

Assessing the potential of Ocean Thermal Energy Conversion (OTEC)

Ray Schmitt

Woods Hole Oceanographic Institution

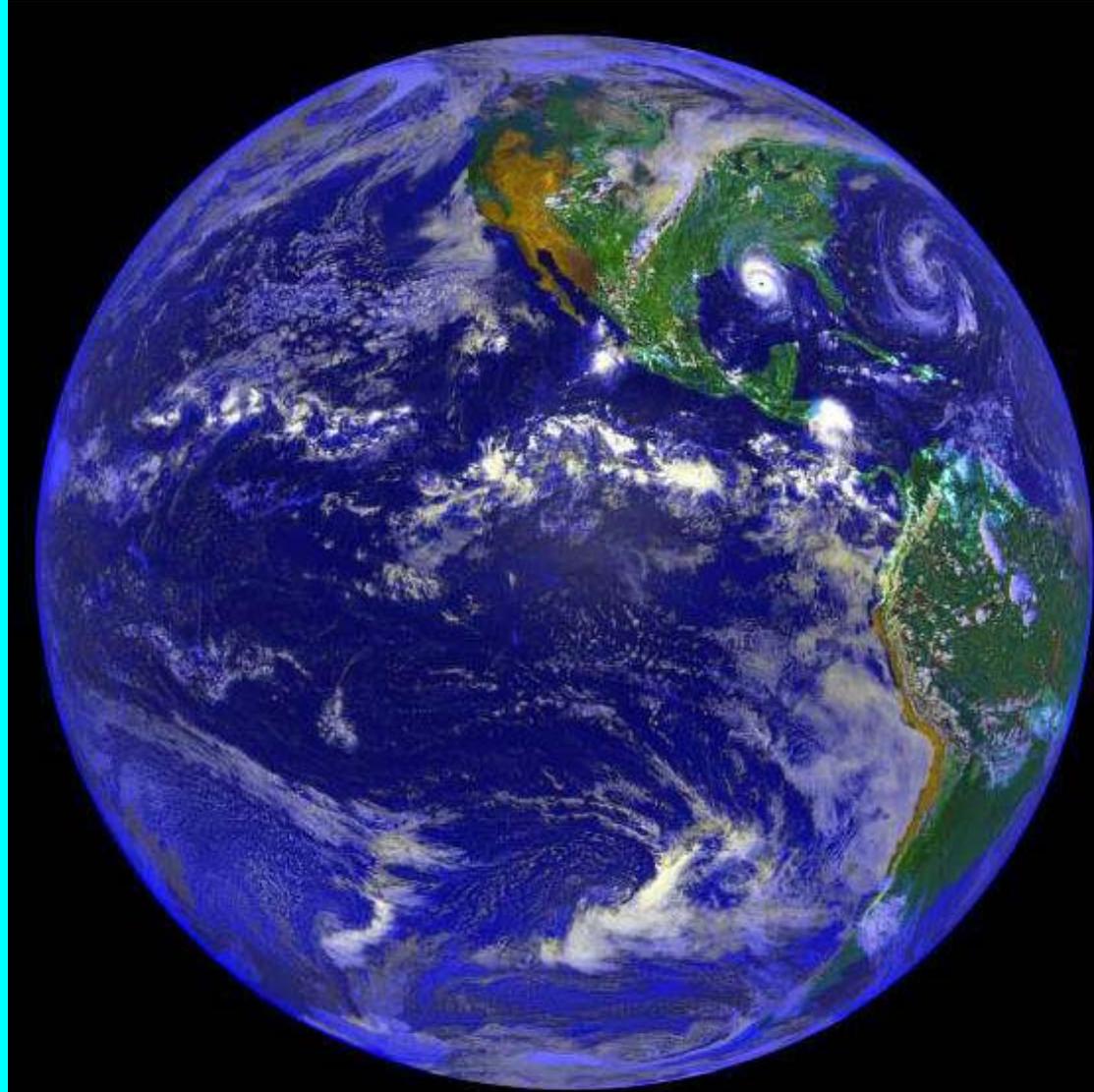
Woods Hole, MA

rschmitt@whoi.edu

Snowmass Energy Modeling Forum, Aug. 2009

Ocean Energy: The ocean is the solar collector for planet Earth.

With 1,100 times the heat capacity fo the atmosphere, it has absorbed 80% of the heat of global warming in the past 50 years. How can we best tap the energy?



Challenges for Ocean Energy

- **Diffuse source**
- **Generally remote from societal needs**
- **Technically challenging (sea-state, corrosion, fouling)**
- **Environmental impacts**

OTEC

- **Thermohaline circulation creates a strong vertical temperature gradient in the tropics**
- **A very large ocean energy source; though it uses a low efficiency heat engine, the resource is vast.**
- **Developed in the 70's in response to oil crisis, demonstration plant built in Hawaii.**
- **Main challenges, cost of cold water pipe, biofouling of heat exchangers, how to use power in remote locations (generate hydrogen, smelt aluminum, etc), low cost of fossil fuels.**
- **US and foreign interest is renewing rapidly....**

OTEC plant

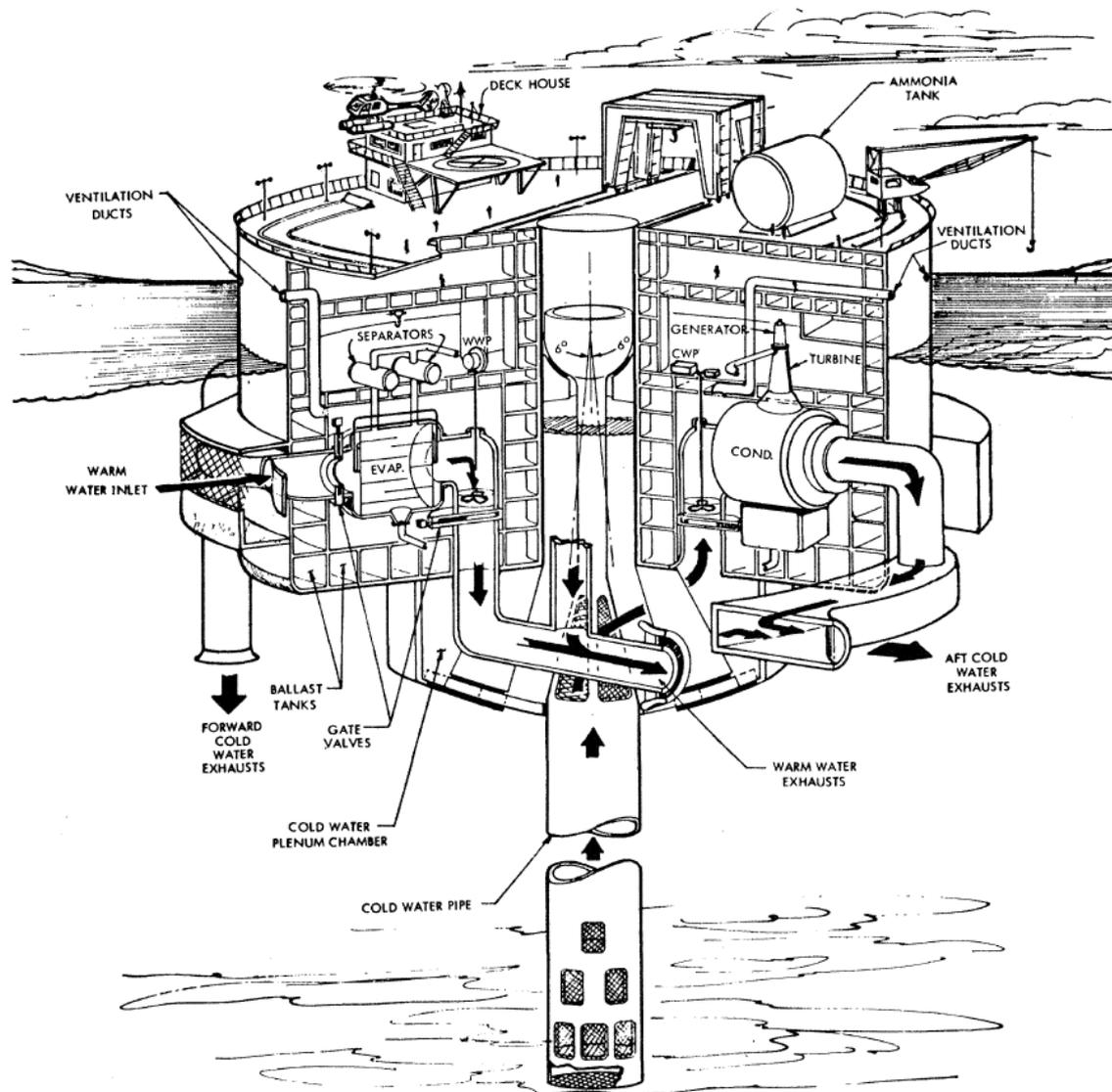


FIGURE 4. The TRW Systems Group, Inc. (1975) concept of a 100 MW_e baseline OTEC power plant. One of the four 25 MW_e power modules is shown in the cutaway portion. The platform has a diameter of 100 m.

