DR. KARL:

WELL, THANK YOU, ROB, AND THANK YOU, DAVID, FOR THAT WONDERFUL PRESENTATION. SOME PEOPLE SAID LAST NIGHT, THIS IS GOING FROM THE RIDICULOUS TO THE SUBLIME.

I HOPE TO TELL YOU ABOUT SOME PLANS THAT SCIENTISTS HAVE BEEN DISCUSSING FOR IMPROVING THE EFFICIENCY OF THE OCEAN'S BIOLOGICAL CARBON PUMP AS A POSSIBLE MITIGATION STRATEGY. AND I'D LIKE TO KEEP THIS IN THE FRAMEWORK OF THE STABILIZATION WEDGES THAT ROB SOCOLOW SO NICELY PRESENTED EARLIER IN THE CONFERENCE. IN MY PRESENTATION, WE ARE GOING TO EXAMINE WHETHER OCEAN FERTILIZATION OR CHANGING THE EFFICIENCY WITH WHICH THE OCEAN CAN STORE CARBON IS ACTUALLY A FEASIBLE STABILIZATION WEDGE IN THE SOCOLOW/PACALA PARLANCE.

FIRST, I WOULD LIKE TO MENTION A SYMPOSIUM THAT TOOK PLACE JUST A MONTH AGO AT WOODS HOLE OCEANOGRAPHIC INSTITUTION, ORGANIZED BY KEN BUESSELER, SCOTT DONEY (WHO IS HERE THIS WEEK AT THIS MEETING), AND HAUKE KITE-POWELL.



THERE'S A WEB SITE THAT YOU CAN GO INTERROGATE. AND THERE'S AN "OCEANUS" ARTICLE THAT JUST CAME OUT, WRITTEN BY HUGH POWELL, WHICH SUMMARIZES THE SYMPOSIUM. SOME OF THE COMMENTS I'M GOING TO BE MAKING TODAY ARE TAKEN FROM THE CONTRIBUTIONS AT THIS SYMPOSIUM.

NOW, THIS WAS A DEBATE ON OCEAN FERTILIZATION, AND IT INCLUDED THE SCIENTIFIC, ECONOMIC, LEGAL, AND POLITICAL ISSUES THEREOF. AND OUR FINAL CONCLUSION OF THE SYMPOSIUM IS THAT WE ARE GOING TO BE MOVING AHEAD, IF WE MOVE AHEAD ON THIS AT ALL, WITH SOME UNCERTAINTY.

I WOULD LIKE TO ACKNOWLEDGE EVERYBODY WHO BROUGHT US HERE. THIS IS A WONDERFUL MEETING. I FEEL LIKE YOU ALL CAME TO MY HOME, BECAUSE AS ROB SAID, I'M THE HAWAIIAN, IF YOU WILL, EVEN IF I CAN'T DO THE HULA. BUT THIS IS THE GROUP THAT MADE IT HAPPEN, MELINDA AND HER TEAM, ALL THE PLANNING PERSONS AND COMMITTEE PERSONS. SO THANK YOU VERY MUCH.

AND THEN I HAVE A TEAM OF ADVISORS FOR THIS TALK, AND I'VE LISTED THEM HERE. THESE ARE PEOPLE THAT I'VE SHARED SOME OF THESE IDEAS AND THOUGHTS WITH, BUT I WILL BE RESPONSIBLE FOR ANYTHING



I SAY.

THIS IS AN OUTLINE OF MY PRESENTATION. I WOULD LIKE TO MENTION STATION ALOHA, WHICH ROB HAS ALREADY MENTIONED, AND SHOW YOU SOME OF THE DATA SETS, FROM THE MAUNA LOA

OF THE SEA; TALK ABOUT THE OCEAN'S BIOLOGICAL CARBON PUMP, WHAT IT IS, HOW IT WORKS, WHY WE'RE INTERESTED IN IT; TALK ABOUT OCEAN FERTILIZATION, SEVERAL DESIGNS THAT HAVE BEEN SUGGESTED; AND TALK A LITTLE BIT ABOUT THE EXPECTED AND ESPECIALLY THE UNEXPECTED CONSEQUENCES; AND IF TIME PERMITS, TALK ABOUT THE FUTURE.

THIS IS STATION ALOHA. IT'S AN ACRONYM FOR A LONG-TERM OLIGOTROPHIC HABITAT ASSESSMENT. THIS IS A STUDY THAT WE BEGAN IN OCTOBER OF 1988, WHERE WE GO TO SEA MONTHLY AND MAKE MEASUREMENTS OF SEVERAL BIOGEOCHEMICAL PARAMETERS, INCLUDING CARBON DIOXIDE.

THIS GRAPH SHOWS A DATA SET FROM STATION ALOHA, IN COMPARISON TO THE MAUNA LOA, THE DATA SET WE HAVE BEEN FOCUSING ON MOST OF THIS CONFERENCE. AND HERE'S THE OCEANIC ANALOGUE OF THAT. YOU CAN SEE WE, TOO, HAVE A SEASONAL CYCLE IN THE OCEAN THAT CAN BE RESOLVED BY THESE MONTHLY SAMPLES.

DURING THE FIRST



DECADE OF SAMPLING, THE OCEAN WAS ALWAYS UNDERSATURATED RELATIVE TO THE ATMOSPHERE, WHICH IMPLIED THAT THE OCEAN AROUND HAWAII WAS A NET SINK FOR CARBON DIOXIDE. AND THEN THERE WAS NEARLY A HALF OF DECADE WHERE THE DIFFERENCE IN PARTIAL PRESSURE OF CARBON DIOXIDE BECAME LESS, ROUGHLY NEUTRAL. UNDER THESE CONDITIONS NO EXCHANGE WILL OCCUR BETWEEN THE ATMOSPHERE AND THE OCEAN. NOW WE HAVE GONE INTO A SINK AGAIN.

