OS51B HC: 315 Friday 0830h

Equatorial Oceanography V

Presiding: **D Moore,** NOAA /PMEL; **G C Johnson,** NOAA/PMEL

OS51B-01 0830h INVITED

Temporal and Spatial Structure of the Equatorial Deep Jets in the Pacific Ocean

Gregory C Johnson[1] (1-206-526-6806; gjohnson@pmel.noaa.gov)

Kristene E McTaggart[1] (1-206-526-6692; kem@pmel.noaa.gov)

[1]NOAA/Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE Bldg. 3, Seattle, WA 98115-6349, United States

The spatial and temporal structure of the equatorial deep jets (EDJs) in the Pacific Ocean is investigated using CTD station data taken on the equator from 1979 through 2001. The EDJs are clearly revealed using vertical strain estimated from the CTD data in a stretched vertical coordinate system. There are 32 meridional sections available, with 27 of these west of the dateline. The meridional sections show the expected equatorial trapping, but yield little new detailed information about meridional structure. Long equatorial time series can be created at a few other longitudes, most notably 110°W and 140°W. Analysis of the equatorial data yields several results. There is a clear vertical wavelength near 400 sdbar (with $N_o = 1.555 \times 10^{-3}$ s^{-1}) associated with the EDJs. This signature is more easily seen in the eastern Pacific (at and east of 140°W), perhaps because there the EDJs are isolated from the influence of relatively short period Rossby waves generated by surface forcing. The EDJ vertical propagation in this region, 4×10^{-7} sdbar s^{-1} (14 sdbar $year^{-1}$), is remarkably slow and downward, suggesting a period of around three decades. Given this time scale, it is no surprise that previous observational analyses of these jets, limited to two years or less, had difficulty finding any significant vertical propagation. The EDJs show some coherence from 95°W to 140°W. However, the zonal scales of the EDJs are apparently so long that they defy quantification over this longitude range. Significant difficulties exist for interepreting the EDJs as linear equatorial waves, but given the EDJ vertical wavelength and propagation, Kelvin and Rossby waves would also have very long zonal wavelengths.

OS51B-02 0855h

Upper and Intermediate Circulation in the Western Equatorial Pacific Ocean in November 1999 and April 2000

Yves Gouriou[1] ((687) 26 07 24; gouriou@ird.fr)

Thierry Delcroix[1] (delcroix@noumea.ird.nc)

Grard Eldin[2] (gerard.eldin@cnes.fr)

Mansour Ioualalen[1,3] (ioualale@soest.hawaii.edu)

[1]Institut de Recherche pour le Dveloppement (IRD), IRD BP A5, Nouma 98848, New Caledonia

[2]Institut de Recherche pour le Dveloppement, IRD/LEGOS/GRGS 18 avenue Edouard Belin, Toulouse, France

[3]Joint Institute for Marine and Atmospheric Research (JIMAR), University of Hawaii 1000 Pope road, Honolulu, Ha 96822, United States

Direct velocity measurements were carried out with a Lowered Acoustic Doppler Current Profiler (LADCP) in the western equatorial Pacific Ocean during 6-month apart cruises in November 1999 and April 2000. The measurements were made from the surface down to 1200 m depth, between 20°S and the equator along 165°E and 180°, as well as along the equator between those two longitudes. The zonal velocity along the 165°E and 180° meridional sections was found in general agreement with the mean section of zonal current constructed from the 41 sections of the Pacific Equatorial Ocean Dynamics (PEQUOD) program at 159°W [Firing, J. Mar. Res., 45, 791-812, 1987]. Yet, an eastward flow near 6°S and 400 m depth was measured at both longitudes for the two cruises, consistent with the observations of Rowe et al. [J. Phys. Oceanogr., 30, 1172-1187,2000]. The upper core of this eastward flow was linked to a deeper core centered near 5°S-1000 m, the resulting pattern could be named the South Equatorial Intermediate Countercurrent (SEICC). The upper core of the SEICC was found at the poleward edge of a region of low vertical gradient of potential density. Along the equator and below the Equatorial Undercurrent (EUC) the zonal current was clearly westward in November 1999 and eastward in April 2000. Such a reversal of the equatorial intermediate currents was already observed in June 1983 at 159°W and in December 1989 at 155°W [Firing et al., J. Geophys. Res., 103, 21413-21423, 1998]. Here the reversal was coherent over 15° of longitude, from 165°E to 180°E. In November 1999, a strong northward flow was observed near 175°W from the surface to 1200 m depth. At that time, the Deep Equatorial Jets (DEJ) broke into smaller vertical scales. Coincidentally, this event seemed to affect the EUC which lost energy and was then formed of two superimposed velocity cores. As the ship steamed eastward along the equator, LADCP data evidenced that the DEJ and the EUC progressively retrieved their 'usual' vertical scales. Processes responsible for our observations remain unclear. The possible role of tropical instability waves and local topography will be discussed.

