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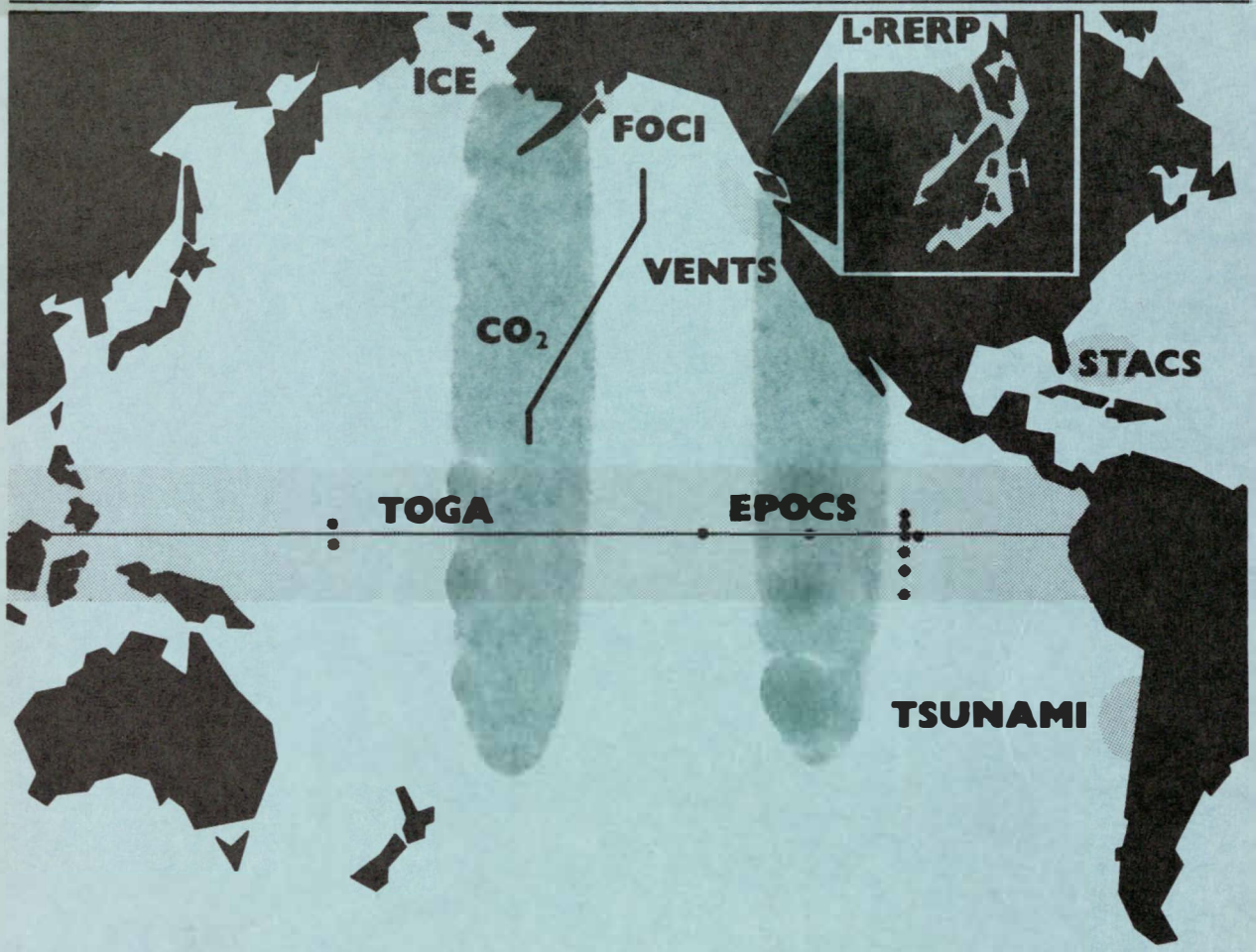
Annual Report for FY 85



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INTRODUCTION

The Pacific Marine Environmental Laboratory (PMEL) is one of nine research laboratories within the Environmental Research Laboratories (ERL), Office of Oceanic and Atmospheric Research (OAR) of the National Oceanic and Atmospheric Administration (NOAA). PMEL, which is located in Seattle, Washington, carries out scientific investigations in physical, chemical and geological oceanography, marine meteorology, and related disciplines in support of NOAA's missions to protect human health and safety from marine hazards and to ensure wise development of ocean resources. PMEL participates in national and international programs that focus on global climate, marine services, marine environmental quality, and marine resources. Its research goal is to improve understanding of coastal and open-ocean processes and, through observation and modeling, to develop a greater capability to monitor and predict marine environmental conditions. Laboratory programs focus on the North and South Pacific Oceans, the Bering Sea, and adjacent coastal regions.

Research conducted by PMEL scientists emphasizes 1) measurements and modeling of forcing mechanisms that drive ocean circulation and global climate, 2) understanding selected physical and geochemical processes that govern the extent and impact of human activity in the marine environment, 3) improvement of environmental forecasting capabilities and other services for marine commerce, fisheries, and recreation, and 4) investigations of physical and geochemical processes associated with formation and transformation of new marine resources at sea floor spreading centers. Products of PMEL's projects include scientific discoveries, marine assessments, environmental information, data synthesis, and models that reflect improved understanding of marine systems. These products are disseminated through refereed scientific journal articles, technical reports, and presentations at national and international meetings, academic and government institutions, and other public gatherings.

The marine environmental studies conducted at PMEL require professional scientists with a wide range of background disciplines, a strong technical support staff, and an integrated experimental and theoretical research approach that utilizes state-of-art field, laboratory, and analytical techniques. PMEL projects are often elements of larger national and international programs and, consequently, its scientists participate actively in the broader oceanographic community, serving on scientific steering committees, program planning panels, and collaborating in multi-institutional field efforts.

The scientific staff is organized into four research divisions: the Marine Assessment Research Division (MARD), the Marine Resources Research Division (MRRD), the Marine Services Research Division (MSRD), and the Ocean Climate Research Division (OCRD). Engineering, computer, and administrative expertise is provided by the Engineering Development Division (EDD), the Computer Support Group (CSG), and the Administrative Support Group (ASG), respectively. Two cooperative institutes, the Joint Institute for the Study of Atmosphere and Ocean (JISAO) and the Joint Institute for Marine and

Radiant Heating of a Wind-Roughened Sea

In a general circulation model of the coupled atmosphere-ocean climate system, the heating terms describing the conversion of solar radiant energy into potential thermal energy drive the motions of the system. In the ocean part of the model, the albedo of the air-water surface is a key factor for defining the heating rate in the upper ocean layer. By combining physical optics and water wave statistics the dependencies of the albedo, over the visible electromagnetic spectrum, on various wind speeds, wind directions, and solar altitudes have been found. In general, the radiant flux across the air-water interface increases with increasing wind speed. Both theory and experiment show that capillary waves, rather than gravity waves, are the dominant determinants of the sea surface's albedo.

Tropical Modeling and Analysis Program

The Tropical Modeling and Analysis Program (TMAP) was established to add a theoretical and numerical modeling balance to PMEL's climate observational program. Procurement of the needed computer hardware and hiring and training of staff was a major part of this effort during FY 1985. Model studies of ENSO phenomena were begun through analysis of a hindcast of the 1982-83 ENSO event done at GFDL. Attention was focused on the evolution of surface currents and sea-surface temperature (SST). During the initial phase of the event, when central Pacific equatorial SST warmed rapidly, the model hindcast indicated that anomalous zonal advection of heat from the west was the primary warming mechanism. Later in the event the processes are more complex.

STACS

Measurements of voltage differences using submarine cables have been shown to be valuable for continuously recording the transport variations of ocean currents such as the Florida Current. In addition to cable voltages induced by ocean currents, there are voltages induced by time varying ionospheric and magnetospheric electric currents. Robust methods have been developed whereby the geomagnetic variations can be removed by using magnetic data obtained at remote magnetic observatories and therefore free of ocean-induced variations. This method has been used to correct voltages from a cable spanning the Florida Straits between Jupiter Inlet, Fla., and Settlement Point, Grand Bahama Island. The geomagnetically induced voltages in submarine cable data can be reduced by using shore-based magnetic data even if the shore site is remote, since geomagnetic variations are coherent over global scales. This data processing technique has also been applied to magnetotelluric survey data where it has proved to be very effective in removing noisy values and yielding superior response estimates to the commonly obtained band-averaged estimates.

In order to expand the cable measurement program, 140 days of hourly mean cable voltages from the telephone cable that spans the Florida Straits between West Palm Beach, Fla. and Eight Mile Rock, Grand Bahama Island (about 20 mi south of Jupiter) were collected with the cooperation of AT & T. These cable voltages represent the voltage difference between the sea-water contacts at West Palm Beach and Eight Mile Rock and can be corrected for fluctuations in

the cable power supply since the power supply electric current was also measured. Measurements of temperature at the power station and a comparison with the Jupiter Inlet/Settlement Point cable voltages established that the power separation filter has a temperature-induced variation, and a temperature coefficient approximately that of copper.

CARBON DIOXIDE RESEARCH

Since about 1850, human activities, including the burning of fossil fuels and deforestation, have raised the atmospheric carbon dioxide (CO_2) level from about 280 ppm to 345 ppm in 1985. This CO_2 increase is thought to affect the Earth's radiation balance, leading to an increase in the Earth's temperature. Major repositories for fossil-fuel-derived CO_2 are terrestrial vegetation, the atmosphere, and the oceans; each of the last two contains close to 50% of the excess according to recent estimates. The buildup rate of atmospheric CO_2 depends on the oceanic uptake rate of CO_2, which is controlled by diffusive and convective mixing processes, by sinking and decomposition of biogenic particulates, and by air-sea exchange rates.

Because the oceans act both as a source and as a sink for atmospheric CO_2, particularly in upwelling and downwelling areas, PMEL scientists continued an interdisciplinary study of the CO_2 system in the surface and intermediate waters of the eastern North Pacific during the summer and winter of FY 1985. The purpose of these investigations was to study the dynamics of the CO_2 system and gas exchange along meridional transects that includes major frontal systems in the North Pacific.

