NATIONAL EMISSIONS VERIFICATION

BY MERGING

EARTH SYSTEM MEASUREMENTS, GLOBAL SOCIAL DATA

and

EARTH SYSTEM MODELS

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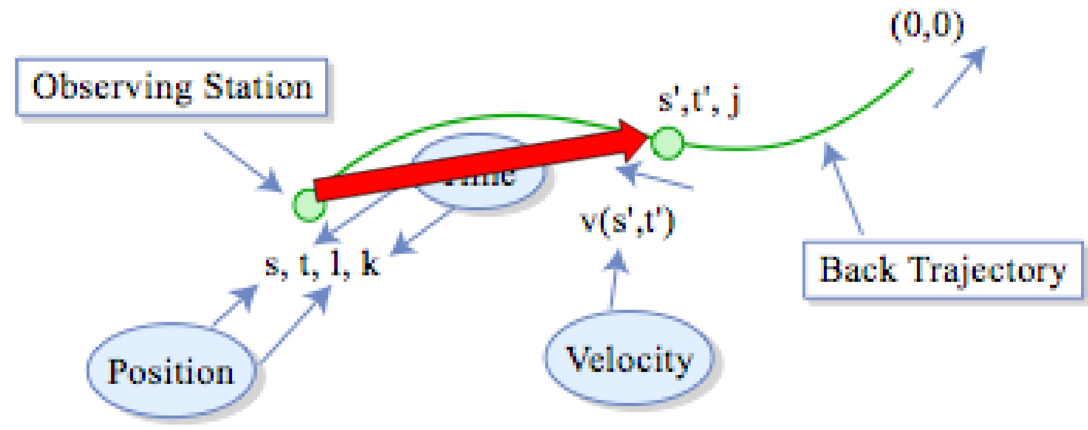
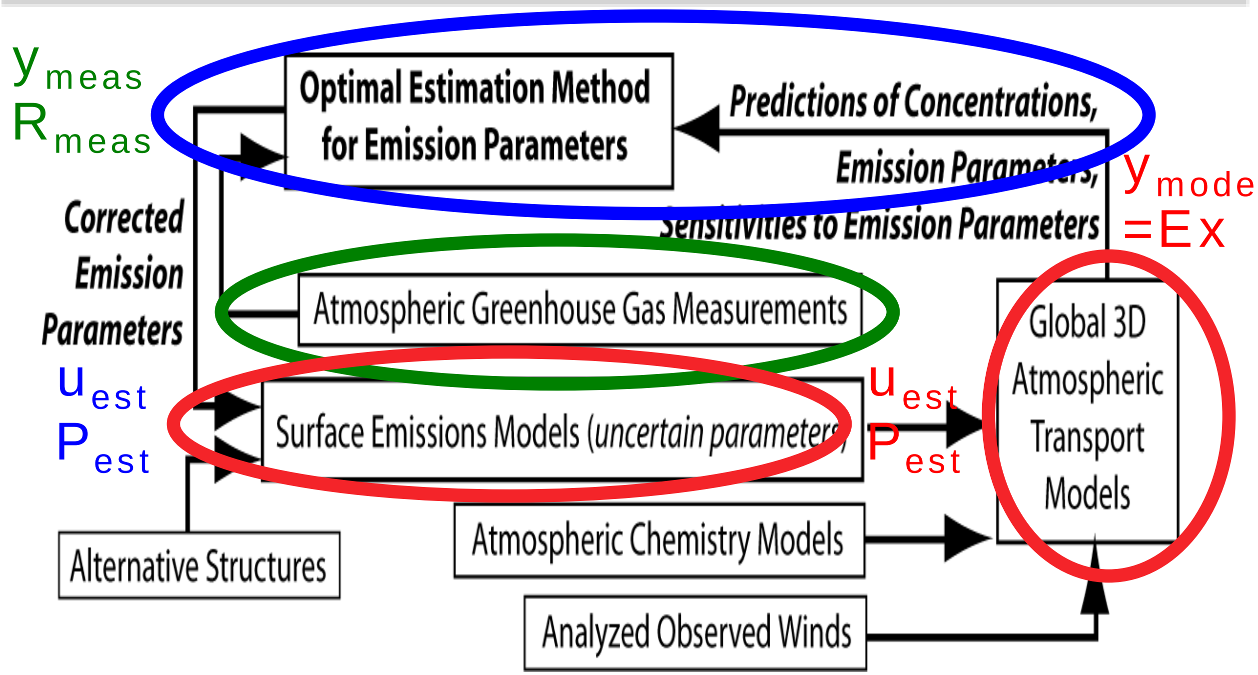
Whether Emission Reductions are claimed through Cap & Trade, Taxes, or Mandates
Reliable Independent Estimates of Anthropogenic Emissions of Greenhouse Gases are arguably ESSENTIAL

