DR. DONEY: SO, AS DICK SAID, I'M GOING TO TALK SOME MORE ABOUT THE CLIMATE FEEDBACKS AND CLIMATE RESPONSES CAUSED BY THE RISE OF ATMOSPHERIC CO2, BOTH THROUGH THE PHYSICAL CLIMATE SYSTEM AND THROUGH THE INCREASE OF THE CARBON DIOXIDE LEVELS IN THE ATMOSPHERE AND THEN THE UPTAKE WITHIN THE OCEAN.

SO NORMALLY WE CAN THINK ABOUT TWO DIFFERENT PATHWAYS OF FEEDBACKS:

ONE IS THE IMPACT OF CHANGING CLIMATE ON THE OCEAN CO2 SINK. THE OCEAN CO2 SINK ACTUALLY REMOVES A LARGE AMOUNT OF CO2 FROM THE ATMOSPHERE, AND SO IMPACTS THAT COULD MODIFY THAT SINK OR MODIFY THE EFFECTIVENESS OF THAT SINK OVER TIME PLAY AN IMPORTANT ROLE IN OUR DISCUSSIONS OF WHAT LEVELS OF CO2 EMISSIONS SHOULD BE ALLOWED IN ORDER TO CONTROL FURTHER CLIMATE.

BUT YOU CAN ALSO HAVE IMPACTS OF CHANGING CLIMATE AND CO2 DOWN THROUGH THE BIOLOGICAL SYSTEM, A RANGE OF IMPACTS ON WHAT ORGANISMS ARE THERE, HOW THEY ARE FUNCTIONING, HOW THEY'RE INTERACTING, HOW

THE DIFFERENT ORGANISMS SET UP INTO AN ECOSYSTEM, AND THEN WHAT EFFECT THAT CHANGES IN ECOSYSTEMS HAVE ON OTHER BIOGEOCHEMICAL CYCLES, NOT JUST OF CARBON, BUT OF NUTRIENTS AND TRACE ELEMENTS. THERE ARE A VARIETY OF OTHER TRACE GASSES PRODUCED BY THE OCEAN THAT COULD HAVE FEEDBACKS THROUGH THE CLIMATE SYSTEM, THINGS LIKE DIMETHYL SULFIDE, METHANE, NITROUS OXIDE. AND SO WE NEED TO LOOK AT THE WHOLE PICTURE, NOT JUST CO2, BUT EXPAND OUT INTO A LARGER BIOGEOCHEMICAL FRAMEWORK.

EQUALLY IMPORTANT, AND VICKI WILL TOUCH ON THIS A LITTLE BIT MORE, IS THAT CHANGES IN OCEAN CHEMISTRY AND OCEAN BIOLOGY CAN AFFECT MANY OF THE ECOSYSTEM SERVICES WHICH WE DEPEND ON, THINGS LIKE FISHERIES, CORAL REEF HEALTH, HEALTH OF THE NEAR-SHORE ENVIRONMENT.

I THINK ONE OF THE THINGS THAT HAS HAPPENED IN THE LAST SEVERAL YEARS IS THAT THERE HAS BEEN AN EMPHASIS, NOT JUST ON THE PHYSICAL CHANGES OF HUMANS ON THE LARGE-SCALE CLIMATE AND ITS PROPAGATIONS TO THIS SYSTEM, BUT ITS MORE DIRECT AND LOCAL IMPACTS, WHICH CAN IN THEIR AGGREGATE HAVE A LARGE-SCALE IMPACT ON REGIONAL AND GLOBAL SCALES. SO I WILL BRIEFLY MENTION DIFFERENT SUGGESTED MECHANISMS FOR OCEAN CARBON MITIGATION, WAYS OF INCREASING THE

OCEAN'S CO2 SINK. UNFORTUNATELY, ANY METHOD THAT IS GOING TO CHANGE THE OCEAN CO2 SINK WILL ALSO PROPAGATE THROUGH AND HAVE BIOGEOCHEMICAL EFFECTS AND ECOSYSTEM EFFECTS THAT CAN, IN TURN, IMPACT THINGS LIKE ECOSYSTEM SERVICES THAT WE DEPEND UPON. SIMILARLY, THERE IS GROWING EVIDENCE THAT OUR UTILIZATION OF THE OCEAN, ECOSYSTEM SERVICES, PARTICULARLY OVER FISHING BUT ALSO CHANGES IN HABITAT ALONG THE COASTAL OCEAN, ARE AT LEAST ON REGIONAL SCALES AND, PERHAPS, EVEN ON BASIN SCALES, ARE HAVING IMPORTANT IMPACTS ON

ECOSYSTEMS. AND THAT HUMAN INFLUENCE NEEDS TO BE INCLUDED IN OUR UNDERSTANDING OF THE ENTIRE SYSTEM.