During February and July 1985, on two cruises in the eastern North Pacific, measurements were made of total CO_2, pCO_2, alkalinity, freons, suspended matter, calcium, salinity, temperature, oxygen, and nutrients. In addition, atmospheric and surface ocean measurements of CO_2 and CH_4 were made in cooperation with scientists from ARL's Geophysical Monitoring for Climatic Change (GMCC) Division. The preliminary data for July indicated significant variations of seawater pCO_2 concentrations along the transect, with below saturation values near the Subpolar Front, and supersaturated values in the Subpolar Gyre. The winter values were significantly lower than the summer values. The high values in the Subpolar Gyre are probably due to seasonal heating of the surface waters. These results suggest that the waters near the Subpolar Front are sinking faster than the time required for equilibration with respect to CO_2, or significant uptake by marine phytoplankton.

The fluorocarbon tracers F-11 and F-12 were also measured on both the winter and summer cruises. The F-11 distribution for the summer cruise revealed maxima in the mixed layer in the Gulf of Alaska near station "P", slightly above saturation equilibrium with respect to the overlying atmospheric burden (as observed for CO_2 as a result of seasonal heating). A subsurface freon maximum was traceable southward across the Subpolar Front and Subtropical Gyre nearly to Hawaii. The fluorocarbon signal was detectible to at least 800 m at 35°-40°N, the deepest penetration along the section. A comparison with previous F-11 profiles taken near "P" in December of 1980 reveals that the near-surface freon concentration has risen in direct proportion to the 20% atmospheric increase during this 4½-year interval. However, below the mixed layer the F-11 burden within the upper thermocline

(σ_T = 26.5-27.0) has at least doubled since 1980. Although a gradual deepening of tracer profile was to be expected as a result of the slower rate of atmospheric increase since the late 1970's, the very rapid fluorocarbon accumulation suggests that this period (1980-85) has been one of unusually efficient thermocline ventilation. Local vertical overturning and/or lateral advection from source regions to the west are the major ventilation mechanisms, but whether the observed increase in freon in the thermocline has been gradual or the result of a particular overturning event cannot be determined from the limited sampling.

PLANS IN FY 1985

EQUATORIAL DYNAMICS

- Implement an array of 12 ATLAS thermistor chains spanning the equatorial Pacific from 165°E to 110°W. The data obtained will be used to provide real-time information on thermal structure variability and to study the low-frequency variability.

- Use the ship-of-opportunity thermal data set to assess the role of variations in wind forcing in changing the thermal field; carry out numerical model verification studies with the data.

- Complete tropical Pacific island surface wind analyses and prepare results for publication.

- Conduct a variety of hindcast studies of the 1982-83 ENSO event, using the GFDL model and surface wind stress fields prepared by different groups, and determine the model mechanisms responsible for the evolution of near-surface currents and SST. Compare model results with ocean data as possible.

- Study the prediction of El Niño and related global atmospheric events, using a new statistical technique based on the discriminant method.

STACS

- Investigate the upstream variations of the Florida Current and the origin of the occasionally large monthly transport bursts by expanding the cable voltage recording system to include telephone cables between Key West, Fla., and Havana, Cuba, and between St. Thomas, Virgin Islands, and Maiguetia, Venezuela, and compare the voltages with those being collected from the Jupiter Inlet/Settlement Point cable.

CARBON DIOXIDE/RITS RESEARCH

- Continue North Pacific time series of fossil CO_2 increase.

- Begin measurements of radiatively important trace species (RITS) in the North Pacific.

- Develop kitetoon atmospheric boundary layer sampling capability.

MARINE ENVIRONMENTAL ASSESSMENT

Marine environmental assessment at PMEL emphasizes understanding the complex physical and geochemical processes that ultimately determine the health of the marine system and its ability to assimilate pollutants. Included in this area are studies of suspended-sediment transport and geochemistry, distributions of hydrocarbons and synthetic organics, coastal and estuarine circulation, theoretical modeling of pollutant transport processes, and a program in marine sources of acid rain. Although the geographic focus of these studies has been Pacific Northwest and Alaskan coastal and estuarine waters, the scientific knowledge acquired and methodologies developed are applicable to other marine systems. Two major activities at PMEL are studies of the long-range fate of chronic pollutants in marine waters and oceanic precursors to acid rain.

ACCOMPLISHMENTS IN FY 1985

LONG-RANGE-EFFECTS RESEARCH

In response to the Marine Protection, Research and Sanctuaries Act of 1982 and the National Ocean Pollution Research and Development and Monitoring Planning Act of 1978, PMEL has addressed environmental concerns associated with transport and marine disposal of municipal waste water and the reaction of marine systems to continuous influx of pollutants. Under the NOAA Long-Range-Effects Research Program (L-RERP), PMEL is examining the role of suspended particulates in transporting pollutants or in removing them from the marine system. In support of these studies researchers are investigating the mechanisms by which heavy metals and organic pollutants adhere to particulates. As these processes become better understood, we will be able to assess the long-term effect of chronic, low-level input of pollutants into the marine system.

Studies in the Puget Sound-Strait of Juan de Fuca system, under way for several years, are leading to a better understanding of Puget Sound's ability to accommodate pollutant inputs. Many pollutants adhere to and move with particles, and ultimately are buried in the sound or transported out of the sound along with particles. The emphasis of much PMEL research, therefore, has been particle transport and fate.

Pollutant Transport in the Water Column

Pollutants are derived from both natural and human sources, including riverine, atmospheric, municipal and industrial sewage discharge, and dredging operations. Mass balance calculations for many pollutants indicate that human sources exceed the natural sources, and buildup in sediments occurs over decadal or longer time scales. The assimilative capacity of an estuary is a function of the individual pollutant's physiological effects on the indigenous marine life, residence time in the estuary, biological availability and uptake, and the physical and chemical transformations occurring in the water column and in the sediments.

During FY 1985, PMEL scientists continued to make significant advances in our understanding of the physical and chemical processes controlling the distribution and fates of toxic trace metals and hydrocarbons in coastal areas and estuaries. Following are descriptions of accomplishments in related theoretical, observational, and modeling research efforts.

Theoretical work on modeling the long-term, two-layer circulation in fjords uses freshwater and salt as convenient tracers to deduce the recirculation, or refluxing, of water between outflowing and inflowing layers at mixing zones where fjord reaches intersect. However, if such an intersection involves more than two reaches, more tracers are necessary to resolve the mathematical indeterminacy. Unfortunately, long-term data sets for other tracers are not usually available. Therefore, a technique based upon entropy maximization has been developed to yield a solution that is maximally noncommittal with regard to the missing tracer information. An application to Puget Sound indicated that less than 1/2 of the seaward-flowing surface water is recirculated landward because of mixing at the Admiralty Inlet sill; this is somewhat lower than earlier estimates of 2/3.

Dissolved copper concentrations were used in conjunction with the refluxing model to both test and improve it. Given estimates of copper inputs to Puget Sound the model predicts copper concentrations, which in turn have been compared with actual observations. Theory and observation show similar trends and agree to within error limits. An advantage of the maximum entropy technique is that new tracer information can be incorporated readily to produce improved reflux coefficients. The model has been run with and without anthropogenic inputs to evaluate the effect of human activities on Puget Sound copper concentrations.

A theoretical index based on the estuarine Richardson number was developed to predict the occurrence and intensity of intrusions of new water into estuaries controlled by sills. For Puget sound, this index was computed from predicted tidal currents in Admiralty Inlet for the period 1970-1989. It shows that the strongest intrusions should occur during 4-month periods centered on the spring and fall equinoxes, with gaps during the winter and summer solstice periods. An apparent 4-5-year cycle in the intrusion index is being compared with observations.

Acoustic observations are being used to deduce the degree of mixing during the onset of intrusions. Once initiated, dense bottom water propagates 70 km up-estuary, replacing water existing below the 65-m sill. Five episodes of deep water renewal were observed at approximately fortnightly intervals in response to enhanced gravitational circulation and reduced turbulent mixing during neap tides over the entrance sill. At mooring sites along the estuary, renewals were characterized by a sequence in which there occurred a rapid change in temperature followed by a 2-10 day up-estuary pulse of deep currents and maxima in salinity and density. The renewal characteristics were phase-lagged with distance from the sill; this lag indicated up-estuary velocities of 7-14 cm s^{-1}. The observations of the advance and vertical structure of the deep intruding water are interpreted as a turbulent gravity current that spreads linearly with a constant mean velocity and a density difference that varies inversely with distance due to entrainment. A classical two-layer box model used to estimate flow during various stratification and runoff conditions indicated a possible seasonal cycle in transport with a maximum in

winter and a minimum in summer. Evaluation of long-term observations of flow at one location are now beginning to confirm the predictions. Transports in January-March are about double those in June-August. The exact monthly intervals, however, would vary for any particular year. Thus, replacement rates for water will obviously vary throughout the year, and incorporation of these ideas with the intrusion index concept is under way. Observations across the section of the long-term measurements are being used to improve calibration of transport estimates.

Investigations are also continuing on the vertical transport of particles and pollutants through the water column. Because of the uncertainties regarding sediment trap efficiency in estuarine environments where current flow may exceed 100 cm s^{-1}, a field experiment was designed to compare the trapping characteristics of drifting traps and moored traps. A special trap that divides the vertical flux into four discrete samples representing different flow regimes was designed and built. Results of the experiment showed that cylindrical sediment traps are efficient collectors of the "true" vertical flux (as measured by drifting traps that sense no relative flow) at current speeds up to approximately 100 cm s^{-1}. Total flux varied by 10% between drifting and moored traps. More importantly, the particle population, as defined by size and density distributions, was the same for drifting and moored traps. This latter result held even during intervals of much higher current speeds when moored traps under-sample the total flux. The success of this field experiment indicates that the vertical particle transport can be measured accurately under most estuarine flow regimes.

Sediment trap investigations have also been valuable in quantifying the transport and fate of toxic metals in Puget Sound. Comparisons of metals in sediment trap particulates and metals in sediments indicate that for many metals, including Fe, Cr, Ni, Zn, and Pb, retention in estuarine waters is enhanced by scavenging processes in the water column. Only a small fraction of the total metal flux is recycled at the sediment-seawater interface and, consequently, most of the toxic metals are retained within the fine-grained sediments of Puget Sound. Trace metals that are rapidly scavenged by particulates are subsequently enriched in the surface layer of the sediments.