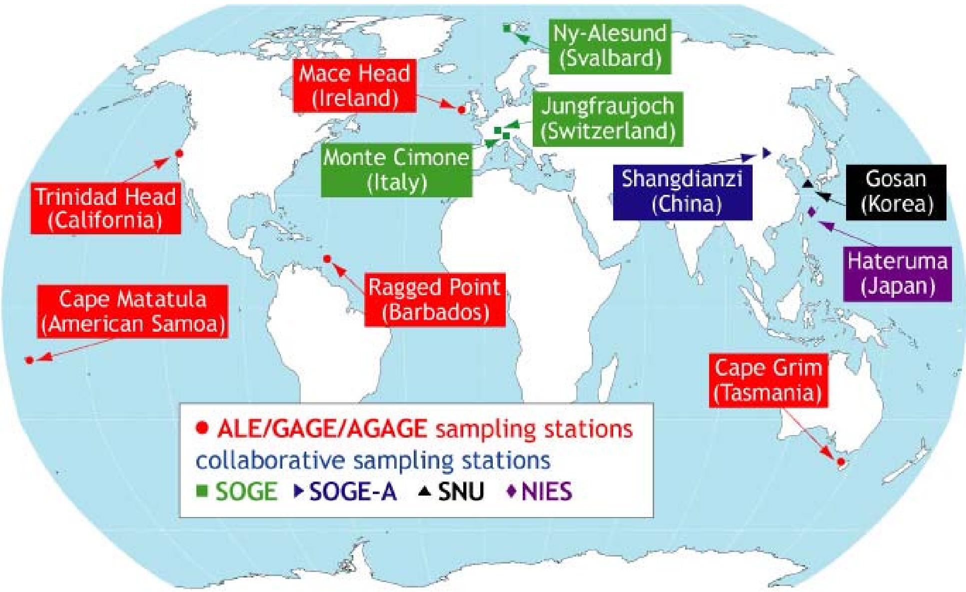
TYPICAL CURRENT APPROACH





EXAMPLE: Advanced Global Atmospheric Gases Experiment

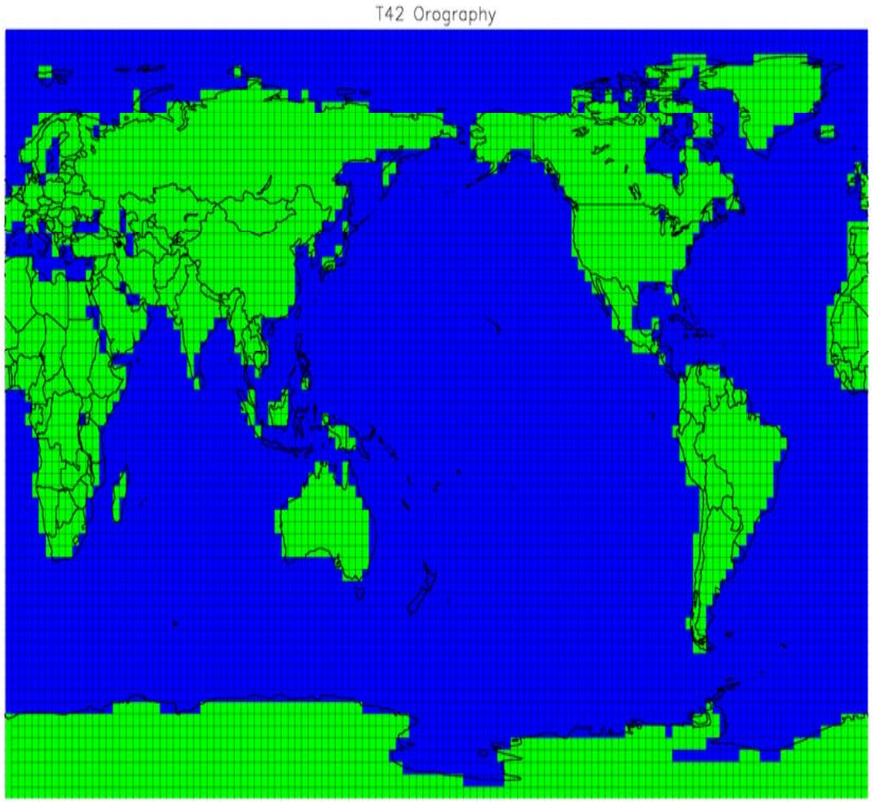
Funding



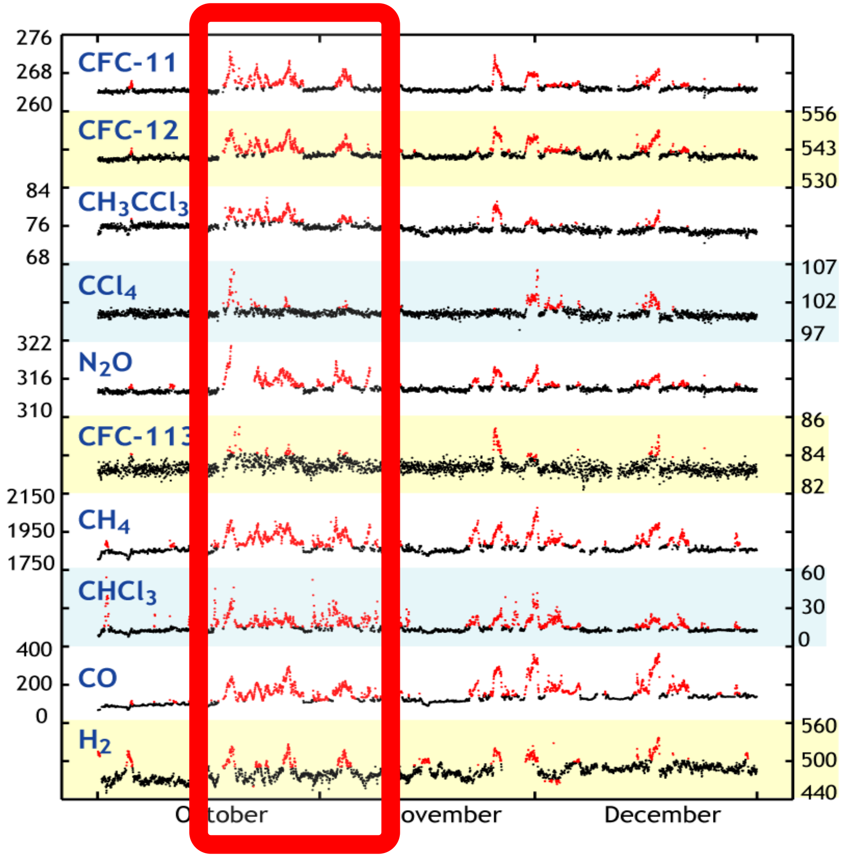
INTERCOMPARISON WITH NOAA-GMD

MAJOR AGAGE GOAL SINCE IT'S 1978 START: ESTIMATE FLOWS OF KYOTO & MONTREAL PROTOCOL GASES USING ON SITE MEASUREMENTS, INVERSE METHODS, & GLOBAL CIRCULATION MODELS

e.g. 28-level 1.8°x1.8° or 2.8°x2.8° Model for Atmospheric Transport & Chemistry (MATCH or MOZART) uses NCEP & ECMWF meteorology



HIGH FREQUENCY MEASUREMENTS IN THE BOUNDARY LAYER NEAR SOURCE REGIONS ARE UNIQUE COMPONENTS IN THE GLOBAL MEASUREMENT NETWORK

