Oceanic Response to Widespread Ocean Thermal Energy Conversion

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Background

Ocean Thermal Energy Conversion (OTEC) is a form of marine renewable energy that harnesses the thermal gradient between warmer surface water and cooler deep waters to power a heat engine and produce electricity.[6] OTEC plants typically pump cool waters from around 1000m depth and warm water from the top 20m of the water column. To generate power efficiently, OTEC requires temperature gradients upwards of 18ºC between the warm-water uptake in the surface waters and the cold-water uptake.[4]

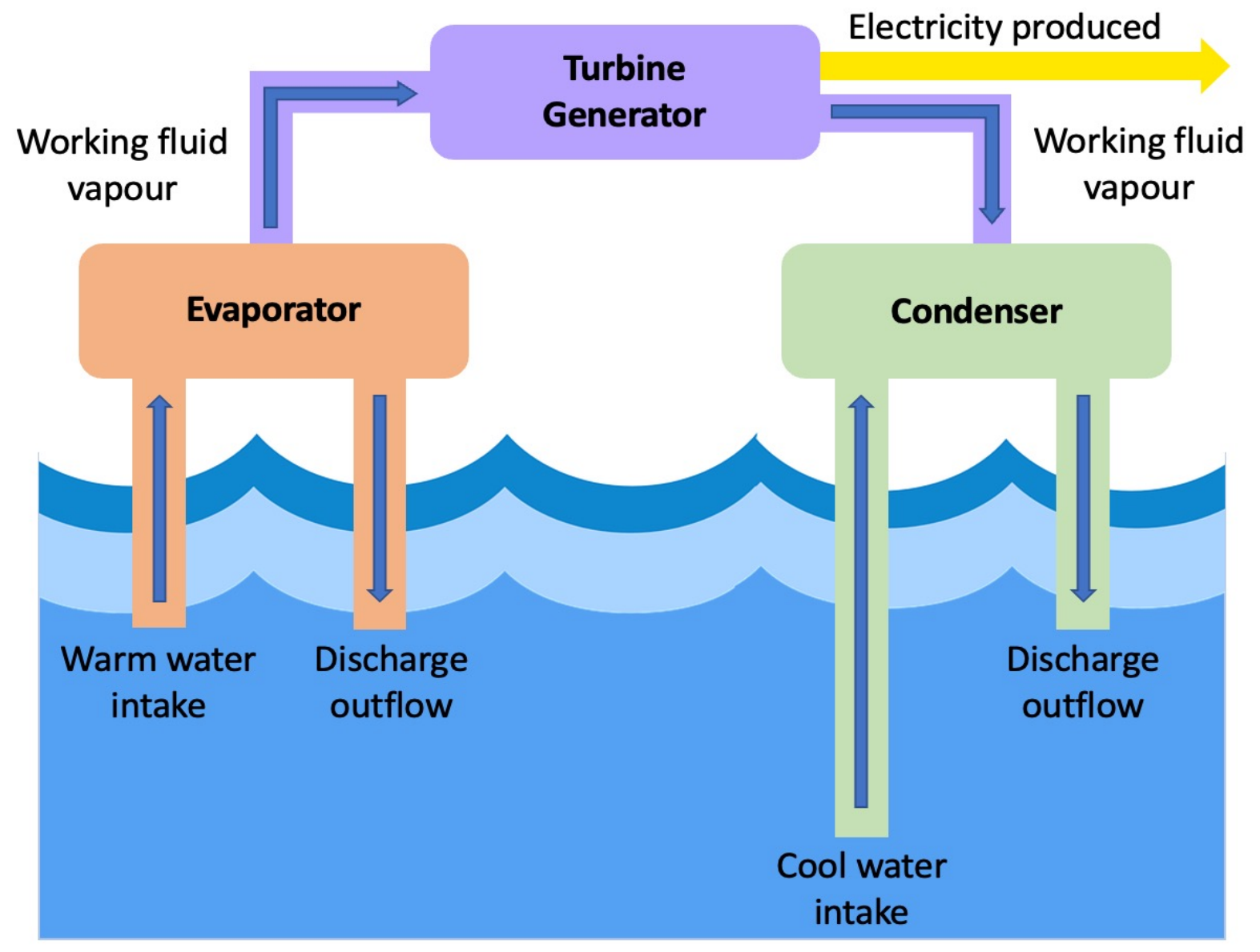

Figure 1. Simplified Schematic diagram of OTEC system.

