Mapping available Ocean Thermal Energy Conversion resources around the main Hawaiian Islands with state-of-the-art tools

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This paper aims to demonstrate how the evaluation of Ocean Thermal Energy Conversion (OTEC) resources can benefit from currently available high-resolution ocean models. The case of waters around the main Hawaiian Islands is presented because of its relevance to the future development of OTEC. OTEC resources are defined here by ocean temperature differences between water depths of 20 and 1000 m, with little loss of generality. Using state-of-the-art tools like the HYCOM+NCODA (1/12°) model affords the possibility to track changes on a daily basis over a wide area (e.g., 17 °N to 24 °N and 153 °W to 162 °W). An examination of numerical data over a time period of 2 years reveals interesting geographical patterns. It is found that average OTEC temperature differences are consistently higher (by about 1 °C) west of the islands, whereas the amplitude of the yearly cycle globally decreases from north to south as expected. Better OTEC resources in the lee of the islands are attributed to the narrow eastward-flowing Hawaiian Lee Counter Current. All other things being equal, a change of 1 °C in the resource typically would amount to a 15% variation in net OTEC power output. © *2010 American Institute of Physics.* [doi:10.1063/1.3463051]

I. INTRODUCTION

Ocean Thermal Energy Conversion (OTEC) aims to recover solar energy stored as sensible heat in the upper layer of tropical oceans. Deep cold seawater originating from the polar margins provides the low temperature needed for an appropriate fluid (such as ammonia) to do mechanical work that can be converted to electricity. Because practical temperature differences are only of the order of 20 °C, with much of this resource needed in the heat exchangers, the thermodynamic efficiency of OTEC processes is of the order of 3%. As a result, large seawater flow rates are required to produce significant amounts of electricity (about 3 m^3/s of deep cold seawater and at least as much surface warm seawater per net megawatt of electrical power). The construction and deployment of OTEC systems at sea has yet to become economically competitive, but future energy markets as well as increased concerns about energy independence and environmental impacts may soon make the vast OTEC resources attractive. From the perspective of pioneers[1,2] to recent synoptic summaries,[3–11] more details about OTEC can be found in the technical literature.

While many renewable energy technologies have to contend with the variability of their sources, such as winds and ocean waves, OTEC is generally considered to be a baseload technology. The difference ΔT between the temperatures of shallow and deep ocean waters is fairly constant across tropical areas in excess of 100×10^6 km^2. Such available thermal resource very much resembles the water head of hydroelectric plants, although there is no obvious flow rate constraint for OTEC. This point gives rise to the caveat that ΔT characterizes extractable OTEC power as long as the local thermal structure is preserved. There are obviously many issues that

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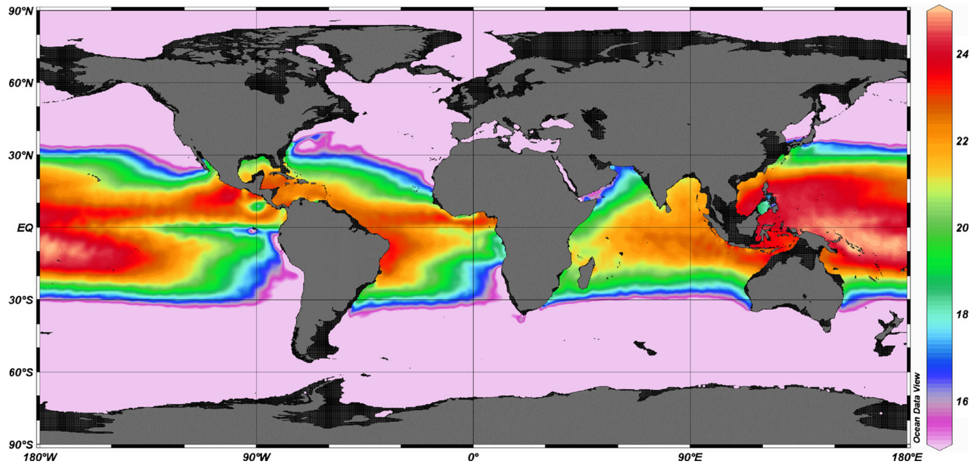

FIG. 1. Worldwide average ocean temperature differences (between 20 and 1000 m water depths) from WOA 2005 (1/4°) data (the color palette is from 15 to 25 °C).

could lead to potential limits on seawater flow rates to prevent a degradation of available thermal resources; these include the avoidance of effluent re-entrainment for a single plant as well as the determination of local, regional, and even worldwide power production limits as plant density increases. Such complex issues are beyond the scope of this paper, and remain to be settled in spite of a substantial body of work.[12–22] In what follows, environmentally available values of ΔT only are considered.