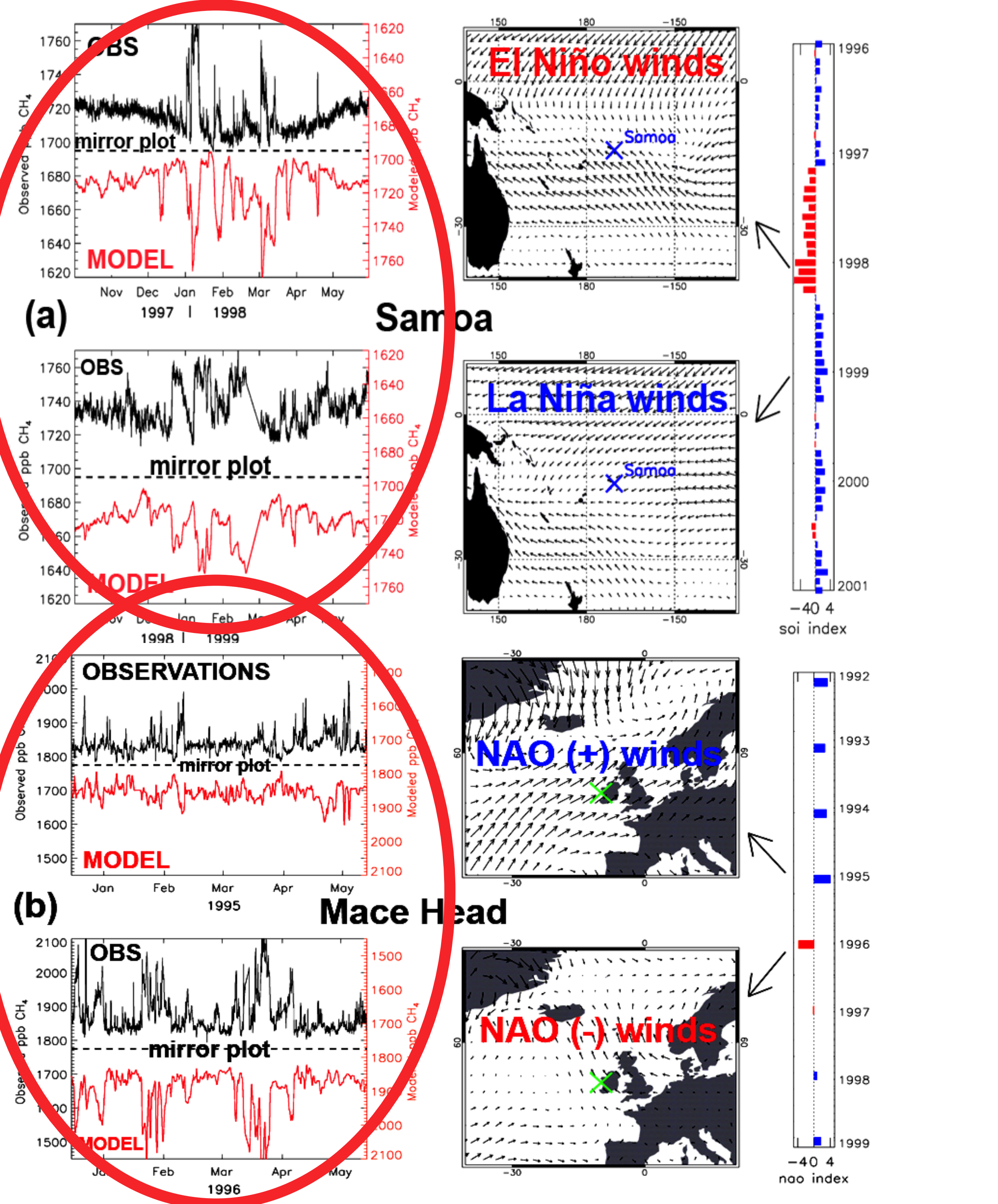


e.g. Saikawa, Thurs AM Talk on HCFC-22 inversions

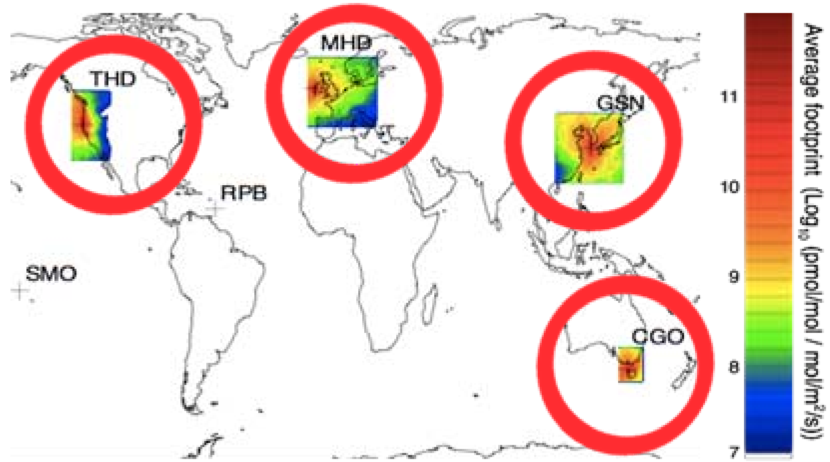
AGAGE

HOW ACCURATE DO THE CIRCULATION MODELS NEED TO BE FOR INTERPRETING TRACE GAS OBSERVATIONS?

e.g. SIMULATIONS OF CH_4 OBSERVATIONS DEMAND PRECISE INCLUSION OF EFFECTS OF weather, ENSO, NAO, etc. **(Chen & Prinn, J. Geophys. Res., 2005)**

