

Model-based Global Assessment of OTEC Resources with Data Validation off Southeast Florida

L. T. Rauchenstein

Florida Atlantic University
Department of Ocean and Mechanical Engineering
101 North Beach Road
Dania Beach, FL 33004 USA

J. H. VanZwieten, Jr.

Florida Atlantic University
Southeast National Marine Renewable Energy Center
777 Glades Road
Boca Raton, FL 33431 USA

H. P. Hanson

Florida Atlantic University
Southeast National Marine Renewable Energy Center
777 Glades Road
Boca Raton, FL 33431 USA

Abstract- As part of an ongoing effort to create a publicly accessible GIS database that characterizes the global OTEC resource, more than two years of daily HYCOM (Hybrid Coordinate Ocean Model) temperature data were processed. This global dataset was used to estimate annual and seasonal averages of the temperature gradient between the sea surface and water at 1000 m depth, a parameter commonly used for quantifying OTEC potential. Periodic annual variation was also explored. At locations where the depth was less than 1000 m, the temperature difference was evaluated between the sea surface and near bottom water. These data show that the mean temperature difference can be as high as 26.5°C and commonly varies by less than 5°C annually. These HYCOM-based estimates were then compared against thermal profile measurements made during 58 sets of CTD casts performed off Southeast Florida.

I. INTRODUCTION

Ocean thermal energy conversion (OTEC) is a method of converting solar energy stored as sensible heat in the upper mixed layer of tropical and subtropical oceans into electricity by evaporating an appropriate working fluid in a Rankine cycle operated between warm surface and cold deep water temperatures. OTEC is commonly considered a viable energy source where the thermal gradient exceeds approximately 20°C between surface and deep waters, with marginal power gains of 10-15% for each increase of 1°C [1]. Because of the low temperature difference between warm and cold sinks, thermal efficiency of OTEC is low at about 3% in existing plants and power generation would consequently require high seawater flow rates on the order of several cubic meters per second per MW [2,3,4]. This challenge and other engineering difficulties typical of the marine environment have so far hampered the development of OTEC. Yet many advocates maintain that the low efficiency may be offset by the large scale of the thermal resource and by the easy availability of the 'fuel' (i.e. the seawater), and that OTEC may become an attractive energy source as current energy costs and concerns about energy security increase [4,5,6,7].

OTEC power plants can be categorized by working fluid. In closed cycle plants, an appropriate, low boiling point working fluid (e.g. ammonia or propane) is cycled continuously from boiler to condenser. Open cycle plants use the warm seawater itself as the working fluid. Once condensed, this desalinated water may be collected and represents a valuable supply of potable water. It is estimated that the production and sale of potable water, itself in high demand in many regions where OTEC is possible, might help to recuperate as much as 1/3 of a plant's electrical generating costs [3]. In both plant types, after being used to condense the working fluid, the cold water may additionally be utilized for purposes of air conditioning and aquaculture.

Previous studies have attempted to quantify the magnitude of the global OTEC resource with varying degrees of complexity. Estimates ranging from 5 TW to more than 1000 TW have been quoted, with the highest of these values calculated from total solar energy absorbed by the ocean and the lowest modeling maximum sustainable extractable energy [5,6,7,8]. It is estimated that the roughly 60 million square miles of tropical ocean waters absorb the energy equivalent to around 245 billion barrels of oil per day [9,2], representing an annual energy resource 1000 times greater than world consumption in 2007 [12]. However, the rate of replenishment of the cold water from the poles via thermohaline circulation imposes an upper limit on actual power output at a site and on OTEC plant spacing. Research into the effect of cold water replenishment on plant power production and sustainability is ongoing [2,8,10,11].