SO I'LL START WITH LOOKING A LITTLE BIT AT THE OCEAN CO2 FEEDBACKS AND HOW THAT COULD AFFECT THE SINK OF CO2 WITHIN THE OCEAN.

SO THIS IS A RANGE OF MODEL PROJECTIONS FROM THE C4MIP PROJECT. THIS WAS AN INTERNATIONAL INTERCOMPARISON OF COUPLED CARBON CLIMATE MODELS, WHERE THEY ATTEMPTED TO ALL USE THE SAME BASIC SCENARIO FOR CO2 EMISSIONS AND THEN SAW HOW CO2 GOT PARTITIONED INTO THE ATMOSPHERE, THE OCEAN, AND THE LAND. ONE OF THE STRIKING THINGS IS THAT THE RANGE OF UNCERTAINTY -- SO WE'RE SOMEWHERE HERE AROUND 380, THE RANGE IN THESE PROJECTIONS TENDS TO EXPAND DRAMATICALLY AS YOU GET OUT TOWARD THE END OF THE

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CENTURY AS YOU'RE STARTING TO SHOVE CO2 INTO DIFFERENT RESERVOIRS WITHIN THE OCEAN. AND SO EVEN WITH THE WONDERFUL SURVEY DATA THAT DICK JUST SHOWED, WE STILL HAVE CONSIDERABLE UNCERTAINTY AT THE EFFECTIVENESS OF THE OCEAN SINK DUE TO OUR UNCERTAINTIES IN OCEAN CIRCULATION AND OCEAN TRANSPORT.

ON TOP OF THAT, AS YOU HAVE CHANGING CLIMATE, YOU HAVE A VARIETY OF MECHANISMS THAT WILL SLOW THE EFFECTIVENESS OF THE OCEAN CARBON SINK. THESE INCLUDE WARMING; WARM WATER WILL HOLD LESS CO2 THAN COLD WATER. YOU'RE GOING TO SLOW IN MANY PLACES THE CIRCULATION AS YOU WARM AND STRATIFY THE SURFACE OCEAN. THAT WILL REMOVE LESS CO2 FROM THE ATMOSPHERE. AND YOU'LL ALSO HAVE AN ALTERATION OF LARGE-SCALE CIRCULATION PATTERNS.

THIS IS JUST A MAP SHOWING THE DIFFERENCE BETWEEN A SIMULATION WITH AND WITHOUT THESE CLIMATE EFFECTS, WHERE YOU SEE LARGE REDUCTIONS IN THE UPTAKE OF ANTHROPOGENIC CO2 IN THE NORTH ATLANTIC, AND AROUND ANTARCTICA, WHERE YOU NORMALLY HAVE DEEP WATER FORM AS COLD, SALTY WATER THAT SINKS TO THE BOTTOM. THAT TENDS TO SLOW UNDER WARMER CONDITIONS AND REDUCE THE EFFECTIVENESS OF THE OCEAN TO REMOVE ATMOSPHERIC CO2.

HERE IS, AGAIN, FOR THE C4MIP MODELS A RANGE OF DIFFERENT CLIMATE SENSITIVITIES, ALTHOUGH A

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NUMBER OF THE MODELS SHOW RELATIVELY WEAK CLIMATE SENSITIVITY. THERE IS A RANGE WITH SOME SIMULATIONS SHOWING QUITE A BIT LARGER SENSITIVITY. AND ONE OF THE INTERESTING THINGS IS THAT THIS CLIMATE SENSITIVITY DOESN'T MAP WELL INTO THE UPTAKE EFFICIENCY UNDER FIXED CLIMATE. THEY'RE TWO SEPARATE PROCESSES. WE NEED TO UNDERSTAND BOTH WHAT THE CIRCULATION EFFECT IS ON THE EFFECTIVENESS OF THE CO2 UPTAKE AND WHAT THE CLIMATE SENSITIVITY IS OF THOSE SYSTEMS.

I WANTED TO GO INTO A LITTLE BIT MORE DETAIL. DICK WAS TALKING ABOUT EVIDENCE FOR REDUCTION IN THE OCEAN EFFECTIVENESS, THE SINK EFFECTIVENESS.