WE DON'T REALLY UNDERSTAND THE DYNAMICS OF THIS, JUST LIKE WE DON'T UNDERSTAND ALL THE DYNAMICS OF THE ATMOSPHERIC SIGNAL.

HERE IS THE PH, SHOWING THE OCEAN IS BECOMING MORE AND MORE ACIDIC. SOME OF THESE DATA ARE CALCULATED FROM DIC AND ALKALINITY, AND SOME ARE DIRECT pH MEASUREMENTS, SO WE HAVE A VERY ROBUST DATA SET SHOWING THAT OCEAN ACIDIFICATION IS REAL.

I SHOULD MENTION THAT DAVE KEELING HAS A VERY STRONG CONNECTION WITH STATION ALOHA. IN FACT, HIS LAST SCIENTIFIC PAPER PUBLISHED LATE IN 2004 WAS ON THE SEASONAL AND LONG-TERM DYNAMICS OF THE UPPER OCEAN CARBON CYCLE AT STATION ALOHA NEAR HAWAII. SO HERE IS DAVE, AND THESE ARE SOME OF THE DATA FROM HIS FINAL PAPER; IN ADDITION TO THE WONDERFUL CONTRIBUTION HE MADE FOR THE ATMOSPHERIC DATA SET. AND HERE'S THE CITATION AT THE BOTTOM,



"GLOBAL BIOGEOCHEMICAL CYCLES."

SO WHAT IS THE OCEAN CARBON PUMP, THE BIOCARBON PUMP? HOW IS IT STRUCTURED, AND HOW DOES IT FUNCTION? WHAT DETERMINES ITS EFFICIENCY? AND HOW DOES IT RELATE TO OCEAN CARBON SEQUESTRATION?

AS MANY OF YOU KNOW, THE OCEAN'S CARBON PUMP HAS TWO FUNDAMENTAL COMPONENTS: ONE IS THE PHYSICAL PUMP, WHICH IS DETERMINED BY THE

THERMODYNAMICS AND BEHAVIOR OF CO2 IN THE ATMOSPHERE AND THE UPPER OCEAN. WHETHER THE OCEAN IS WARM OR COLD DETERMINES HOW MUCH CO2 CAN BE HELD BY THE WATER. THE OCEAN CIRCULATES, AS YOU KNOW, FROM THE POLES THROUGH THE ENTIRE OCEAN BASIN AND FROM THE ATLANTIC INTO THE PACIFIC. THIS COMBINATION OF OCEAN CIRCULATION AND THERMODYNAMICS DETERMINES THE EFFICIENCY OF THE PHYSICAL CARBON PUMP. I WON'T SAY MUCH MORE ABOUT THE PHYSICAL CARBON PUMP. DICK FEELY TALKED ABOUT IT IN SOME DETAIL YESTERDAY.

WHAT I WOULD LIKE TO FOCUS ON TODAY IS THE BIOLOGICAL CARBON PUMP; AND THE BIOLOGICAL CARBON PUMP HAS BOTH AN INORGANIC COMPONENT AND ORGANIC COMPONENT. THE BIOLOGICAL CARBON PUMP IS VERY IMPORTANT FOR SEQUESTERING CARBON DIOXIDE IN THE OCEAN. IN FACT, MODEL ESTIMATES FROM MARNANE AND SARMIENTO AT PRINCETON HAVE SHOWN THAT IF YOU COMPARE MODEL-BASED ESTIMATES OF BOTH THE PHYSICAL AND BIOLOGICAL CARBON PUMPS WITH



ACTUAL DATA (NOTE: THE GREEN LINE IS FROM THE GEOSECS DATA SET)

YOU CANNOT RECONSTRUCT THE VERTICAL PROFILES OF DISSOLVED INORGANIC CARBON UNLESS YOU INCLUDE A BIOLOGICAL PUMP IN THE MODEL. IN FACT, IT'S ALSO BEEN SHOWN THAT IF YOU TURNED OFF THE BIOLOGICAL PUMP, YOU WOULD ADD ABOUT 200 PARTS PER MILLION CO2 INTO THE ATMOSPHERE. SO THE BIOLOGICAL CARBON PUMP IS VERY IMPORTANT FOR CONTROLLING THE CARBON DIOXIDE IN THE ATMOSPHERE.

THIS SLIDE IS A CARTOON OF HOW THE BIOLOGICAL CARBON PUMP WORKS. IT RUNS ON NUTRIENTS AND SOLAR ENERGY. IT'S MANIFESTED THROUGH SMALL PHYTOPLANKTON, MICROSCOPIC PLANTS THAT LIVE IN THE OCEAN THAT ABSORB SOLAR ENERGY AND USE THAT TO DRIVE PHOTOSYNTHESIS. PHOTOSYNTHESIS IS A PROCESS WHEREBY CARBON DIOXIDE IS CONVERTED TO ORGANIC MATTER. SOME OF THAT ORGANIC MATTER IS USED TO FUEL HIGHER TROPHIC LEVELS, INCLUDING THE MAHIMAHI THAT WE HAD LAST NIGHT AT THE SAM CHOY BANQUET, AND SOME OF THE ORGANIC MATTER ACTUALLY WORKS ITS WAY OUT OF THE UPPER OCEAN INTO THE DEEPER PART OF THE WATER COLUMN. THE LATTER PORTION, TERMED THE EXPORT CARBON FLUX, IS A VERY IMPORTANT PART OF OCEANIC SEQUESTRATION PATTERN BECAUSE MOST OF THE CARBON DIOXIDE THAT'S FIXED BY THE PLANTS



IN THE UPPER OCEAN, ESPECIALLY IN SUBTROPICAL AND TROPICAL REGIONS LIKE HAWAII, MOST OF THE PRIMARY PRODUCTION IS JUST REMINERALIZED IN PLACE, BURNED BACK TO CARBON DIOXIDE. SO THERE'S A NEUTRAL EFFECT ON CO2 IN THE ATMOSPHERE.