Geographic distribution of the ocean thermal resource was explored recently on a global scale using data from the World Ocean Atlas at 1 degree and later at ¼ degree latitude/longitude resolution. Surface temperatures were taken at 20 m depth and cold water temperatures at 1000 m. These studies estimated maximum steady-state global OTEC power at 3-5 TW and posited that it is unlikely that these limits will ever be approached in practice. The resource surrounding Hawaii was additionally analyzed using the Hybrid

Coordinate Ocean Model (HYCOM+NCODA) spanning the same depths [1,8]. These analyses represent a valuable source for OTEC resource information, but are limited to the waters in which bottom depth exceeds 1000 m, lacking information for many coastal and island regions where water is shallower.

The ultimate goal of the present analysis is the creation by the U.S. Department of Energy's National Renewable Energy Laboratory of a public GIS tool for use in visualization of the global OTEC resource. Compared with previous assessments, this analysis will provide higher spatial resolution than has been available in earlier studies, will characterize the entire temperature resource using high (daily) time resolution source data, and will include predictions for thermal resources in the shallow waters near shore. The results will incorporate information predicted by the 3-dimensional, data-assimilative hindcast/forecast HYCOM+NCODA model [13].

Gridpoints in HYCOM are meshed at approximately $1/12^\circ$ latitude and $1/12^\circ$ longitude resolution, corresponding to ~ 7 km resolution at the equator. The hybridized vertical coordinate transitions smoothly from isopycnal in open, stratified waters to terrain-following (sigma) in shallow coastal regions, and to z-level in mixed layer and unstratified seas, ensuring sufficient vertical resolution in the latter two cases while also conserving water mass characteristics over long time periods.

The HYCOM model forecast is used as a first guess in a multi-variate optimal interpolation (MVOI) scheme. Available satellite altimeter data along with *in situ* sea surface temperature and vertical temperature and salinity profiles acquired from XBTs, ARGO floats, and moored buoys are assimilated. Surface forcing includes wind stress, wind speed, heat flux (using bulk formula), and precipitation. Data represents model prediction for 6 p.m. until midnight GMT each day, with assimilated data ranging from -12 days to +12 hours (for more details on the HYCOM model, NCODA data assimilation, and for other validation studies, consult [13,14]).

The global thermal predictions and validation discussed in this paper are divided into four logically progressing sections beyond this introduction. In Section II, the extraction of the data from HYCOM and data processing are discussed. Following this, the global thermal predictions and OTEC potential are discussed in Section III. These thermal predictions are compared with thermal measurements made off of Southeast Florida to help evaluate its accuracy in predicting this resource (Section IV). Finally, conclusions are drawn and suggestions are made for future work in Section V.

II. DATA EXTRACTION AND PROCESSING

Daily global temperature data were obtained via the HYCOM organization's web site (hycom.org) from the HYCOM+NCODA (Hybrid Coordinate Ocean Model-Navy Coupled Ocean Data Assimilation) experiments 90.6, 90.8, and 90.9 for days spanning mid-September 2008 through February 2011. 431 billion total grid points (1.9 TB of data) were processed to produce a full set of mean monthly

temperature matrices. Seasonal and yearly mean temperatures were then calculated using weighted averages of the monthly means. Mean temperature difference between warm surface and cold deep waters were calculated using the sea surface temperatures (at a depth of 0 m) for the source of warm water. Cold water temperatures were determined for each monthly, seasonal, and yearly-averaged dataset. These temperatures were taken at a depth of 1000 m when the seafloor exceeded this depth. In water depths less than 1000 m, the deepest applicable grid point was utilized

III. GLOBAL OTEC RESOURCE

A. Mean Thermal Resource

Mean temperature for the two year period spanning 2009-2010 is depicted in Figure 1. Mean annual temperatures for these two years were impacted in the Pacific Ocean by an El Niño event toward the end of 2009 and a rebounding La Niña event at the end of 2010. It is worth noting that these events affected the magnitude, but not the geographic extent, of the Pacific OTEC resource, with surface water temperatures depressed in 2010 relative to 2009. In the Atlantic and Indian oceans, the mean temperature difference varied little between the two years.

