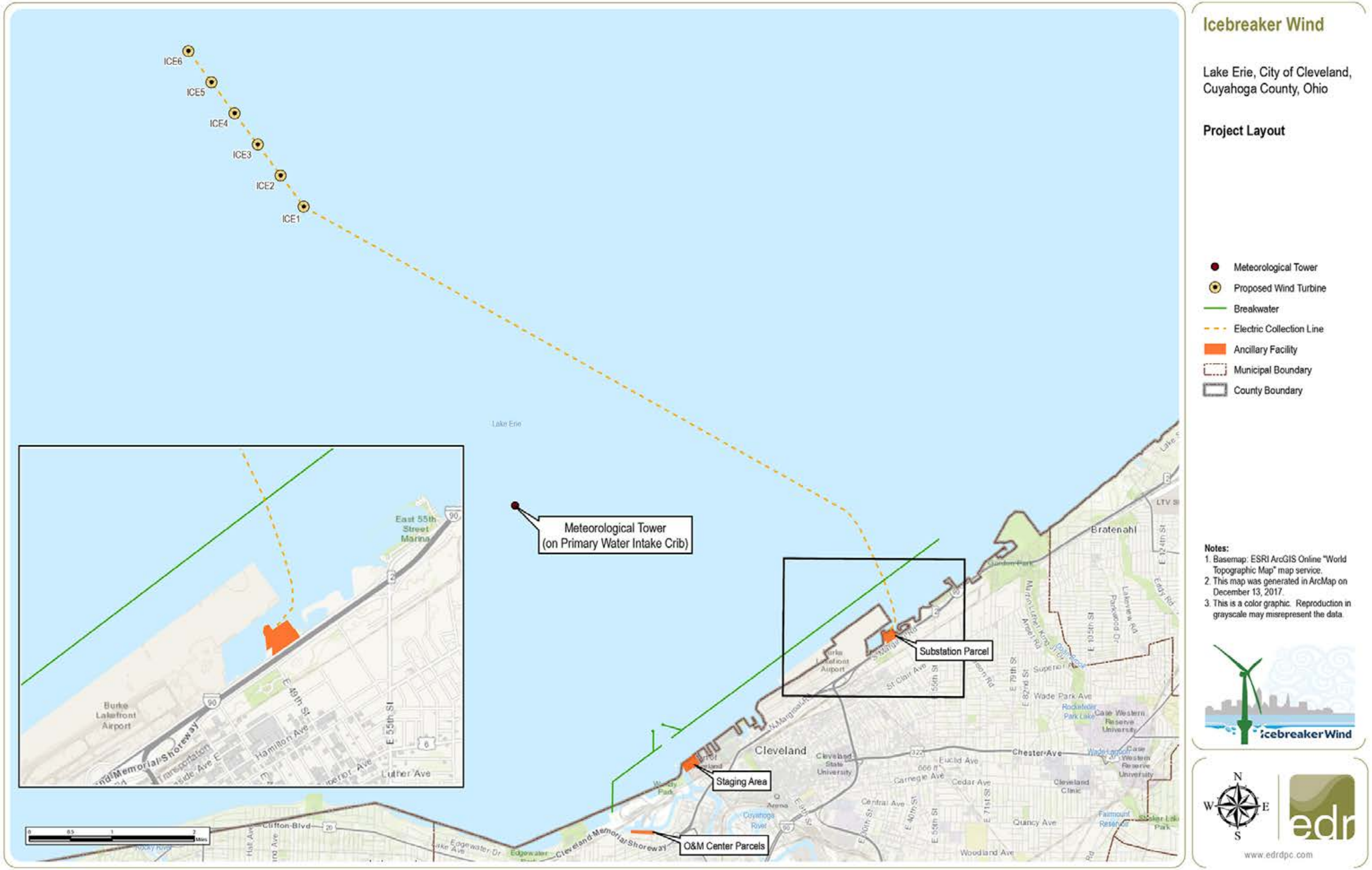
Ice-Breaker Project

http://www.leedco.org/index.php/about-icebreaker

The first step is the Icebreaker Wind Project, a 20.7 MW demonstration wind farm that will consist of six 3.45 MW turbines located 8 miles north of Cleveland, Ohio. Icebreaker Wind will be the first freshwater offshore wind farm in North America.



COHERENS : Basic model equations

- Continuity equation, Momentum equations (u,v), Hydrostatic approximation, $p = P_a$ on $z = \zeta$ (surface elevation), no tides, Thermodynamic Equation (T, potential temperature)
- $\partial u/\partial x + \partial v/\partial y + \partial w/\partial z = 0 \quad ; \quad \partial p/\partial z = -\rho g$
- $\partial u/\partial t + u\, \partial u/\partial x + v\, \partial u/\partial y + w\, \partial u/\partial z - fv = -(1/\rho_0)(\partial p/\partial x) + (\partial/\partial z)(\nu_T\, \partial u/\partial z) + (\partial/\partial x)\, \tau_{xx} + (\partial/\partial y)\, \tau_{xy}$
- $\partial v/\partial t + u\, \partial v/\partial x + v\, \partial v/\partial y + w\, \partial v/\partial z + fu = -(1/\rho_0)(\partial p/\partial y) + (\partial/\partial z)(\nu_T\, \partial v/\partial z) + (\partial/\partial x)\, \tau_{yx} + (\partial/\partial y)\, \tau_{yy}$
- $\partial T/\partial t + u\, (\partial T/\partial x) + v\, (\partial T/\partial y) + w(\partial T/\partial z) = (1/\rho_0\, c_p)\, (\partial I/\partial z) + (\partial/\partial z)\, (\lambda_T\, \partial T/\partial z) + (\partial/\partial x)\, (\lambda_H\, \partial T/\partial x) + (\partial/\partial y)\, (\lambda_H\, \partial T/\partial y)$

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Irradiance and Heat Fluxes

- $I(x_1, x_2, z) = Q_{rad}\,(R\, e^{-z/\lambda 1} + (1 - R)\, e^{-z/\lambda 2})$

- $Q_{rad} = Q_{cs}\,(1 - 0.62\, f_c + 0.0019\, \gamma_{\odot,max})(1 - A_s)$

- $Q_{nsol} = Q_{la} + Q_{se} + Q_{lw} = - Q_s$

- $Q_{lw} = \epsilon_s\, \sigma_{rad}\,(T_s + 273.15)^4\,(0.39 - 0.05\, e_a^{\,1/2})\,(1 - 0.6\, f_c^{\,2})$

- $\sigma_{rad} = 5.67 \times 10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}$

Water Surface Boundary Condition

- Current: $(\rho_0\, \nu_T/h_3)\,(\partial u/\partial s\,,\, \partial v/\partial s) = (\tau_{s1}, \tau_{s2}) = \rho_a\, C_{ds}\, W_{10}\,(U_{10}, V_{10})$
- Temperature: $(\rho_0\, c_p\, /\, h_3)\,(\lambda_T\, \partial T/\partial s) = Q_s$ (Q_s is the downwards directed heat flux at the surface)

Water Bottom Boundary Condition

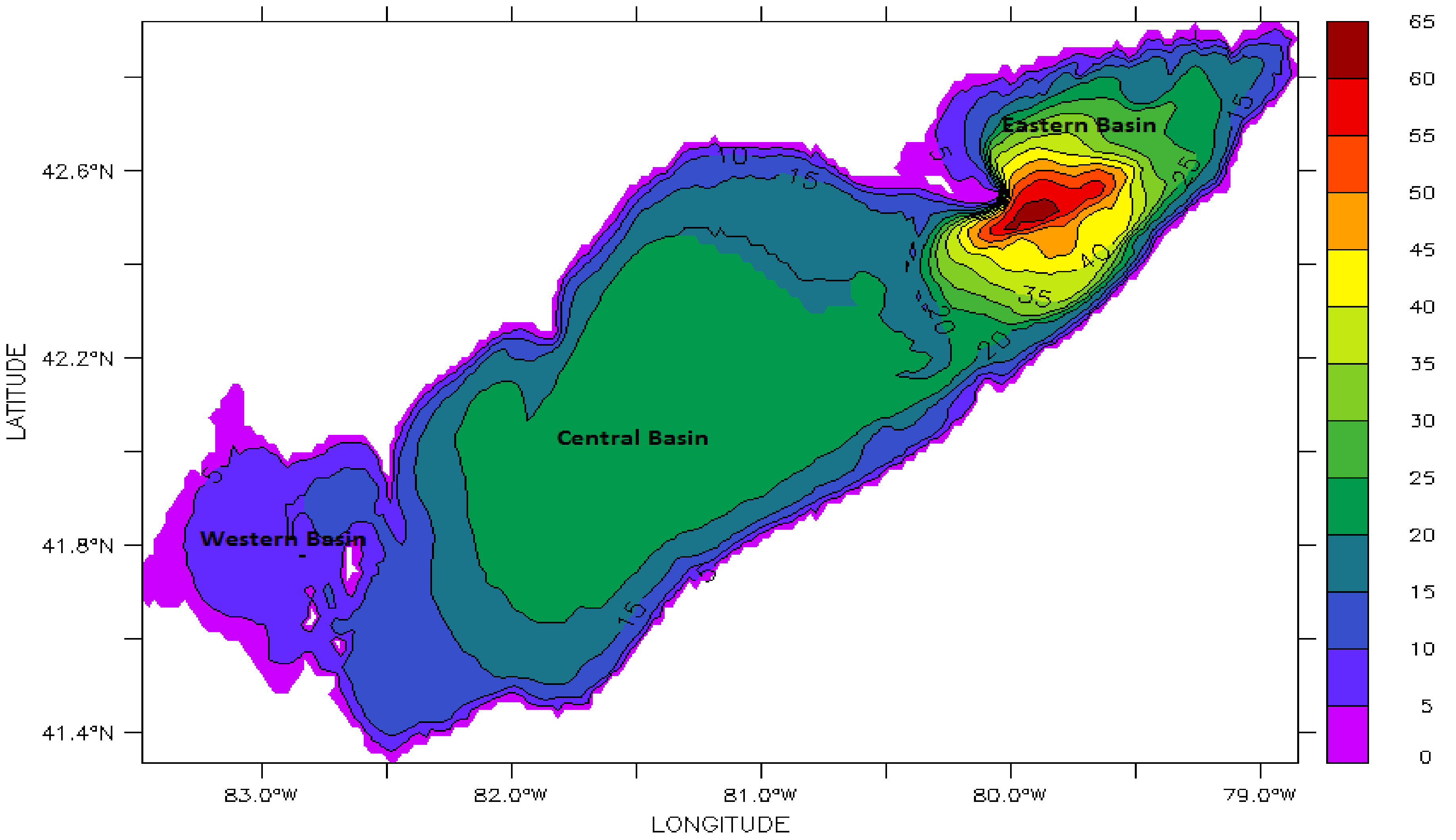
- Current: $(\nu_T/h_3)\,(\partial u/\partial s\,,\, \partial v/\partial s) = (\tau_{b1}, \tau_{b2})$;
- $(\tau_{b1}, \tau_{b2}) = C_{db}\,(u_b^2 + v_b^2)^{½}\,(u_b, v_b)$
- $C_{db} = (\kappa/\ln(z_r/z_0))^2$
- Temperature: $\lambda_T / h_3\,(\partial T/\partial s) = 0$

1D Mode Conclusion – run through open water season with water depths 10, 25, 60m, with and without wind speed reductions (25%)

In the presence of wind turbines:

- Surface water currents decrease in response to a decrease in the wind speed
- The water temperature gradient increases as there is a higher surface water temperature in response to reduced mixing and a potentially shallower mixed layer and lower bottom temperature due to less heat diffusion
- The thermocline in this case develops slightly faster and is stronger
- In deep water cases the wake effect in summer causes the near-surface water temperature to increase due to the high solar radiation and slower winds, while the bottom layer remains cold. Warmer surface temperatures and reduced mixing can potentially lead to reduced dissolved oxygen, stress on the fish population, and increased potential for algal blooms (IJC, 2014)
- Wakes impact deeper waters more than shallow water. Deeper water currents decrease more relative to shallower cases. Also, thermocline and stratification are strengthened by wake effects