OS51B-03 0910h

Deep Equatorial Current Structure in the JAMSTEC Model Compared to Observations

Francois Ascani[1] (francois@soest.hawaii.edu)

Eric Firing[1] (efiring@soest.hawaii.edu)

Akio Ishida[2] (aishida@soest.hawaii.edu)

Humio Mitsudera[3] (humiom@soest.hawaii.edu)

[1]University of Hawaii, Department of Oceanography 1000 Pope Rd., Honolulu, HI 96822, United States

[2]Japan Marine Science and Technology Center, 2-15 Natsushima, Yokosuka 237-0061, Japan

[3]International Pacific Research Center, University of Hawaii 1680 East-West Rd., Honolulu, HI 96822, United States

One of the unsolved challenges of numerical modelling is a realistic simulation of the equatorial current structure below the thermocline. Although spatial and temporal coverage are poor, observations from all three oceans show complex patterns of deep zonal currents near the equator. Within a degree of the equator, a stack of eastward and westard relative maxima with a vertical wavelength of several hundred meters is typically found; these are the equatorial deep jets. They are embedded in narrow, meridionally-reversing, zonal flows with much larger vertical extent. There is neither a generally accepted theory for these deep equatorial currents nor an accurate ocean general circulation model (GCM) simulation of them.

With 55 levels, the 1/4-degree JAMSTEC GCM has greater potential to resolve deep equatorial current structure than most comparable models. In the Pacific it produces structures resembling the Equatorial Intermediate Current on the equator and the Equatorial Intermediate Countercurrents off the equator. It also produces equatorial deep jets that appear to be realistic in many respects, with one major exception: their vertical scale is about twice the observed scale. The JAMSTEC deep jets in the Pacific do not propagate in the vertical or undergo temporal reversals, but they vary in amplitude with seasonal changes in the larger-scale currents. In the Indian and Atlantic oceans the JAMSTEC deep jets are weaker than in the Pacific, and highly variable in time; they do not appear in the annual mean. Temporal variability of the observed as well as the modelled currents, together with the lack of current profile time series, make model-data comparison more difficult than in the Pacific.

OS51B-04 0925h

Seasonal Variability of Deep Currents in the Equatorial Atlantic: a Model Study

Claus W. Böning[1] (49-431-600-4003; cboening@ifm.uni-kiel.de)

Jürgen Kröger[1] (jkroeger@ifm.uni-kiel.de)

[1]Institut für Meereskunde, Düsternbrooker Weg 20, Kiel 24105, Germany

A suite of high-resolution models of the Atlantic Ocean is used to study the seasonal variability and spatial structure of the deep current field in the equatorial regime. The model behavior confirms previous suggestions based on solutions of the WOCE "Community Modelling Effort" and the "DYNAMO" model intercomparison project, of the presence of a system of baroclinic zonal currents in the deep water, spanning the zonal extent of the basin, and oscillating at annual and semi-annual period. The host of model experiments demonstrates that in contrast to annual mean fields, there is relatively little sensitivity of the seasonal flow patterns to model factors such as grid choices and mixing parameterizations. A particular manifestation of the seasonal variability concerns the Deep Western Boundary Current (DWBC). Amplitude and phase of the simulated seasonal cycle are in quantitative agreement with observational results. The simulations indicate that the interaction of the deep equatorial current bands with the DWBC gives rise to a complex patterns of seasonal recirculation cells. This suggests that DWBC measurements not extending across these cells may not be representative of low-fequency variations of the net meridional transport near the western boundary.