A SMALLER PERCENTAGE (<10% OF THE TOTAL) LEAKS INTO THE DEEPER WATERS, WHERE IT IS THEN REMINERALIZED IN THE DEEP WATERS THAT HAVE A LONGER RESIDENCE TIME IN THE OCEAN, UP TO HUNDREDS OF YEARS OR EVEN UP TO 1,000 YEARS, AND THIS REALLY REPRESENTS THE LONG-TERM SINK OF CARBON DIOXIDE. SO THE NET EFFECT OF THE

BIOLOGICAL CARBON PUMP IS TO PUMP ORGANIC MATTER INTO THE DEEP WATERS WHERE IT IS SEQUESTERED FOR TIME SCALES LONGER THAN A CENTURY.

THERE ARE A LOT OF IMPORTANT CONSEQUENCES OF THE BIOLOGICAL PUMP AND MECHANICS OF THE BIOLOGICAL PUMP. THIS SLIDE JUST SHOWS TWO OF THEM, AND IT RELATES TO THE SIZE OF THE INITIAL PRIMARY PRODUCER. IN THE WATERS AROUND HAWAII, WE HAVE TWO DIFFERENT TYPES OF PHYTOPLANKTON, TWO DIFFERENT TYPES OF PRIMARY PRODUCERS: THE LARGE CELLS CALLED MACROPLANKTON SHOWN HERE AS DIATOMS AND THE VERY TINY CELLS WHICH ARE SUBMICRON IN SIZE WHICH ARE CALLED PICOPLANKTON. THE LATTER TEND TO DOMINATE THE POPULATION OF PLANTS AROUND HAWAII. MAYBE 90 PERCENT OF THE TOTAL BIOMASS



IS TIED UP IN VERY SMALL ORGANISMS.

BUT WHEN YOU FERTILIZE THE OCEAN, YOU SWITCH OVER TO LARGER ORGANISMS, AND THAT'S AN IMPORTANT PART OF OCEAN FERTILIZATION, OR AT LEAST CONCEPTUALLY IT IS AN IMPORTANT PART BECAUSE THESE LARGER CELLS FUEL SHORTER FOOD WEBS THAT SEQUESTER A GREATER PERCENTAGE OF CARBON INTO THE DEEP SEA. SHOWN AT THE BOTTOM OF THIS SLIDE IS THE EXPORT FLUX OR THE AMOUNT OF CARBON THAT ACTUALLY LEAVES THE EUPHOTIC ZONE. YOU SEE IN THIS DIAGRAM THAT THERE IS MORE CARBON COMING DOWN FROM LARGER CELLS BECAUSE PRIMARILY IT'S A SHORTER FOOD WEB AND IT HAS A HIGHER CARBON TRANSFER EFFICIENCY.

SO WHAT WE'D REALLY LIKE TO KNOW IS HOW THE BIOLOGICAL CARBON PUMP MANIFESTS ITSELF IN THE OCEAN AND HOW WE CAN USE THAT TO DETERMINE THE FLUXES OF CARBON DIOXIDE AT THE SEA/AIR INTERFACE. HOW DO WE GET FROM THE MARINE FOOD WEB, ACOMPLICATED MICROBIAL-BASED PROCESSING OF CARBON AND ENERGY, TO A GLOBAL ASSESSMENT OF CO2, AND PERHAPS EVEN THEN TO A MITIGATION POLICY. I WOULD LIKE TO SUGGEST, WITH GREAT DIFFICULTY.

SEVERAL STRATEGIES HAVE BEEN SUGGESTED AS POSSIBLE SEQUESTRATION OPTIONS. ONE IS THE FERTILIZATION OF HIGH NUTRIENT, LOW CHLOROPHYLL (HNLC) REGIONS OF THE



WORLD WITH IRON. IN THEORY, YOU COULD ALSO PUT IRON OR IRON AND PHOSPHORUS INTO LOW NUTRIENT, LOW CHLOROPHYLL (LNLC) REGIONS, FOR EXAMPLE REGIONS AROUND THE HAWAIIAN ISLANDS. YOU COULD ADD PHOSPHORUS TO PHOSPHORUS-STRESSED REGIONS, LIKE THE MEDITERRANEAN SEA, OR YOU COULD CREATE AN ARTIFICIAL UPWELLING IN THE OPEN OCEAN AND THEREBY BRING UP NUTRIENTS THAT WOULD STIMULATE THE BIOLOGICAL CARBON PUMP.

BECAUSE OF TIME LIMITATIONS, I'M ONLY GOING TO FOCUS ON THE TWO STRATEGIES IN RED. THE FIRST CASE STUDY WOULD BE OCEAN IRON FERTILIZATION, WHICH A LOT HAS BEEN WRITTEN ABOUT IT. THIS IS A VERY SITE-CRITICAL PROCESS. THESE HNLC REGIONS ARE THE TARGET. AND EXPORT OF ORGANIC MATTER INTO THE SUBEUPHOTIC ZONE AND THE DEEP SEA IS REALLY THE KEY TO ITS SUCCESS.