Locations with a sufficient temperature gradient to support OTEC implementation are largely constrained to deep warm seas in the tropics, especially the Caribbean, the Red Sea, and much of the Indo-Pacific Ocean.[1,2]

Objective

OTEC has capacity to produce immense amounts of continuously available, renewable energy, although currently the technology has only been implemented in small-scale, pilot plants. Some have proposed widespread implementation of OTEC technology to contribute to the world's energy needs. Prior to widespread implementation of OTEC technology, the biological, physical, and chemical implications of such a deployment must be quantified. In my research I use the UVic Earth Systems Model (ESCM) to assess the magnitude and significance of these impacts.

Methods

The UVic ESCM version 2.9 was used to generate 3 modelled scenarios which employed OTEC at varying energy demands. The UVic ESCM is coupled and global in coverage. The model has a zonal and meridional spherical grid resolution of 3.6º and 1.8º, respectively. The model comprises an energy-moisture balance atmospheric model, a dynamic-thermodynamic sea-ice model, and a primitive equation oceanic general circulation model.

The model determines potential plant locations based on the temperature gradient in each grid cell. The greatest temperature gradients are most efficient and therefore plant placement in grid cells with high-temperature gradients are prioritized. If the temperature gradient in a cell is depleted below the 18ºC threshold, plants are decommissioned and relocated.

This study primarily focused on 4 modelled runs. All runs used emissions diagnosed from the "high CO_2" RCP 8.5 scenario.[3] The first modelled scenario which underwent global warming without any OTEC power generation is used as a "no intervention" scenario to which the runs with OTEC power generation are compared. Three scenarios were modelled at varying OTEC power demands: 3TW, 7TW, and 10TW. These levels of power generation are similar to the 2019 global energy consumption from electricity, oil and natural gas, and the total energy consumption excluding electricity, respectively. In the modelled runs with OTEC power generation, deployment of OTEC plants began in 2030 and reached peak power generation in 2100. Power generation remains constant until the end of the modelled period in 2500.

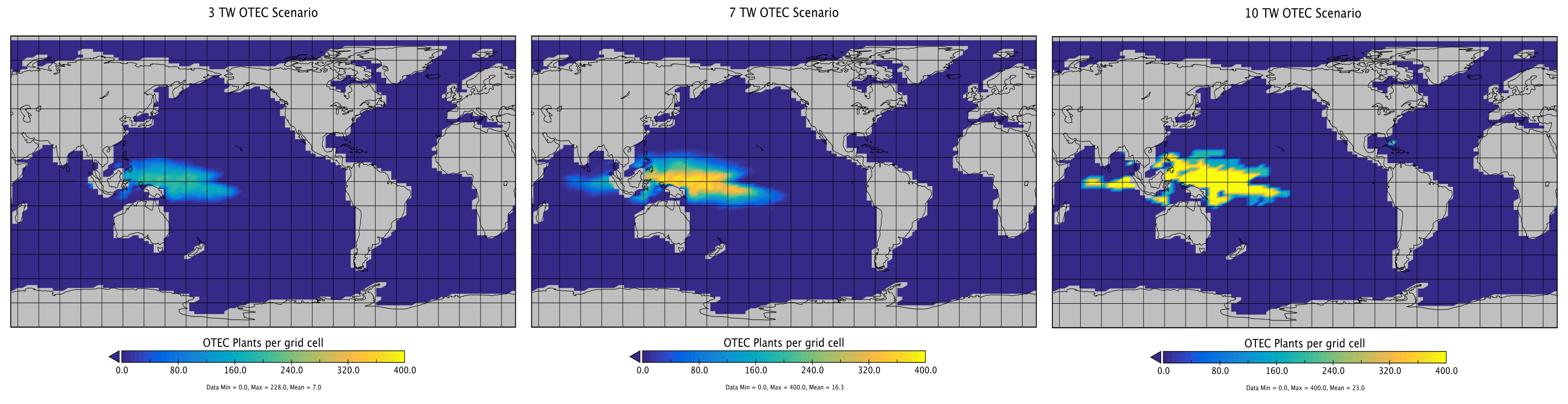

Figure 2. OTEC Plant density at peak power generation in 2100 for 3TW, 7TW, and 10TW modelled scenario

Surface Water Cooling

During OTEC power generation cool deep-waters are transported to the ocean surface. This causes a decrease in surface water temperatures in areas that undergo OTEC power generation. The cooling is centered in the tropics, specifically the West Pacific Warm Pool where the majority of the OTEC plants are situated (Fig. 2). Surface water temperatures decrease by up to 4ºC by 2500 in the 10TW scenario relative to the no OTEC scenario. It is important to note that while temperatures are decreased relative to a "no intervention" scenario, absolute surface water temperatures rise due to the overwhelming global warming signal. The relative change in ocean temperatures in 2500 for each OTEC scenario is shown in Figure 3.