OS51B-05 0940h

Thermocline Processes in the Tropical Pacific and Their Role in Decadal Climate Variability

Antonietta Capotondi[1] (303-497-6105; mac@cdc.noaa.gov)

Michael A Alexander[1] (303-497-6030; maa@cdc.noaa.gov)

Clara Deser[2] (303-497-1359; cdeser@ucar.edu)

[1]Climate Diagnostics Center, 325 Broadway, R/CDC1, Boulder, CO 80305, United States

[2]National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307, United States

The thermocline is the layer of the ocean that is characterized by large vertical temperature gradients. Thermocline variability can arise through subduction processes as well as baroclinic Rossby wave propagation, processes that have been invoked in several recent theories of decadal climate variability. In the Pacific, the thermocline exhibits two tropical centers of variability, at approximately 10°S and 13°N. A large fraction of the variance in these areas is characterized by long timescales, in the decadal range. In this study we investigate the origin of the centers of variability at 10°S and 13°N using the output from a numerical simulation performed with the National Center for Atmospheric Research ocean general circulation model (OGCM) forced with observed fluxes of momentum, heat, and freshwater over the period 1958-1997. Both centers of variability are associated with first mode baroclinic Rossby waves forced by anomalous Ekman pumping. The waves propagate to the western boundary, and continue equatorward along the boundary. After reaching the equator, they propagate eastward along the equator, where they appear to produce a low-frequency modulation of the thermocline depth. A simple Rossby wave model is used to examine which aspects of the forcing (amplitude, spatial and/or temporal coherency) are responsible for creating the large thermocline signals at 10°S and 13°N. At those latitudes, the thermocline deepens poleward in both hemispheres, so that meridional excursions of the thermocline can also give rise to large local changes in thermocline depth and temperature. The contribution of this process to the thermocline variability at 10°S and 13°N is also examined.

URL: http://www.cdc.noaa.gov/~mac/publications.shtml

OS51B-06 0955h

Coupled ocean-atmosphere response to the equatorial emergence of spiciness anomalies.

Niklas Schneider ((858)5344218; nschneider@ucsd.edu)

Scripps Institution of Oceanography, University of California, San Diego 9500 Gilman Drive, Mail Code 0224, La Jolla, CA 92093-0224, United States

The response of the atmosphere-ocean system to the surfacing of temperature anomalies from the oceanic thermocline is a key processes in deterministic low-frequency climate variability. Of interest here is the appearance of salinity compensated temperature anomalies (spiciness anomalies) in the upwelling region of the equatorial Pacific. This coupled adjustment is investigated by forcing a sophisticated, coupled ocean- atmosphere model with prescribed spiciness fluxes in the upper thermocline of the western Pacific. Two experiments, one associated with an increase the other with a decrease of temperature and salinity on isopycnal surfaces were conducted. Each experiment was run for ten years and repeated three times.

Results indicate that the emergence of warm spiciness anomalies in the central equatorial Pacific is reflected at the ocean surface as warm and salty anomalies. The atmospheric response includes increases in easterlies in the eastern Pacific, and westerly wind anomalies in the western Pacific. These winds and associated Ekman pumping depress the thermocline in the central tropical Pacific. This leads to a weak nonlinear response in that the equatorial isopycnal outcrops east of the data line are located further west in the run with warm spiciness forcing compared to the cold spiciness forcing.

These changes in the tropics result in a eastward shift of the centers of deep atmospheric convection and force teleconnected changes in the atmosphere. During northern winter the emergence of warm spiciness anomalies is accompanied by westerly anomalies north

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of 40N in Pacific, and easterly anomalies between 30-40N. The associated Ekman pumping excited anomalies in thermocline depth that spread to the western boundary and force an anomalous circulation in the North Pacific east of the date line with southward anomalies of the western boundary currents.

Most tantalizing is an increase in the amplitude of simulated ENSO in the run with cool spiciness anomalies compared to the warm forcing. A heuristic explanation is as follows: The cool spiciness anomaly in the thermocline increases in the eastern Pacific the vertical temperature gradient without changing the density gradient. In response to a easterly wind stress anomaly and dynamic adjustment of the ocean density, colder waters enter the surface layer. This leads to a more vigorous Bjerknes feedback and larger ENSOs.