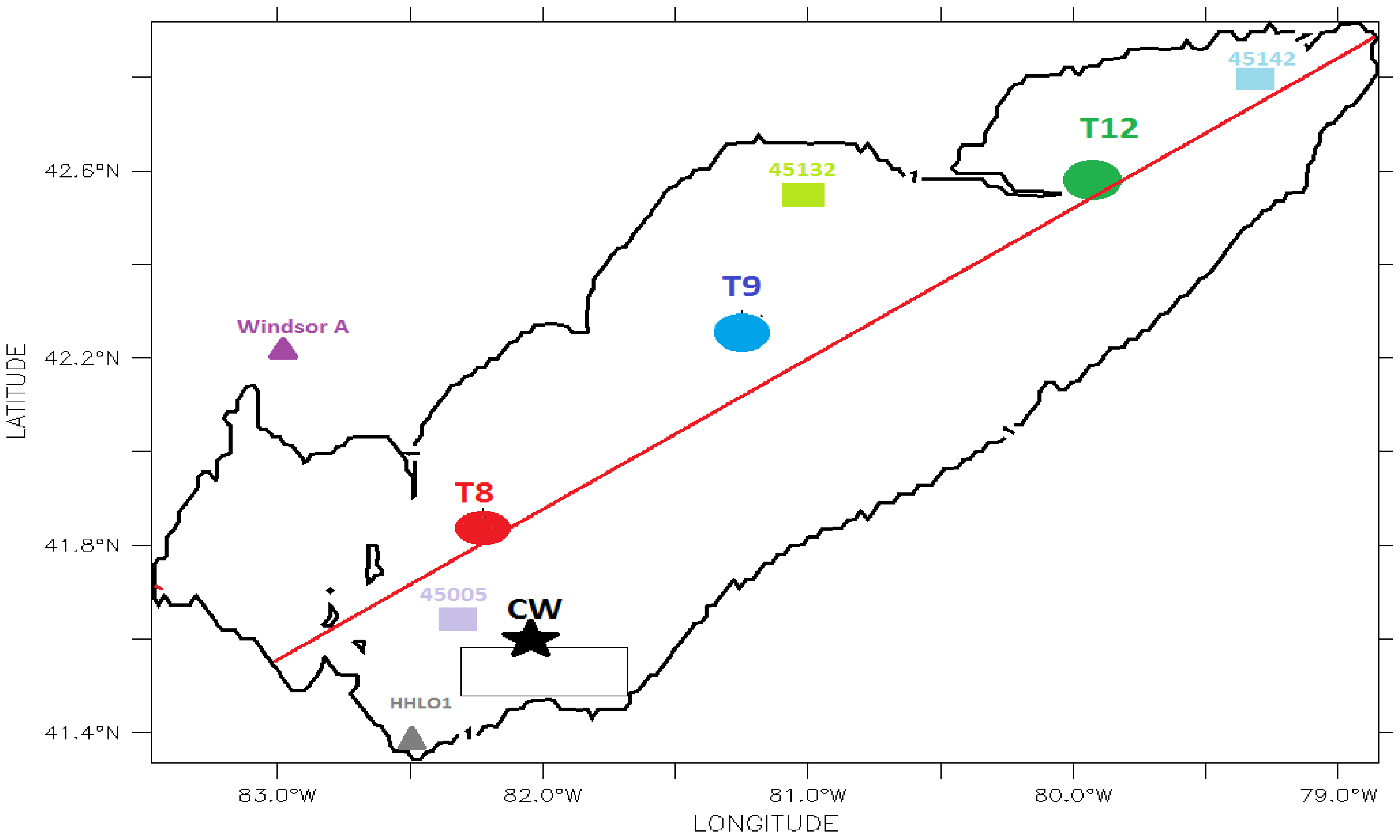
3-D Mode study



Lake Erie

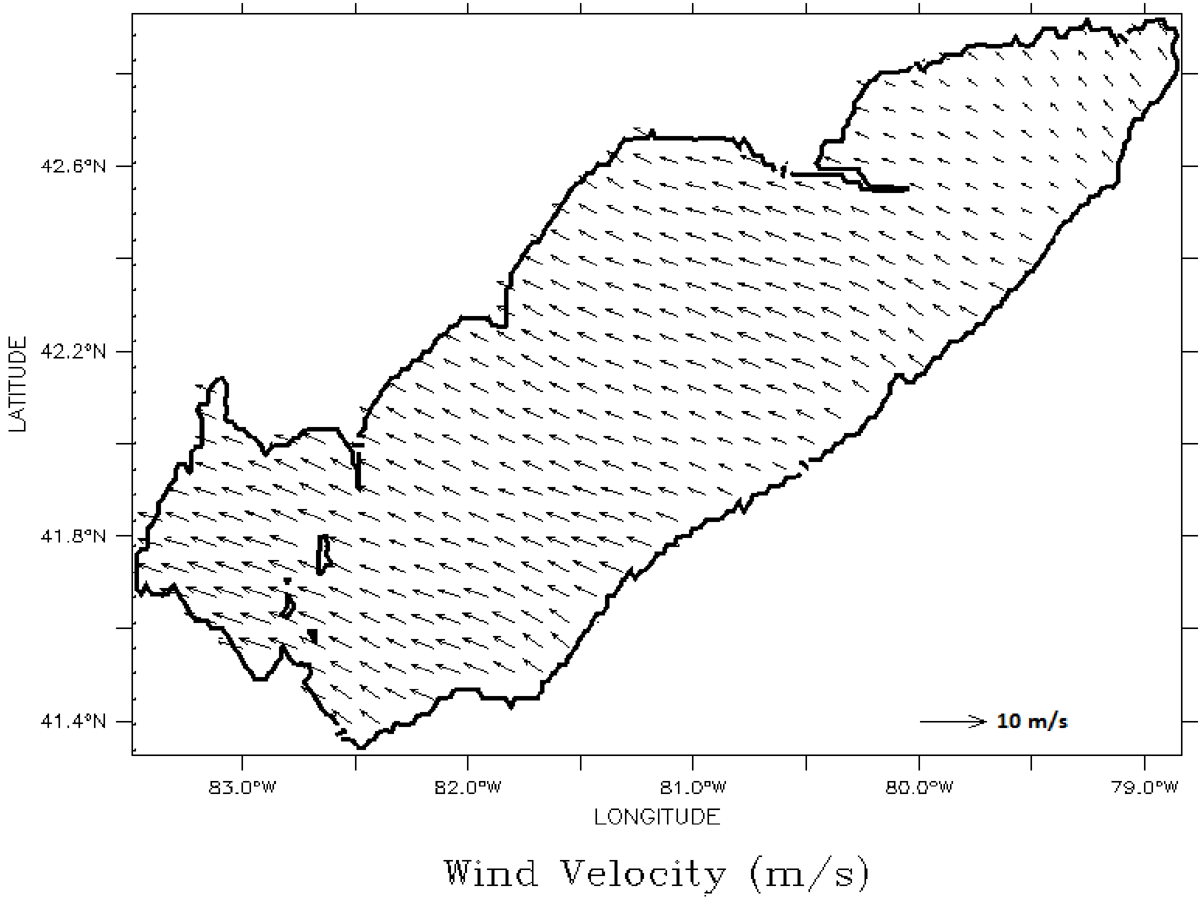
Bathymetry (m)

Lake Erie Mooring Locations and Section Line

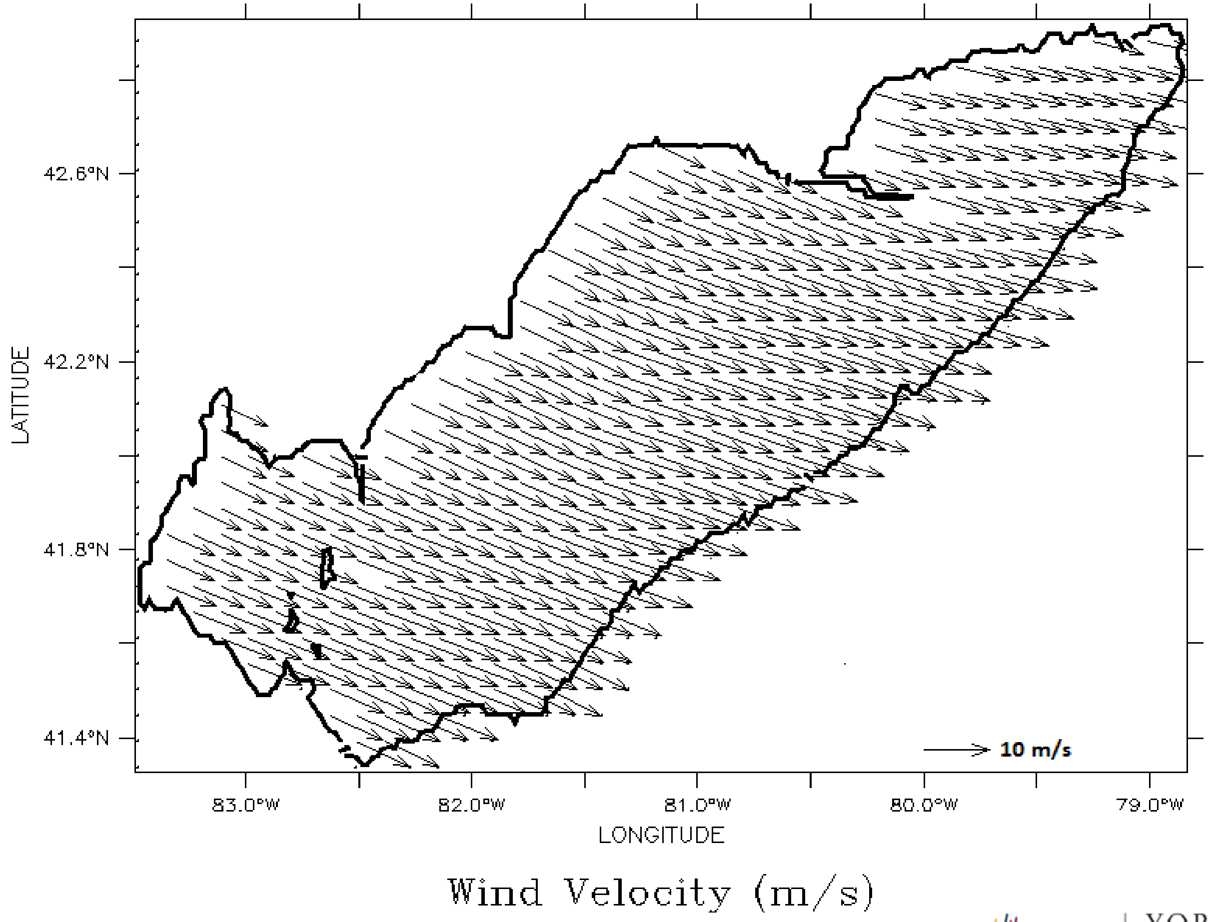


Instantaneous NARR 10m winds (10 m/s scale)