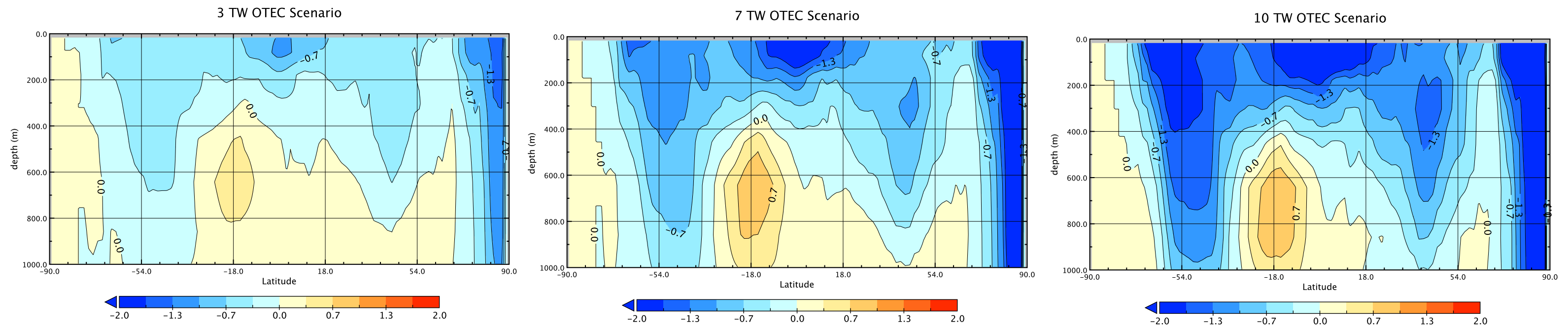

Figure 3. Change in temperature of the uppermost 1000m of the water column for a 3TW, 7TW, and 10TW OTEC scenario in 2500 relative to the same year in a scenario without OTEC.

Alteration of Surface Water Properties

OTEC power generation involves the artificial upwelling of large volumes of deep water to the ocean surface. Deeper waters tend to be cooler, saltier, and have higher nutrient concentrations relative to surface waters. This results in major alteration of the surface water properties in areas of OTEC power generation. Additionally, the cooling of surface water in areas undergoing OTEC power generation will affect the rates of diffusive gas exchange at the air-sea interface. This will further alter surface water properties.

The changes of some key properties for the levels of OTEC power generation outlined previously are shown in Figure 4. Any level of OTEC power generation causes an appreciable change to surface water properties, but the magnitude of change is amplified at higher OTEC power generation rates.

