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Answers to Key Scientific Questions

Ocean and Climate:

• How do oceans control and modify climate?
This was the main theme of all the presentations. For example, the MOC presentation by Molly Baringer showed a relationship between the strength of the MOC, atmospheric CO_2 levels, and surface air temperatures globally, motivating our efforts to measure the MOC. The presentation by Enfield illustrated the relation between the Atlantic Multidecadal Oscillation, the Atlantic Warm Pool (an expression of SST anomalies) and both rainfall and hurricanes. The presentation by Wang showed the impact of global warming on wind shear in the main development region of Atlantic hurricanes, on the size of the Atlantic Warm Pool, and on the rate of landfalling hurricanes in the US east coast. In the presentation by Goni it was shown that ocean parameters that control air-sea exchanges, such as significant changes in intensity and location of major surface currents and of gyres, have been exhibiting strong trends over the past decade. In the presentation by Lumpkin, it was demonstrated that oceanic mesoscale processes have significant climate impacts on ocean-atmosphere coupling, heat budgets, air-sea fluxes, and ocean transports. In the poster presentation by Lee it was shown that the persistence of El Niño throughout January-March is essential for the warming of tropical North Atlantic SST and the associated modulation of climate (e.g. rainfall) variability. On 100 thousand year timescales the ocean will absorb about 90 % of the excess CO2 emitted by fossil fuel burning because of its large buffer capacity. However the uptake currently is about 25 % of annual emissions because the uptake is limited by large-scale thermohaline circulation. Changing is rate and patterns of this circulation can have a direct effect on the uptake rate of CO2 of the ocean.

• How is the Meridional Overturning Circulation changing?
The presentation by Baringer showed that the MOC undergoes large variations at a range of time scales from weeks to years. Baringer also showed results in critical chokepoints of the MOC indicating that the contribution of North Brazil Current rings may represent up to 50% of the interhemispheric exchange of waters in the Atlantic Ocean, and Agulhas Current rings up to 30% of the Indian-Atlantic exchange. Additionally Goni showed that this same areas are exhibiting significant trends in current location and intensity. In a poster by Meinen it was shown that there is not yet any sign of the MOC changing at decadal time scales at the western boundary near 26°N. That does not imply that there is not change, only that the change may be occurring in the basin interior. The poster by Baringer showed that eddy heat transports can represent as much as 10% of the total heat transport by the MOC in the North Atlantic. In the poster by Enfield it was shown that a decrease in MOC strength will result in a increase in vertical wind shear and less rainfall in the western hemisphere warm pool region. The Enfield poster also showed how a slowdown in the AMOC and the resulting slower Atlantic warming will diminish Atlantic hurricane activity by 2100 AD.

• To what extent does interior mixing alter the overturning circulation?

Presentation by Lumpkin discussed the critical role of mesoscale and smaller scale mixing and eddies in the proper representation of air-sea exchange, which is a critical component for accurate modeling of the MOC. The Lumpkin presentation also showed that inertial and super-inertial variability is now detectable from drifter data and that it is consistent with internal gravity wave dynamics, which will lead to an improved knowledge of the spatial and temporal variability of the energy input that drives interior mixing. In the poster presentation by Schmid the key role of the expanding observing system, in particular the role of Argo, was shown to be important for understanding the heat budget of the ocean and air-sea interaction. An assessment of the Southern Ocean mixed layer budget in a poster by Dong discusses imbalances in the mixed layer heat budget using the available data and what improvements are needed in order to better close the heat budget.

• How do variations in the Atlantic Warm Pool influence US rainfall?
The presentation by Enfield showed that the Atlantic Warm Pool provides a source of moisture for rainfall in the US. Enfield also showed that the variability of the warm pool from seasonal-to-multidecadal time scales significantly influences rainfall over the US. These results are being provided to hydrologists for use in public water policy decision-making.

• What is the relationship between climate change and hurricane formation, track and intensity?
The presentation by Wang demonstrated that global warming is associated with a secular increase of vertical wind shear in the main development region, which coincides with a downward trend in US landfalling hurricanes. Wang also showed that the Atlantic Multidecadal Oscillation variability is related to warm-pool induced atmospheric changes. The warm pool reduces the vertical wind shear and increases the moist static instability of the troposphere, both of which favor Atlantic hurricane activity. These research results can be transitioned into the NOAA Hurricane Outlook program. Mark Powell discussed how scientists from Tulane University are using AOML's H*Wind gridded wind fields to find links to the carbon budget. It turns out that a storm like Katrina can remove a carbon sink equivalent to the total annual sink of all forests in the US.