Thermal resources were strongest along the low-latitude western boundaries in both the Atlantic and Pacific ocean basins, with global maxima among the island nations of the southeastern Pacific, including Indonesia, the Philippines, and Oceania. Resources along the eastern boundaries of these oceans were more restricted, a consequence of strong upwelling along the western coasts of South America and Africa. Equatorial upwelling also negatively affected thermal resources along the equators of both the Atlantic and Pacific oceans. This phenomenon was highly pronounced in the eastern two-thirds of both oceans, but tapered out as longitude progressed westward. Equatorial resource depletion was not noted in the Indian Ocean. Thermal resources in the equatorial waters west of South America were so far reduced as to make this location unsuitable for power generation from OTEC, with temperature differences from sea surface to 1000 m depth of only $16-17^\circ\text{C}$. This region represented the only equatorial location of poor OTEC potential not driven by shallowness of the seafloor.

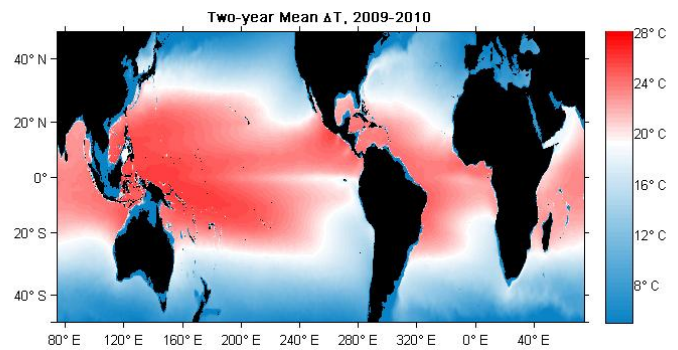


Figure 1: Temperature difference between sea surface and 1000 m depth (or sea floor, if ocean depth < 1000 m), averaged for the years 2009-2010.

Other strong OTEC candidates included the full coast of Brazil, much of coastal India, the Caribbean and Gulf of Mexico, Africa's Gulf of Guinea, Hawaii, and much of eastern Africa, although this list is not exhaustive.

B. Seasonal Dependence

Here, 'summer' and 'winter' are defined relative to climatological seasons in the Northern hemisphere, with summer including the full months of June, July, and August, and winter including December, January, and February. Figures 2a and 2b reveal more pronounced seasonal variability in the northern hemisphere than in the southern, possibly due to a strong La Niña event which occurred in the winter of 2010. The thermal resource remains strong in both seasons throughout the Pacific island nations, in Hawaii, Brazil, India, and the Gulf of Guinea. Predictably, seasonal variation increases with latitude, with pronounced variability in the Gulf of Mexico and east of Africa. Such variation can be seen easily in Figure 2c.