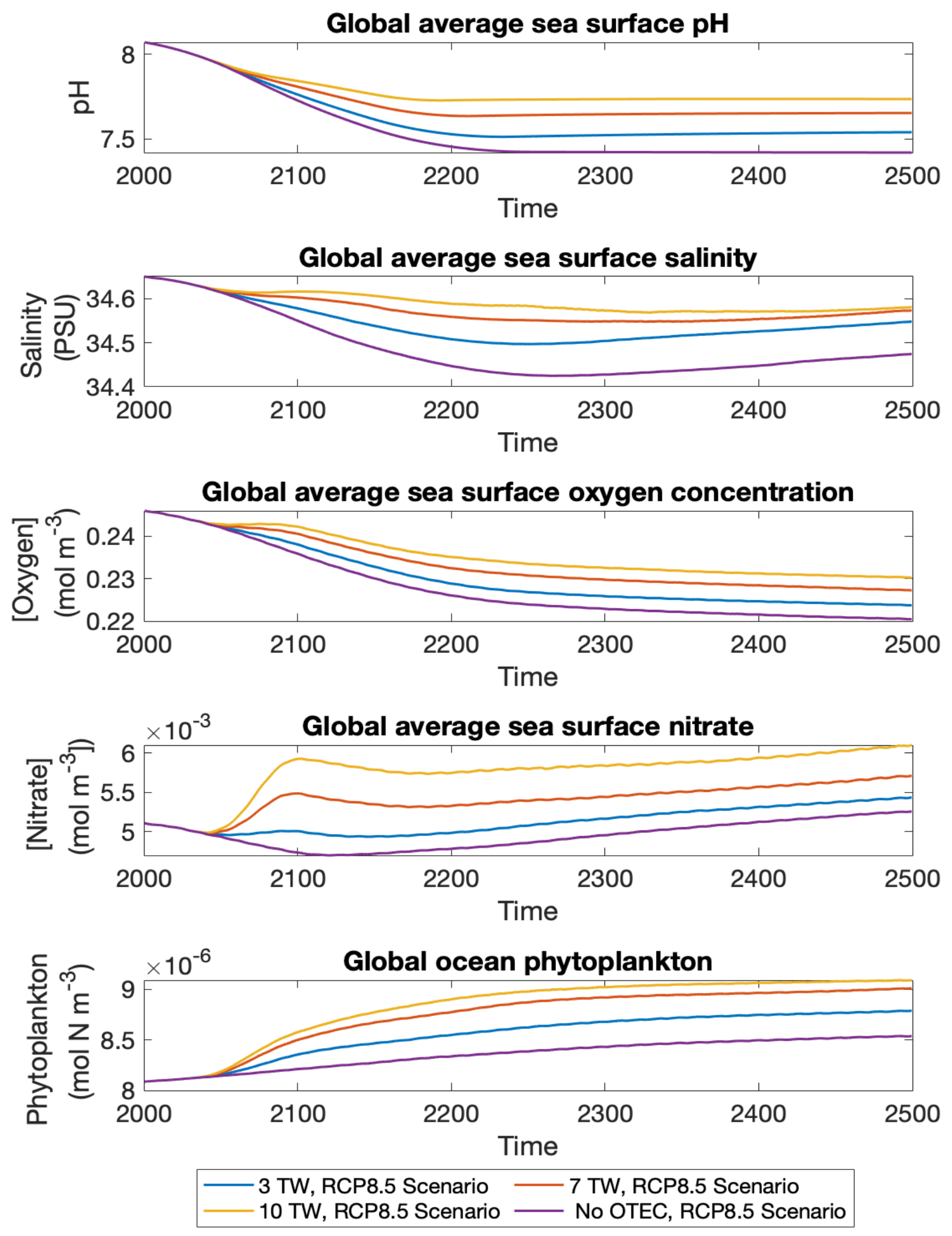

Figure 4. Time series of various surface water properties from 2000 to 2500 for varying levels of OTEC power generation

Changes to Large-scale Circulation

Disruption of the Atlantic Meridional Overturning Circulation (AMOC) is of key concern. The AMOC plays a pivotal role in the regulation of Earth's climatic conditions. Previous literature[5] has projected that implementation of OTEC technology would lead to a strengthening of the overturning circulation, with the magnitude of the increase magnified as OTEC power generation rates increase. The same trend was observed in the three OTEC scenarios where there were consistently greater meridional overturning streamfunction values relative to the no-intervention warming scenario (Fig. 5). While the scenario without OTEC experiences a decrease in the strength of the overturning circulation of nearly 1.2 Sv by 2500, the 10TW scenario sees relatively constant values over the modelled period.