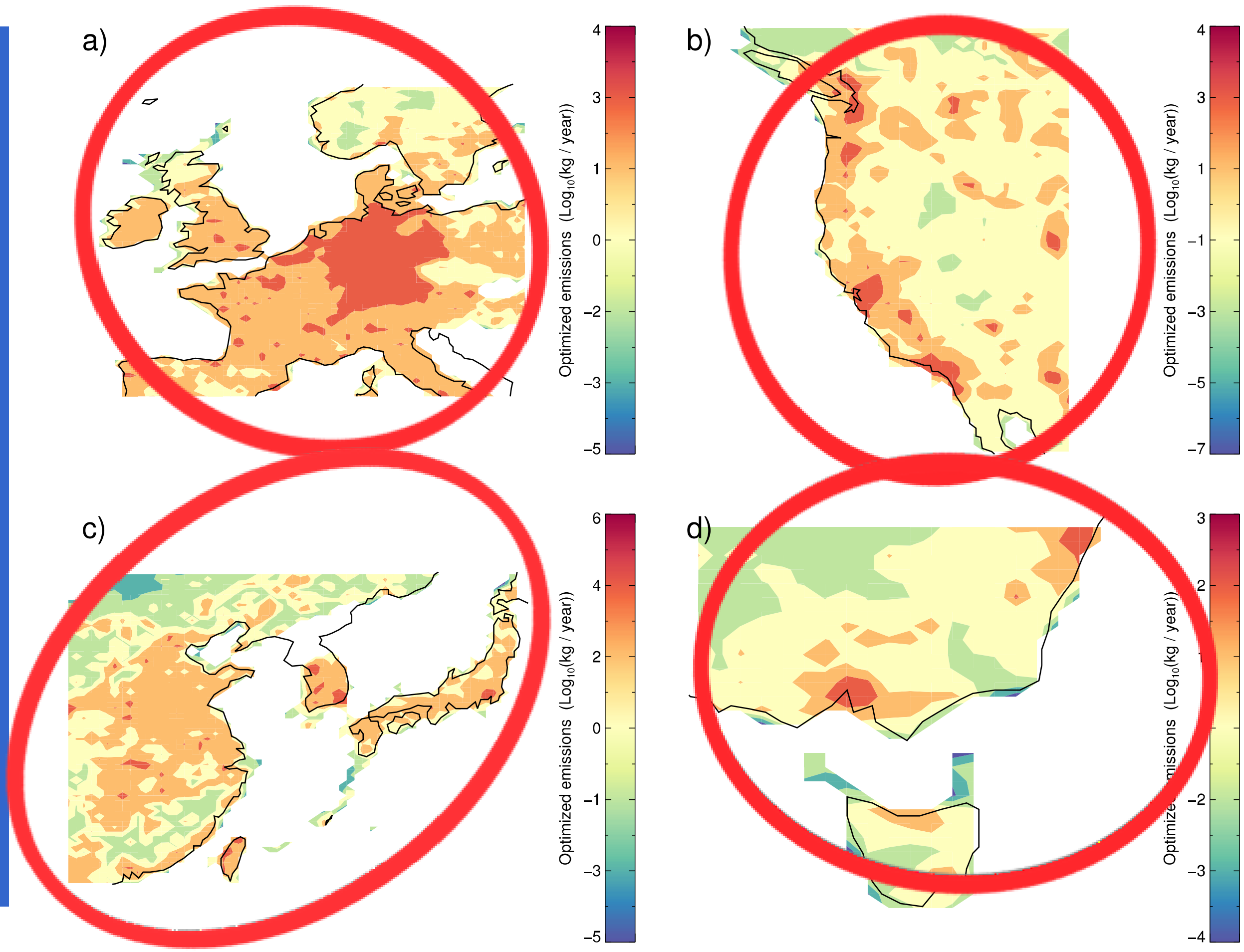


RECENT ADVANCE: IMBEDDING HIGH RESOLUTION REGIONAL MODELS INTO A GLOBAL MODEL



DEDUCED REGIONAL SF_6 EMISSIONS using AGAGE measurements and combined sensitivities from Eulerian MOZART (2.8°x2.8°, NCEP/NCAR) and Lagrangian NAME (0.38°x0.56°, UKMO) 3D models.

Ref: Rigby Manning & Prinn, *Atmos. Chem. Phys.*, 2011



LOOKING TO THE FUTURE

Enhancing Understanding as well as Addressing Essential Needs to Verify Emission Reductions, Requires Very Important Improvements in Current Capabilities

Significant advances in the Global Observing System and Economic Data Collection System with close attention to Precision & Accuracy

For Greenhouse Gases: Higher time & Space Resolution; GLOBAL measurements (SURFACE, PROFILES, MOLE FRACTIONS, FLUXES); ISOTOPIC Composition (e.g. Rigby Tues Poster)

Significant improvements in: Adjointed Models of Natural Processes; Analysed Atmospheric & Oceanic Circulation; & Economic Emission Modeling

Estimation Models & Statistical Methods should Incorporate all Reliable Information (weighted by Precision and Accuracy)

Example current DATA AND OBSERVATIONS

ATMOSPHERIC GREENHOUSE GAS OBSERVATIONS

Earth System Research Laboratory (NOAA-ESRL)
Advanced Global Atmospheric Gases Experiment (AGAGE-NASA)
Network for Detection of Atmospheric Composition Change (NDACC)
Scanning Imaging Absorption Spectrometer (SCIAMACHY-ESA)
Greenhouse Gases Observing Satellite (GOSAT-Japan)
Orbiting Carbon Observatory (OCO-NASA)
Atmospheric Infrared Sounder (AIRS-NASA)
Civil and Research aircraft (CARIBIC, HIPPO, ESRL flasks)

NATURAL AND MANAGED LAND ECOSYSTEMS

Net Fluxes of carbon from Towers (FLUXNET)
International Long Term Ecological Research biomass network (ILTER)
Advanced Very High Resolution Radiometer (AVHRR)
Moderate Resolution Imaging Spectro-radiometer (MODIS)

OCEANS

In situ measurements of CO_2, nutrients, pH, chlorophyll, particles (GLODAP, CLIVAR, JGOFS, WOCE, BATS, HOT)
Satellite derived products (SeaWifs, MODIS-Aqua, OCTS, chlorophyll)

