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

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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 wind farm, with 432 5MW 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 2ºC in and around the wind farm but the overall impact is relatively small in other parts of the lake.

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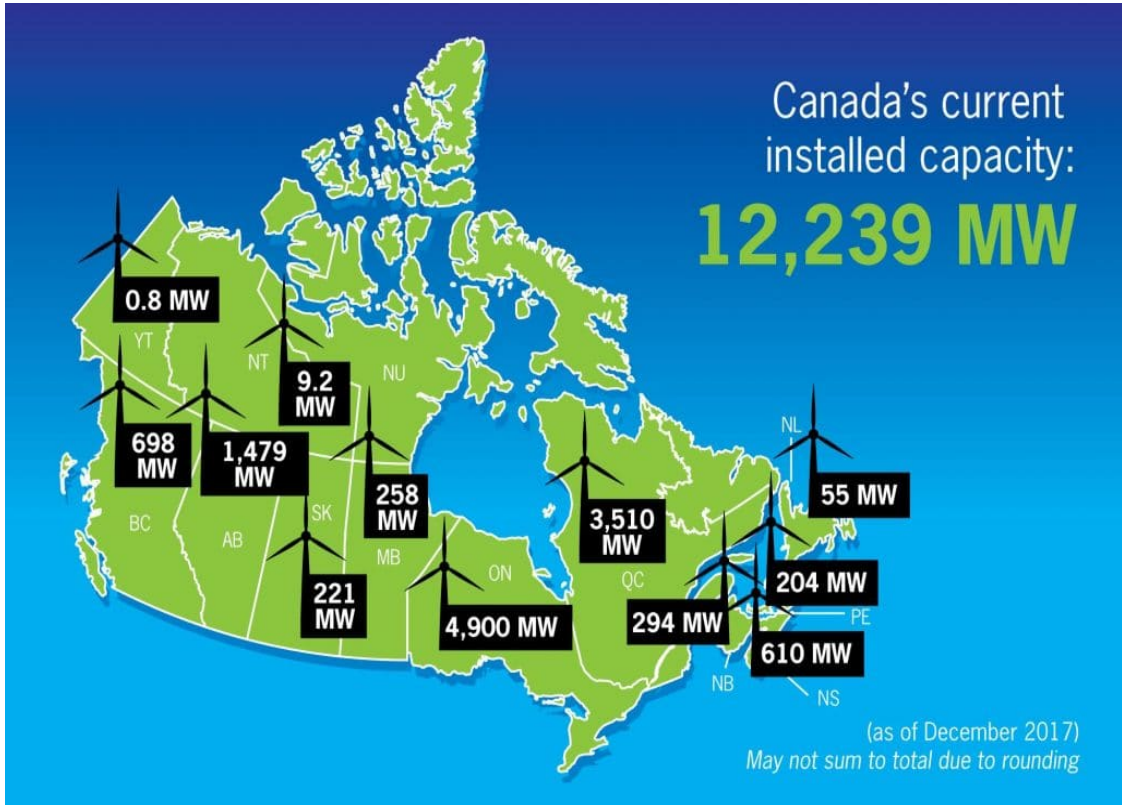
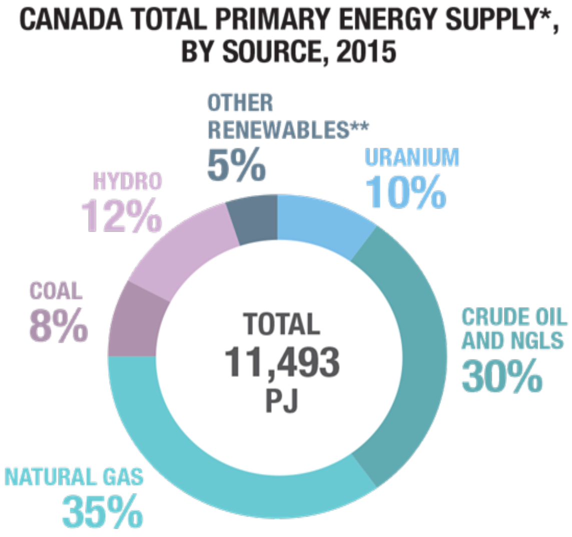
CANWEA's wind vision 2025: calls for 55000 MW by the end of following decade. By 2025, the wind energy industry is projected to create 52,000 new "Green Collar Jobs" in Canada. According to the government of Canada, wind power has become the second largest renewable power source in Canada 2017.





All Electrical power capacity in Canada, Nuclear, Hydro, Oil, Coal etc. 135,000 MW in 2015 (Wikipedia)

Offshore Wind Plans in:

Ontario

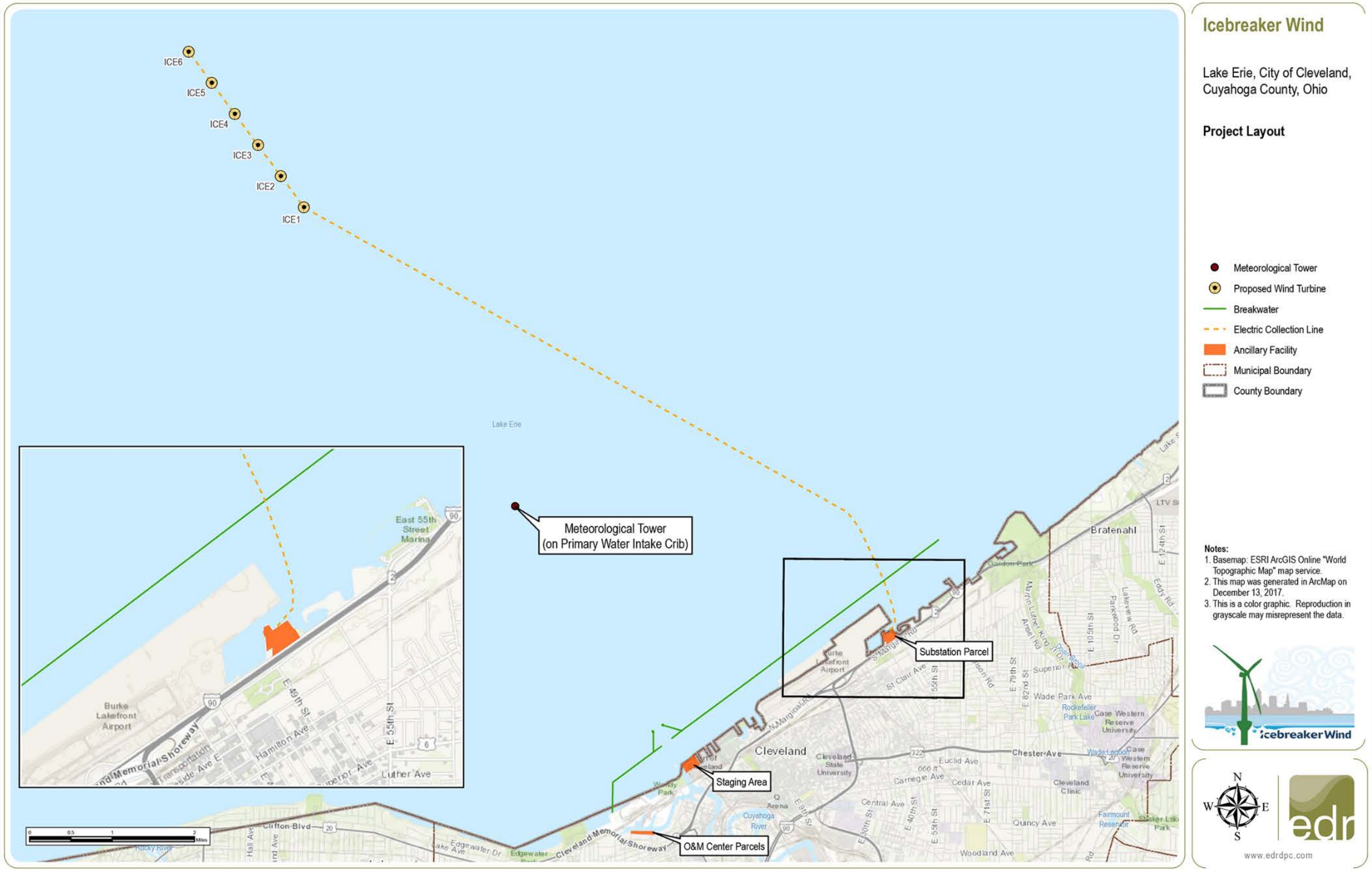
- up to 86 GW of offshore projects to be developed by 2050. The Great Lakes can generate about 15 percent of the development
- (Hamilton, 2016, Ontario's love-hate relationship with Great Lakes wind turbines. Retrieved from https://tvo.org/article/current-affairs/climate-watch/ontarios-love-hate-relationship-with-great-lakes-wind-turbines).

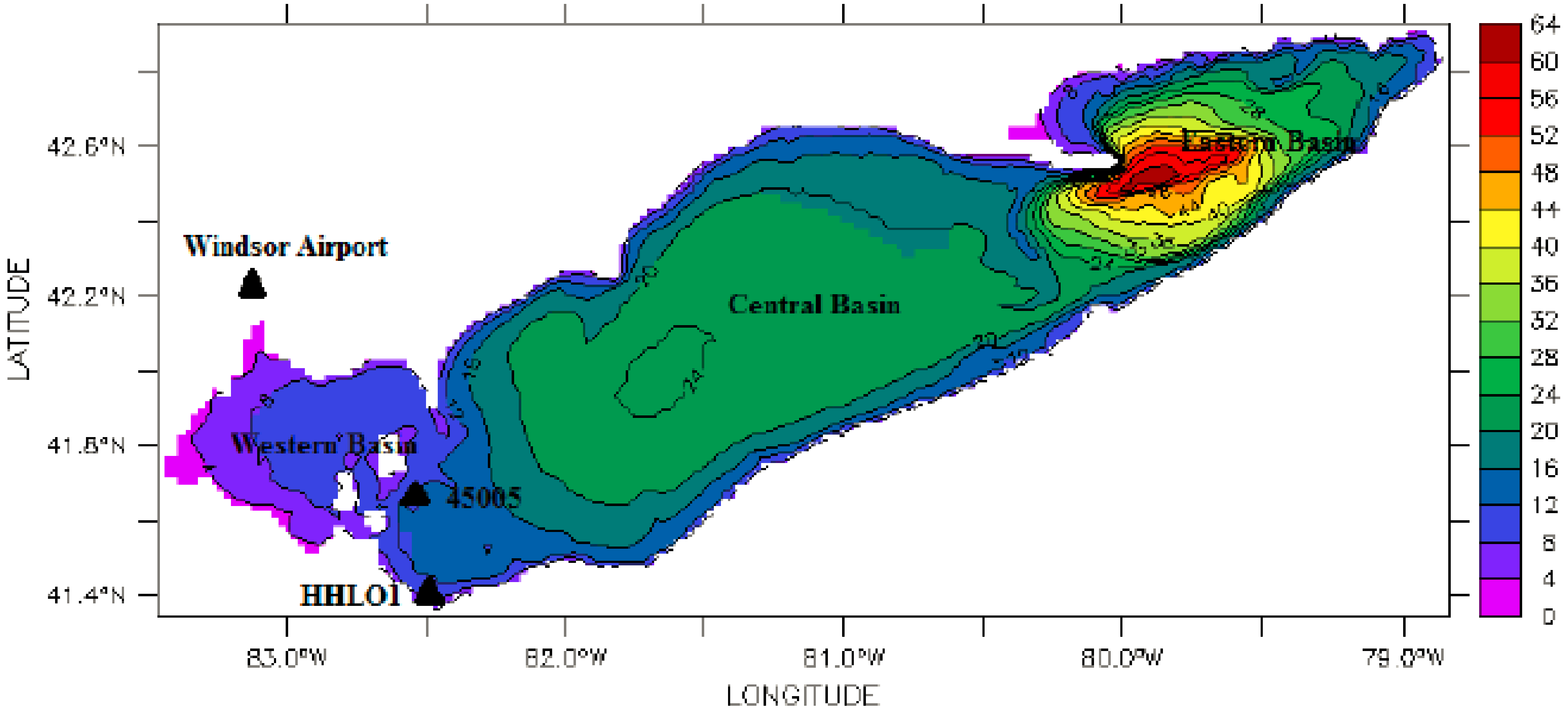
Lake Erie

- 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
- Our modelled Lake Erie large wind farm, 4.1 GW (432 x 9.5MW turbines – largest currently available)

Ice-Breaker Project

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. Construction planned for Summer 2020 with Operation in November 2020





Mean water depth (m)

Figure 1. Lake Erie bathymetry and stations. Isobaths shown every 4 m.

COHERENS : Basic model equations

- Continuity equation, Momentum equations (u,v), Hydrostatic approximation, Thermodynamic Equation (T, potential temperature), surface elevation, $z = \zeta$, from w at mean surface (z=0). f-plane approximation,
  σ (0 …1) coordinates in vertical, $\sigma = (z + h) / (h + \zeta)$, mean water depth h(x,y).
- $\partial u/\partial x + \partial v/\partial y + \partial w/\partial z = 0$; $\partial p/\partial z = -\rho g$; $\rho = \rho(T, p)$ but Bousinesq approximation used.
- $\partial u/\partial t + u\, \partial u/\partial x + v\, \partial u/\partial y + w\, \partial u/\partial z - fv = -(1/\rho_0)(\partial p/\partial x) + F^t_x + (\partial/\partial z)(\nu_T\, \partial u/\partial z) + (\partial/\partial x)\, \tau_{xx} + (\partial/\partial y)\, \tau_{xy}$
- $\partial v/\partial t + u\, \partial v/\partial x + v\, \partial v/\partial y + w\, \partial v/\partial z + fu = -(1/\rho_0)(\partial p/\partial y) + F^t_y + (\partial/\partial z)(\nu_T\, \partial v/\partial z) + (\partial/\partial x)\, \tau_{yx} + (\partial/\partial y)\, \tau_{yy}$
- $\partial T/\partial t + u\, (\partial T/\partial x) + v\, (\partial T/\partial y) + w(\partial T/\partial z) = (1/\rho_0\, c_p)\, (\partial I/\partial z) + (\partial/\partial z)\, (\lambda_T\, \partial T/\partial z) + (\partial/\partial x)\, (\lambda_H\, \partial T/\partial x) + (\partial/\partial y)\, (\lambda_H\, \partial T/\partial y)$

Uses a simplified RANS model for turbulent transfers.

https://odnature.naturalsciences.be/coherens/

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Solar and IR Irradiance

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

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

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

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

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

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: $(\rho_0\, c_p\, /\, h_3)\, (\, \lambda_T\, \partial T/\partial s) = Q_s$