Even in this sense, the stability of ΔT is an important issue for OTEC plant design and operation. The optimized turbo-generator output P_{gross} varies with the square of ΔT so that for typical values of 20 °C, a change of 1 °C in ΔT will produce relative fluctuations of about 10% in P_{gross}. Measurements during the operation of a small experimental OTEC facility in Hawaii[23] confirmed this point. From a net power perspective, matters are even more sensitive since the in-plant power consumption needed to run all pumps is quite large and represents about 30% of the reference ("design") value of P_{gross},[24,25] hence, changes of the order of 10% in P_{gross} approximately translate in 15% variations in net power output, which is the true basis for the determination of electricity production costs.

Having stressed the importance of ΔT for OTEC systems, this available thermal resource is defined in what follows as the temperature difference between 20 and 1000 m water depths, with little loss of generality. This choice of depths reflects practical engineering constraints for typical tropical thermoclines and it is understood that more precise values would be the result of site specific technical and economic optimization. In Sec. II, the thermal resource is briefly presented and discussed from a global point of view. Section III evaluates ΔT around the main Hawaiian Islands using high-resolution computer tools constrained by data assimilation.

II. GLOBAL OTEC THERMAL RESOURCES

The most recent 2005 version of the World Ocean Atlas (WOA05) compiled by the National Ocean Data Center (NODC) represents an extremely valuable source of objectively analyzed statistical fields, including ocean temperature.[26] The data include long-term historical averages of variables that have been determined from all available oceanographic measurements. Monthly averages are also available. The data are provided with a resolution of one-quarter degree latitude by one-quarter degree longitude.

Figure 1 shows a map of the average OTEC thermal resource ΔT from the WOA05 database plotted with the Ocean Data View software.[27] Areas that are shallower than 1000 m are displayed in white to indicate that ΔT is not defined there with our choice of a reference cold water depth of 1000 m (different selections would be possible among the 33 levels of the WOA05 database). A restricted color palette from 15 to 25 °C was used to enhance the practical OTEC range of temperature differences. It is clear that the latitude band between 30 °S and 30 °N globally defines the OTEC region. Striking exceptions within this tropical zone can be seen along the west coasts of Africa and America, where cold surface currents in both hemispheres pinch the OTEC region by 10°–20° of latitude. Another interesting feature is the impact of the Red Sea outflow along the southern edge of the Arabian Peninsula. While the variability in ΔT generally reflects that of surface temperature, the variability in deep water temperatures (at 1000 m) nevertheless can be seen, for example, in the consistently lower values of ΔT found across the Indian Ocean, as opposed to those in the Western Pacific. More extreme albeit isolated cases are found in deep enclosed tropical basins with shallow sills, such as the Red Sea and the Sulu Sea, between Borneo and the Philippines; in those locations, deep water temperature is much higher and often determined by the depth of the sill(s).

The knowledge of the time variability of ΔT is also crucial, even as OTEC is expected to stand out for its baseload potential among renewable energy sources. To this end, a 12-slide animation of the monthly OTEC thermal resource determined from the WOA05 database was prepared.[28] Aside from a general but slight shift between northern and southern hemispheres as seasons proceed, one can also detect localized areas where the amplitude in ΔT fluctuations would be too great for practical OTEC systems. A good example is found along the northern coastal waters of the Gulf of Mexico.

III. OTEC THERMAL RESOURCES AROUND THE MAIN HAWAIIAN ISLANDS

The main reason OTEC has not matured beyond modest pilot scale projects is economic.[10,29] Such hurdles are not uncommon for marine renewable energy technologies since large initial investments and relatively higher risks typically are involved. Arguments for the development of OTEC in Hawaii remain strong, however. As can be seen in Fig. 1, the Hawaiian Archipelago is very well located from a thermal resource perspective. The volcanic islands have a steep bathymetry that affords good access to deep water. Their isolation and nearly complete dependence on fossil fuels today make any local *baseload* power production technology particularly attractive. Additional factors that would hamper other renewable energy technologies in Hawaii, such as limited land availability, pristine reefs, and valuable surf resources, would hardly affect OTEC. As a matter of fact, much of OTEC development to date did take place in Hawaii from the 1970s through the early 1990s.[7,10,23]