Estimates of available power

-Isaacs and Schmitt, 1980

Only salinity and thermal gradients are globally comparable to human consumption rate

(~18 TW)

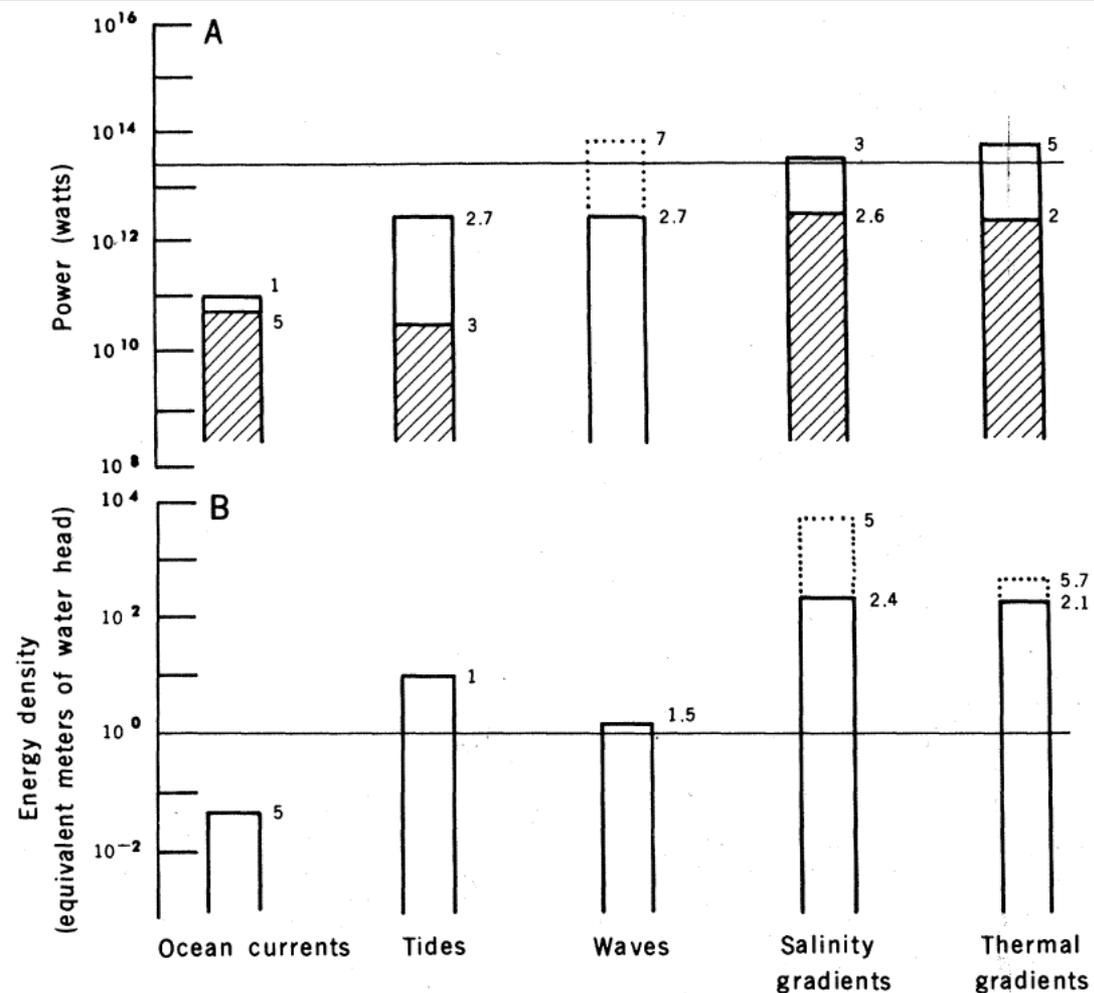


Fig. 1. (A) Power or energy flux for ocean energy. On the "ocean currents" bar, the shading represents the power contained in concentrated currents such as the Gulf Stream. Estimated feasible tidal power is also shaded. The dotted extension on "waves" indicates that wind waves are regenerated as they are cropped. "Salinity gradients" includes all gradients in the ocean; the large ones at river mouths are shown by shading. Not shown is the undoubtedly large power that would result if salt deposits were worked against freshwater or seawater. On "thermal gradients," the shading indicates the unavoidable Carnot-cycle efficiency. The horizontal line at 30×10^{12} watts is a projected global electricity consumption for the year 2000. (B) Intensity or concentration of energy expressed as equivalent head of water. "Ocean currents" shows the velocity head of major currents. For tides, the average head of favorable sites is given. For waves, the head represents a spatial and temporal average. The salinity-gradients head is for freshwater versus seawater, the dotted extension for freshwater versus brine (concentrated solution). The thermal-gradients head is for 12°C ; that for 20°C is dotted; both include the Carnot efficiency. [From Wick and Schmitt (22)]

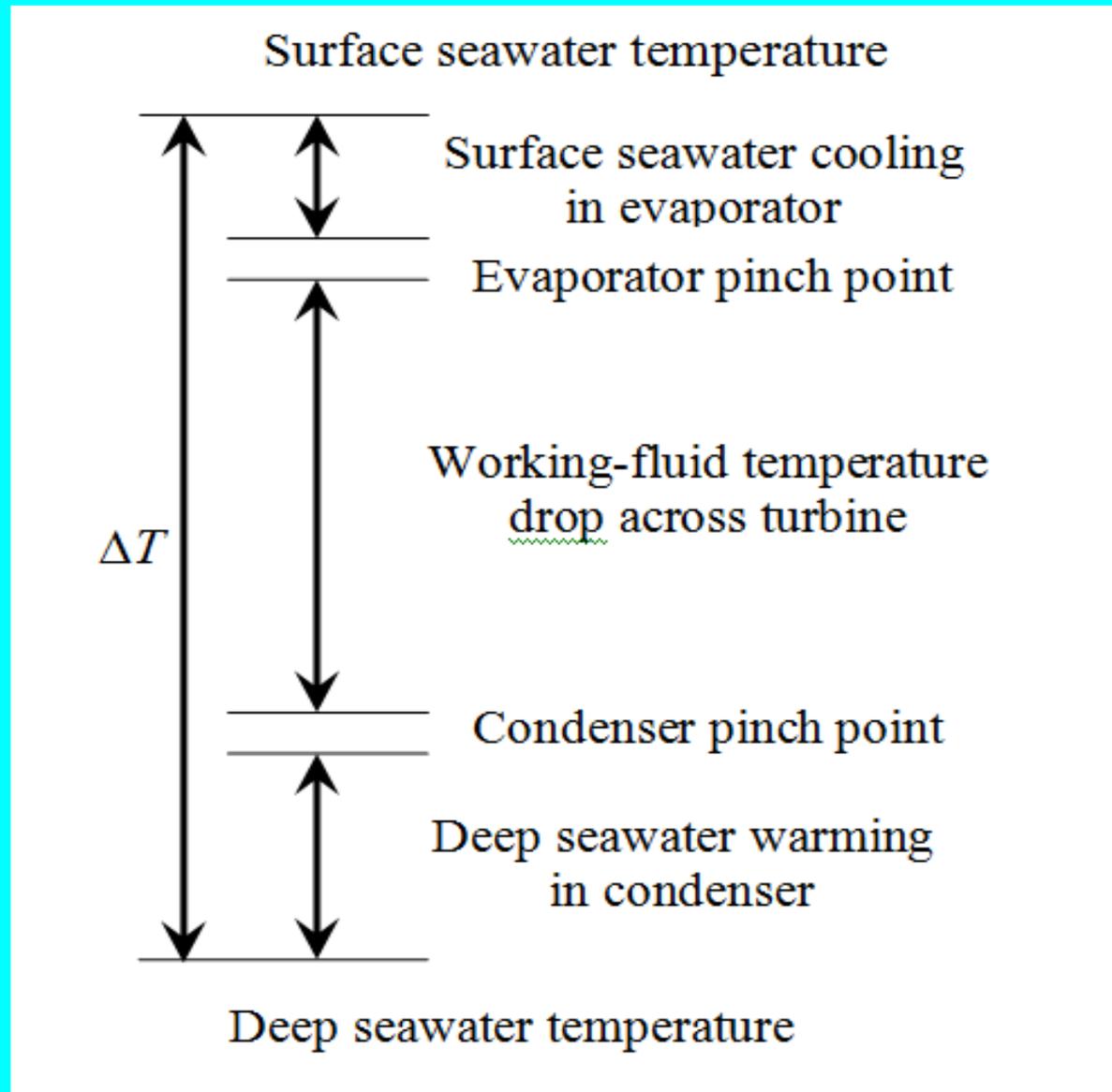
Ocean Energy Paradox: The lower the energy source the more actively it is pursued!