OS51B-07 1030h

Origins of Pacific Decadal Climate Variability

Lixin WU[1] (608-263-0232; lixinwu@facstaff.wisc.edu)

Zhengyu Liu[1] (608-262-0777; zliu3@facstaff.wisc.edu)

Robert Gallimore[1]

Robert Jacob[2]

[1]Center For Climate Research, University of Wisconsin-Madison 1225 West Dayton Street, Madison, WI 53706

[2]Computational Math Division, Argonne National Lab, Argonne, IL

The origin of Pacific decadal climate variability is investigated in a coupled ocean-atmosphere general circulation model. The impact of regional ocean-atmosphere coupling and oceanic teleconnection on decadal variability is evaluated by performing a set of specifically designed experiments. It is found that decadal variability in the tropical and North Pacific originates predominantly from coupled ocean-atmosphere processes within the tropical and North Pacific region, respectively. Futhermore, tropical Pacific decadal variability appears to be associated with higher baroclinic modes and can be enhanced substantially by extratropical-tropical oceanic teleconnection.

OS51B-08 1045h

Pathways, Transports, and Variability in Pacific Subtropical Cells 1988-1998

Victoria J Coles[1] (410 221-8248; vcoles@hpl.umces.edu)

Michele M Rienecker[2] (301 614-5642; michele.rienecker@gsfc.nasa.gov)

[1]Horn Point Laboratory, UMCES, PO Box 775, Cambridge, MD 21613, United States

[2]Oceans and Ice Branch, Code 971 NASA/GSFC, Greenbelt, MD 20771, United States

The watermasses associated with equatorial Pacific upwelling have their origin in the northern and southern hemisphere subtropics. Recent attention has focused on possible interactions of the Subtropical Cells (STC) with the Pacific Decadal Oscillation, and with decadal variability in ENSO. Observations suggest large decadal variations in thermocline, near-equatorial, salinity in the southern hemisphere (Kessler,2000, JPO), which must imply variability in the thermal stratification.

Using a global ocean model, we investigate the mean and variability in pathways, properties, transport and of the subtropical cells over the period from 1988-1998. The mean STC's are generally consistent with other model and observational results. The meridional transport (22-26 sigma-theta, excluding the mixed layer) shows distinctive structure across the tropical Pacific Ocean, with primarily western boundary current transport in the northern hemisphere, and a balance of interior transport (dominantly 180-130W), and western boundary transport in the southern hemisphere. The southern hemisphere source (36 Sv) is larger by 17 Sv than the northern hemisphere source. This asymmetry is somewhat larger than recent estimates of 10 Sv (Johnson et al.2001, JPO). Equatorward convergence is interrupted by weak poleward thermocline transport in both hemispheres east of 110W, and unexpectedly, between the western boundary current and 170E. While the mean density of the equatorward convergence is symmetric about the equator, the salinity and hence temperature differ substantially, with mean thermocline temperature in the northern hemisphere of 18C, and 16C in the southern hemisphere. This is consistent with other model studies, but has the not with observations (Johnson et al.2001, JPO).

Substantial interannual variability in equatorward transport occurs in both hemispheres consistent with a response to shifts in equatorial upwelling on ENSO timescales. The interior and western boundary current pathways for the STC's in both hemispheres do not always vary on the same timescales.

OS51B-09 1100h

Decadal Changes in the Pacific Ocean Equatorial Undercurrent

S. Cristina Urizar[1] (979-845-3238; cristina@ocean.tamu.edu)

Benjamin S. Giese[1] (979-845-2306; bgiese@ocean.tamu.edu)

[1]Texas AM University, Department of Oceanography, College Station, Tx 77843, United States

Observations of zonal wind stress and SST indicate a shift in the mean state during the 1970's in the tropical Pacific Ocean. Time series of zonal wind stress show a weaker mean and annual cycle, especially in the region from 160°W to 120°W and from 10°S to 10°N. Mean SST in the eastern tropical pacific increased while north of the equator the annual cycle increased and south of the equator the annual cycle decreased. An ocean general circulation model (OGCM) is used to explore the change in ocean dynamics as a result of these changes in surface forcing.

The OGCM assimilates surface and subsurface temperature data from XBTs, MBTs, and thermistors. The model is forced with weekly NCEP winds that have been biased corrected by adjusting the NCEP reanalysis mean and variance to the mean and variance of the NCEP production run winds. Sea surface temperatures are damped to NCEP weekly values and the sea surface salinities are damped to the monthly mean climatology from the COADS. The model was run from 1948 to 1999.

Dynamic changes in the tropical Pacific Ocean parallel the changes at the sea surface. The core of the undercurrent deepened in the eastern Pacific after 1976, while it shifted southward along its entire length. Additionally, there are changes in the undercurrent volume transport. Surface currents from 160°W to 100°W and from 5°N to 10°S weakened. The heat content of the ocean also increased in a region from 150°W to South America from 10°S to 10°N, caused by the shoaling of the thermocline in the west and deepening in the east as seen in the shifting of the undercurrent.

