**EDDIE Module: Paleoclimate and Ocean Biogeochemistry**

This student handout will guide you through the module step by step. Record your answers to the following questions in a separate document and be sure to include the (labeled!) graphs you create, either in-text or at the end of the document. You will need to complete this lab in a software program that allows you to calculate R-values and P-values. Excel and the Data Analysis Toolkit are recommended. Google Sheets is not recommended.

**Activity A: Productivity and Macronutrients**

Ocean productivity plays a critical role in modulating global climate because photosynthetic organisms living in the surface of the ocean 'fix' inorganic carbon dissolved in the water and bind it in organic compounds. When these organisms die and are aggregated by secondary consumers like zooplankton, they become more dense than the surrounding water and sink out of the surface ocean, exporting carbon into the deep ocean. If the amount of carbon that is removed from the surface ocean by biological productivity is greater than the amount of carbon released by oceanic upwelling, then carbon can be stored in the deep ocean and, other variables held constant, Earth’s climate will ultimately cool.

Nitrogen (N) and phosphorous (P) are critical macronutrients that support primary productivity – the production of organic carbon by phytoplankton - in the world oceans. The production of organic carbon can be limited by N and/or P because organisms require both.

Begin by examining the dissolved concentrations of N, as nitrate (NO3-), and P, as phosphate (PO43-), in the ocean using the maps provided to you. These maps have been created using a program called Ocean Data View, which aids in the spatial visualization of data that have been measured at thousands of points in the ocean by scientists on ships and autonomous floats. The chlorophyll data come from NASA’s Sea-viewing Wide Field-of-view Sensor (SeaWiFS), and the nutrient data (N and P) are from the 2013 World Ocean Atlas.

In answering the following questions, consider broad ocean regions (for example: “the North Pacific,” “gyres,” “western continental boundaries”) and recall what you have learned about the processes that deliver (e.g. rivers, wind, hydrothermal vents) and redistribute (currents, upwelling) nutrients.

*1.* *What is the range of NO3- concentrations (include units!) in the ocean?*

*2.* *What is the range of PO43- concentrations (include units!) in the ocean?*

*3.* *Where in the ocean (broadly) do NO3- concentrations appear highest, where are they lowest?*

*4.* *Where in the ocean (broadly) do PO43- concentrations appear highest, where are they lowest?*

Photosynthesizing organisms require both nitrate and phosphate, but not in equal quantities. Most marine photosynthesizers require 16 moles of nitrate for every one mole of phosphate. In other words the macronutrients are required in a ratio of 16:1 N:P, this is known as the Redfield ratio, named for its discoverer Alfred C. Redfield.

Examine the map of global surface ocean “N/P.” This map shows the molar ratio of nitrate to phosphate in the ocean. Using the names of broad ocean regions (as above) answer the following questions:

*5. Where in the ocean is there too little NO3- relative to PO43- to satisfy organisms’ macronutrient requirements?*

*6. Where in the ocean is there ‘the ideal’ ratio of NO3- relative to PO43-?*

Examine the map of "Surface Ocean Chlorophyll." Chlorophyll is a pigment that is produced by marine primary producers and thus can be used as an indicator of photosynthetic output, with higher chlorophyll concentrations indicating higher productivity and vice versa.

*7.* *Where in the ocean (broadly) is productivity highest, where is it lowest?*

*8.* *Where in the ocean do ‘ideal’ N/P ratios and high productivity seem to overlap?*

*9. Name and describe the large region of the global ocean where there appears to be a disconnect between the availability of macronutrients and the amount of productivity that is observed.*

**Activity B: Productivity and Micronutrients**

Phosphorous and nitrogen are critical macronutrients for phytoplankton in the ocean. Micronutrients are also nutrients that are important for primary productivity, but they are required in smaller amounts than the macronutrients. You can think of these micronutrients like the vitamins and minerals that are important for human health. You don't need a diet primarily composed of zinc or calcium, but for optimal health and growth, you need a little bit of these micronutrients (and others). One of the most important micronutrients in the ocean is iron (Fe), which is critical for respiration, photosynthesis, and the 'fixation' of atmospheric N2 gas into biologically-useful forms.

There are several important sources of Fe to the oceans, with the relative importance of these sources varying with location. Sources include riverine inputs, mid-ocean vent systems, and aeolian (wind-blown) dust. For open ocean locations, which are far away from mid-ocean ridges, aeolian dust is the largest source of Fe.

There are a few areas of the global ocean in which Fe limits productivity despite an abundance of available nitrate and phosphate. You identified one of these regions in your answer to Activity A, Question 9. Ocean regions like these, where nitrate and phosphate are abundant but productivity is not, are called high-nutrient low-chlorophyll (HNLC) regions. Some of these regions are the consequence of insufficient Fe, while others occur seasonally due to a lack of light (another important ingredient for photosynthesis).

Thus far, the maps you have examined show nutrient and productivity patterns at present. Continue your investigation of ocean nutrients by examining how the delivery of dust-borne iron to the ocean has changed through time, specifically on glacial-interglacial timescales at two locations. Download the data file for Activity B. The file contains one dataset from the equatorial Pacific – published by Loveley *et al*., 2017- and a second data set from the Southern Ocean – published by Martínez-Garcia *et al*., 2011. Familiarize yourself with the units of the variables. Check with a partner that you understand these units both in the numerator (up on top, above or to the left of the ‘/’) and in the denominator.