- Current, Tidal and Wave projects are actively underway by ~100 companies, but these sources have limited power and will prove useful only in certain areas. At best could meet ~10% of US power needs.**
- Salinity and Thermal gradients have much larger available power, sufficient to meet 100% of global societal needs, but have been neglected since the 1970's**

Some OTEC projects being planned:

- **The US Navy is doing feasibility studies for OTEC plants on Guam and Diego Garcia**
- **Hawaii is planning for one or two plants**
- **Being considered for American Samoa**
- **Since air conditioning is much of the power load on tropical islands, cold water pipes for A/C is already economical**

OTEC Temperature Ladder



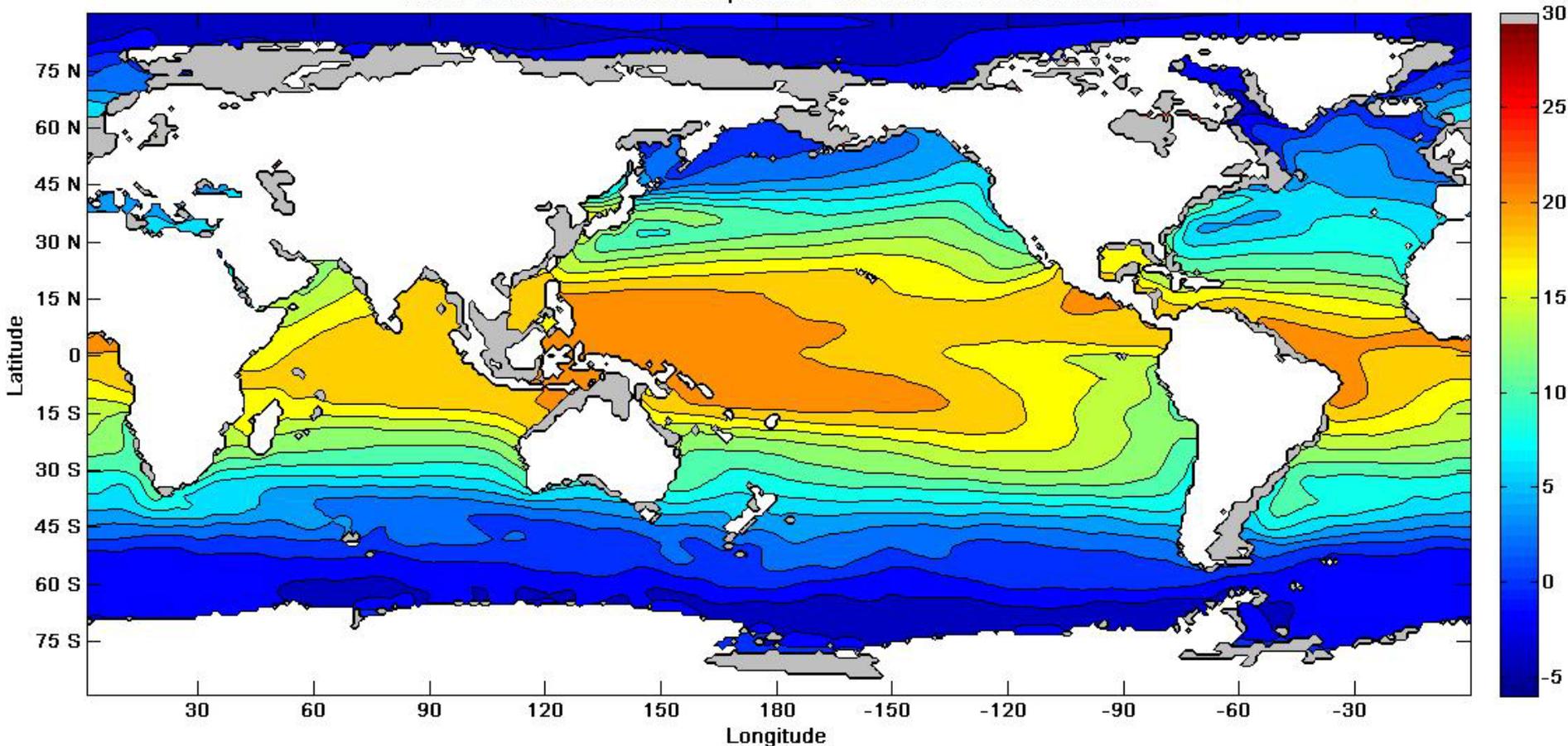
What is the size of the resource?

How quickly does it renew?

- **New understanding of the ocean thermohaline circulation suggests that the resource would be rapidly renewed.**
- **Main limits seem to be on the size of individual plants and how closely they can be spaced.**
- **In order to guide designers and decision makers, we have developed a program to map the power density available for given pipe length, efficiency and pumping loss for any season from climatology or any individual month in the last 7 years.**

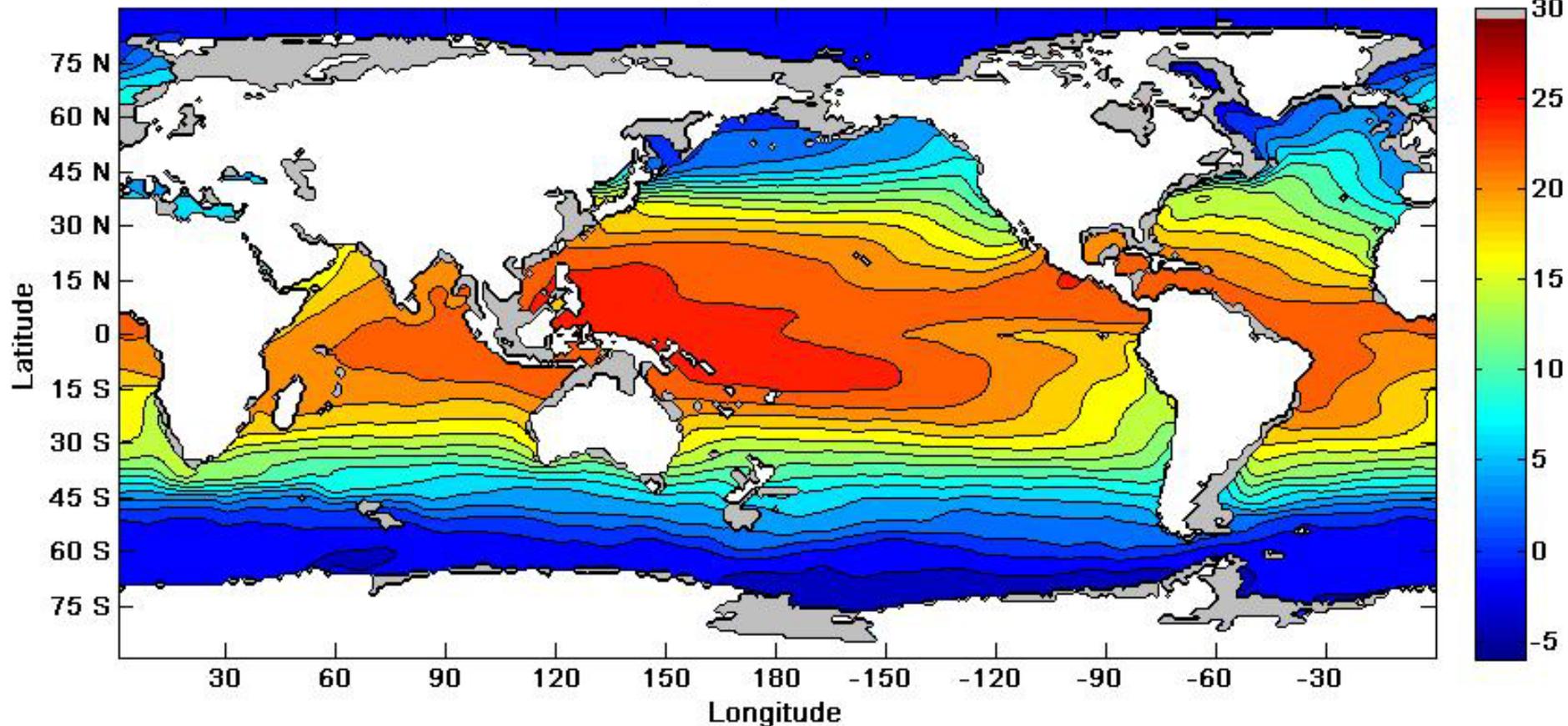
Avg. Temperature difference between surface and 500m depth