Regarding OTEC thermal resources around the main Hawaiian Islands, a closer look at the WOA05 data, e.g., in Fig. 1, already suggests that such resources do not get better from north to south, as would be intuitive, but roughly from northeast to southwest. Recently available predictive tools afford a much more detailed analysis. An ocean model called hybrid coordinate ocean model (HYCOM), subject to routine data assimilation via the Naval Research Laboratory (NRL)'s Coupled Ocean Data Assimilation (NCODA) protocol, allows daily assessments of ocean variables at a spatial resolution of 1/12° latitude by 1/12° longitude across the water column (e.g., at 30 levels from the ocean surface to 4000 m depth).[30] Although the output from the model is given as a snapshot in time ("midnight"), the time resolution for wind forcing is 3 h while heat fluxes are input as daily averages; hence, the diurnal cycle is not resolved and model output essentially should be interpreted as daily averages; for numerical stability purposes, however, a time step of 4 min is implemented. These data can be downloaded via public-domain servers such as http://ferret.pmel.noaa.gov/las; ongoing calculations also have a five-day predictive window (providing, in essence, an "ocean forecast"). The development of HYCOM is the result of collaborative efforts among the University of Miami, NRL, and the Los Alamos National Laboratory as part of the multi-institutional consortium funded in 1999 to develop and evaluate a data assimilative hybrid isopycnal-sigma pressure (generalized) coordinate ocean model. NCODA is an oceanographic version of the multivariate optimum interpolation technique widely used in operational atmospheric forecasting systems. The ocean analysis variables in NCODA are temperature, salinity, dynamic height, and velocity. NCODA assimilates all available operational sources of ocean observations. This includes along-track satellite altimeter observations, multichannel sea surface

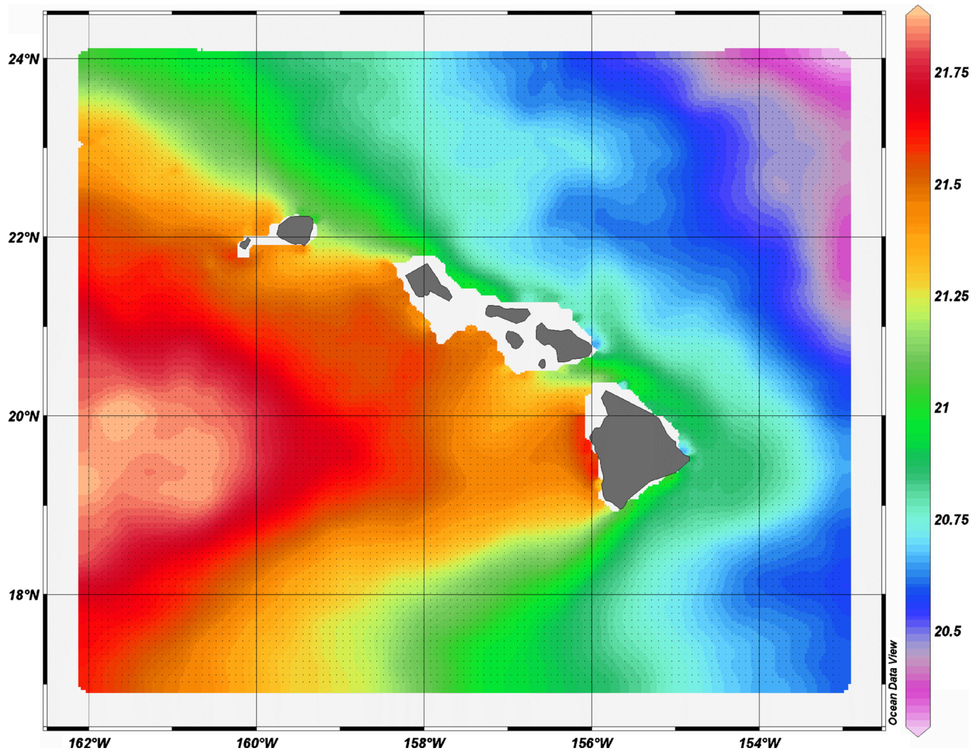

FIG. 2. Average ocean temperature differences (between 20 and 1000 m water depths) around the main Hawaiian Islands from HYCOM+NCODA (1/12°) data for the period 1 July 2007 through 30 June 2009 (color palette in °C).

temperature (SST), and *in situ* observations of SST and sea surface salinity (SSS), subsurface temperature and salinity profiles from bathythermograph profiling floats, and sea ice concentration.