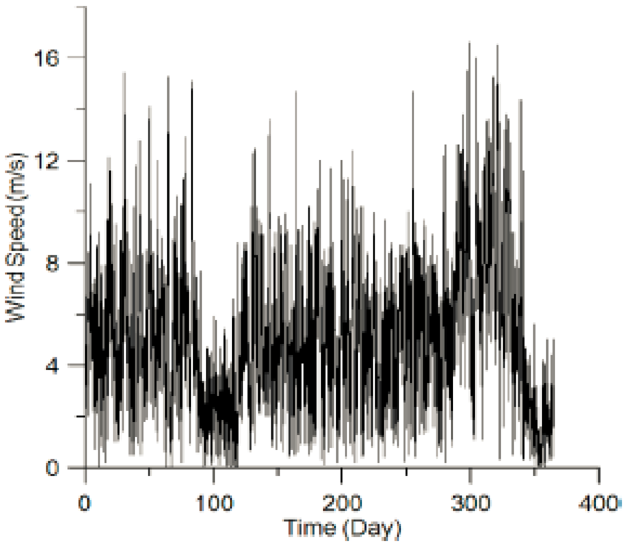
Water Bottom Boundary Condition

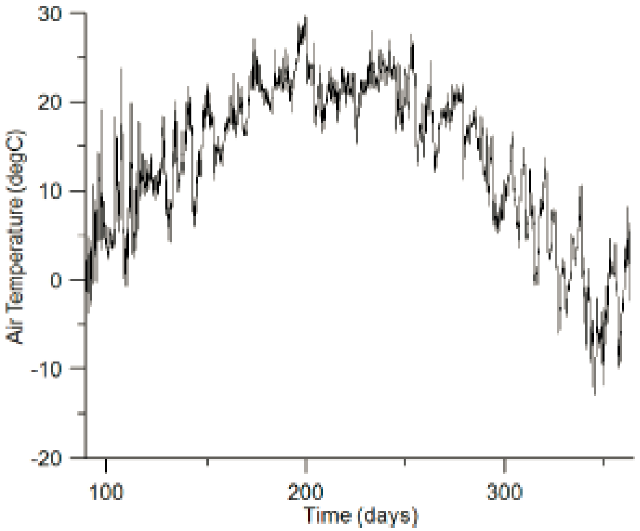
- Current: $(\nu_T/h_3)\, (\partial u/\partial s\ ,\ \partial v/\partial s) = (\tau_{b1},\, \tau_{b2})$;
- $(\tau_{b1},\, \tau_{b2}) = C_{db}\, (u_b^{\,2} + v_b^{\,2}\,)^{½}\ (u_b,\, v_b)$
- $C_{db} = (\kappa/\, \ln(z_r\, /z_0))^2$

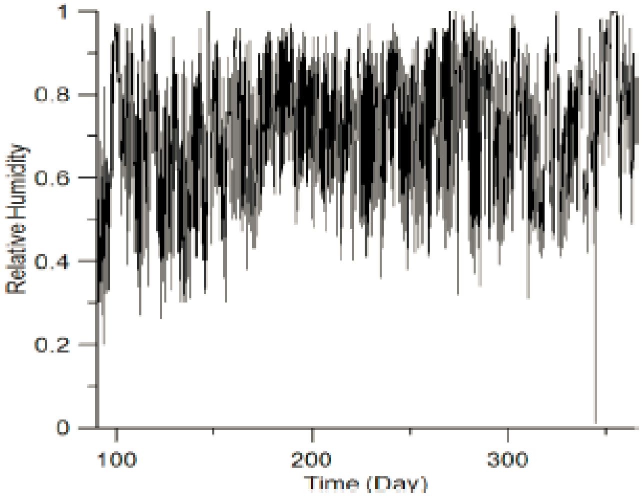
- Temperature: $\lambda_T\, /\, h_3\, (\partial T/\partial s) = 0$

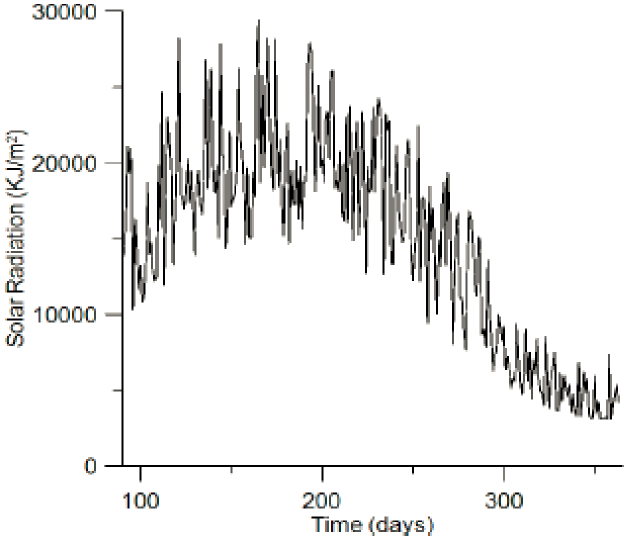
Preliminary 1-D model considerations (2013 input data)

- The infinite wind farm – what wind speed reduction. 25% used.
- 2013 Met observations from Buoys and Windsor airport used as input









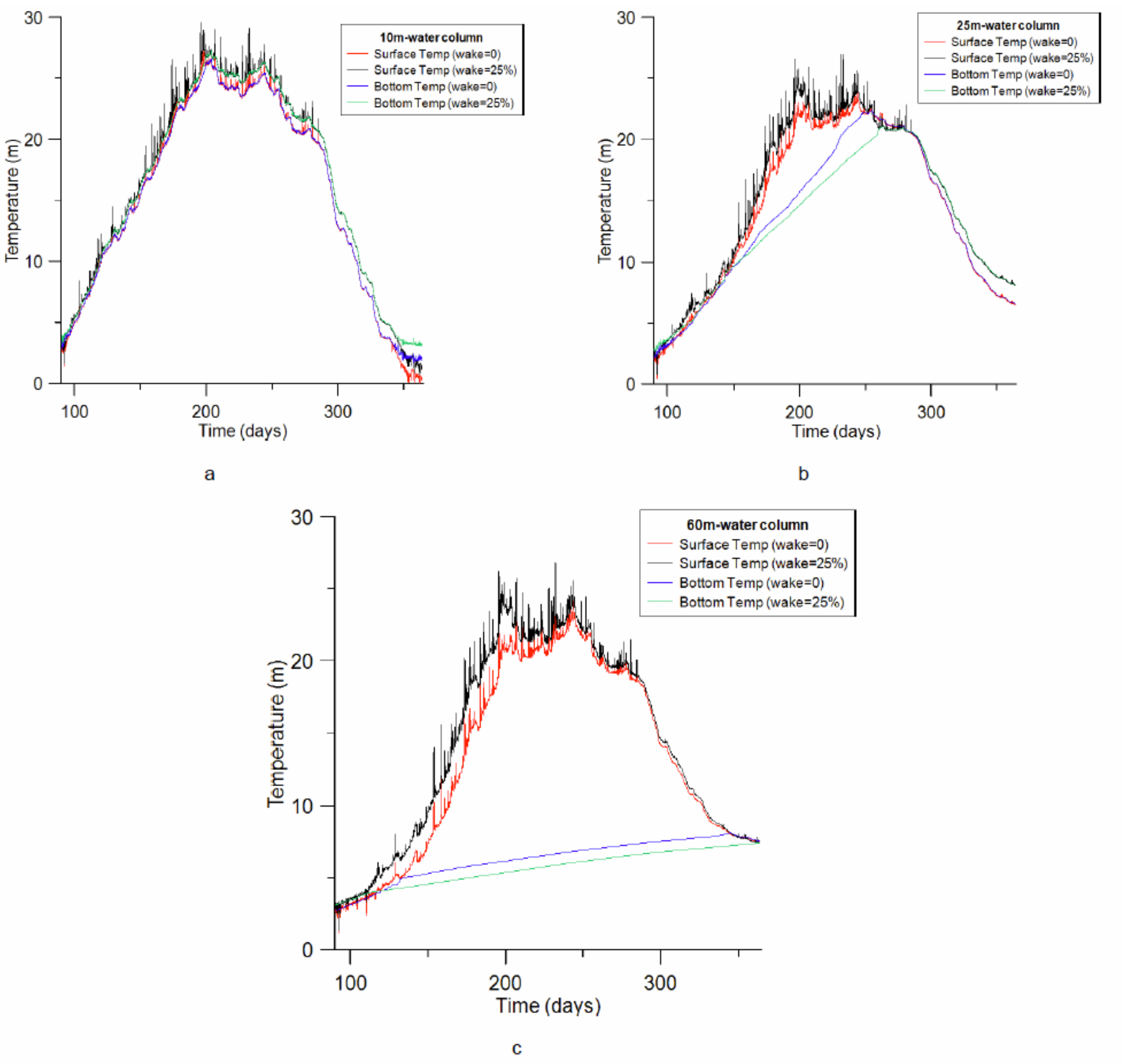


Figure 3. Surface and near bottom temperatures throughout the 2013 open water season. 1-D model results for water depths of 10, 25 and 60 m, with measured meteorological input and with a 25% wake reduction in wind speed.

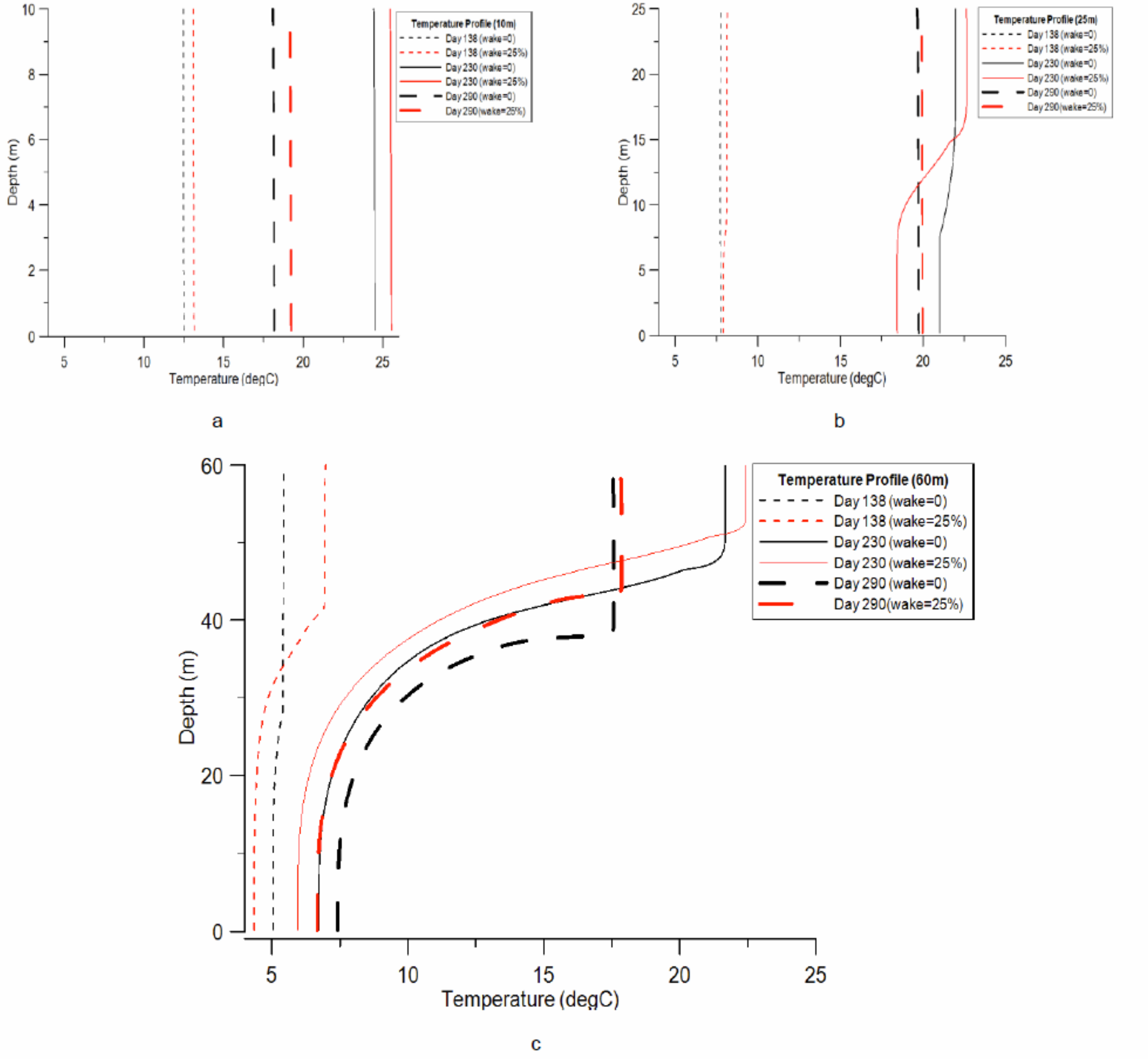


Figure 4. Sample temperature profiles at noon on DOY 138, 230 and 290, for water depth of 10 m, 25 m and 60 m, with and without wake effect wind speed reductions.

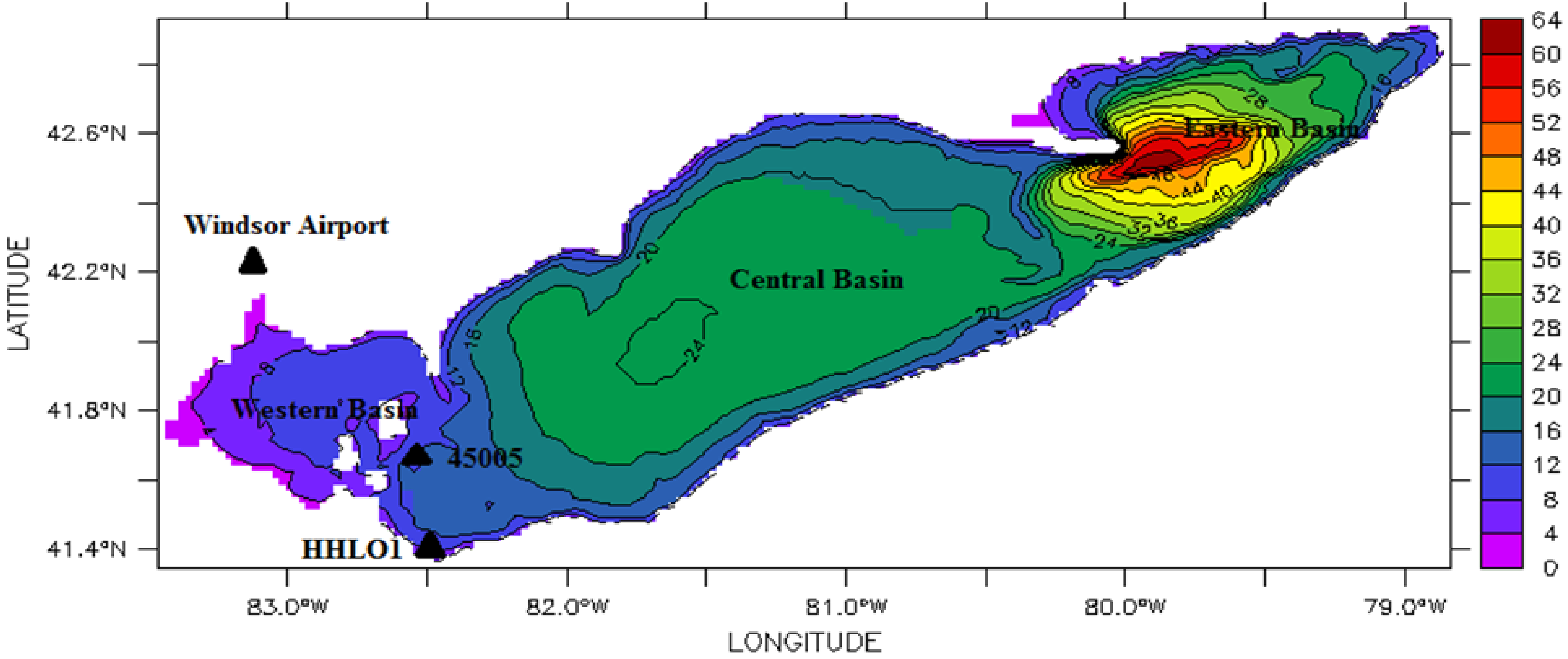
1D Mode Conclusion – run through open water season with water depths 10, 25, 60m, with and without wind speed reductions (25%)