Polycyclic aromatic hydrocarbons (PAH) are toxic hydrophobic compounds and are also generally associated with particulates. Particulate hydrocarbon concentrations in the main basin of Puget Sound decrease with depth in the water column and with distance from Seattle. The residence time of these pollutants in the water column is not sufficient for mixing to take place throughout the estuary or out of the estuary. Although these compounds are rapidly transported to the bottom sediments, resuspension and lateral transport in the bottom nepheloid layer disperse the compounds throughout the fine-grained sediments in the center basin.

During the past year, PMEL also began, for EPA, multidisciplinary field studies of pollutant transport in the two main urbanized embayments of Puget Sound, Elliott Bay, and Commencement Bay. Earlier PMEL studies of transport processes in Elliott Bay had shown that pollutant-bearing particles are added to the surface waters by river inflow, combined sewer outfalls, atmospheric precipitation, and other routes. Those particles that remain suspended above the pycnocline are advected out of the bay by the estuarine circulation. Particles that rapidly settle out of the surface layer contribute to pollutant

accumulation in the bottom sediments. Bottom sediments may be a new sink for particles rather than a source to the main basin.

Bottom Boundary Layer Processes

In the bottom boundary layer, active processes determine much of the transport and deposition of sediment and particulate-borne pollutants. Tidal and other currents resuspend material from the bottom; the material is then diffused upward by turbulence into the overlying water. There, this material reacts with dissolved and suspended chemical constituents before settling back to the bottom. Entering the layer from above and upstream are new sediment and dissolved constituents. Manganese and iron ion particles, for example, scavenge toxic metals from the water column and carry them down to the bottom sediment. Some of the manganese and iron are chemically reduced in bottom sediment and diffuse back into the water column. Boundary layer processes help determine the extent and duration of the exposure of biota to pollutants on and near the bottom.

A boundary layer model using turbulence closure was implemented to simulate chemical, sediment, and flow processes near the bottoms of estuaries. Obtained from the Swedish Meteorological and Hydrological Institute, this model supplements the high-resolution boundary layer models that have been developed at PMEL. One result of the investigations was the finding of undulating patterns in the eddy viscosity profiles, due to tidal currents. The effects of the undulating pattern on sediment and trace metal processes are now being studied. The distributions of dissolved and particulate manganese are found to be strong functions of the time constants for chemical reactions relative to the time scales of diffusion and tidal currents. The model played a central role in the planning of a near-bottom experiment in Puget Sound that was carried out in FY 1985.

One focus of the L-RERP sediment transport work has been on erosion rates, their characterization and prediction. A critical review of the literature and a match of a high-resolution model to laboratory observations indicated that erosion of abiotic, fine sediment occurs at bottom stresses well below those often cited as critical stresses. This can be seen from a statistical point of view in which the turbulent currents produce random concentrations of stress over a bed of particles with randomly varying exposures to the flow. This line of research is continuing through intensive modeling and field experiments. A two-dimensional model under development will simulate the erosion and transport of sediment down the major axis of Puget Sound.

Pollution Accumulation In Sediments

Recent sedimentation in estuaries is of special interest because it is one important way anthropogenic particulate-borne contaminants are isolated from the estuarine biosphere. In the past year, work was completed on the analysis and interpretation of 210-Pb data from cores taken along the axis of the main basin of Puget Sound. The results suggest that a zone of rather high deposition is off Elliott Bay. The results also show that biota within the upper part of the sediment column can be churning surface-deposited material

to a depth of 35-40 cm. This rather rapid mixing helps bury newly deposited contaminants, but it also exposes much older sediments and contaminants to the sediment-seawater interface.

The sediment column also provides a historical record of the usage of materials indicative of industrialization. The record is blurred by the stirring of sediments by the infauna, but 210-Pb profile analysis allows us to quantify the pattern of mixing. Historical records of pollutant sources can then be related to the pollutant profile of the sediment column. By using as source history the sum of tetraethyl lead in the Puget Sound area and a steady contribution from industrial sources that began in 1890, the profiles of stable Pb within the sediment column were determined. The result compares favorably with the measurements of stable Pb made on a core near Meadow Point, Seattle, for which coincident 210-Pb data were acquired. PAH profiles are being similarly compared.

ACID RAIN

Reduced sulfur compounds are produced biologically in the photic zone of the ocean. Our initial studies showed that dimethylsulfide (DMS), the most abundant volatile sulfur compound in surface ocean waters, contributes significantly to the global atmospheric burden of sulfate. Our recent efforts have stressed the coastal ocean and its potential impact on regional sulfur budgets. Regional sulfur budgets are necessary to assess the relative importance of natural and anthropogenic emissions on the chemistry of precipitation, since the tropospheric residence time of sulfate is thought to be insufficient for this species to be well mixed on a global or even hemispheric scale.

DMS concentrations were measured in ocean waters along the West Coast of the United States on four cruises from May 1983 to May 1985. Concentrations in surface waters ranged from 13-380 ng S L^{-1}, with a summer average of 60 and a winter average of 20 ng S L^{-1}. By use of the stagnant film boundary layer model, the flux of sulfur from the ocean to the atmosphere was calculated to be 30 mg S m^2 yr^{-1}. Based on average surface zonal wind velocities and an assumed non-sea-salt sulfate atmospheric residence time of 5 days, the calculated net flux of biogenic sulfur to the West Coast of the United States is 0.05 Tg yr^{-1}. Because of the many assumptions, the net flux is known only within a factor of 2-3.

The depositional area for this marine sulfur is more difficult to estimate. The principal mechanism by which sulfur is removed from the atmosphere is cloud scavenging and precipitation. Much of the rainfall in the western United States occurs on the western slopes of the mountain ranges. We pose two continental regions of potential deposition for this oceanic sulfur, the region west of the Cascade/Sierra Nevada Mountains and the region west of the Rocky Mountains. The estimated oceanic biogenic sulfate is 13% of the anthropogenic emissions in the first region and 4% in the second region. It is possible that the oceanic sulfur is largely deposited in an even smaller region, such as the area west of the Olympic/Coastal mountain ranges.

PLANS FOR FY 1986

LONG-RANGE-EFFECTS RESEARCH

- Complete analysis of selected 1984 cores to determine the along-channel and cross-channel patterns of organic pollutant accumulations in Puget Sound.
- Continue the development of one- and two-dimensional models of chemical, sediment, and flow processes in the bottom boundary layer.
- Carry out an experiment in Puget Sound to calibrate and test models of bottom boundary layer processes.
- Obtain reliable, first-order estimates of the relative scale of pollutant transport paths (surface plume vs. bottom nepheloid layer) in Elliott Bay.

ACID RAIN

- Refine flux estimates by measuring DMS and its precursors in the ocean and DMS and its oxidation products in the atmosphere.

MARINE OBSERVATION AND PREDICTION

Marine observation and prediction research is directed toward understanding and improving the prediction of phenomena related to marine warning and forecasting services. Research subjects include sea-ice processes, hazardous winds, hazardous waves, and tsunami propagation and run-up. PMEL scientists work closely with colleagues from operational service components of NOAA, such as the Northwest Ocean Service Center and the Navy/NOAA Joint Ice Center. Studies of sea-ice processes are also applicable to NOAA's climate research. These studies of coastal meteorology, physical oceanography, and sea-ice processes are carried out through a combination of field measurements, remote-sensing techniques, and numerical modeling.

ACCOMPLISHMENTS FY 1985

SEA ICE RESEARCH

The Arctic Polynya Experiment

The Arctic Polynya Experiment (APEX) was conducted in the vicinity of St. Lawrence Island in the northern Bering Sea during the winter of 1984-85. The purpose was to investigate physical processes in the atmosphere, sea ice, and ocean and to observe the interaction of a wind-driven polynya with regional dynamics and thermodynamics. The relative importance of baroclinic currents due to brine rejection during the freezing of ice in the polynya, barotropic currents due to set-up on the shelf (particularly differences between the Anadyr Strait and Sphanberg Strait), internal ice stress due to presence of St. Lawrence Island, wind stress, and Coriolis force on sea ice motion are being considered. The measurement program included a variety of field measurements from ocean moorings, from the sea ice, and from St. Lawrence Island.

Nine ocean moorings, 15 ARGOS position buoys, 2 GOES shore meteorological stations, and 2 GOES ice stations were deployed in and around the Bering Sea. Weather conditions during January over the eastern Bering Sea and western Alaska were anomalous with the warmest air temperatures on record and the least ice ever recorded for a January, both due to prolonged southerly winds throughout the month. During the last three weeks in February, the winds shifted to northerly, air temperatures dropped, and the ice recovered its previous minimum both by freezing in situ and by the return of Bering Sea ice from the Chukchi Sea. The ARGOS buoys initially drifted south-to-southwestward. In February the buoys turned and drifted northward. This is consistent with the idea that reversals in Anadyr Strait (periods of southward flow) are of shorter duration than in Sphanberg Strait, although this was certainly one of longest reversals ever observed for Anadyr Strait. The eastern array lost two ARGOS buoys on the southward transit past the island and one on the northward transit from crushing or shear, and both arrays exhibited greater deformation than the MIZEX-West array had while passing St. Matthew Island during 1983. The buoys in the western array melted out at the ice edge between 18 March and 2 April and in the eastern array between 17 May and 16 June.

The data from the over-winter current meter moorings, the arrays of drifting ice buoys, and the regional meteorological stations should provide new information on high-latitude sea/ice/air interactions and contribute to our understanding of Arctic heat, salt, and ice budgets.

Vessel Icing

Ability to forecast icing is one of the most important marine meteorological problems in high-latitude waters because rapid accretion on superstructure creates an extreme hazard. Icing conditions require the presence of sub-freezing air temperatures, strong winds, and sea surface temperatures not more than 6° above freezing; thus, it is not always obvious which way a vessel should head to mitigate a situation. Actual icing rate is a characteristic of each vessel, depending on its design and sea-keeping ability.