DICK MENTIONED CORINNE LE QUERE'S WORK, NIKI

GRUBER, AND RICH MATEAR HAVE ALSO COME UP WITH THESE RESULTS INDEPENDENTLY, AND IT HAS TO DO WITH CHANGES IN THE CIRCULATION OF THE SOUTHERN OCEAN. IN THE SOUTHERN OCEAN -- THIS IS ANTARCTICA -- YOU HAVE UPWELLING DRIVEN BY THE WESTERLY WINDS AROUND ANTARCTICA. YOU HAVE UPWELLING OF DEEP WATER THAT BRINGS OLD WATER THAT HAS HIGH-DISSOLVED INORGANIC CARBON LEVELS. THIS IS ESSENTIALLY THE REMNANTS OF BIOLOGICAL MATERIAL THAT'S RAINED DOWN INTO THE DEEPSEA. AS YOU INCREASE

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THAT UPWELLING DUE TO A STRENGTHENING OF THE WINDS, THAT TENDS TO VENT MORE OF THAT CARBON TO THE ATMOSPHERE. SO YOU GET A LARGE SOURCE OF CARBON TO THE ATMOSPHERE. AT THE SAME TIME, YOU'RE BRINGING UP WATER THAT HASN'T BEEN EXPOSED TO THE ANTHROPOGENIC CO2 SIGNATURE. THAT ACTUALLY INCREASES THE SINK OF CO2 OUT OF THE ATMOSPHERE. CURRENTLY, THIS NATURAL SOURCE TENDS TO DOMINATE OVER THE ANTHROPOGENIC SINK; AND IF YOU LOOK, THIS RED CURVE IS A MODEL ESTIMATE OF WHAT THE SINK OF CO2 SHOULD BE OVER TIME IN THE SOUTHERN OCEAN. THESE GRAY LINES ARE DIFFERENT ATMOSPHERIC INVERSIONS THAT ARE SUGGESTING THAT INSTEAD OF THE SINK CONTINUING TO GROW AS ATMOSPHERIC CO2 HAS GROWN, IT HAS TENDED TO FLATTEN OUT.

THIS IS ACTUALLY THE SAME CURVE. IT'S JUST SHIFTED DOWN, SHOWING WHAT WE PROJECT FOR THE OCEAN CO2 SINK, AND THIS IS NOW AN OCEAN MODEL THAT SHOWS SIMILAR RESULTS TO THE ATMOSPHERIC INVERSIONS. AND THERE'S A VARIETY OF DIFFERENT MODEL PROJECTIONS THAT SUGGEST THAT THIS STRENGTHENING OF THE WINDS, THIS STRENGTHENING OF THE UPWELLING SHOULD CONTINUE INTO THE FUTURE. IT IS LINKED TO BOTH CHANGES IN THE OZONE DISTRIBUTION AROUND ANTARCTICA AND ALSO, PERHAPS, DUE TO THE RISE IN ATMOSPHERIC CO2.

NOW, WHAT I HAVE SHOWN YOU UP TO NOW HAS

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BEEN FAIRLY SIMPLE BIOGEOCHEMICAL ESTIMATES OF WHAT'S GOING TO HAPPEN IN THE FUTURE. WHAT WE HAVEN'T FACTORED IN, IN GREAT DETAIL, ARE THE BIOLOGICAL RESPONSES; AND THE BIOLOGICAL RESPONSES ARE GOING TO VARY REGIONALLY. THERE'S A COUPLE OF DIFFERENT FACTORS I'LL TRY TO GO THROUGH.

IN THE SUBTROPICAL REGIONS, SUCH AS THE WATERS OFFSHORE OF HAWAII, THE WATERS IN THE SURFACE HAVE FAIRLY LOW NUTRIENTS, AND SO YOU HAVE A CONDITION WHERE PRODUCTIVITY IS LIMITED BY THE RATE AT WHICH NUTRIENTS ARE BEING MIXED UP FROM BELOW. AND SO UNDER A WARMING SITUATION WHERE YOU STRATIFY THE WATER COLUMN, YOU WOULD TEND TO REDUCE THAT FLUX OF NUTRIENTS INTO THE SURFACE LAYER, GET LESS BIOMASS AND LESS PRODUCTIVITY AT THE SURFACE. OR AT LEAST THAT'S THE FIRST PRINCIPAL ESTIMATE.

