Dr. Tans: The title is a little bit too overarching for what I will be able to talk about. I will only cover a few aspects that are revealed by the CO2 records, the ones that I have time to talk about. There are, really, two aspects that I will cover: one is the cumulative rise in CO2, and what we can learn from that, so really the overall record; and secondly, I will be talking about short-term variability in the rate of increase of CO2, about interannual variations, even leaving out variations on the time scale of five and ten years. The latter will be removed to reveal short term variations only.

Slide 2
Here's another way to look at the entire record. I start the plot on the Y-axis at 280 ppm, standing for, more or less, the pre-industrial concentration. You see this is the entire record from Mauna Loa. The thick curve going through the seasonal cycle is the de-seasonalized growth rate or increase of CO2; and to the right is the global rate of emissions due to fossil fuel burning and cement production, as tabulated by the CDIAC, the Carbon Dioxide Information and Analysis Center.

Now, if you use a model of the oceans, of the ocean uptake of anthropogenic CO2, and apply that to the fossil fuel emissions as tabulated by the CDIAC, what you would expect is the curve in the red, and you can immediately see two discrepancies. First of all, when Dave Keeling started these measurements in '58, CO2 was significantly larger than what one would expect from fossil fuel burning alone. So, in other words, there had to have been a source other than fossil fuel burning before he started his measurements. And secondly, that the rate of rise that you would expect from fossil fuel burning alone is slightly larger at the end than what we actually see.

Slide 3
First I need to say something about the ocean model that I'm using. It is the Hamburg ocean carbon cycle model that was published by Maier-Reimer in 1987, long ago; it is a fully three-dimensional model of ocean circulation and uptake of CO2, including ocean chemistry; what he did was to characterize the response of his ocean model.
YOU CAN ACTUALLY ATTRIBUTE WHERE THE CO2 HAS GONE.

Slide 5  FIRST THE RED CURVE. THEY ARE CO2 EMISSIONS

AS TABULATED BY CDIAC. THE CUMULATIVE EMISSIONS ARE

ARE NOW AT 331, PLUS OR MINUS 25. THIS IS THE CDIAC'S

OWN ESTIMATE OF CUMULATIVE EMISSIONS SINCE THE START

OF THE INDUSTRIAL ERA, TAKEN TO BE 1850.

THEN THERE'S THE ATMOSPHERIC INCREASE (BLACK)

AS MEASURED BOTH BY THE MAUNA LOA RECORD AND THE ICE

CORE RECORD GOING BACK TO 1000 AD. THE BLUE

CURVE IS WHAT THE OCEAN MODEL PREDICTS WHAT THE

UPTAKE IN THE OCEAN SHOULD HAVE BEEN, WITH THE

ATMOSPHERIC INCREASE AS RECORDED. THE OCEAN MODEL

YIELDS TOTAL EMISSIONS IN THE ATMOSPHERE, POSITIVE OR

NEGATIVE, NECESSARY TO EXACTLY MATCH THE RECORDED

ATMOSPHERIC

INCREASE. TERRESTRIAL EMISSIONS WERE PLAYING AN IMPORTANT

ROLE

IN THE 19TH CENTURY. IT WAS ONLY IN 1940 THAT FOSSIL FUEL 21

BURNING OVERTOOK TERRESTRIAL EMISSIONS. THE MODEL PREDICTS THE

OCEAN INCREASE AS SHOWN IN THE BLUE CURVE. THERE IS ONE

DATA POINT THERE, AND IT REPRESENTS A SUMMARY BY CHRIS SABINE

AND COLLEAGUES OF DECADES OF OCEAN MEASUREMENTS,
NORMALIZED TO 1994 AND PUBLISHED IN 2004. IT SUMMARIZES THE

MEASURED CUMULATIVE

0106

UPTAKE OF ANTHROPOGENIC CO2 THROUGH THE YEAR 1994, AND

THAT'S THE ONE DATA POINT THERE; THE MAIER-REIMER MODEL

ACTUALLY GOES THROUGH THIS DATA POINT ALMOST EXACTLY, WITH

OF

COURSE A LITTLE BIT OF LUCK. THE MODEL, PUBLISHED IN 1987, WAS

A PREDICTION. IT IS ENCOURAGING THAT THIS OCEAN MODEL IS NOT

TOTALLY FANTASY, AND I WILL USE IT.