ALL OF THIS WORK STARTED WITH JOHN MARTIN'S HYPOTHESIS TWO DECADES AGO, AS SHOWN HERE FROM A NASA WEBSITE, THE EARTH OBSERVATORY, ON THE SHOULDERS OF GIANTS, THERE IS A BRIEF BIOGRAPHY OF JOHN MARTIN WHO WAS QUITE AN OUTSTANDING SCIENTIST AND INDIVIDUAL; I SPENT A LOT OF TIME AT SEA AND IN DISCUSSIONS WITH HIM WHEN HE WAS FIRST FORMULATING HIS IDEAS IN THE 1980S.

MARTIN HAS A FAMOUS QUOTE, "GIVE ME A TANKER FULL OF IRON, AND I WILL GIVE YOU AN ICE AGE."



THE SUGGESTION WAS THAT IF YOU FERTILIZE THE OCEAN WITH ENOUGH IRON IN THESE HNLC REGIONS YOU WILL SEQUESTER ENOUGH CARBON INTO THE DEEP SEA THAT IT WILL DRAW DOWN THE ATMOSPHERIC LEVELS PERHAPS TO THE GLACIAL PERIODS THAT RALPH CICERONE SHOWED US ON WEDNESDAY; APPROXIMATELY 180 OR 280 PPM.

SO MARTIN REALLY STARTED ALL THIS, AND HE DID EXPERIMENTS IN BOTTLES AT SEA.  THESE WERE VERY SIMPLE EXPERIMENTS IN THE NORTH PACIFIC OCEAN, A KEY HNLC REGION.  HE ADDED IRON TO SOME BOTTLES, AND HE LEFT SOME AS NEGATIVE CONTROLS. AND HE FOUND OUT THAT AFTER A COUPLE OF DAYS, THOSE BOTTLES WITH IRON ADDITIONS HAD A LOT MORE CHLOROPHYLL. AND THAT IS SHOWN HERE AS THE BOTTLES TURNING GREEN.  CHLOROPHYLL IS THE PLANT PIGMENT THAT ABSORBS SOLAR ENERGY IN THE PROCESS OF PHOTOSYNTHESIS.  SO FROM THESE SMALL BOTTLE EXPERIMENTS, HE PROJECTED THAT IF YOU WERE TO PUT A LOT OF IRON INTO THE OPEN OCEAN, THAT PERHAPS YOU WOULD GET A VERY LARGE RESPONSE THAT WOULD LEAD TO ENHANCED PHOTOSYNTHESIS AND EXPORT, HENCE ENHANCED CARBON SEQUESTRATION.

WE HAVE TO BE VERY CAREFUL IN ECOSYSTEM ECOLOGY, THOUGH, ABOUT SCALING.  DAVID SCHINDLER WROTE THIS WONDERFUL PAPER IN "ECOSYSTEMS" A COUPLE OF YEARS AGO ABOUT WHOLE ECOSYSTEM EXPERIMENTS, REPLICATION VERSUS REALISM.  AND HE POINTED OUT QUITE EMPHATICALLY IN THIS PAPER THAT BOTTLE EXPERIMENTS



JUST WON'T WORK IF YOU HOPE TO UNDERSTAND THE WAY THE REAL WORLD WORKS BECAUSE THERE ARE SCALING PROBLEMS THAT ARE SUFFICIENTLY LARGE THAT ONE CANNOT EXTRAPOLATE BOTTLE-SCALE EXPERIMENTS UP TO THE LEVEL OF AN ECOSYSTEM.  HE EFFECTIVELY SAID, ALL PROBLEMS PALE TO SCALE, BOTH IN TERMS OF TIME AND SPACE.

SO THIS LED TO A DECADE-LONG EFFORT OF CONDUCTING OPEN OCEAN FERTILIZATION EXPERIMENTS, EFFECTIVELY CONDUCTING THIS MARTIN BOTTLE EXPERIMENT ON A WHOLE ECOSYSTEM LEVEL.  THIS SLIDE IS TAKEN FROM A RECENT REVIEW PAPER BY BOYD, ET AL.  IT WAS PUBLISHED JUST THIS YEAR.  AND EVERY ONE OF THESE WHITE CROSSES ON THE MAP -- THERE SHOULD BE 11 OF THEM -- ARE MESOSCALE IRON FERTILIZATION EXPERIMENTS THAT HAVE ALREADY BEEN CONDUCTED TO EXAMINE THE BEHAVIOR AND THE CARBON CYCLE CONSEQUENCES OF ADDING IRON TO THESE HNLC REGIONS.  THE BACKGROUND FOR THIS SLIDE IS THE CONCENTRATION OF NITRATE IN THE SURFACE OCEAN, SHOWING VERY HIGH

NITRATE AROUND THE ANTARCTICA, HIGH NITRATE IN THE NORTHEAST AND NORTHWEST PACIFIC, AND HIGH NITRATE ALONG THE EQUATOR, THE LATTER A RESULT OF EQUATORIAL UPWELLING.

SO THESE ARE THE TARGETS FROM THESE MESOSCALE IRON FERTILIZATION EXPERIMENTS THAT HAVE

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BEEN CONDUCTED. THERE'S TWO IMPORTANT REVIEW ARTICLES THAT HAVE BEEN PUBLISHED, ONE IN "THE JOURNAL OF GEOPHYSICAL RESEARCH" IN 2005 BY DeBAAR, ET AL, AND ONE THAT I JUST MENTIONED BY BOYD, ET AL, IN "SCIENCE." THESE PAPERS SUMMARIZE ALL THE MECHANICS AND THE OUTCOMES OF THE OCEAN IRON FERTILIZATION EXPERIMENTS, WHICH I WILL SUMMARIZE VERY BRIEFLY HERE.