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

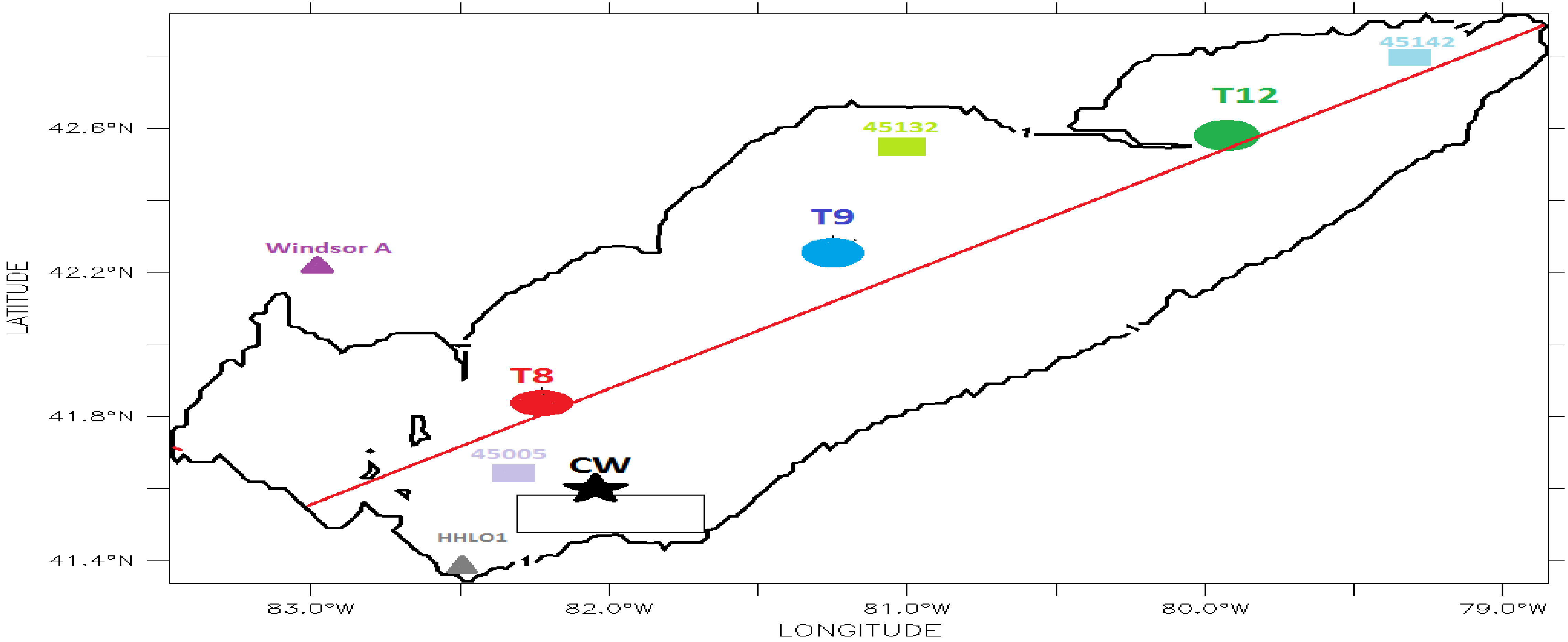
3-D Model study (2005 data)

Lake Erie
Bathymetry (m)



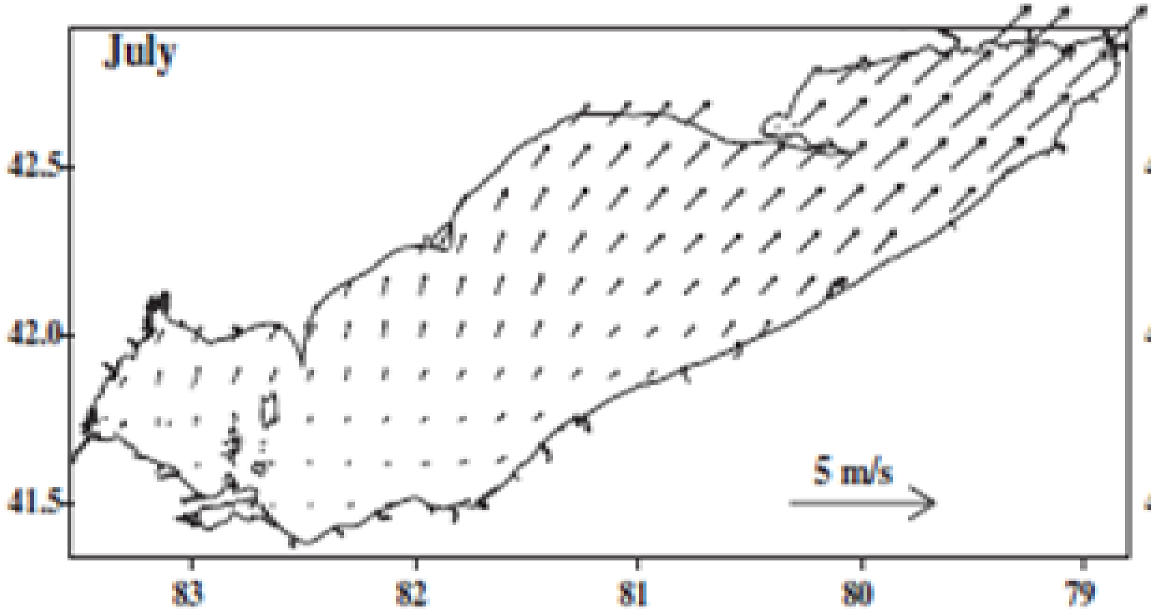
Mean water depth (m)

Lake Erie Mooring Locations and Section Line

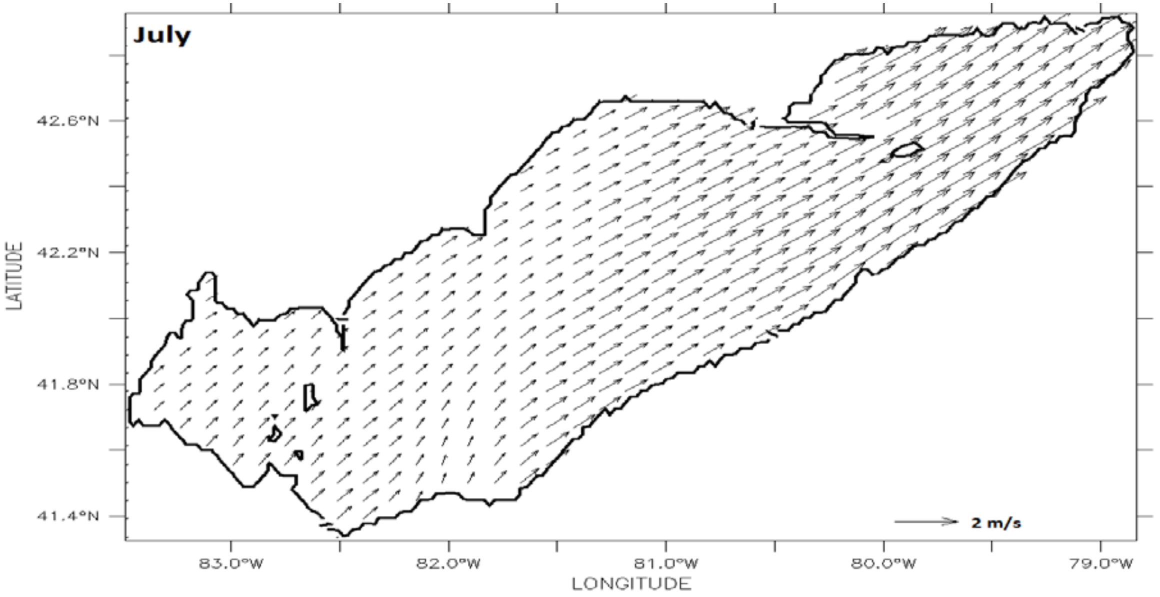


July 2005 vector averaged 10m wind

GEM wind input (5 m/s)
POM - Beletsky et al (2013)

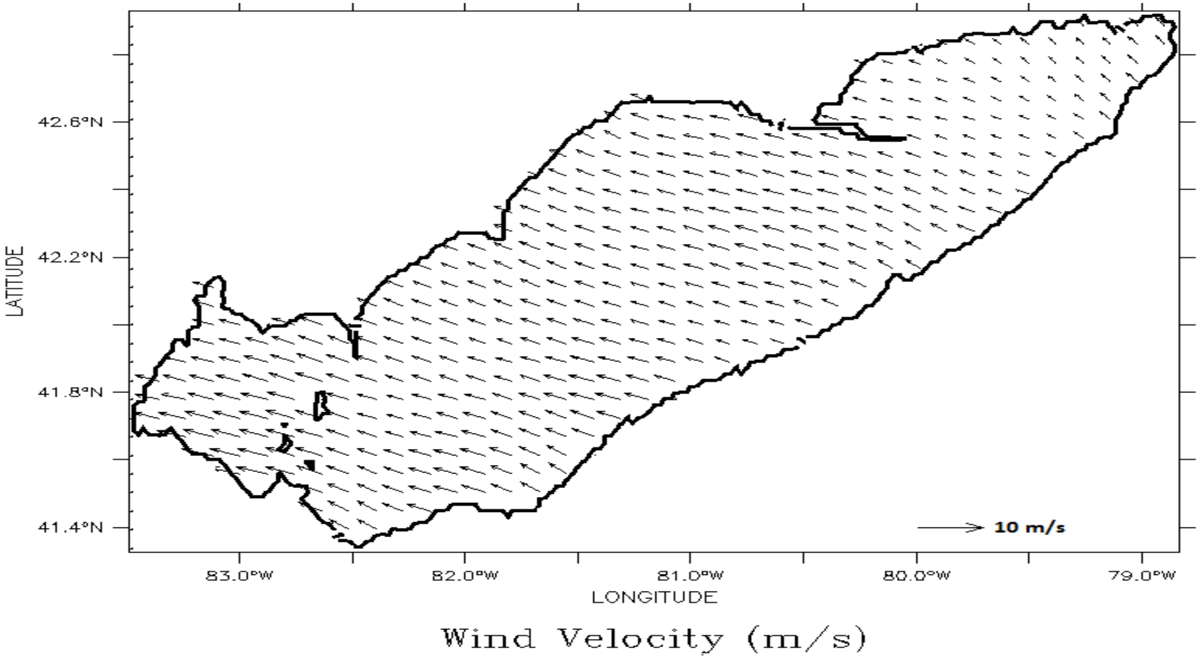


NARR wind input (2 m/s)
COHERENS

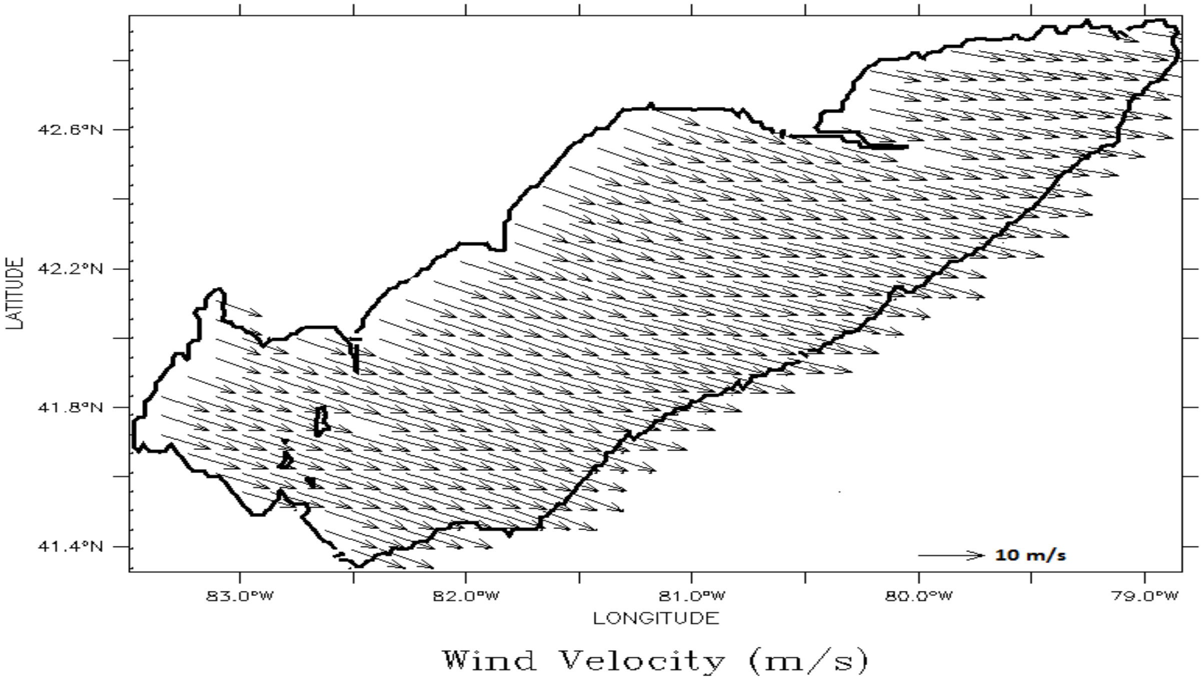


Instantaneous NARR 10m winds (10 m/s scale)

