Precipitation and the Global Air-Sea CO_2 Flux

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Acknowledgments:

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Air-Sea Gas Flux Climatology Workshop September 26, 2013

Overview

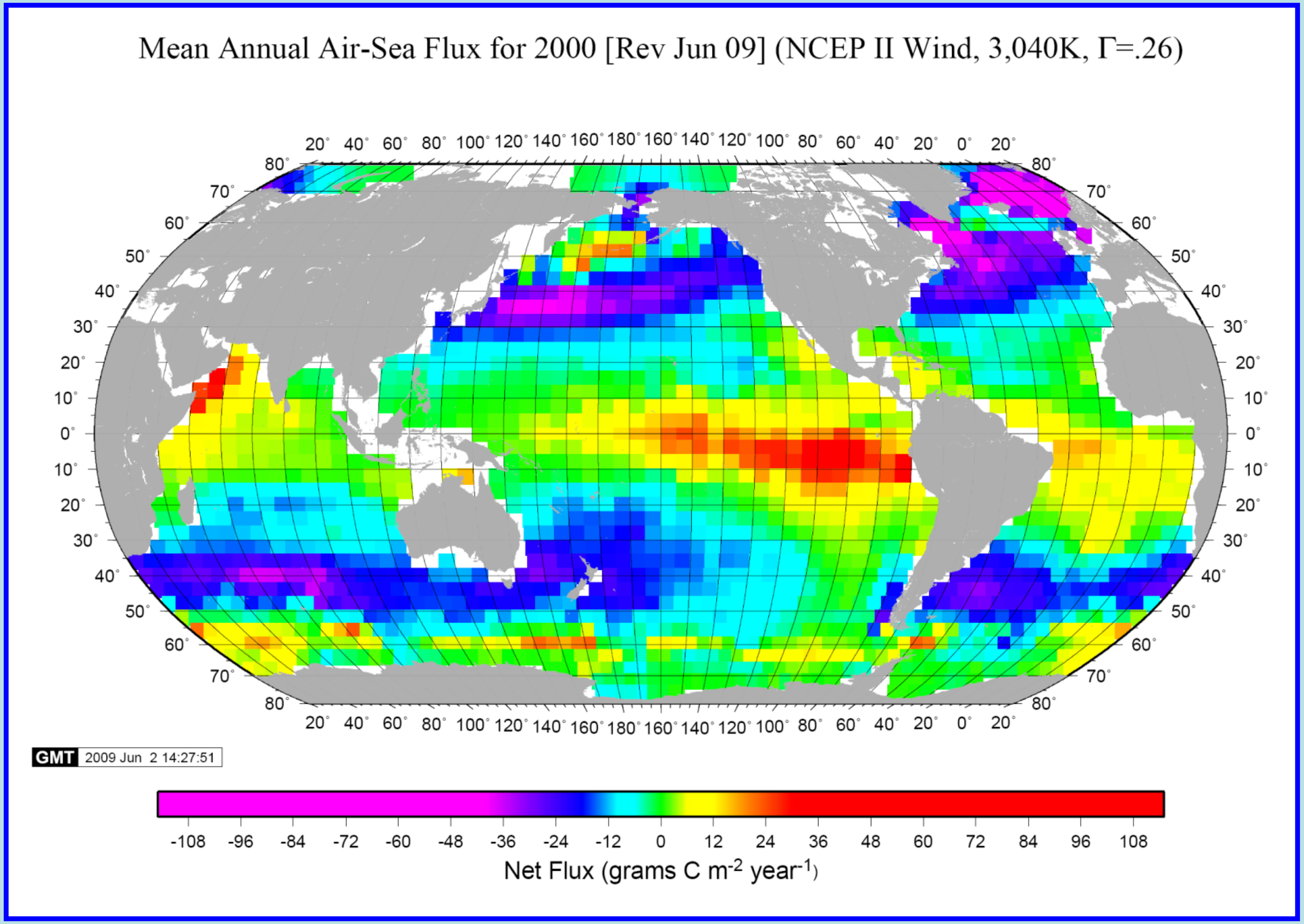
- **Komori et al (2007) investigated the effects of impinging rain and rain deposition on the net global CO2 flux.**

- **Observations from Biosphere2 III (Rain) Experiments in 2003**
  - **SSS dilution and dependence on rain rate**
  - **K_{rain} scales with KEF in saltwater as it does for freshwater**

- **Describe the effect of** Chemical Dilution **on the enhancement of gas exchange.**
  - **As this effect is confined to a very near-surface layer it is neglected in surface mixed layer and climate models as well as by standard measurements of surface pCO_2 that are normally made at 3-5 m depth.**

- **Quantify the range of precipitation effects on the global CO_2 flux**
  - **Takahashi et al. (2009) ΔpCO_2 and NCEP II winds**
  - **Global Precipitation Climatology Program daily rain product**

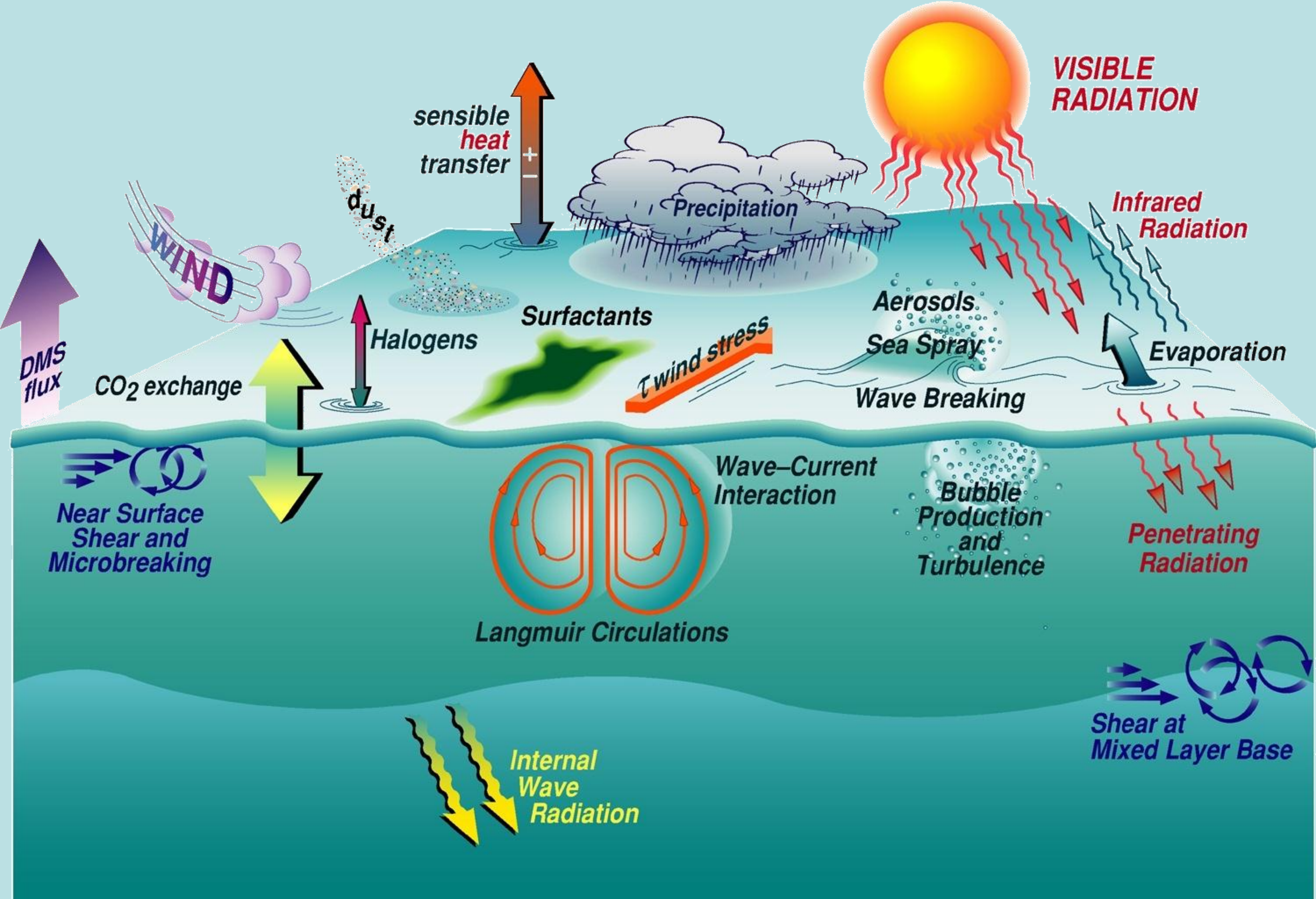
Global Flux of CO_2



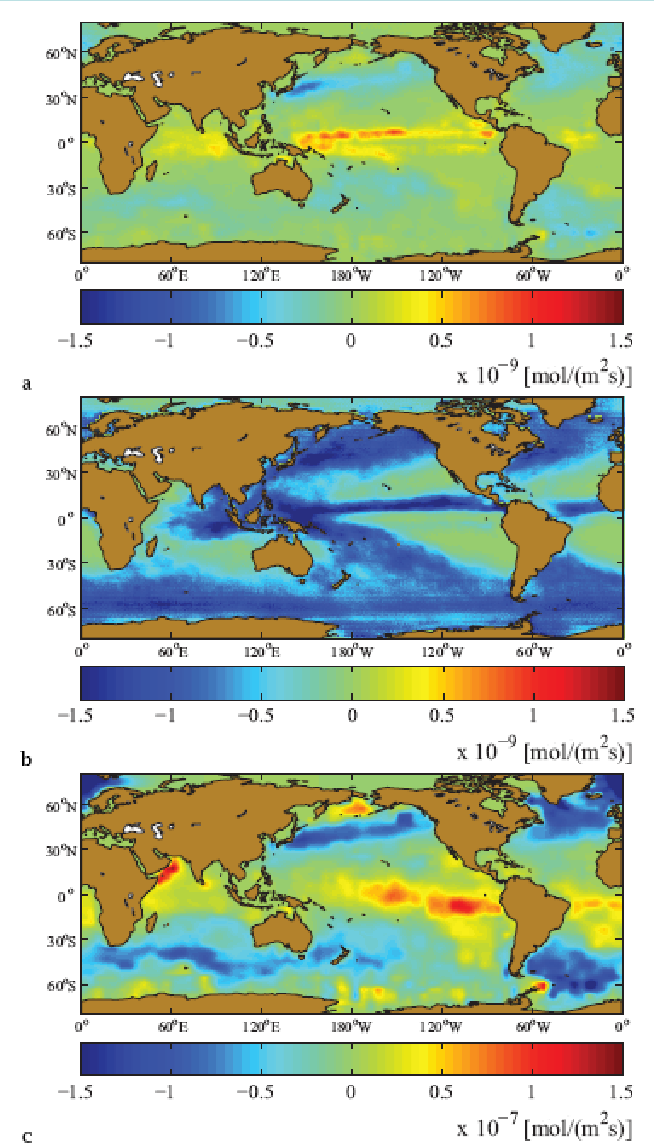
The flux of gas is the product of the gas transfer velocity and the concentration difference between atmosphere and the ocean

Takahashi et al., 2009

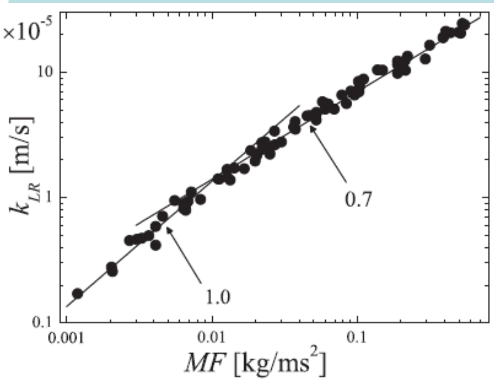
Air-Sea Interaction Processes



Global Flux of CO_2 Due to Rain for 2001



Komori et al., 2007

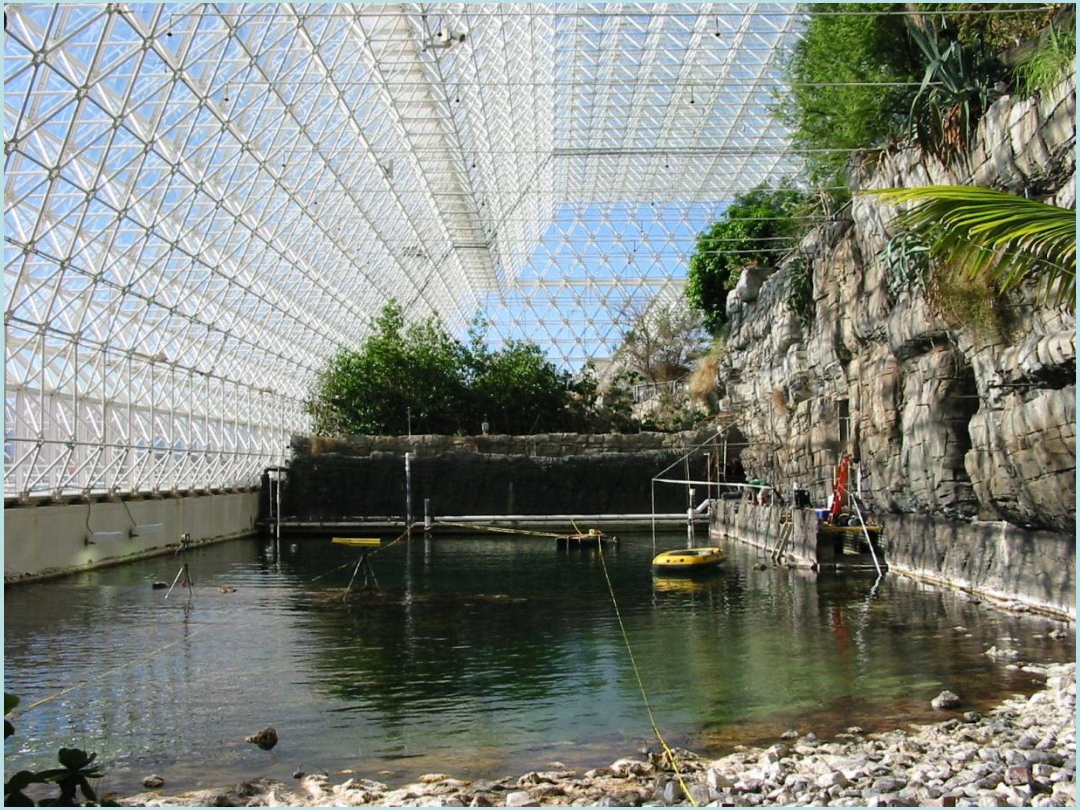


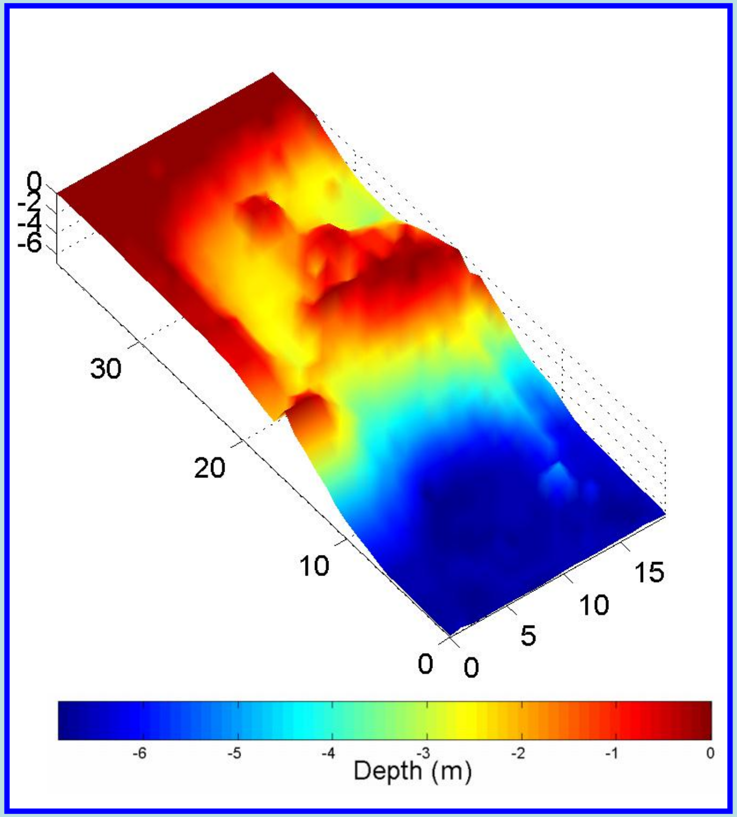
Impinging raindrops enhance turbulence (Ho et al., [1997, 2000, 2004], Takagaki & Komori [2007], Zappa et al., [2009])

Raindrop comes to equilibrium before impinging (Sugioka and Komori [2007]).

Komori et al. [2007] suggested that the effect of rainfall on the net global CO_2 budget for 2001 is less than 3%. Also found that rainfall effects were significant for the local air-sea CO_2 budget in equatorial and mid-latitude regions compared to the

Biosphere 2 Ocean





Mean depth of 3.5 m

- **2,650 m^3 of saltwater**
- **Surface area of 711 m^2**
- **Salinity of 35.5; Water maintained at 26.5 ˚C**
- **Vacuum wave generator**
- **Most of the ceiling above ocean > 13 m**

Zappa, C. J., D. T. Ho, W. R. McGillis, M. L. Banner, J. W. H. Dacey, L. F. Bliven, B. Ma, and J. Nystuen (2009), Rain-induced turbulence and air-sea gas transfer, *Journal Of Geophysical Research Oceans, 114(C07009), doi:10.1029/2008JC005008.*

Bio2 RainX III

• Investigate the effect of freshwater rain on the gas transfer velocity for a saltwater ocean

•Significant dilution of the near-surface salinity in addition to enhancement of turbulence and gas transfer velocity.