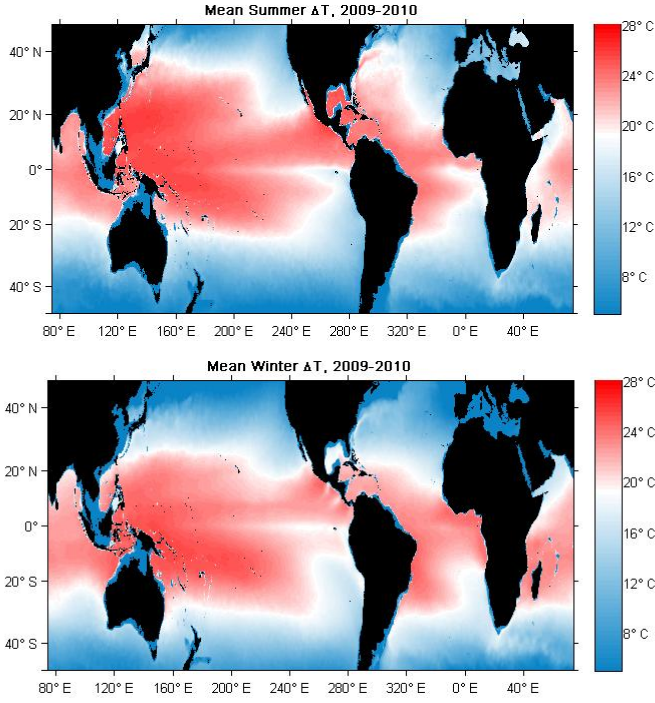
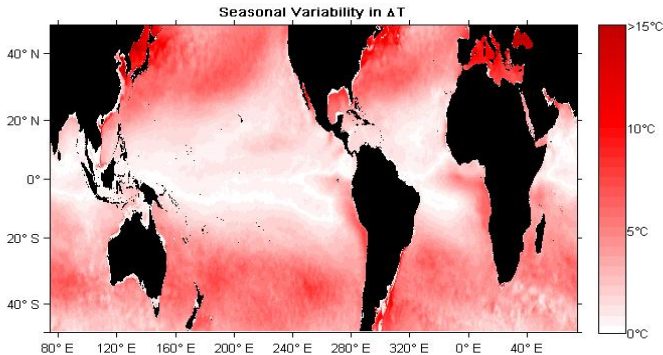


Figure 2: Boreal summer, winter, and (below) magnitude of the summer-winter difference in ΔT from the HYCOM analysis.



IV. VALIDATION

In order to validate the HYCOM OTEC resource predictions, model data was compared against CTD (conductivity-temperature-depth) measurements maintained as part of an ongoing OTEC resource assessment in the waters off southeast Florida. These temperature transect measurements were collected at a location where the thermal profile offshore represents a significant OTEC resource next to a significant onshore energy load [11]. The full resource assessment effort includes thermal measurements taken along four unique transects, each separated by 61 km and traced along lines of constant latitude. The transect sampled most frequently and for which the greatest store of data has been maintained is located off of Fort Lauderdale at a latitude of $26^{\circ}05'N$. Along this transect, CTD casts have been collected over a total of 58 boat trips sampling the same 11 locations down to within 10 m of the sea floor. Due to weather and other limitations, all 11 sites were not sampled during each trip, and the total number of casts at each location resulting from these 58 trips range from 45 to 53 casts. These casts span the ocean from approximately 3 km to 43 km from shore. An example cross section showing the thermal stratification measured during one day of casts is shown in Figure 3. Figure 3 also shows the locations of the 11 CTD casts, as well as the grid point longitudes and depths for the closest gridded HYCOM data located both north and south of the CTD transect line.

To compare the monthly-averaged HYCOM thermal estimates with the CTD measurements, the 5 closest HYCOM grid locations both north (lat = $26^{\circ}05.33'N$) and south (lat = $26^{\circ}01.01'N$) of the CTD transect (lat = $26^{\circ}05'N$) were used. The HYCOM data were interpolated linearly between the north and south grid points at each longitude and depth. Linear interpolation was then used between the CTD casts that are just east and west of the HYCOM locations to create the CTD thermal estimates used in the comparison.

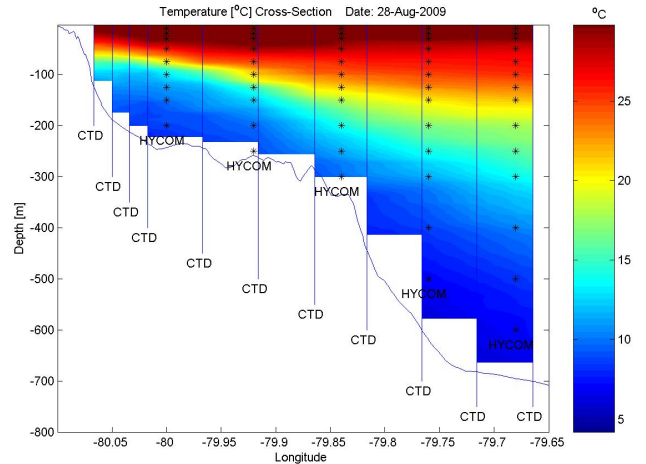


Figure 3: Cross-section showing the thermal structure derived from a set of CTD casts performed along latitude of $26^{\circ}05'N$ on August 28, 2009. The actual CTD cast locations are indicated by the vertical lines and the HYCOM grid locations along the transect are shown by (*)