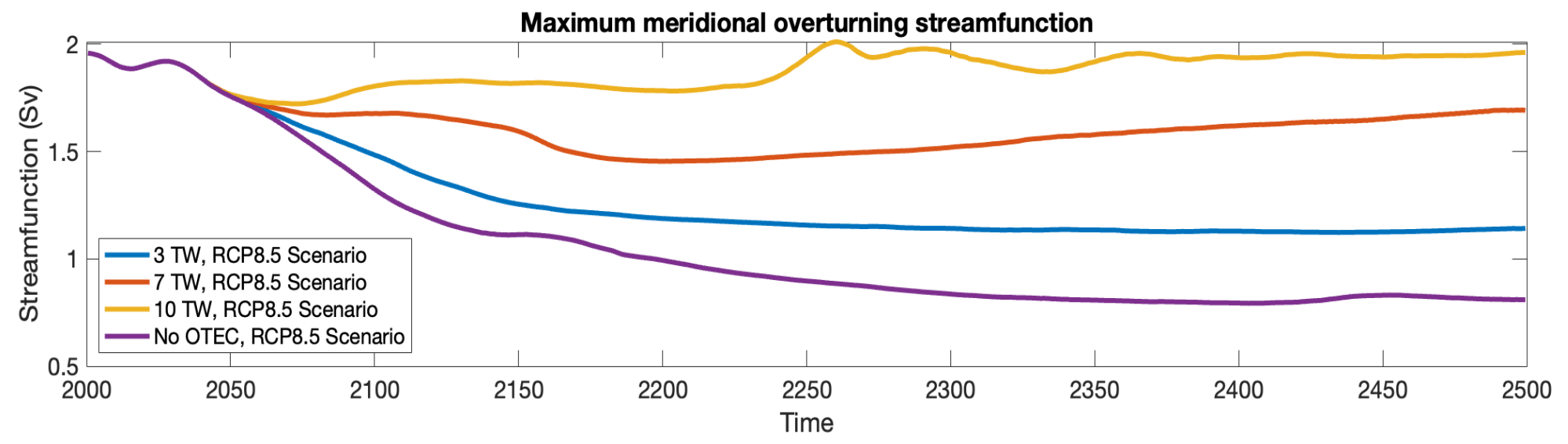

Figure 5. Maximum meridional overturning streamfunction in Sverdrup from 2000 to 2500 for a 3TW (blue), 7 TW (orange), 10 TW (yellow), and no OTEC (purple) scenarios .

Effect on the Atmosphere

Implementation of OTEC technology at any power level results in a decrease in atmospheric carbon dioxide concentrations (Fig. 6). The decline is driven primarily by the emissions reductions associated with OTEC sourced energy replacing higher emission forms of energy. Greater levels of OTEC power generation results in incrementally lower carbon dioxide emissions (Fig. 6).