AT HIGH LATITUDES, YOU OFTEN HAVE LOTS OF NUTRIENTS UP AT THE SURFACE. WARMING ACTUALLY WILL REDUCE THE DEEP MIXING IN THOSE REGIONS AND EXPOSE THOSE PLANTS TO MORE LIGHT. AND MORE LIGHT WOULD

ACTUALLY DRIVE HIGHER PRODUCTIVITY. AND SO ONE EXPECTATION IS THAT IF YOU WERE TO LOOK AT PRODUCTIVITY AS A FUNCTION OF LATITUDE -- SO THIS WOULD BE THE NORTH POLE, SOUTH POLE -- YOU'D GET A REDUCTION IN PRODUCTIVITY IN THE TROPICS AND

SUBTROPICS AND AN INCREASE IN PRODUCTIVITY AT THE HIGH LATITUDES.

THERE ARE SOME SATELLITE STUDIES THAT SUGGEST THAT THIS KIND OF PATTERN WHERE YOU HAVE REDUCED PRODUCTIVITY, WHEN YOU HAVE INCREASED STRATIFICATION, MAY HAVE BEEN OBSERVED OVER THE LAST DECADE, ASSOCIATED WITH CHANGES IN ENSO PATTERNS IN THE SUBTROPICS.

NOW, THE CATCH TO THIS IS THIS ASSUMES A RELATIVELY SIMPLE ECOSYSTEM RESPONSE; AND AS DAVE KARL MAY TALK ABOUT IN HIS TALK, THAT IS NOT ALWAYS TRUE. THERE ARE ORGANISMS THAT CAN PRODUCE THEIR OWN NUTRIENTS, PARTICULARLY THE DIASOTROPHS OR NITROGEN-FIXERS; AND THERE'S A VARIETY OF DIFFERENT SUGGESTIONS THAT SAY THE TROPICS MIGHT ACTUALLY GO THE OPPOSITE DIRECTION, BECAUSE AS YOU STRATIFY THE TROPICS, YOU ACTUALLY MAKE IT MORE HABITABLE AND MORE PLEASANT FOR THE NITROGEN-FIXERS. THEY MAY BLOOM AND ACTUALLY ADD NUTRIENTS TO THE SYSTEM. RIGHT NOW, EVEN THE SIGN OF THE PRODUCTIVITY CHANGES IN DIFFERENT OCEAN REGIONS IS STILL UP FOR GRABS, I THINK, IN MANY WAYS.

EXPANDING A LITTLE BIT INTO THIS IDEA OF

MORE COMPLICATED BIOLOGY IS THE ARGUMENT OF ECOLOGICAL NICHES. RIGHT NOW ORGANISMS GROW IN DEFINED BIOGEOGRAPHICAL REGIMES, AND THEY DEPEND UPON VARIATIONS IN SEASONAL TEMPERATURE, THINGS LIKE SATURATION STATE, LIGHT LEVELS. WE'RE SHIFTING, AS WE WARM THE PLANET, WE'RE ACTUALLY SHIFTING THE BOUNDARIES OF MARINE ECOSYSTEMS. SO FOR TEMPERATURE YOU CAN THINK OF IT AS RIGHT NOW WE HAVE WARM TROPICS AND SUBTROPICS. WE'RE GOING TO MAKE THOSE WARMER. WE'RE ALSO GOING TO MAKE THE POLES WARMER. AND YOU WOULD EXPECT, IF AN ORGANISM WANTED TO STAY IN THE SAME TEMPERATURE HABITAT, THEY WOULD HAVE TO MOVE POLEWARD. AND THERE IS GOOD EVIDENCE PARTICULARLY FOR MANY FISH SPECIES OF A POLEWARD EXPANSION OF THEIR RANGES.

UNFORTUNATELY, OTHER FACTORS WOULD TEND TO FIGHT AGAINST THAT. SO, FOR EXAMPLE, DICK TALKED ABOUT SATURATION STATE FOR CALCIUM CARBONATE. SATURATION STATE IS CURRENTLY HIGH IN THE TROPICS AND LOW IN THE POLES. WE'RE DRIVING THE SATURATION STATE DOWN. THAT WOULD ACTUALLY CAUSE AN EQUATORWARD SHIFT IF AN ORGANISM WANTED TO STAY IN THE SAME TYPE OF HABITAT.

LIKELY WHAT WE'RE GOING TO FIND IS THAT WE'RE GOING TO SQUEEZE OCEAN ECOSYSTEMS. DIFFERENT

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ORGANISMS ARE GOING TO RESPOND IN DIFFERENT WAYS, AND WE'RE GOING TO DISRUPT THE FOOD WEB INTERACTIONS OF MANY OF THE DIFFERENT SPECIES, WHICH WILL HAVE IMPACTS ON PREDATOR-PREY INTERACTIONS, WHICH WILL PROPAGATE UP THROUGH THE ECOSYSTEM. IT IS UNLIKELY THAT IT WILL BE A SIMPLE SLIDING AROUND OF CURRENT BIOMES INTO NEW REGIONS; MORE LIKELY, IT WILL BE A DISRUPTION OF THOSE BIOMES, WHICH CAN HAVE BOTH POSITIVE AND NEGATIVE IMPACTS ON DIFFERENT SPECIES.