• What are the effects of global warming on CO_2 uptake?
In the presentation by Wanninkhof it was illustrated that global warming is significantly changing in where CO_2 uptake is occurring and where storage is changing in relation to climate signals such as El Nino. Models suggest that uptake rate will decrease in response the global warming primarily due to decreases in the thermohaline circulation. Secondary effect are decreases in CO2 uptake due to decreases in solubility with warmer ocean temperatures and a competing increase due to enhanced biological productivity in the surface ocean with warmer temperatures

• How can models best extract information about climate from observations?
In the poster presentation by Thacker it was demonstrated that through data assimilation the differences between observations and their model counterparts provide useful information for correcting model simulation. If a model is to be used for designing an observing system either

to generate synthetic data typical of what might be observed or to study their impact when assimilated, its error characteristics must first be fully understood. The presentation by Lumpkin showed that all of the state-of-the-art atmosphere-ocean coupled climate models cannot reproduce the annual cycle of tropical Atlantic SSTs. Due to this shortcoming in the climate models, currently we do not have a skill to simulate or predict the tropical Atlantic climate variability. The exact cause of large tropical Atlantic errors is currently unknown largely because the role of upper ocean representations in the generation and amplification of the tropical Atlantic bias has not been clearly understood. The poster presentations by Schmid and Dong showed the on-going analysis work by AOML that attempts to map the tropical Atlantic mixed layer heat budget using ARGO data that is essential for validating the coupled climate models.

Coastal Ecosystems

What is the impact of ocean acidification on marine ecosystems?

We learned from the talks by Jim Hendee and Rik Wanninkhof that ocean acidification can cause decreased production of $CaCO_3$ (i.e., slower calcification rates in organisms that build calcareous shell), and Increased rates of dissolution. 'Healthy' coral reefs exhibit low net accretion due to high rates of physical, chemical, and biological erosion. Thus, any disturbance that causes either decreased accretion or increased erosion may tip the tenuous balance from reef framework growth to loss. Most coral reef ecosystems are already highly degraded because of other anthropogenic disturbances, therefore, acidification poses a serious threat to entire persistence of coral reef ecosystems as we know them.

What are the long-term trends of meteorological and oceanographic parameters at key U.S. coral reef areas?

In Jim Hendee's ICON presentations showed that we are taking the measurements necessary to answer these questions. New instrumentation, parameters, and data sets are being developed and added as scientific advancement progresses.

Can data from various sources be integrated in real time to provide for ecological forecasts at coral reef and coastal ecosystems areas?

Yes. In Jim Hendee's ICON project (http://ecoforecast.coral.noaa.gov/) we saw how this is being done effectively to the benefit of coastal managers and other user groups. In addition, the Ocean Carbon program is collaborating with scientists in NESDIS to produce an aragonite saturation state index for the Caribbean using in situ and remotely sensed SST, winds, and color.

Can molecular analysis be used to quickly and reliably identify human pathogens and indicators of human fecal contamination in coastal waters?

In Chris Sinigalliano's talk he presented his work in developing, adapting, and deploying molecular microbiology approaches to quickly and reliably detect pathogens and fecal indicators in coastal ecosystems, and to investigate linkages between sources of nutrients, pathogens, and fecal indicators in coastal waters. He showed laboratory-based molecular methods for the environmental detection, quantitation, and source-tracking of microbial contaminants, and reported elevated indicators, pathogens, and nutrients exported together from inlets to coastal waters. An important need is for validating and standardizing these molecular approaches, and presented on-going efforts to transition these molecular assays to a portable biosensor format. Further investigations, of course, are essential for better understanding of how to manage their impacts on human, fisheries, and ecosystem health.

How are ecosystems connected regionally and what is the effect of this connection on the individual ecosystems, e.g., fisheries.

In Libby Johns's talk she presented results from a series of interdisciplinary cruises, conducted jointly with scientists from NOAA's Southeast Fisheries Science Center, that were designed to determine the physical and biological linkages between coral reef ecosystems in the Florida Keys, the Mexico/Belize Yucatan, and the northeastern Caribbean Sea. Results from these cruises have clearly shown direct connectivity between the regions, and cruise results have further demonstrated the importance of eddies and gyres in establishing the relevant time and length scales. This physical connectivity may be the key to understanding and quantifying the degree of biological connectivity between widely separated larval populations, and will need to be taken into consideration in the optimal design of regional-scale Marine Protected Areas (MPAs). In Chris Kelble's talk we also learned how NOAA is playing a critical role in describing the variability of salinity and nutrients in FL Bay and how these fluctuations impact that ecosystem. Science conducted by AOML and other agencies are providing results that guide water management strategies for the State of Florida and the US Army Corps of Engineers.

What are the impacts of hurricanes on coastal ecosystems?

In the talk presented by Dr. Sinigalliano, the impacts on the microbial landscape in the New Orleans environment were discussed. The microbial measurements returned to background values in water locations after approximately two days. Hurricanes do cool surface waters, which may actually benefit thermally-stressed corals (see Manzello et al., 2007 PNAS). Dr. Kelble also addressed our ability to conduct rapid assessment of coastal ecosystems resulting from freshwater outflow after Hurricane Katrina impacted Biscayne Bay off Florida's coast and the Gulf of Mexico south of Louisiana. Mark Powell discussed how scientists from USGS are using H*Wind data to study how track endangered marine mammals (manatees) respond to hurricanes. Scientists from Emory University are using H*Wind to study sea turtle nesting patterns.