The HYCOM grid points at $80^{\circ}00'W$ correspond to shallow waters atop the Miami Terrace, where an interesting potential exists for some OTEC production in waters less than 250 m deep. Mean temperature difference from sea surface to near bottom water has been estimated previously at $18.1^{\circ}C$, with a representative 150 MW gross OTEC plant capable of producing an average of 76 MW of power under these circumstances. The furthest offshore HYCOM grid points at $79^{\circ}40.80'W$ ($79.6799^{\circ}W$) are located within a more predictable, deeper water OTEC resource. Measurements suggest a mean temperature difference between surface and near bottom water near this location has a value of $21.6^{\circ}C$ and that a representative 150 MW gross OTEC plant could produce an average of 125 MW of power [11].

To compare the thermal predictions from HYCOM with CTD measurements that are most relevant to OTEC, a depth of 20 m is used for the warm water resource. The depth is chosen to represent a likely depth for the warm water intake pipe. The cold water resource is estimated from the deepest HYCOM grid point (when comparisons with CTD data are possible at this depth). It is noted that since the HYCOM estimates have a fixed depth grid, the distance between the deepest HYCOM grid point and the actual sea floor can vary significantly between grid points. Conversely, for relatively shallow water OTEC locations, such as the area presented in this validation section, an OTEC cold water pipe will most likely be custom built to extract cold water from a fixed depth above the sea floor.

For 20 m water depth, all of the HYCOM mean temperature measurements were within $0.2^{\circ}C$ of the corresponding CTD estimates. Seasonal trends also matched well for this depth, as shown in Figures 4 (top) and 5 (top). On the other hand, for temperature estimates near the sea floor HYCOM overpredicted the mean temperatures at all of the evaluated locations. At the 5 HYCOM locations shown in Figure 3, HYCOM overpredicted the mean deep temperatures by 2.7, 2.1, 1.8, 1.2, and $1.1^{\circ}C$, respectively, as one moves sequentially from the near shore location to furthest offshore location. These findings suggest that HYCOM significantly underpredicted the OTEC resource potential off of southeast Florida. It is noted that for the second of the five HYCOM locations (counting from west to east), the CTD estimates for the 250 m water depth were taken from the 6th CTD cast location from shore rather than an interpolation between CTD cast locations 5 and 6. This was done because the depth of cast 5 was less than 250 m. It is also noted that at the third HYCOM location from shore, the comparison was made at a water depth of 250 m since the depth of the CTD casts did not allow for a comparison at the HYCOM grid point depth of 300 m. Time histories of the utilized bottom water estimates for the shallowest and deepest evaluated locations are presented in Figures 4 (bottom) and 5 (bottom). It is noted that the CTD measurements are averaged over each calendar month and then these monthly averages are then averaged over the year to