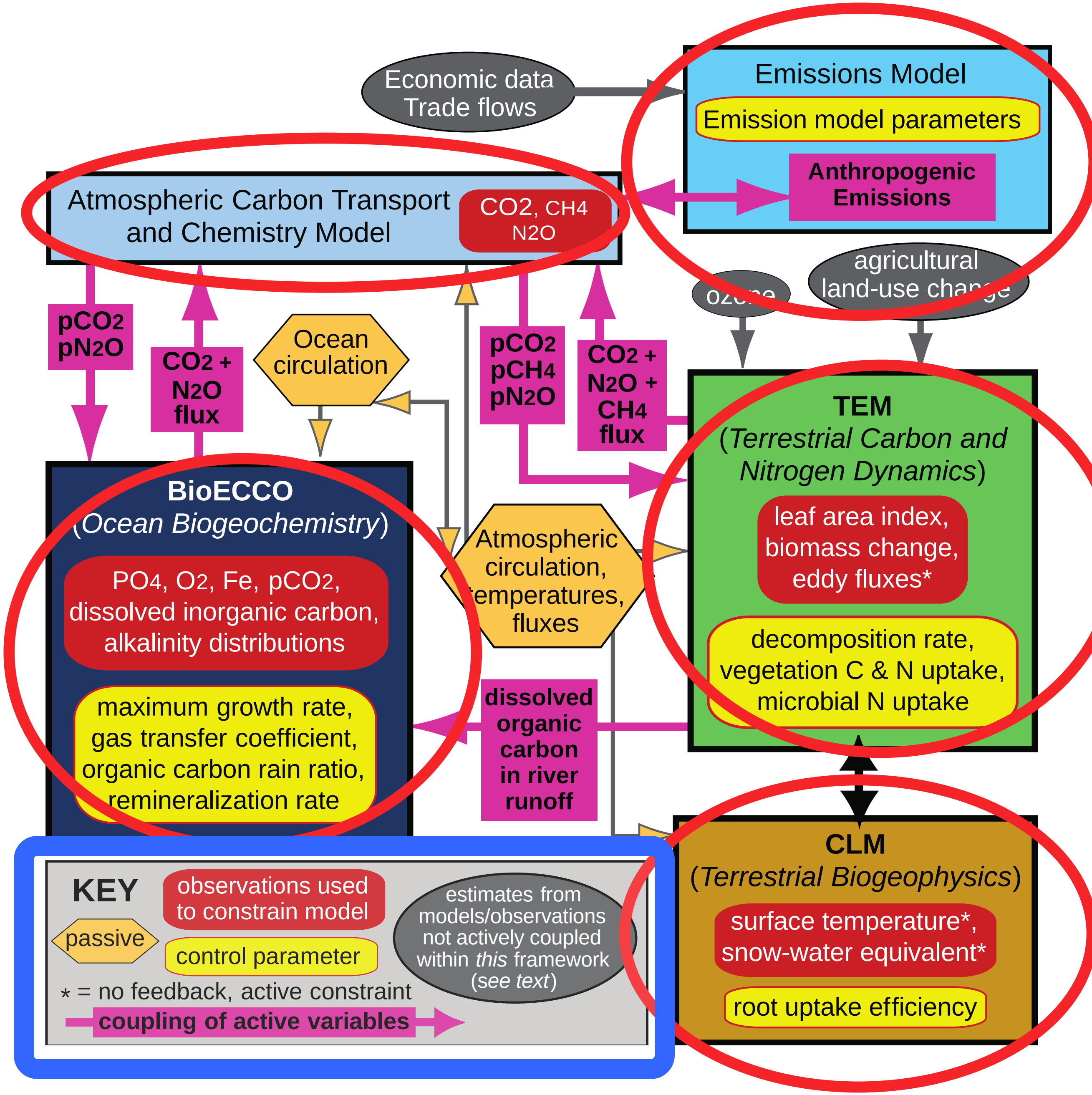
ECONOMICS DATASETS

Economic Activity & Emission Factors (IEA, FAO, CDIAC, USGS, IRRI, IFA, CRF, UNFCC)
Input/Output Data (EXIOPOL, WIOD, IDE, OECD)

STRATEGY FOR A GLOBAL OBSERVING SYSTEM FOR VERIFICATION OF NATIONAL GREENHOUSE GAS EMISSIONS