Relevant Measurements:

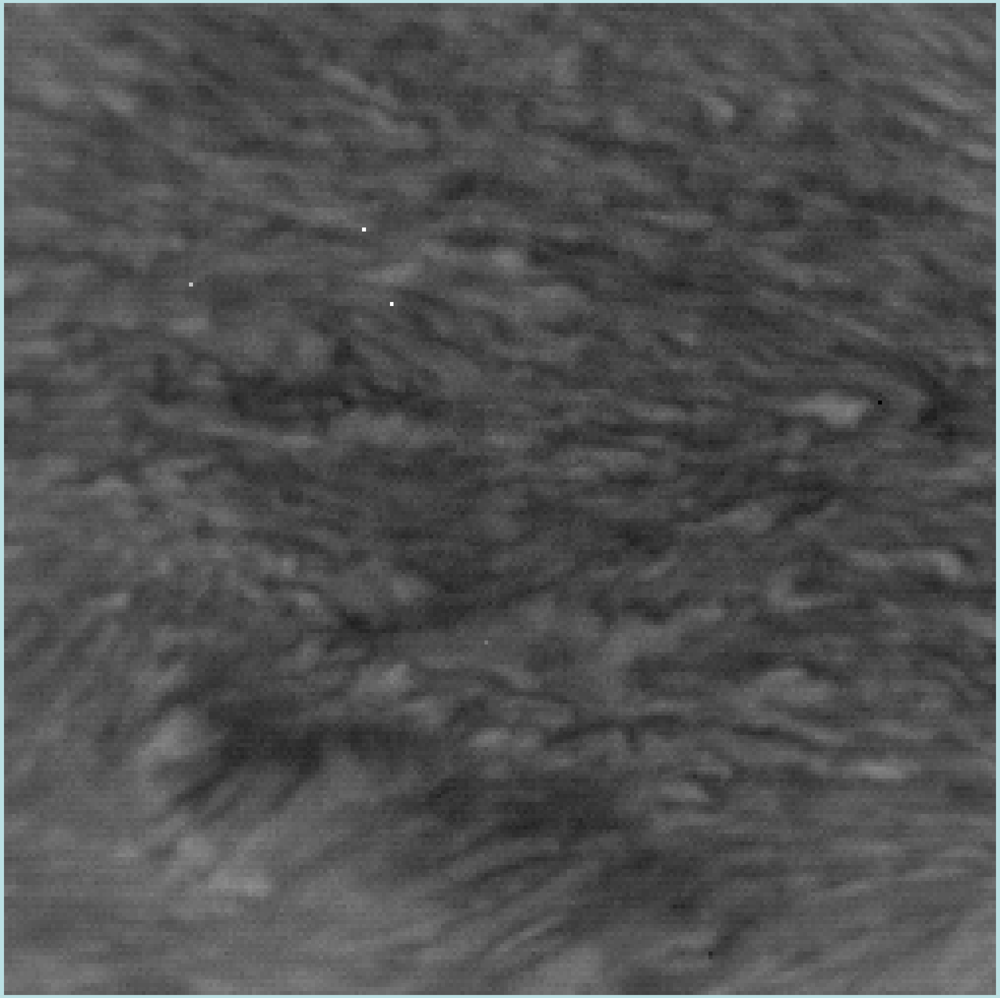
- **Gas exchange determined by SF_6 evasion experiment.**
- **Rain rate and drop size distribution using NASA's Rain Imaging Sensor.**
- **Monitoring the high-resolution temperature and salinity gradients.**
- **Turbulence measurements using a pulse coherent sonar.**

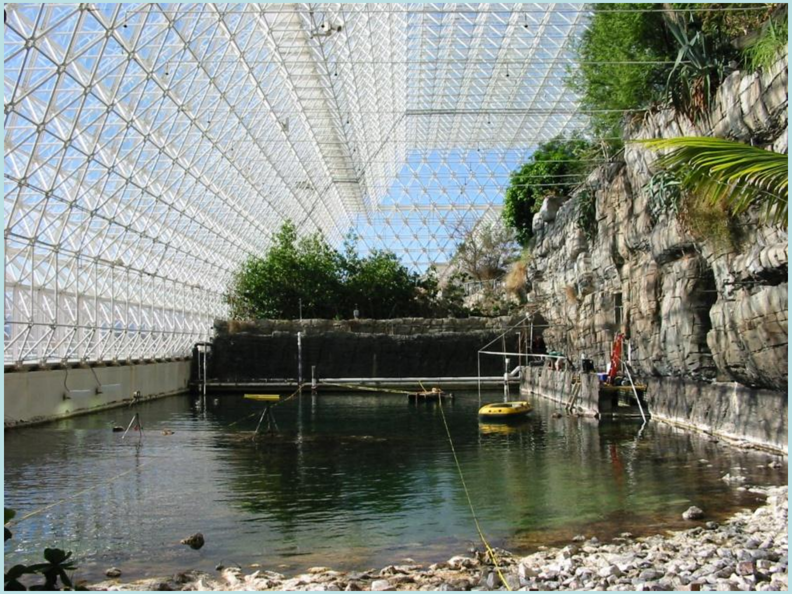
•RE1: a long rain event (180 min).

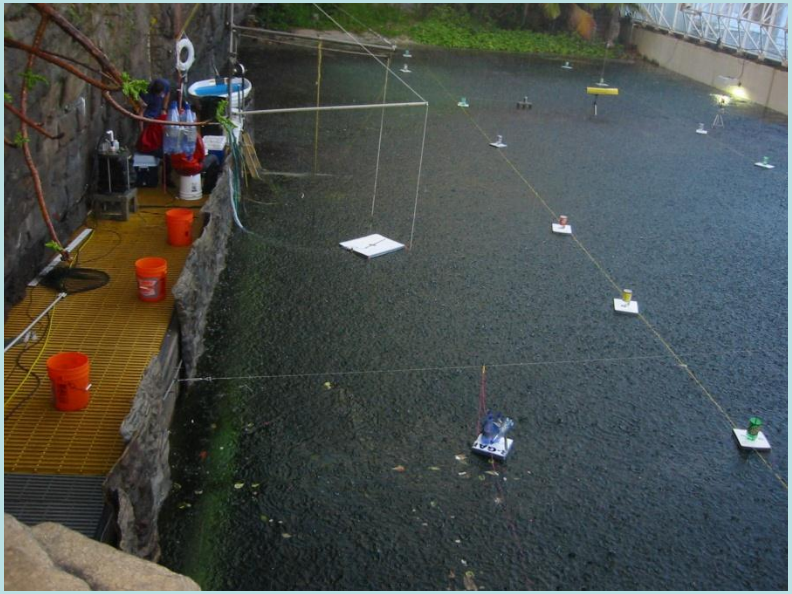
•RE2/3: a short rain events (30 min).

•RE4: a longer rain event (122 min), during which an SF_6 evasion experiment was conducted.

Infrared Imagery of Impinging Rain



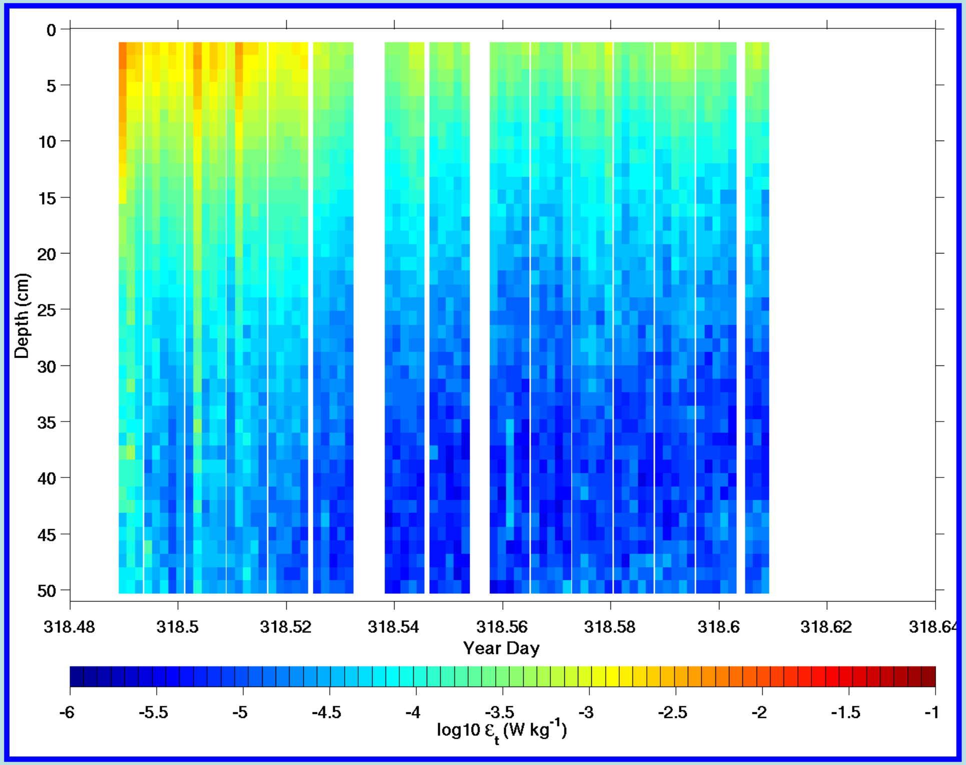




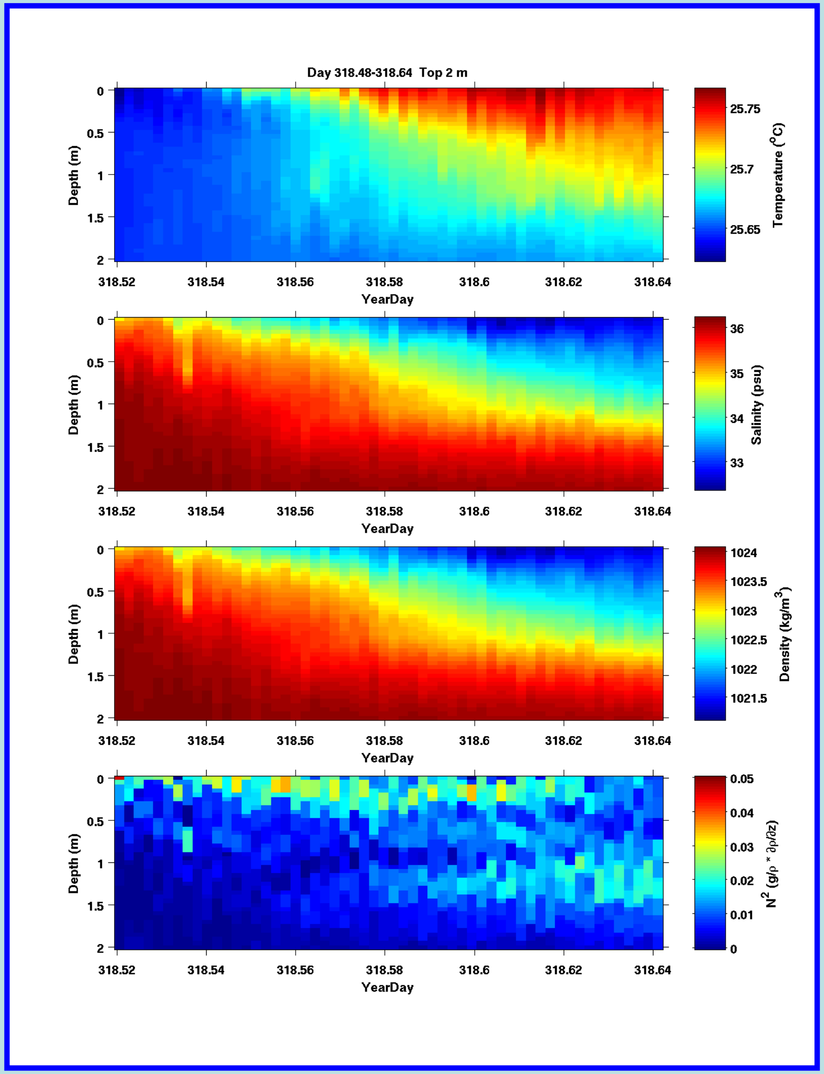
Effect of Stratification on Near-Surface Turbulence

- Turbulence decays with depth from the air-water interface, trapped by stratification
- Turbulence very near the surface is key to transfer.

Turbulent Dissipation Rate



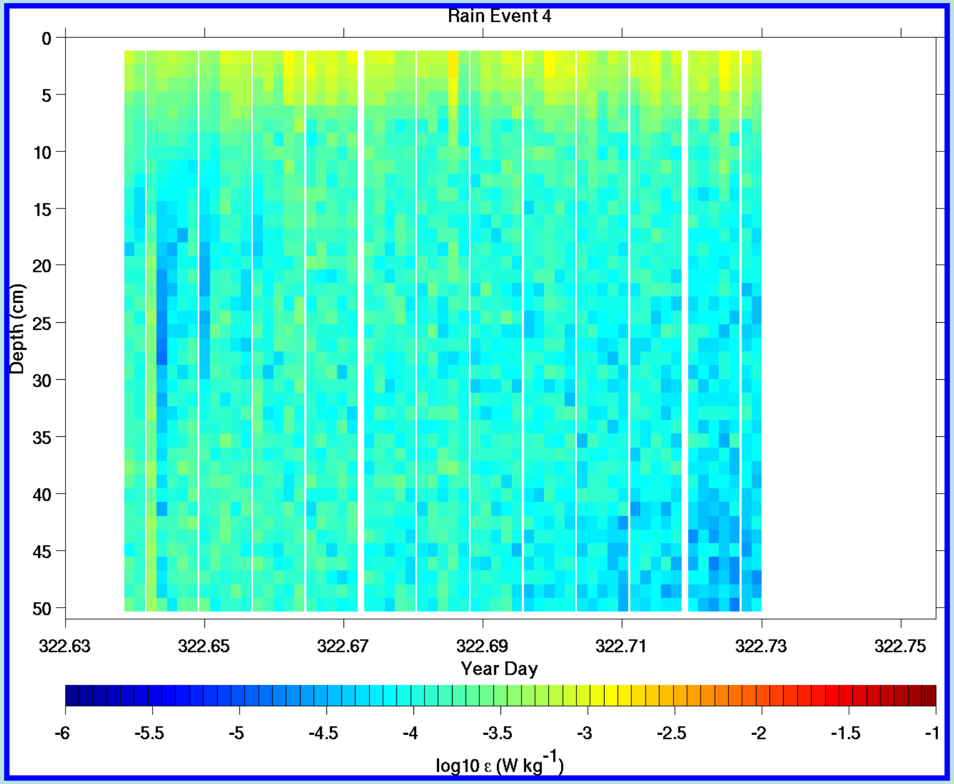
Stratification



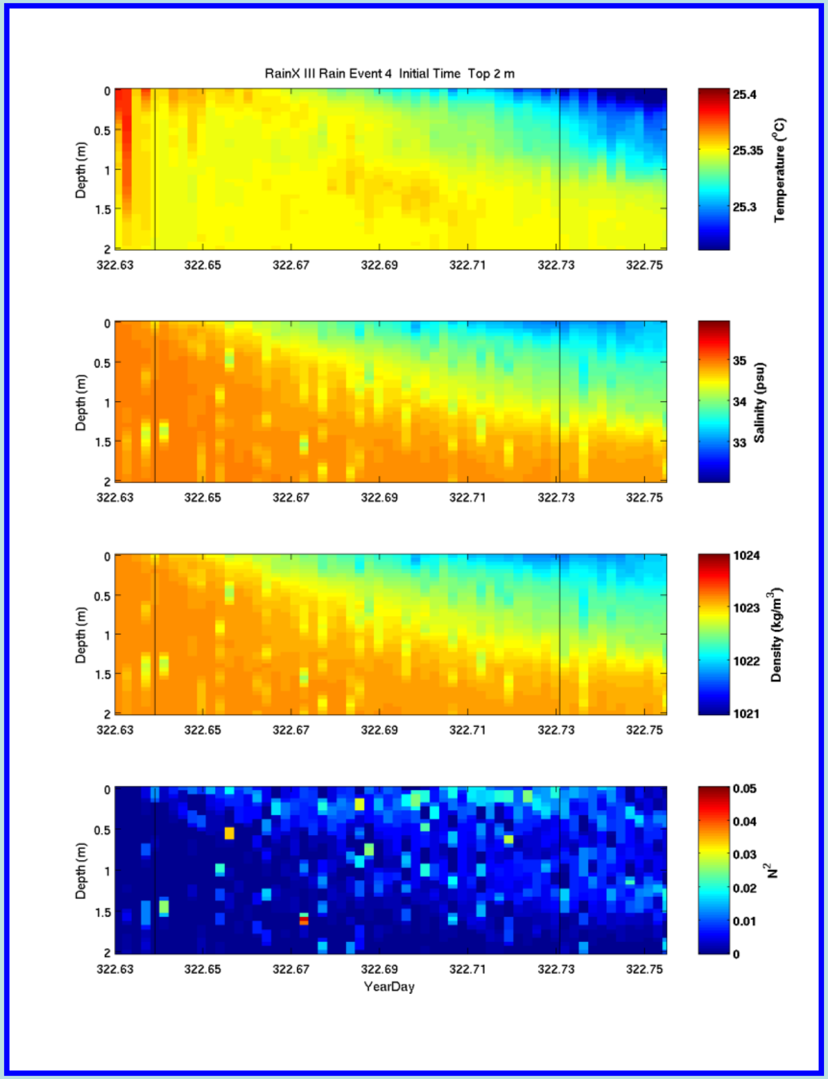
Effect of Stratification on Near-Surface Turbulence

- **Turbulence decays with depth from the air-water interface,**
- **Less Stratified because of background mixing**
- **Turbulence very near the surface is key to transfer.**