UTC 5 A.M. May 5, 2005



UTC 5 A.M. October 15, 2005



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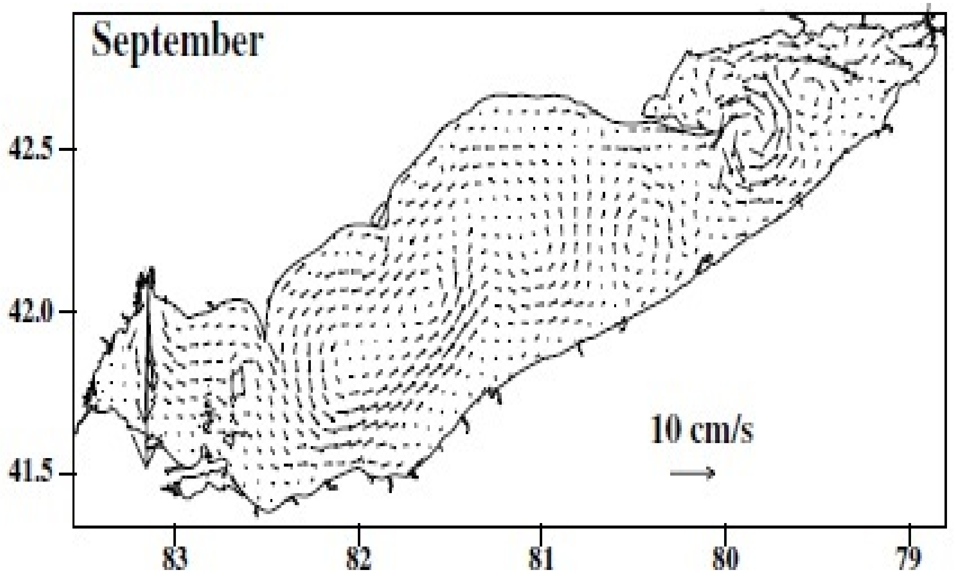
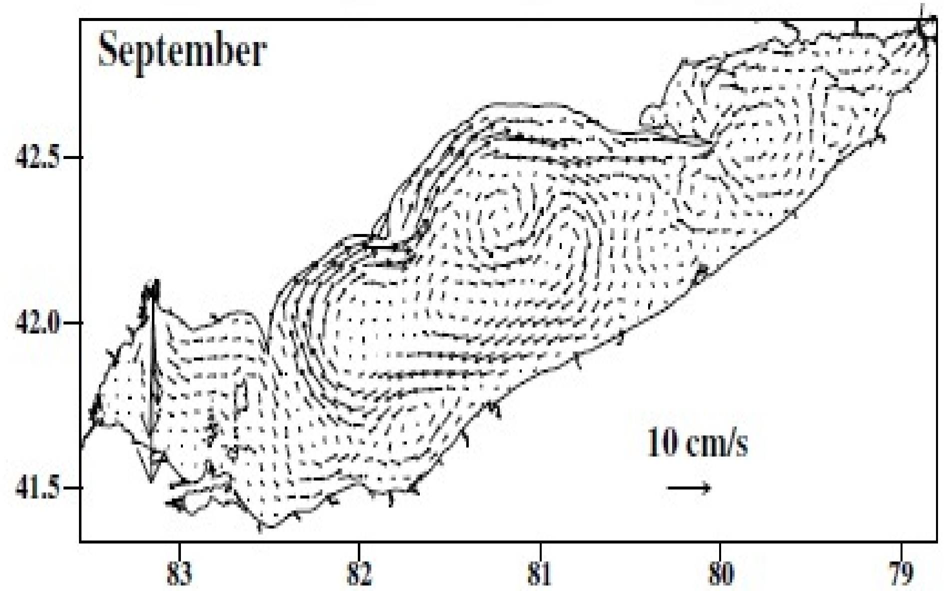
Monthly averaged, depth averaged water circulation.

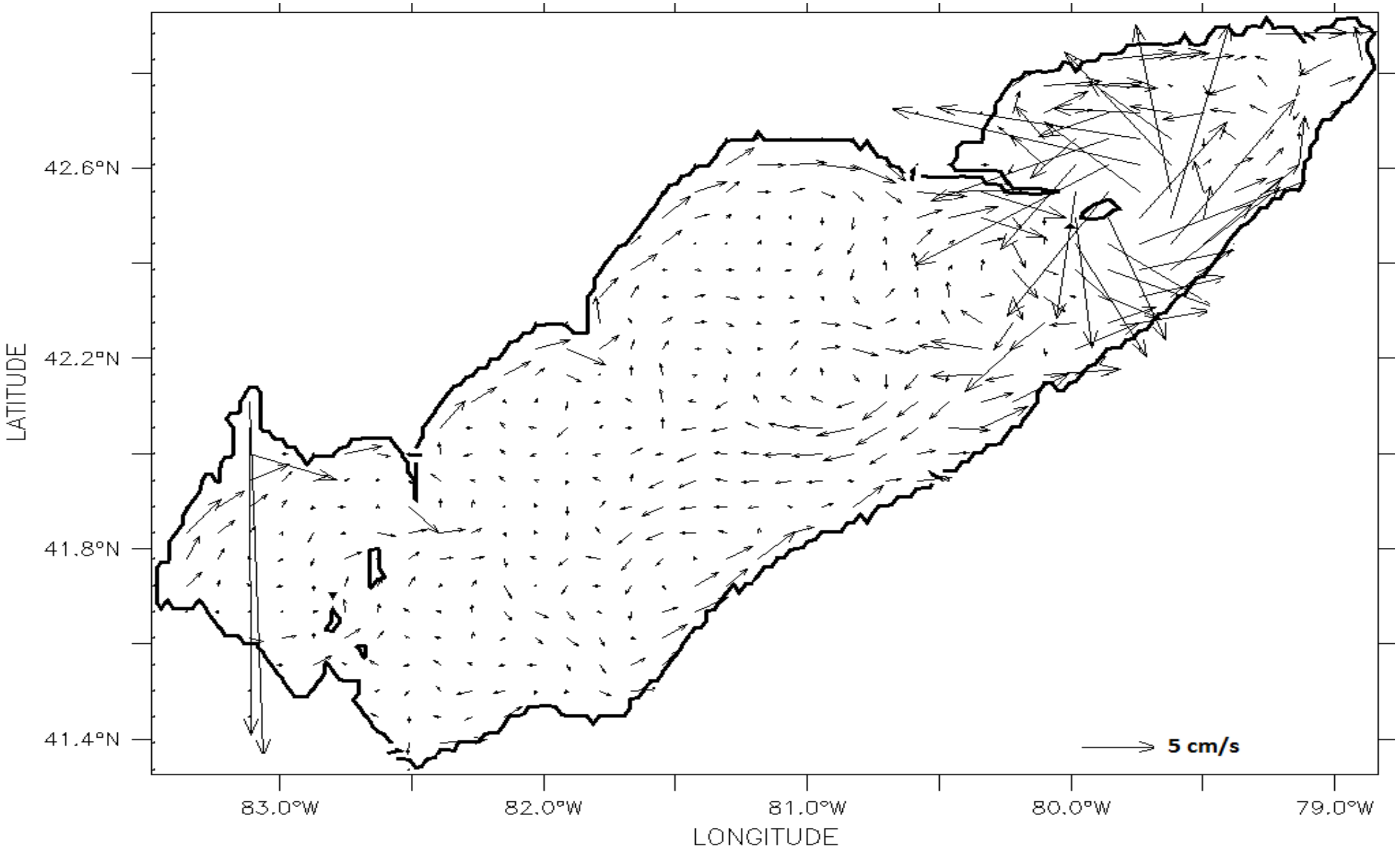


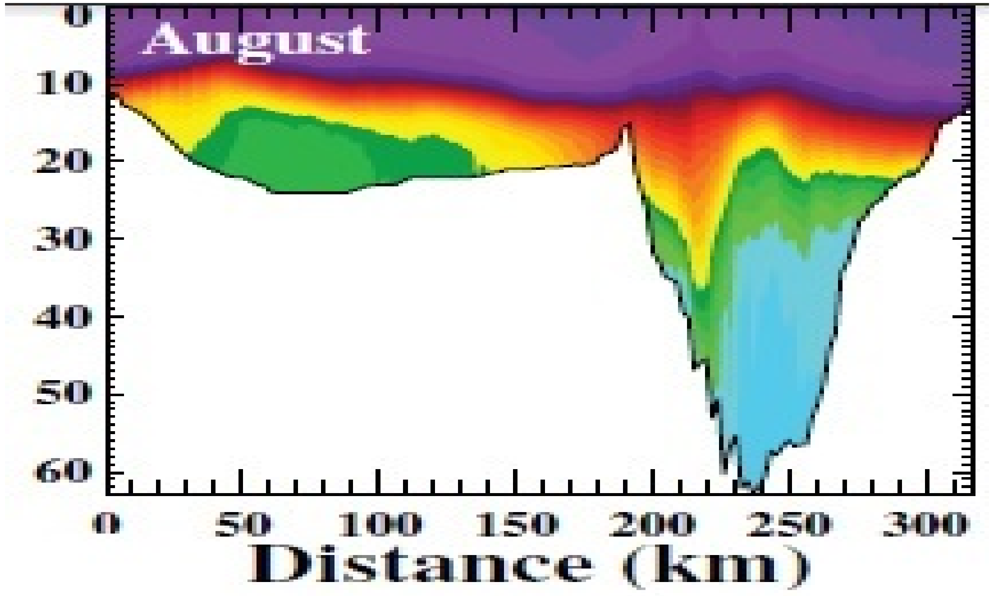
GEM, from Beletsky (2013)