NOW, WHAT YOU CAN SEE, BOTH FROM THE

CURVES, AND FROM THE NUMBERS AT THE TOP, THAT

WHEN YOU EXTRAPOLATE THE OCEAN UPTAKE BEYOND 1994

THROUGH THIS OCEAN MODEL, THEN YOU WOULD EXPECT THAT

THE OCEANS BY NOW HAVE TAKEN UP ALMOST 150 BILLION TONS

OF CARBON. IF YOU ADD UP THE NUMBERS, YOU SEE THAT, WITHIN

ERROR, THE TERRESTRIAL BIOSPHERE PLAYS NO SIGNIFICANT ROLE.

YOU CAN EXPLAIN THIS AS THE SUM OF ATMOSPHERIC

AND THE OCEANIC INCREASES EQUALING, WITHIN ERROR, TOTAL

FOSSIL FUEL EMISSIONS. HOWEVER, IF WE WANT TO MATCH THE

ATMOSPHERIC RECORD EXACTLY, WE NEED SOMETHING ELSE

BESIDES FUEL BURNING TO EXACTLY FOLLOW THE INCREASE RATE IN
THE ATMOSPHERE. THIS "SOMETHING ELSE" IS NET CHANGES IN THE TERRESTRIAL BIOSPHERE, PAINTED IN GREEN. SO THAT'S BASICALLY WHAT IS NEEDED TO CLOSE THE MASS BALANCE, TO CLOSE THE ACCOUNTING BOOKS EXACTLY, IF WE BELIEVE THE ATMOSPHERIC RECORD IS INDEED 100 PERCENT CORRECT AND WE BELIEVE THE FOSSIL FUEL EMISSIONS ARE EXACTLY AS COMPILED BY THE CDIAC. TO CLOSE THE BOOKS, WE SEE FROM THE TIME HISTORY OF CUMULATIVE EMISSIONS THAT THE NET EMISSIONS WERE POSITIVE IN THE 19TH CENTURY UNTIL ABOUT 1940, AND THEN BECAME NEGATIVE. WE FIND THAT NET TERRESTRIAL UPTAKE SINCE THEN HAS HAS BEEN ABOUT 0.3 BILLION TONS OF CARBON PER YEAR ON AVERAGE. THAT IS NOT VERY MUCH. WE SHOULD REMEMBER THAT THIS IS TOTAL NET TERRESTRIAL UPTAKE. IF THERE IS A SOURCE, SAY, MOSTLY FROM TROPICAL DEFORESTATION OF 1 AND A HALF BILLION TONS OF CARBON PER YEAR, GLOBAL NET UPTAKE IS STILL 0.3. THAT MEANS THE TOTAL UPTAKE OUTSIDE OF THE TROPICS, OR MAYBE EVEN IN THE TROPICS BUT NOT ACCOUNTED FOR, TOTALS THAT ONE AND A HALF PLUS 0.3, SO THERE IS 1.8 TERRESTRIAL UPTAKE SOMEWHERE.