UTC 5 A.M. May 5, 2005



UTC 5 A.M. October 15, 2005



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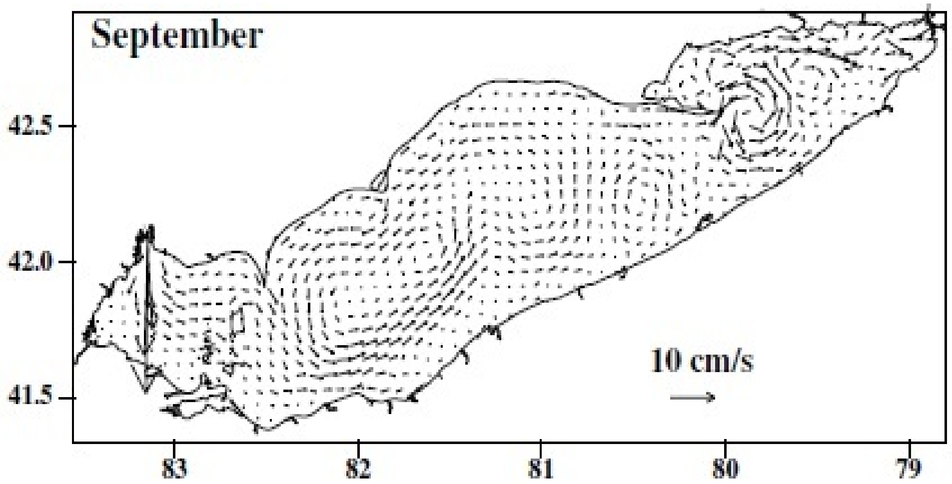
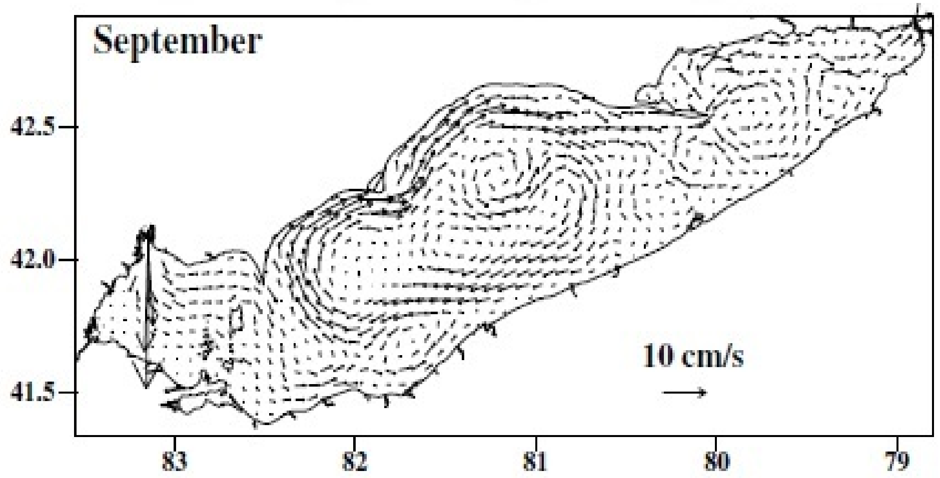
Monthly averaged, depth averaged water circulation.

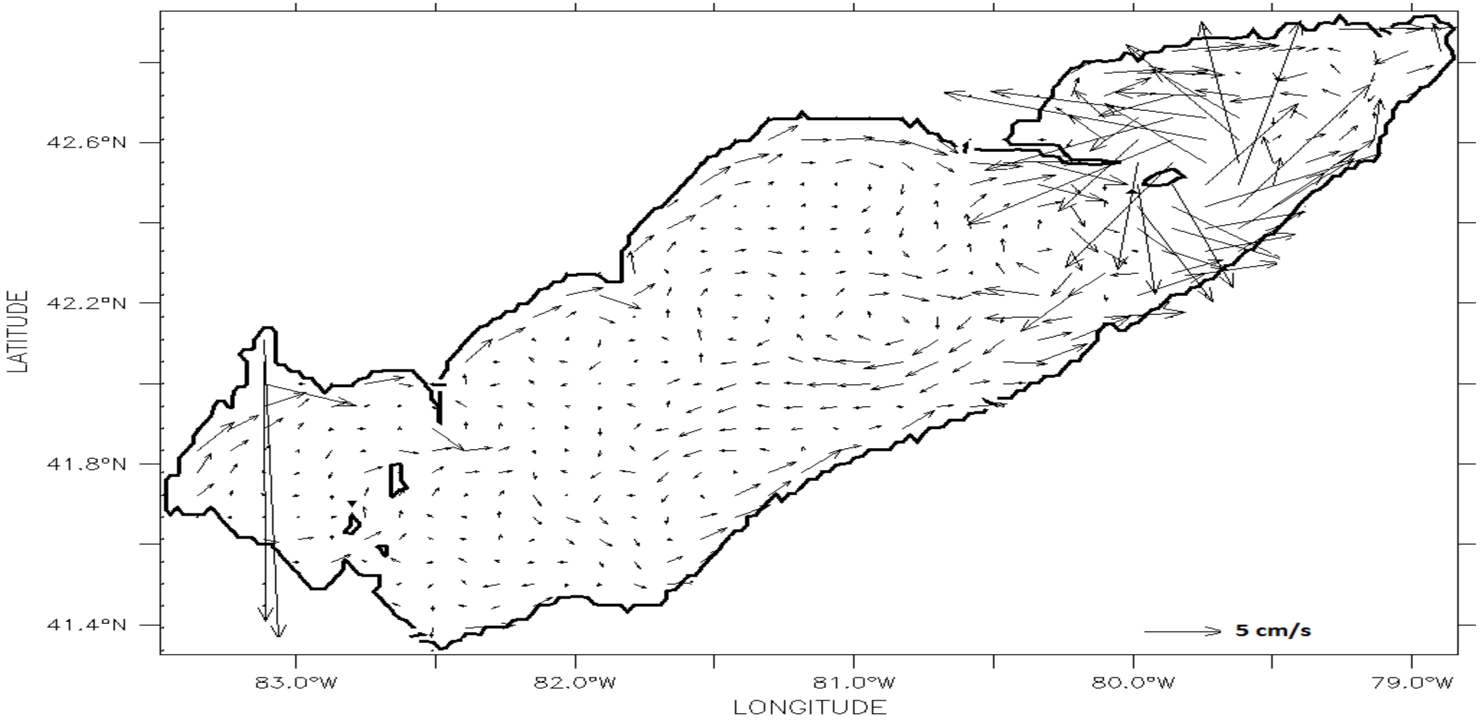
Using GEM uniform wind

COHERENS

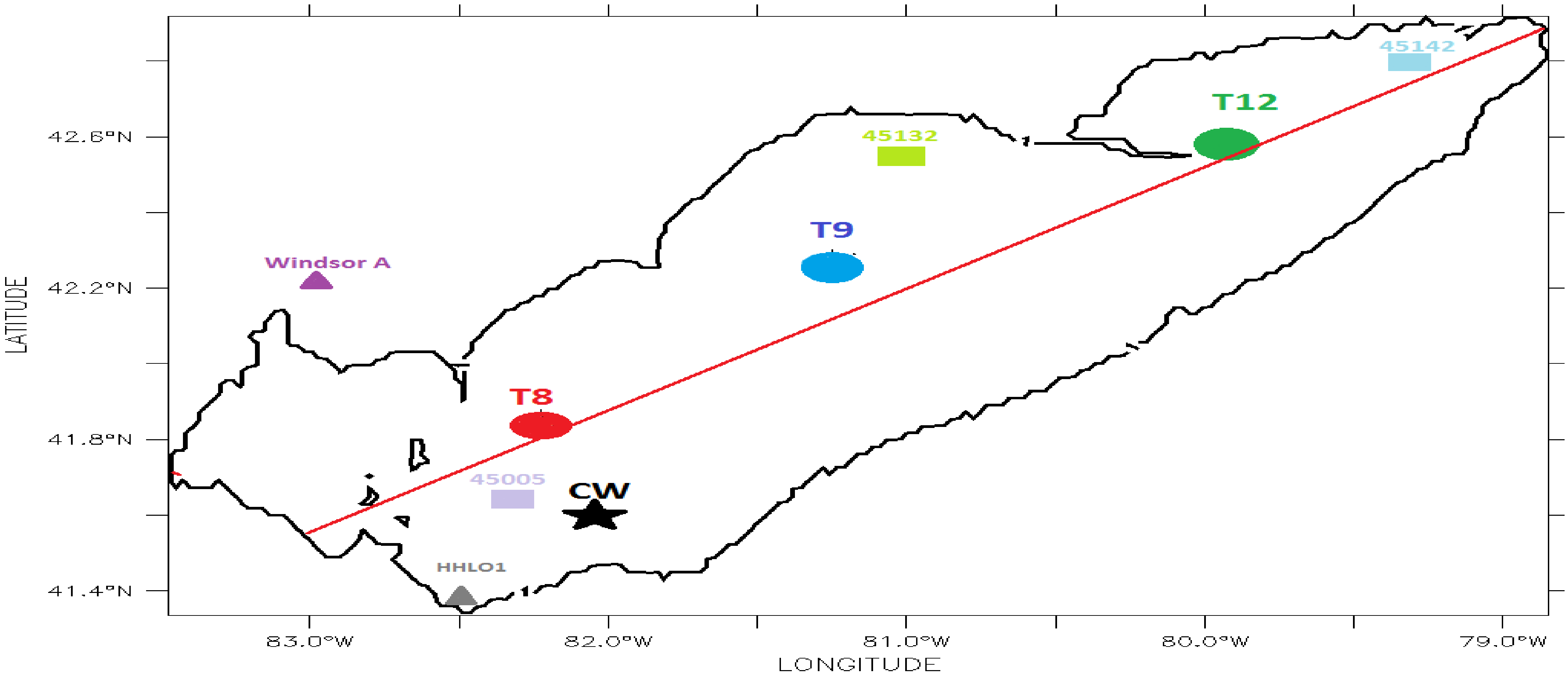


POM, GEM, from Beletsky (2013)



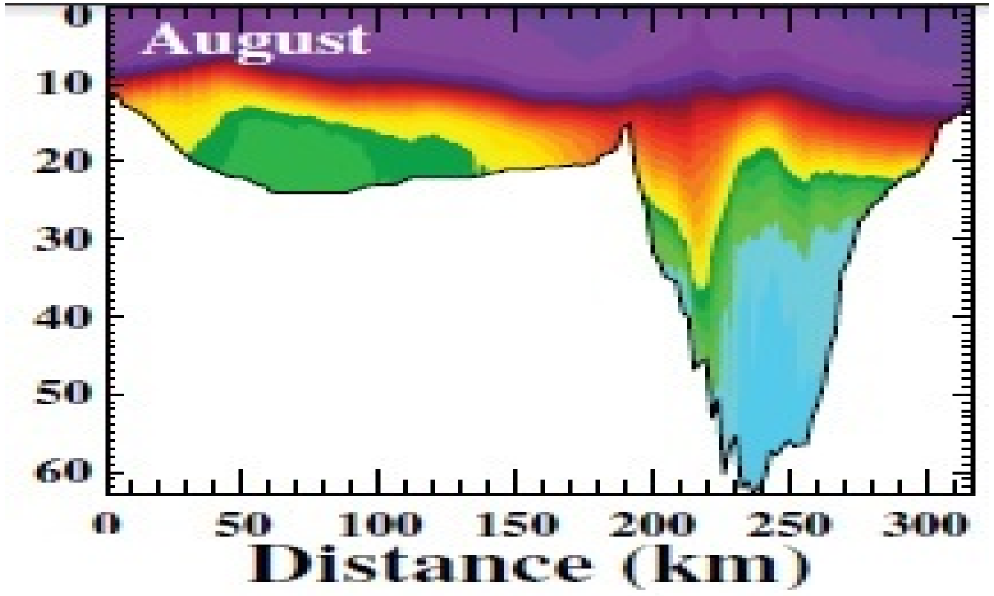


Lake Erie Mooring Locations and section (note station 45005 and CW locations)