VERIFYING EMISSION REDUCTIONS FOR GASES SUCH AS CO_2, CH_4 & N_2O THAT HAVE SIGNIFICANT NATURAL SOURCES & SINKS

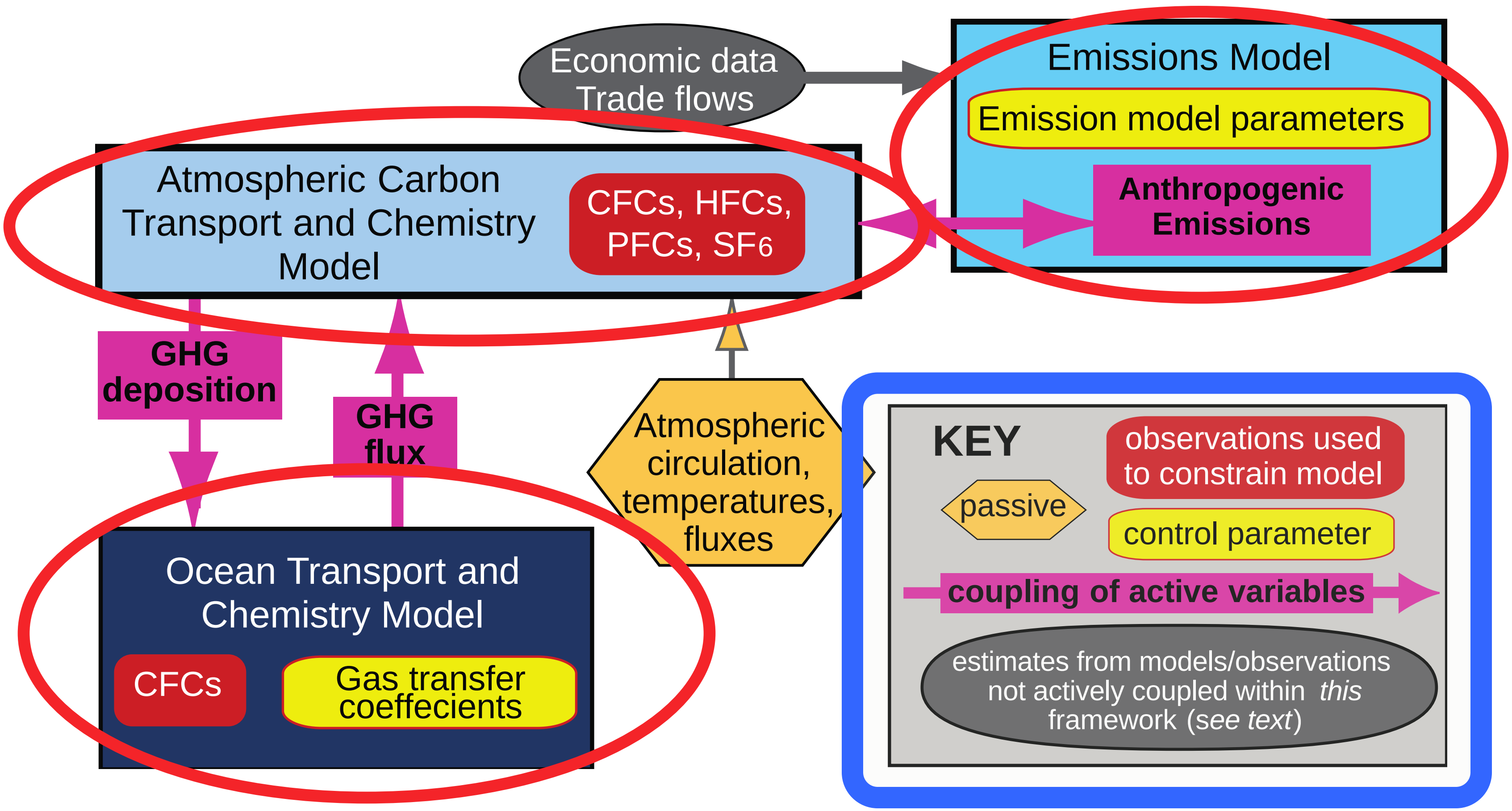
AN “OPTIMAL” APPROACH USING “NOTATION” OF CONTROL THEORY