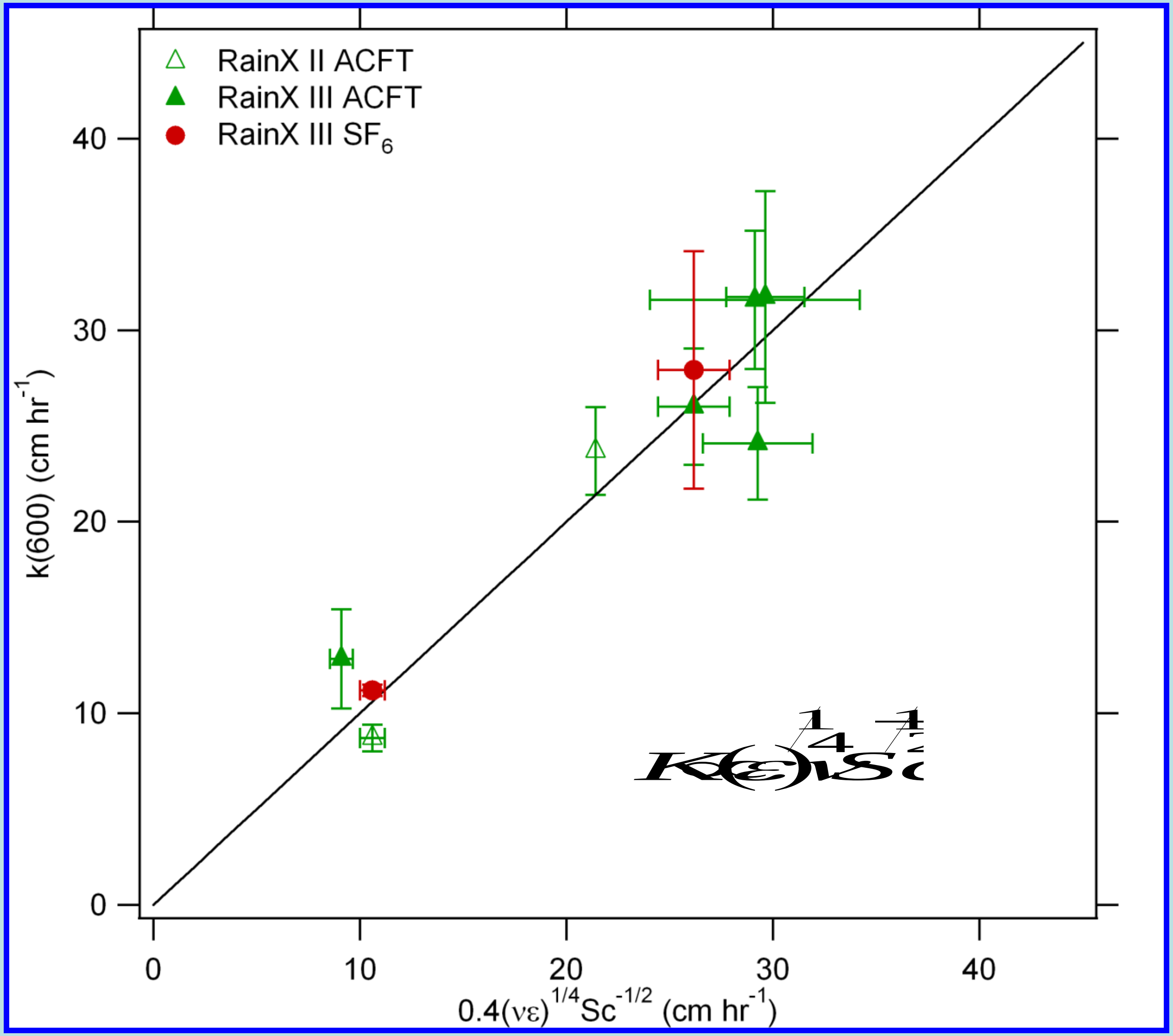
Turbulent Dissipation Rate



Stratification



Gas Transfer Scaling



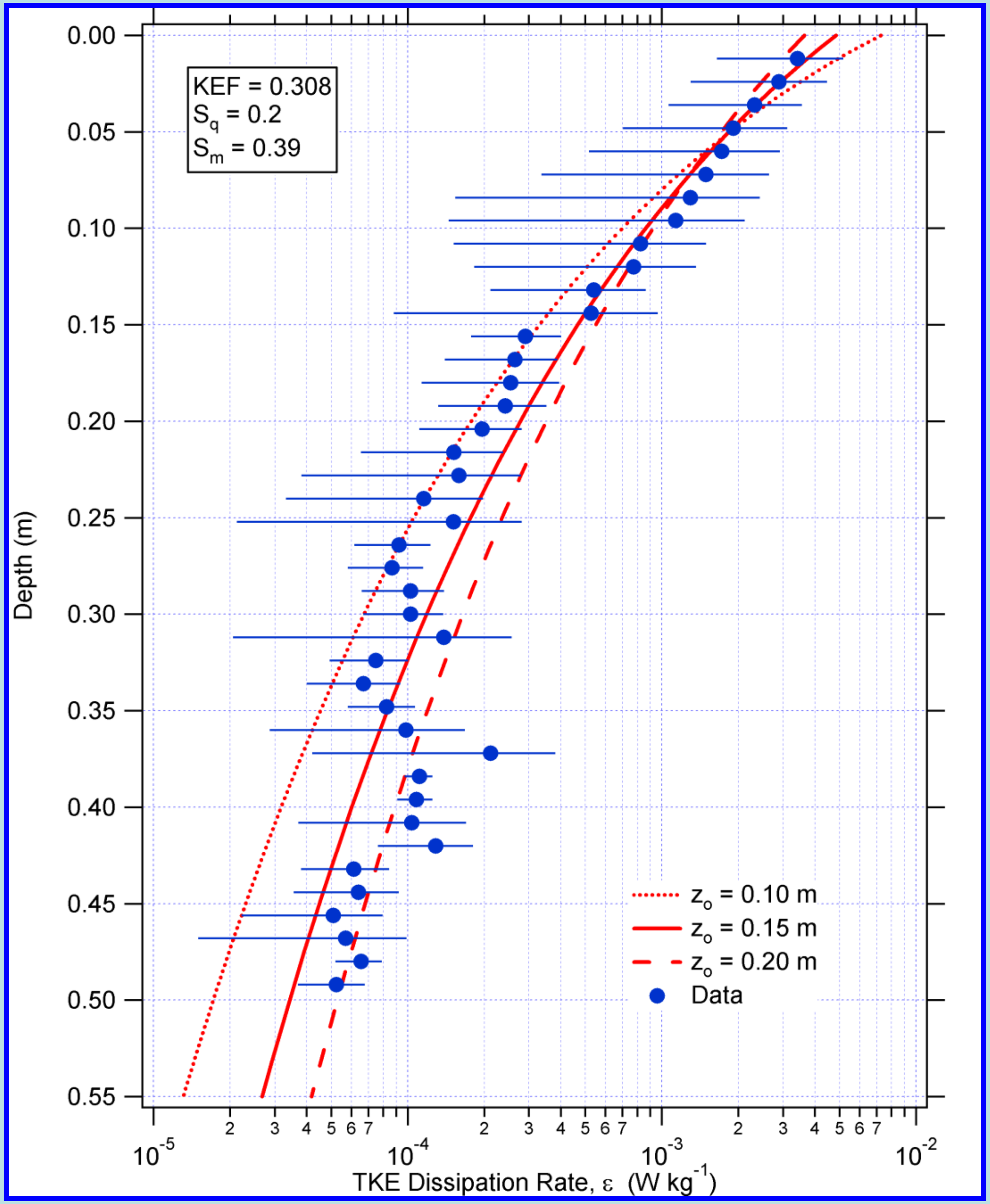
Gas transfer velocity from ACFT versus modeled *k* as determined from (1) for all rain rates during both RainX II (see *Ho et al.* [2004]) and RainX III at Biosphere 2. The gas transfer measurement using the SF_6 tracer release during RainX III is also shown for comparison.

Mean Turbulence Profile

- **Turbulence decays with depth from the air-water interface**

- **Compared to Craig-Banner model with standard Mellor-Yamada coefficients, the measured KEF input, and variation in zo based on previous field measurements.**

- **Note: turbulence very near the surface is key to air-sea gas transfer.**



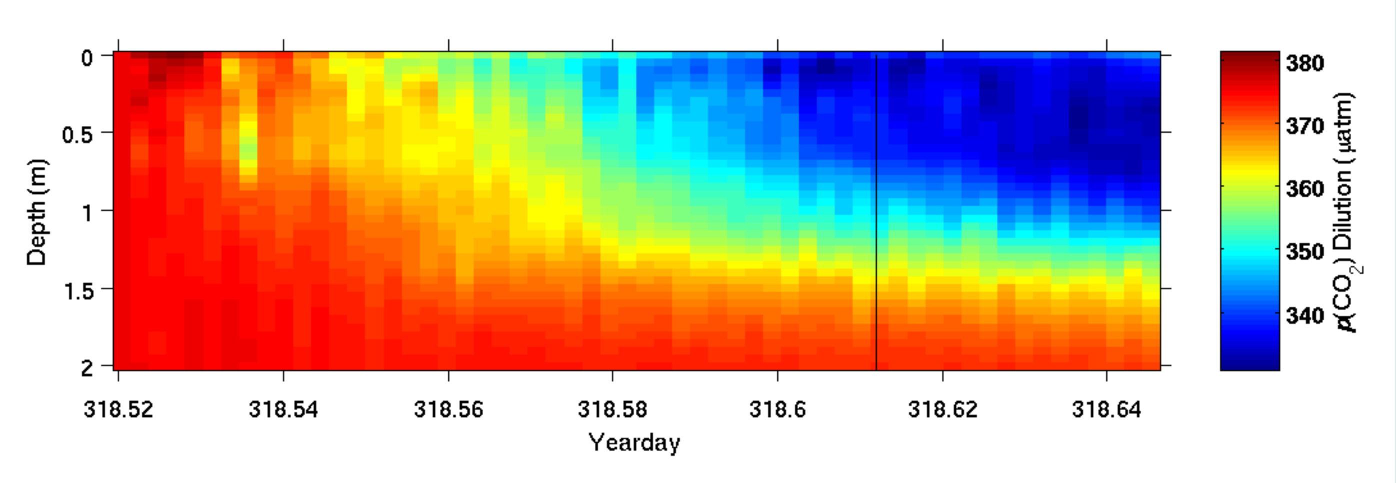
Dissipation Rates:

Breaking Waves:
10^{-5} to 10^{-2} W kg^{-1}

Energetic Mixed Layers:
10^{-6} to 10^{-4} W kg^{-1}

Hudson River:
10^{-7} to 10^{-5} W kg^{-1}

Sea Surface Chemical Dilution



• Near-surface salinity, total alkalinity (TA), and dissolved inorganic carbon (DIC) are diluted during rainfall in proportion to the excess of precipitation over evaporation. This dilution also decreases *p*(CO_2) in the surface boundary layer [*Dickson et al.*, 2007].

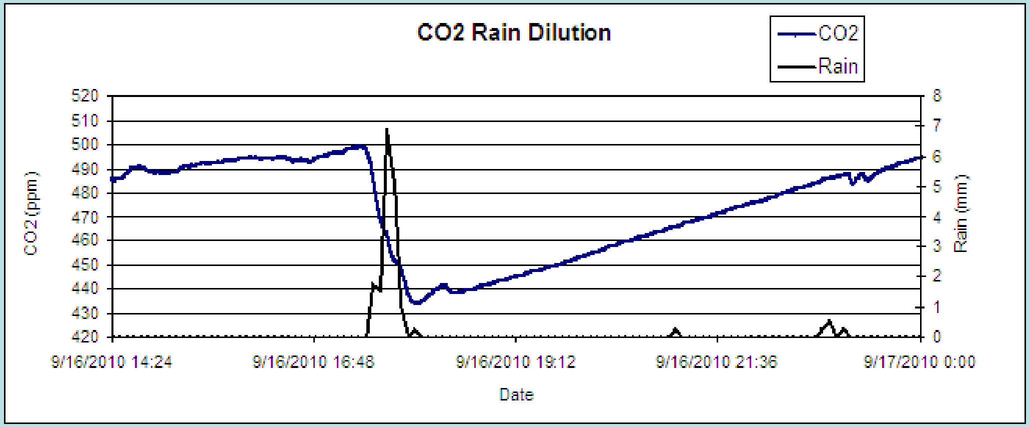
• Observational data from the model ocean studies [*Zappa et al.*, 2009] showed the rate of sea surface salinity (SSS) dilution is linearly dependent on the measured rain rate.

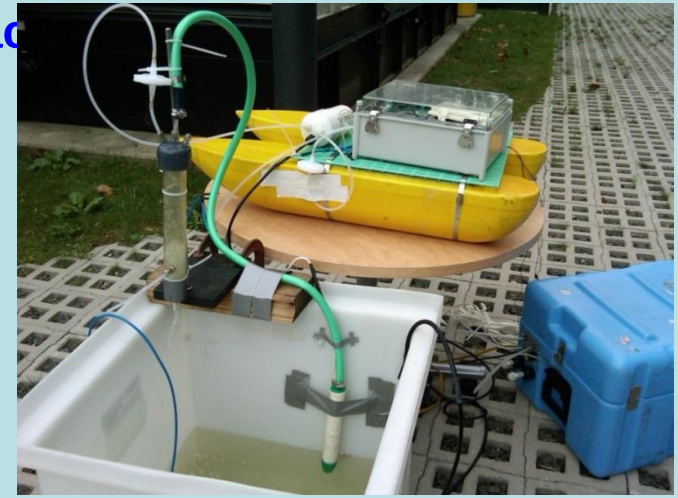
• Effects of dilution of DIC and TA on *p*(CO_2) are determined based on standard carbon system models [*Dickson et al.*, 2007].

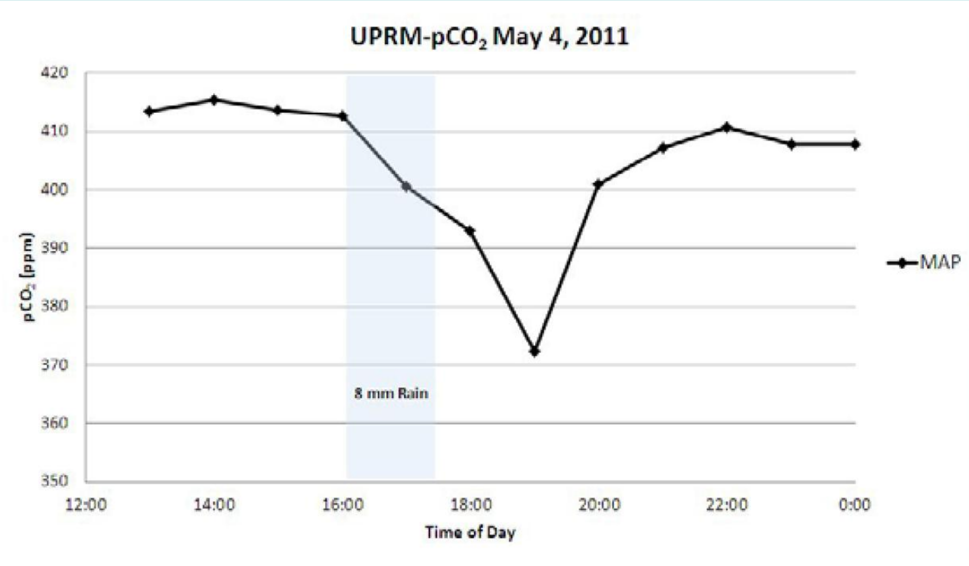
• Due to the strong stratification, surface effect can be maintained for a significant time.

Field Observations

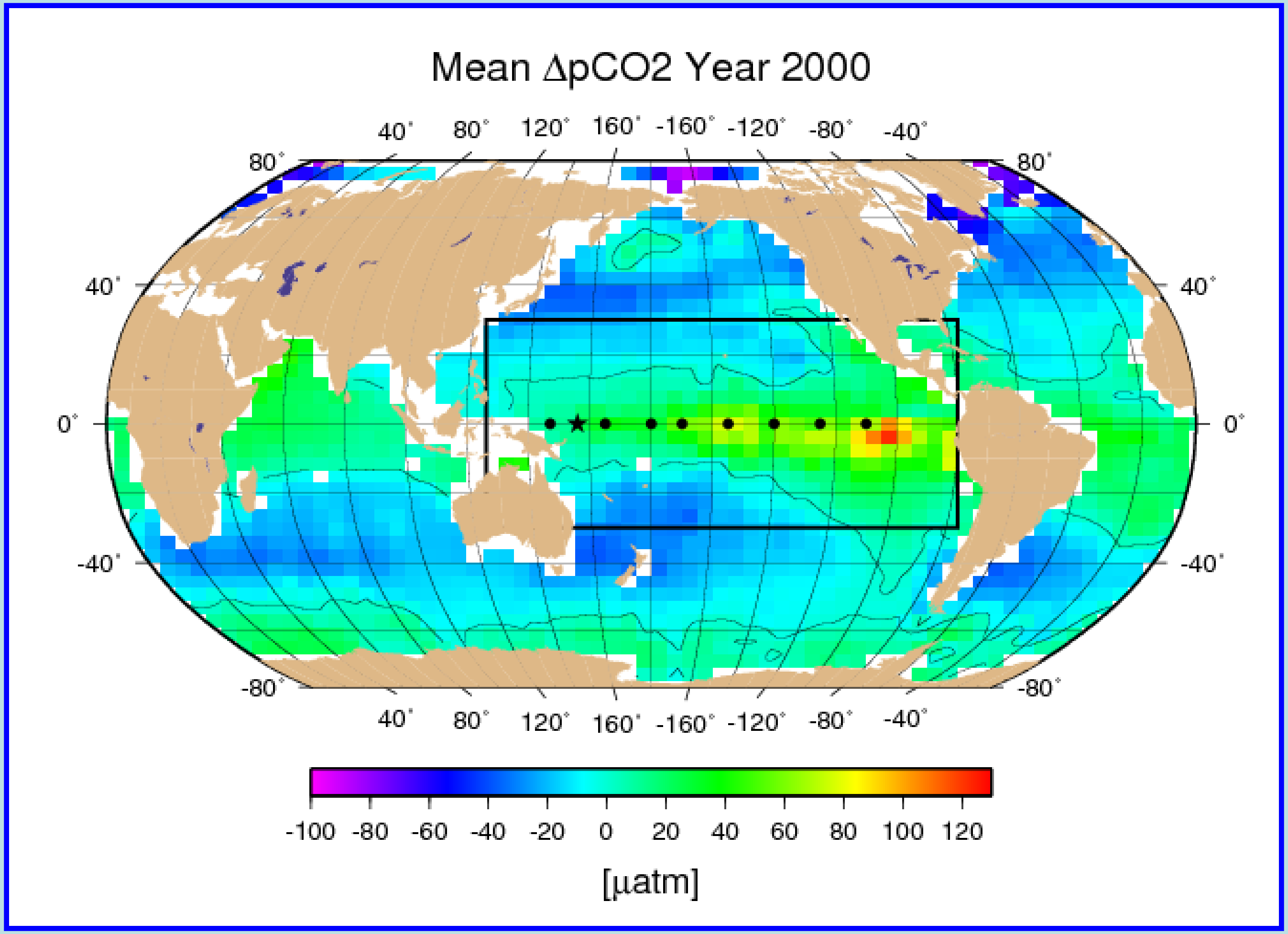
- **Seawater collected from Long Island Sound.**
- **Realistic chemicals mimicking the ocean surfac**







Takahashi ΔpCO_2 Database for 2000



The flux of gas is the product of the gas transfer velocity and the concentration difference between atmosphere and the ocean

Takahashi et al., 2009

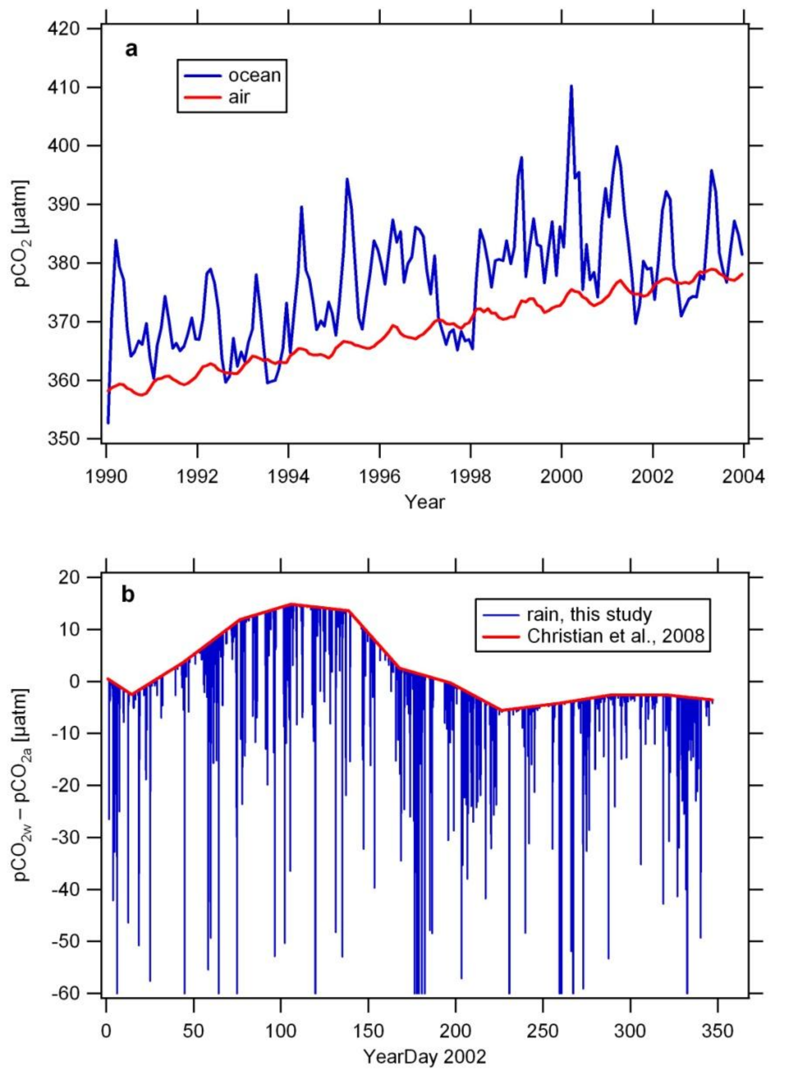
Quantifying the Flux Components

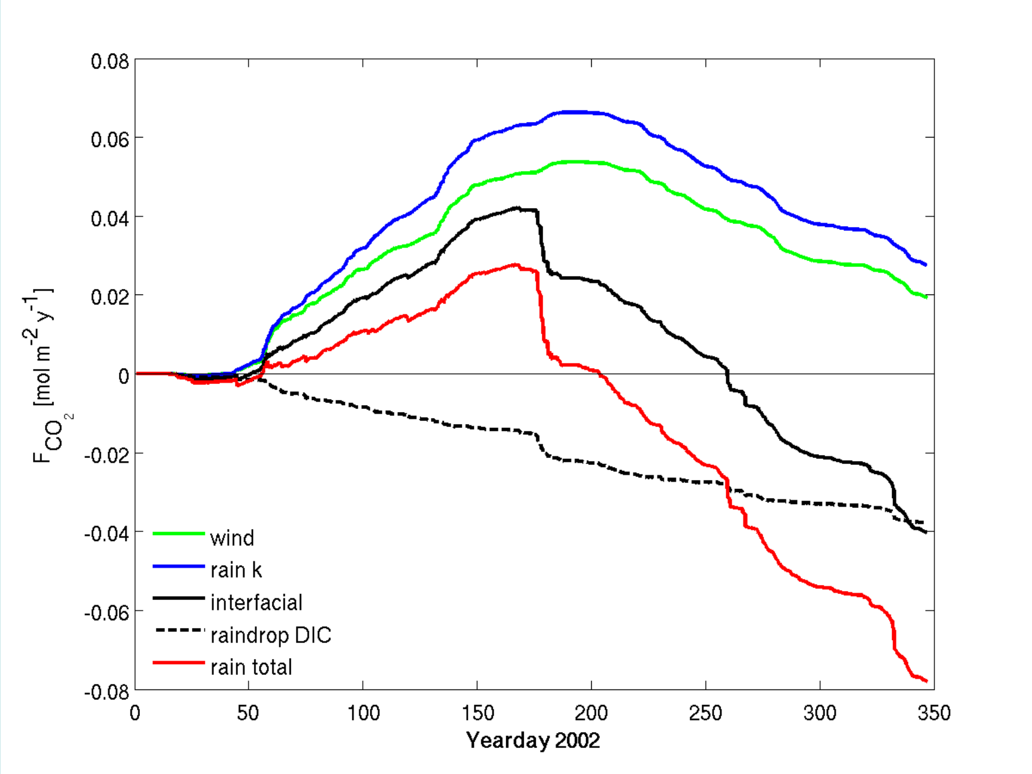
•Transfer velocity due to wind is determined from the quadratic relationship of *Wannhikhof* (1992).