Using GEM uniform wind

COHERENS

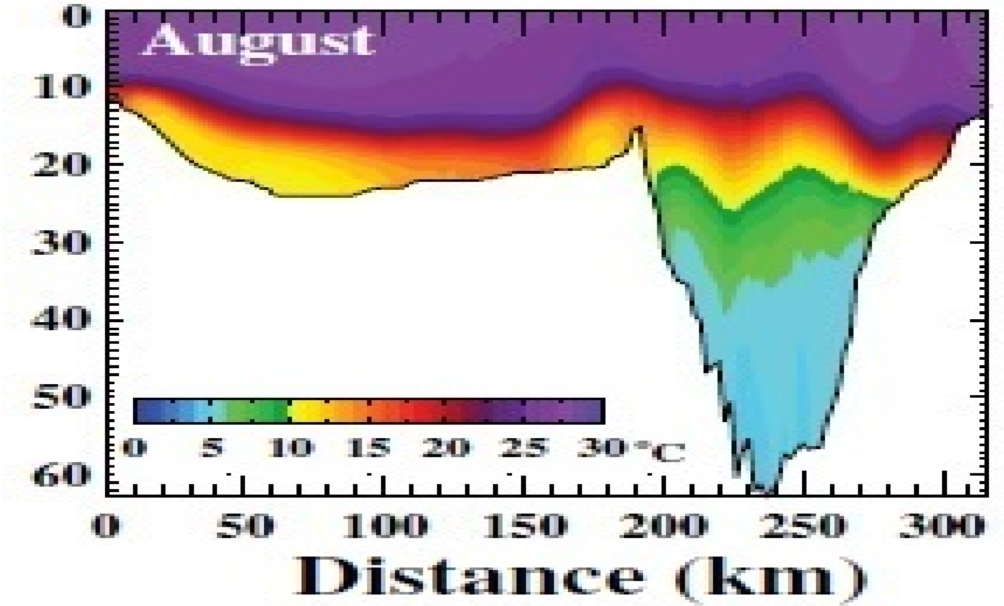




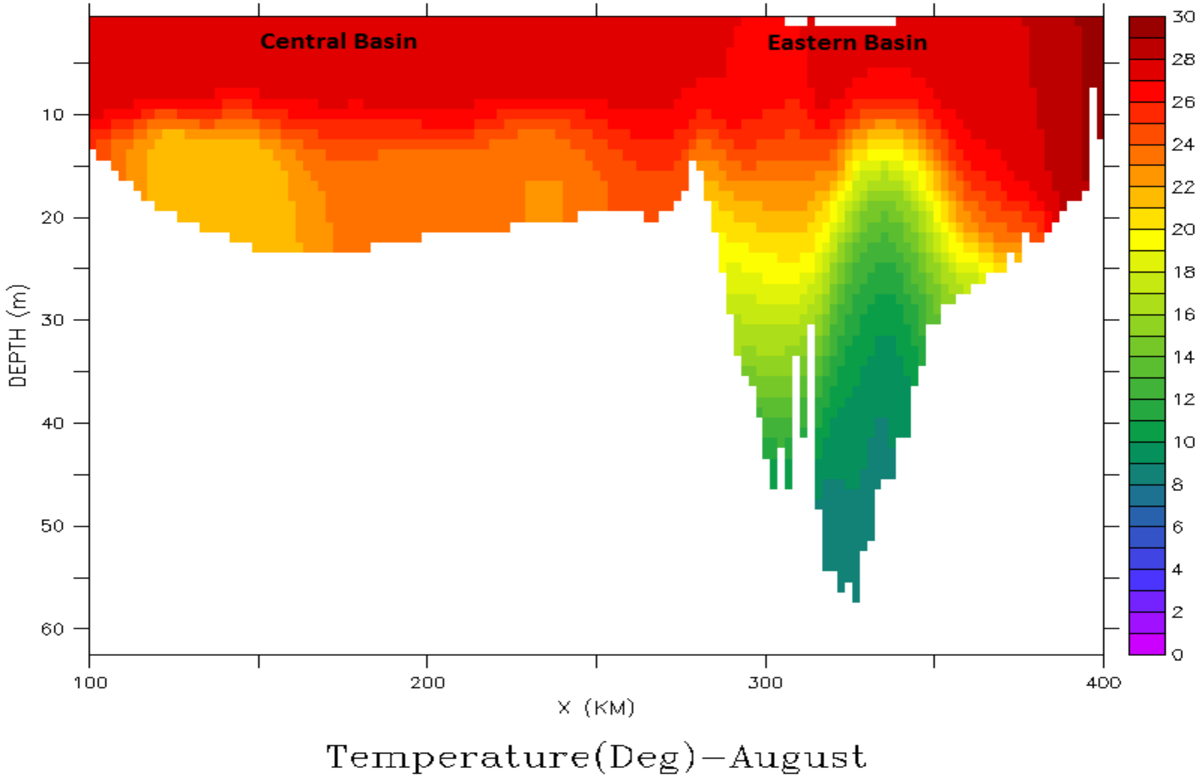
Using uniform GEM wind

Temperature sections, August 2005

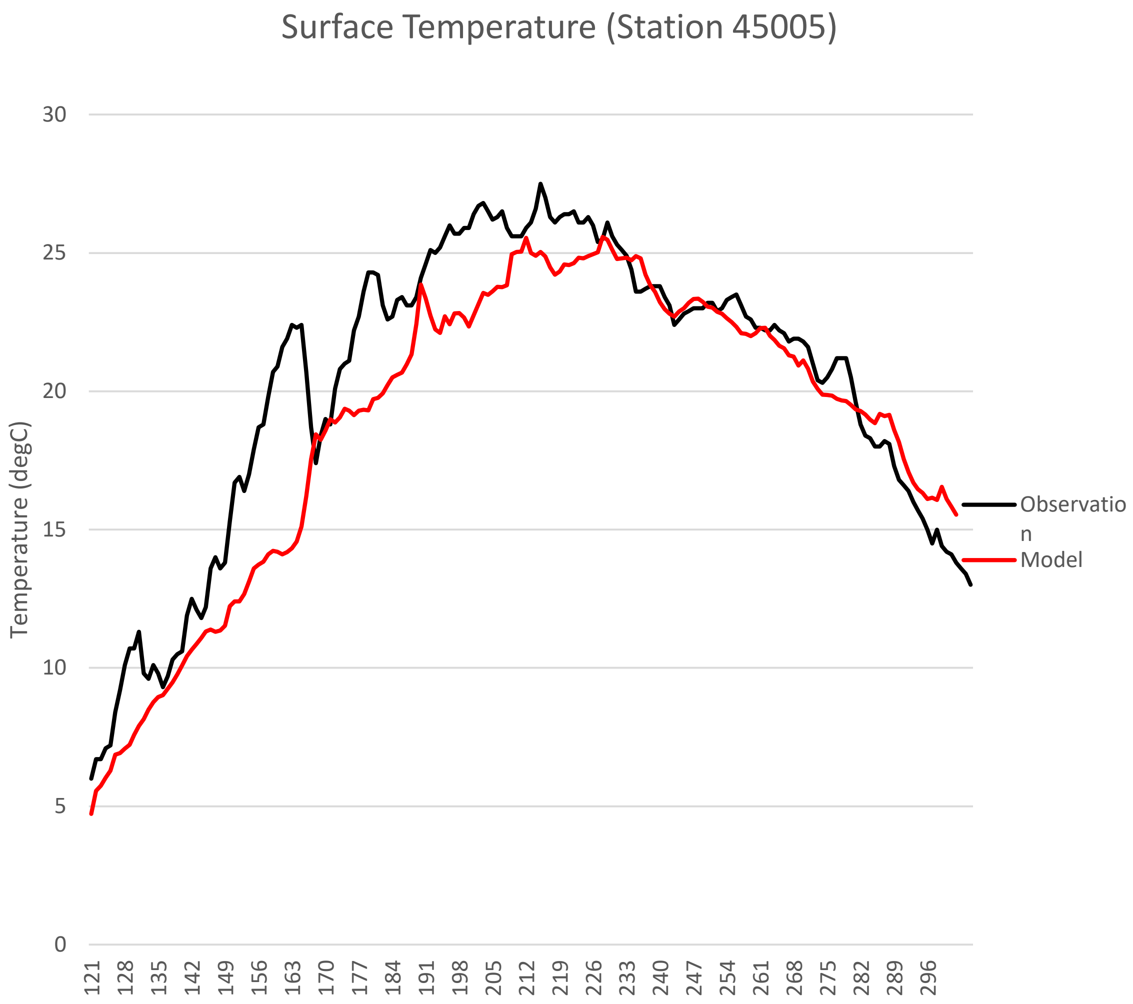
POM (Beletsky et al 2013)

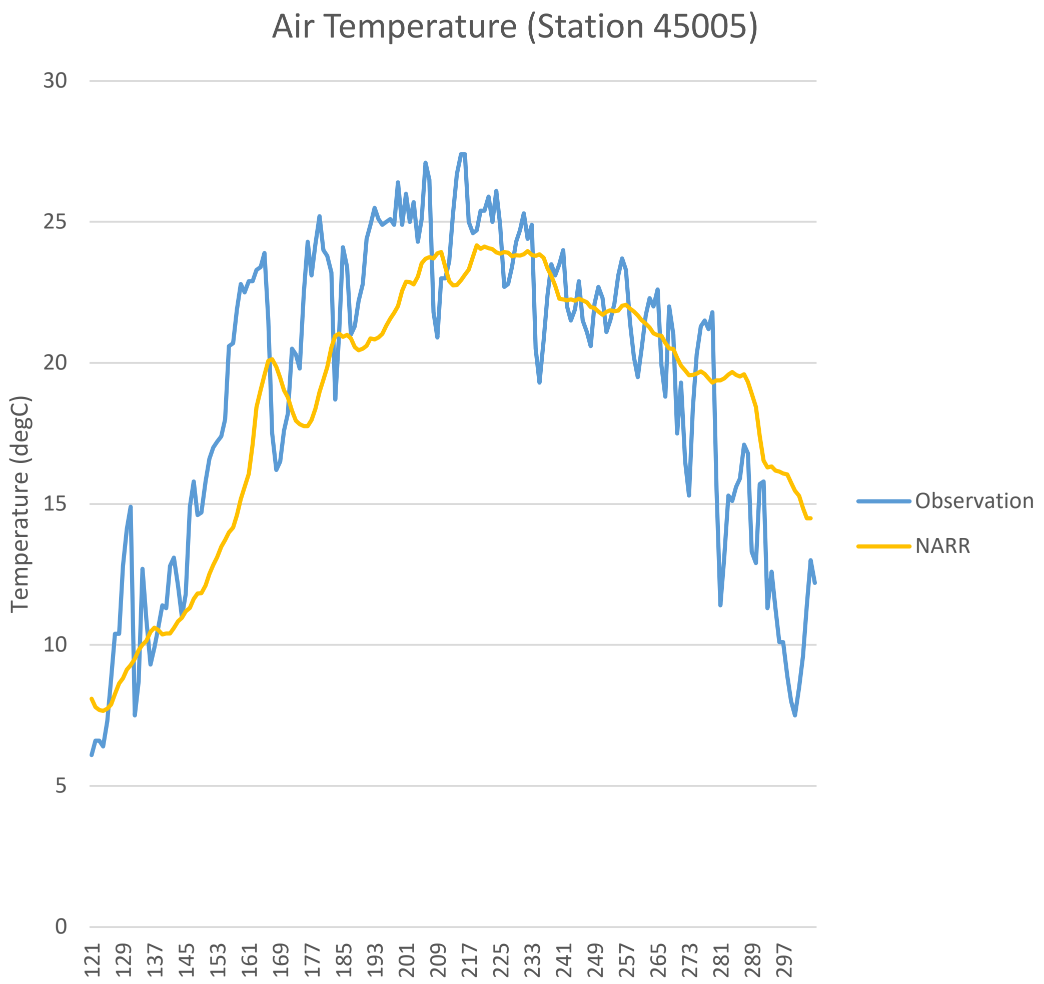


COHERENS

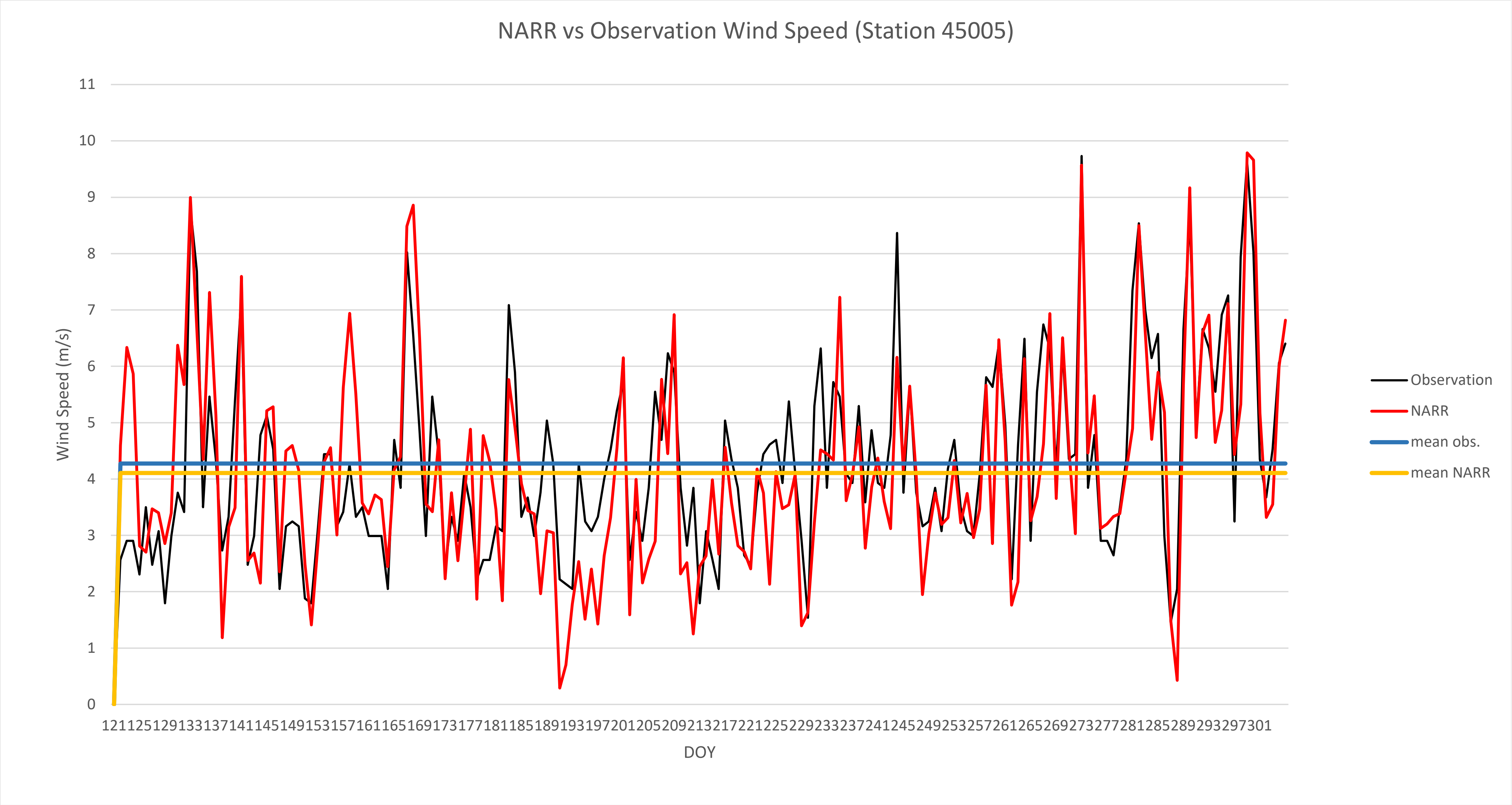


Modeled versus observation a) surface water temperature and b) Air temperature at meteorological buoy 45005, in 2005 (May – October)





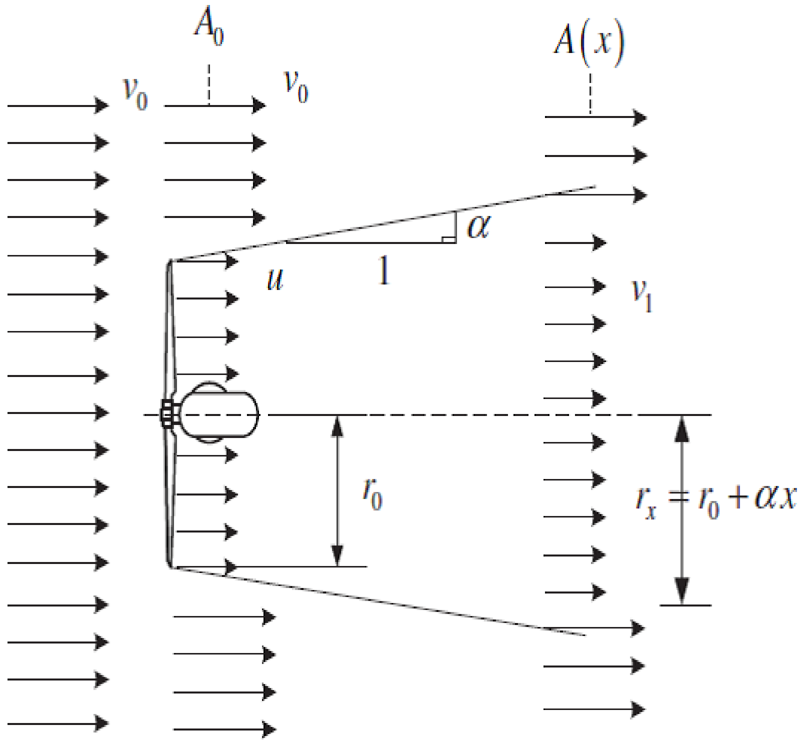
Modeled (red) versus observation (black) adjusted to 10 m wind speed at meteorological buoy 45005, in 2005 (May – October)



3D Mode Conclusion

Western Basin	Central Basin	Eastern Basin
Circulation is affected by the river inflow input	There are two patterns for circulation: Cyclonic and Anti Cyclonic	Cyclonic pattern
Most of the year water is mixed	Thermocline during summer	Thermocline persists during warm seasons
West to East Current	Bowl Shape Thermocline	Dome shape Thermocline

COMPARING RESULTS WITH AND WITHOUT A LARGE WIND FARM



Jensen model, square wave wake.