I'M NOT SURE I'LL HAVE ENOUGH TIME, BUT THERE'S ANOTHER ARGUMENT BASED ON ISOTOPIC RATIOS, INDEPENDENT OF THIS MASS BALANCE ARGUMENT, THAT POINTS TO FUEL BURNING. IF YOU IMAGINE THAT YOU ARE FROM MARS AND YOU DON'T KNOW ANYTHING OR YOU DON'T WANT TO ACKNOWLEDGE THAT FOSSIL FUEL BURNING HAS SOMETHING TO DO WITH INCREASING CO2, BUT YOU ARE ABLE TO MEASURE WHAT IS GOING ON IN THE ATMOSPHERE AND THE OCEANS, WHAT COULD YOU CONCLUDE FROM THOSE MEASUREMENTS? WELL, THERE ARE SEVERAL ISOTOPIC RATIOS THAT CAN HELP YOU DRAW CONCLUSIONS ABOUT WHAT'S GOING ON, AFTER YOU HAVE MEASURED THE INCREASE OF CO2 IN THE ATMOSPHERE. FIRST OF ALL, THIS ISOTOPIC RATIO, THE RATIO OF C-13 TO C-12, IS ABOUT 1 PERCENT. MOPE PRECISELY, 1.1 PERCENT OF ALL CARBON ON THE SURFACE OF THE EARTH IS ACTUALLY THE ISOTOPE C-13; THE OTHER 99 OR 98.9 PERCENT IS C-12. THOSE ARE THE RATIOS IN THAT MIDDLE COLUMN. THESE ARE THE RATIOS THAT ARE OBSERVED TYPICALLY IN THE VARIOUS RESERVOIRS. IN THE ATMOSPHERE, THE ABUNDANCE OF C-13
IS 1.1147% OF THAT OF C-12; IN THE OCEANS, OR RATHER WHAT COMES OUT OF THE OCEANS AND JOINS THE ATMOSPHERIC RESERVOIR, HAS THE SAME RATIO. THE TERRESTRIAL BIOSPHERE IS A LITTLE BIT DEPLETED IN C-13. COAL, OIL, AND NATURAL GAS ARE DEPLETED FURTHER. OVERALL THE AGGREGATE OF THE FOSSIL FUELS IS MORE DEPLETED IN CARBON-13 THAN, BUT STILL QUITE SIMILAR TO, THE TERRESTRIAL BIOSPHERE -- THERE'S A GOOD EXPLANATION FOR THAT -- BUT THE SMALL DIFFERENCE IS NOT HELPFUL FOR US TO DISTINGUISH BETWEEN THOSE TWO SOURCE TYPES. WE CAN REALLY ONLY DISTINGUISH, WITH C-13 ALONE, BETWEEN TERRESTRIAL OR FOSSIL SOURCES ON THE ONE HAND AND OCEANIC SOURCES ON THE OTHER. THAT'S WHAT WE CAN DO AT THIS POINT. HOWEVER, THERE IS ALSO C-14. THE FOSSIL FUELS ARE THE ONLY RESERVOIR FROM WHICH CO2 CAN BE PRODUCED THAT ENTERS THE ATMOSPHERE WITHOUT ANY C-14 IN IT; WHEREAS, THE OTHER RESERVOIRS HAVE PRETTY MUCH THE SAME C-14 TO TOTAL CARBON RATIO AS THE ATMOSPHERE. WHAT DO WE SEE? THIS IS A TIME HISTORY FROM THREE DIFFERENT RECORDS OF WHAT HAPPENED TO C-13 IN THE ATMOSPHERE OVER THE LAST 250 YEARS. WE SEE THAT THE ATMOSPHERE IN PRE-INDUSTRIAL TIMES WAS MINUS 6 AND A HALF PER MIL, AND IT BECAME LOWER. NOW, IF YOU SEE THE INCREASE OF CO2 IN THE ATMOSPHERE AND YOU WANT TO POSTULATE THAT IT COMES FROM THE OCEANS, YOU HAVE A CONTRADICTION. AN OCEANIC SOURCE WOULD NOT HAVE CHANGED THE 13C/12C RATIO IN THE ATMOSPHERE. WHAT COMES OUT OF THE OCEAN HAS THE SAME ISOTOPE RATIO AS WHAT'S ALREADY THERE. AT THIS POINT WE KNOW THE SOURCE TO BE EITHER