OS51B-10 1115h

Radiocarbon Record in a Fanning Island Coral: Inter-Decadal Variability in Waters Upwelling in the Central Equatorial Pacific From 1922-1956.

Andrea G Grottoli[1] (215-898-9269; grottoli@sas.upenn.edu)

Sarah T Gille[2] (sgille@ucsd.edu)

Ellen RM Druffel[3] (edruffel@uci.edu)

Robert DB Dunbar[4] (dunbar@pangea.stanford.edu)

Braddock K Linsley[5] (blinsley@csc.albany.edu)

[1]University of Pennsylvania, Department of Earth and Environmental Science, 240 South 33rd Street, Philadelphia, PA 19104-6316, United States

[2]Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA 92093-0230, United States

[3]University of California Irvine, Department of Earth System Science, Irvine, CA 96972-3100, United States

[4]Stanford University, Geological and Environmental Science, Stanford, CA 94305-2115, United States

[5]University at Albany-SUNY, Department of Earth and Atmospheric Sciences 1400 Washington Ave, Albany, NY 12222, United States

Oceanographers have a limited record of the natural variation in ocean circulation patterns on interdecadal timescales in the central equatorial Pacific prior to the 1950s. Here, we reconstructed the interdecadal variation in the water masses contributing to the currents of the central equatorial Pacific from 1922-1956 using bimonthly high-precision AMS radiocarbon (Δ^{14}C) measurements in a *Porites* sp. coral skeleton core from Fanning Island (3°54'N, 159°19'W). Coral Δ^{14}C levels averaged -51$^o/_{oo}$ and ranged from -71$^o/_{oo}$ to -17$^o/_{oo}$. The most pronounced feature in this record is the large positive shift in Δ^{14}C beginning in 1947 and lasting until at least 1956. The overall yearly average Δ^{14}C increased by almost 17$^o/_{oo}$ shifting from -55$^o/_{oo}$ to -38$^o/_{oo}$ starting around 1947. This dramatic shift in coral Δ^{14}C coincides with the distinct switch of the Pacific Decadal Oscillation (PDO) to a negative phase starting in the mid-1940s. The high levels of Δ^{14}C observed in the coral record starting in 1947 are consistent with reported pre-bomb Δ^{14}C values for the surface water of the North Pacific Gyre (NPG). Thus the coral evidence suggests that during the negative PDO phase, NPG surface water is subducted, travels equatorward and is upwelled in the equatorial Pacific. Previous coral research has shown a link between ocean circulation patterns and the positive phase shift of the PDO regime in the mid-1970s. In addition, stable isotope measurements reveal that the meridional extent of the upwelled water may have expanded north to $\sim$ 4°N during the 1940s and 50s, then contracted south to some latitude between Fanning and Kiritimati Island (2°N). Pre-1950 Δ^{14}C measurements from additional central equatorial corals would greatly enhance our ability to confirm the presence of, and to fully resolve the extent of the mid-40s regime shift in the central Pacific.

OS51B-11 1130h

A Coupled Decadal Recharge Oscillator of the Tropical Pacific

Fei-Fei Jin (jff@soest.hawaii.edu)

Department of Meteorology, University of Hawaii at Monoa, Honolulu, HI 96822, United States

We use a simple model to show that the broad scale ocean-atmosphere interactions in the tropical Pacific in both equatorial and off-equatorial regions can transform a very low-frequency mode of the tropical ocean dynamics into a decadal coupled mode. The essential physical mechanism of this coupled decadal mode is similar to the so-called equatorial recharge oscillator for El Nio-Southern Oscillation (ENSO) phenomenon. The decadal recharge oscillator has a broad meridional scale. It not only involves the equatorial dynamical feedbacks which are essential also for ENSO, but also involves positive large-scale ocean-atmosphere feedbacks in the off-equatorial eastern Pacific regions. These feedbacks reduce the decay rate of the uncoupled decadal mode. The periodicity of the decadal mode depends on its meridional extent. The decadal modes captured in this simple model may be of relevance to the Pacific decadal variability observed in nature and simulated in coupled general circulation models.