Figure 2 shows the average available OTEC thermal resource $\langle \Delta T \rangle$ over a period of 2 years, from 1 July 2007 through 30 June 2009, for which 731 files of daily data were processed. Although overall geographic variations in the selected area covering 7° of latitude and 9° of longitude are within 2 °C, a prominent wedge can be seen; its apex roughly lies at the eastern tip of the Big Island, and the feature is somewhat symmetric across the latitude of that point; from the apex, a line running along the northeast (windward) coasts of the islands defines the angular overture of the wedge. The emergence of such a feature is likely to be the result of the strong influence the islands exert on large-scale ocean currents.[31–34] The westward flowing North Equatorial Current forks at the Big Island and gives rise to a branch that follows a northwesterly direction (North Hawaiian Ridge Current). The North Hawaiian Ridge Current compensates for an imbalance in meridional flow between interior Sverdrup transport and net southward transport.[32] West of the islands, the vorticity of the wind-stress curl associated with the wake of the islands causes a clockwise circulation centered at 19 °N and a counterclockwise circulation centered at 20° 30′N, with the narrow Hawaiian Lee Counter Current (HLCC) extending between them from 170 °W (or from as far as the Dateline) to 158 °W.[31–34] The eastward flowing HLCC is responsible for the advection of warm water toward the lee of the Hawaiian Archipelago.

The ability of HYCOM+NCODA to resolve the time variability of ΔT on a daily basis is demonstrated in supplementary material. The data are presented in daily-map animations for the months of August 2008 (31 slides)[28] and February 2009 (28 slides).[28] The performance of the model in tracking fronts and eddies can easily be appreciated. In the lee of the Big Island, for example, mesoscale eddies are frequently spun;[31,35] the effect of strong cold-core (cyclonic) events is quite visible on the 14th and 18th of August 2008.

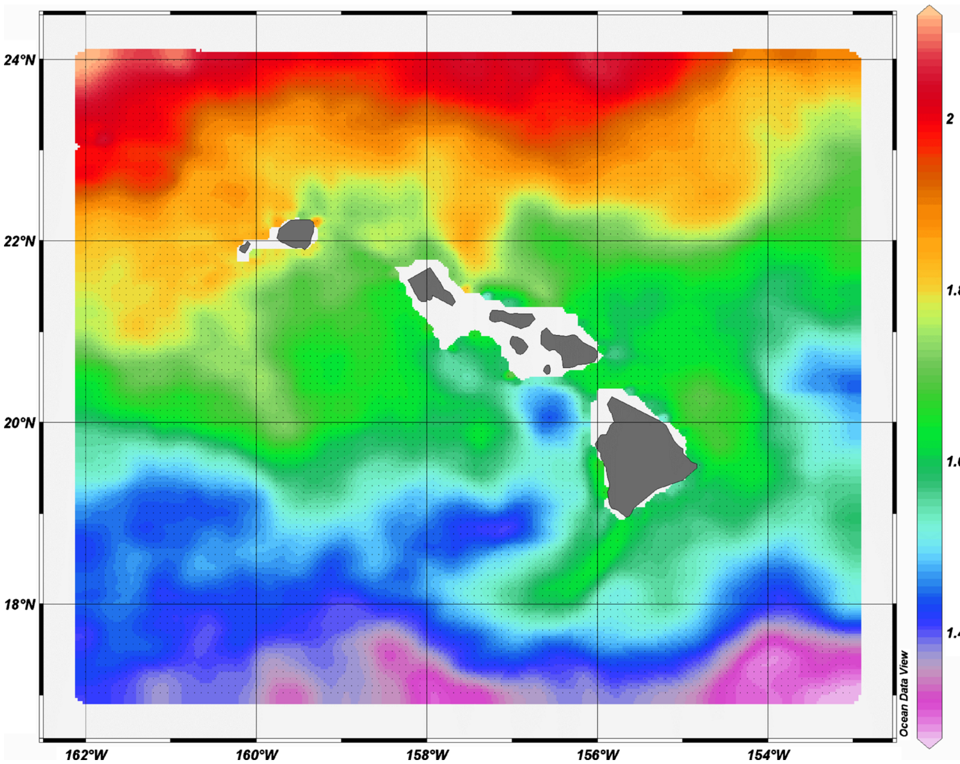

FIG. 3. Yearly amplitudes of ocean temperature differences (between 20 and 1000 m water depths) around the main Hawaiian Islands from HYCOM+NCODA (1/12°) data for the period 1 July 2007 through 30 June 2009 (color palette in °C).