World Ocean Atlas Annual Temperature Difference from 0.0m to 500.0m



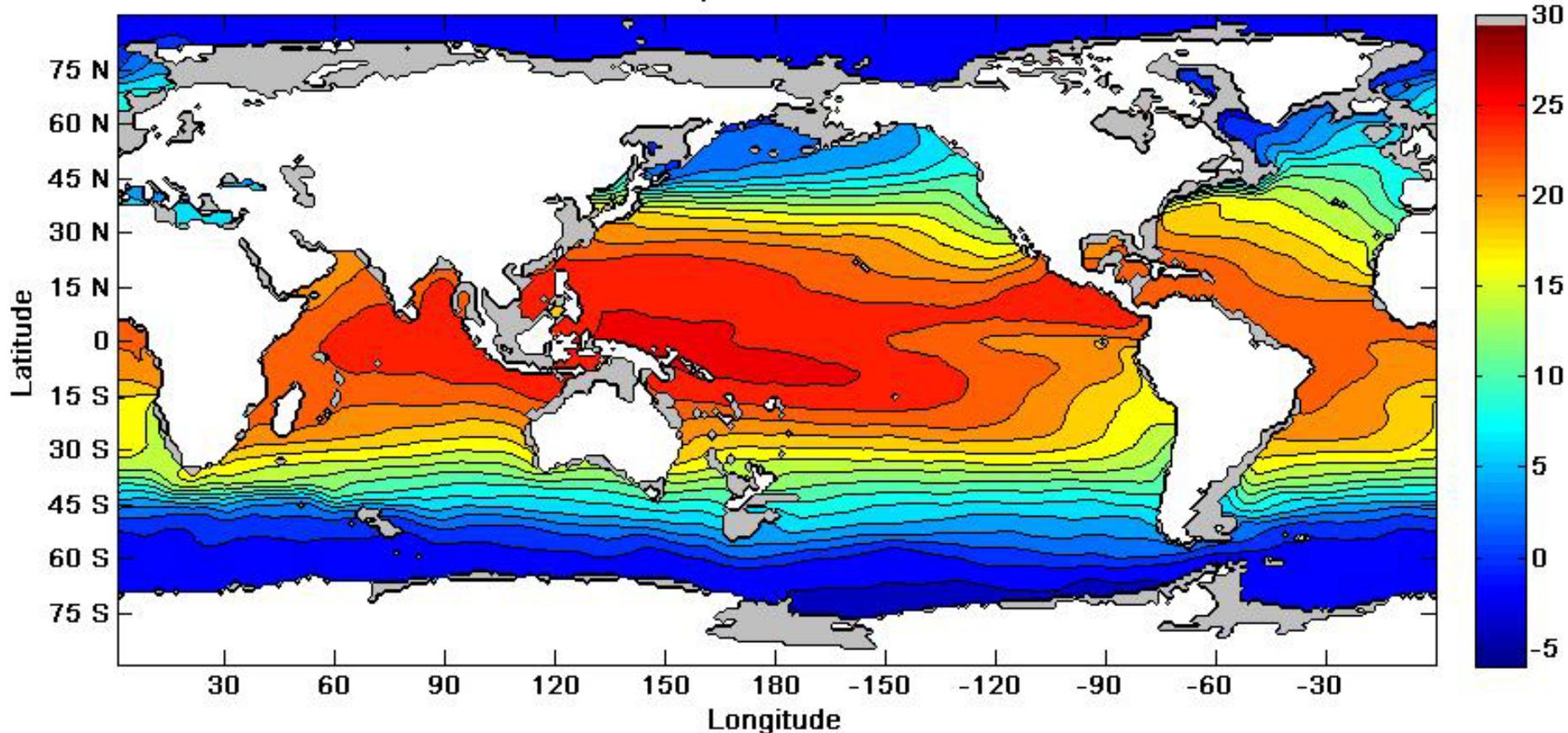
Avg. Temperature difference between surface and 1000m depth

World Ocean Atlas Annual Temperature Difference from 0.0m to 1000.0m



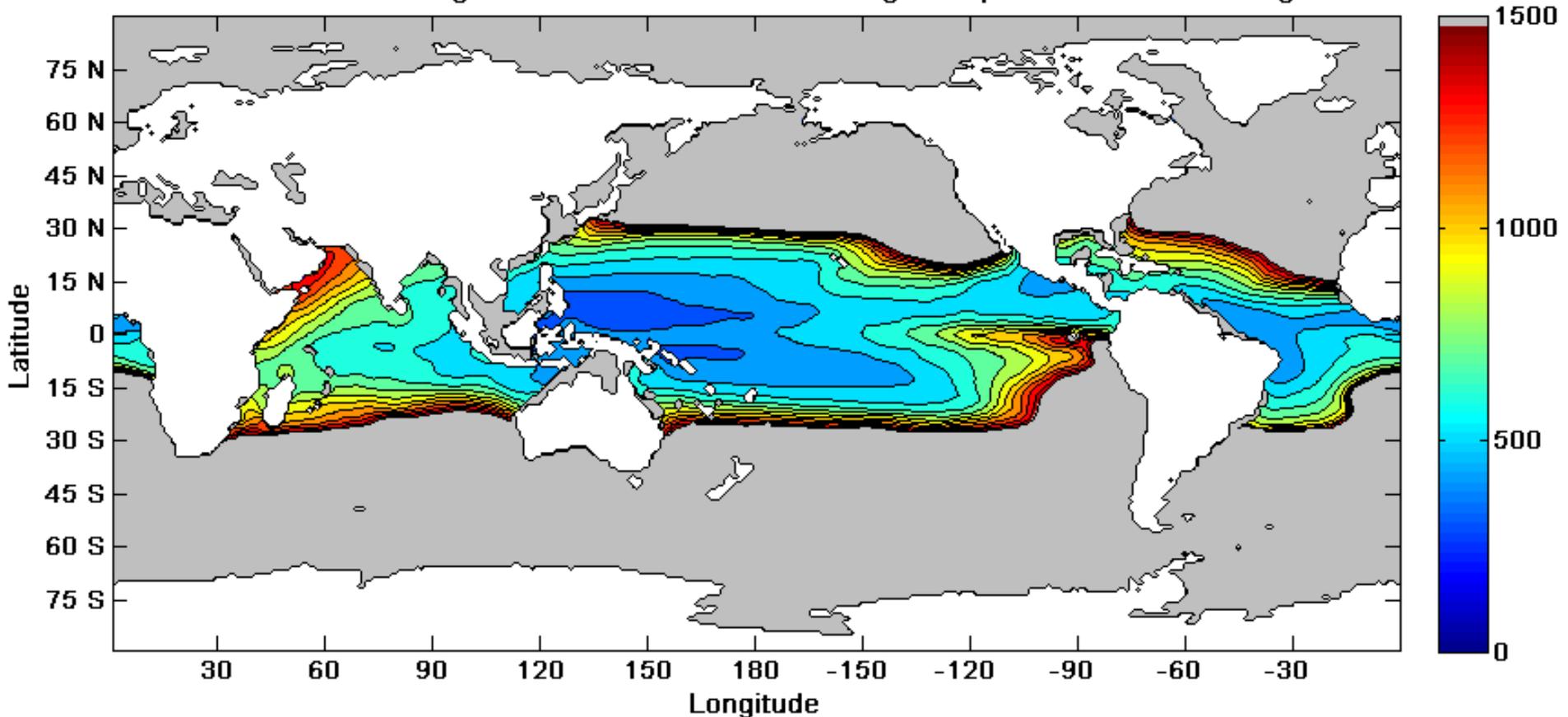
Avg. Temperature difference between surface and 1500m depth

World Ocean Atlas Annual Temperature Difference from 0.0m to 1500.0m



Min. Cold Pipe Length for $\Delta T = 20\text{C}$

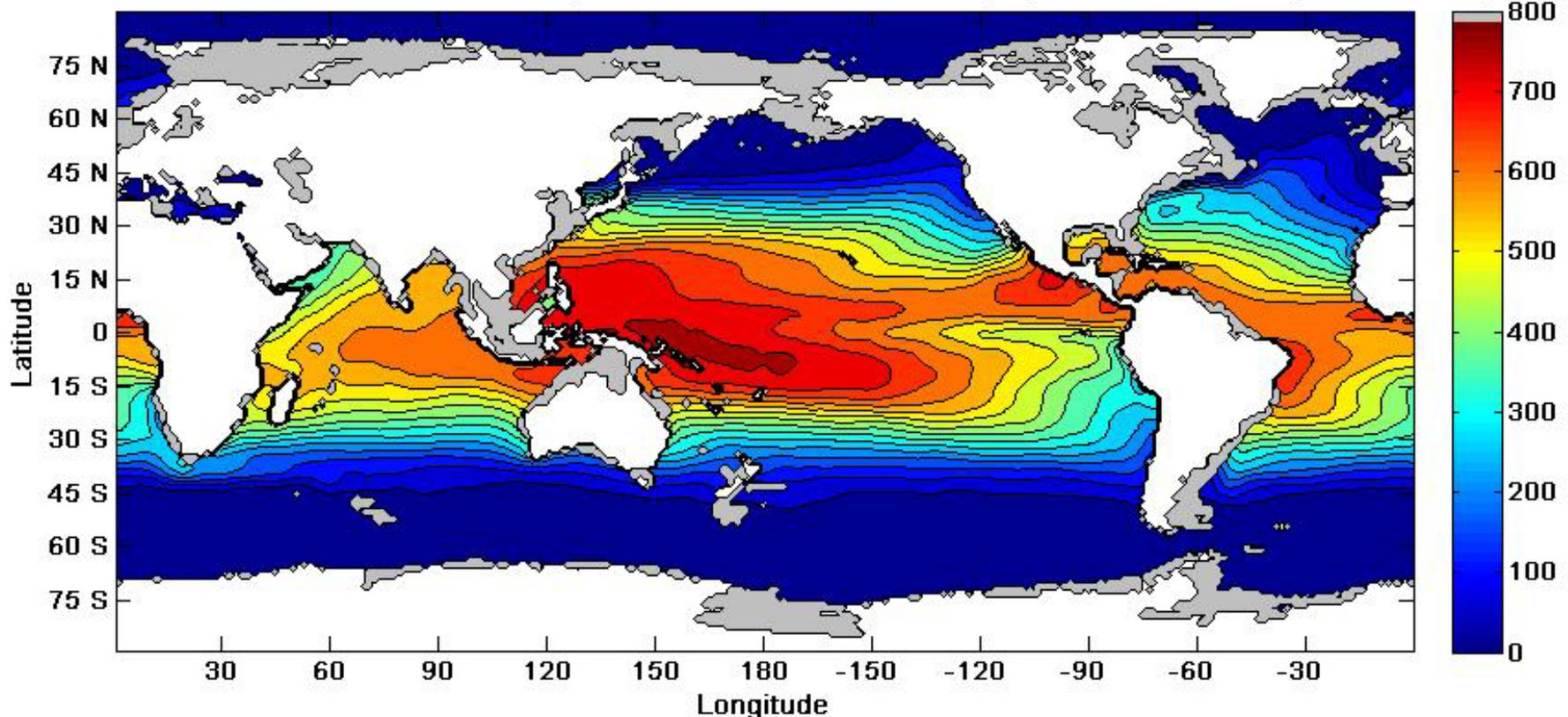
World Ocean Atlas Annual Length of the Shortest CWP Starting at Depth 0.0m and Reaching dT of 20.0 C