•Transfer velocity for both wind and rain is determined from the sum of the quadratic relationship of *Wannhikhof* (1992) and k_{rain}. The transfer velocity due to rain is determined from Ho et al. (1997) and the results are compared. Ho et al. (2007) have suggested that the k_{wind} and k_{rain} are linearly additive.

• Diluted surface $p(CO_2)$ is ocean surface $p(CO_2)$ after chemical dilution and is determined using a dilution model with measured salinity and rain rate. Strong dilution is typically missed by surface mixed layer and climate models, as well as measurements.

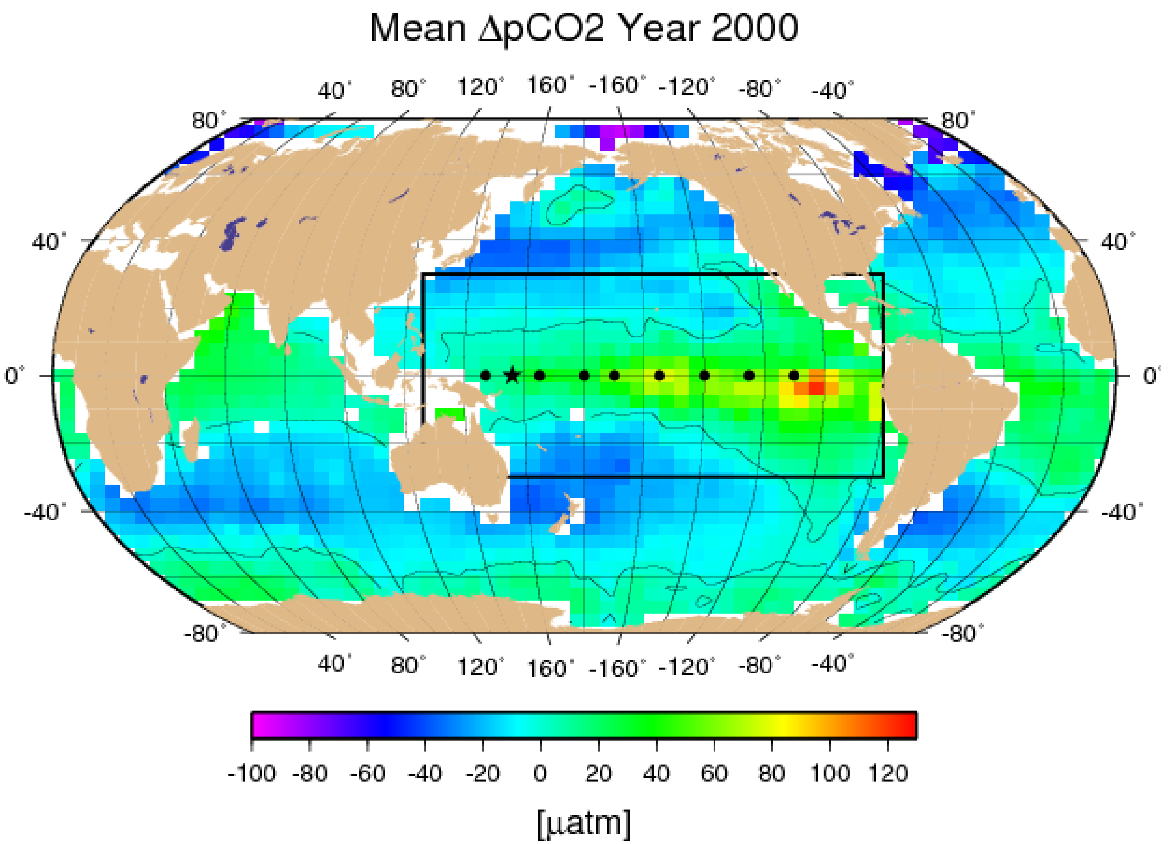
Western Equatorial Pacific

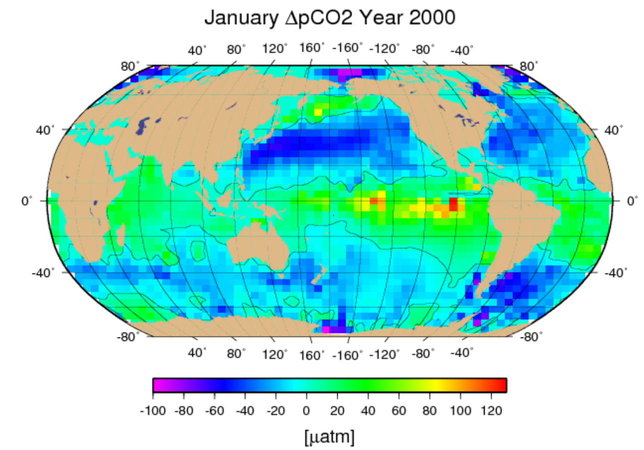


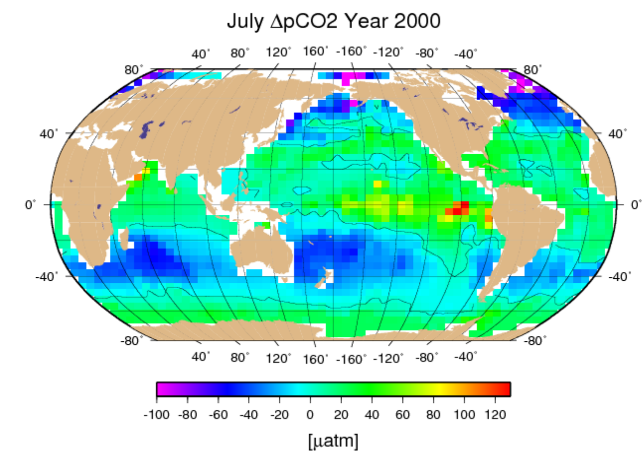


Turk, D., C. J. Zappa, C. S. Meinen, J. R. Christian, D. T. Ho, A. G. Dickson, and W. R. McGillis (2010), Rain impacts on CO_2 exchange in the western equatorial Pacific Ocean, Geophys. Res. Lett.,doi:10.1029/24 2010GL045520.

Takahashi ΔpCO$_2$ Database for 2000



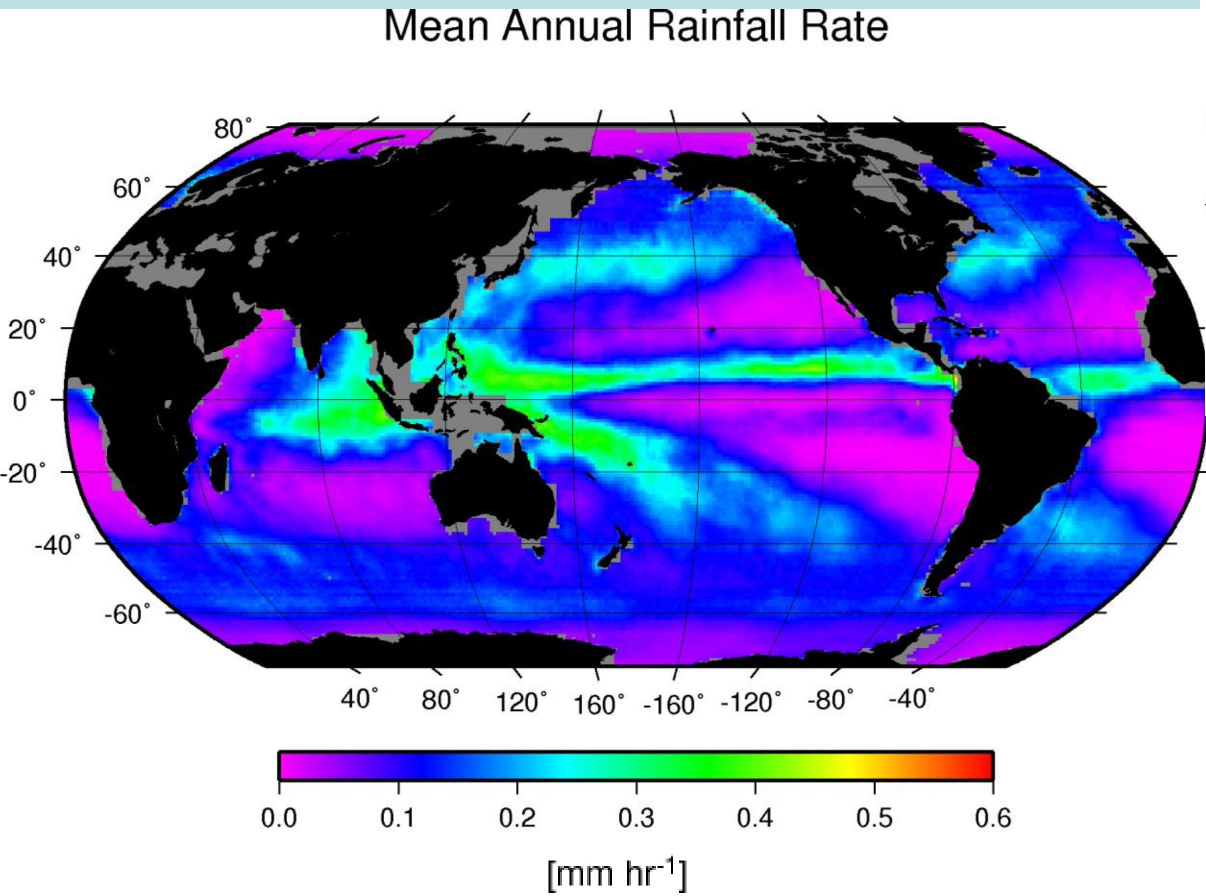


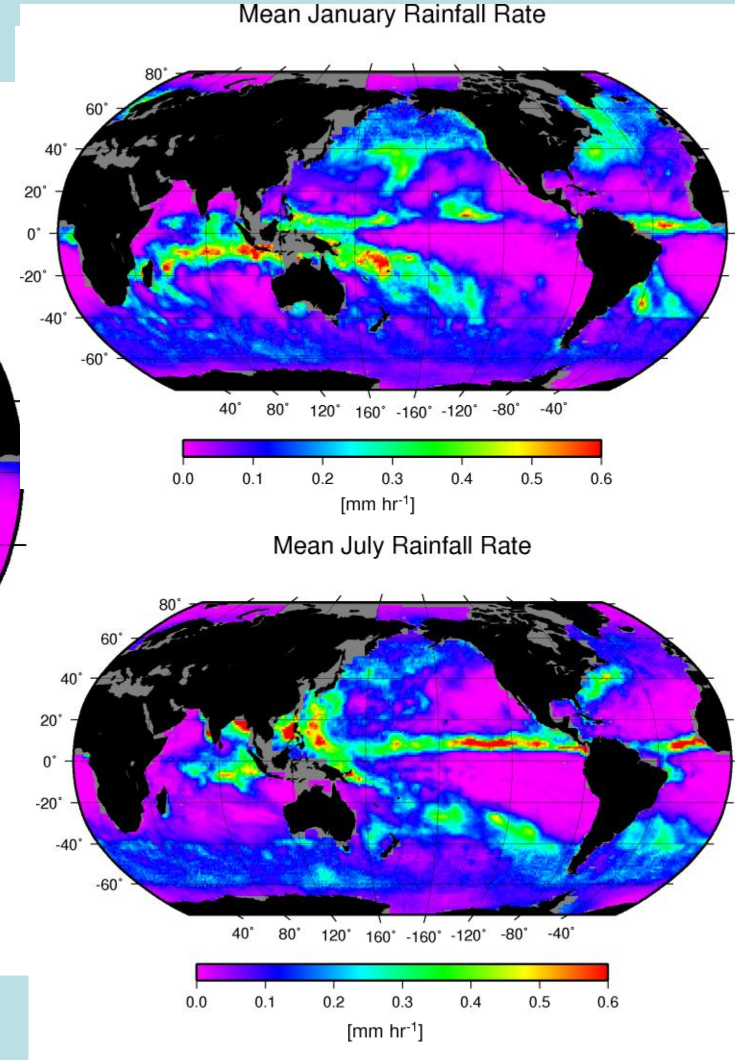


The flux of gas is the product of the gas transfer velocity and the concentration difference between atmosphere and the ocean

Takahashi et al., 2009

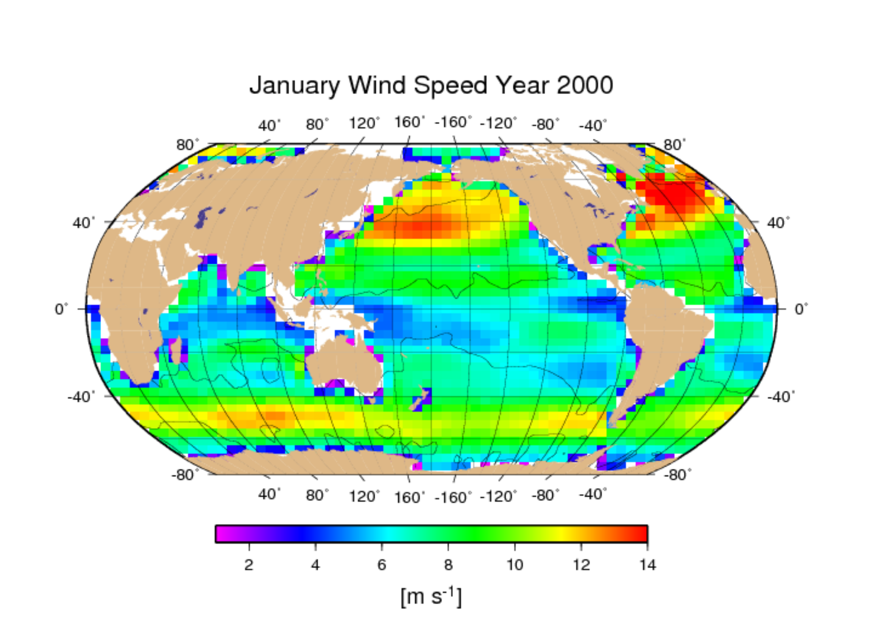
Global Precipitation Climatology Project

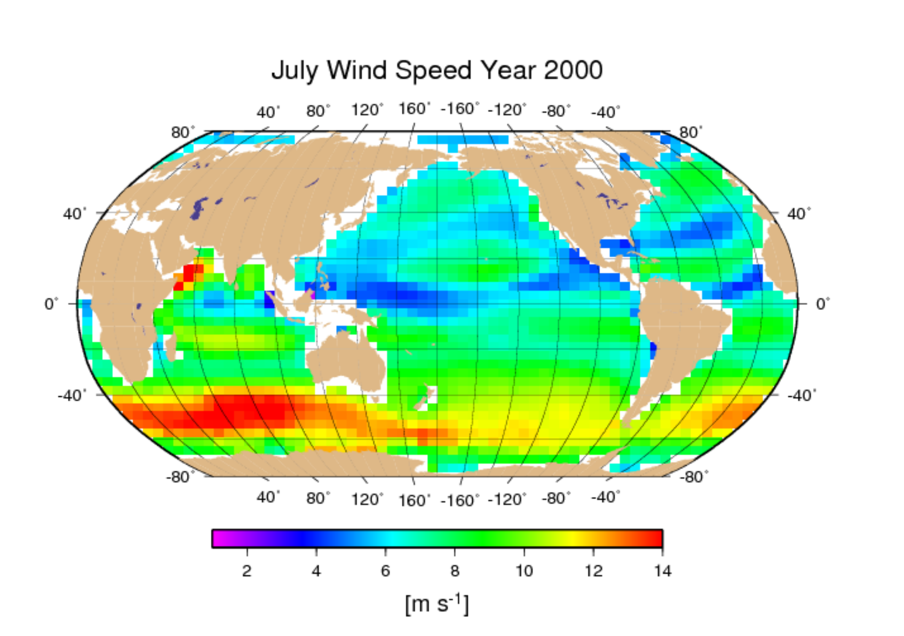




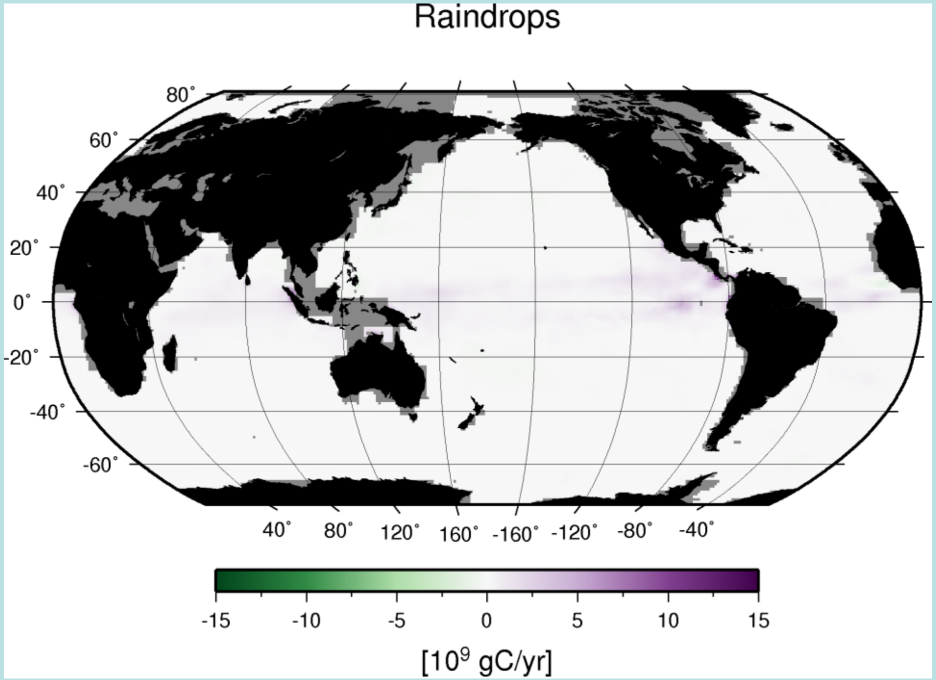
- **Combination of Special Sensor Microwave/Imager (SSM/I) data, infrared (IR) sensor estimates, Atmospheric Infrared Sounder (AIRS data from the NASA Aqua) and Television Infrared Observation Satellite Program (TIROS) Operational Vertical Sounder (TOVS) and Outgoing Longwave Radiation Precipitation Index (OPI) data from the NOAA series satellites..**