THE TERRESTRIAL BIOSPHERE OR SOME OLD SOURCE. I DON'T HAVE A SLIDE OF C-14. IT'S MORE COMPLICATED BECAUSE THE 14C/C RATIO OF THE ATMOSPHERE WAS MESSED UP, IF YOU WILL, BY NUCLEAR TESTING, UNTIL THE TEST BAN TREATY IN LATE 1962, SO IT IS A MORE DIFFICULT RECORD TO READ. BUT IF YOU READ IT CAREFULLY AND YOU ACCOUNT FOR NUCLEAR TESTING, YOU CAN ALSO DEMONSTRATE THAT WHAT WE SEE NOW, THE BUILDUP OF CO2, IS CAUSED BY A SOURCE OF CARBON THAT IS VERY OLD. SO NOW WE KNOW IT CANNOT BE THE OCEANS, AND THE SOURCE HAS TO BE VERY OLD.
IN ADDITION TO THAT, THERE IS ANOTHER
PIECE OF EVIDENCE. ALTHOUGH THE WAY I'M TALKING ABOUT IT
IS STILL QUALITATIVE, IT IS THE CONCENTRATION OF CO2 IN
THE NORTHERN HEMISPHERE BEING HIGHER THAN THE SOUTHERN
HEMISPHERE. IT TELLS YOU THAT THE EXTRA CO2 COMES FROM
THE NORTHERN HEMISPHERE PRIMARILY. AND THE DIFFERENCE
BETWEEN THE TWO HEMISPHERES HAS INCREASED OVER TIME.
SO YOU'RE LOOKING AT AN INCREASING SOURCE OF CARBON
PRIMARILY IN THE NORTHERN HEMISPHERE THAT IS OLD.
WELL, I THINK BY NOW WE HAVE TO HYPOTHESIZE THAT IT
HAS TO BE FOSSIL FUELS.
Slide 8 ONE MORE LOOK AT THE OVERALL RECORD.
THE BLACK CURVE IS WHAT IS REQUIRED FOR THE TOTAL NET
SOURCE, BOTH FROM FOSSIL FUEL BURNING AND THE TERRESTRIAL
BIOSPHERE, TO EXACTLY MATCH THE CO2 WIGGLES THAT ARE
SEEN AT HIGH RESOLUTION IN THE MAUNA LOA RECORD AND
AT LOWER RESOLUTION IN THE ICE CORE.
Slide 9 I'LL SKIP THAT.
Slide 10 AT THIS POINT I REACH MY FIRST
CONCLUSION: THE OBSERVED INCREASE IN
ATMOSPHERIC CARBON DIOXIDE SINCE PRE-INDUSTRIAL TIMES
IS ENTIRELY DUE TO HUMAN ACTIVITIES -- NOT MOSTLY --
BUT ENTIRELY. WE KNOW THAT EVEN THE NET TERRESTRIAL SINK
IS UNDER GREAT HUMAN INFLUENCE. AND BESIDES
THAT, IT IS ONLY A SMALL, QUITE SMALL, NET SOURCE COMPARED
TO FOSSIL FUELS ALONE.
Slide 11 NOW I GO ON TO THE NEXT PART. LET'S TALK
ABOUT INTERANNUAL VARIABILITY. FIRST, I WANT TO SHOW
YOU OR DEMONSTRATE TO YOU THAT WHAT WE SEE AT MAUNA LOA
IS REPRESENTATIVE OF THE GLOBE. IN BLACK IS THE SMOOTH CURVE
FROM WHICH THE SEASONAL CYCLE HAS BEEN REMOVED, AND WE
HAVE TAKEN THE TIME DERIVATIVE OF IT. IT IS THE GLOBAL
RATE OF INCREASE WITH THE SEASONAL CYCLE REMOVED.
WE DO THE SAME THING FOR MAUNA LOA (IN RED), LIMITED TO THE
TIME PERIOD WE HAVE FOR THE GLOBAL RECORD SINCE 1980. THE
LATTER IS BASED ON ABOUT 20 DIFFERENT MARINE SITES INITIALLY,
AND THE NUMBER HAS SLOWLY GROWN OVER TIME. YOU SEE THERE IS
NOT REALLY MUCH DIFFERENCE. MAUNA LOA GIVES, INDEED, A GOOD
REPRESENTATION OF THE GLOBAL GROWTH RATE. THAT'S ONE
THING TO KEEP IN MIND.