Avg. Power Density with 1000m pipe

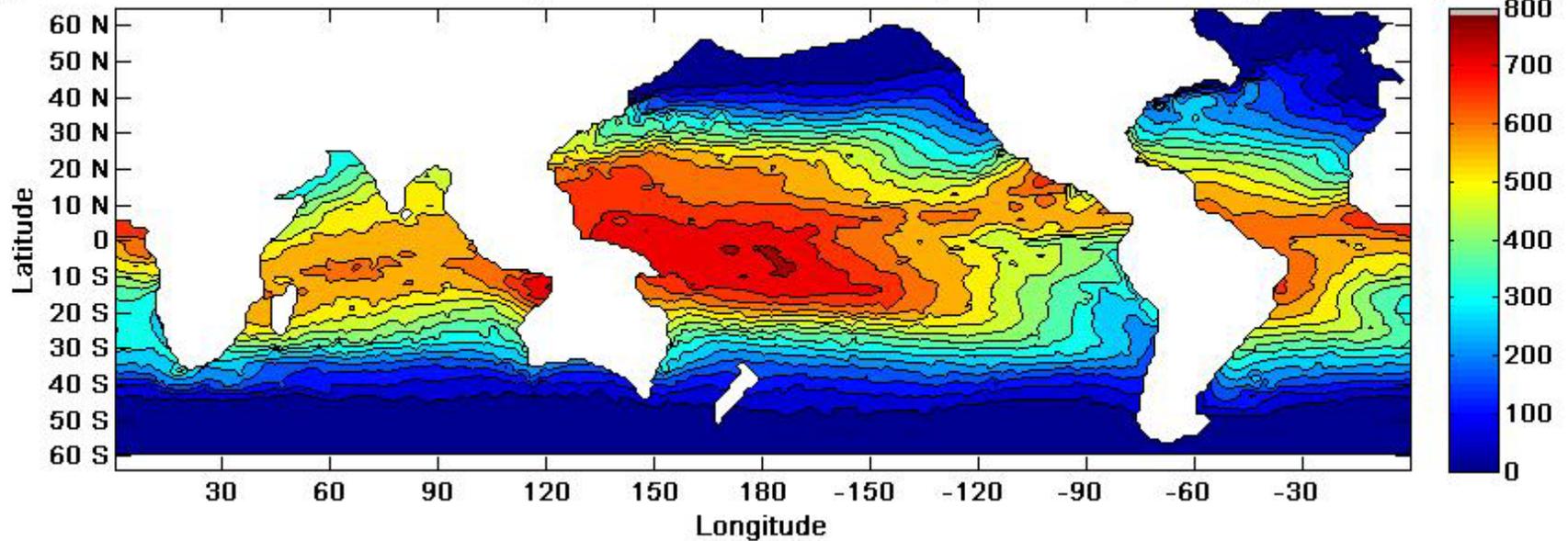
$$P_{\text{net}}/Q_{\text{cw}} = \rho C_p * TGE * (\Delta T)^2 (1-PL) / 8(273+T_1)$$

World Ocean Atlas Annual OTEC Power Density with 1000.0m Cold Water Pipe (TGE=0.90, PL=0.20) in kilowatts/(m³/sec)

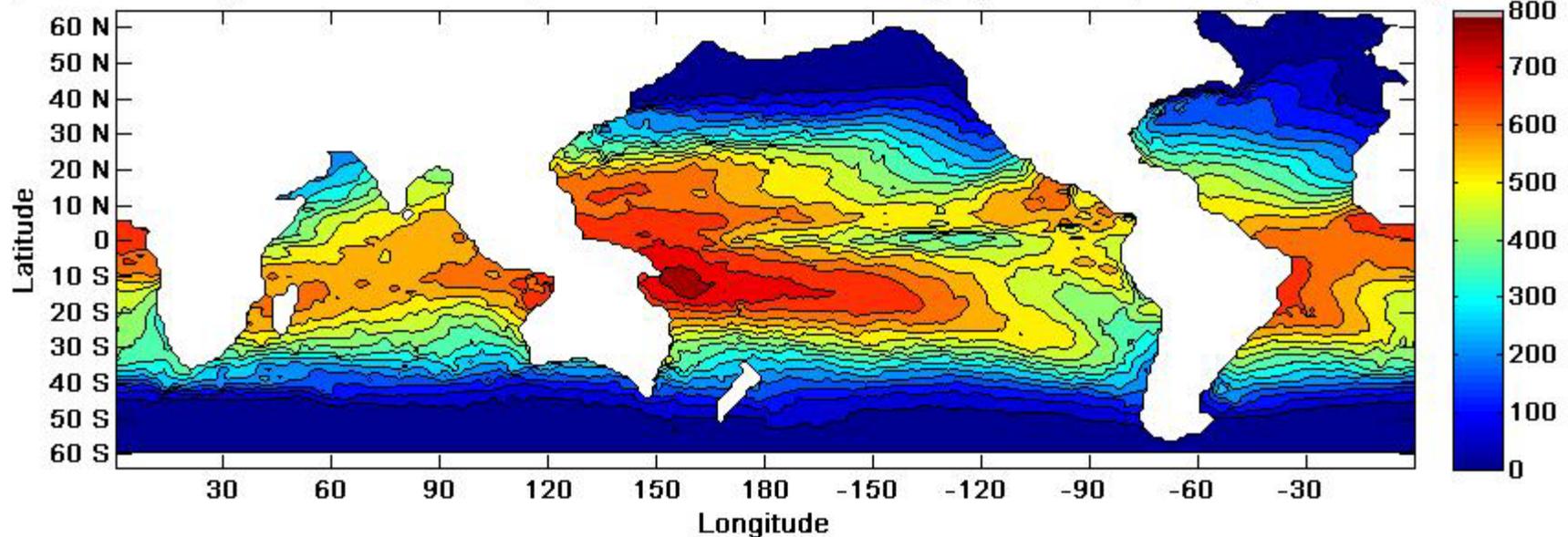


El Nino (top) vs La Nina (bottom)

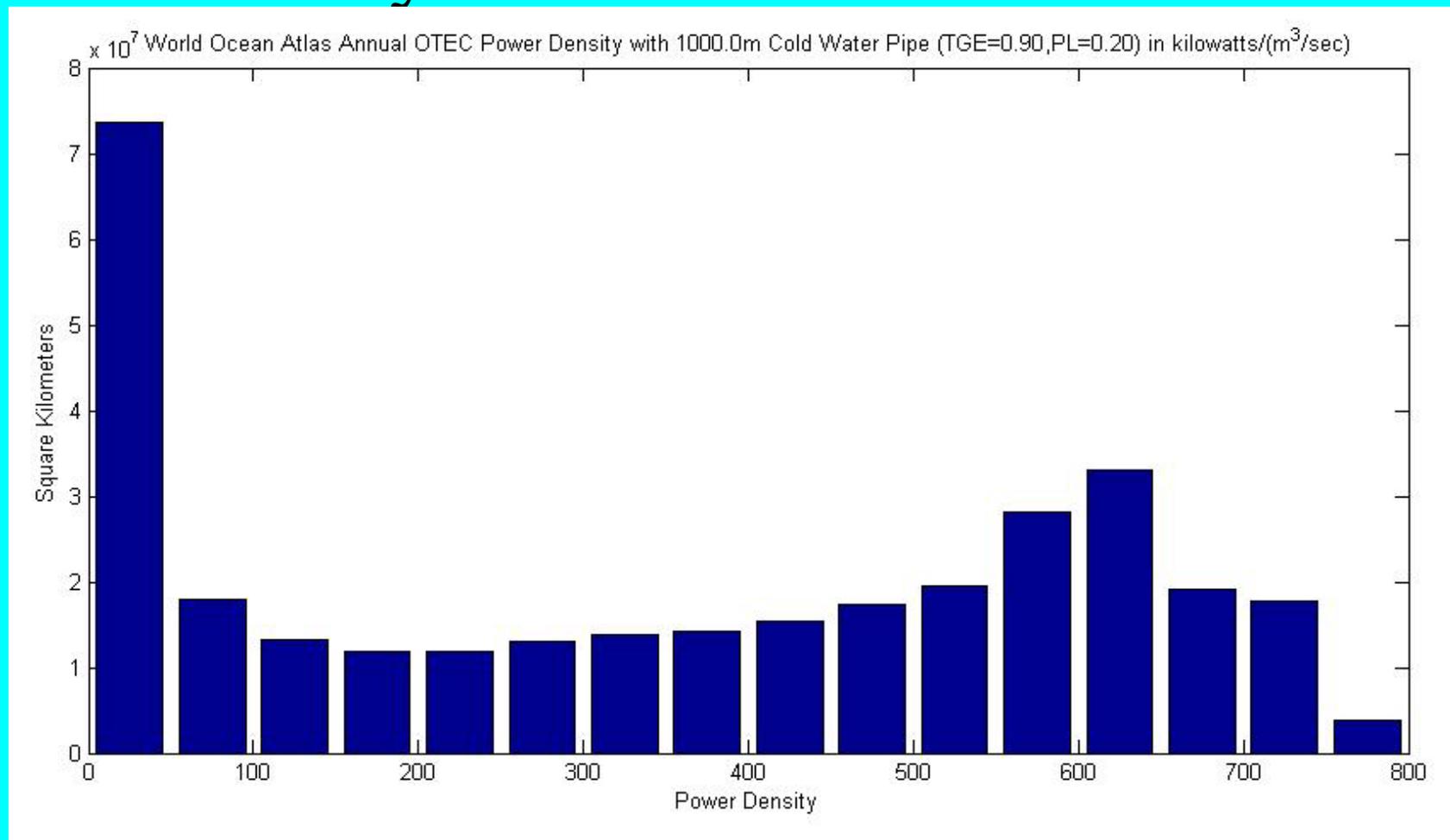
Argo2006-December OTEC Power Density with 1000.0m Cold Water Pipe (TGE=0.90,PL=0.25) in kilowatts/(m³/sec)