OS51B-12 1145h

A Global Quasi-Biennial Wave in Surface Temperature and Pressure and its Decadal Modulation From 1900 to 1994

Warren B. White[1] (1+858-534-4826; wbwhite@ucsd.edu)

Rob Allan[2] (+44 1344 856 904)

[1]Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive, La Jolla, CA 93092-0230, United States

[2]Hadley Center for Climate Prediction and Research, Meteorological Office, London Road, Bracknell RG12 2SY, United Kingdom

Zonal wavenumber-frequency spectra of surface temperature (ST) and sea level pressure (SLP) anomalies extending around the global tropical ocean at 10°N from 1950 to 1997 display significant peaks for 2.0 and 2.4 year periods, dominated by eastward propagating zonal wavenumbers of global scale. Applying complex principal component analysis to quasi-biennial ST, SLP, and surface wind (SW) anomalies for 25 years from 1973 to 1997 separates this global quasi-biennial wave (GBW) from the corresponding global standing mode of the troposphere quasi-biennial oscillation (TBO), both similar to traveling waves and standing modes associated with the El Niño-Southern Oscillation [White and Cayan, 2000]. The GBW is centered on the equatorial waveguide and takes 3 to 4 years to transit the global tropical ocean at 0.30 to 0.40 m s^{-1}. We find the GBW contributing to the quasi-biennial signal in Niño-3 ST and SLP indices with amplitude twice that of global standing mode of the TBO. In the GBW, the ocean forces the atmosphere, with SW anomalies converging on warm SST anomalies, while the atmosphere forces the ocean with SW-induced Kelvin waves on the equator and SW-induced sensible-plus-latent heat flux and/or vertical mixing anomalies elsewhere, together advancing covarying ST and SLP anomalies eastward in the coupled ocean-atmosphere system. Examining the GBW from 1900 to 1994 finds its amplitude modulated by the decadal signal of $\sim$10 year quasi-periodicity, robust (weak) when tropical temperature gradients and trade winds were stronger (weaker) than normal. The amplitude and phase of the GBW influences the magnitude and phase of El Niño/La Niña in the eastern equatorial Pacific Ocean.

OS51C HC: 318 A Friday 0830h

Air-Sea Exchange IV

Presiding: **R Wanninkhof,** NOAA Atlantic Oceanographic and Meteorological Laboratory**; W Drennan,** RSMAS/University of Miami

OS51C-01 0830h INVITED

Air-Sea Fluxes in High Winds

James B Edson ((508) 289-2935; jedson@whoi.edu)

Woods Hole Oceanographic Institution, MS 12, 98 Water Street, Woods Hole, MA 02543, United States

The destructive nature of high wind events along our coastlines has a profound impact on society. Over the ocean, episodic high wind events contribute significant fractions of the total flux of momentum and energy across the air-sea interface. This statement is based on scaling arguments that predict a momentum flux that increases as the wind speed squared. This has been substantiated by numerous observations of measured drag coefficients that generally increase with wind speed, which implies that the momentum flux increases somewhat faster than the wind speed squared. Therefore, even infrequent storms can strongly impact the structure of the upper ocean in many regions of the world, and impact processes at the ocean bottom along continental shelves (e.g., sediment transport and benthic biological processes). However, direct observations of momentum flux over the ocean are extremely scarce at winds above 20 m/s. There are even fewer measurements of heat and mass fluxes under these winds. As a result, there is no definitive understanding of the transfer coefficients for heat and mass even under moderate winds. The uncertainty in the drag and transfer coefficients at high winds has hampered our ability to accurately predict the intensity of extreme storms such as tropical cyclones and hurricanes. For example, modelers have shown that simple extrapolation of existing formulations to high winds does not produce realistic hurricanes. In fact, these simulations predict that the ratio of the drag to enthalpy coefficient must become less than 1 to obtain realistic hurricane winds, i.e., the frictional drag of the ocean must decrease and/or the energy input must increase at extreme winds.