STRATEGY FOR A GLOBAL OBSERVING SYSTEM FOR VERIFICATION OF NATIONAL GREENHOUSE GAS EMISSIONS

VERIFYING EMISSION REDUCTIONS FOR ANTHROPOGENIC GASES SUCH AS CF_4, SF_6 & CHF_3

AN “OPTIMAL” APPROACH USING CONTROL THEORY NOTATION



VARY CONTROLS U_E (AND INITIAL CONDITIONS $X_E(t=0)$) OF COUPLED SYSTEM, TO SEEK A SOLUTION OF THE COUPLED STATE $X_E(t)$, WHICH MINIMIZES THE OBJECTIVE FUNCTION *J (Atmospheric, Terrestrial, Oceanic)*.

$$J = \sum_{\Xi}^{A,T,O} \left[x_\Xi(0) - x_{\Xi_0} \right]^T P(0)^{-1} \left[x_\Xi(0) - x_{\Xi_0} \right]$$

departure of initial state $x_E(0)$ from a first guess x_{E0};

$$+ \sum_{\Xi}^{A,T,O} \sum_{t=0}^{t_f} \left[E(t) x_\Xi(t) - y_\Xi(t) \right]^T R(t)^{-1} \left[E(t) x_\Xi(t) - y_\Xi(t) \right]$$

model $E(t)x_E(t)$ minus observed $y_E(t)$ at time t

$$+ \sum_{\Xi}^{A,T,O} \sum_{t=0}^{t_f-1} u_\Xi(t)^T Q(t)^{-1} u_\Xi(t)$$

deviation $u_E(t)$ of the controls from a prior

$$- 2 \sum_{\Xi}^{A,T,O} \sum_{t=0}^{t_f} \mu_\Xi(t) \left[x_\Xi(t) - L_\Xi[\ldots] \right]$$

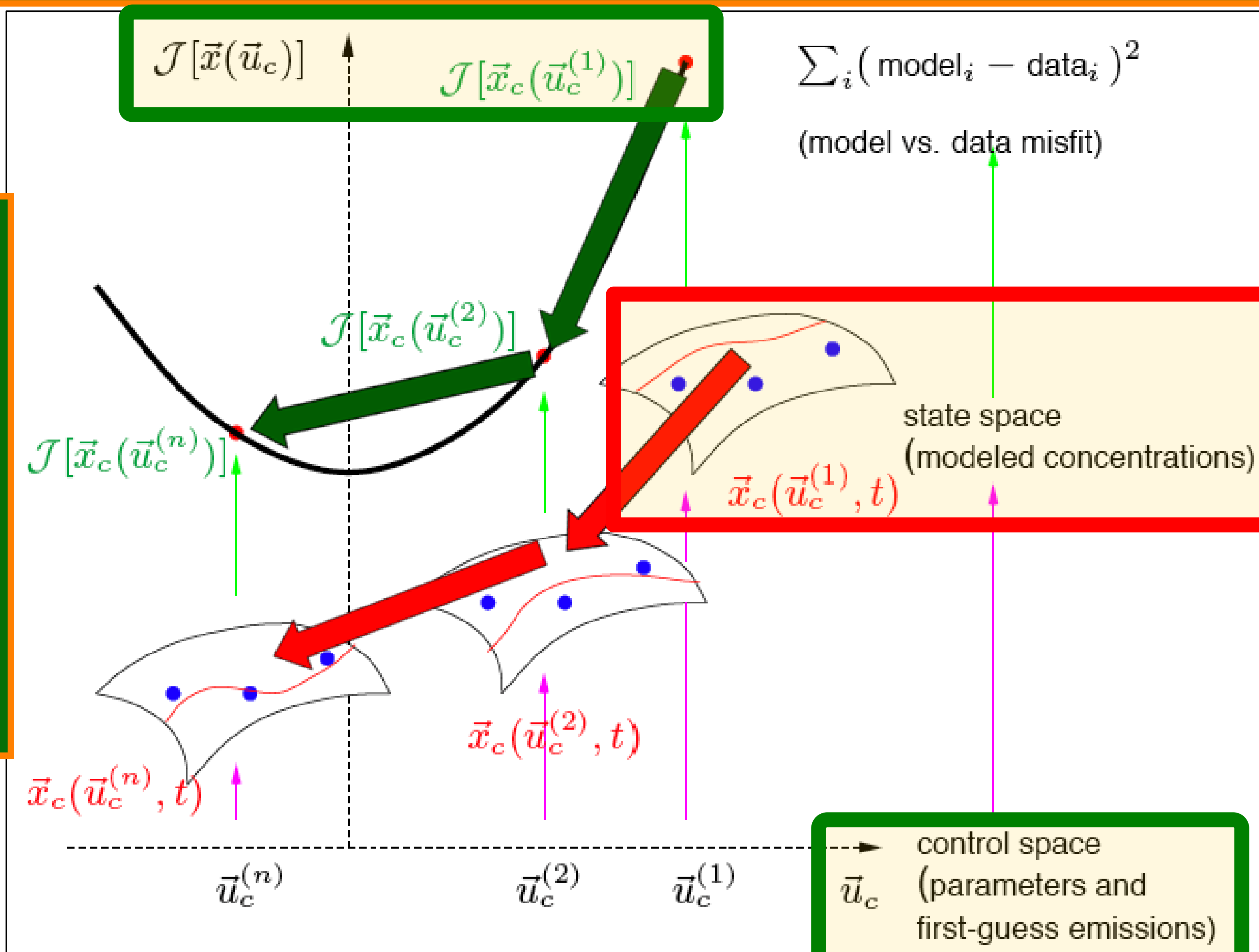
$$- 2 \sum_{t=0}^{t_f} \mu_{A2TO}(t) \left[q_{TO}(t) - M_{A2TO}[x_A(t+1)] \right]$$