Slide 12 ANOTHER POINT IS THIS: WHEN WE LOOK AT
THE ISOTOPIC RECORD AS RECORDED WITH THE GLOBAL OBSERVING
SYSTEM, WE SEE THAT THE WIGGLES, THE VARIATIONS IN THE
CO2 GROWTH RATE SINCE ABOUT 1990 ARE ALMOST EXACTLY, BUT NOT
ENTIRELY, MIRRORED, IN A NEGATIVE WAY, BY THE WIGGLES IN
THE RATE OF CHANGE OF THE 13C/12C RATIO. A HIGHER
RATE OF INCREASE OF CO2 CORRESPONDS TO A DECREASE OF
13C/12C. IF YOU LOOK AT THIS

RELATIONSHIP CAREFULLY, YOU CAN SAY THIS HAS
TO BE THE TERRESTRIAL BIOSPHERE. IT HAS THE ISOTOPIC
SIGNATURE OF THE TERRESTRIAL BIOSPHERE. SO YOU SEE THE
VARIABILITY AS RECORDED BY MAUNA LOA IS GLOBAL; AND
SECONDLY, IT IS CAUSED PRIMARILY BY THE TERRESTRIAL
BIOSPHERE RATHER THAN BY THE OCEANS.

Slide 13 NOW, WHAT I'M GOING TO USE IS THIS: HERE
YOU SEE THE MOST RECENT PART OF THE MAUNA LOA RECORD.
ABOUT FIVE YEARS OR SO IN THE RED, AND I HAVE REMOVED
THE AVERAGE SEASONAL CYCLE FROM THAT, AND THEN WHAT
IS LEFT IS THE UNDERLYING SLOW INCREASE, BUT THERE IS
VARIATION FROM MONTH TO MONTH. THESE VARIATIONS
ARE SIGNIFICANT, THESE DIFFERENCES BETWEEN SUCCESSIVE
MONTHS. WE BELIEVE THESE NUMBERS ARE GOOD TO ABOUT 0.1
PPM, BASED ON ONGOING COMPARISONS BETWEEN INDEPENDENTLY
DERIVED RECORDS, RECORDS DERIVED INDEPENDENTLY BY
SCRIPPS AND BY NOAA. THE
UNCERTAINTY IS ABOUT AS LARGE AS THE THICKNESS OF THE
LINE. SOME PART OF THE VARIATIONS IN THE GROWTH
RATE FROM MONTH TO MONTH, THE DE-SEASONALIZED GROWTH
RATE, ARE CAUSED BY REAL CHANGES IN ATMOSPHERIC
SOURCES OF CO2, AND SOME OF IT BY VARIATIONS IN
AIR MASSES MOVING OR ARRIVING AT MAUNA LOA. YOU CAN
HAVE ONE MONTH WITH MORE THAN THE AVERAGE NUMBER OF AIR
MASSS COMING FROM THE NORTH OR THE SOUTH, AND THAT CAN
GIVE RISE TO SLIGHT VARIATIONS OF THE TREND. I WILL
USE THESE VARIATIONS, THE MONTH-TO-MONTH VARIATION. I CALL THEM THE GROWTH RATE, THE MONTHLY GROWTH RATE.
Slides 14-18 I HAVE TO SKIP THESE. THEY ARE JUST
SOME SLIDES TO PROVE THAT MY METHOD WORKS. I HAVE NO
TIME FOR THAT NOW.
Slide 19 WHAT I'M DOING IS, I USE THESE MONTH-
TO-MONTH VARIATIONS (WITH THE 5-YEAR AVERAGE TREND
AND RELATE THEM TO MONTH-TO-MONTH ANOMALIES IN CLIMATE, IN THIS CASE TEMPERATURE. AND WHAT I'M LOOKING FOR IS THE RESPONSE, THE DELAYED RESPONSE OF THE CO2 GROWTH RATE ANOMALIES TO TEMPERATURE ANOMALIES. THE OVERALL RESULT IS IN THE BLACK CURVE. SO IF YOU HAVE A PARTICULARLY WARM MONTH, AN ANOMALOUSLY WARM MONTH, SAY IN JUNE OF SOME YEAR, THE CO2 GROWTH RATE GOES UP; BUT IN THE FOLLOWING MONTH, IN JULY, THE GROWTH RATE IS STILL HIGHER DUE TO THE PREVIOUS MONTH, AND ON AND ON. WE FIND THAT THERE IS A DELAYED RESPONSE TO A SINGLE MONTHLY MEAN TEMPERATURE ANOMALY. THE RESPONSE INITIALLY IS POSITIVE, A HIGHER GROWTH RATE FOR A HIGHER TEMPERATURE, AND THEN IT TAPERS OFF AND BECOMES NEGATIVE ABOUT A YEAR LATER. I THINK THIS HAS SOMETHING TO DO WITH THE NITROGEN CYCLE, THE AVAILABILITY OF NITROGEN TO PLANTS.