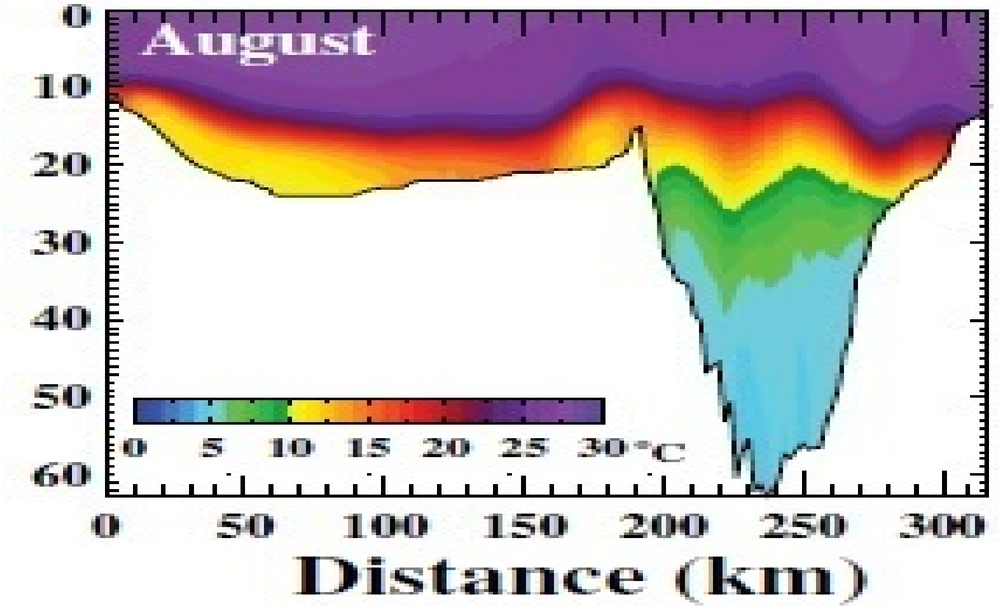


Temperature sections, August 2005

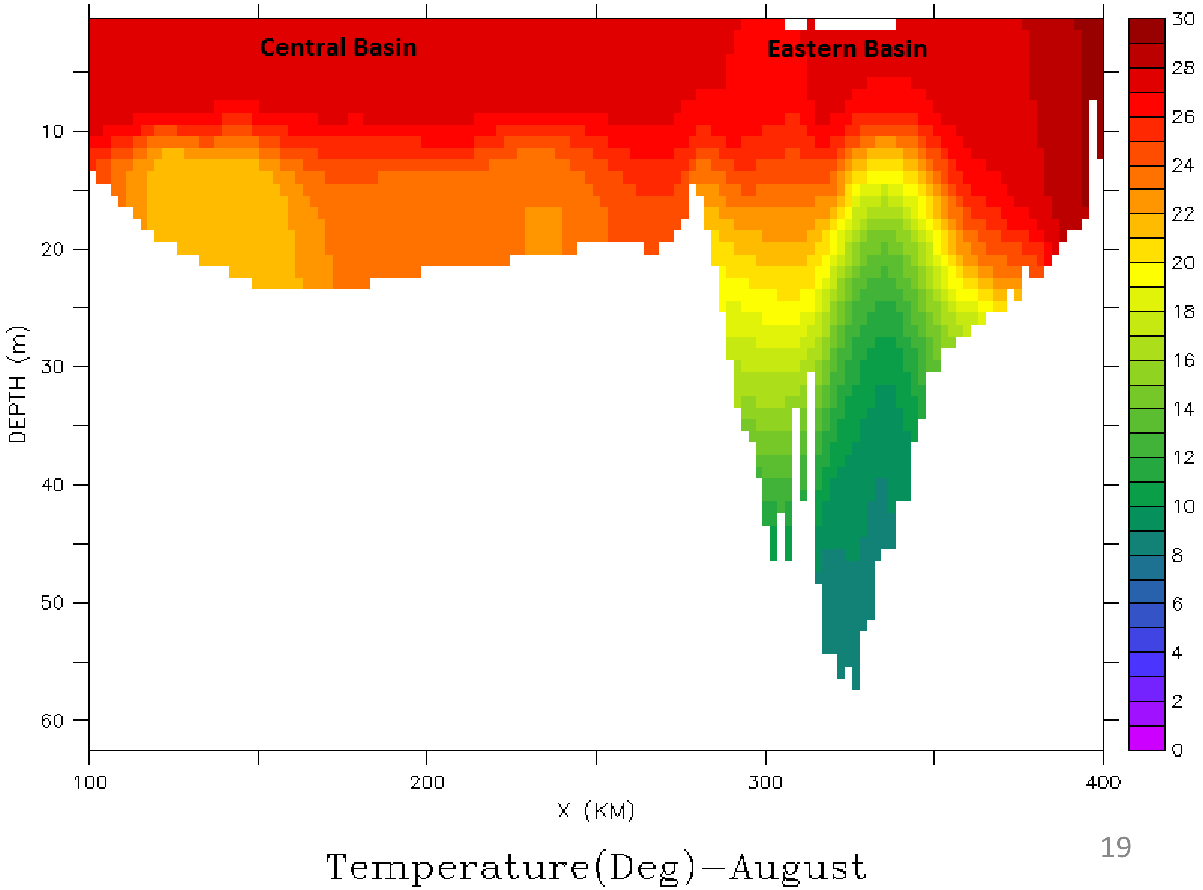
Using uniform GEM wind



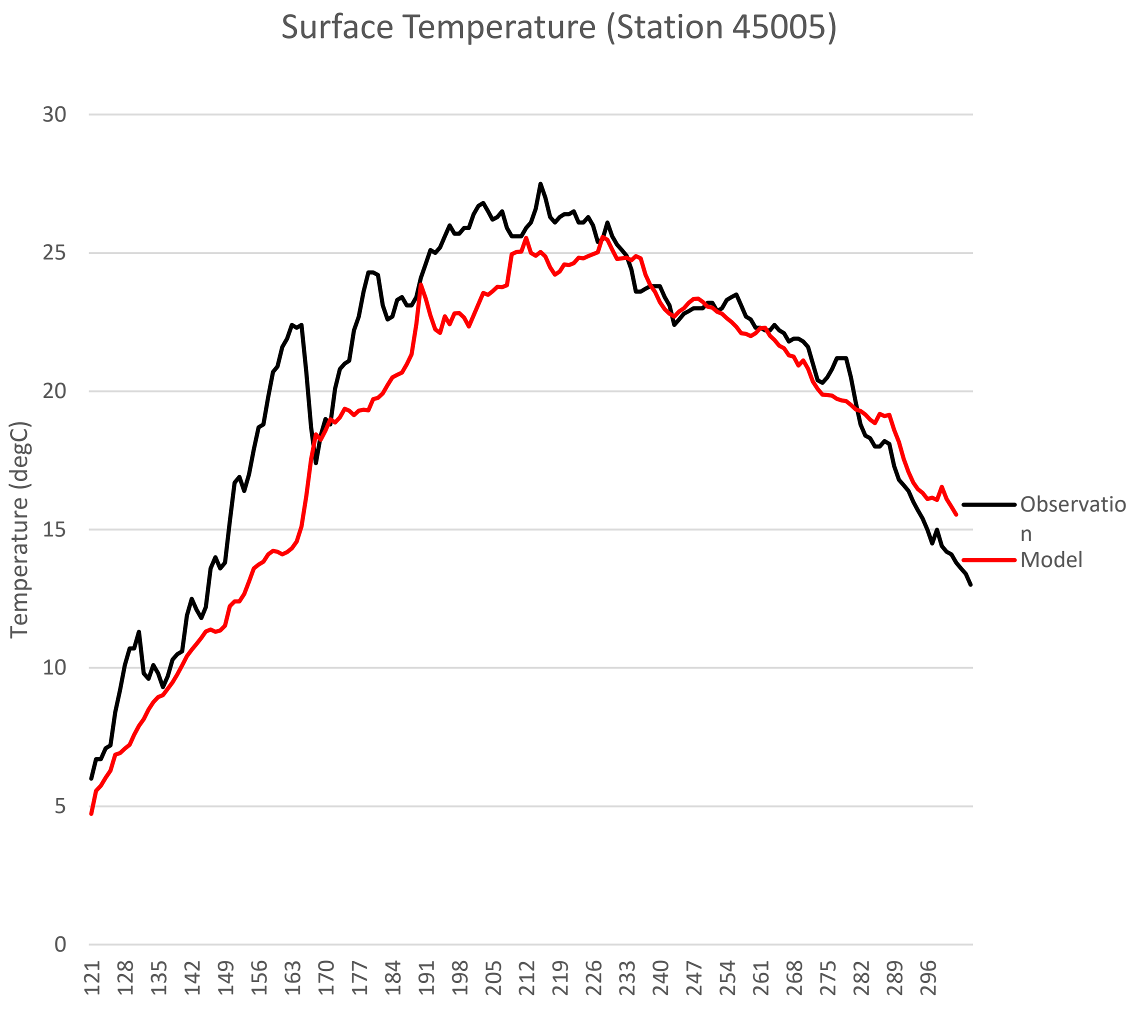
POM (Beletsky et al 2013)

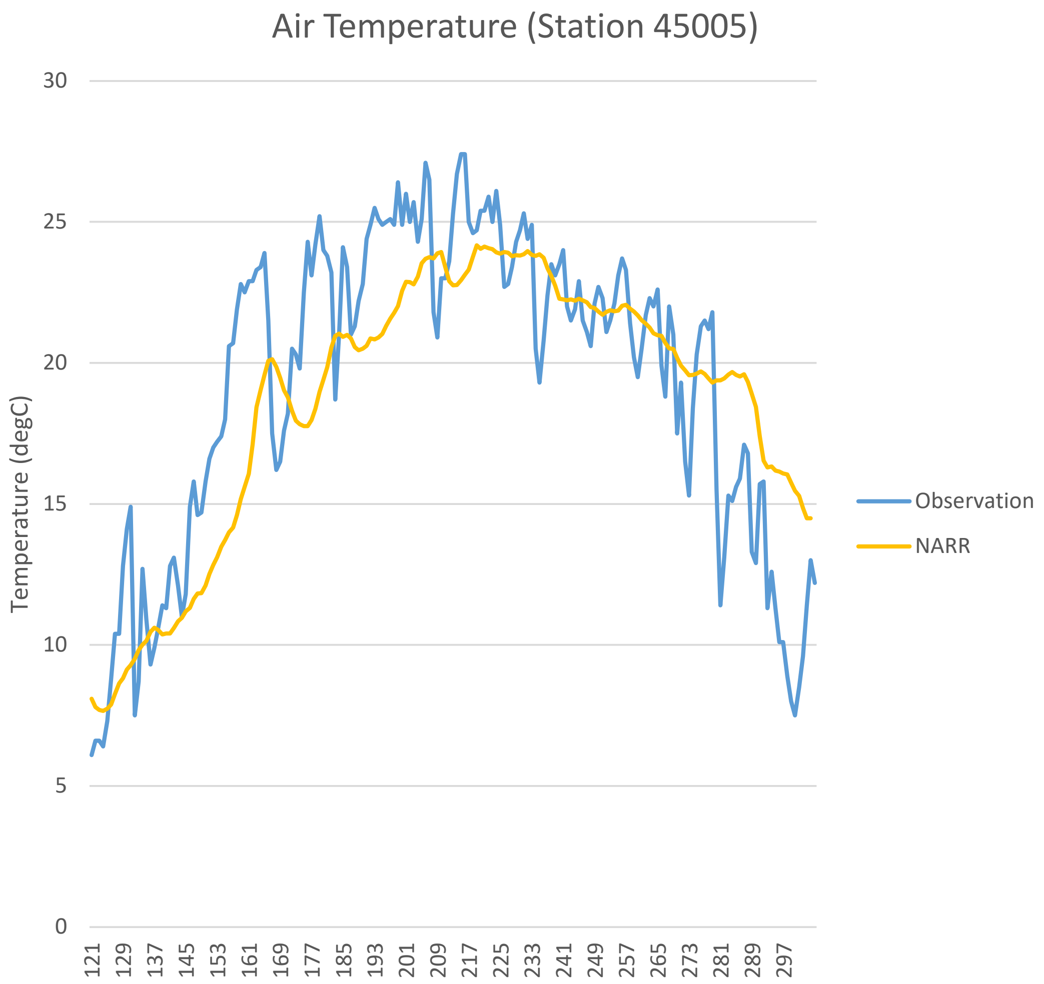


COHERENS

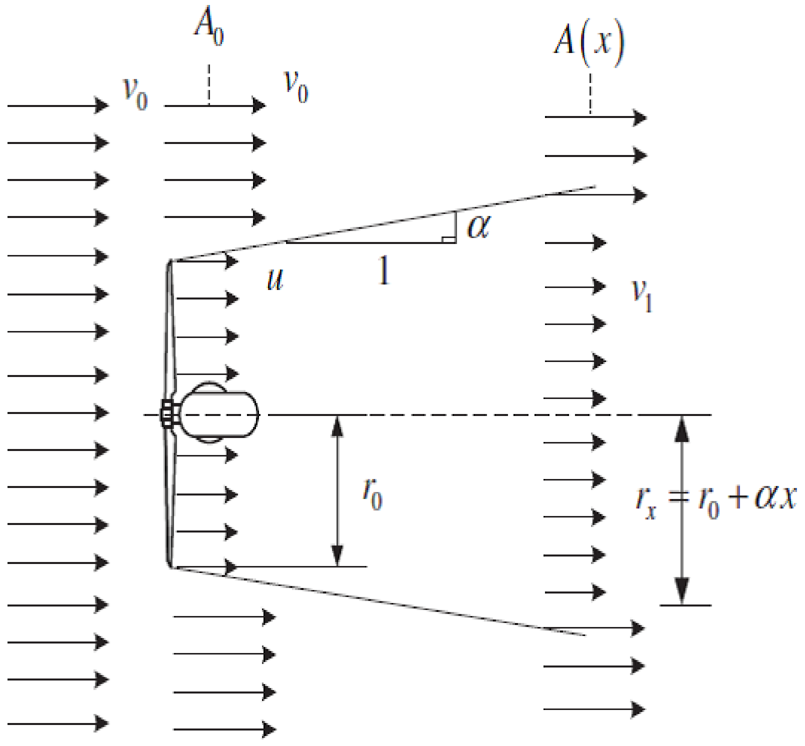


Modeled versus observation a) surface water temperature and b) Air temperature at meteorological buoy 45005, in 2005 (May – October)





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)

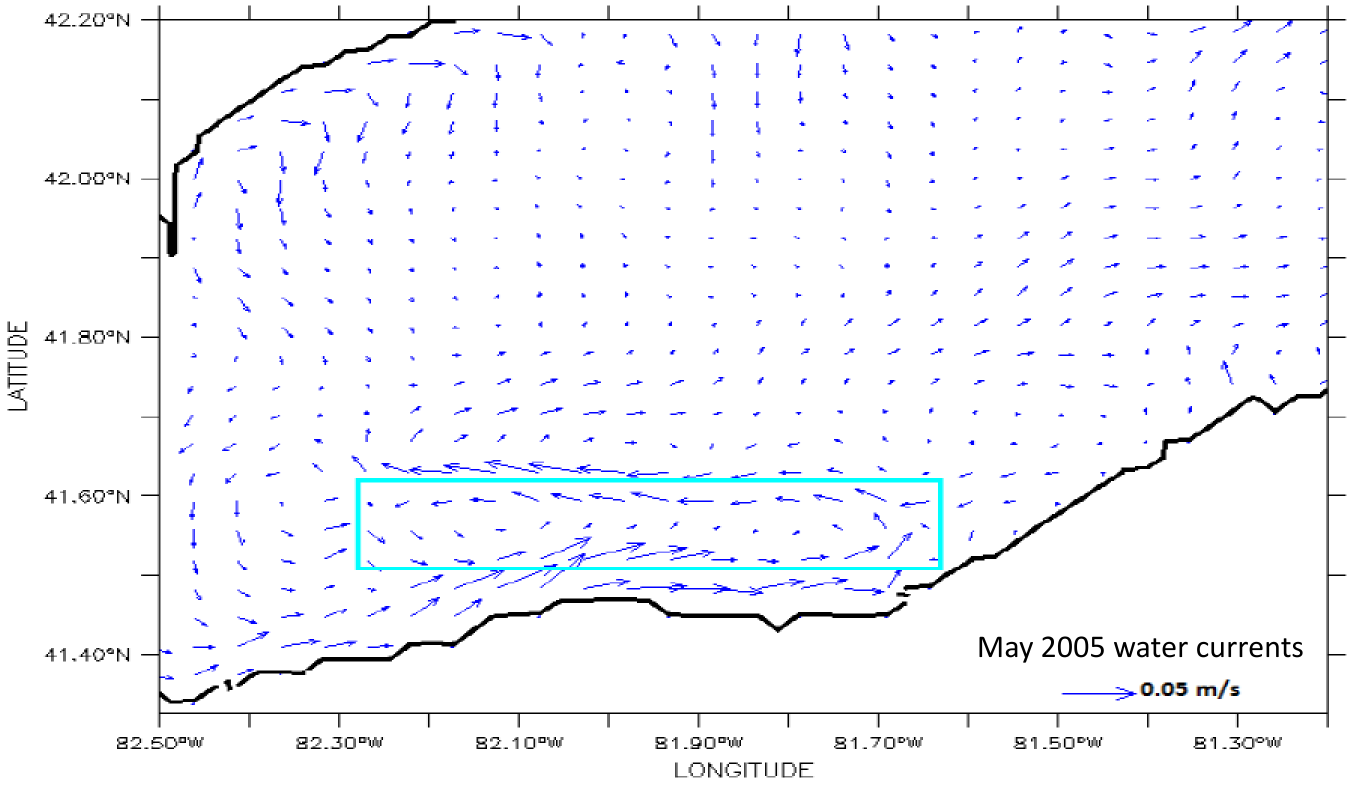
$$\Delta U/U_\infty = [(1-(1-C_T)^{1/2}/8(k^*x/D+\varepsilon)^2 \times \exp(-1/2(k^*x/D+\varepsilon)^2\{((z-z_h)/D)^2+(y/D)^2\}) \quad (3.21)$$

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)

A hypothetical, large, wind farm – arbitrary location

The wind farm is set up with 18 (N-S) rows of 24 turbines. The first turbine, in the southwest corner, is located at 41.51 N and 82.279 W. Spacings between wind turbines are 500 m (≃3 D) N-S and 3000 m (≃18 D) E-W, respectively, where D is the wind turbine's rotor diameter of 164 m. 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.