During FY 1985 a categorical algorithm was completed that related vessel icing to meteorological parameters. An initial set of 195 icing incidents from Alaskan waters during 1980 to 1983 was reduced to a data set of 85 observations verified by interviews with the observers. Meteorological information in these reports was compared for consistency with the Anchorage Weather Service Forecast Office meteorological analyses. Fifteen icing rates were greater than 2.0 cm h^{-1}, substantially higher than those in the Alaskan observation base available for our previous icing rate nomogram.

A major feature of the algorithm development is the use of a robust statistical procedure to relate icing rates to meteorological parameters. The method is considered robust because the influence of inaccuracies in any individual observation in the data set is minimized by basing the algorithm upon icing and predictor categories. This contrasts with standard regression techniques in which extreme observations either have undue weight or are excluded from the data set as outlying values.

The new algorithm predicts icing rates greater than three times those of the previous NOAA nomogram. The new results will be incorporated in National Weather Service guidance products issued from the Marine Products Branch of the National Meteorological Center, and the Alaskan Region.

HAZARDOUS WAVES

On 12 October, 1984, during a flight of the U.S. Space Shuttle *Challenger*, the Shuttle Imaging Radar-B (SIR-B) system acquired imagery of the ocean surface near Hurricane Josephine, which had a peak maximum sustained wind speed of approximately 90 kn. Such wave data--large-scale, synoptic, directional, and near a hurricane--are rare. Imagery, taken over a period of about 2.5 min, covered an area 25 km wide by 600 km long and had a resolution of about 33 m. Surface wave patterns were clearly evident. Sub-areas of the imagery were subjected to two-dimensional fast Fourier transform analysis, from which estimates of the dominant wavenumber vectors could be derived. A primary wave system was evident that moved away from the storm track and was distinguished by a smooth and continuous variation in wavelength and direction along the entire 600 km length of the radar swath. The system underwent a 90°

rotation in direction, and displayed a decrease in wavelength of more than 30% from >300 m to <200 m. Also evident were secondary systems that displayed considerable variation in wavelength and direction.

TSUNAMI

The Agency for International Development (AID) awarded PMEL a contract for a project titled THRUST (Tsunami Hazard Reduction Using System Technology). THRUST's purpose is to demonstrate the effectiveness of a regional early warning system for an underdeveloped country. The pilot project will take place in Chile. The major efforts this year were the development of a Pacific basin tsunami data base and the development of instrumentation for the THRUST system. The system uses existing seismic instrumentation connected to satellite communication to establish a warning system. With this system, Chile will have rapid data acquisition and analysis, and quick information dissemination.

Time series analyses were performed on data collected at six coastal tide stations during a low amplitude, Pacific-wide tsunami that occurred on 3 March 1985 just offshore of Valparaiso, Chile. All records were characterized by significant energy in the 50-60 min period band. Higher frequency energy, though dominant at the two southernmost stations, decayed rapidly away from the source in a northerly direction. Initially, low-frequency energy also decayed northward, but then increased monotonically after reaching a minimum at Caldera.

Bottom pressure recorders were deployed in the equatorial Pacific to record the characteristics of passing tsunamis in the open ocean. Several small tsunamis have been recorded, as well as signals from distant storm events.

PLANS FOR FY 1986

SEA ICE RESEARCH

- The second phase of the APEX experiment ice buoy deployments will be conducted in the northern Bering Sea to study sea ice drift in the vicinity of Bering Strait, to provide a scientific basis for extending the sea ice forecasting model to this region.

- A two-dimensional, coupled ice/water model for the Bering Strait region will be developed as the first phase of a complete Bering/Chukchi ice forecasting model.

HAZARDOUS WAVES

- Further studies of the *Challenger* SIR-B imagery will focus on the dynamics of hurricane wave generation and propagation, and the influence of fundamental hurricane parameters such as the radius to maximum winds, the maximum sustained wind speed, and the hurricane forward velocity.

TSUNAMI

- Additional numerical simulations are planned of long wave propagation along the entire west coast of South America for a variety of tsunami-generating mechanisms. More detailed studies of the response of the Valparaiso harbor to nearby sources will be carried out on a relatively fine-scale grid.

MARINE RESOURCES

Hydrothermal venting, which occurs along seafloor-spreading centers, represents a basic input of heat and materials into the oceans. The effect of hydrothermal venting on the marine environment is the focus of PMEL's marine resources program called VENTS (not an acronym). Research efforts have been specifically designed to define and quantify the chemical, geological, and physical oceanographic processes evolving from the venting of hydrothermal fluids. Current studies of hydrothermal venting have focused on the Gorda and Juan de Fuca Ridges.

In PMEL's second major area of research in marine resources, fisheries-oceanography program development and preliminary field experimentation continued in anticipation of future funding of the Fisheries-Oceanography Cooperative Investigations (FOCI) initiative. FOCI, which combines the expertise of PMEL and of NOAA's Northwest and Alaska Fishery Center, has the primary research objective of understanding the influence of variability of North Pacific meteorology and physical oceanography on commercially important fisheries.

ACCOMPLISHMENTS IN FY 1985

VENTS

VENTS conducts research on seafloor-spreading processes to assess the consequences of high-temperature hydrothermal venting at geologically active ridges. Hydrothermal venting systems are thought to have a significant effect on the oceanic thermal and mass budgets. They are a major source for mineralization of seafloor sediments and a primary source for the formation of a variety of metallic sulfides. Further, the close association between active venting and characteristic vent communities constitutes an important element in NOAA's ongoing research in marine living resources.

One of the principal goals of VENTS is to quantify the effects of hydrothermal venting on the biogeochemistry and physics of the oceans. Materials and heat hydrothermally cycled between the Earth's crust and seawater along mid-ocean-ridge spreading centers, at hot spots, and in back-arch basins are known to play an important role in the global distributions of many elements. Localized deposits resulting from hydrothermal venting may provide significant reserves of economically important metals. VENTS investigators examine the composition and flux of venting materials and study the biogeochemical and physical processes that occur as these materials are mixed with and dispersed by induced and ambient ocean motion.

During FY 1985, three major field experiments were conducted in support of VENTS: three *Surveyor* cruises to the Gorda and Juan de Fuca Ridges, a *Researcher* cruise to the Mid-Atlantic Ridge, and an *Atlantis II/Alvin* submersible cruise to the Galápagos Ridge.

On the Gorda Ridge, hydrothermal indicators showed a strong along-strike variation consistent with the known variation of spreading rates. Stations on the slowly spreading (~1.5 cm yr^{-1}) southern and central portions of the ridge exhibited no enrichment in dissolved or particulate hydrothermally derived material. At the two most northerly stations, where the spreading rate is ~5.5 cm yr^{-1}, plumes of almost certain hydrothermal origin were identified on the basis of increased particle concentration, a potential temperature anomaly of 10-20 millidegrees, and increases in dissolved methane and radon and dissolved manganese and particulate ion trace metals. The plumes were found between 2700 and 3000 m and were as much as 600 m above the floor of the axial valley, suggesting that the vent sources are located somewhere on the adjacent valley walls as has been observed for the similar topography of the Mid-Atlantic Ridge. The Gorda Ridge is the only known section of hydrothermally active ridgecrest that lies within the Exclusive Economic Zone (EEZ) of the United States.

Hydrothermal plumes from three tectonically dissimilar regions of the Juan de Fuca Ridge were sampled from *Surveyor* in June to provide the first internally consistent data representative of several different plume types. A metal-dominated, high-exit-temperature plume was found over the Southern Juan de Fuca Ridge whereas a sulfur-dominated plume was found above the Endeavour Ridge segment of the Northern Juan de Fuca Ridge. On the central Juan de Fuca, a low-exit-temperature-type plume was mapped within the caldera of an axial seamount.

Short-term current observations at the Southern Juan de Fuca site in 1984 showed predominantly northward flow for about 20 days. However, there was an indication of some westward flow during the first 5 days, which could have carried the observed plumes to the west. A year-long mooring on the west rim of the ridge showed 2 months of northward flow, followed by 8 months of westward flow, and then a return to northward flow for 3 months. Low-frequency speeds were typically 1-2 cm s^{-1}. Tidal oscillations of 4-10 cm s^{-1} are also evident in the data.

Vent particulates from the southern Juan de Fuca and Endeavour Ridge sites were studied for their chemical and mineralogical composition by X-ray diffraction and X-ray microanalysis procedures. Samples from the southern Juan de Fuca Ridge consisted mainly of sphalerite, pyrite pyrrhotite, barite, elemental sulfur, and two unidentified Fe- and Ca-Si silicate phases that have not been observed in other hydrothermal systems. These phases are the result of mixing intermediate-temperature (200°-270°C) hydrothermal fluids enriched in Fe, Si, Zn, Ba, Ca, and S with seawater. The major phases emanating from the Endeavour Ridge vents included chalchopyrite, anhydrite, pyrite, sphalerite, pyrrhotite, marcasite, barite, and elemental sulfur. These phases are characteristic of reactions involving the mixing of high-temperature (>290°C) hydrothermal fluids with ambient seawater.

Microbial geochemistry studies focused on the role of bacteria in the precipitation and transportation of metals such as Mn and Fe within the plumes. Transmission electron microscopy with X-ray micro-elemental analysis was used to identify, count, and analyze individual microparticles. Other microbiological parameters under study include bacterial number (direct epifluorescent microscopy) and two independent and complementary measures of biomass (ATP and lippopolysaccharide). Additionally, radiotracer experiments

were performed at sea in order to examine rates of Mn-54 and Fe-59 precipitation under biologically controlled conditions.

Early results indicate that the metal encrusted capsules of certain bacteria are significant contributors to the plume particulate Mn loads. These encapsulated bacteria are very abundant (10-25% of total bacterial numbers) and represent the only microparticles, so far, that contain detectable Mn. Though Fe deposits are always associated with the capsules, the capsuled bacteria's relative contribution to total plume particulate Fe is variable.