Investigations of processes that could explain this predicted behavior have been severely hampered by the lack of direct flux measurements. Some of these processes include the generation and re-entry of sea-spray and the modulation of ocean surface characteristics due to extensive wave breaking and bubble entrainment. Even at moderate winds, direct measurements of the heat and moisture flux above 15 m/s are still required to improve our understanding of the transfer coefficients. Clearly, the scarcity of measurements is not driven by a lack of interest but rather by the difficulties associated with direct measurement of the turbulent flux in the marine environment. These difficulties include flow distortion, motion contamination, and the corrosive and contaminating effects of sea spray. However, in recent years, a number of groups have made significant process at addressing these issues and computing fluxes from a number of platforms. This talk presents the analysis of several data sets taken by the air-sea interactions groups at WHOI and NOAA/ETL. The data has been taken on ocean-going ships, moored buoys, the R/P FLIP, a coastal research platform, and at a coastal observatory facing the north Atlantic. The high wind data contains numerous direct measurements of the fluxes above 15 m/s and a number of measurements above 20 m/s. Whenever possible the data sets are combined with information describing the sea state. The drag and transfer coefficients computed from these measurements will be compared with previous and newly developed parameterizations including those that attempt to account for sea state, wave age, and the role of sea spray. Some ideas on how to extend these observations to even higher winds will be discussed.

OS51C-02 0845h

A Bulk Turbulent Air-Sea Flux Algorithm for High-Wind, Spray Conditions

Edgar L Andreas (603-646-4436; eandreas@crrel.usace.army.mil)

U.S. Army Cold Regions Research and Engineering Laboratory, 72 Lyme Road, Hanover, NH 03755, United States

In high winds, breaking waves and whitecaps disrupt the ocean surface; spray proliferates. Because these spray droplets start with the same temperature and salinity as the surface water, they effectively increase the ocean's surface area and may thereby enhance the exchange of any constituent normally transferred across the air-sea interface. My interest here is in how spray affects the air-sea exchange of momentum and sensible and latent heat.

I will present a bulk turbulent flux algorithm that accounts for both the interfacial and spray routes by which sensible and latent heat cross the air-sea interface. The algorithm is appropriate for 10-meter wind speeds up to a least 30 m/s. To model the interfacial fluxes, the algorithm uses the COARE bulk flux algorithm (Fairall et al., 1996), with some high-wind-speed modifications. The spray component of the algorithm results from tuning Andreas's (1992) theoretical spray model with heat flux data from HEXOS, the experiment to study Humidity Exchange over the Sea (DeCosmo et al., 1996).

When spray droplets are formed, they accelerate quickly to the local air speed. This process extracts momentum from the wind. When the spray droplets ultimately crash back into the ocean, they transfer this momentum to the sea surface and therefore also, potentially, enhance the surface stress. Although this spray momentum flux is small for wind speeds less than 30 m/s, it increases as the fourth power of the friction velocity, while the usual wind-driven, interfacial stress increases only as the square of the friction velocity. Consequently, as the wind speed approaches 60 m/s, in hurricanes for example, the interfacial and spray momentum fluxes become comparable.

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OS51C-03 0900h

Effect of Wind Speed on Aerosol Fields Generated by Breaking WavesA Scanning Lidar Investigation

Shiv K Sharma[1] (1-808-956-8476; sksharma@soest.hawaii.edu)

Barry R Lienert[1] (1-808-956-7815; lienert@soest.hawaii.edu)

John N Porter[1] (1-808-956-6483; jporter@soest.hawaii.edu)

[1]Hawaii Institute of Geophysics Planetology, 2525 Correa Rd, Honolulu, HI 96822, United States

We have been monitoring time dependent 3-D marine aerosol fields as a function of meteorological parameters with a multi-wavelength scanning lidar at Bellows Air Force Station (AFS) on NE side of Oahu, Hawaii. These measurements include extensive field investigations during the ONR sponsored Shoreline Environment Aerosol Study (SEAS) program, April 21-30, 2000. The focus of these studies was to provide a long-term database to evaluate and model the effect of aerosols generated up to 100 m above the sea surface on optical transmission and visibility in coastal areas.

Here we describe our measurements of salt-aerosol plumes generated at a reef at $\sim$1.6 km from the lidar, and their effect on the aerosol extinction coefficient. The lidar is located at the University of Hawaiis Atmospheric Research Site at Bellows AFS.

A set of vertical lidar scans were collected during the SEAS experiment on April 24, 2000, under normal trade wind conditions.. The meteorological parameters during these scans were wind direction 48-52^{O}E, wind speed=8.1-8.3 m/s, RH=82-84% and temperature=23.4^{O}C. Plumes of salt spray were observed to rise to heights of about 50 m above the reef. A time sequence of vertical scans at three wavelenghts (355, 532, 1064 nm) were taken under light wind conditions ($\sim$2 m/s) over the same reef on March 20, 2001. Large salt plumes more than 600 m high were found to develop. The much greater height of these plumes suggests that they are being dispersed less rapidly at the lower wind speed, allowing them to rise to greater heights. Earlier data collected at Bellows (Sharma et al., 2001) showed reef plumes rising to $\sim$120 m/s in winds of $\sim$5 m/s, indicating a consistent trend of increasing plume height with decreasing wind speed.