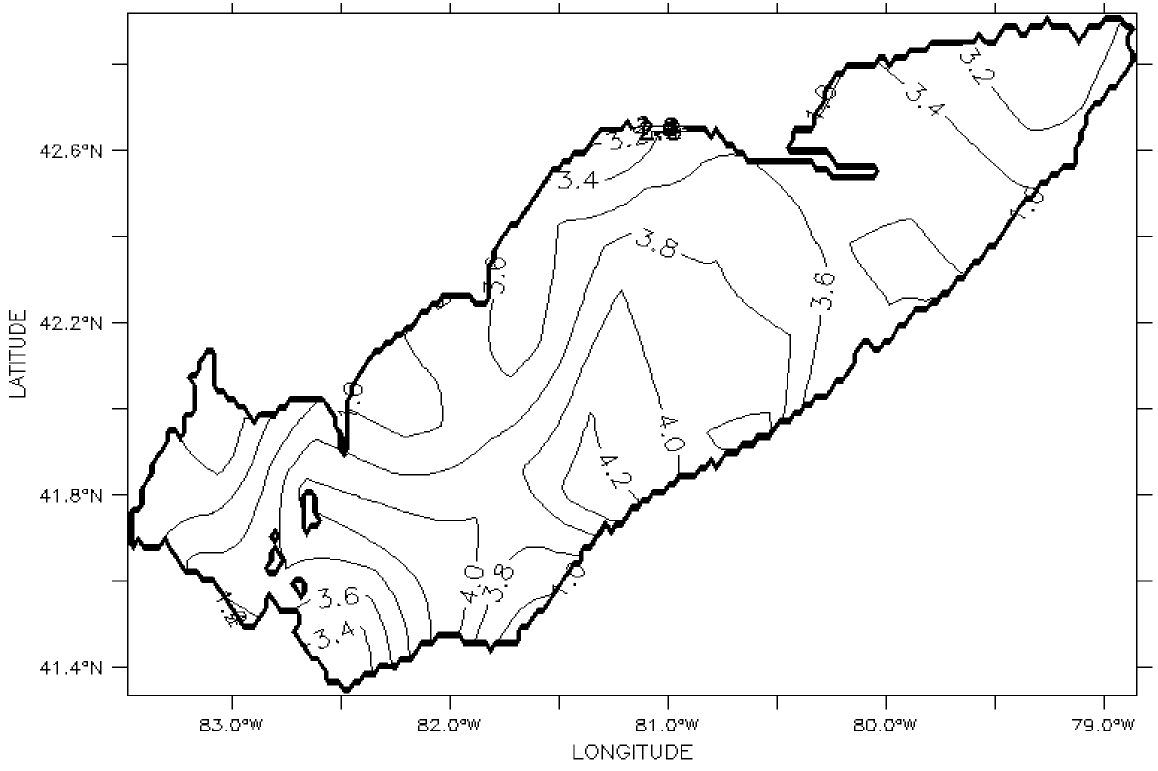
The V164-95 MW model wind turbine which is used in our simulation is the most powerful serially produced wind turbine in the world at present. The V164 platform has an 80-m blade, (Vestasoffshore, 2017), has a rotor diameter of 164m and hub height of 140 m.

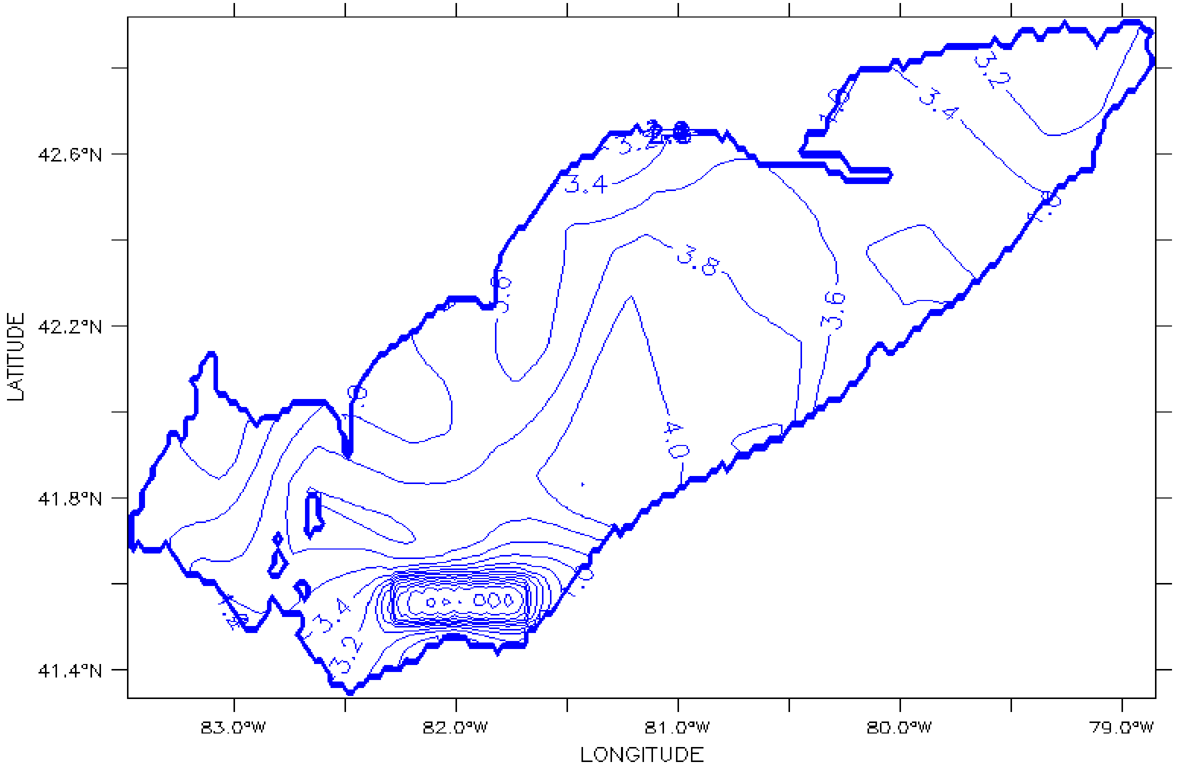


The blue rectangle of the wind farm area.