Sampling and shipboard analytical capabilities were further enhanced through the acquisition of a sea-going Zeeman modulated atomic absorption spectrophotometer and several high-resolution CTD systems. A four-chamber, remotely activated plume sampler was designed to accompany the horizontally towable CTD system (SLEUTH) which included integrating nephelometers and high resolution transmissometers. These tow-systems provide continuous and real-time sensing and sampling of hydrothermal plumes and allow scientists to adjust operational strategies to use ship time most efficiently.

High-resolution deeptow side-scan sonar images were obtained at Axial Seamount on the Juan de Fuca Ridge. Ground-truth data were obtained by numerous camera tows and provide the first physiographic map sufficiently detailed for submersible navigation.

The *Atlantis II/Alvin* cruise was specifically designed to survey the surficial extent of the massive sulfide deposits associated with an extinct vent site on the Galápagos spreading center as well as to conduct state-of-the art magnetics and electrical experiments to define the subsurface extent of the sulfide enrichment. This experiment marked the conclusion of a series of NOAA-sponsored diving programs at this site and provided information on the duration and volume of vent activity during the entire life cycle of vent systems.

A VAX 11/750 computer system was brought on line for the primary purpose of processing digital SEABEAM bathymetry to produce detailed maps within areas of VENTS interest. All previously existing NOAA software to accomplish bathymetric data processing was reconfigured to operate on the PMEL system. The unique capability for large-scale plotting, in color, of bathymetric maps became operational approximately 6 months ahead of schedule, and initial map products were used in FY 1985 VENTS field expeditions.

FISHERIES-OCEANOGRAPHY

The Fishery-Oceanography Experiment (FOX) was funded jointly by PMEL and the Northwest and Alaska Fishery Center (NWAFC) to study the effects of the biotic and abiotic environment on early life stages of pollock in Shelikof Strait, Alaska. Field operations for FOX were conducted between August 1984 and August 1985. They provided initial research for FOCI, which will examine interannual variations in the environment and relate them to fluctuations in recruitment of commercially valuable fish and shellfish stocks. The paradigm that guides this research is that year class strength is primarily determined by interactions with predators and prey during early life stages and that

variability in these interactions is a function of fluctuations in the abiotic ocean climate which in turn are driven by atmospheric variability.

For the stock of pollock in Shelikof Strait, our primary hypothesis is that larvae and juveniles remaining near the coast of the Alaska Peninsula are more likely to survive than those that are transported off the shelf. Exchange of mass with adjacent slope waters of the Alaskan Stream affects water properties and the composition of plankton communities. These factors can also affect survival at early life stages. Thus, the key process in the physical environment is transport, and the factors that influence its variation must be understood.

The two major activities of the 1985 fishery-oceanography program were to conduct field operations and to synthesize existing data and knowledge regarding the abiotic environment of the Gulf of Alaska. On six oceanographic cruises, operations included deployment and recovery of ten current and bottom pressure moorings; collection of 563 water samples for nutrient analyses, 344 samples for estimation of chlorophyll concentration, 449 zooplankton samples, and 144 micro-zooplankton samples; acquisition of CTD data at 324 stations; and 40 atmospheric radiosonde observations. Nine flights were made with the NOAA P-3 research aircraft, to study the unique meteorological conditions in Shelikof Strait and along the coast of Alaska. Ancillary meteorological data were collected from the ship's weather logs and three land-based platforms southwest of the strait.

The 1985 pollock egg survey in April indicated that abundance was similar to that in previous years (1980-84). Spawning occurred at a similar time and in about the same location in lower Shelikof Strait. Results of the survey of larvae in early May, however, were markedly different from those for previous years. Few larvae were found, even after the search pattern was expanded to cover all areas where larvae might conceivably have drifted, an area four times larger than originally planned. Four possible causes for the unexpected absence of larvae are under investigation: (1) unusually strong off-shelf transport, (2) mass starvation due to low food abundance, (3) excessive predation, and (4) poor condition of the eggs. Wind and current meter data will be used to address the question of transport. The other causes will be evaluated from biological samples collected during FOX.

Preliminary examination of weather and CTD data indicated that anomalous conditions existed in early 1985. Throughout January and in early February a ridge of high pressure existed over the Gulf of Alaska, resulting in a westward displacement of the Aleutian Low. As a result, the primary storm track was northward into the Bering Sea rather than into the Gulf of Alaska. In late winter and early spring, a winter storm pattern rather than a typical spring pattern was established with anomalously persistent northerly winds in the region. There was an unusually large number of storms that passed through the western Gulf of Alaska. Although the ramifications of this perturbation are not yet fully known, CTD data indicate significant differences between 1985 and 1981 (a year when the number of larvae collected was several orders of magnitude larger than in 1985). During 1985, surface waters were about 1.5°C colder, the mixed-layer depth was approximately 25 m deeper, and bottom waters were 0.3°C warmer and 0.4 g kg^{-1} more saline than in 1981. It appears that this condition continued through May. The changes in surface temperatures and mixed layer depth suggest the action of increased storm

activity; the changes in bottom water characteristics may be related to enhanced transport in the upper layer with compensating flow of slope waters into the Shelikof sea valley.

PLANS FOR FY 1986

VENTS

- Field work will continue within specific areas along the Gorda Ridge, to survey what appear to be hydrothermally active vent sites discovered during the FY 1985 field season.
- Time-series sampling of vent-associated waters will continue at several known active hydrothermal sites along the Juan de Fuca Ridge, in order to begin quantification of the long-term variations in vent fluid output.
- The detailed photogeologic, seismic, and high-resolution side-scan sonar mapping of the Axial Volcano vent fields will be completed in anticipation of the arrival of *Alvin* in FY 1987.
- A series of *Alvin* dives will be requested to follow up the discovery of the active mid-Atlantic vent fields and bring to a successful close the VENTS field work on the Mid-Atlantic Ridge so that full concentration of program resources can be allocated to the Gorda and Juan de Fuca Ridges.
- The high-resolution data (e.g., bathymetric and side-scan sonar) processing capability at Newport will be augmented with interactive high-resolution graphics capability.
- Efforts will begin, to plan and implement the capability for submersible-based long-term monitoring of selected geological, biological, and oceanographic variables at the seafloor within and close to the active vent systems.

FISHERIES-OCEANOGRAPHY

- Analyze field observations obtained during the 1985 FOX experiment.
- Prepare a coordinated FOCI planning document with NWAFC.
- Conduct field operations in the vicinity of Shelikof Strait to study slope/sea valley water exchange processes.
- Assess new measurement techniques for field operations in the Bering Sea (e.g., bottom-mounted Doppler acoustic current profilers, satellite-tracked drifters, and CTD systems).

JIMAR

The Joint Institute for Marine and Atmospheric Research (JIMAR) is located at the University of Hawaii. JIMAR was formed in FY 1978 in association with the University and PMEL. The principal research interests of JIMAR are climate, equatorial oceanography, and tsunami.

ACCOMPLISHMENTS FY 1985

CLIMATE RESEARCH

JIMAR's climate research in FY 1985 included studies of interactions between middle-latitude and tropical circulation, Pacific island rawinsonde profiles, and surface wind fields derived from surface and satellite data.

Composites of middle-latitude dropwindsonde data collected near tropical east Pacific cirrus surges during the Global Weather Experiment (Special Observing Period-1) were analyzed. The analyses indicated that surges were caused by equatorward-penetrating middle-latitude systems. Cross sections of individual events agreed with the composites. We confirmed a published composite model that linked Asian winter monsoon activity with synoptic developments in the Hawaiian region.

Empirical orthogonal function analysis showed an inverse relationship between large-scale convective activity over the Australian monsoon region and the Society Islands. Spectral analysis indicates that systems with 20-40 day periods account for the inverse relationship.

Pacific island station rawinsondes for 1971-1976 were also examined. Power spectrum analysis of zonal winds showed 15-30 day oscillations in the midtroposphere for the 1972-1973 El Niño. In the upper troposphere 30-60 day modes were insignificant during El Niño but appeared significant during pre- and post-El Niño periods.

The meshed data from ships, buoys, small islands, and atolls, and derived surface winds from low-level satellite winds were analyzed and grid point data extracted through March 1983 for the Pacific Ocean. Owing to the extreme wind anomalies during the 1982-83 ENSO, our normal method of using climatological shear to derive surface winds from satellite data was modified for the period November 1982 through May 1983. Subjective analysis and evaluation of the Comprehensive Ocean-Atmosphere Data Sets (COADS) revealed many instances of suspect and/or misplaced data. The COADS data have proved sufficient for a very reasonable wind analysis over most areas of all three oceans. The COADS pressure data permit a subjective analysis of the atmospheric pressure at sea level, which is in good agreement with the winds.

EQUATORIAL OCEANOGRAPHY

JIMAR's equatorial oceanography activities in FY 1985 included new observational efforts with the Line Islands Array and Western Equatorial Pacific Ocean Circulation Study (WEPOCS), data analysis of NORPAX and PEQUOD data sets, and theoretical studies. Several sea level networks, data centers, and projects also continued.

In February and March 1985, inverted echo sounders and shallow subsurface pressure gauges were installed in the equatorial central Pacific using the R/V *Machias*. The Line Islands Array consists of these instruments in combination with island tide gauges. This array will be maintained for five years to study synoptic oscillations in sea level and their relation to wind and current fluctuations. Sixty-two hydrographic stations were occupied on two meridional sections throughout the array.

WEPOCS field work started in June 1985. Large-scale hydrographic surveys were conducted, and five shallow subsurface pressure gauges were deployed from the R/V *Thompson* in the Solomon and Bismarck seas. Pegasus current profiles at six sites along 150°E were carried out aboard the Australian R/V *Franklin*. An Acoustic Doppler Current Profiling program began on the R/V *Moana Wave* and R/V *Franklin*. Near-surface relative current profiles were made on both WEPOCS cruises and on an equatorial transit aboard the R/V *Moana Wave*.

Analysis of NORPAX and PEQUOD data continued, using more than 500 Pegasus profiles taken during the Line Islands Profiling Project. Studies of the structure of the deep equatorial jets indicated that the jets did not propagate vertically during the 16-month period of these observations.