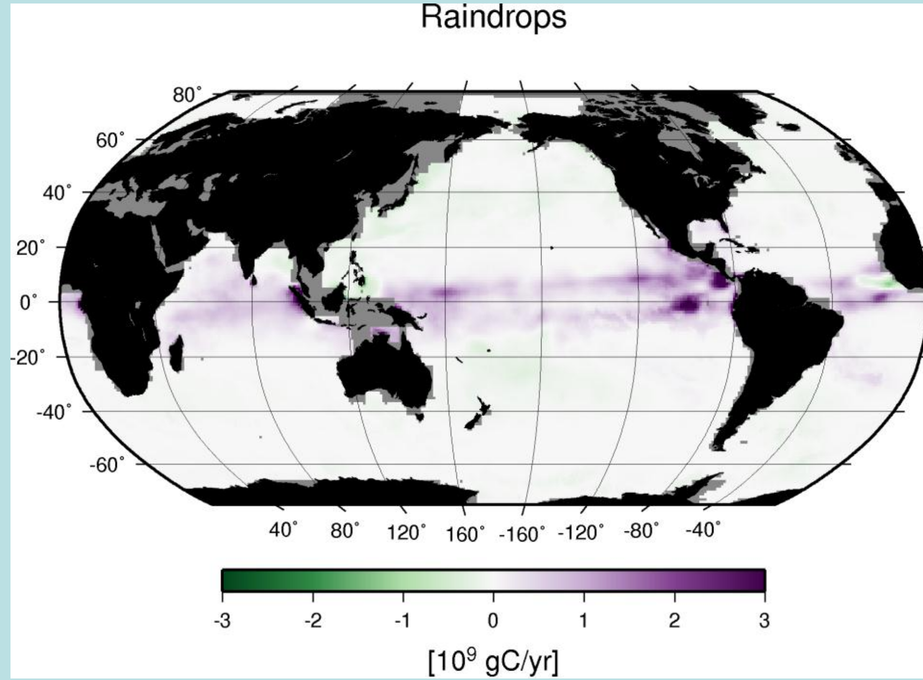
Global Seasonal Wind Speed





Global Uptake of CO_2 Due to Rain Turbulence





k_{total} from Harrison et al. [2012]

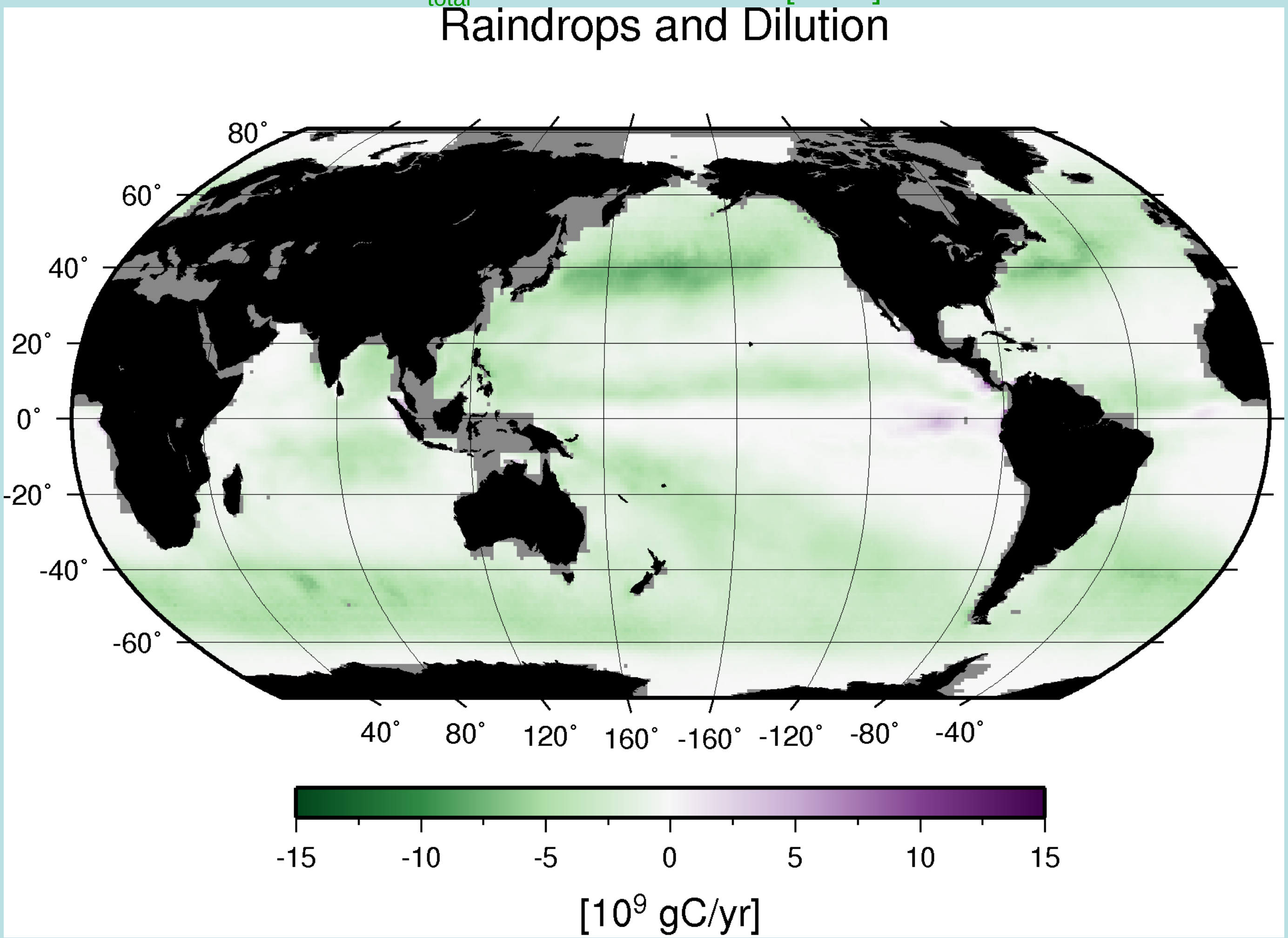
$$k(600)_t = k(600)_w + \left(1 - e^{-a\beta}\right) k(600)_r$$

$$k(600)_r = 63.02(KEF_r)^{0.6242}$$

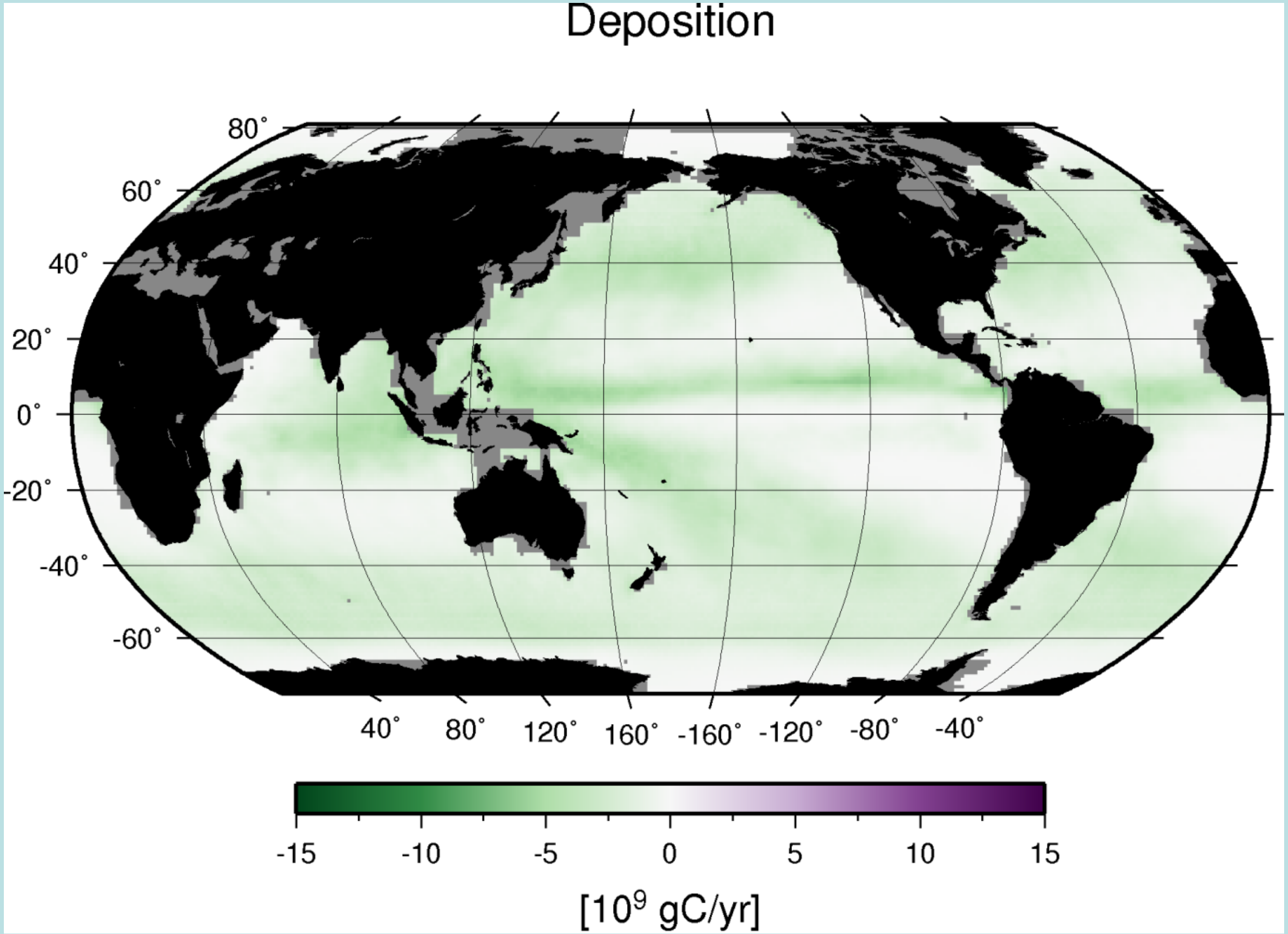
$$KEF_r = 0.0112R$$

Global Uptake of CO_2 Due to Rain Turbulence and Dilution

k_{total} from Harrison et al. [2012]



Global Rain Deposition of CO_2

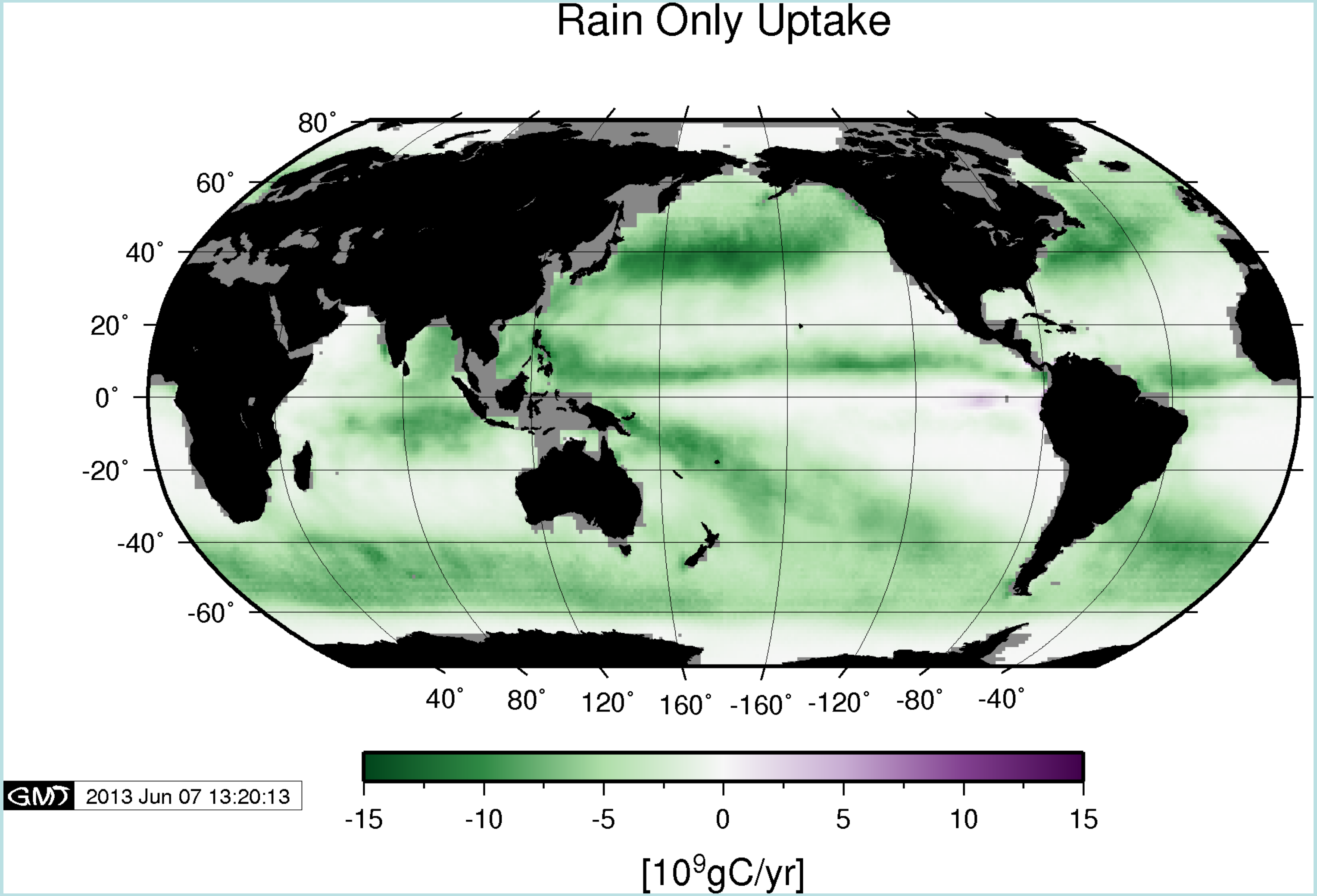


The deposition flux of gas is the product of the rain rate and the concentration of CO_2 in the atmosphere.