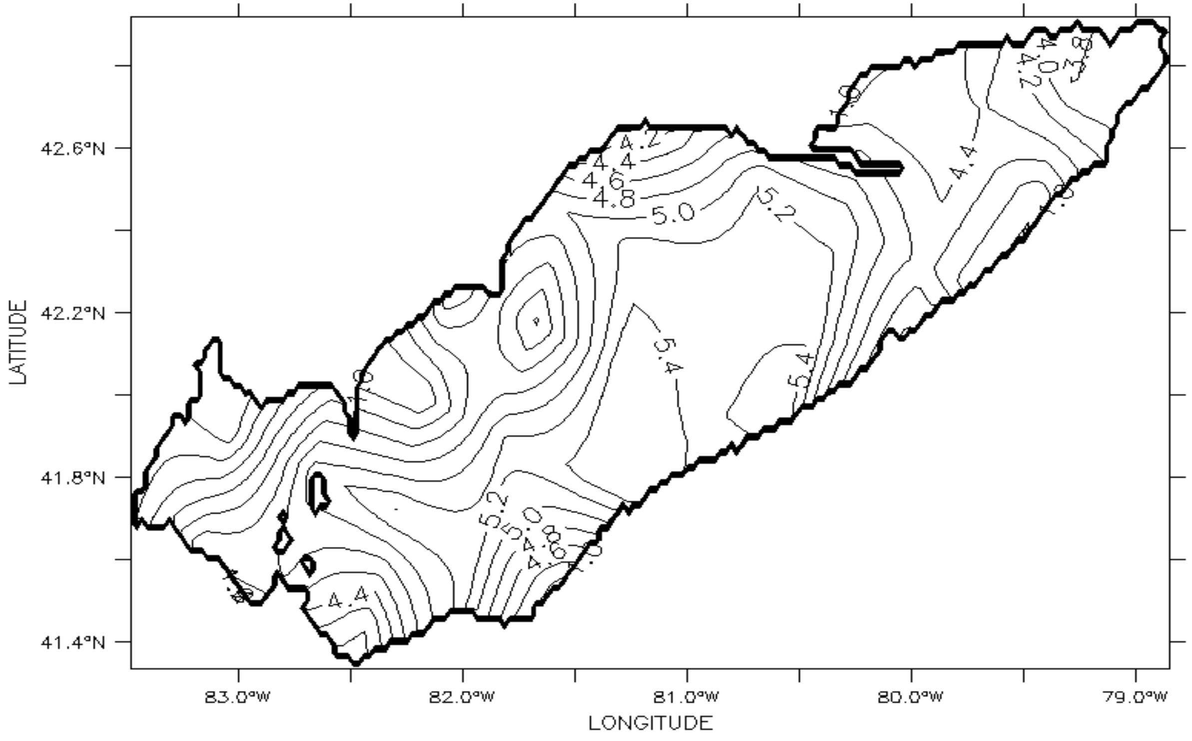
Wind Speed Contours

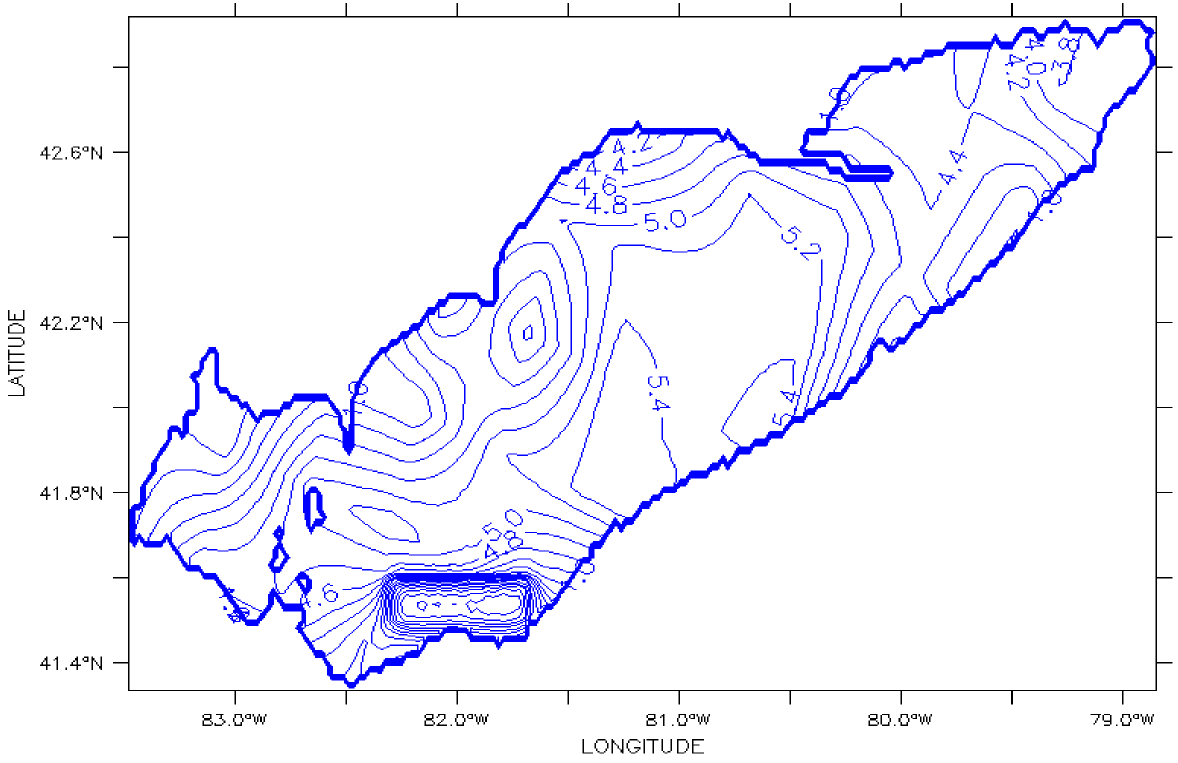
May average wind speed (m/s), 2005



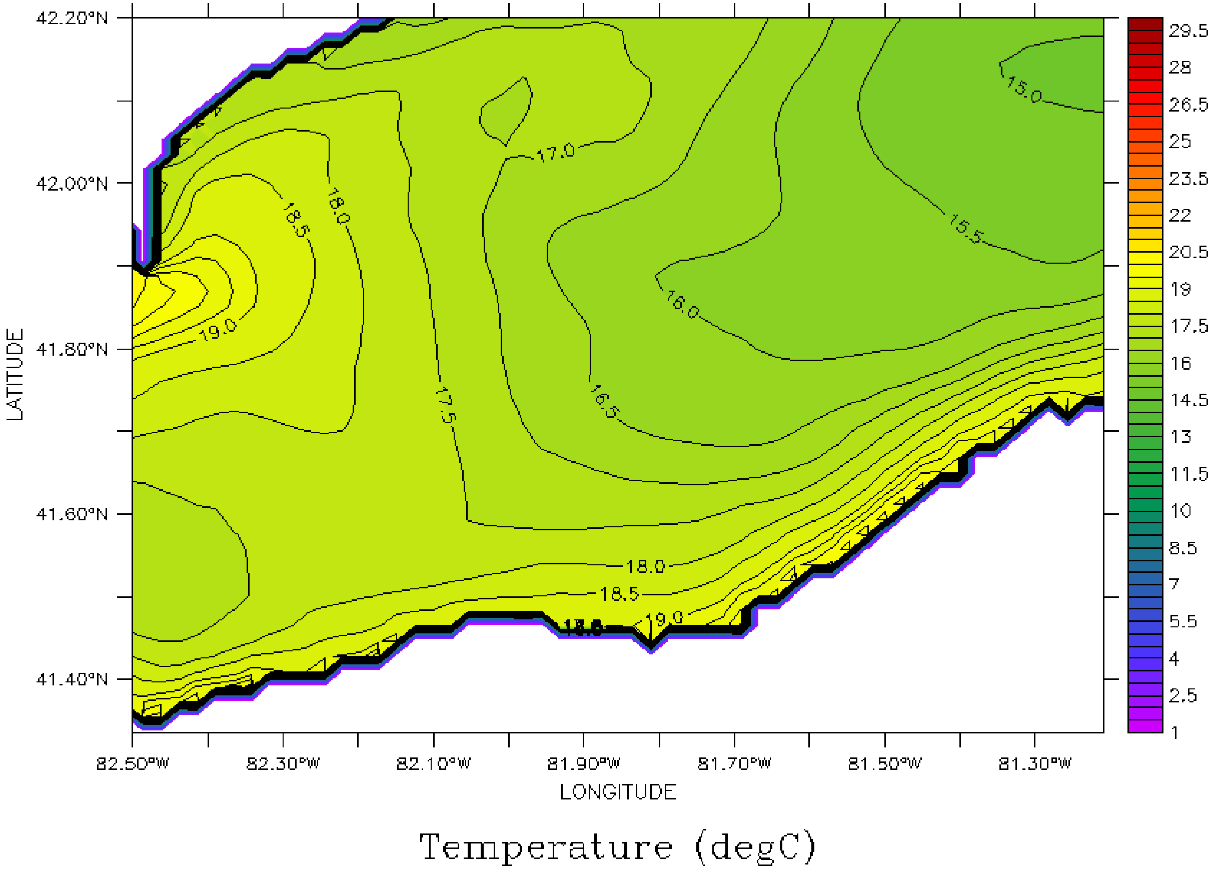


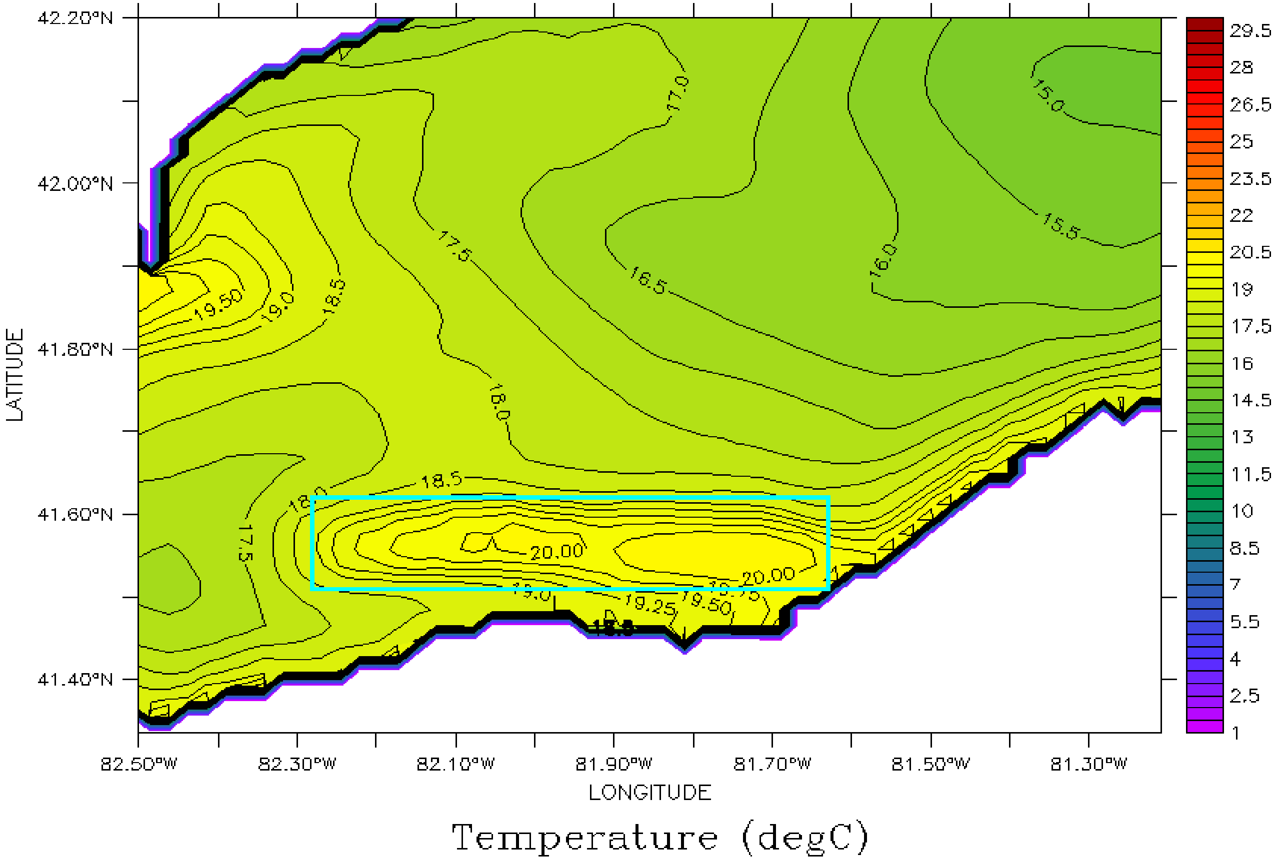
October average 10-m wind speed (m/s), 2005



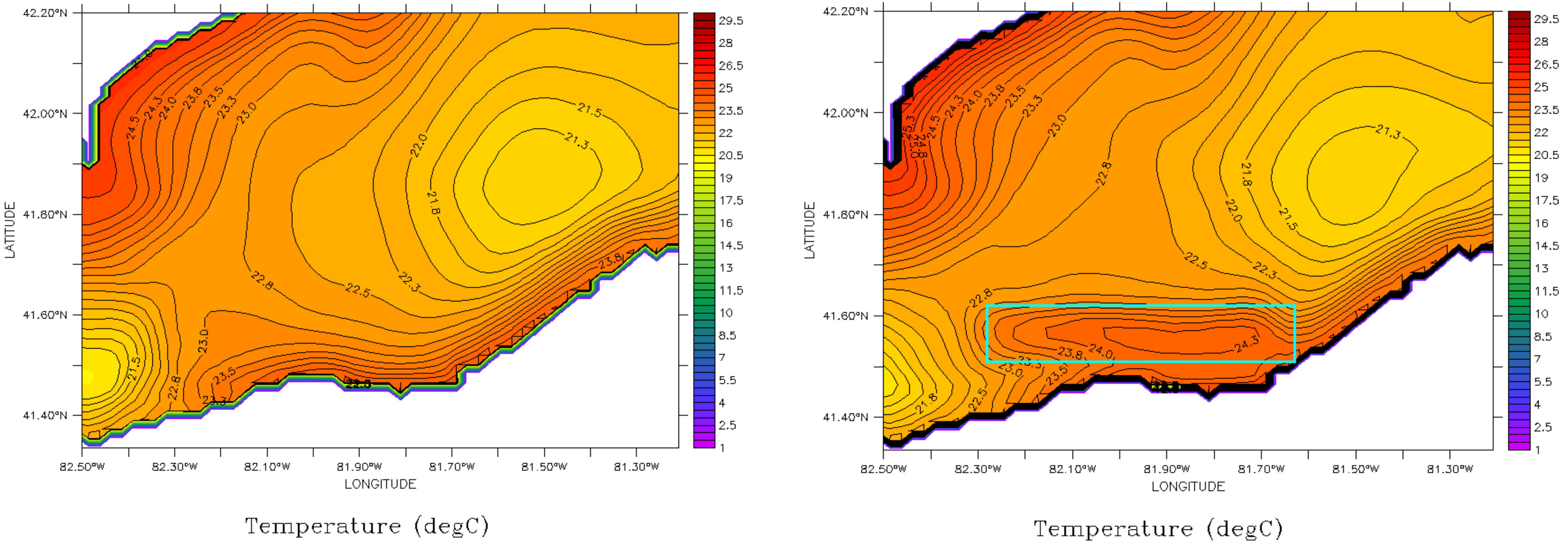


June-averaged surface water temperature in the a) absence and b) presence of a wind farm, 2005





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

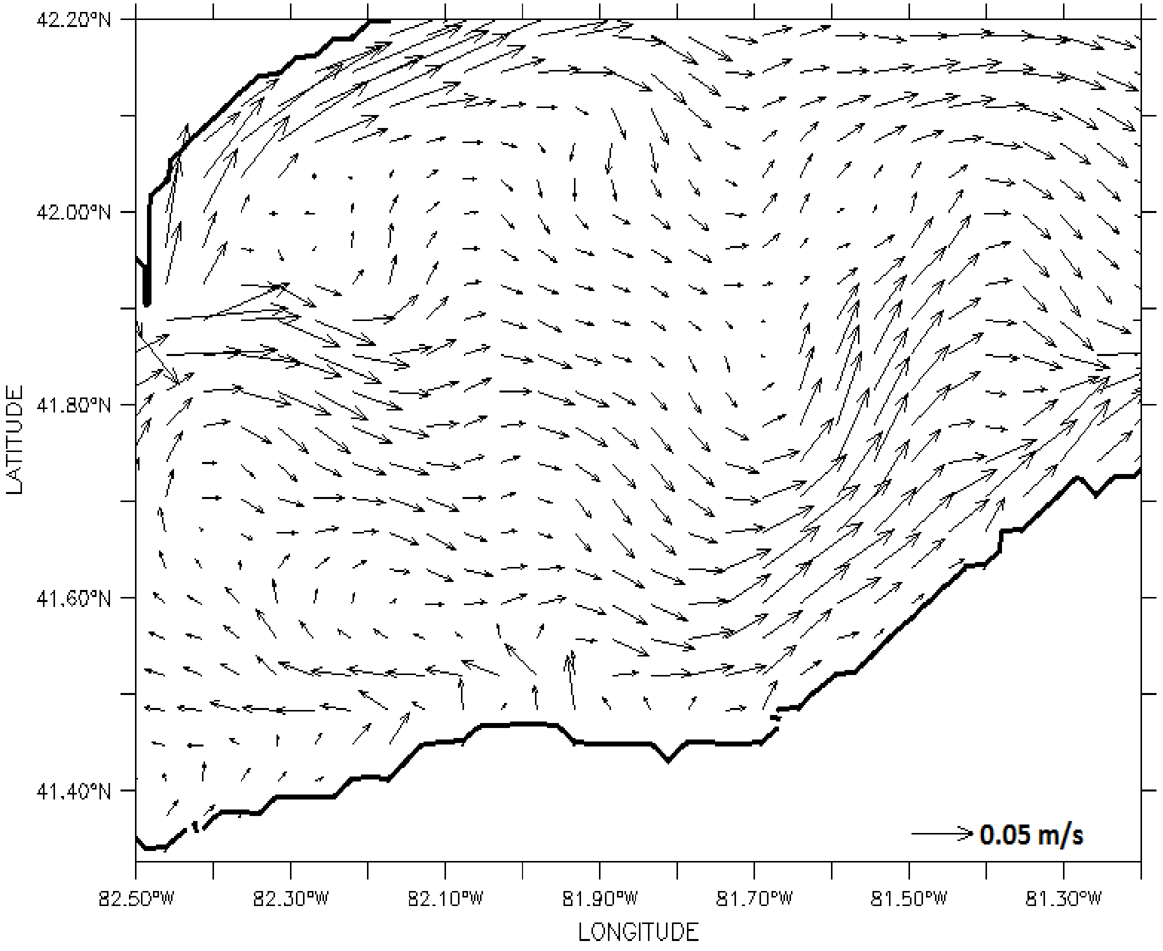


Central Basin Surface Layer Water Temperature

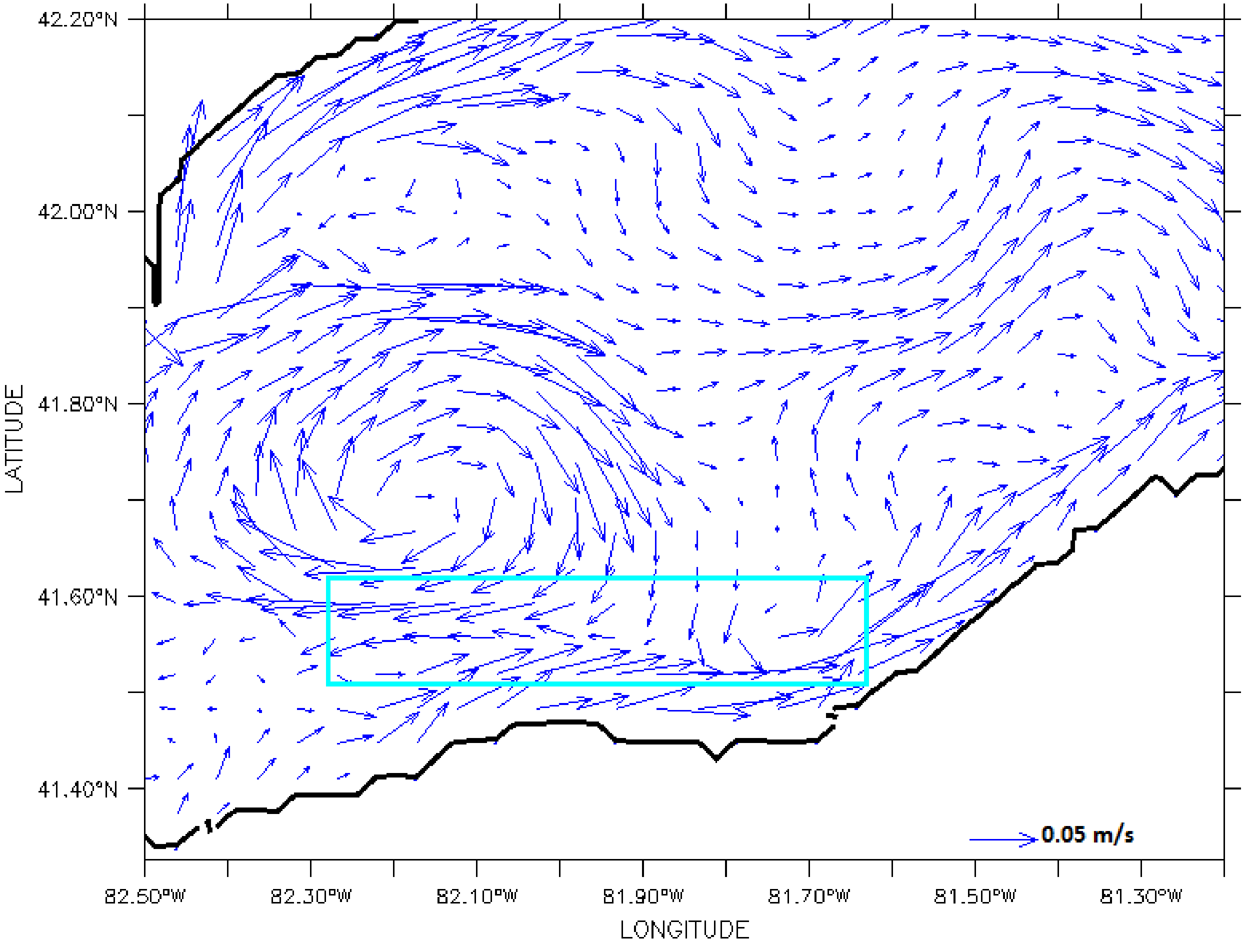
Center of the wind farm wake surface layer water temperature (°C), May-October 2005