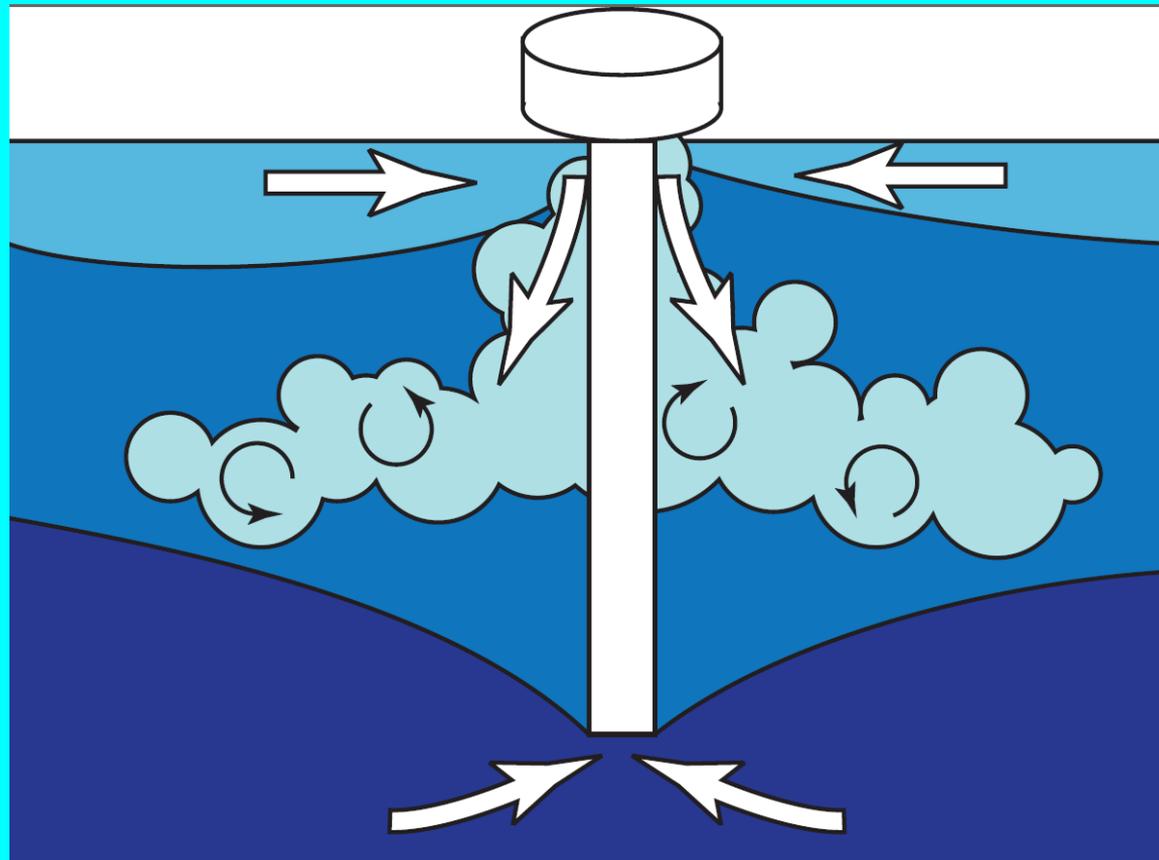
Argo2008-February OTEC Power Density with 1000.0m Cold Water Pipe (TGE=0.90,PL=0.25) in kilowatts/(m³/sec)



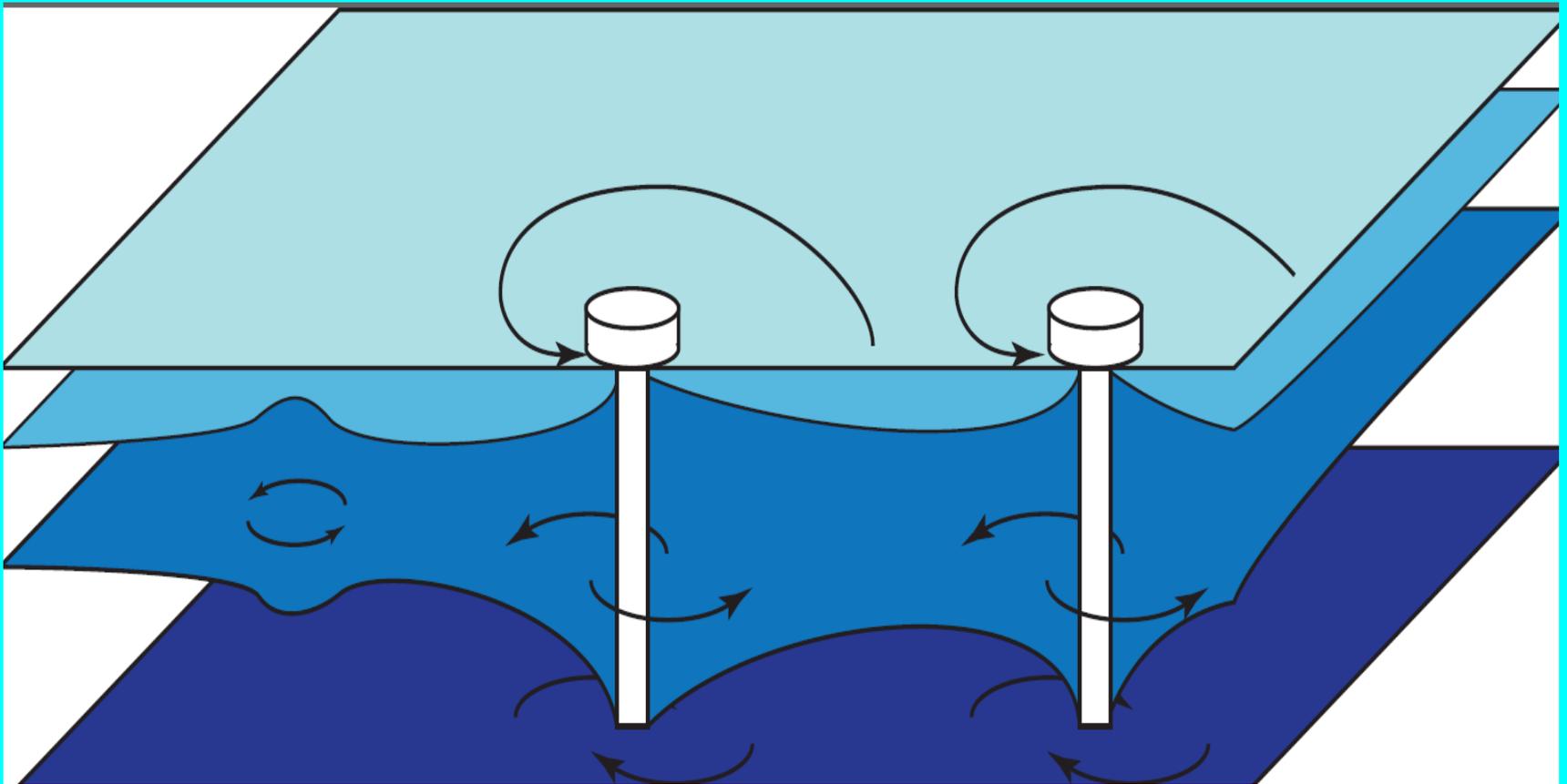
Program also gives power density distribution; here over 120 M km² have a yield above 500 kw/m³/s



How large can OTEC plants be before they adversely affect local stratification?