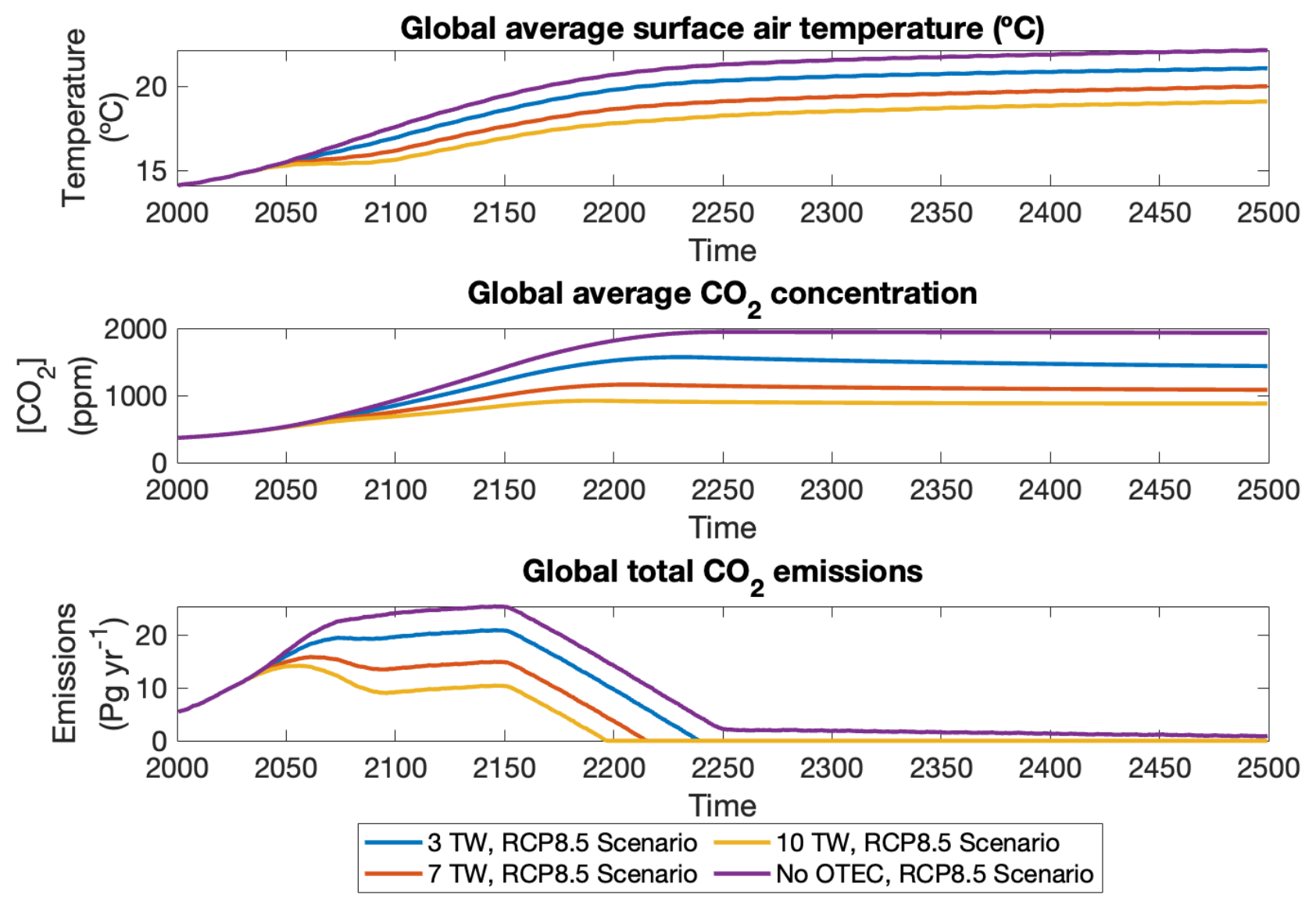

Figure 6. Chances in surface air temperature, CO_2 concentration, and CO_2 emissions from 2000 to 2500 for varying levels of OTEC power generation

OTEC-driven cooling of the surface waters increases heat uptake by the ocean leading to an associated atmospheric cooling (Fig. 6 and 7). The change in surface air temperatures in each OTEC scenario relative to the scenario without OTEC is shown in Figure 7. This differencing isolates the temperature signal from OTEC deployment from that of global warming. It is clear that the greater level of power generation intensifies the magnitude of cooling. The largest cooling occurs in the 10TW scenario with values greater than 6.4ºC.

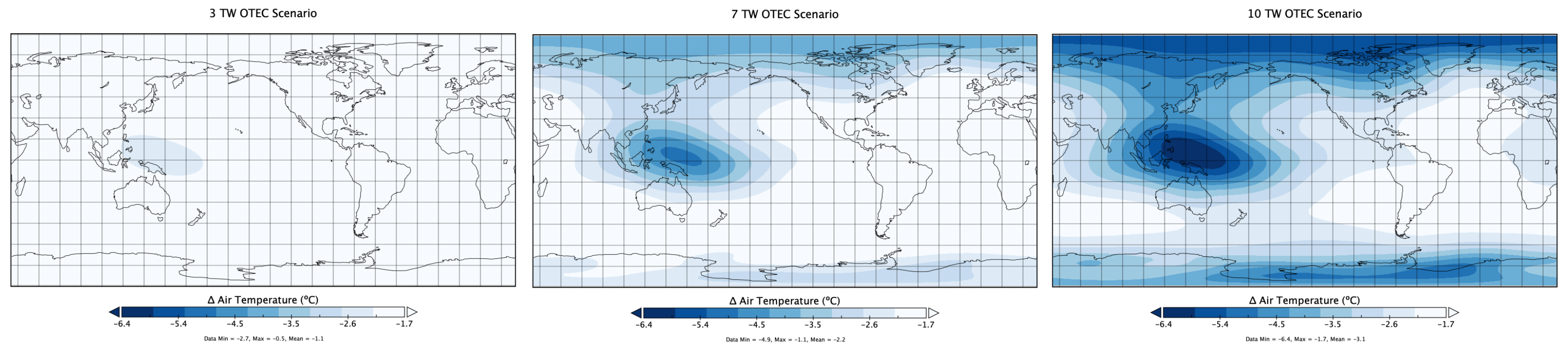

Figure 7. Change in surface air temperature for a 3TW, 7TW, and 10TW OTEC scenario in 2500 relative to the same year in a scenario without OTEC.

Conclusion

OTEC provides a unique opportunity for relatively clean, continuous energy to be produced. While our modelled scenarios indicate it is possible for our oceans to produce a vast amount of power (up to 10 TW) via OTEC implementation, the process is not without significant environmental concerns. In addition to the major alteration of sea surface properties, disrupting the thermal structure of the ocean may affect rates of ice sheet destabilization, the severity of monsoons, and El Niño Southern Oscillation patterns. The severity of these environmental concerns scales with the level of power generation; The greatest disruptions to Earth systems occurred in the 10 TW scenario while the 3 TW scenario experienced relatively minor ramifications. OTEC presents many potential benefits, such as atmospheric and oceanic cooling and strengthening of the overturning circulation, which oppose trends caused by climate change. The effect on ocean systems cannot be understated and must be considered in any further analysis of the feasibility of implementing OTEC technology.

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