How can we measure low nutrient concentrations with high precision and accuracy?

In Dr. Zhang's talk he presented both the development and application of the liquid-waveguide technology. This technology provides a 2-order of magnitude enhancement of sensitivity. This enables measurement of low nutrient concentrations with high precision and accuracy in both deep and coastal ocean waters.

What are the sources of nutrients, pathogens, and fecal indicators in coastal waters?

Prospective nutrient sources to coastal waters include upwelling, wastewater outfalls, groundwater and atmospheric deposition. In the talks of John Proni, Jia-Zhong Zhang and Chris Sinigalliano, we presented time series data from the Boynton Inlet that showed that the Inlet was a major source of said quantities. Time series of other the other prospective nutrient sources are required to obtain a more complete picture of the nutrient budget of the coastal ocean.

Hurricanes

How do the multi-scale interactions affect the predictability of hurricane formation, track, and intensity?

Track is mainly considered a large-scale problem, and the impact of smaller-scale features on track will be examined as the resolution of the models increases. For intensity use of scale spanning numerical models down to 1-3 km resolution will help in isolating some of the intensity related issue. Mark Powell's presentation on H*Wind showed that even assessing the intensity of a storm is a challenge. Intensity is very difficult to measure, and it's uncertainty depends on the characteristics of the measuring system. Therefore to understand predictability we must also understand the limits of our observation system and evaluate alternative metrics for intensity that are meaningful for hurricane prediction. One such metric is the integrated kinetic energy.

What is the best mix of model ensembles to bound the uncertainty and test predictability of intensity and structure?

This question remains to be answered with the research we have planned in the development of the improved hurricane forecast system. The strategy we are proposing to follow is to investigate model ensembles with idealized cases to look at the predictability issues for intensity and structure. In terms of addressing the uncertainty issue we are investigating model ensembles that will use perturbed initial condition, multiple physics packages (i.e. different boundary layer schemes, microphysics schemes, etc.), and multi-model ensembles (e.g., different flavors of WRF, COAMPS TC, GFDL etc.). Some of these issues will be addressed with the group of models identified at the HFIP modeling workshop.

What is the optimal observing strategy for initializing models for track, intensity and structure forecasts?

AOML, in tandem with our academic, national, and international partners, have looked at various targeting strategies in various basins, including the ensemble variance, the Ensemble Transform Kalman Filter, the Total Energy Singular Vectors, and the Adjoint-Derived Steering

Sensitivity Vector with Observing Systems Experiments. We are actively participating in the THORPEX-Pacific Area Regional Campaign (T-PARC) this summer to continue to address these issues. We are also looking at targeting humidity for track forecasting. Some of this work has been transitioned to operations at NHC.

How can we take advantage of information gleaned from field experiments (IFEX, RAINEX, CAMEX, TCSP, CBLAST) to improve analytical and numerical models of tropical cyclones?
By designing robust methods for evaluating numerical models based on data collected in the various field experiments (IFEX, RAINEX, CAMEX, TCSP, CBLAST), deficiencies in numerical models can be identified and rectified. Verifications are being done by producing "best possible" simulation from numerical models at the highest possible resolution. Mark Powell's discussion on drag coefficient behavior considered data from nearly ten years of GPS sonde sampling that comprised all the above field experiments, and still there are challenges with sample size. When sonde profiles are binned by wind speed, water depth, radius, and azimuth, even a dataset of 2000 sondes can becomes too small to establish effective relationships for use in model parameterizations. An aggressive annual field campaign is necessary to collect sufficient data to improve boundary layer and surface layer exchange physics.

What emerging observing technologies will provide the key observations to improve track, intensity, and structure forecasts?
New technologies are being investigated in the Atlantic and Western Pacific (T-PARC) this summer. They include Unmanned Aerial Vehicles, airborne instruments such as Doppler radars, Lidars, new profiling instruments for clear air surrounding the tropical cyclone, and the driftsonde. The use of Doppler Radar from the NOAA aircraft and UAS for initializing boundary layer profiles at the highest resolution could improve forecasting at vortex scales. The emerging data assimilation techniques to do this are EnKF and the 4D var. Another use of emerging observing platforms would be their utility in the model evaluations addressed in 4. The hurricane is too harsh an environment for safe low-altitude in situ measurements from airborne platforms. Remote observing technologies have great promise to provide key observations to improve forecasts. Among these are the Doppler radar, GPS dropsonde and airborne remote sensing strategies, such as HIRAD, that can first be tested in a field program and once proven, be applied to use on satellites. UAVs and wing-mounted, tethered drones also show great potential.