The 532-to-355 nm extinction coefficient ratios indicate that there is no significant wavelength dependence in and out of the plume. However, the 1064-to-532 nm extinction coefficient ratios are smaller outside the plume than in it, suggesting that the size of aerosol particles decreases outside the plume.

URL: http://www.soest.hawaii.edu/lidar

OS51C-04 0915h

Near-Surface Turbulence in the Presence of Breaking Waves

Johannes R. Gemmrich[1] (1-250-363-6448; gemmrichj@pac.dfo-mpo.gc.ca)

David M. Farmer[2] (dfarmer@gso.uri.edu)

[1]Institute of Ocean Sciences, 9860 West Saanich Road, Sidney, BC V8L 4B2, Canada

[2]University of Rhode Island, Graduate School of Oceanography, Narragansett, RI 02882-1197, United States

Breaking surface waves are believed to be a major pathway for the energy input from the atmosphere to the ocean and a source of enhanced turbulent kinetic energy levels in the near-surface layer. Increased turbulence levels relate to enhanced air- sea exchange processes. However, the direct link between enhanced turbulence levels and wave breaking has not been shown yet.

During the recent FAIRS experiment in the North Pacific we deployed three orthogonal short-range acoustic Doppler profilers, originating $\sim$1m beneath the free surface, to obtain high-resolution velocity profiles beneath breaking waves. The high spatial (6 mm) and temporal (20 Hz) resolution allow us to estimate turbulent kinetic energy dissipation directly from wave number spectra, without the requirement of Taylors assumptions of frozen turbulence. Acoustic resonators are used to assess the near-surface bubble field and give information on the air entrainment through wave breaking. The turbulence and bubble field measurements are linked to breaking events via simultaneous video recordings, which also provide estimates of size and speed of the breaking wave. A broad suite of scanning sonars, monitoring the wave field and larger scale mixed layer structures such as Langmuir circulation, supplement the turbulence measurements. Results showing enhanced turbulence levels linked to wave breaking and the detailed structure of the turbulence and bubble field associated with breaking waves will be presented. Implications for air- sea exchange processes will be discussed.

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Measurements of Wave Breaking: Kinematics, Dynamics and Air-Sea Interactions

W. Kendall Melville[1] (858 534 0478; kmelville@ucsd.edu)

Peter Matusov[1] (858 822 1224; pmatusov@ucsd.edu)

Eric Terrill[1] (858 822 3101; et@mpl.ucsd.edu)

[1]Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093-0213, United States

Wave breaking plays an important role in determining the air-sea fluxes of mass (gas, aerosols/spray), momentum and energy. Breaking limits the height of surface waves and transfers momentum flux from the wave field to currents. The energy lost from the wave field is available to mix the surface layers of the ocean. Small gravity-capillary waves may break with no significant air entrainment, but larger gravity waves entrain air as whitecaps. The classical description of whitecaps has been in terms of whitecap coverage: the fraction of sea surface covered by foam; however, of more interest are the kinematics and dynamics of breaking. In this paper we present airborne measurements, from the SHOWEX and RED experiments, of the kinematics of breaking in terms of $Lambda(c)dc$, the average length of breaking crests with speeds in the range $(c, c + dc)$, a measure first introduced by Phillips (1985). We show that airborne imagery and image processing techniques, including PIV, can be used to measure $Lambda(c)$ and its first 5 moments, which are interpreted in terms of the kinematics and dynamics of breaking. The significance of the results for surface-wave and air-sea interaction processes will be discussed. Research sponsored by ONR.

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Eddy correlation measurements of CO2 flux over a large lake

Mark A. Donelan[1] (305-361-4717; mdonelan@rsmas.miami.edu)

William M. Drennan[1] (305-361-4798; wdrennan@rsmas.miami.edu)

Eugene A. Terray[2] (508 457-2438; eterray@whoi.edu)

[1]Rosenstiel School of Marine and Atmospheric Science, University of Miami 4600 Rickenbacker Cswy., Miami, FL 33149, United States

[2]Woods Hole Oceanographic Institution, Dept. of Applied Ocean Physics Engineering, Woods Hole, MA 02543-1053, United States

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