DICK ALSO MENTIONED OCEAN ACIDIFICATION, AND I WANTED TO FOLLOW UP ON THIS ISSUE. THIS IS A PLOT OF TIME SHOWING WHERE WE ARE FOR THE GLOBAL PH. THIS WAS THE PRE-INDUSTRIAL VALUE, ESTIMATED AT A LITTLE BIT BELOW 8.2. CURRENTLY, THE GLOBAL MEAN IS A LITTLE BIT BELOW 8.1. THIS IS THE SCATTER DUE TO THE SEASONAL CYCLE AND SPATIAL VARIATIONS. GLACIAL PERIODS WERE MORE ALKALINE. AND THE QUESTION IS HOW FAR DOWN THIS TRAJECTORY DO WE WANT TO GO WITH TIME?

THERE WAS A REPORT PUT TOGETHER BY A GROUP OF GERMAN SCIENTISTS WHO ARGUED THAT WE SHOULD SET UP A GUARDRAIL FOR HOW LOW WE WANT OCEAN PH TO GO BASED ON LIMITING THE IMPACTS ON CALCIFYING ORGANISMS. THEY PUT THE GUARDRAIL AT .2 PH BELOW THE PRE-INDUSTRIAL LEVEL. THE ARGUMENT FOR THE MAGNITUDE OF THAT WAS BASED PRIMARILY ON THE SIZE OF THE

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VARIATIONS SEEN BETWEEN THE GLACIAL PERIOD AND THE PRESENT AND ALSO THE NATURAL SPATIAL AND TEMPORAL RANGE.

IT IS NOT CLEAR WHETHER THIS IS AN APPROPRIATE THRESHOLD, BUT IT CERTAINLY PUTS A TANTALIZING GOAL OF ONE OF THE THINGS THAT THE SCIENTIFIC COMMUNITY NEEDS TO ADDRESS: IS THERE A NONLINEARITY IN THAT THRESHOLD? AT WHAT POINT DOES REDUCED PH HAVE SUCH A STRONG IMPACT ON CALCIFYING ORGANISMS?

AS AN INTRIGUING HISTORICAL NOTE, IN THE '70S, THE EPA ACTUALLY PUT A WATER QUALITY CRITERIA FOR OPEN OCEAN WATERS; THAT THE OPEN OCEAN WATERS SHOULDN'T BE REDUCED MORE THAN 0.2 PH. THAT IS ACTUALLY WITHIN THE U.S. REGULATIONS. AS DICK MENTIONED, THAT REQUIRES A REDUCTION, KEEPING ATMOSPHERIC CO_2 BELOW 500 PPM.

WE TEND TO FOCUS ON ONE PROBLEM AT A TIME, EITHER THE OCEAN ACIDIFICATION PROBLEM OR THE CLIMATE PROBLEM. PARTICULARLY FOR MANY OF OUR MARINE ECOSYSTEMS IN THE COASTAL ENVIRONMENT, THEY ARE VULNERABLE TO A WIDE VARIETY OF IMPACTS. ONE OF THE CONCERNS IS THAT THESE IMPACTS WILL BE NONLINEAR AND INTERACTIVE IN THAT A TEMPERATURE RISE AND AN ACIDIFICATION RISE, TOGETHER,

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WILL HAVE MUCH WORSE IMPACTS THAN EITHER OF THOSE INDEPENDENTLY. AND ONE OF THE THINGS THAT DICK AND I HAVE BEEN LOOKING AT IS THE FACT THAT THERE ARE OTHER FACTORS THAT CAN DRIVE ACIDIFICATION OF THE COASTAL

OCEAN, IN PARTICULAR, ACID RAIN DEPOSITION.

THIS IS A MAP SHOWING WHERE ANTHROPOGENIC CO2 IS GOING INTO THE OCEAN, AND THEN THESE ARE MAPS SHOWING WHERE WE'RE DEPOSITING SULFATE OR SULFUR AND NITROGEN SPECIES DUE TO FOSSIL FUEL COMBUSTION AND ADGRICULTURE. THEY TEND TO BE HIGH IN REGIONS DOWNWIND OF THE HIGHEST INDUSTRIALIZATION REGIONS OFF NORTH AMERICA, SOUTH AND EAST ASIA, AND ALSO AROUND WESTERN EUROPE.