Aside from the average value $\langle \Delta T \rangle$, it is important to have a sense of the long-term time variability of the OTEC thermal resource. One anticipates a dominant yearly periodicity. If the signal is represented as an equivalent sine function, its amplitude a would be equal to the standard deviation of the signal multiplied by $2^{1/2}$. Figure 3 shows the distribution of a calculated from the HYCOM data over the same two-year period as in Fig. 2. The result indicates amplitudes of the order of 2 °C with a general decrease from north to south. Hence, the geographic pattern observed for $\langle \Delta T \rangle$ does not extend to a. It should be noted that by definition, the average of the square of ΔT is equal to the square of $\langle \Delta T \rangle$ plus the variance of the signal, i.e., $\langle \Delta T^2 \rangle = \langle \Delta T \rangle^2 + 0.5a^2$. Therefore, the average gross power P_{gross} is known from $\langle \Delta T \rangle$ and a (for given OTEC design and seawater flow rates).

Nearly every month since October 1988, data have been collected for the Hawaii Ocean Time-series (HOT) program. These include observations of the hydrography, chemistry, and biology of the water column at the deep-water Station ALOHA (A Long-term Oligotrophic Habitat Assessment; 22° 45′N, 158° 00′W) 100 km north of Oahu. Other locations are routinely sampled en route to Station ALOHA, such as Station 1 off of Kahe Point, Oahu (21° 20.6′N, 158° 16.4′W). HOT data are readily accessible through the internet-based Hawaii Ocean Time-series Data Organization and Graphical System.[36] Figures 4 and 5 display ΔT determined from HOT measurements over a period of 20 years (at Station 1, where depth sampling is variable, ΔT was redefined for measured temperatures closest to the surface and to a depth of 1000 m; average actual depths are 6.5 and 1016 m, with respective standard deviations of 6.2 and 27 m). Expected overall yearly cycles with amplitudes of the order of 2 °C are confirmed and no trend is apparent. ΔT at Station 1 is roughly 1 °C higher. While the difference in latitude might suggest greater

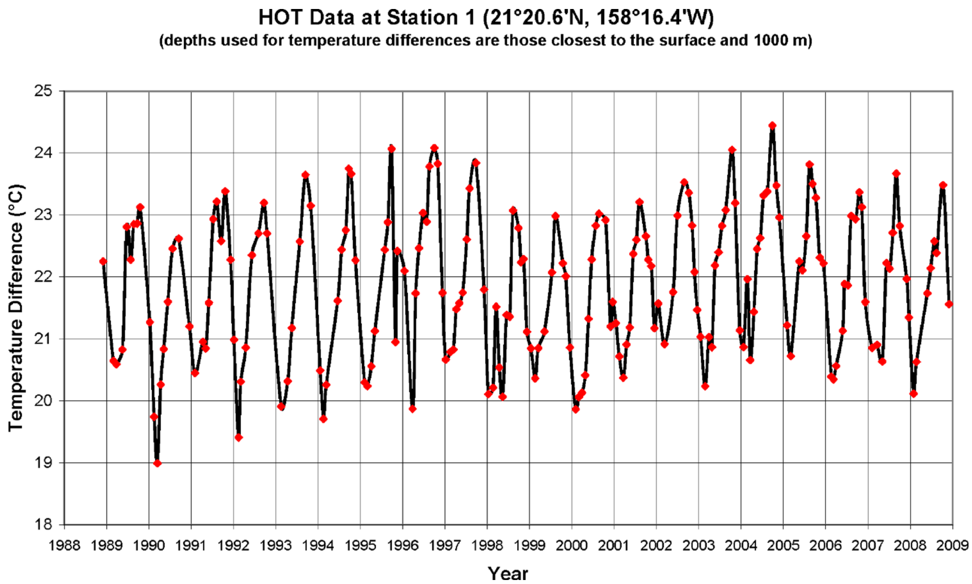

FIG. 4. Measured ocean temperature differences (between water depths closest to 0 and 1000 m) at HOT Station 1 ("Kahe Point:" 21° 20.6′N, 158° 16.4′W) from November 1988 through 2008.

values of ΔT further south, Fig. 2 reveals that such a perception would be simplistic. Finally, Figs. 6 and 7 illustrate the adequacy of the data assimilation protocol NCODA for HYCOM by simultaneously plotting available computed values and HOT data.

IV. CONCLUSIONS

This paper considered the evaluation of OTEC resources with currently available high-resolution ocean models. Worldwide historical averages of the temperature difference ΔT between standard water depths (20 and 1000 m) were first determined from the WOA05 database at a