Event detection methods were used to study near-equatorial sea level events. Many events appear to be Kelvin wave pulses generated by westerly wind bursts, best described statistically by a Poisson process model. A seasonal cycle of event frequency, and interannual variability of both event frequency and event sign were observed in the data.

Theoretical studies continued, and development began on a model of the influence of Indian Ocean coastal geometry on equatorial wave generation. This model will be used extensively to look at 40-50 day oscillations in the Indian Ocean as part of an India/U.S. bilateral effort on monsoon variability. Work on a second model began cooperatively with investigators from JISAO on a model to study interaction of equatorial waves and mean flows. Studies on vertically propagating Kelvin waves have led to a more general study of equatorial waves.

Research on sea level studies continued in several areas. Operation of the Pacific Sea Level Network continued through 1985, and data were routinely processed and evaluated. Four additional stations were converted to satellite data transmission, bringing the total to ten. Sea level observations were used to estimate the amounts of warm water exchanged during the 1982-83 El Niño event; an eastward flux of about 40×10^6 m^3 s^{-1} is indicated.

The TOGA Sea Level Data Center, established in 1984, acquired necessary equipment and moved into new accommodations. A data-handling system was

developed, and the bulk of past monthly mean sea level data for the tropical oceans was acquired. Acquisition of past daily sea level data from a variety of sources started.

The Integrated Global Ocean Station System (IGOSS) Sea Level Pilot Project, established in early 1984, continued to issue monthly maps of sea level for the Pacific Ocean. Data from 67 stations located in 25 IGOSS member states are included in the analysis for each Pacific map.

TSUNAMI RESEARCH

The construction of five solid-state tsunami gages was funded by the University of Hawaii. The electronic and package work was completed as well as design and fabrication of a prototype model. The tsunami observer list was updated with the addition of five new observers.

PLANS FOR FY 1986

Climate Research

- Examine the role of tropical storms in ENSO and delineate large-scale climate system fluctuations necessary for their occurrence.
- Participate in the United States/Peoples' Republic of China western Pacific research project cruises starting in December 1985.
- Continue production of the Pacific Ocean surface wind data set and evaluate non-U.S. satellite products and meteorological reports from fishing fleets.

Equatorial Oceanography

- Continue PEQUOD analysis and comparison with NORPAX shuttle observations.
- Continue to operate the Pacific Sea Level Network and convert three more stations to satellite data transmission.
- Establish a data base of the Indian Ocean at the TOGA Sea Level Data Center.

Tsunami Research

- Deploy five gauges to test calibration and gain field experience.

JISAO

The Joint Institute for Study of the Atmosphere and the Ocean (JISAO) was formed in FY 1977 with the University of Washington. The main areas of emphasis within JISAO continue to be climate dynamics, estuarine processes, and environmental chemistry.

ACCOMPLISHMENTS FY 1985

CLIMATE

JISAO contributed to the EPOCS and TOGA programs through the support of four postdoctoral appointees and one visiting scientist, whose research involved both observational and theoretical studies, and through active participation in planning for TOGA at the national and international levels.

A continuing study of nonlinear Rossby waves showed that critical layers provide a theoretical framework on which to base many ideas concerning the breaking of Rossby waves. More and more evidence is becoming available that in the atmosphere this process is extremely important in the transport of potential vorticity and chemical tracers.

This study of nonlinear Rossby waves concentrated on four topics: (1) Evolution of a nonlinear critical layer. Novel physical effects include the possibility of long-term absorption, the formation of a wake in which material contours are highly contorted, and the tendency for closed-streamline regions to be inhibited as the enduring vorticity field in turn alters the streamfunction. (2) Barotropic instability of a nonlinear critical layer. A great deal of time was spent on simulating the evolution of the entire nonlinear critical layer including the instability in a numerical model. This effort provided very strong evidence that the instability is highly effective in changing the evolution of the nonlinear critical layer. A number of problems remain to be solved before this study is complete. (3) Simple analytical and numerical solutions of critical layer behavior. A precise picture was revealed of the way in which reflecting/absorbing properties of critical layers are affected by numerical resolution and flow curvature. (4) Research related to the effect of potential vorticity mixing in the stratosphere on atmospheric free modes.

Another climate study area focused on low-frequency variability of the sea level and near surface temperature at the Galápagos Islands during 1979-84. The analysis concentrates on the 2-30 day frequency band where peaks are observed at 5 and 12 days.

Previous theoretical work was extended on the ocean response to spectral wind forcing on a continental margin, removal of the long-wave approximation, handling the "corner" region and merged Ekman layers, and cross shelf variation in bottom friction.

Scientific activity at the Experimental Climate Forecast Center focused on the preparation of a reformatted version of the National Meteorological Center (NMC) data. The new form is intended to be one that can be updated with NMC grids in real time. Real-time diagnostics in the context of the long-term climatic record will then be done.

ENVIRONMENTAL CHEMISTRY

Research continued on the absorption and removal of dissolved constituents in sea water by settling particles, which is termed scavenging. Scavenging is considered to be one of the main removal mechanisms of trace elements from seawater and a sink for pollutants in the coastal zone. The rates of scavenging under natural conditions were estimated by measurements of the distribution of dissolved and particulate Th-234. Laboratory experiments were used to extend the field measurements on Th-234 to a wide range of other elements. Experiments on the kinetics and equilibrium uptake of Th-234 and other elements by natural marine particulate matter were designed and conducted. Field and laboratory measurements were brought together to develop a model for scavenging in the open ocean and in Puget Sound. A box model to predict the rate of uptake of reactive elements in Puget Sound was constructed.

JISAO continued to play an active role in facilitating collaboration and interaction among environmental chemists working in several departments on the University campus. The annual Environmental Chemistry Day was held on January 24.

PLANS FOR FY 1986

- Continue an active program in climate with four postdoctoral appointees, a senior visiting scientist in residence, and a large number of short-term visitors who will be giving seminars.
- Secure funding for continuation of the core program in Environmental Chemistry.
- Sponsor a 3-day workshop on oceanic general circulation in January 1986: 25 from outside the Laboratory are expected to attend.
- Begin a Distinguished Scientist Program.

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PMEL Seminars

DATES	NAME AND AFFILIATION	SEMINAR TOPIC
1984		
9 Oct	Dr. Colin Grant Fisheries Division, Department of Primary Industry Australia	Australian fisheries and their management.
23 Oct	Dr. William Crawford Institute of Ocean Sciences Sidney, British Columbia Canada	Two aspects of oceanic turbulence: 1) A universal decay time for turbulence in stably stratified flows and 2) Turbulent rectification of equatorial Kelvin waves.
13 Nov	Dr. Curtis D. Mobley JISAO/PMEL	Statistical analysis of historical climate data sets.
27 Nov	Dr. Norbert Untersteiner Polar Science Center University of Washington	Remarks on differential drift of low concentration sea ice.
18 Dec	Dr. David A. Rothrock Polar Science Center University of Washington	Some observations of flow break-up.
1985		
4 Jan	Dr. Greg Holloway Institute of Ocean Sciences Sidney, British Columbia Canada	Statistical dynamics of oceans, atmospheres and stuff that lives there.
8 Jan	Dr. Christopher Fox NAVOCEANO	The use of multibeam SONAR in interpretation of seafloor roughness applied to the Gorda Ridge.
22 Jan	Dr. Paul Johnson University of Washington	Along-strike variation of hydrothermal activity on Explorer Ridge.
19 Feb	Dr. Motoyoshi Ikeda Bedford Institute of Oceanography Canada	Coastal ice flows over the Labrador Shelf.

26 Feb	Dr. Richard A. Feely PMEL	Current inventory of anthropogenic carbon dioxide in the North Pacific Gyre.
6 Mar	Karen von Damm U.S. Geological Survey Menlo Park, CA	Chemistry of submarine hydrothermal solutions from the Southern Juan de Fuca Ridge.
26 Mar	Dr. Roy A. Walters U.S. Geological Survey	Columbia Bay: An upside-down estuary.
28 Mar	Mike Perdue Georgia Institute of Technology	Soil acidity - sources, reactions and transport to surface waters.
9 Apr	David Kadco College of Oceanography Oregon State University	Preliminary results of radiochemical studies on the Endeavor Ridge.
2 May	Dr. Peter Brewer Woods Hole Oceanographic Institution Woods Hole, MA	What controls the variability of CO_2 in the surface ocean: models and data.
4 Jun	Dr. Stuart Wakeham Woods Hole Oceanographic Institution Woods Hole, MA	Dynamics of volatile organic compounds in coastal seawater.
11 Jun	Dr. James K. Bishop Lamont Doherty Geological Observatory Columbia University	The storage and utilization of biogenic particulate matter in deep convective mixed layers.

JISAO Seminars

DATES	NAME AND AFFILIATION	SEMINAR TOPIC
1984		
5 Oct	Dr. Meinrate Andreae University of Antwerp Belgium	The role of the oceans in the global atmospheric sulfur cycle.
	Mr. Walter Robinson GISS and Columbia University	Interactions between traveling and stationary planetary waves.
17 Oct	Dr. George Woodwell Marine Biological Laboratory Woods Hole, MA	On the carbon cycle in the biosphere.
23 Oct	Dr. Alan Plumb CSIRO Division of Atmospheric Physics Melbourne, Australia	Three-dimensional diagnostics of stationary and transient eddies.
26 Oct	Dr. Byron Boville National Center for Atmospheric Research Boulder, CO	Simulation of the general circulation of the winter lower stratosphere.
7 Nov	Dr. Gilles Reverdin Museum of Natural History Paris, France	Temperature profiles in the equatorial Indian Ocean: observations and simulations.
7 Nov	Dr. Robert Toggweiler Geophysical Fluid Dynamics Program Princeton University	Glacial and interglacial changes in the atmospheric carbon dioxide: the importance of marine surface waters in high latitudes.
9 Nov	Lee Panetta NOAA/GFDL Princeton, NJ	Eddy heat flux in quasi geostrophic turbulence.
	Dr. Syukuro Manabe NOAA/GFDL Princeton, NJ	Simulation of ice ages using a general circulation model with an oceanographic layer.
20 Nov	Dr. David Enfield Oregon State University	Peru coastal climatology and the 1981-83 El Niño.