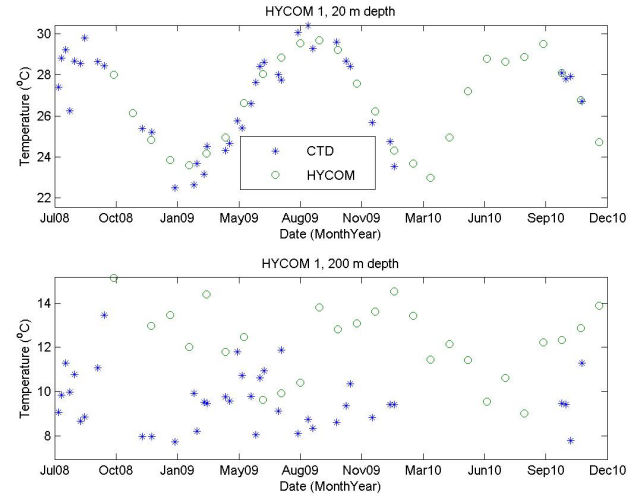


Figure 4: Time histories of the monthly averaged HYCOM estimates and CTD based estimates for a latitude of $26^{\circ}05'N$ and longitude of $80^{\circ}00'W$ at a depth of 20 m (top) and 200 m (bottom).

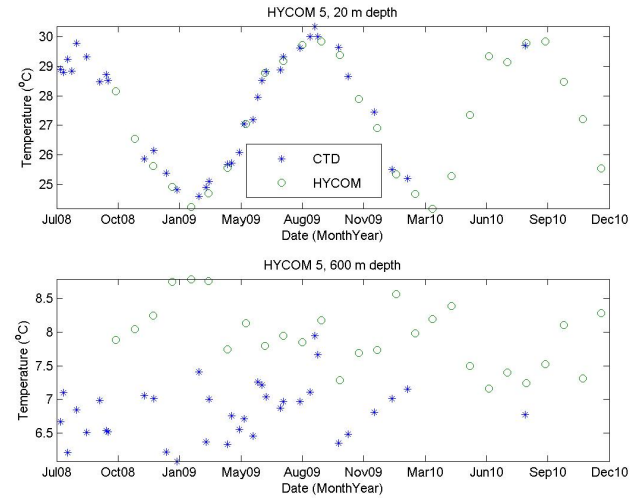


Figure 5: Time histories of the monthly averaged HYCOM estimates and CTD based estimates for a Latitude of $26^{\circ}05'N$ and Longitude of $79^{\circ}40.8'W$ at a depth of 20 m (top) and 600 m (bottom).

calculate the average CTD measured temperatures used in this analysis. This is done to avoid introducing a seasonal bias to the estimate caused by some seasons containing more CTD measurements than others.

V. CONCLUSIONS

This paper details a global OTEC resource assessment derived from daily HYCOM thermal estimates. The resource was visualized first as an average of the full dataset, then broken into summer and winter averages for which variability was explored. Water temperature differences were evaluated between the sea surface and 1000 m depth at locations where the seafloor met or exceeded this number, and near the

seafloor where the depth was less than 1000 m. These data show locations where significant OTEC potential exists, with mean temperature differences at the evaluated depths of over 20°C occurring at latitudes as low as 30°S and as high as 42°N. The HYCOM predicted thermal estimates off of Southeast Florida were compared with *in situ* thermal measurements demonstrating that at this location, HYCOM underpredicted the thermal difference by between 1.1° C and 2.7° C.

Suggested future work related to defining the global OTEC resource includes analyzing the amount of energy that can be extracted using a generic OTEC plant model, quantifying the amount of energy that can be sustainably extracted from an area (including the exploration of plant spacing and sustainable seawater flow rates), and further validating the HYCOM model. To evaluate the potential of a single OTEC plant, both efficiencies and losses should be accounted for and the cold water pipe length should be optimized to fit the thermal profile of its site location. The amount of energy that should/can be extracted from a particular area will typically be limited by the flow speed of the deep water currents. Therefore, the deep water currents should be estimated and the amount of producible energy may be written as a percent of the volumetric flow rate of the cold water resource in the area being considered. Finally, the thermal predictions made by the HYCOM model should be validated using measurements at several different areas where OTEC potential exists. Further validation of the HYCOM thermal predictions off Southeast Florida should also be conducted using the daily HYCOM predictions to examine its usefulness for predicting the higher frequency variability of the cold water resource in this area.

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