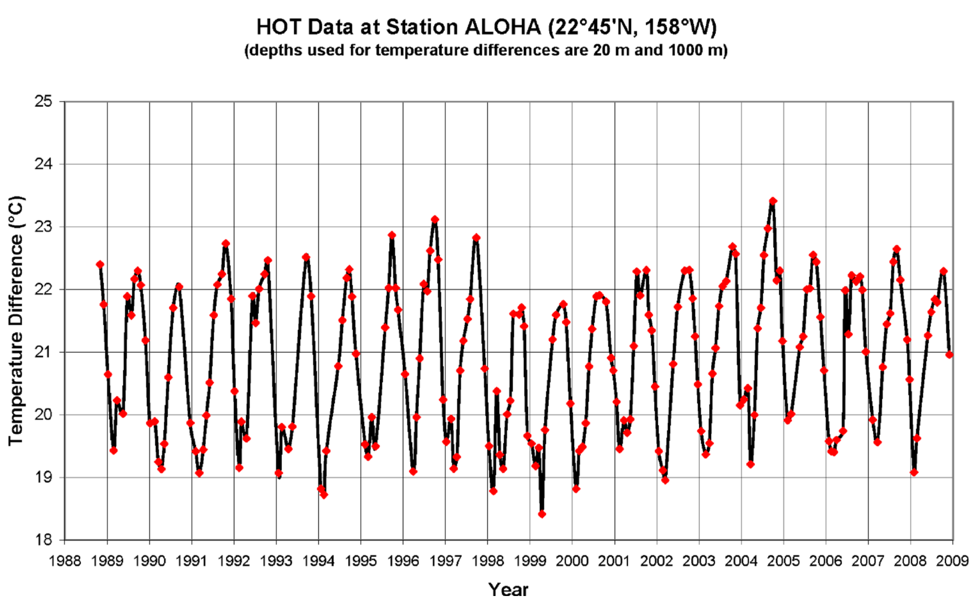

FIG. 5. Measured ocean temperature differences (between 20 and 1000 m water depths) at HOT Station ALOHA (22° 45′N, 158 °W) from November 1988 through 2008.

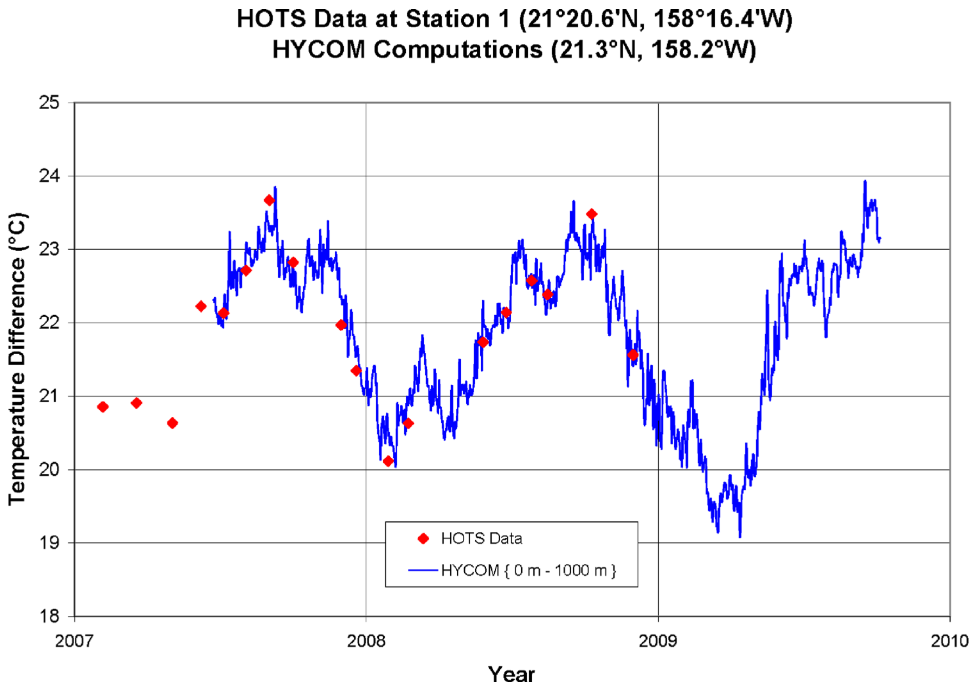

FIG. 6. Comparison between HYCOM+NCODA and HOT data sets at HOT Station 1 (Kahe Point).

spatial resolution of one-quarter degree latitude by one-quarter degree longitude. The case of waters around the main Hawaiian Islands was then examined more closely because of its relevance to the future development of OTEC. The state-of-the-art HYCOM+NCODA (1/12°) model was used to track changes on a daily basis over a wide area (e.g., 17 °N to 24 °N and 153 °W to