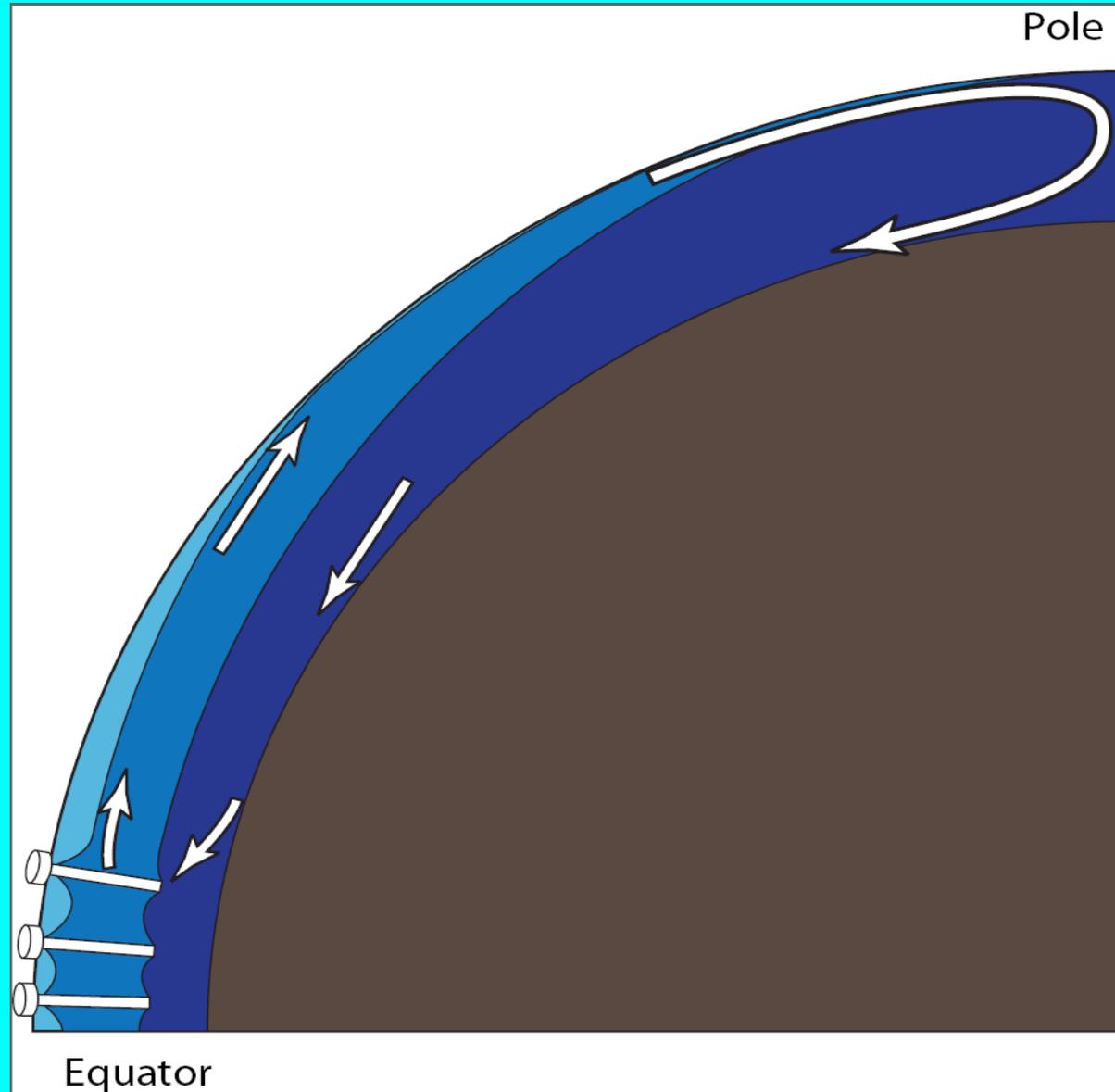


How closely can plants be spaced before they interfere with each other?



How many OTEC plants can the Earth support?

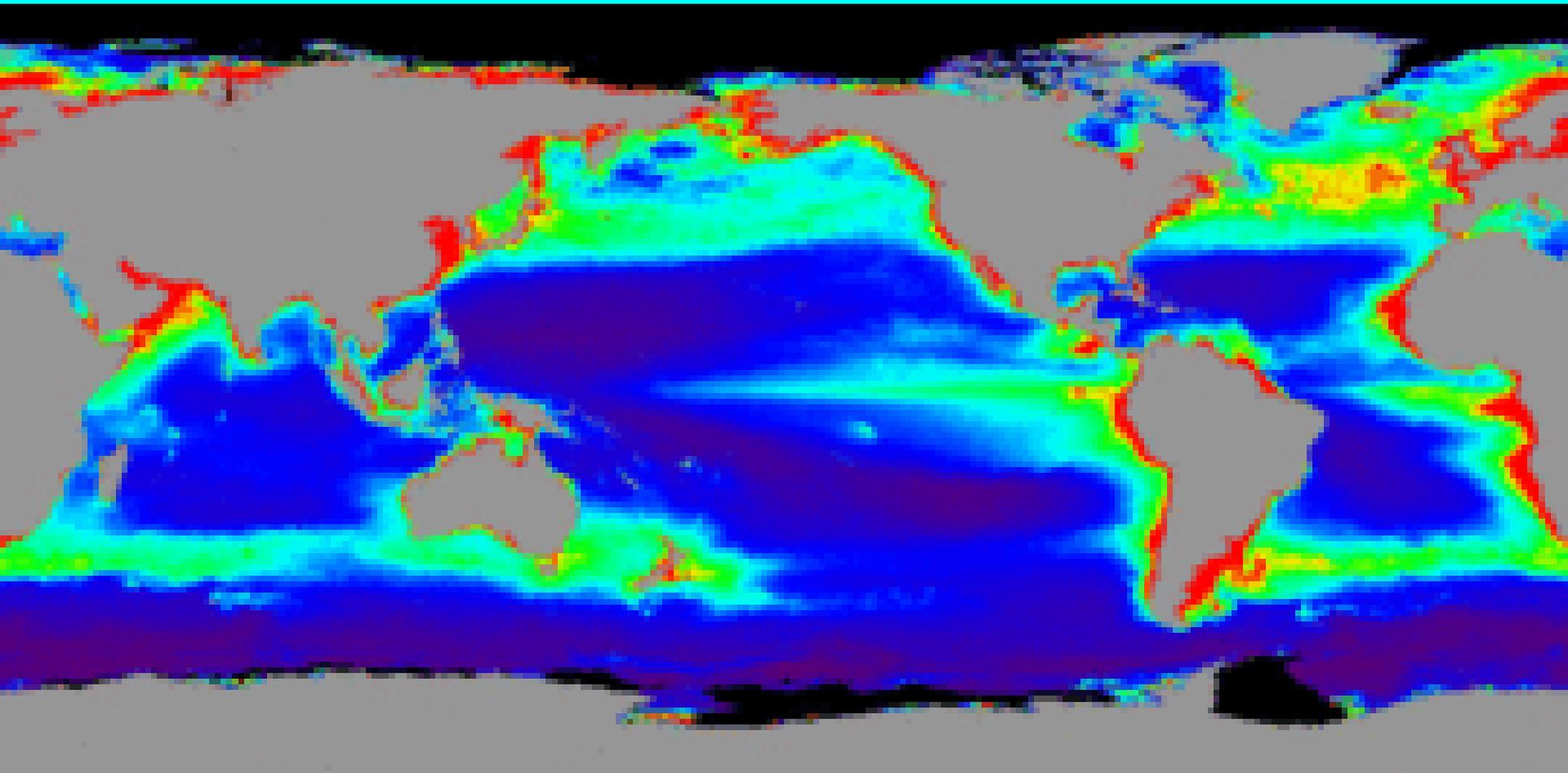
How will they affect the Thermohaline Circulation?