*1.* *What are the units of dust flux for each of the two data sets?*

*2.* *Why do you think the units used by these two authors are different?*

Graph the two dust time series using their original units. You should create a scatter plot (not a line plot) so that both axes are quantitative. Make sure to scale your axes appropriately to display the data and label your axes. You may choose to make two separate plots or to plot each dataset on its own x axis in its own plot. Only plot the most recent 500 ka of the Martínez-Garcia *et al*. data (from the Southern Ocean). To answer questions in Activity B, zoom in even further on the most recent 100 kyr. You will use the rest of the Martínez-Garcia record in Activity C so you should plot the most recent 500 kyr now even though you will not use the full plot for this part of the activity.

*3.* *Describe any 'unusual' values or excursions you observe in one or both records.*

*4. Ignoring the feature(s) you described in 4, what are the more representative maximum and minimum values for the two time series over the last 100 ka (4 numbers total)?*

Scale your plots (change the y-axis value(s)) so that you can see the temporal variability in both data sets. In other words, zoom-in on the y-axis so that the ‘unusual’ excursion(s) you described above do not hide the variability in your plot(s).

*5.* *When (broadly speaking) do higher and lower values occur in each of the two time series? Is the timing the same between the two time series?*

*6. What is the magnitude of variability in the dust flux time series at each of the two sites? Hint: Take the average maximum value divided by the average minimum value.*

*7.* *Propose a hypothesis as to why these data sets respond on this time scale of variability (the same timescale as glacial-interglacial cycles). Your answer should include a statement summarizing how dust/Fe enters the ocean and why that is different during glacial and interglacial periods. Hint: you may want to look back at the module slides to remind yourself of the timescale of glacial-interglacial cycles.*

Because dust-borne Fe is an important micronutrient that can promote organic carbon export we might expect to find a correlation between dust inputs (fluxes) and organic carbon export (productivity).

Graph the two productivity time series (on separate axes) for the most recent 100 kyr.

*8.* *What are the units for each of the two productivity time series? What type of proxy data do they each use?*

*9.* *Looking at the most recent 100 kyr of each data set, when do productivity minima and maxima occur? Is the temporal pattern the same between the two productivity time series?*

Equatorial Pacific Maxima (2):

Equatorial Pacific Minima (2):

Southern Ocean Maxima (2):

Southern Ocean Minima (3):

*10. Can you compare these productivity data sets to one another qualitatively? Can you compare them quantitatively? How do the data sets' units inform your answer?*

Create scatter plots of dust and productivity for each of the two sites over the most recent 100 ka (two separate plots). Add a trendline to each plot and calculate the R-value (correlation coefficient) that describes the relationship between the two variables. Be sure to consider which is the dependent and independent variable so that your x and y axes are correct. Note: this is not asking you to create another time-series plot, here you are comparing productivity and dust.

*11.* *What is the* *R-value for the linear best fit line relating* *dust and productivity for the equatorial Pacific site? Is this a strong relationship? What does the sign of this relationship tell you?*

*12.* *What is the R-value for the linear regression relating dust and* *productivity* *for the Southern Ocean site? Is this a strong relationship? What does the sign of this relationship tell you?*

*13. Calculate and interpret the P-values for each of these two correlations. Is either one statistically significant?*

*14. Propose a hypothesis that might explain the relationships you found. How would you test that hypothesis? What type of experiment(s) could help you gather data to assess this hypothesis?*

**Activity C: Productivity and Climate**

Thus far we have examined dust-driven iron fertilization at two sites in the global ocean: the equatorial Pacific and the Southern Ocean. Scientists have obtained a substantial body of data showing that glacial changes to the Southern Ocean were important in increasing the amount of carbon present in deep ocean bottom waters. Data show that deep waters formed in the Southern Ocean were more carbon-rich during glacial periods, reflecting both greater productivity in that region and lower upwelling of carbon-rich waters. In activity C, you will choose a data set to examine the consequences of this carbon 'sequestration' for climate and the deep ocean.

Before choosing a data set, refresh your memory (using the module slides or other resources) as to what each of the proxies represents (benthic oxygen isotopes (δ18O), authigenic uranium (aU), and Antarctic CO2).

*1. Write a hypothesis that you will test with your selected data set.*

Plot your chosen data set alongside (separate plot or separate y-axis) the Southern Ocean productivity data (full 500 ka time series). Adjust the range of the x-axes so that they are appropriate for your comparison data set (δ18O, aU, or *p*CO2). Note: If you choose the *p*CO2 data you will need to convert the time units from years to ka.

*2. What, roughly, is the average period of the data sets (time between one data maximum and the next)?*

*3. Examine the temporal relationship between your proxy and the Southern Ocean productivity data set. Are the data sets in phase or out of phase (maxima and minima at the same time)?*

*4. What do your previous two answers suggest about the relationship between the two data sets?*

*5. What do your plots suggest about your hypothesis from question 1? What additional information might you need or want to investigate further?*

Team up with partners who explored the other two data sets. Show your plots to your collaborators and explain your findings. 

*6. What are the temporal relationships between the four data sets (Southern Ocean carbon export, δ18O, aU, or pCO2)? Comment on leads or lags between the data sets, relative rates of change, timing of minima and maxima.*

*7. How could you examine the relationships between these data sets? What kinds of issues might you need to resolve first?*

*8. What do the relationships you observed suggest about the interrelated nature of these data sets? Are any related? Do any appear unrelated? How might you test any apparent relationships, especially to see if they are causal or simply correlative?*