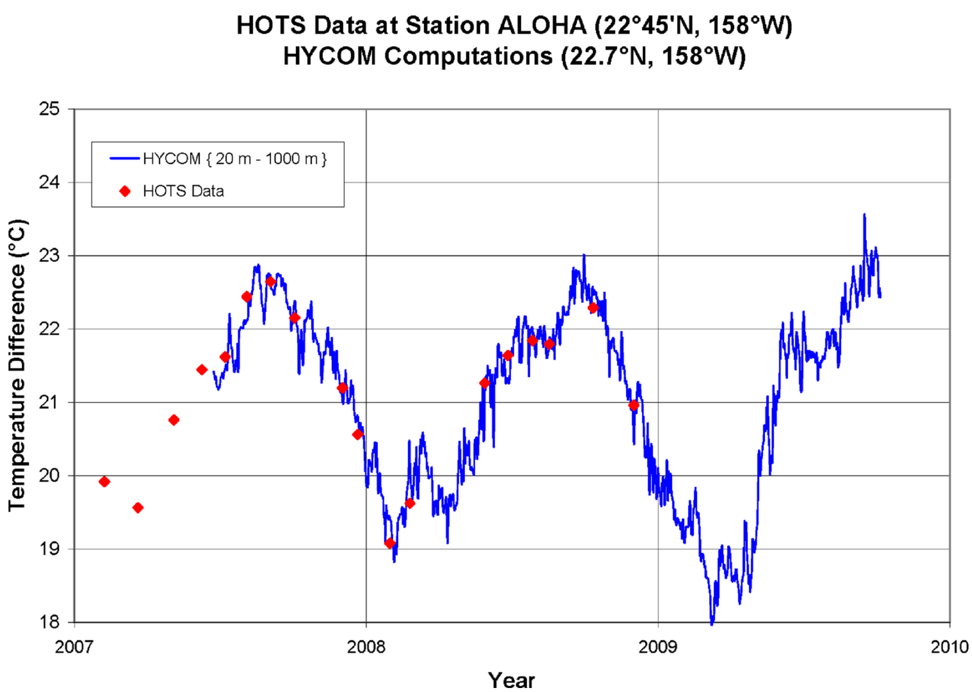

FIG. 7. Comparison between HYCOM+NCODA and HOT data sets at HOT Station ALOHA.

162 °W). An examination of numerical data over a time period of 2 years revealed that average OTEC temperature differences are consistently higher (by about 1 °C) west of the islands, whereas the amplitude of the yearly cycle globally decreases from north to south. The existence of a wedge of better OTEC resources in the lee of the archipelago was attributed to the influence of the narrow eastward flowing HLCC. Long-term measurements taken over two decades for the HOT program at two selected locations were also shown in order to give a longer perspective. These data were used to illustrate the adequacy of the data assimilation protocol NCODA for the high-resolution HYCOM calculations.

This study is not likely to fundamentally change the prospects of ocean thermal energy conversion (the basic pros and cons of the technology). The immense size of OTEC resources, as well as the baseload capability of OTEC systems, remain very promising aspects of the technology for many island and coastal communities across tropical latitudes; potential benefits, however, must be weighed against high capital costs and the need for state-of-the-art engineering. Instead, it was demonstrated here that advanced models can reveal regional variability in OTEC temperature resources that would have a significant long-term impact (of the order of 10%–15% per 1 °C) on the cost effectiveness of given OTEC power plants (all other things being equal).