AND AT LEAST WITHIN A LOT OF THESE COASTAL REGIMES, THE EFFECTS OF ACIDIFICATION FROM ACID RAIN COULD BE COMPARABLE TO THAT OF OCEAN ACIDIFICATION AND IN ADDITION TO OCEAN ACIDIFICATION.

SO WE CAN'T JUST THINK ABOUT, WE CAN'T JUST FOCUS ON THE GLOBAL PROBLEM; WE ALSO NEED TO LOOK AT A WIDE VARIETY OF REGIONAL ISSUES. THESE COASTAL WATERS ARE ALSO THE REGIONS WHERE WE'RE HAVING THE STRONGEST IMPACT DUE TO OVER FISHING, WHERE WE HAVE NUTRIENT EUTROPHICATION DUE DO AGRICULTURAL RUNOFF. WE NEED TO LOOK AT THESE AS INTEGRATED ECOSYSTEMS, NOT AS INDIVIDUAL RESPONSES.

LASTLY, I WANTED TO TOUCH ON ISSUES OF

MITIGATION. THERE HAVE BEEN TWO PRIMARY TOPICS DISCUSSED FOR OCEAN CARBON MITIGATION OVER THE LAST SEVERAL YEARS. THERE ARE ALSO A WHOLE HOST OF NEW TOPICS THAT HAVE ONLY COME OUT, RECENTLY, I WOULD SAY, WITHIN THE LAST FEW WEEKS TO MONTHS, WHICH WE CAN TALK ABOUT DURING THE PANEL. BUT I WANTED TO TALK ABOUT THE TWO THAT HAVE GOTTEN MORE AIR PLAY, AND THOSE ARE DIRECT CO2 INJECTION AND DELIBERATE IRON FERTILIZATION.

THE IDEA OF DIRECT CO2 INJECTION IS VERY SIMILAR TO THE GEOLOGICAL SEQUESTRATION THAT WAS DISCUSSED YESTERDAY; BUT RATHER THAN PUMPING IT INTO A SUBSURFACE GEOLOGICAL RESERVOIR, IT IS SIMPLY TO PUT THE CO2 INTO THE DEEP OCEAN, WHERE IT WOULD RESIDE THERE FOR LONG PERIODS OF TIME, THE TIME SCALE ASSOCIATED WITH OCEAN CIRCULATION. I'M NOT ADVOCATING EITHER OF THESE, BUT THE RATIONALE FOR THIS IS THAT IF THE CO2 WERE LEFT IN THE ATMOSPHERE, THE EVENTUAL SINK WOULD BE THE OCEAN ON TIME SCALES OF HUNDREDS TO THOUSANDS OF YEARS, AND ALL YOU WOULD BE DOING IS ACCELERATING THAT. THIS COULD BE DONE EITHER THROUGH INJECTING CO2 GAS OR LIQUID CO2. A POTENTIAL ADVANTAGE OF LIQUID CO2 IS THAT LIQUID CO2 MIGHT FORM LAKES WHERE YOU WOULD GET A CRUST OF CO2 HYDRATE THAT WOULD LIMIT THE DIFFUSION.

THE TIME SCALE DEPENDS VERY MUCH ON WHERE YOU INJECT IT AND HOW DEEP YOU INJECT IT. THE DEEPER YOU INJECT IT IN THE WATER COLUMN, THE LONGER THE TIME THE CO2 WOULD STAY SEQUESTERED, UP TO DECADES FOR THERMOCLINE WATERS TO HUNDREDS OF YEARS IF YOU GET IT INTO THE INTERMEDIATE AND DEEP WATERS. OF COURSE, DEEPER INJECTION REQUIRES HIGH PRESSURIZATION, AND THERE ARE ECONOMIC AND TECHNOLOGICAL TRADE-OFFS.

FROM A BIOLOGICAL POINT OF VIEW, INCREASING CO_2 IN THE DEEP WATER WOULD LEAD TO ACUTE ACIDIFICATION EFFECTS AT THE DEPOSITION SITE OR THE INJECTION SITE AND WOULD LEAD TO MORE CHRONIC EFFECTS ON A WIDER SCALE, DEPENDING UPON THE DISPERSION AND CIRCULATION OF THAT CO_2 AWAY FROM THE INJECTION SITE.