A new analytical model for wind turbine wakes that is able to capture a better estimation for wake states: (Bastankhah and Porté-Agel , 2014)

$$\Delta U/U_\infty = [(1 - (1 - C_T)^{1/2} /8(k^* x/D + \varepsilon)^2 \times \exp(-1/\ 2(k^* x/D + \varepsilon)^2\ \{((z - z_h)/D)^2 + (y/D)^2\}) \qquad (3.21)$$

where y and z are span wise and vertical coordinates, respectively, and z_h is the hub height. k^* is a growth rate and measures lies 0.023 and 0.055. From different offshore experimental values, a value of 0.03 is used in our study. ε is equivalent to the value of σ/D as x approaches to zero. According to the Large-Eddy Simulation (LES) data of a wind turbine wakes: $\varepsilon = 0.2\ (\beta)^{1/2}$, where β is a function of C_T and can be expressed as : $\beta = (1 + (1 - C_T)^{1/2}) / 2\ (1 - C_T)^{1/2}$ (3.22)

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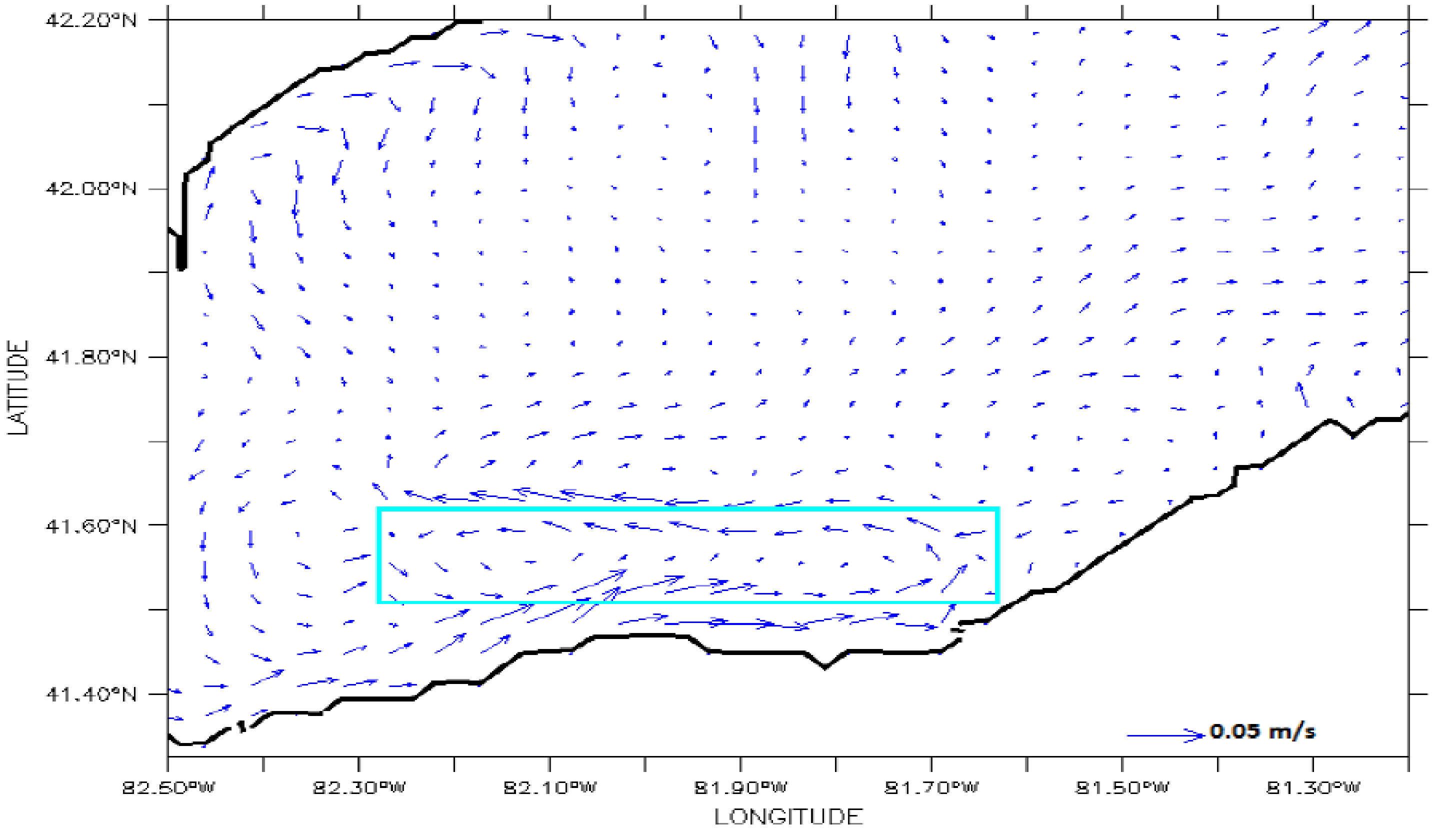
A hypothetical, large, wind farm – possible location

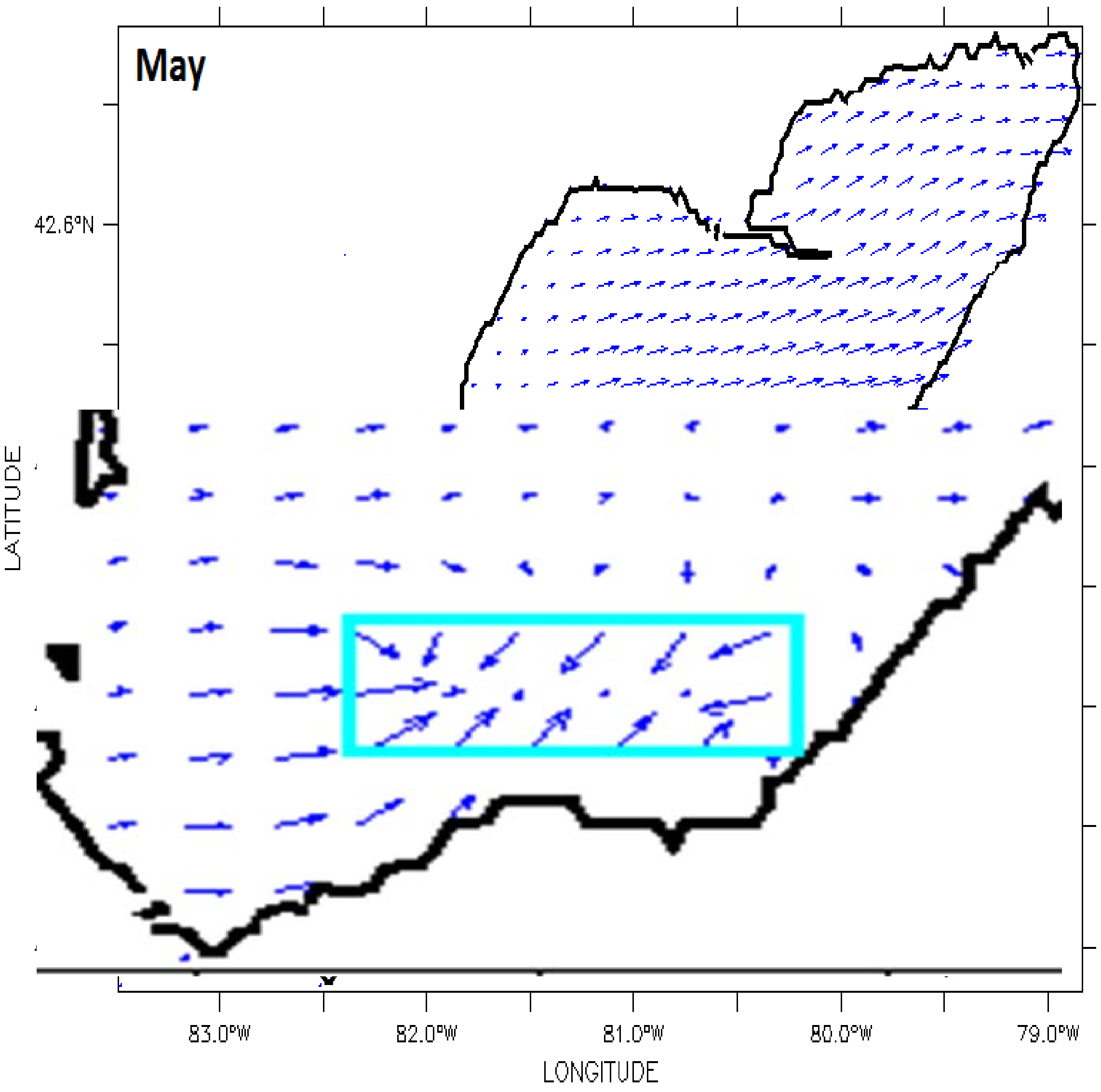
The wind farm has 18 (N-S) rows of 24 turbines. Spacings are 500 m (≃3 D) N-S and 3 km (≃18 D) E-W, where D is the wind turbine's rotor diameter. Depth of water within the wind farm zone ranges between 9.9 m to 19.2 m and has an average depth of 15.8 m.

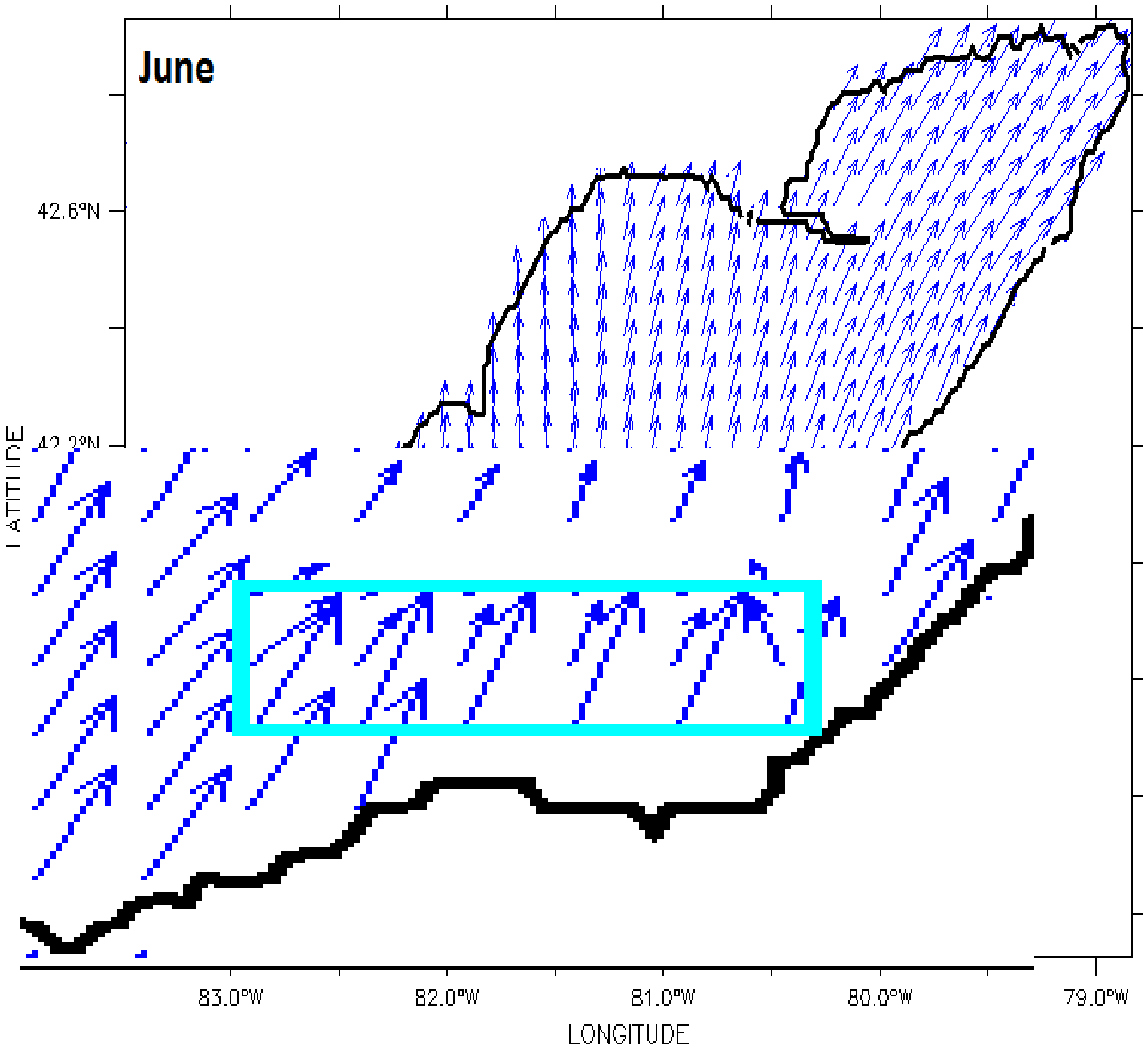
The V164 platform has an 80-m blade, (Vestasoffshore, 2017), has a rotor diameter of 164m and hub height of 140 m.