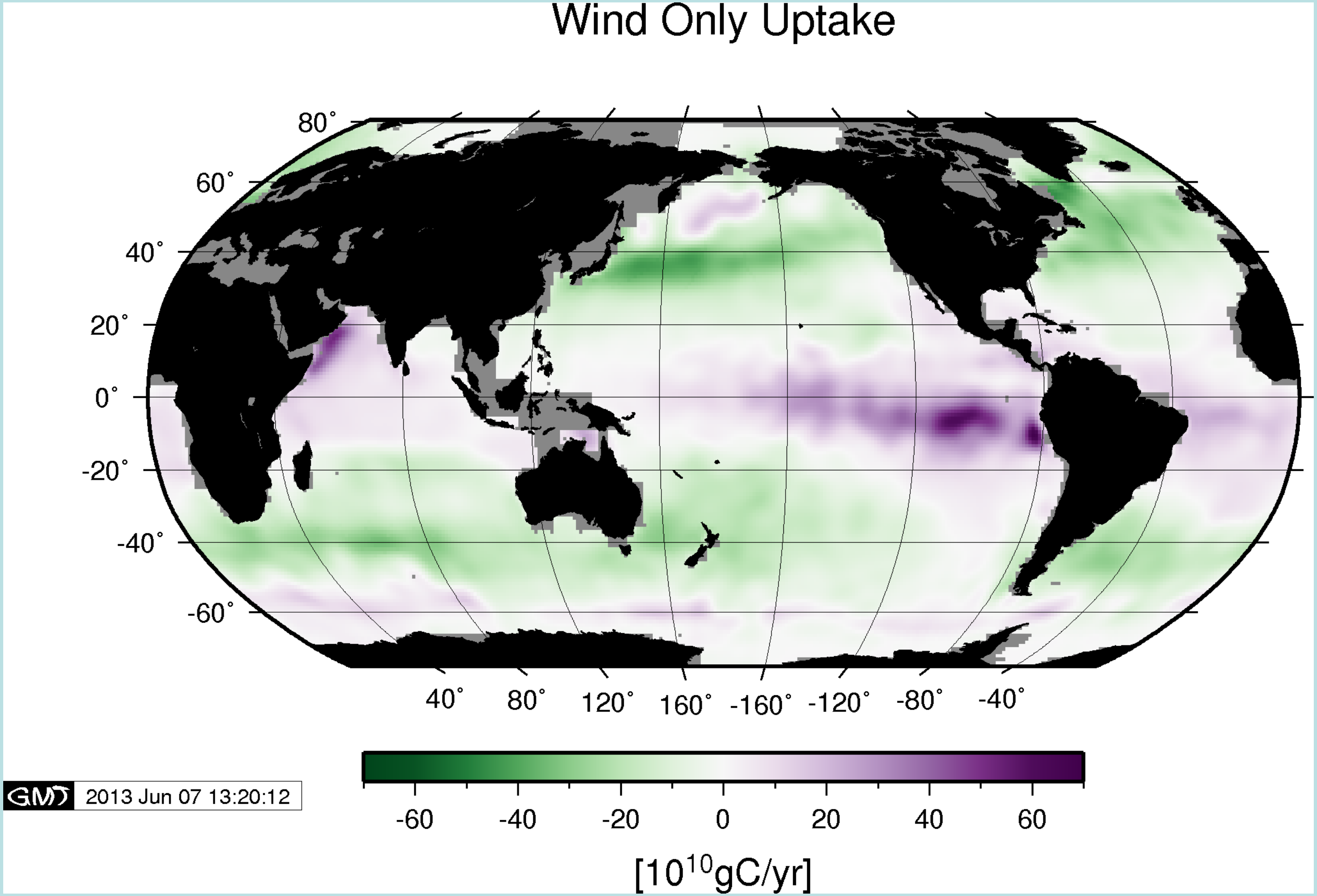
Komori et al., 2007

Global Uptake of CO_2 Due to Rain

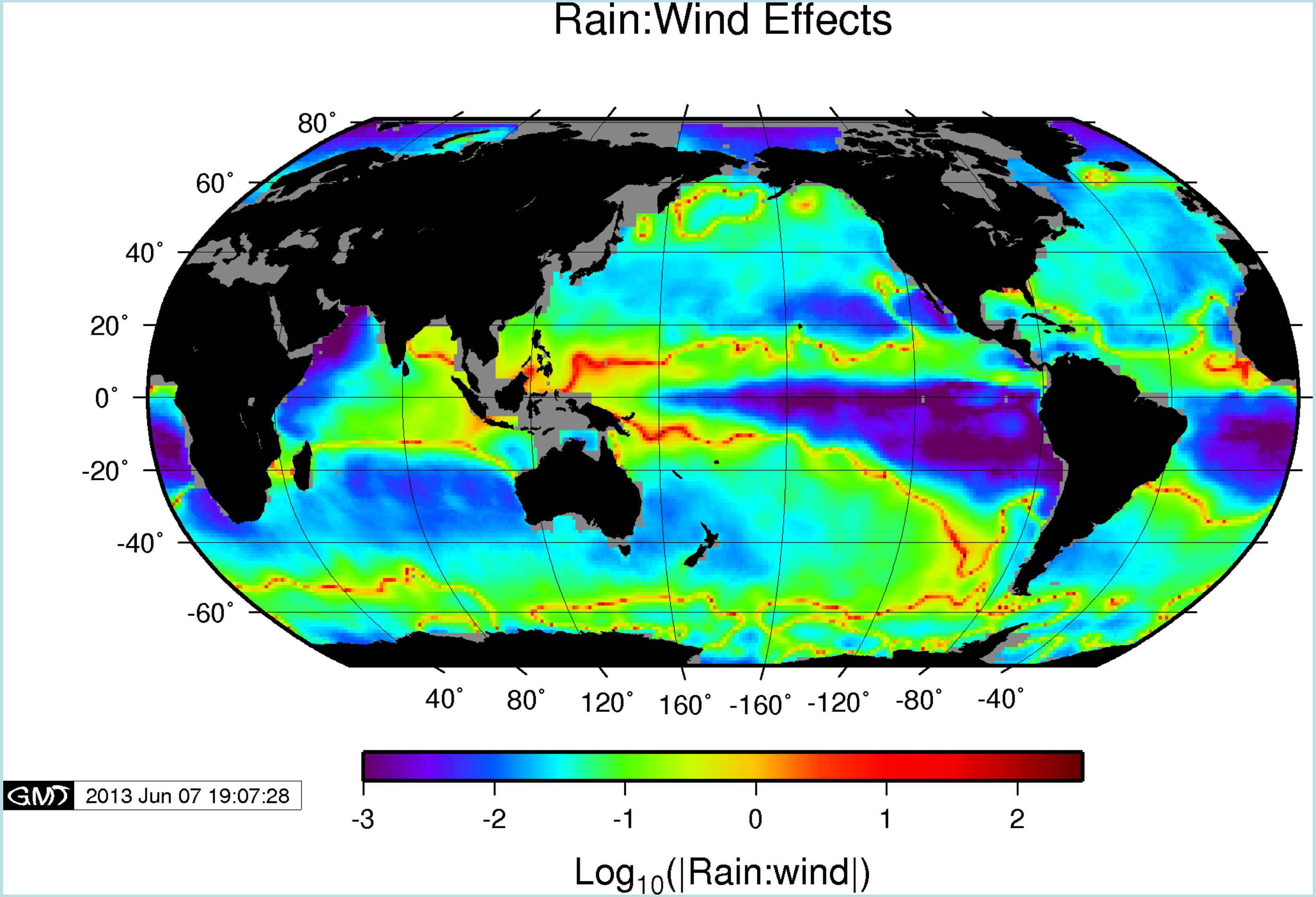
k_{total} from Harrison et al. [2012]



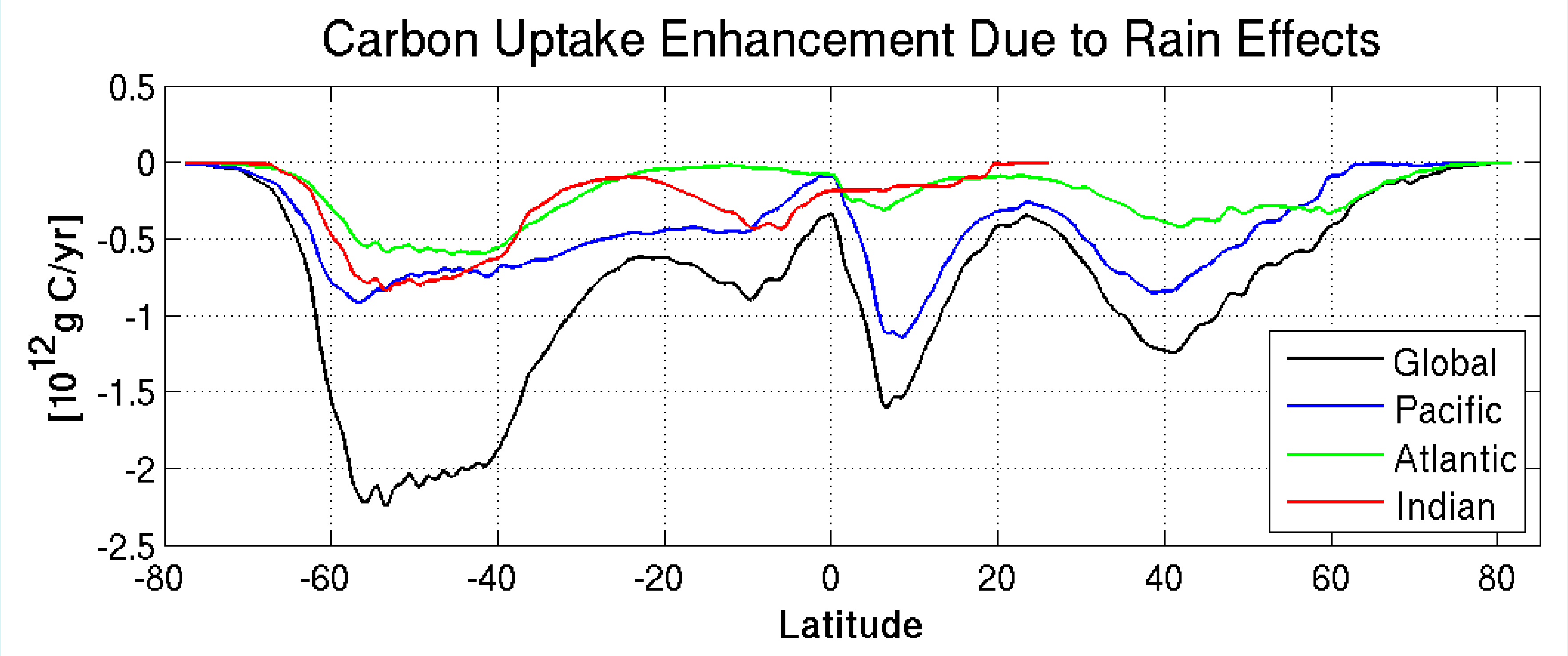
Global Uptake of CO_2 Due to Wind



Ratio of Rain to Wind Effects on Global Uptake of CO_2



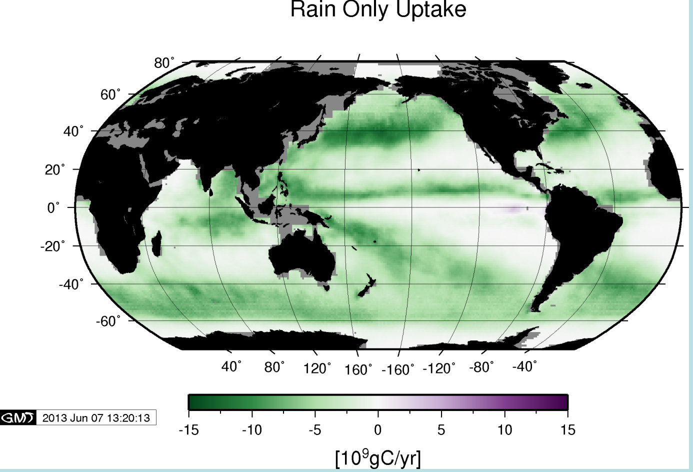
Latitude Variation in the Global Uptake of CO_2 Due to Rain



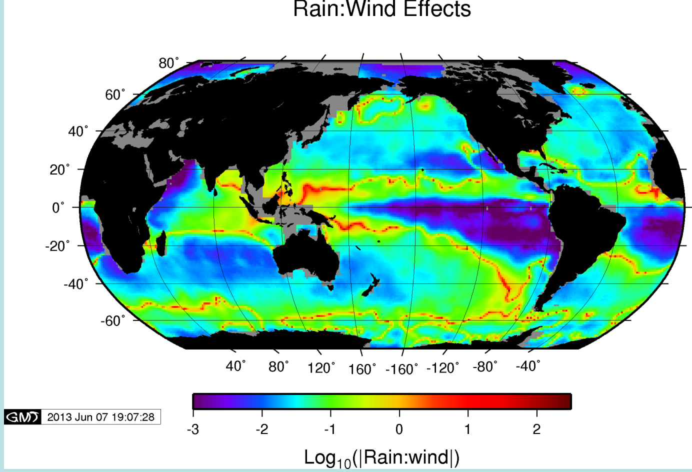
These two rain processes increase the ocean sink of atmospheric carbon dioxide by more than 0.2 Pg C/year.

Global CO_2 Budget Summary of Results

	Pg C per Year	Increase in CO_2 Uptake
Takahashi et al. [2009]	**-1.380**	
Deposition	**-1.443**	**+ 4.51%**
Rain-enhanced K without dilution		
Harrison et al. [2012]	**-1.379**	**-0.16 %**
Ho et al. [1997]	**-1.404**	**1.61 %**
Komori et al. [2007]	**-1.385**	**0.21 %**
Rain-enhanced K plus dilution		
Harrison et al. [2012]	**-1.453**	**5.16 %**
Ho et al. [1997]	**-1.482**	**7.25 %**
Komori et al. [2007]	**-1.459**	**5.61 %**
All Rain Effects		
Harrison et al. [2012]	**-1.515**	**9.59 %**
Ho et al. [1997]	**-1.544**	**11.69 %**
Komori et al. [2007]	**-1.521**	**10.04 %**



Concluding Remarks



- Explored the effects of precipitation on the global flux of CO_2, including enhanced transfer velocity, chemical dilution of the near surface, and deposition.
  - **Built on the results of Komori et al. (2007) to include the effect of chemical dilution.**

- For the year 2000, results show that the effects of precipitation increase the net global CO_2 flux by more than 10%.
  - **Applied Harrison et al. [2012] gas transfer wind speed parameterization with enhanced rain effect**
  - **Compared Ho et al., [1997] and Komori et al., [2007] gas transfer velocity parameterizations for rain**
  - **Compared assumption for linearly additive k for all wind speeds versus up to a cutoff of 5 m s^{-1}**

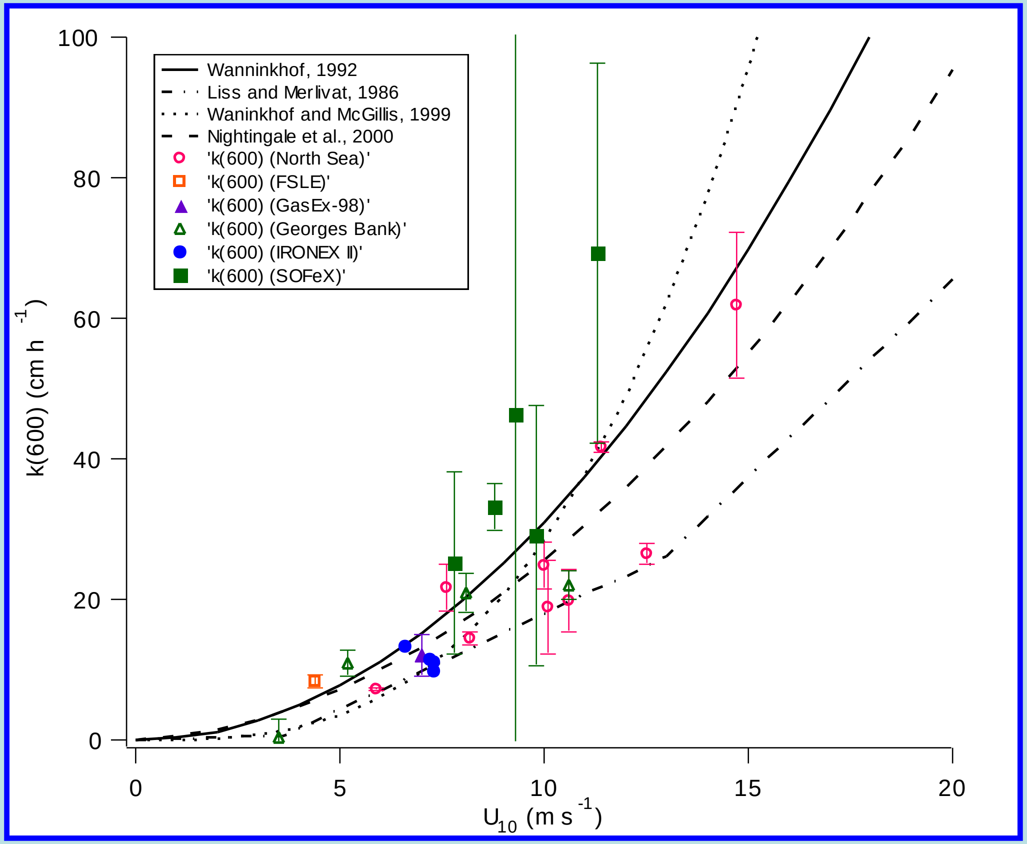
- Conservative estimate for the flux given the temporal resolution of the global datasets and the nonlinear nature of the enhanced transfer velocity
  - Furthermore, the significant observed stratification may increase the residence time of the surface dilution before it is mixed.

- As ocean uptake is forecast to decrease in time, the contribution from rain may increase to 30% of the total atmosphere to ocean carbon dioxide flux by 2100

Transfer Velocity vs. Wind Speed

- **The transfer velocity is a function of the diffusivity and the turbulence at the interface, and is parameterized by**

$$K \propto Sc^{-n} f(u', \ell)$$

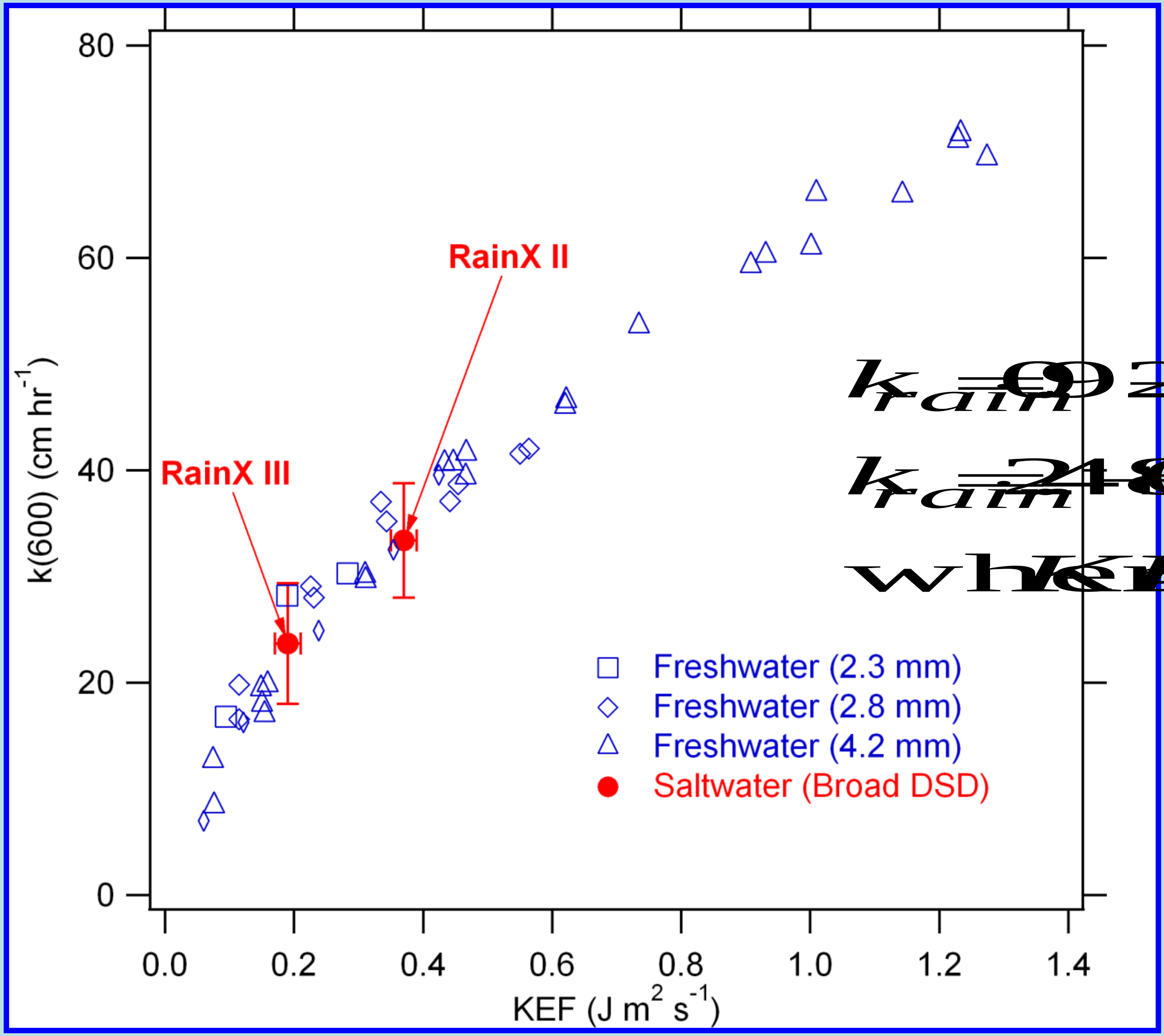


courtesy of D. Ho

- **Wind forcing plays a central role in generating near-surface turbulence.**

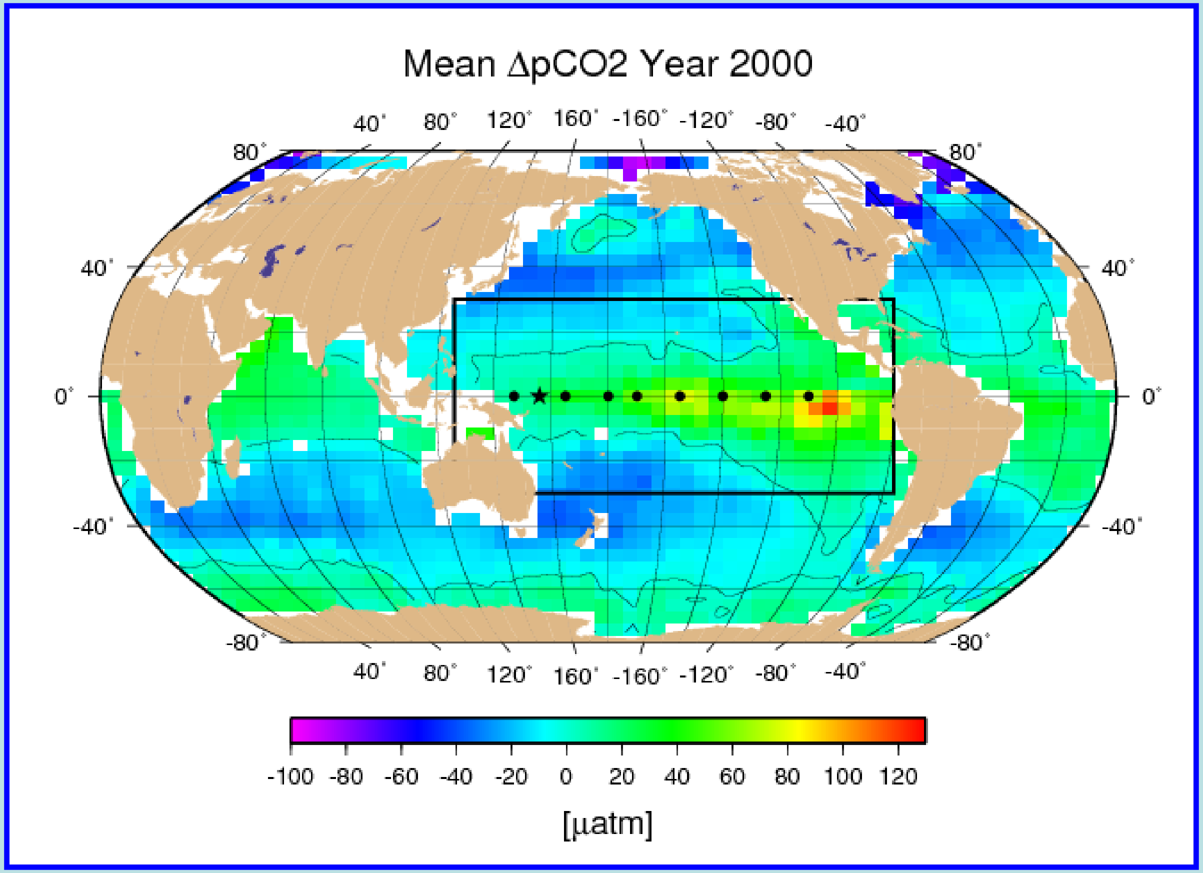
Relate known K for one gas to any other gas using $K_1 = K_2 \left[\frac{Sc_1}{Sc_2}\right]^{-n}$

Gas Transfer with KEF



Gas transfer velocity versus kinetic energy flux, KEF. Freshwater data represent distinct raindrop sizes with diameters of 2.3 mm, 2.8 mm, and 4.2 mm from experiments at the Wallops rain facility and are summarized in *Ho et al.* [2000]. Saltwater data represent broad raindrop size distributions and are from RainX II (see *Ho et al.* [2004]) and this study of RainX III at Biosphere2.