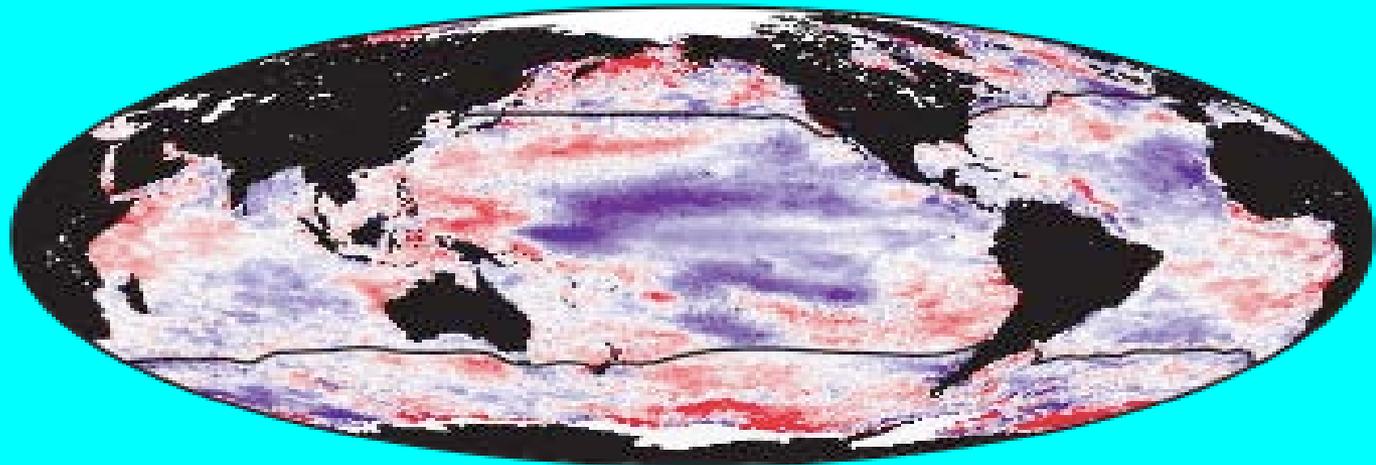
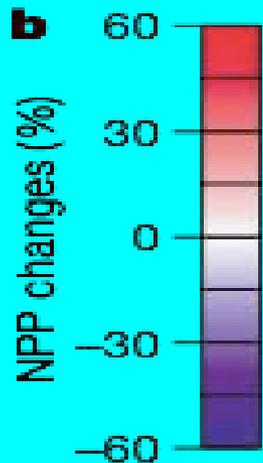
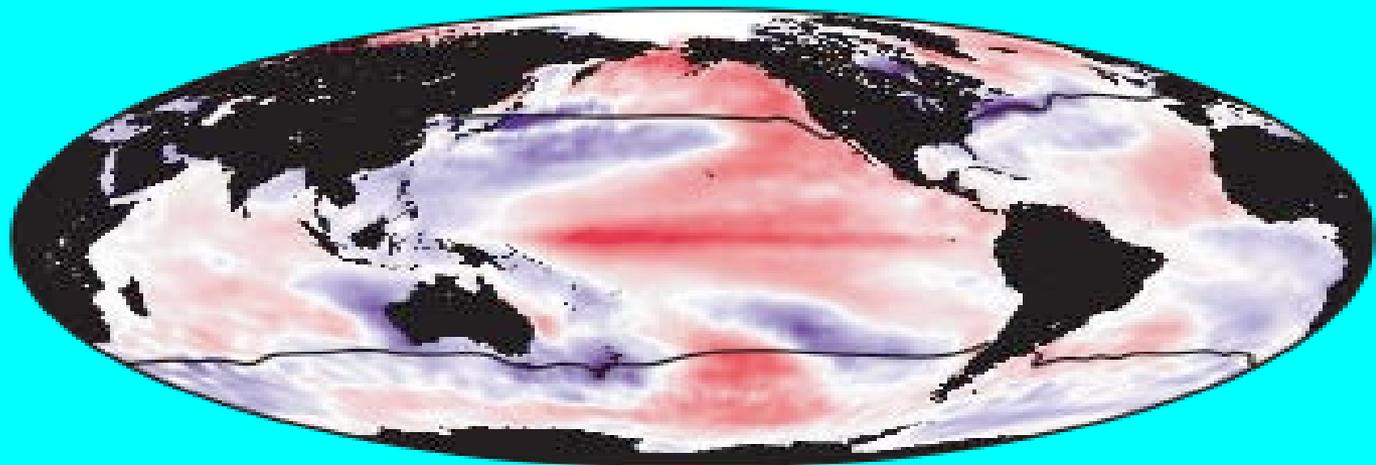
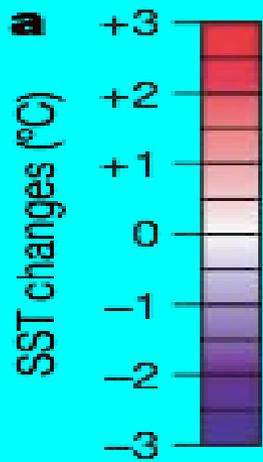


These are problems in Geophysical Fluid Dynamics

- If plant spacing is not limiting, how much energy could be extracted from the climate system?
- Taking $500\text{-}800\text{kW/m}^3/\text{s}$ as the rate of extraction, a precautionary limit may be taken to be a total pumping rate comparable to the thermohaline circulation $\sim 30 \times 10^6 \text{ m}^3/\text{s}$
- This gives 15-24 TW!
- ($\sim 100\text{MW}$ plant every 30 km...)

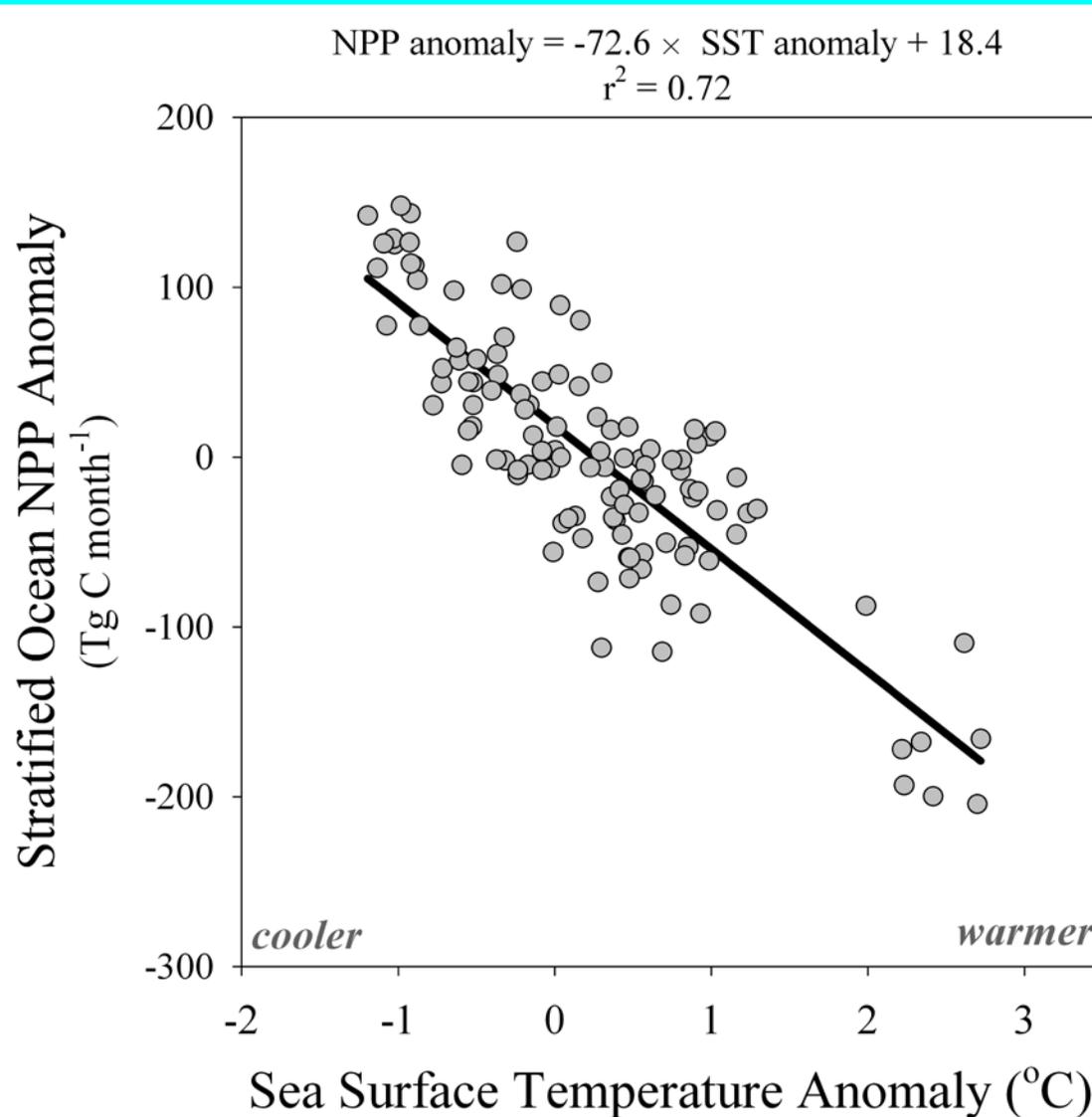
Ocean Primary Productivity: Cold waters are more productive





- Changes in average sea surface temperature **(a)** and Net Primary Productivity [NPP] **(b)** for a period of global ocean warming from 1999 to 2004. The black lines demarcate the region of permanently stratified oceans. Within this region, there is a strong negative correlation between regional variation in temperature and NPP, indicating that as the ocean continues to warm we can expect NPP to diminish. From Behrenfeld *et al.* 2006.

A warmer ocean is more stratified, has less mixing and is less productive



OTEC summary:

- **Large, zero-emissions energy source**
- **Potential for ocean fertilization to increase yield of protein from the sea**
- **Combat ocean acidification**
- **Lowering of surface temperature (hurricane abatement)**
- **Stabilize thermohaline circulation**
- **Slow sea level rise (contraction on mixing)**
- **Excellent potential in S. China Sea to substitute for Chinese coal**

Ocean Thermal Energy Conversion:

- **Has much to recommend it as a long term planetary solution to energy, food and climate/CO₂ problems.**
- **Lets get back to OTEC R&D!**

Thank you!

rschmitt@whoi.edu