The blue rectangle of the wind farm area.

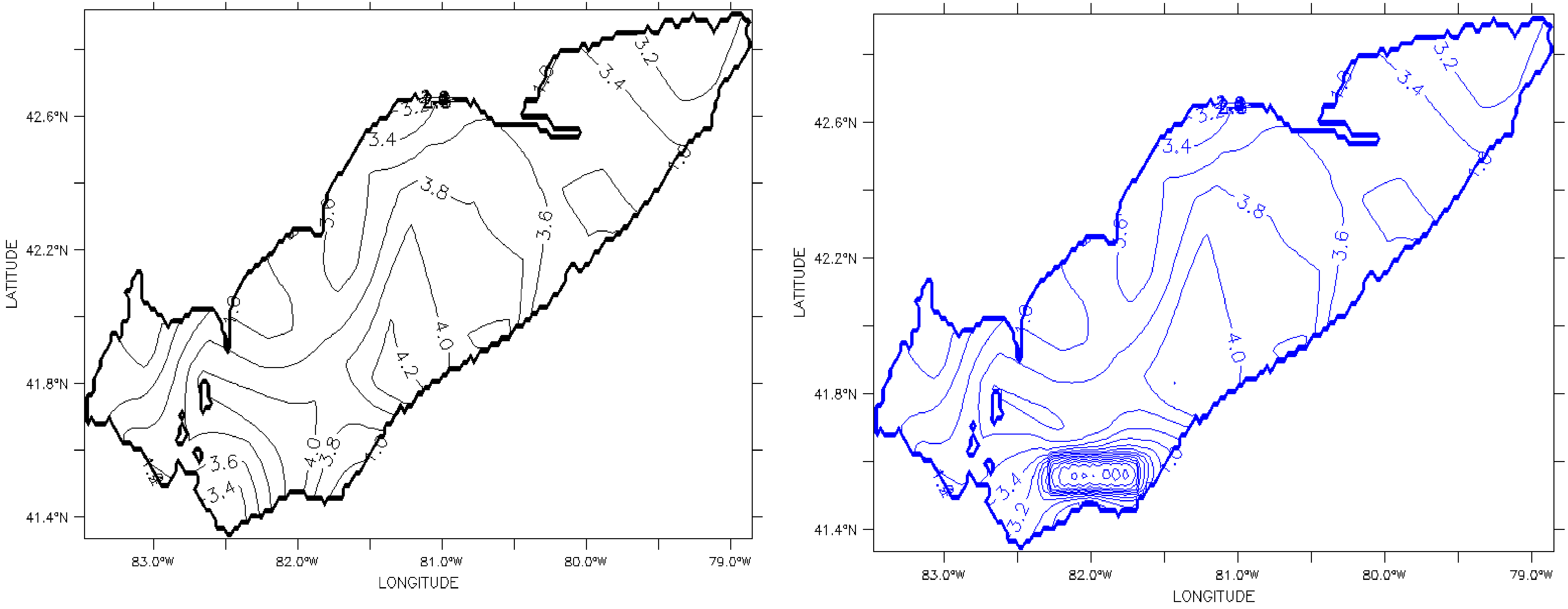
Wind Field – Monthly, Vector averaged



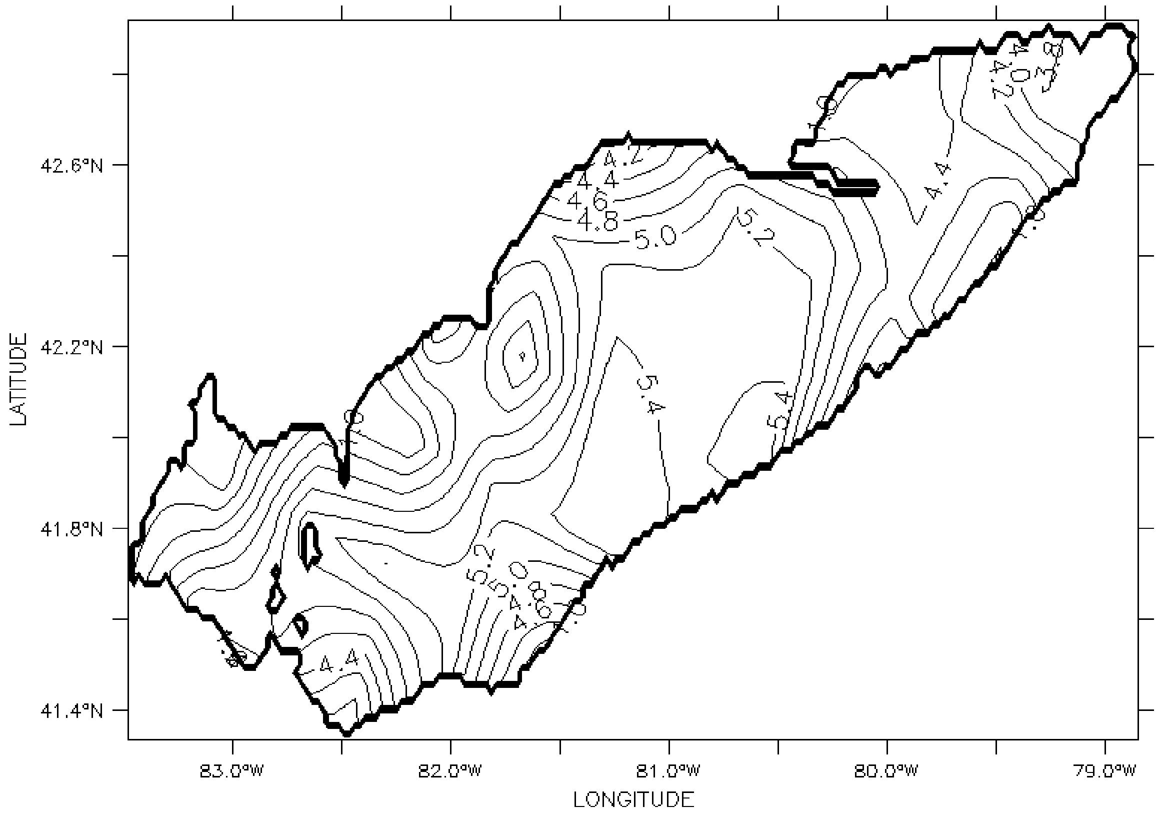


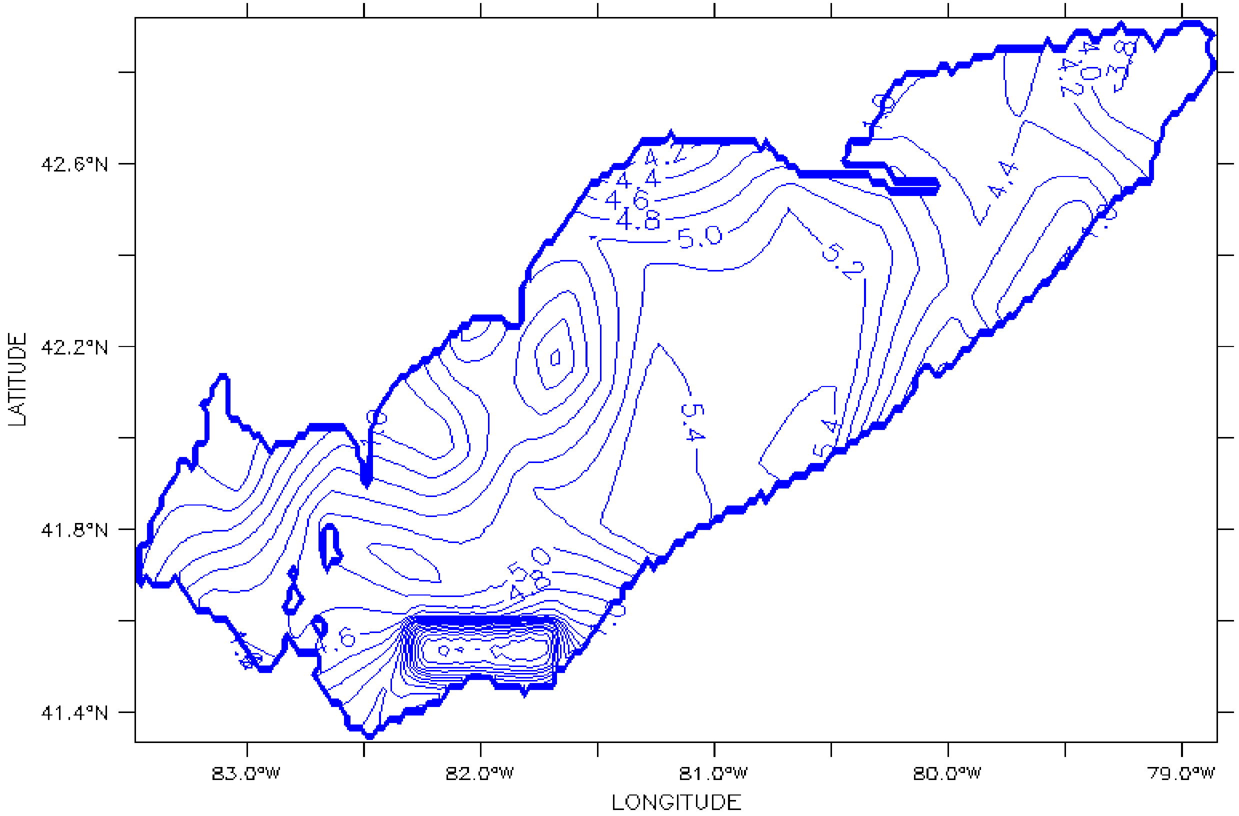
Wind Speed Contours, without/with wind farm.