28 Nov	Dr. Richard Eppley Scripps Institution of Oceanography University of California, San Diego	"New" marine primary production and vertical carbon fluxes.
5 Dec	Dr. Søren Larsen Riso National Laboratory Denmark	Climatology: low and slow.
7 Dec	Dr. Kevin Hamilton University of British Columbia	The semiannual oscillation.
13 Dec	Dr. Henning Rohde Sweden	Clouds as seen by a chemical meteorologist.
14 Dec	Robert Pellenbarg Naval Research Lab Washington, D.C.	*Spartina alterniflora* litter and the trace metal biogeochemistry of a salt marsh.
1985		
10-11 Jan	Dr. K. K. Tung Massachusetts Institute of Technology	A zonally averaged model of tracer transport in isentropic coordinates. On the low frequency variability and predictability of stationary long waves.
21 Jan	Dr. Vladimir Alexandrov Computing Center of the USSR Academy of Sciences Moscow, USSR	Nuclear winter.
23-24 Jan	Dr. David Keeling Scripps Institution of Oceanography University of California, San Diego	Precise total carbon measurements in sea water. Predicting future atmospheric carbon dioxide levels: restraints imposed by the carbon cycle.
7-8 Feb	Dr. Mel Shapiro NOAA Boulder, CO	Detailed analysis of the February 27, 1984 polar low in the Norwegian city. The migratory characteristics of the polar vortex and its relationship to Arctic cold air outbreaks.

13-14 Feb	Dr. Catherine Gautier Scripps Institution of Oceanography	Variability of solar radiation over the ocean derived from satellite data. Methods to compute the short-wave and longwave radiation at the surface using satellite data.
13 Mar	Dr. Bo Jorgenson University of Aarhus Denmark	Ecology of sulfide oxidation in sediments.
13 Mar	Dr. Erland Källén Department of Meteorology Stockholm University	Hysteresis-like effects in an orographically forced model.
	Dr. Äke Johansson Department of Meteorology University of Stockholm	Sub-grid scale fluxes of momentum and heat due to internal gravity waves and their interaction with the mean flow.
25 Mar	Frans Nieuwstadt Koninklijk Nederlands Meteorologisch Institut De Bilt, The Netherlands	Simulation of turbulence.
29 Mar	Mike Purdue Georgia Institute of Technology	Modeling the acid-base chemistry of humic substances.
1-2 Apr	Dr. Steve Zebiak Lamont-Doherty	Simple atmospheric and oceanic models relevant to the El Niño/ Southern Oscillation phenomenon.
8 Apr	Susan Solomon NOAA Aeronomy Laboratory Boulder, CO	Transport processes on ozone perturbations.
10 Apr	Marvin Geller NASA Laboratory for Atmospheres Greenbelt, MD	Investigations of the strato-spheric general circulation using data from satellites.
15-19 Apr	Dr. Michael McIntyre University of Cambridge England	On the application of isentropic potential vorticity. More thoughts on critical layers, conservation relations for wave activity, etc.

3 May	Dr. David Karoly National Center for Atmospheric Research Boulder, CO	Southern Hemisphere circulation features associated with El Niño-Southern Oscillation events.
10 May	Dr. E.S. Schneider University of Maryland	A model of the modified Hadley circulation.
20 May	Dr. John Horel Scripps Institution of Oceanography	A case study of the atmospheric conditions associated with the 1982/83 El Niño along the west coast of South America.
31 May	Dr. Pablo Lagos Jicamarca Radio Observatory Geophysical Institute Lima, Peru	Meteorological and oceanographic fields in the eastern Pacific during the 1982-83 El Niño event: some new perspectives on the mechanisms for El Niño.
3-4 Jun	Dr. Stuart Wakeham Woods Hole Oceanographic Institution Woods Hole, MA	Particulate organic matter in the oceans: Sediment traps and *in situ* pumping.
5 Jun	Dr. Michael L. Banner University of New South Wales Australia	Oscillatory properties of splitting zones of quasi-steady breaking waves.
11 Jun	Dr. James Bishop Lamont Doherty Geological Observatory Columbia University	Particulate matter geochemistry in warm core rings of the Gulf Stream - the storage and utilization of particulate carbon.

JIMAR Seminars

DATES	NAME AND AFFILIATION	SEMINAR TOPIC
1984		
7 Nov	Ms. Esther Brady Woods Hole Oceanographic Institution Woods Hole, MA	Diagnostic model of circulation in the equatorial Pacific Ocean.
1985		
20-22 Feb	Dr. Gary Mitchum Florida State University Department of Meteorology Tallahassee, FL	Continental Shelf water response to large-scale, low-frequency wind forcing.
3-9 Mar	Leang-Chwan Charles Sun Department of Marine, Earth and Atmospheric Sciences North Carolina State University, NC	On Gulf Stream dynamic instabilities off St. Augustine, Florida: Model and observations.

Aagaard, K., A. ROACH, and J. D. SCHUMACHER. On the wind-driven variability of the flow through Bering Strait. *Journal of Geophysical Research, 90*:7213-7222 (1985).

Analysis of time series from 1981-82 near Bering Strait shows the meridional wind component, the current, and the oceanic pressure gradient to be well correlated. We argue that because of the constraining coastal geometry, there are wind-driven flow divergences which perturb the oceanic pressure field and account for the majority of the current variability. For example, northerly winds cause a pronounced set-down of sea level southeast of Bering Strait, and if the winds are strong enough, they will reverse the mean slope downward to the north through the strait. Winds during 1976-77 were also well correlated with the Bering Strait transport estimates of Coachman and Aagaard (1981), and we therefore use the calculated winds from 1946-82 to examine the low-frequency transport variability. There is a marked seasonal cycle, with summer transport about 50% greater than during winter. The long-term mean transport is calculated as less than 0.6 Sv, which is much lower than earlier estimates. Abnormally large transports apparently occurred during a number of years from 1948-67, but during the past 15 years transports have tended to be considerably less, corresponding to the stronger northerly winds during these years. The interannual wind variability near Bering Strait, together with the corresponding variability in the transport through the strait, is in fact part of the large-scale variability of the atmospheric circulation over the North Pacific and its oceanic effects.

Abbott, D. H., R. W. EMBLEY, and M. A. Hobart. Correlation of shear strength, hydraulic conductivity, and thermal gradients with sediment disturbance: South Pass Region, Mississippi Delta. *Geo-Marine Letters,* 5:113-119 (1985).

The degree of sediment disturbance in the South Pass area is correlated to the average hydraulic conductivity, shear strength, and thermal gradient. Hydraulic conductivity averages 18, 6 and 4 $\times 10^{-7}$ cm/s in the undisturbed, moderately disturbed, and most disturbed sediments, respectively. Shear strength also decreases with increasing disturbance, from 7.6 to 4.4 to 3.5 kPa. Excluding the four stations dominated by annual temperature variations, the remaining 19 thermal gradients correlate well with sediment disturbance. The average gradient is positive in all of the disturbed sediments (0.12 $\pm$ 0.07° C/m) and 0 in the undisturbed sediments (0.02 $\pm$ 0.05° C/m).

BAKER, E. T., J. W. LAVELLE and G. J. MASSOTH. Hydrothermal particle plumes over the southern Juan de Fuca Ridge. *Nature, 316*:342-344 (1985).

No abstract.

BATES, T. S., and J. D. CLINE. The role of the ocean in a regional sulfur cycle. *Journal of Geophysical Research, 90*(C5):9168-9172 (1985).

Dimethylsulfide (DMS) concentrations were measured in ocean waters along the West Coast of the United States on three cruises during 1983 and 1984. Concentrations in surface waters ranged from 13 to 380 ng S/L with a summer average of 60 and a winter average of 20 ng S/L. The flux of sulfur from the ocean to the atmosphere was calculated using the stagnant film boundary layer model to be 28 mg $S/m^2/a$. On the basis of a non-sea salt sulfate residence time of 5 days, the calculated net flux of biogenic sulfur to the West Coast of the United States is 0.045 Tg/a. This is 4-13% of the combined total anthropogenic emissions from the western United States.

Beardsley, R. C., R. Limeburner, H. Yu, and G. A. CANNON. Discharge of the Changjiang (Yangtze River) into the East China Sea. *Continental Shelf Research, 4*(1/2):57-76 (1985).

Hydrographic and current meter data collected in the East China Sea during June 1980, August 1981, and November 1981, have been used to describe the spatial and temporal structure of the Changjiang (Yangtze River) discharge over the inner and mid continental shelf off eastern China. In summer during high runoff, the freshwater discharge near the mouth of the Changjiang exhibited a bimodal distribution, with the freshest water extending in a band to the south along the coast, and a relatively shallow, low salinity plume-like structure extending offshore on average towards the northeast. Relatively warm, saline bottom water characteristic of the Taiwan Current Warm Water flowed into the Changjiang estuary along a submerged relic river valley. Direct current measurements suggest that significant transient offshore fluxes of relatively fresh Changjiang water can also occur from the southward-flowing coastal current south of the Changjiang estuary. In winter, the reduced Changjiang discharge flowed southward in a narrow band confined to the coast. Some possible physical causes for the observed structure of the Changjiang discharge are presented.

BERNARD, E. N., and H. B. MILBURN. Long-wave observations near the Galápagos Islands. *Journal of Geophysical Research, 90*(C2):3361-3366 (1985).

Two bottom pressure recorders were deployed from April to August 1982 at 2.5°S, 95.0°W in 3751-m water depth and at 0.5°S, 89.5°W in water of 16-m depth to ascertain the background level of wave energy in the period range of 4-90 min. Preliminary analysis of these data reveals the instrument is capable of detecting: (1) tsunami as small as 1 cm in the open ocean and (2) disturbances from distant hurricanes.

Betzer, P. R., R. H. Byrne, J. G. Acker, C. S. Lewis, R. R. Jolley, and R. A. FEELY. The oceanic carbonate system: A reassessment of biogenic controls. *Science, 226*:1074-1077 (1984).