THE OTHER CARBON MITIGATION PROPOSAL IS DELIBERATE IRON FERTILIZATION. IN LARGE REGIONS OF THE OCEAN, PARTICULARLY IN THE SOUTHERN OCEAN, BUT ALSO IN THE EQUATORIAL PACIFIC AND THE SUBPOLAR NORTH PACIFIC, SURFACE WATERS APPEAR TO BE LIMITED BY THE TRACE ELEMENT IRON. SO THERE ARE SUBSTANTIAL LEVELS OF THE NUTRIENTS OF NITRATE AND PHOSPHORUS, BUT THERE IS NOT ENOUGH IRON. THIS HAS BEEN SHOWN NOW THROUGH A DOZEN DELIBERATE EXPERIMENTS WHERE PEOPLE HAVE GONE OUT AND ADDED IRON TO THE WATER COLUMN, AND WHAT YOU SEE IS A LARGE PHYTOPLANKTON BLOOM IN THE SURFACE WATERS,

WHERE YOU CAN GET A TENFOLD INCREASE IN PLANT BIOMASS ON A TIME SCALE OF A FEW WEEKS.

THIS IS A SATELLITE IMAGE FROM THE SOUTHERN OCEAN FROM THE SOIREE EXPERIMENT SHOWING THE STRETCHING OUT OF THIS BLOOM OVER TIME ASSOCIATED WITH THE MESOSCALE OCEAN CURRENTS.

IT IS FAIRLY CLEAR WHEN AND WHERE WE CAN TRIGGER BLOOMS. THE QUESTION IS WHAT HAPPENS TO THIS CARBON. WHAT IS THE FATE OF THIS CARBON?

TYPICALLY, MOST OF THE PRIMARY PRODUCTION IN THE UPPER OCEAN GETS RESPIRED IN THE SURFACE OCEAN. THAT CARBON WOULD THEN BE QUICKLY LOST BACK OUT TO THE ATMOSPHERE, BUT SOME SMALLER FRACTION DOES GET REMOVED FROM THE SURFACE OCEAN IN THE FORM OF SINKING PARTICLES; AND IF THOSE PARTICLES CAN SINK DEEP ENOUGH IN THE WATER COLUMN BEFORE THEY'RE RESPIRED, THAT WOULD ACT AS A WAY OF SEQUESTERING CARBON FOR A TIME PERIOD OF DECADES TO PERHAPS CENTURIES IF IT GETS DEEP ENOUGH IN THE WATER COLUMN.

DAVE KARL WILL TALK IN MUCH MORE DETAIL ABOUT THIS TOMORROW, BUT THERE ARE A WHOLE VARIETY OF ISSUES ASSOCIATED WITH THIS AS A CARBON MITIGATION SCHEME. ONE IS WHETHER IT IS VERIFIABLE. WE HAVE VERY LITTLE INFORMATION ON THESE SINKING CARBON

FLUXES. IT IS DIFFICULT TO MEASURE THOSE AT THIS POINT AND TO TRACK THOSE, AND IT'S ALSO DIFFICULT TO VERIFY THE LONG-TERM FATE OF THE SINKING CARBON.

ALSO, ADDITIONALITY; BY ADDING NUTRIENTS IN ONE SPOT OF THE OCEAN AND TRIGGERING A BLOOM, YOU DO ALTER THE BIOLOGY DOWNSTREAM FOR THAT SITE. IT IS ONLY AN EFFECTIVE CARBON SINK IF IT IS IN ADDITION TO WHAT THE NATURAL BACKGROUND IS. SO IF ALL YOU'RE DOING IS STRIPPING OUT NUTRIENTS IN ONE SPOT THAT WOULD HAVE BEEN USED SOMEWHERE ELSE IN THE OCEAN, THEN YOU'RE NOT ACTUALLY EFFECTIVELY INCREASING THE STORAGE OF THE CARBON IN THE OCEAN.

THERE ARE A WHOLE HOST OF POTENTIAL ECOLOGICAL CONSEQUENCES OF ALTERING THE ECOSYSTEM IN THIS WAY, AND DAVE WILL GO THROUGH THIS IN MORE DETAIL. BUT ONE OF THEM IS INCREASING THE LOW OXYGEN ZONES. OTHERS ARE PRODUCING AND DISRUPTING FOOD WEBS.

AND THEN, FINALLY, THE LEGAL AND POLITICAL FRAMEWORK FOR DOING THIS IS STILL QUITE A BIT UP IN THE AIR. THERE HAS BEEN SOME WORK DONE ON THE OPEN OCEAN CONDITIONS THROUGH THE LONDON PROTOCOL, SOMETIMES CALLED THE LONDON DUMPING PROTOCOL. BUT RIGHT NOW THERE ISN'T AN INTERNATIONAL FRAMEWORK TO

REGULATE ACTIVITIES OF OCEAN FERTILIZATION IN THE OPEN OCEAN BEYOND THE ECONOMIC ZONES OF INDIVIDUAL COUNTRIES.