I BELIEVE THIS RESULT IS ROBUST BECAUSE WHEN I APPLY MY METHOD TO THE FIRST HALF OF THE RECORD ALONE, IT GIVES YOU THE LOWER (DASHED) CURVE; IF I APPLY THE ALGORITHM TO THE LAST HALF OF THE RECORD, YOU GET THE DOT-DOT-DASH RECORD THAT IS JUST ABOVE IT, WHICH BASICALLY GIVES THE SAME ANSWER. IF YOU LOOK AT THE FLASK RECORDS, NOT AT MAUNA LOA BUT AT THE GLOBAL FLASK RECORD IN BLUE, IT MIMICS THE 2ND HALF OF THE MAUNA LOA RECORD; YOU GET THE RED CURVE IF YOU AVERAGE OVER MONTHS, WHEN YOU MAKE THREE-MONTHLY AVERAGES, DIVIDING EACH YEAR INTO FOUR DATA POINTS. IN OTHER WORDS, THE GROWTH RATE ANOMALIES IN THE FIRST THREE MONTHS, SECOND THREE MONTHS, ETCETERA. WE FIND THE SAME GENERAL CHARACTER OF THE RESPONSE. ONE CAN DO THE SAME THING WITH PRECIPITATION ANOMALIES. NOW THE RESPONSE IS A DECREASE IN GROWTH RATE TO HIGH PRECIP, WHICH GRADUALLY TAPERS OFF OVER TIME, AND IT DOES NOT CHANGE SIGN A YEAR LATER.

NOW, IF I APPLY THESE TWO RELATIONSHIPS THAT I FOUND, IF YOU APPLY THEM TO TEMPERATURE AND PRECIPITATION ANOMALIES, YOU WOULD PREDICT WHAT IS DEPICTED IN THE RED CURVE. THIS IS WHAT THE INTERANNUAL VARIATIONS WOULD LOOK LIKE, AND ACTUALLY IT EXPLAINS 63 PERCENT OF THE OBSERVED VARIANCE (IN BLACK) OF THE INTERANNUAL GROWTH RATE. THE UNEXPLAINED (RESIDUAL) VARIATIONS ARE AT
THE BOTTOM, THE DIFFERENCE BETWEEN THE OBSERVED AND THE PREDICTED GROWTH RATE. WE CAN EXPLAIN TWO-THIRDS OF THE VARIANCE BY THESE SIMPLE CLIMATIC RELATIONSHIPS.

SO THE CONCLUSION IS WHAT I JUST MENTIONED. THE FACT THAT WE CAN EXPLAIN A GOOD CHUNK OF THE INTERANNUAL VARIABILITY IMPLIES THAT THE OBSERVED 5-YEAR AVERAGED GROWTH RATE VARIATIONS ARE SIGNIFICANT, NOT JUST "NOISE".