THE OBJECTIVE OF THESE EXPERIMENTS IS TO STIMULATE PRIMARY PRODUCTION AND THE PRODUCTION OF ORGANIC MATTER FROM CO2. IF YOU DRAW DOWN THE CO2 IN THE SURFACE OCEAN BY THIS PROCESS, YOU WILL GET INVASION OF CO2 FROM THE ATMOSPHERE. SO OVER TIME THIS WOULD BE A WAY OF MOVING CARBON DIOXIDE FROM THE ATMOSPHERE INTO THE DEEP SEA, WHERE IT IS THEN REMINERALIZED AND SEQUESTERED FOR PERIODS OF A HUNDRED TO A THOUSAND YEARS.

SO THE INTENDED CONSEQUENCES -- NOW, I EMPHASIZE "INTENDED CONSEQUENCES" -- THIS IS REALLY WHAT WE HOPE TO DO WITH THESE EXPERIMENTS -- IS TO INCREASE DEEP OCEAN CO2, NITRATE, AND PHOSPHATE. THE NET EFFECT OF A GLOBAL APPLICATION OF THESE WOULD BE TO INCREASE CO2 IN THE DEEPER WATERS. AND REMEMBER FROM DICK FEELY'S TALK, THAT THAT MEANS WE'RE

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INCREASING THE ACIDIFICATION OF THE DEEP SEA AND PERHAPS THESE DEEPSEA WATERS WILL COME TOWARD THE SURFACE AND PENETRATE OUR CONTINENTAL SHELVES RESULTING IN A RELEASE OF CO2 FROM THE DISSOLUTION OF CARBONATES.

ANOTHER INTENDED CONSEQUENCE IS TO DECREASE DEEP OCEAN OXYGEN. NOW, THAT IS NOT INTUITIVE, BUT I SHOULD SAY THAT WHEN ORGANIC MATTER SINKS TO THE DEEP SEA AND GETS DECOMPOSED, IT CONSUMES OXYGEN. SO WE ARE REALLY STRIPPING THE DEEP WATERS OF OXYGEN AS AN INTENDED CONSEQUENCE OF IRON FERTILIZATION. AND THEN, OF COURSE, WE WANT TO DECREASE THE SURFACE OCEAN OF ITS NUTRIENTS BECAUSE THAT'S THE WAY THAT THE CO2 WILL BE DRAWN DOWN. SO THESE ARE THE INTENDED ECOLOGICAL CONSEQUENCES.

THEN, OF COURSE, WE HAVE POSSIBLE SECONDARY EFFECTS, WHICH WE MIGHT CALL UNINTENDED CONSEQUENCES. THIS IS NOT WHAT WE EXPECT TO HAPPEN OR WHAT WE WANT TO HAPPEN. THINGS LIKE FORMING A VERY LARGE PHYTOPLANKTON BLOOM THAT WOULD BE REMINERALIZED RIGHT IN THE SURFACE OCEAN, FORMING AMMONIA, WHICH IS A REMINERALIZATION PRODUCT. SOME

OF THAT AMMONIA CAN BE NITRIFIED, WHICH IS A PROCESS WHEREBY BACTERIA OBTAIN THEIR METABOLIC ENERGY FROM

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THE OXIDATION OF AMMONIA, AND IN SO DOING, PRODUCE NITROUS OXIDE. THIS A PROCESS CALLED NITRIFICATION, AND IT'S RESPONSIBLE FOR MOST OF THE N2O THAT OCCURS IN THE SURFACE OCEAN AROUND THE WORLD. THIS N2O COULD THEN INVADE THE ATMOSPHERE AND NEGATE THE POSITIVE EFFECT OF REMOVING SOME OF THE CO2 SINCE N2O IS A VERY POTENT GREENHOUSE GAS, MORE POTENT THAN CO2 ON A MOLAR BASIS.

THERE ARE A LOT OF OTHER UNINTENDED CONSEQUENCES THAT WE HAVEN'T EVEN THOUGHT ABOUT AND MAYBE CAN'T EVEN THINK ABOUT UNTIL WE HAVE A MORE COMPREHENSIVE UNDERSTANDING OF THE ECOSYSTEM. REDFIELD IS ONE OF THE PIONEERS IN MARINE BIOLOGY AND MARINE BIOGEOCHEMISTRY, AND HE WROTE AN ARTICLE BACK IN '58, WHICH IS STILL VERY APPROPRIATE. THE TITLE WAS "THE INADEQUACY OF EXPERIMENTS IN MARINE BIOLOGY." AND HE WAS BEMOANING THE FACT THAT WE REALLY DO NEED TO DO ECOSYSTEM-LEVEL MANIPULATION EXPERIMENTS TO FULLY UNDERSTAND THE BEHAVIOR OF THE NATURAL ECOSYSTEMS ON OUR PLANET. HOWEVER, IN ORDER TO DESIGN THESE EXPERIMENTS CAREFULLY AND PROPERLY, WE NEED TO FULLY UNDERSTAND ALL THE COMPLEX INTERACTIONS THAT CAN AND WILL HAPPEN WHEN WE START TO MANIPULATE ECOSYSTEMS. SO THE POINT OF HIS PAPER WAS THE FACT THAT WE

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HAVE ALL THESE EXCITING EXPERIMENTS WE NEED TO DO, BUT WE CAN'T DO THEM YET BECAUSE WE DON'T HAVE A FULL INVENTORY OF BEHAVIOR OR OF PROCESSES IN THE OPEN OCEAN.