May average wind speed (m/s), 2005

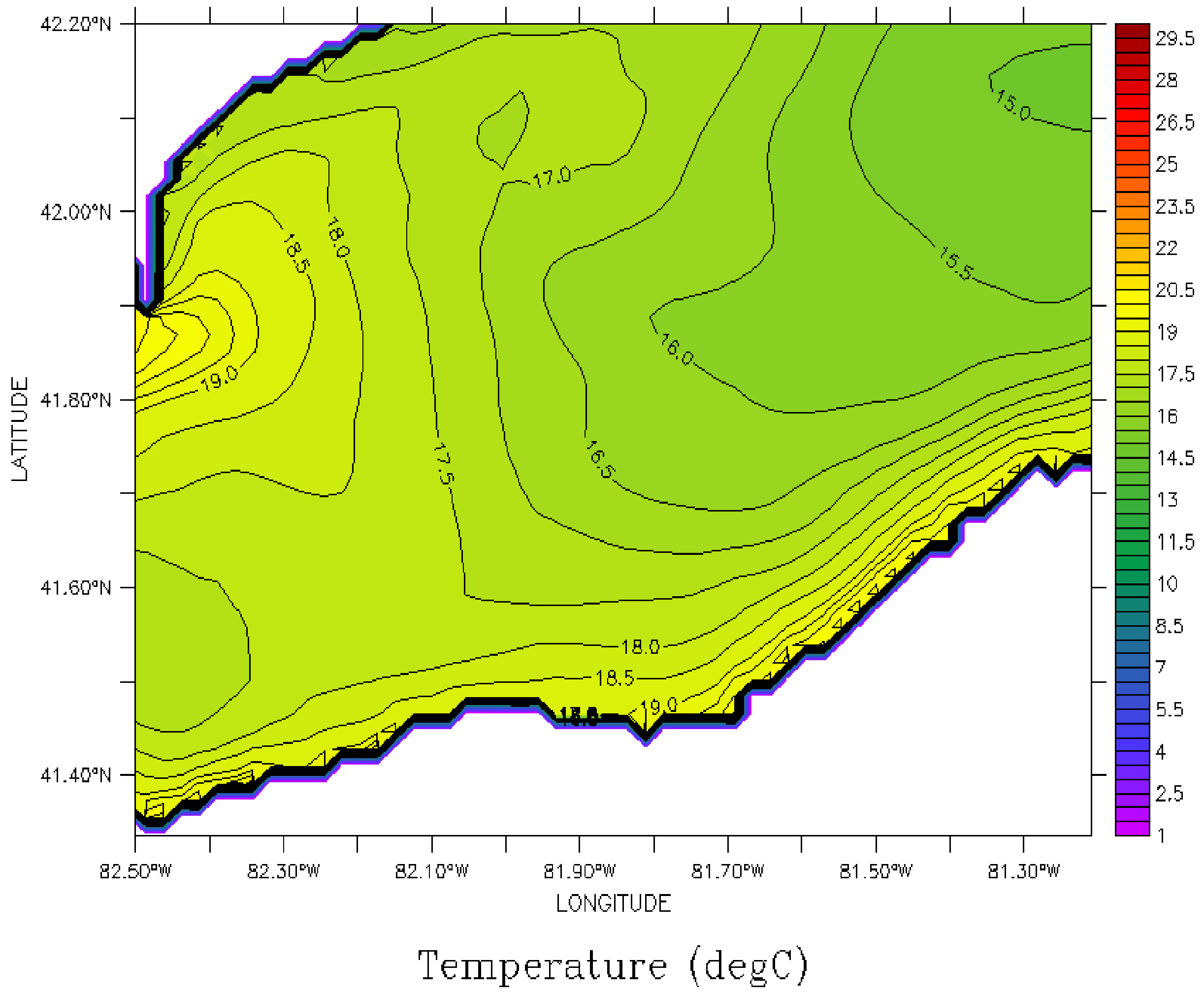


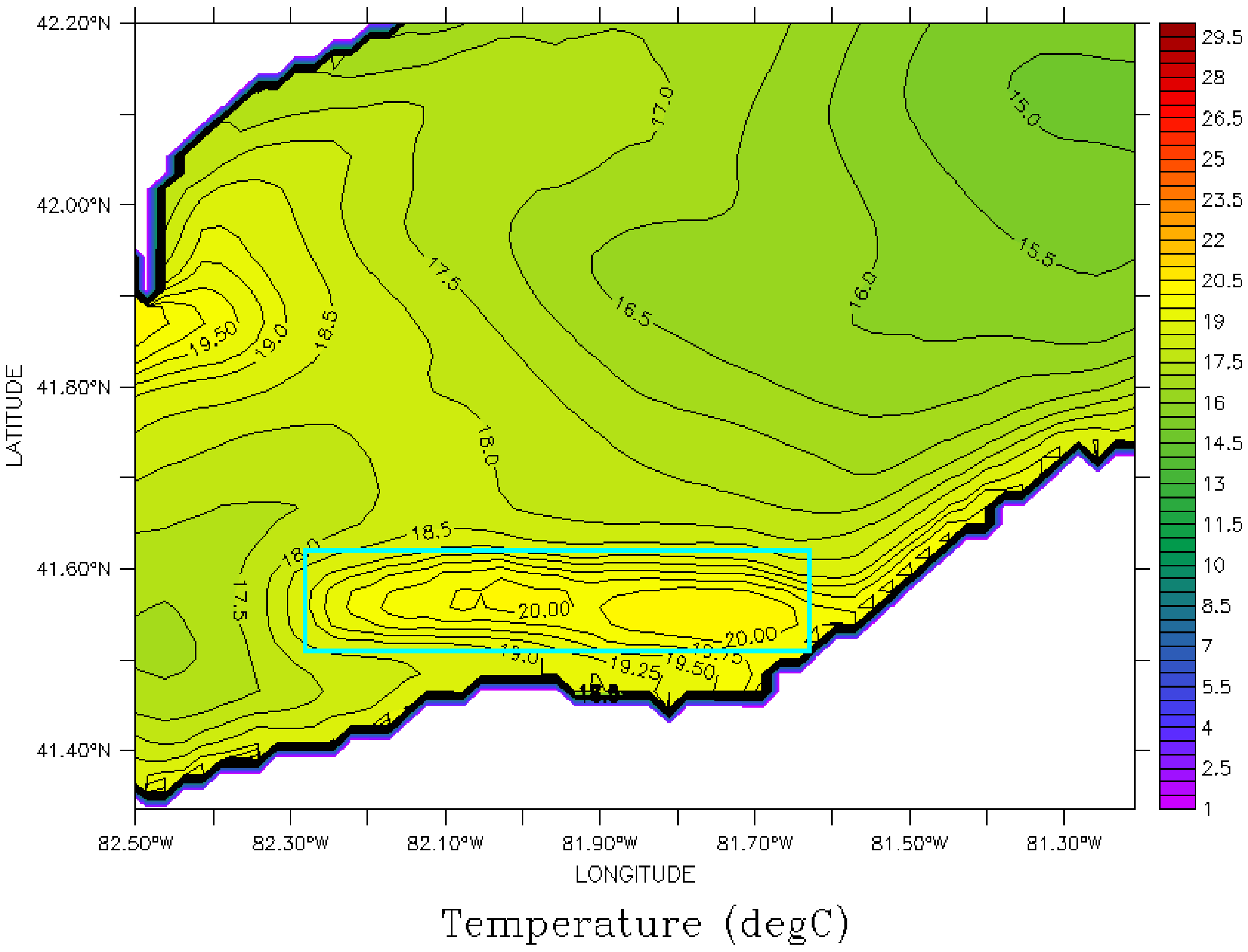
October average wind speeds (m/s), 2005



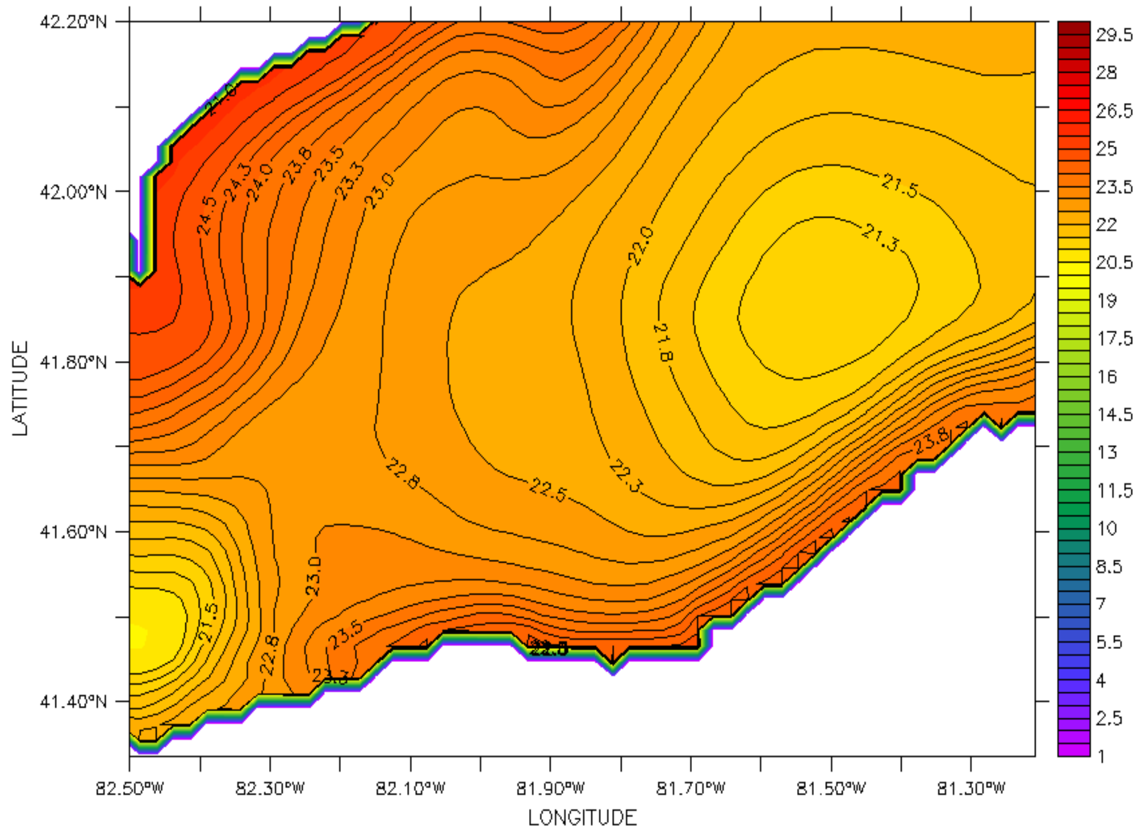


June-averaged surface water temperature in the a) absence and b) presence of a wind farm, 2005

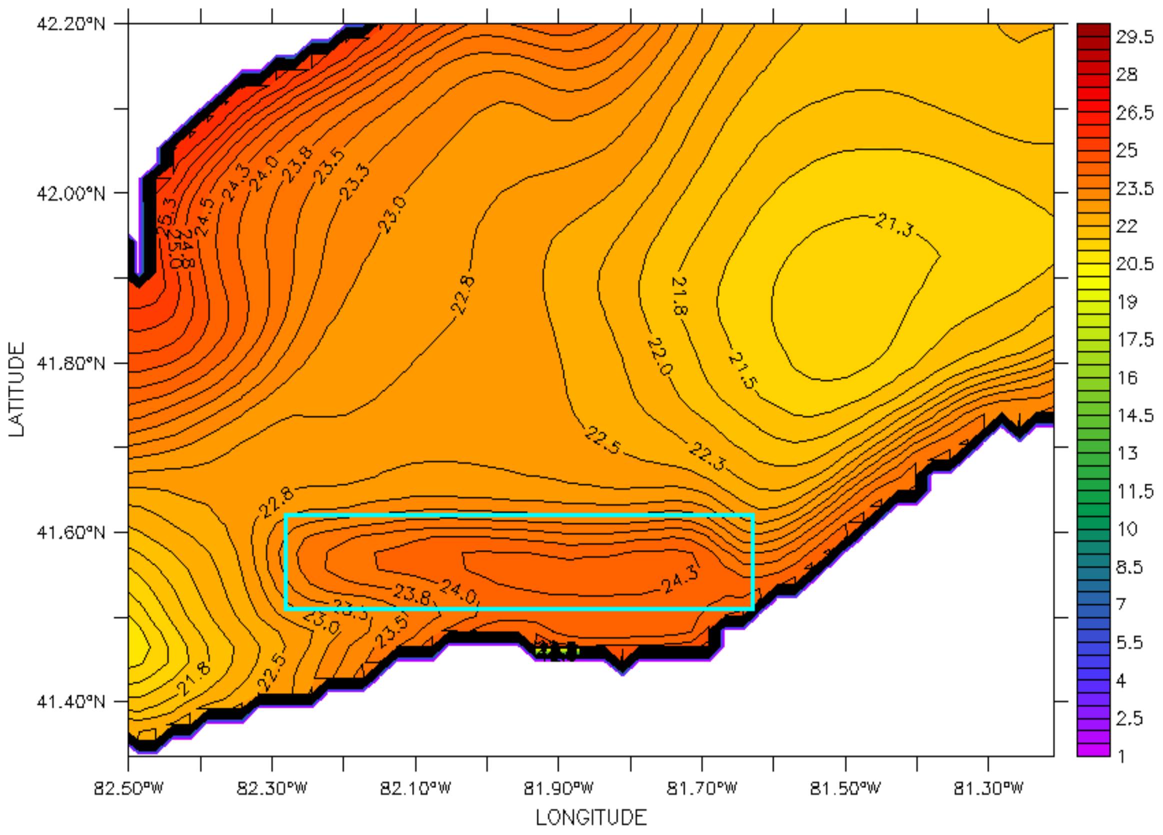




July-averaged surface water temperature in the a) absence and b) presence of a wind farm, 2005