I DID WANT TO ADD ONE LAST THING, WHICH FEEDS INTO THE TALK BY JIM ZACHOS AFTER LUNCH, WHICH IS METHANE HYDRATES. THIS HAS BEEN DISCUSSED IN THE LITERATURE FOR PROBABLY WELL ON A DECADE NOW AS A POTENTIAL LARGE SOURCE OF CARBON. METHANE HYDRATES ACTUALLY OCCURRED IN THE SEDIMENTS.

THIS IS THE STABILITY DIAGRAM SHOWING THAT THE STABILITY OF METHANE HYDRATES TENDS TO INCREASE AS YOU GO DOWN THE WATER COLUMN WITH PRESSURE. IF YOU GET A REGION WHERE YOU HAVE ENOUGH PRESSURE AND THE TEMPERATURES ARE COLD ENOUGH, YOU CAN BUILD UP A ZONE OF METHANE HYDRATES. THESE ARE BASICALLY METHANE WATER ICES THAT ARE OCCURRING WITHIN THE SEDIMENTS. THE METHANE IS COMING FROM THE DECOMPOSITION OF ORGANIC MATTER BURIED IN THE SEDIMENT. THE METHANE THEN PERCOLATES UP AND GETS TRAPPED IN THESE HYDRATES OR CLATHRATES. AND ONE OF THE SUGGESTIONS IS THAT THESE HYDRATES COULD BE SENSITIVE TO RISING TEMPERATURE BECAUSE OF THE STABILITY CURVE, AS YOU WARM, THEY TEND TO DESTABILIZE AND THEN COULD BUBBLE UP TO THE SURFACE, RELEASING EITHER CO2, IF THEY ARE OXIDIZED IN THE WATER COLUMN, OR METHANE.

MOST OF THE MODEL CALCULATIONS SUGGEST THAT THIS IS A RELATIVELY SMALL SOURCE OVER A LONG PERIOD OF TIME. THERE IS QUITE A LARGE STORAGE AND ALSO A LARGE UNCERTAINTY IN THE STORAGE OF METHANE HYDRATES, SOMETHING FROM 1,000 TO 10,000 PG C, DEPENDING UPON WHICH NUMBERS AND WHICH SURVEYS YOU WANT TO EXTRAPOLATE FROM.

BUT THE QUESTION IS, REALLY: WOULD THIS BE A CATASTROPHIC RELEASE ON THE TIME SCALE OF DECADES TO A HUNDRED YEARS, OR IS THIS A THOUSAND-YEAR, MULTITHOUSAND-YEAR PROBLEM. MOST OF THE MODEL ESTIMATES SUGGEST THAT IT IS MORE OF A GRADUAL RELEASE, BUT JIM WILL TALK ABOUT IT MORE THIS AFTERNOON IN TERMS OF WHAT THE LONG-TERM GEOLOGICAL RECORD HAS SHOWN AND SUGGESTS.

SO I JUST WANTED TO WRAP UP THERE BY REMINDING PEOPLE THAT THIS IS A FAIRLY COMPLICATED ISSUE OF WHAT ARE THE OCEAN RESPONSES AND FEEDBACKS.

MOST OF THE RESULTS THAT HAVE BEEN LOOKED AT SO FAR HAVE BEEN LOOKED AT WITH RELATIVELY SIMPLE MODELS THAT DON'T INCLUDE A LOT OF THE BIOLOGICAL COMPLEXITY THAT WE KNOW EXISTS IN THE REAL WORLD. AND SO ONE OF THE THINGS THAT WE HAVE TO BE CAREFUL OF IS MAKING ASSUMPTIONS BASED ON THE SMALL CHANGES THAT WE'VE SEEN TO DATE THAT THOSE SMALL CHANGES WILL

EXTRAPOLATE IN THE FUTURE.

AS VICKI WILL TALK ABOUT IN THE NEXT TALK, THERE IS QUITE A BIT OF EVIDENCE THAT OCEAN ECOSYSTEMS CAN UNDERGO REGIME CHANGES, WHERE YOU HAVE ECOLOGICAL SHIFTS, AND I DON'T THINK WE YET HAVE ENOUGH INFORMATION TO REALLY EXTRAPOLATE WELL INTO THE FUTURE AT THE FULL RANGE OF POTENTIAL BIOLOGICAL AND BIOGEOCHEMICAL RESPONSES.

SO I'LL STOP THERE.