I WOULD LIKE TO SUGGEST THAT 50 YEARS LATER WE STILL DON'T. THIS PAPER IS STILL PRETTY RELEVANT.

THAT HASN'T STOPPED SCIENTISTS FROM GOING OUT AND CONDUCTING MESOSCALE EXPERIMENTS THAT I HAVE ALREADY MENTIONED. SO I WOULD LIKE TO SHOW YOU WHAT SOME OF THE RESULTS ARE.

THIS PHOTO FROM PHIL BOYD IS WHAT WE MIGHT CALL CHEMICAL-TANK MARINE CHEMISTRY. THESE ARE TANKS FILLED WITH ACIDIFIED IRON SULFATE, WHICH IS USED AS THE SEED FOR FERTILIZING THE OCEAN WITH IRON. THIS HAPPENS TO BE A NEW ZEALAND SHIP, AND THIS IS FROM ONE OF THE EXPERIMENTS THAT PHIL BOYD WAS RUNNING. IRON IS ADDED, ALONG WITH AN SF6 INERT GAS, IS A TRACER FOR DILUTION. RAY WEISS ALREADY TOLD US THAT THE SF6 ITSELF IS A GREENHOUSE GAS. THE AMOUNT OF SF6 ADDED IN THESE EXPERIMENTS ISN'T REALLY THAT LARGE. AND THESE ARE REALLY EXPERIMENTAL TREATMENTS. THIS ISN'T MEANT TO BE A MITIGATION STRATEGY. SO IF THIS WERE EVER TAKEN OUT TO A COMMERCIAL SCALE, THERE WOULD PROBABLY BE NO NEED TO PUT A TRACER IN BECAUSE WE WOULDN'T NECESSARILY BE INTERESTED IN WHAT REALLY

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HAPPENS OR HOW IT HAPPENS AS MUCH AS WHAT THE FINAL RESULT WOULD BE.

THIS SLIDE SHOWS A TIME COURSE FROM THE POINT AT WHICH IRON WAS ADDED WITH THE SF6; WHAT YOU SEE IN THIS CONTOUR PLOT IS THE AMOUNT OF SF6 PRESENT; AND YOU CAN SEE THAT OVER THIS 10-TO-15-DAY PERIOD, THE IRON ADDITION DIFFUSED DOWNWARD AND WAS DILUTED IN CONCENTRATION. THESE ARE CONCENTRATIONS OF SF6, AND THE CONCENTRATIONS OF IRON WEREN'T MEASURED, BUT PRESUMABLY THERE WOULD BE A LOSS OF IRON BY THE PROCESS OF PHOTOSYNTHESIS. THAT WAS THE WHOLE PURPOSE OF THE EXPERIMENT.

THIS FIGURE IS TAKEN FROM THE FRONT COVER OF "NATURE" MAGAZINE, WHERE BEHRENFELD PRESENTED A VERY NICE 3D IMAGE OF SHOWING THE EFFECT OF IRON ADDITION ON THE ENHANCEMENT OF PHOTOSYNTHESIS. THE BRIGHT RED SHOWS ENHANCED PHOTOSYNTHESIS RELATIVE TO THE SURROUNDING CONTROL AREAS.

ALL OF THE 11 MESOSCALE EXPERIMENTS THAT HAVE BEEN CONDUCTED TO DATE HAD THE SAME DESIGN, NAMELY, ADDING IRON TO THE SURFACE OCEAN, AND THESE ARE JUST IMAGES FROM SPACE OF THREE OF THESE EXPERIMENTS. THE GREEN IN ALL OF THESE SHOWS THE ENHANCED PHOTOSYNTHESIS, AS DETECTED BY EARTH-ORBITING SATELLITES, INTEGRATING THE AMOUNT OF CHLOROPHYLL

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THAT'S FOUND IN THE FIRST OPTICAL DEPTH, ROUGHLY 25 METERS OF THE WATER COLUMN. AND YOU CAN SEE THAT FROM A POINT ADDITION OF IRON, YOU END UP WITH AN IRREGULAR DISTRIBUTION BECAUSE THE OCEAN IS MOVING THE IRON AROUND. THIS IS AN UNCONTROLLED PROBLEM; THAT IRON DIFFUSES, IT GETS MOVED BY THE OCEAN CURRENTS. HERE IT GOT STRUNG OUT. AND ALL OF THESE FEATURES TURN OUT TO BE ABOUT SOMEWHERE BETWEEN 100 SQUARE KILOMETERS AND 1,000 SQUARE KILOMETERS. AND THESE ARE LARGE ENOUGH TO BE SEEN FROM SPACE.

THIS SLIDE SHOWS THE AMOUNT OF CHLOROPHYLL PRESENT IN EACH ONE OF THESE EXPERIMENTS. AND YOU CAN SEE THERE IS QUITE A BIT OF VARIATION FROM ONLY A COUPLE MICROGRAMS OF CHLOROPHYL PER METER OR MILLIGRAMS PER CUBIC METER, ALL THE WAY UP TO 18 IN AN EXPERIMENT CONDUCTED NORTH OF JAPAN IN THE NORTHWEST PACIFIC OCEAN.