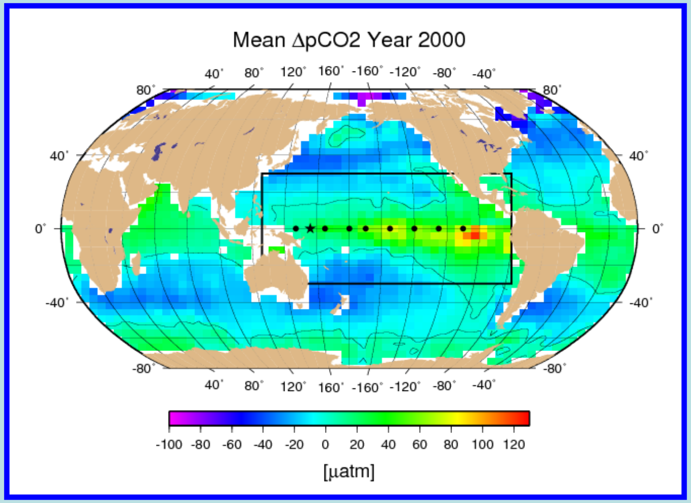
Future Directions



- Equatorial Pacific ΔpCO_2 database from 1990 to 2004 [Christian et al., 2008].
- Examine the decadal variability in the CO_2 uptake by the equatorial Pacific.

Takahashi et al., 2009

Future Directions



- **Examine the effects of increasing temporal resolution on globally integrated CO2 uptake**
- **Deposition expected to be unaffected as it is based on volume of rainfall**
- **Instantaneous gas transfer rates predicted to be larger**

- **Daily: GPCP daily rainfall climatology, daily NCEP wind speed climatology**
- **Sub-daily: TRMM three-hourly rainfall data (±50 latitude), Merra re-analysis hourly wind speeds**

- **Preliminary results from the daily climatologies suggest an additional 2.5% increase in the oceanic uptake of CO2**

Future Directions

Kwajalein (Marshall Islands)

Average Monthly Rainfall

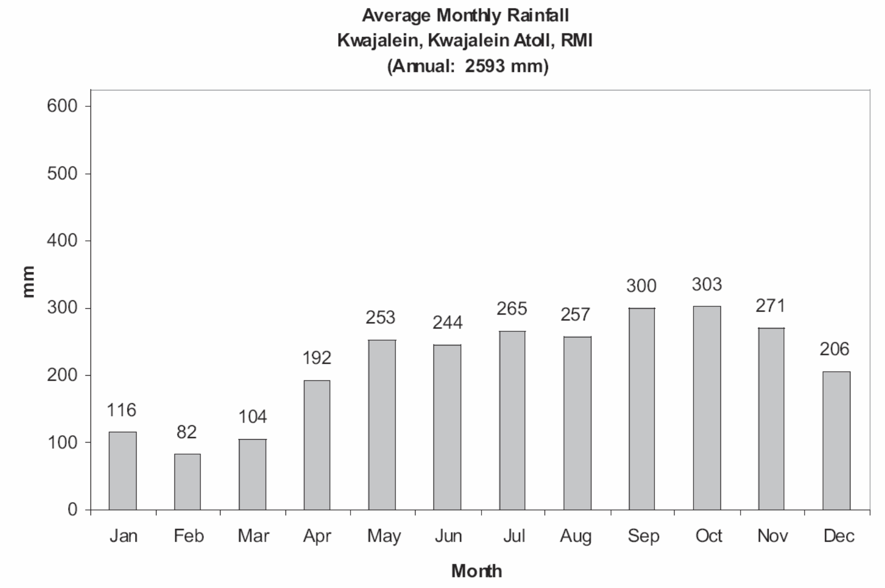
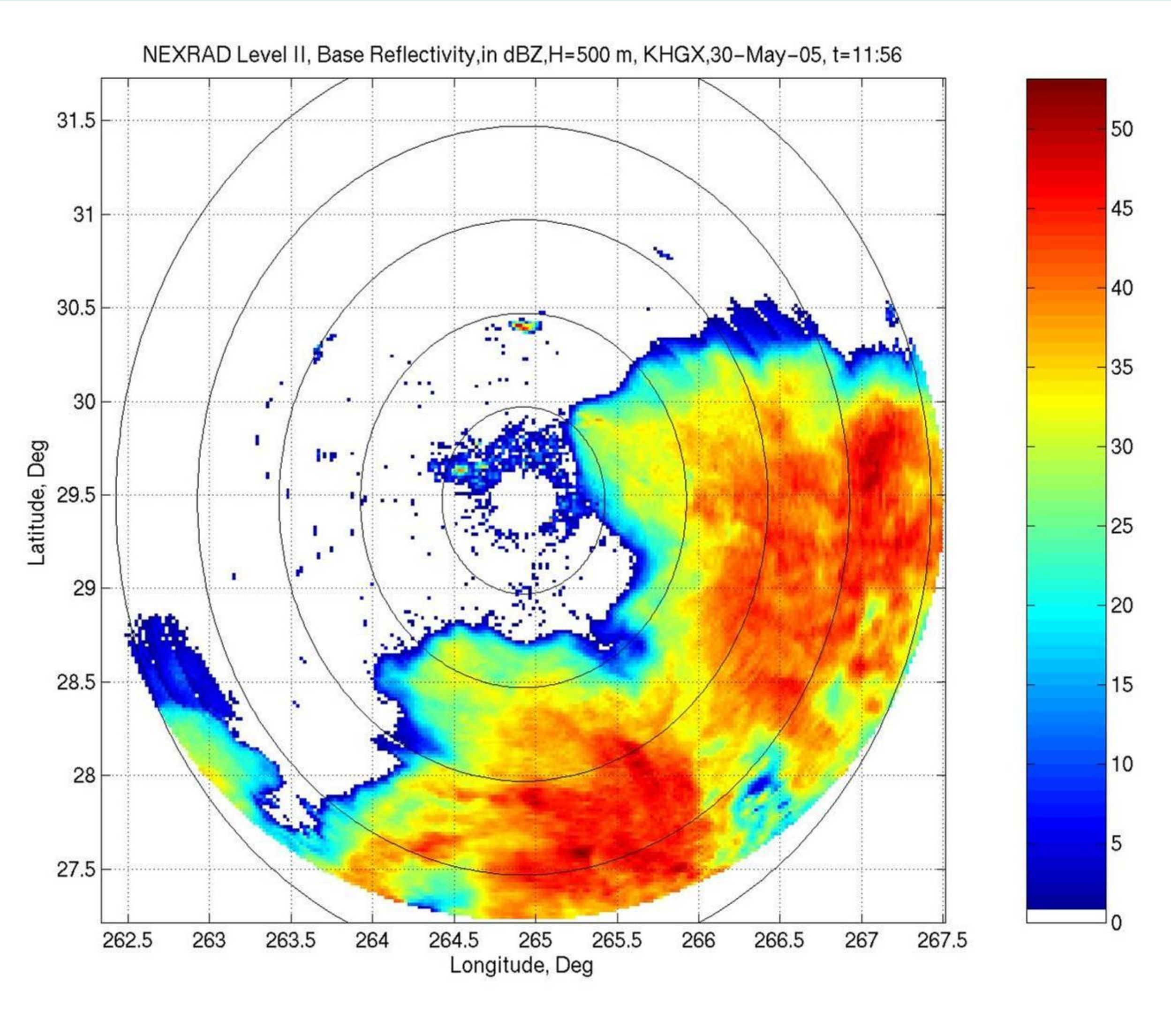


***Figure 32.** Rainfall for Kwajalein Island, RMI [NCDC].*

- **Measure the physical and chemical effects of rain in an open ocean environment ocean.**
- **Improve our model for the chemical dilution due to rain and the impacts of mixing (e.g., wind and waves).**
- **Investigate the effects of deposition on the chemistry of the near-surface ocean including the raindrop chemistry.**

Future Directions

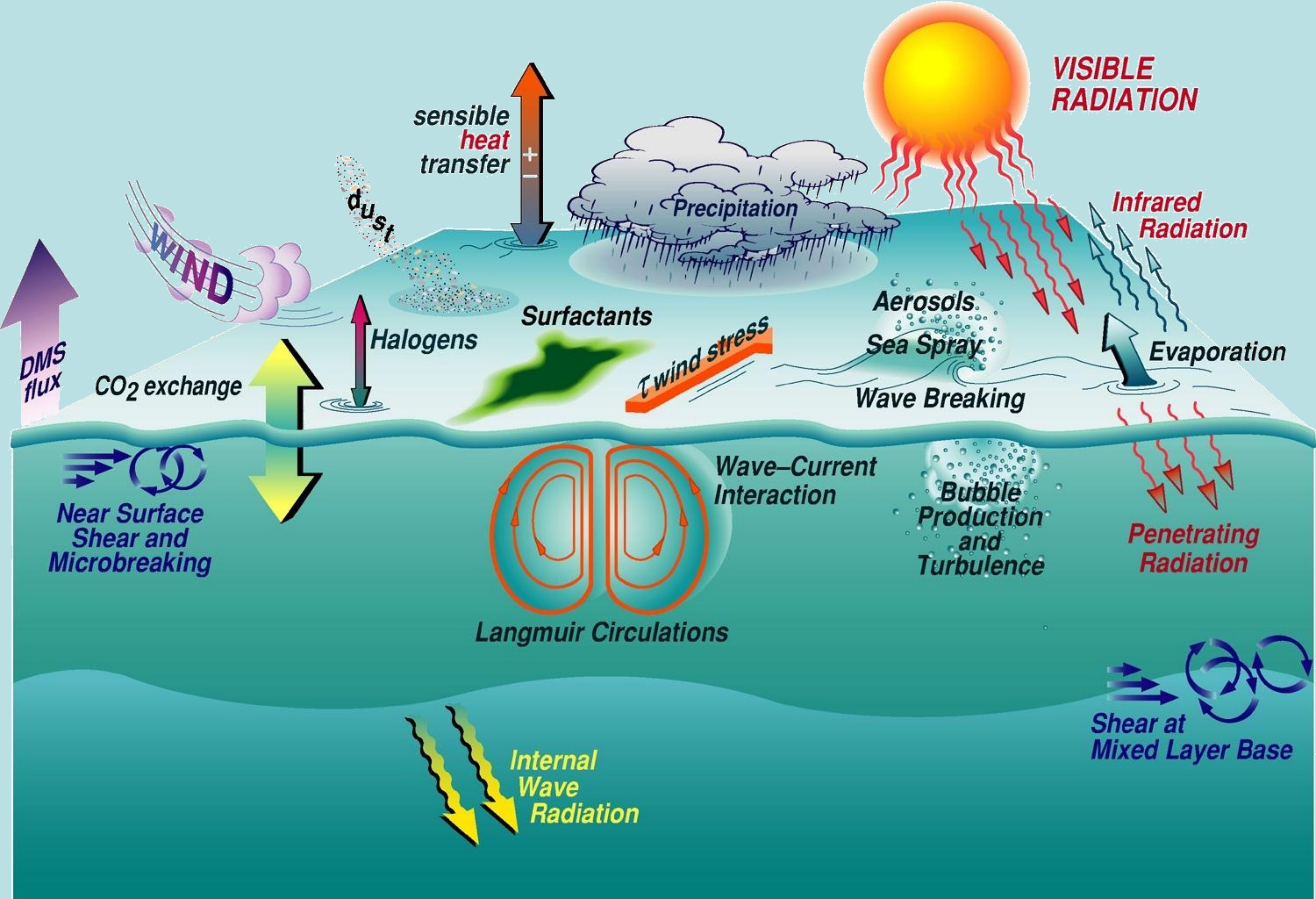
NEXRAD Base Reflectivity



Interpolated S-band reflectivity at an altitude of 500 meters elevation, in dBZ (40 dBZ = 20 mm/hr rainfall), out to range of 250 km

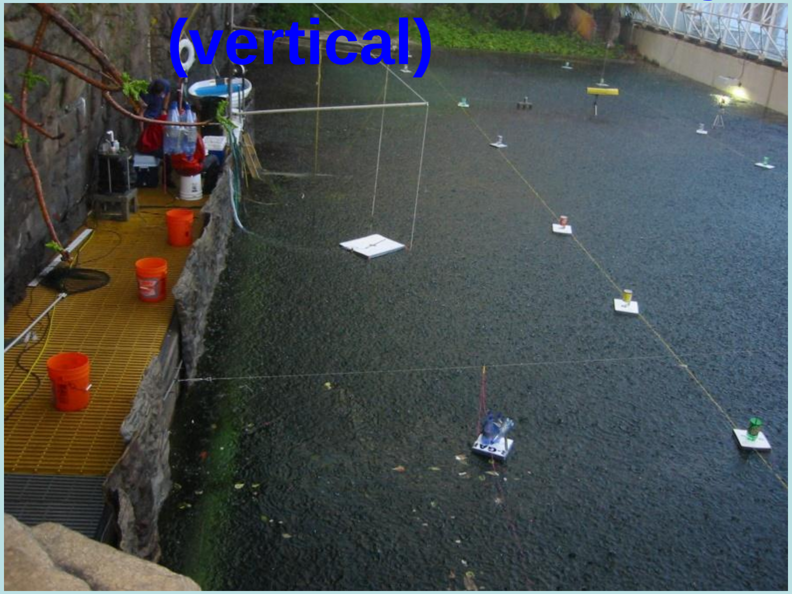
David E. Weissman
Hofstra University

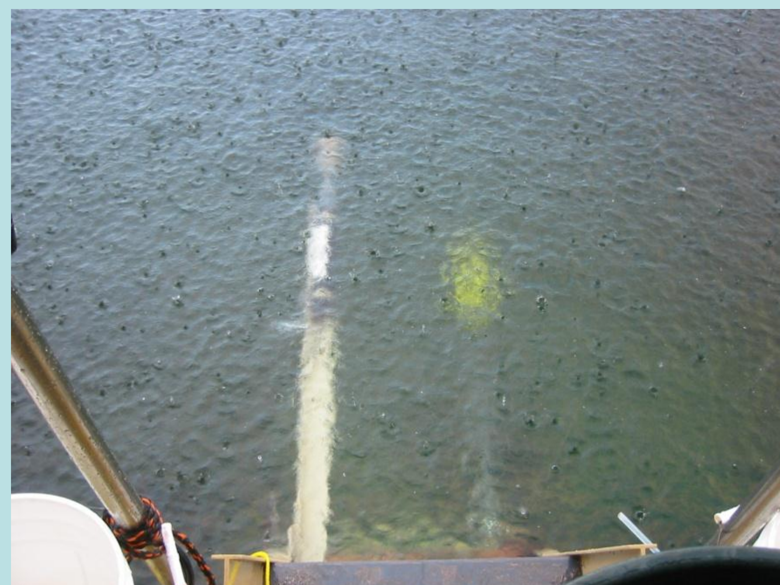
Air-Sea Interaction Processes



DopBeam Measurements

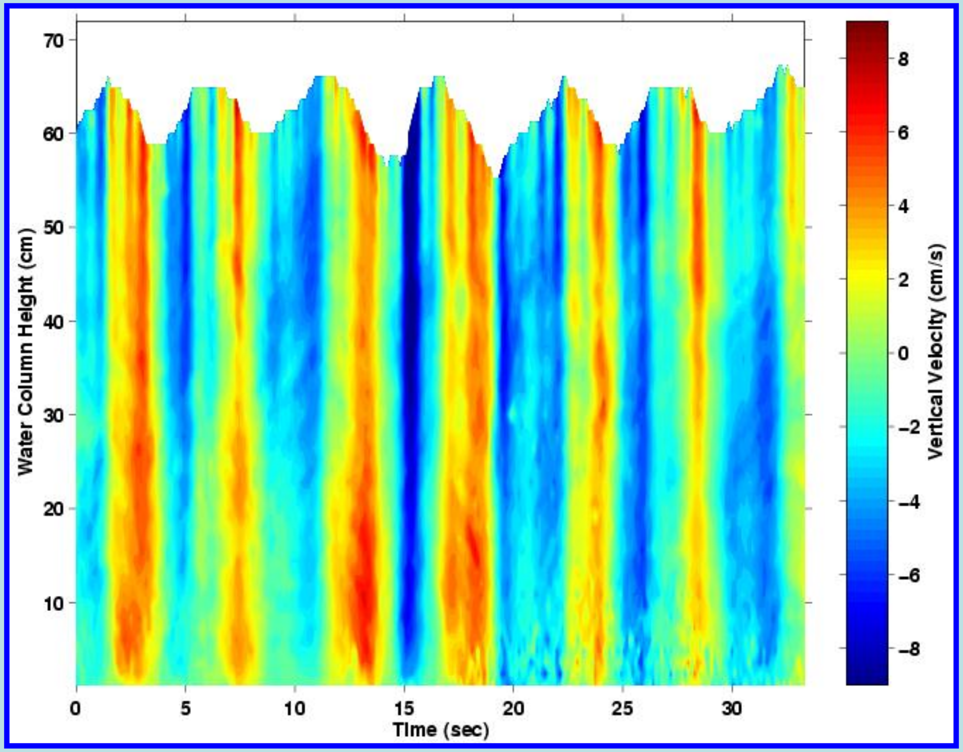
Profiles of velocity along the beam (vertical)