Temperature (degC)



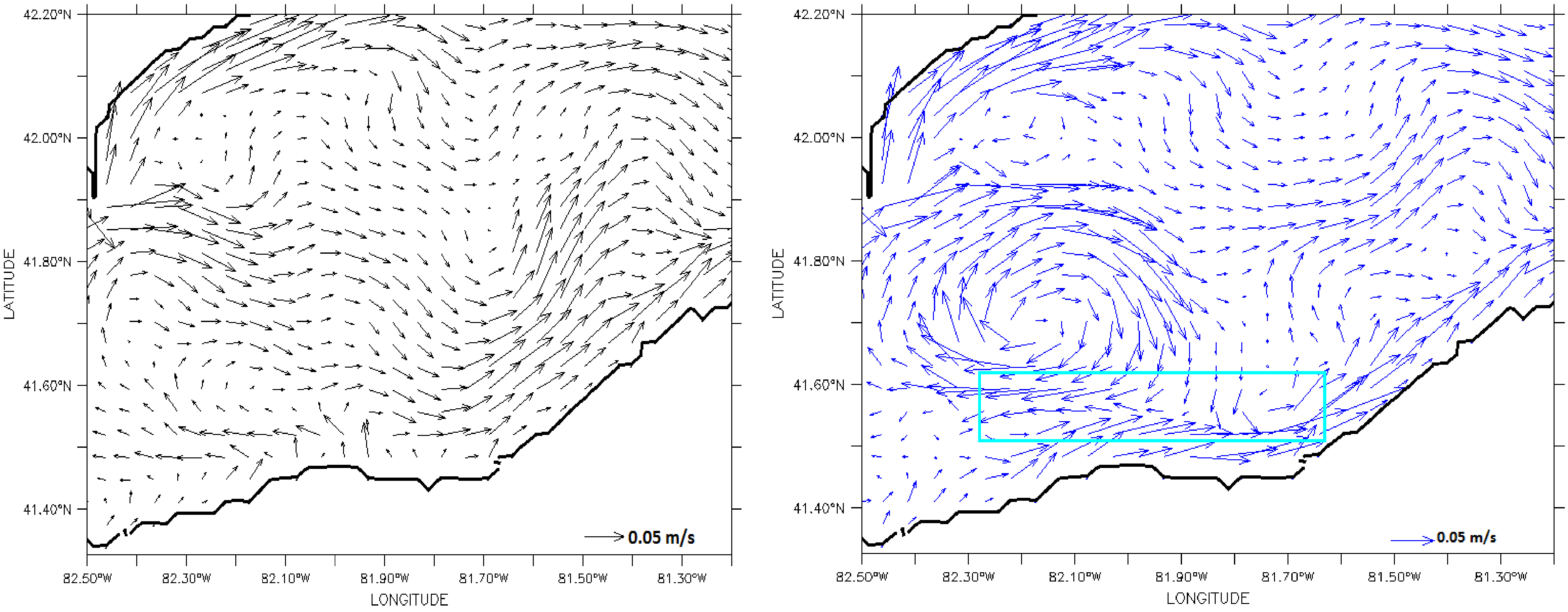
Temperature (degC)

Central Basin Surface Layer Water Temperature

Center of the wind farm wake surface layer water temperature (°C), May-October 2005

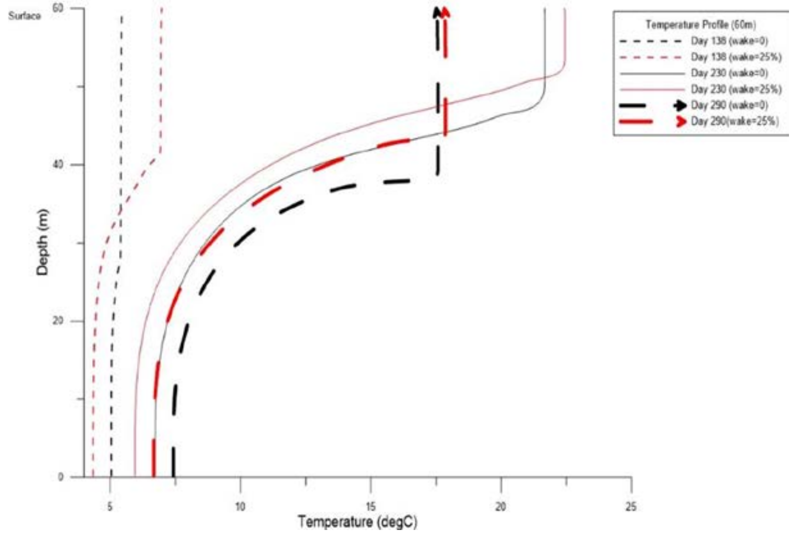
Center of the wind farm, surface layer water temperature(°C)		
Month	**Absence of a wind farm**	**Presence of a wind farm**
May	9	10.5
June	17.5	20
July	23	24.3
August	25.7	28.5
September	22	23.5

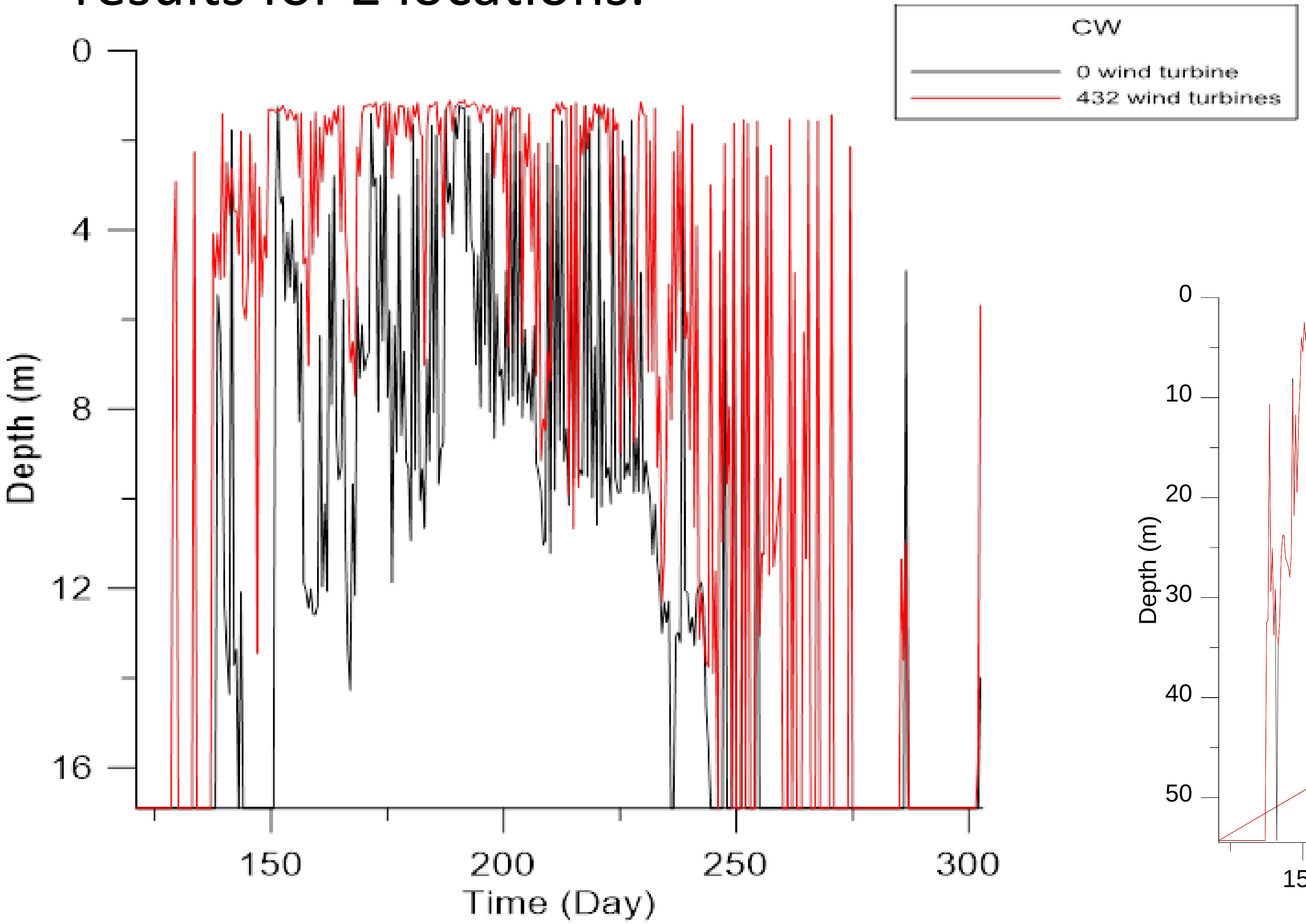
July-averaged surface water current in the a) absence and b) presence of a wind farm, 2005.

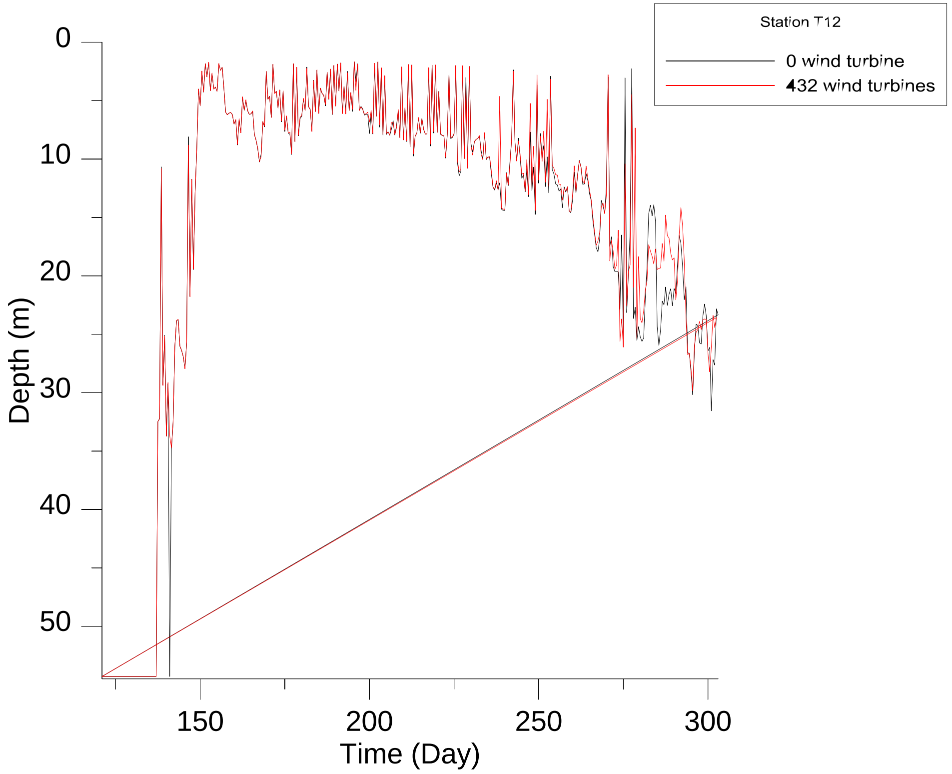


Water current velocity (m/s)

Temperature Mixed Layer Depth (TMLD) 1-D model results, 3-D results for 2 locations.







CONCLUSION

- By including a large wind farm in Lake Erie, wind speed is reduced by maximum and average values of 60 and 17 percent of the undisturbed values in the center of the wind turbine wake zone.
- This wind reduction leads to a potential increase of a few degrees (1 to 3°C), in the water surface temperature, which varies with time and has a maximum impact in summer.
- Another effect is reducing the surface current magnitude and changing the surface water current directions.
- The combination of these two, in turn, affects the thermocline and TMLD (temperature mixing length depth).
- The thermocline onsets earlier and decays later when a wind farm is applied, with a deeper and sharper thermocline.
- The COHERENS model predicts higher surface temperature and cooler bottom temperature during warm months and vice-versa in cooler months compared to the case when there isn't any wind farm.
- The persistent thermocline and slower winds lead to a shallower temperature mixing length.

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