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
October	18	19

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

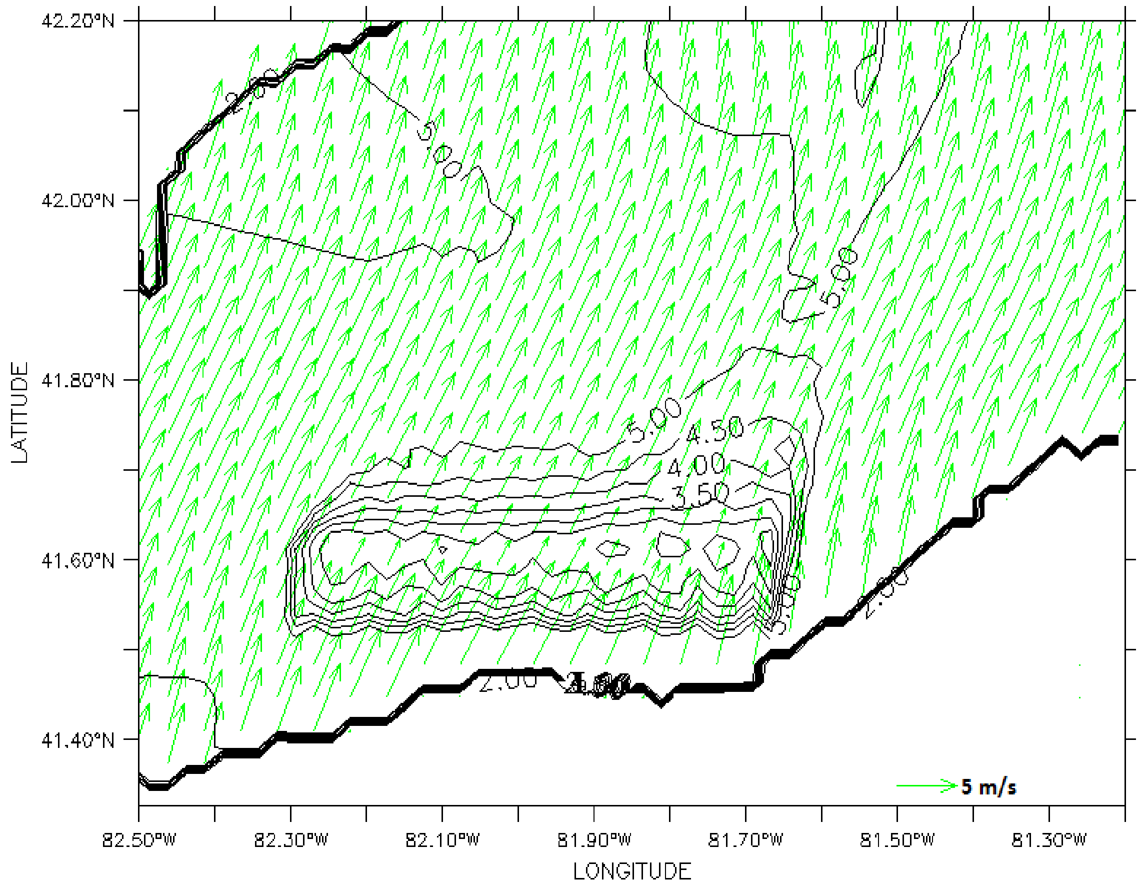


Water current velocity (m/s)

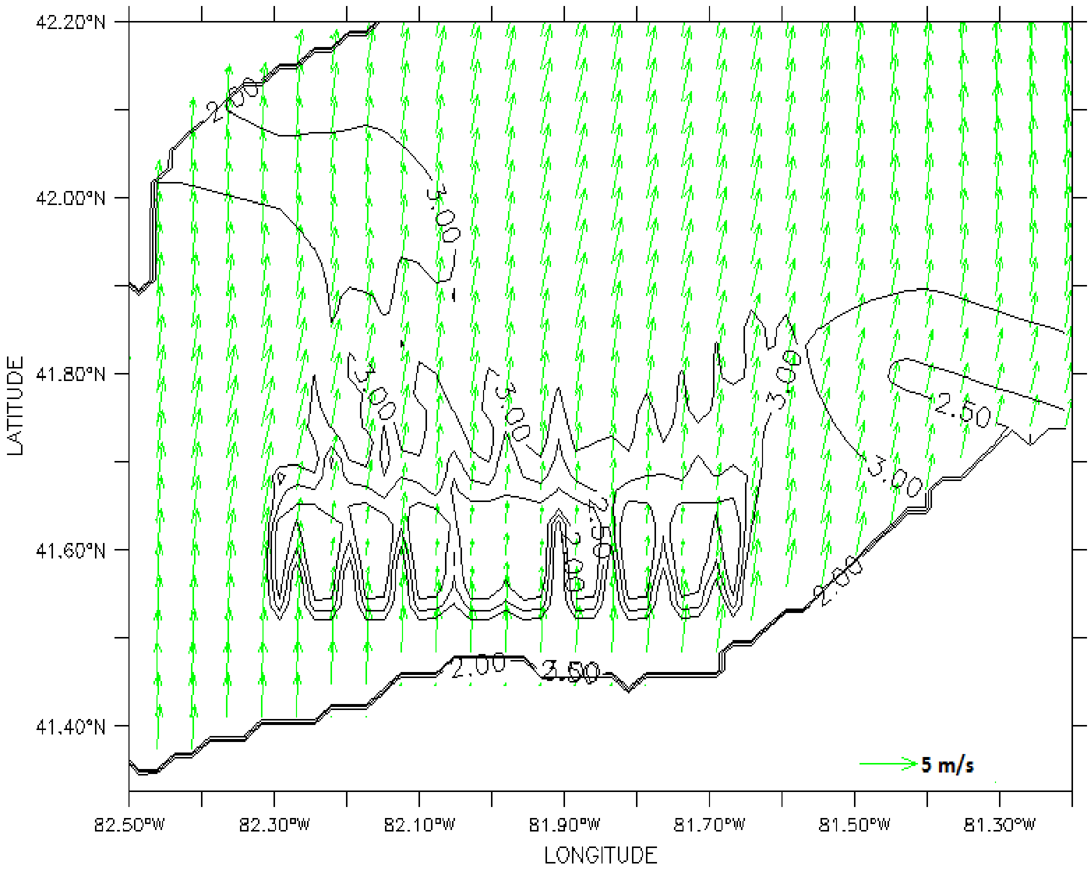


A Few Days 10-m Wind Plot in the Presence of a Wind Farm

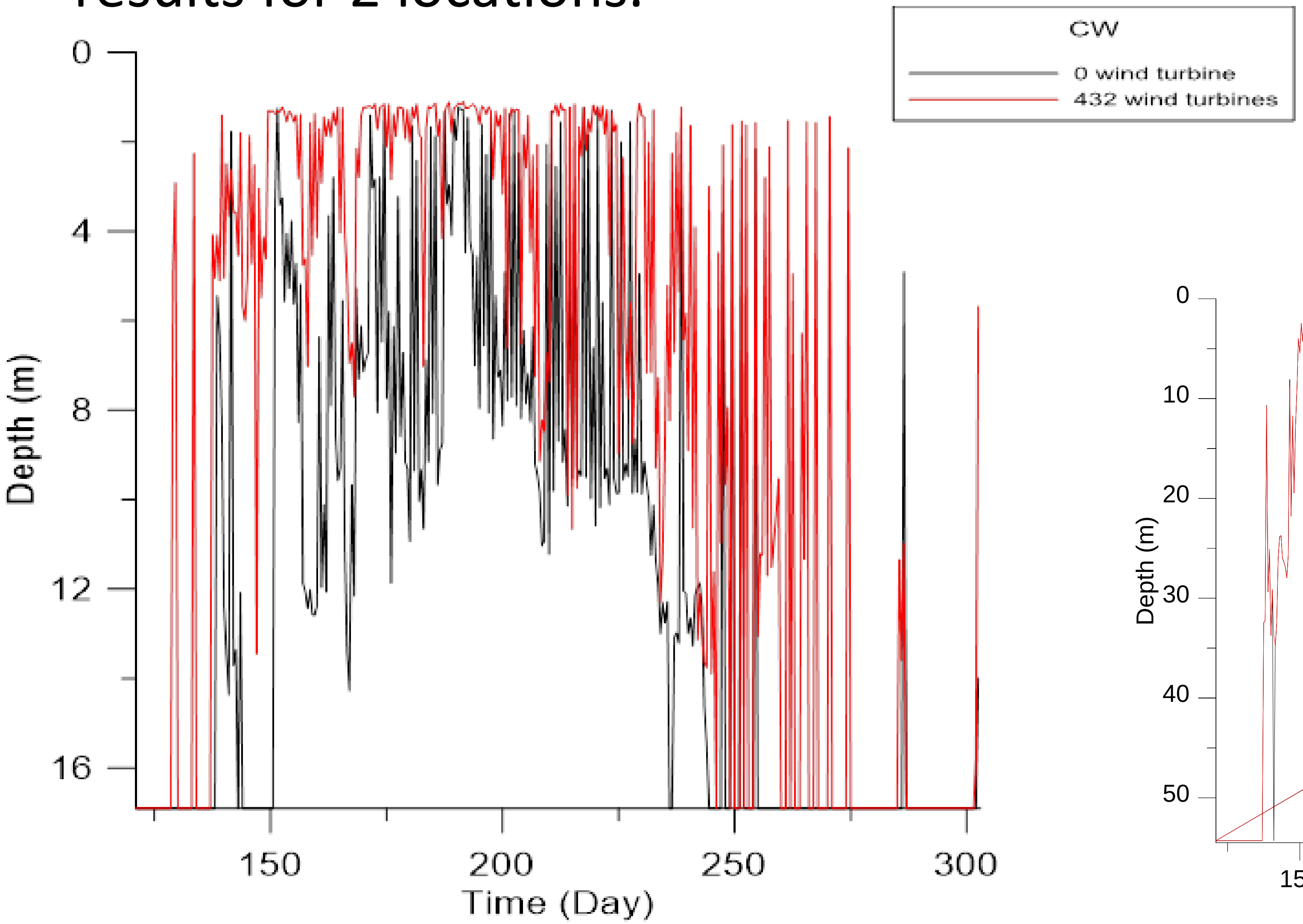
May 10, 2005

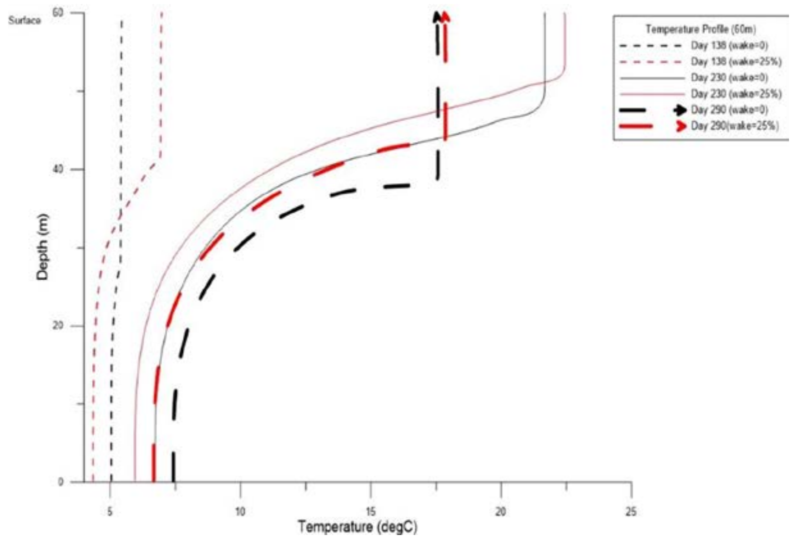


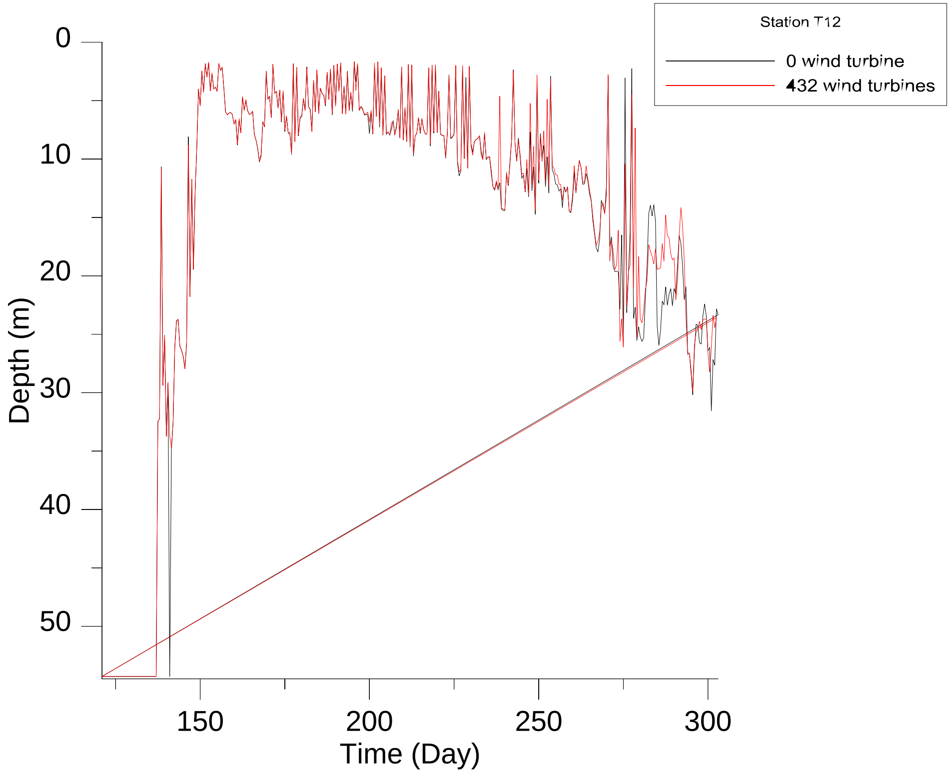
July 24, 2005



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.

REFERENCES

- Bastankhah M. and Porté-Agel F., (2014), A new analytical model for wind-turbine wakes. Elsevier Ltd. 10.1016/j.renene.2014.01.002
- Beletsky, D., N. Hawley, Y. R. Rao, H. A. Vanderploeg, R. Beletsky, D. J. Schwab, and S. A. Ruberg (2012), Summer thermal structure and anticyclonic circulation of Lake Erie, Geophys. Res. Lett., 39, L06605, doi:10.1029/2012GL051002.
- Beletsky, D., N. Hawley, and Y. R. Rao (2013), Modeling summer circulation and thermal structure of Lake Erie, J.Geophys. Res. Oceans, 118, 6238–6252, doi:10.1002/2013JC008854.
- Bolsenga, S. J., and C. E. Herdendorf (1993), *Lake Erie and Lake St.Clair Handbook*, Wayne State Univ. Press, Detroit.
- CANWEA (2017a), Wind Energy Ontario. Retrieved from http://canwea.ca/wind-energy/ontario/
- CANWEA (2017b), Installed Capacity. Retrieved from http://canwea.ca/wind-energy/installed-capacity/
- IJC (2014). A Balanced Diet for Lake Erie: Reducing Phosphorus Loadings and Harmful Algal Blooms, Report of the Lake Erie Ecosystem Priority. International Commission on the Great Lakes, 96pp.
- Hamilton T., (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
- LEEDCO (2017), Draft Environmental Assessment LEEDCo Project Icebreaker Lake Erie, City of Cleveland, Cuyahoga County, Ohio, U.S. Department of Energy.
- The Canadian Atlas online (2017). Wind Energy, How Off-shore Wind Farms Work. Retrieved from http://www.canadiangeographic.com/atlas/themes.aspx?id=windenergy&sub=windenergy _farms_offshore&lang=En