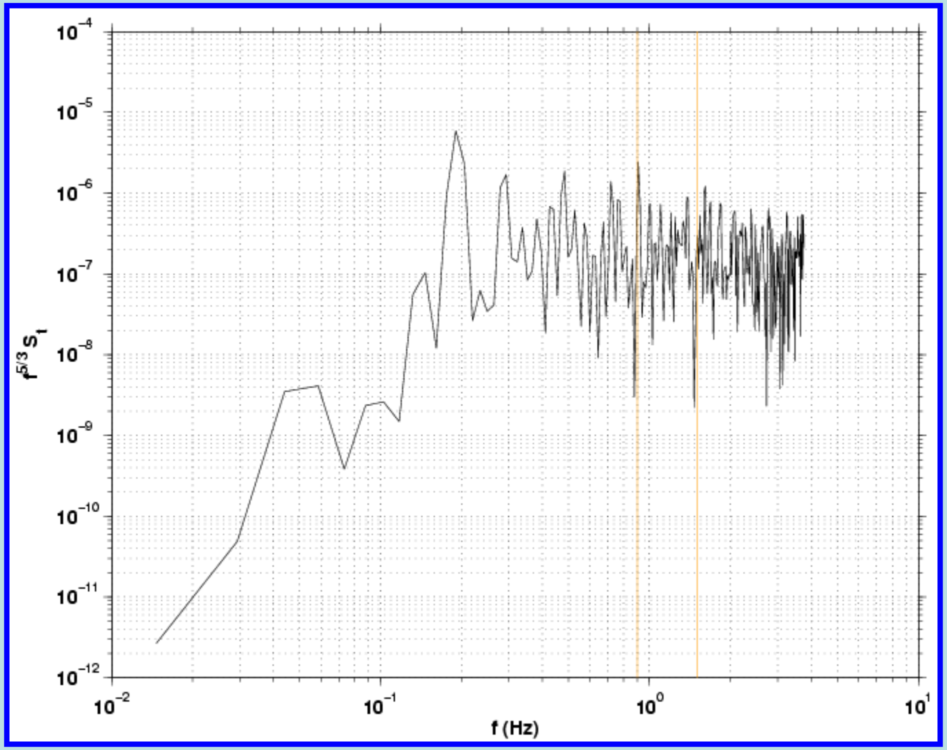


DopBeam Measurements

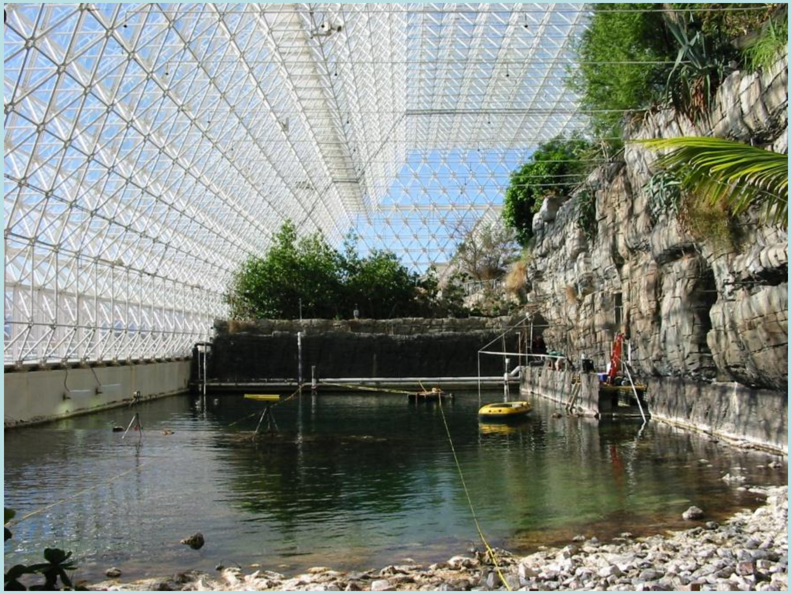
Profiles of velocity along the beam (vertical)

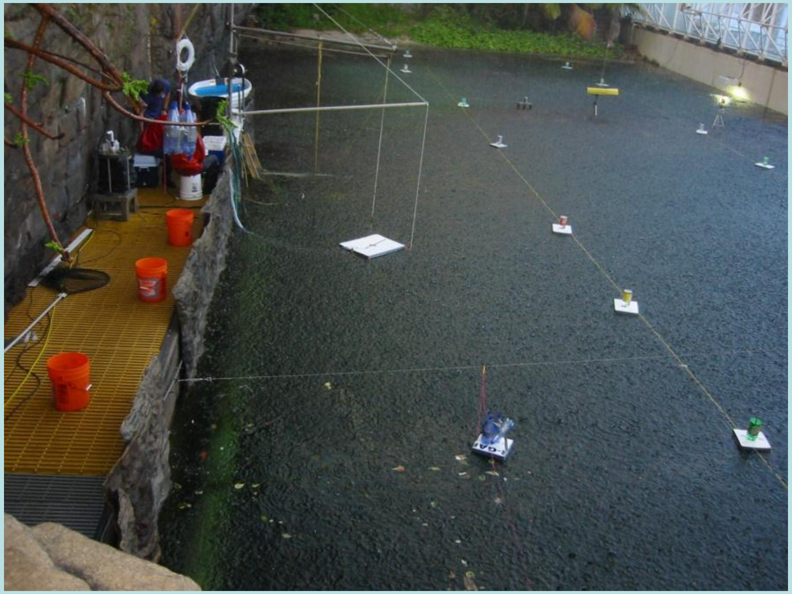


Frequency Spectrum of Vertical Velocity at single bin

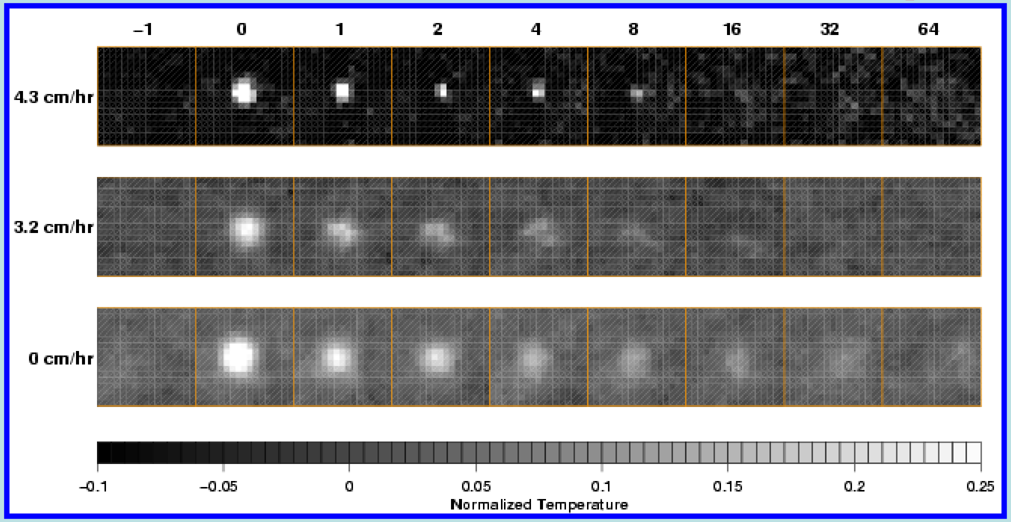


Infrared Imagery and CFT Measurements

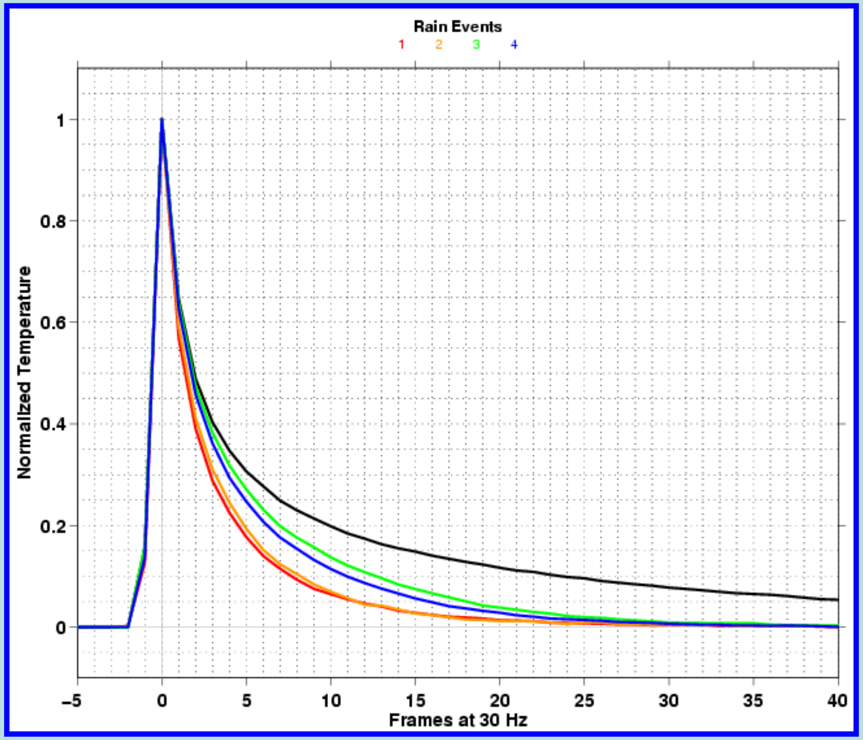





Controlled Flux Technique



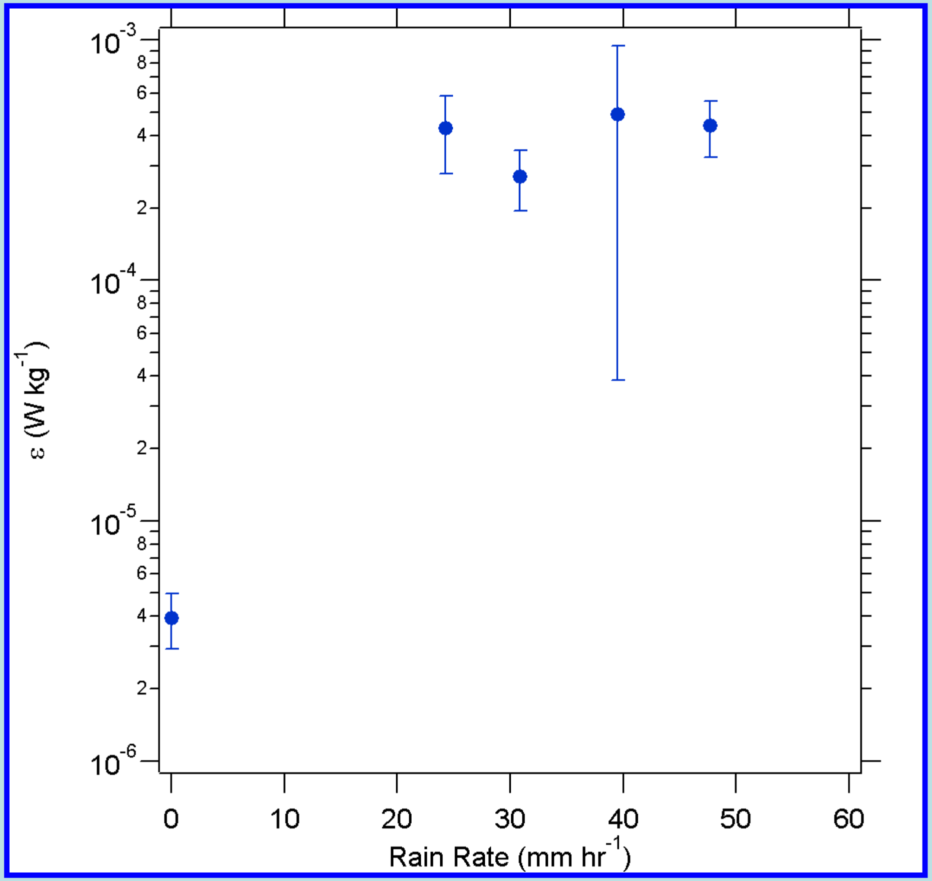
Faster Decay
= Faster Renewal
= Faster Transfer

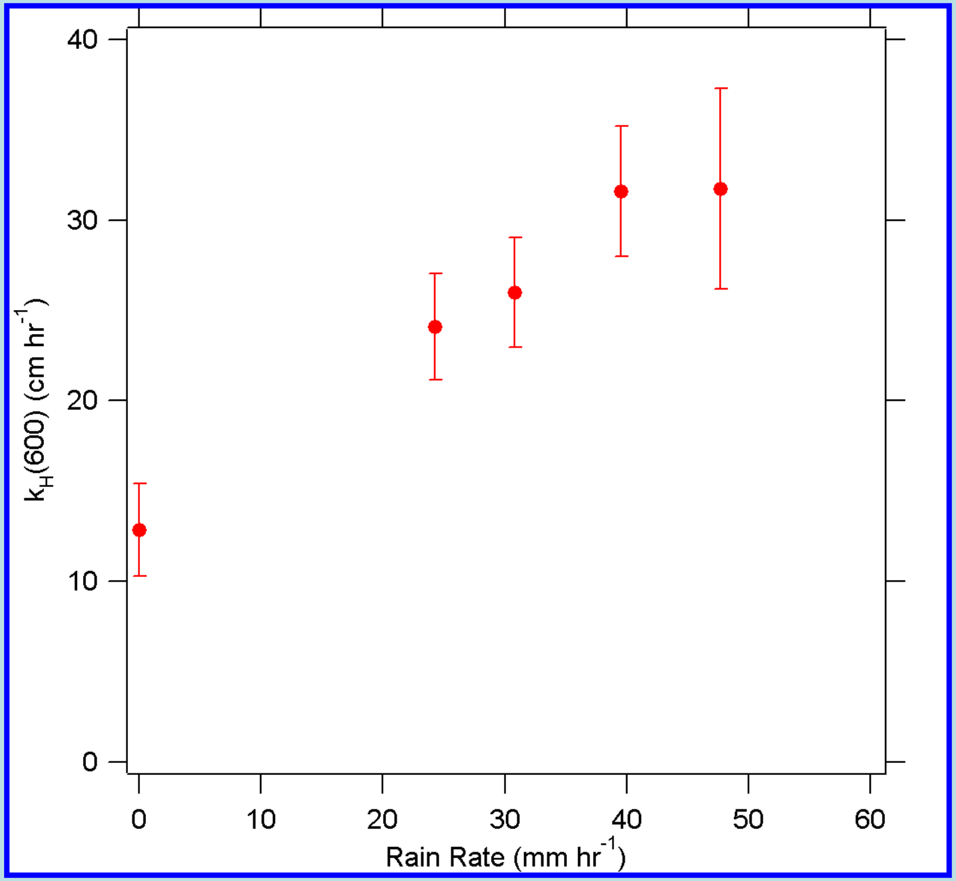


Turbulence and Transfer Velocity

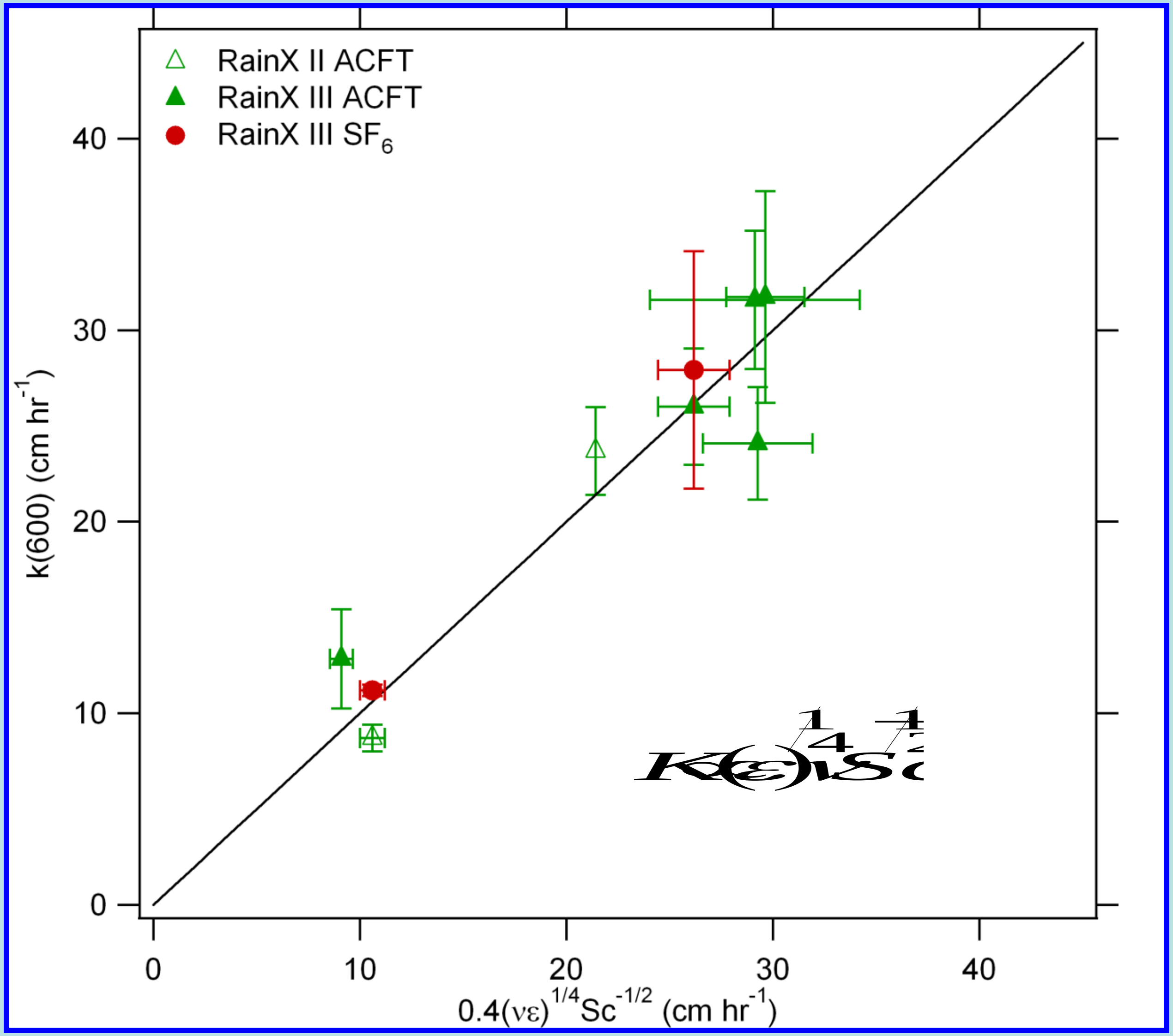
Turbulent Dissipation Rate

Transfer Rates from CFT





Gas Transfer Scaling



Gas transfer velocity from ACFT versus modeled *k* as determined from (1) for all rain rates during both RainX II (see *Ho et al.* [2004]) and RainX III at Biosphere 2. The gas transfer measurement using the SF_6 tracer release during RainX III is also shown for comparison.

Mean Turbulence Profile

- **Turbulence decays with depth from the air-water interface**

- **Compared to Craig-Banner model with standard Mellor-Yamada coefficients, the measured KEF input, and variation in zo based on previous field measurements.**

- **Note: turbulence very near the surface is key to air-sea gas transfer.**

Dissipation Rates:

Breaking Waves:
10^{-5} to 10^{-2} W kg^{-1}

Energetic Mixed Layers:
10^{-6} to 10^{-4} W kg^{-1}

Hudson River:
10^{-7} to 10^{-5} W kg^{-1}