$$- 2 \sum_{t=0}^{t_f} \mu_{TO2A}(t) \left[q_A(t+1) - M_{TO2A}[x_{TO}(t+1)] \right]$$

demand that $x_E(t)$ satisfy the model equations L_E and the coupling functions M_{abcd} (linking outputs of one model to inputs of another) through the introduction of Lagrange multipliers $\mu_E(t)$ and $\mu_{abcd}(t)$.

Iterative minimization of modeled (red trajectory) vs. observed (blue dots) concentration misfit $\mathcal{J}$, by variation of control variables. Optimal fit achieved for adjusted controls (parameters and emissions) $u=u_c^{(n)}$, which lead to best estimate concentrations $x=x_c^{(n)}$.

Vary u_c such as to minimize $\mathcal{J}$ ($d\mathcal{J}/du_c = 0$) via gradient-based optimizing algorithms (steepest descent, conjugate gradient, Newton method).



Observing System Simulation Experiments (OSSEs)

Powerful tools to address critical questions regarding the value of each measurement or approach & the needed precision, accuracy, & spatial & temporal resolution to lower the uncertainty in emission estimations.

OSSE 1. Optimizing Parameters:

How many and which parameters can be optimized by the system?

Assume that we have a "perfect" pseudo-dataset and provide some randomization to the parameter values used in the coupled system.

How sensitive are the parameters to the pseudo-data? Which parameters can be accurately recovered by optimizing the system?

Thus determine the level of model parameter uncertainty reduction (compared to prior estimates) possible using existing observations.

OSSE 2. Validating Emissions:

Is system constrained enough to optimize for "correct" emissions?

Assume a "perfect" pseudo-dataset for all but the anthropogenic emissions, and assume a perfect parameter dataset.

Can the framework optimize to reproduce the "real" emissions?

What is the influence of potential measurement biases on the derived emissions (e.g. satellite retrieval errors due to aerosol scattering).

OSSE 3. Value of Additional Measurements:

What new measurements (higher spatial and temporal resolution, greater precision) would improve estimations? Are multiple measurement systems required to avoid potential biases?

e.g. What if OSSE 2. *shows that the emissions cannot be completely re-captured even with near-perfect pseudo-data and "perfect" parameters. Can perform several additional experiments with "what-if" scenarios.*

Would we improve the model framework performance if we had:

- *Many more stations measuring atmospheric GHG mole fractions?*
- *Add on-site high frequency isotopic composition?*
- *Vertical profiles of GHG mole fractions and/or boundary layer height?*
- *Higher certainty in the surface distribution of GHGs (e.g. OCO-type measurements)?*

- *Considerably better coverage of ocean and land biomass?*
- *Considerably higher confidence in ocean and land satellite measurements (e.g. 10% error as opposed to 30%), different satellite orbit patterns (altered spatial and temporal coverage), different remote sensing techniques (active vs. passive), or different retrieval algorithms?*
- *An extended network of surface flux observations (e.g. using eddy covariance measurements)?*

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http://web.mit.edu/global change

BY HOW MUCH WILL IT IMPROVE SCIENTIFIC UNDERSTANDING?

HOW ACCURATE SHOULD IT BE?

WHAT WILL IT COST & WHO WILL PAY?

WHO WILL GOVERN & OPERATE IT?

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A Strategy for a Global Observing System for Verification of National Greenhouse Gas Emissions

R. Prinn, P. Heimbach, M. Rigby, S. Dutkiewicz, J.M. Melillo, J.M. Reilly, D.W. Kicklighter and C. Waugh

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