IN SUMMARY OF THE OCEAN FERTILIZATION BY IRON EXPERIMENTS, WE'VE GOT A THUMBS UP AND A THUMBS DOWN. MARGARET LEINEN FROM CLIMOS, ONE OF THE LEADING COMMERCIAL VENTURES, SAYS “IRON FERTILIZATION IS NOT A SILVER BULLET, LET'S LOOK AT IT ON OUR PORTFOLIO FOR MITIGATION. UNCERTAINTY SHOULD NOT PRECLUDE FURTHER RESEARCH.”

LISA SPEAR

0711

FROM THE NATIONAL RESOURCES DEFENSE COUNCIL, "THERE IS A LIMITED AMOUNT OF MONEY AND TIME. THE WORST POSSIBLE THING WOULD BE TO INVEST IN SOMETHING THAT DOESN'T WORK AND HAS BIG IMPACTS."

IN SUMMARY OF IRON FERTILIZATION, IF YOU ADD IRON, YOU GET A BLOOM. THERE'S A LOT OF UNRESOLVED ISSUES, INCLUDING THE STOICHIOMETRY OF THE IRON ADDITION, HOW MUCH EXPORT, UNINTENDED CONSEQUENCES, AND THEN THE SCALING ISSUES THAT I MENTIONED PREVIOUSLY.

CASE STUDY TWO IS A FUNDAMENTALLY DIFFERENT PROCESS. IT'S ARTIFICIAL UPWELLING. AGAIN, IT IS VERY SITE-CRITICAL. AND IT IS CRITICAL BECAUSE THE STOICHIOMETRY OF THE WATER THAT YOU BRING UP WILL LARGELY DETERMINE THE END RESULT. IT IS DEPENDENT ON THE COMMUNITY SUCCESSION LINK, AND IT IS DEPENDENT ON THE STOICHIOMETRY OF THE WATER.

THIS PARTICULAR PROCESS GAINED SOME NOTORIETY JUST A COUPLE OF WEEKS AGO. THIS IS A PAPER FROM "NATURE" PUBLISHED A MONTH AGO BY SOME VERY DISTINGUISHED SCIENTISTS, INCLUDING JAMES LOVELOCK. "OCEAN PIPES COULD HELP THE EARTH TO CURE ITSELF." AND THIS WAS A CORRESPONDENCE IN "NATURE." "SIR, WE PROPOSE A WAY TO STIMULATE THE EARTH'S



CAPACITY TO CURE ITSELF AS AN EMERGENCY TREATMENT FOR THE PATHOLOGY OF GLOBAL WARMING."

WELL, IN THE NEXT ISSUE OF "NATURE" MAGAZINE, THERE WAS AN IMMEDIATE RETORT FROM THE SCIENTIFIC COMMUNITY: "WHAT ARE YOU SMOKING IN THOSE PIPES?" WAS BASICALLY THE WAY IT COULD BE CHARACTERIZED. PEOPLE WERE POINTING OUT THE VERY OBVIOUS FACT THAT WHEN YOU BRING UP DEEP SEA WATER, YOU ARE ALSO BRINGING UP CARBON DIOXIDE THAT HAS BEEN REGENERATED FROM THE EXPORT OF THE ORGANIC MATTER AND THE NUTRIENT REMINERALIZATION. SO THE CRITICAL ISSUE BECOMES THE CARBON TO NITROGEN TO PHOSPHORUS RATIO OF THE UPWELLED WATER IS. I SAY HERE, "NOTHING IS AS FUNDAMENTAL AS ELEMENTAL."

THIS IS AN EXAMPLE OF THE WAY THIS WOULD WORK. THIS IS A WAVE-DRIVEN PUMP, WHERE YOU WOULD TRANSFER NUTRIENTS BY A SEA ELEVATOR. YOU'D BRING NUTRIENTS UP FROM SOME TARGET DEPTH, LET'S SAY 250 OR 300 METERS, AND YOU BRING THEM UP TO A REFERENCE DEPTH OF YOUR CHOICE. IT COULD BE THE SURFACE, IT COULD BE RIGHT AT THE BASE OF THE MIXED LAYER. YOU WOULD THEN REMOVE CARBON BY THE BIOLOGICAL PUMP, IF YOU HAD THE CORRECT STOICHIOMETRY.

IT WOULD LEAD TO MICROBIAL



COMMUNITY SUCCESSION, AND IT WOULD PROBABLY DEPEND ON SOME LUCK AS WELL.

AT STATION ALOHA THAT I'VE ALREADY MENTIONED, THIS SHOWS A DISTRIBUTION WITH DEPTH OF THE CARBON TO PHOSPHORUS RATIO, TAKING AWAY THE SURFACE VALUES. THIS RATIO IS THE CONSEQUENCE OF PARTICLE EXPORT AND REMINERALIZATION.

YOU CAN SEE THAT THERE IS THIS BIG BULGE OF CARBON JUST BELOW THE EUPHOTIC ZONE. YOU WOULD NOT WANT TO BRING UP

WATER FROM THAT TARGET DEPTH BECAUSE YOU WOULD BE BRINGING UP AN EXCESS AMOUNT OF $CO_2$ RELATIVE TO THE AMOUNT OF PHOSPHORUS. HOWEVER, IF YOU BRING UP WATER FROM A DEPTH OF ABOUT 400 METERS OR 350 METERS, WHICH IS FEASIBLE, THAT WATER TENDS TO HAVE A NITROGEN TO PHOSPHORUS RATIO THAT IS SUITABLE FOR THE STIMULATION OF NITROGEN-FIXING ORGANISMS. IF YOU BRING UP THIS WATER WITH A REDFIELD RATIO OF LESS THAN 16 TO 1 FOR N TO P, YOU WOULD LEAD TO A REDFIELD BLOOM, WHERE YOU WOULD EXPORT ORGANIC MATTER AND LEAVE A LITTLE RESIDUAL DIC AND A LARGER PERCENTAGE OF RESIDUAL PHOSPHORUS.  THIS SITUATION WOULD THEN STIMULATE A NITROGEN-FIXING BLOOM, WHICH WILL THEN DRAW DOWN BOTH NITROGEN AND $CO_2$ FROM THE ATMOSPHERE AND EXPORT CARBON WITH A VERY HIGH C TO P RATIO.