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[1] A. d'Arsonval, Rev. Sci. Tech. **17**, 370 (1881).
[2] G. Claude, Mech. Eng. (Am. Soc. Mech. Eng.) **52**, 1039 (1930).
[3] C. Zener, Phys. Today **26** (1), 48 (1973).
[4] C. Zener, Mech. Eng. (Am. Soc. Mech. Eng.) **99**, 26 (1977).
[5] T. R. Penney and D. Bharathan, Sci. Am. **256** (1), 86 (1987).
[6] T. R. Penney and T. H. Daniel, Year Book for 1989, Encyclopaedia Britannica, pp. 98–115, 1989.
[7] W. H. Avery and C. Wu, *Renewable Energy from the Ocean – A Guide to OTEC* (Oxford University Press, New York, 1994), p. 446.
[8] L. A. Vega, *Encyclopedia of Energy Technology and the Environment*, edited by A. Bisio and S. Boots (John Wiley & Sons, New York, 1995), Vol. 3, pp. 2104–2119.
[9] S. M. Masutani and P. K. Takahashi, *Encyclopedia of Electrical and Electronics Engineering*, edited by J. G. Webster (John Wiley & Sons, New York, 2000), Vol. 15, pp. 93–103.
[10] G. C. Nihous, M. G. Brown, M. Gauthier, D. Levrat, and J. Ruer, Proceedings of the Second International Conference on Ocean Energy (ICOE), Brest, France, 2008.
[11] G. C. Nihous, *International Energy Agency Implementing Agreement on Ocean Energy Systems (IEA-EOS), 2008 Annual Report*, edited by A. Brito-Melo and G. Bhuyan 2009, pp. 45–49, http://www.iea-oceans.org/_fich/6/Annual_Report_2008_(1).pdf.
[12] E. E. Adams, D. Fry, D. Coxe, and D. Harleman, R. M. Parsons Laboratory for Water Resources and Hydrodynamics Technical Report No. 250, MIT, June 1979.
[13] D. Coxe, D. Fry, and E. E. Adams, MIT Energy Laboratory Report No. MIT-EL 81-049, 1981.
[14] G. O. Roberts, Proceedings of the Fourth Annual Conference on OTEC, New Orleans, LA, 1977, pp. 7–25.
[15] P. J. Martin and G. O. Roberts, Proceedings of the Fourth Annual Conference on OTEC, New Orleans, LA, 1977, pp. 26–34.
[16] T. R. Sundaram, E. Sambuco, A. M. Sinnarwalla, and S. K. Kapur, Proceedings of the Fourth Annual Conference on OTEC, New Orleans, LA, 1977, pp. 42–49.
[17] J. A. Whitehead, Jr. and N. A. Gershenfeld, Ocean Eng. **8**, 507 (1981).
[18] R. A. Paddock and J. D. Ditmars, Argonne National Laboratory Report No. ANL/OTEC-EV-2, 1983.
[19] D.-P. Wang, Argonne National Laboratory Report No. ANL/OTEC-EV-3, 1985, p. 46.
[20] G. C. Nihous, ASME J. Energy Resour. Technol. **127**, 328 (2005).
[21] G. C. Nihous, ASME J. Energy Resour. Technol. **129**, 10 (2007).
[22] G. C. Nihous, Ocean Eng. **34**, 2210 (2007).
[23] L. A. Vega and D. E. Evans, Proceedings of Oceanology International '94 Conference, Brighton, UK, 1994, Vol. 5.
[24] G. C. Nihous, M. A. Syed, and L. A. Vega, Proceedings of the International Conference on Ocean Energy Recovery, Honolulu, HI, 1989, pp. 207–216.
[25] L. A. Vega and G. C. Nihous, Proceedings of Oceanology International '94 Conference, Brighton, UK, 1994, Vol. 5.
[26] R. A. Locarnini, A. V. Mishonov, J. I. Antonov, T. P. Boyer, and H. E. Garcia, in *World Ocean Atlas 2005, Volume 1: Temperature*, NOAA Atlas NESDIS 61, edited by S. Levitus (U.S. Government Printing Office, Washington, DC, 2006), p. 182.
[27] R. Schlitzer, Ocean Data View, http://odv.awi.de, 2009.
[28] See supplementary material at http://dx.doi.org/10.1063/1.3463051 for monthly OTEC thermal resource determined from the WOA05 data base, for daily OTEC thermal resource determined from HYCOM+NCODA calculations for August

2008, and for daily OTEC thermal resource determined from HYCOM+NCODA calculations for February 2009.
[29] L. A. Vega, *Ocean Energy Recovery: The State of the Art*, edited by R. J. Seymour (ASCE, New York, 1989), pp. 152–181.
[30] E. P. Chassignet, H. E. Hurlburt, E. J. Metzger, O. M. Smedstad, J. A. Cummings, G. R. Halliwell, R. Bleck, R. Baraille, A. J. Wallcraft, C. Lozano, H. L. Tolman, A. Srinivasan, S. Hankin, P. Cornillon, R. Weisberg, A. Barth, R. He, F. Werner, and J. Wilkin, Oceanogr. **22**, 65 (2009).
[31] P. Flament, S. Kennan, R. Lumpkin, M. Sawyer, and E. D. Stroup, Ocean Atlas of Hawai'i, http://www.soest.hawaii.edu/hioos/oceanatlas/index.htm, 1996.
[32] B. Qiu, D. A. Koh, C. Lumpkin, and P. Flament, J. Phys. Oceanogr. **27**, 431 (1997).
[33] S. P. Xie, W. T. Liu, and M. Monaka, Science **292**, 2057 (2001).
[34] Z. Yu, N. Maximenko, S.-P. Xie, and M. Nonaka, Geophys. Res. Lett. **30**, 1215 (2003).
[35] P. H. R. Calil, K. J. Richards, Y. Jia, and R. R. Bidigare, Deep-Sea Res., Part II **55**, 1179 (2008).
[36] D. M. Karl and R. Lukas, Deep-Sea Res., Part II **43**, 129 (1996).