AND WE KNOW THIS HAPPENS.  THIS IS AN IMAGE FROM NORTH OF THE HAWAIIAN ISLANDS, SHOWING THAT THESE BIG BLOOMS DO OCCUR.  WE CAN PLACE A SEDIMENT TRAP UNDER THOSE BLOOMS AND COLLECT THE MATERIAL AND SHOW THAT THESE ARE NITROGEN-FIXING ORGANISMS WITH THESE VERY HIGH C TO P RATIOS.

SO IN SUMMARY OF THE ARTIFICIAL UPWELLING, YOU HAVE DEEP WATER NUTRIENT LOADING OF THESE LOW NUTRIENT, LOW CHLOROPHYLL REGIONS.  YOU GET A BLOOM. THE PLANKTON COMMUNITY SUCCESSION WOULD LEAD TO A NITROGEN FIXATION EVENT, WHICH WOULD THEN -- IF THE N TO P RATIO IS LOWER THAN REDFIELD.  AND THAT WOULD BE THE NET SEQUESTRATION POTENTIAL.  I WOULD SUGGEST THAT THE TRAJECTORY AND EFFICIENCY OF THIS TYPE OF NUTRIENT PERTURBATION MIGHT BE MORE PREDICTABLE THAN WITH IRON.

SO WHERE DOES THIS LEAD US?  HERE'S A QUOTE FROM PRESIDENT JOHN F. KENNEDY:  "WE ARE JUST AT THE THRESHOLD OF OUR KNOWLEDGE OF THE OCEANS.  THIS KNOWLEDGE IS MORE THAN A CURIOSITY.  OUR VERY SURVIVAL MAY HINGE ON IT." AND I THINK YOU'D ALL AGREE WITH THAT.

HERE'S SOME GRAPHS TAKEN FROM THE IGBP GLOBAL CHANGE.  EVERYTHING'S CHANGING.  HERE'S THE $CO_2$ PLOT.  HERE'S EXTINCTIONS.  HERE'S THE AMOUNT OF NITROGEN THAT WE'RE FIXING AS A SOCIETY.  AND HERE'S HUMAN POPULATION.  I WOULD LIKE TO SUGGEST THAT THIS



IS ALL SCALING ON HUMAN POPULATION, WHICH I'VE HEARD VERY LITTLE ABOUT AT THIS CONFERENCE.

WE HAVE SCIENCE-SOCIETY CONNECTIONS AND CONCERNS.  EVERYTHING, AS RALPH CICERONE TOLD US ON WEDNESDAY, IS BASED ON SCIENCE, BUT IT'S NOT SUFFICIENT.  YOU NEED DISCUSSIONS WITH SOCIETY, THINGS LIKE CARBON CREDITS, STANDARD OF LIVING, COST OF LIVING, AND SO ON.

IN CONCLUSION, IS OCEAN FERTILIZATION A VIABLE STABILIZATION WEDGE OPTION?  I WOULD SUGGEST THAT THE SCIENTIFIC JURY IS STILL OUT ON THIS. ECOLOGY WILL ALWAYS TRUMP ECONOMICS AND POLICY.  BY

THAT, I MEAN NATURE WILL ALWAYS RULE.

ENVIRONMENTAL IMPACTS ARE NOT WELL CONSTRAINED OR NOT EVEN WELL PREDICTED OR UNDERSTOOD. AND WE HAVE THIS VERY LARGE IMPORT OF EXPORT. SO IF WE DO MOVE AHEAD, IT NEEDS TO BE WITH SOME UNCERTAINTY.

THERE IS A CODE OF ETHICS THAT HAS BEEN PUBLISHED IN "SCIENCE" MAGAZINE BY CLIMOS, ONE OF THE FOR-PROFIT COMPANIES TRYING TO UNDERSTAND THE PROCESS OF OCEAN IRON FERTILIZATION. THEY PUT OUT SOME OF THE BEST PRACTICES THAT THEY SEE, AND HERE IS THEIR WEBSITE.

I WOULD LIKE TO MENTION IN CLOSING THAT THE

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UNIVERSITY OF HAWAII HAS ITS OWN MANOA CLIMATE CHANGE COMMISSION, WHICH IS INTERESTED IN LOOKING AT THE GREENHOUSE FOOTPRINT OF OUR CAMPUS. THE STATE HAS A TASK FORCE, AND IT'S TOO BAD THAT NOBODY FROM THE STATE FOUND IT IMPORTANT ENOUGH TO ATTEND THIS WONDERFUL CONFERENCE.

SO I WILL LEAVE YOU WITH THIS LARGE PUZZLE, A VERY COMPLICATED PUZZLE WITH MANY PIECES, AND MANY PIECES NOT EVEN SHOWN HERE. THE ONLY THING I THINK WE CAN SAY WITH ANY CERTAINTY IS THAT PASTEUR SAID IT RIGHT, "IT IS THE MICROBES THAT WILL HAVE THE LAST WORD."

SO THANK YOU VERY MUCH.

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