Fluxes of biogenic carbonates moving out of the euphotic zone and into deeper undersaturated waters of the North Pacific were estimated with free-drifting sediment traps. Short-duration (1 to 1.5 day) sampling between 100 and 2200 meters points to a major involvement in the oceanic carbonate system by a class of organisms which had been relegated to a secondary role--aragonitic pteropods. Pteropod fluxes through the base of the euphotic zone are almost large enough to balance the alkalinity budget for the Pacific Ocean. Dissolution experiments with freshly collected materials shed considerable light on a mystery surrounding these labile organisms: although plankton collections from net tows almost always contain large numbers of pteropods, these organisms are never a major component of biogenic materials in long-duration sediment trap collections. Their low abundance in long-duration collections results from dissolution subsequent to collection. Short-duration sampling showed significant increases in the ratio of calcitic foraminifera to aragonitic pteropods in undersaturated waters, indicating the more stable mineralogic form, calcite, was preserved relative to aragonite. Approximately 90 percent of the aragonite flux is remineralized in the upper 2.2 kilometers of the water column.

Byrne, R. H., J. G. Acker, P. R. Betzer, R. A. FEELY, and M. H. Cates. Water column dissolution of aragonite in the Pacific Ocean. *Nature, 312*(5992):321-326 (1984).

Pelagic pteropods are an important component of the oceanic CO_2 system. Their shells appear to be a principal source of excess alkalinity in the upper water column of the North Pacific Ocean. Dissolution of aragonite must therefore be taken account of in generating models of the oceanic CO_2 system and is also an important cause of sample loss from long-term sediment traps deployed in undersaturated seawater.

CANNON, G. A., D. E. Bretschneider, and J. R. HOLBROOK. Transport variability in a fjord. In *The Estuary as a Filter*, V.S. Kennedy (ed.), Academic Press, 67-80 (1985).

Bottom water renewal in Puget Sound has been found to occur over short intervals several times during the year and is dependent on tidal and mixing processes over the entrance sill. In addition, the inflow of new bottom water entrains some fraction of seaward flowing upper water at the landward side of the sill. This process acts as a "filter" in that some dissolved and suspended contaminants do not leave the system, but rather make one or more circuits through the basin and possibly contribute to some unknown amount of long-term accumulations.

CANNON, G. A., R. K. REED, and P. E. PULLEN. Comparison of El Niño events off the Pacific Northwest. In *El Niño North: Niño Events in the eastern subarctic Pacific Ocean*, W.S. Wooster and D.L. Fluharty (eds.), Washington Sea Grant, Seattle, 78-84 (1985).

Observations show that El Niño events of 1940-41, 1957-58, and 1982-83 had large coastal effects off Washington and British Columbia. Subsurface temperature anomalies were comparable during the three episodes, and average profiles between the coast and 127°W had anomalies of about 1.5°C at 100 m; individual anomalies sometimes exceeded 3°C, with the highest values near the coast. Positive anomalies were observed to extend over 200 km offshore and to depths of about 500 m. These scales were similar to those farther north in the Gulf of Alaska and were about half the offshore extent off southern California. Monthly average sea level anomalies showed that the largest increases occurred almost simultaneously from California to Alaska. Thus we suggest these data support the concept that the events are initiated by long ocean waves but that subsequent development is strongly affected by anomalous coastal winds.

Chase, R. L., J. R. Delaney, J. L. Karsten, H. P. Johnson, S. K. Juniper, J. E. Lupton, S. D. Scott, V. Tunnicliffe, S. R. HAMMOND, and R. E. McDuff. Hydrothermal vents on an axis seamount of the Juan de Fuca ridge (Canadian American Seamount Expedition). *Nature, 313*(5999):212-214 (1985).

The Juan de Fuca Ridge, a 500-km section of the mid-ocean ridge system, is bounded by the Sovanco and Blanco fracture zones. Although the ridge spreads at a medium rate (29 mm yr^{-1} half-rate), a significant portion of its crest has a morphology typical of faster spreading ridges; the axial valley is 1-2 km wide within a central horst structure. The ridge crest shoals to 1,500 m at the intersection with the Cobb-Eickelberg Seamount chain forming a broad edifice called "Axial Seamount" (Fig. 1). Previous studies both north and south of Axial Seamount demonstrated hydrothermal activity associated with the shallowest portions of each of the ridge segments along the Juan de Fuca, a similar coincidence to that noted for the East Pacific Rise. We report here the results of the first manned submersible expedition to the Juan de Fuca Ridge, which found hydrothermal activity and at least 14 new vent animals in the caldera of Axial Seamount.

CLINE, J. D., R. A. FEELY, K. KELLY-HANSEN, J. F. GENDRON, D. P. WISEGARVER, and C. T. Chen. Current inventory of anthropogenic carbon dioxide in the north Pacific subarctic gyre. NOAA-TM-ERL-PMEL-60 (PB85-187938/AS), 46 pp. (1985).

No abstract.

COKELET, E. D., and R. J. STEWART. The exchange of water in fjords: The efflux/reflux theory of advective reaches separated by mixing zones. *Journal of Geophysical Research, 90*(C4):7287-7306 (1985).

Many fjords consist of deep, stratified reaches separated by shallower sills above which most of the mixing between water masses occurs. On a long time scale, each reach can be modeled as a steady, two-layer advective flow. These flows intermingle in turbulent mixing zones, where the flow from any incoming layer can be split into two parts: an efflux fraction, which continues on into the next reach, and a reflux fraction, which mixes vertically and recirculates into its original reach. Using conservation of mass, we define these fractions and express them in terms of the salinities observed in the reaches. The processes of the complex mixing zones need not be considered in detail. These ideas are applicable to complicated branched fjords and linked sequences of reaches. Where more than two reaches meet at a multiple junction the conservation of two tracers (usually fresh water and salt) is insufficient to determine completely the efflux/reflux fractions. We propose an entropy maximization technique to resolve the uncertainty. Long-term pollutant concentrations relate directly to the circulation via the new efflux/reflux formulation. The method demonstrates that refluxing leads to conservative pollutants being broadcast throughout the fjord system with magnified concentrations. A new quantity, the mean tracer age, provides a relevant time scale that includes the effects of recirculation and to which the rates of non-conservative processes should be compared. Conservative pollutants may be retained for a surprisingly long time in a refluxing system.

COKELET, E. D., R. J. STEWART, and C. C. Ebbesmeyer. The exchange of water in fjords: A simple model of two-layer advective reaches separated by mixing zones. Proceedings, 19th Coastal Engineering Conference, ASCE/September 3-7, 1984, Houston, Texas (1984).

We propose a model for the two-layer, mean transport within a branched, recirculating fjord system. The recirculation is parameterized in terms of efflux/reflux coefficients at distinct mixing zones. The mass fluxes and efflux/reflux coefficients are determined from long-term salinity and current meter observations. The model provides a way to predict the mean concentrations of pollutants introduced within the system. An application to Puget Sound shows that different discharge sites markedly affect the concentrations *landward* of the sites themselves.

Crane, K., F. Aikman, R. W. EMBLEY, S. R. HAMMOND, A. MALAHOFF, and J. Lupton. The distribution of geothermal fields on the Juan de Fuca Ridge. *Journal of Geophysical Research, 90*:727-744 (1985).

Near bottom water temperatures were mapped along 400 km of the strike of the Juan de Fuca Ridge as part of a combined Sea MARC/Seabeam experiment to image the variability of morphology and structure along a spreading center segment. The water temperature data collected by a continuously towed thermistor chain, in addition to salinity data, indicate that there are four geothermal areas spaced at distances of 100 km from each other south of the Cobb propagator and one field just to the north of the propagator on

the Endeavor Ridge segment. Each thermal region is located above a morphological dome on the spreading center. These domes are an average of 100-200 m shallower than the rest of the axis. The structure of bottom water suggests that the geothermal regions are on average 20 km long and that the heat from these fields raises the temperature in the water column by a minimum of 0.06°C up to 300 m above the bottom. Two simple models are used to estimate the heat flux associated with these features.

EMBLEY, R. W. A locally formed deep-ocean canyon system along the Blanco Transform, Northeast Pacific. *Geo-Marine Letters,* 5:99-104 (1985).

A dissected terrain resembling a shelf-edge canyon system with individual canyons up to 100 m in relief, 3 km in width, and 10 km in length is found along the south flank of the Cascadia Channel within the central Blanco Transform zone. The channels apparently formed from a combination of downcutting from turbidity currents off the Blanco Ridge and from backcutting due to mass-wasting. The relationships between the transform tectonics and the formation of the canyon are presented in a model which proposes both a direct link via triggering of slides from earthquakes and an indirect link associated with lowering the local base level of Cascadia Channel, thalweg downcutting, and wall-steepening leading to increased mass-wasting.

Fairhall, A. W., and A. W. YOUNG. Historical ^{14}C measurements from the Atlantic, Pacific, and Indian Oceans. *Radiocarbon, 27*(3):473-507 (1985).

No abstract.

FEELY, R. A., R. H. Byrne, P. R. Betzer, J. F. GENDRON, and J. G. Acker. Factors influencing the degree of saturation of the surface and intermediate waters of the North Pacific Ocean with respect to aragonite. *Journal of Geophysical Research, 89*(C6):10631-10640 (1984).

New carbonate chemistry data obtained during a 1982 cruise have been combined with earlier GEOSECS and INDOPAC data to determine the degree of aragonite saturation of surface and intermediate waters of the North Pacific. Large gradients in saturation state occur in the region of the Subarctic Front in the north-south direction and across the Subtropical Gyre in the east-west direction. These gradients are primarily due to the extensive mixing that occurs in the intermediate waters of the western North Pacific. The major variations in saturation state were primarily related to the carbonate ion concentration, which, in turn, is primarily a function of mixing and biological processes. The present aragonite saturation depth at our northernmost station in the western North Pacific was calculated to be within 120 m of the surface. The result was directly corroborated by observations of aragonite dissolution under in vitro conditions. Our calculations show that one possible effect of fossil fuel-derived CO_2 on the surface of the North Pacific will be a steady progression of undersaturation from the northern to southern and western areas, with the first sign of undersaturation possibly occurring as early as the second half of the next century.

Feldman, G., D. Clark, and D. HALPERN. Satellite color observations of the phytoplankton distribution in the eastern equatorial Pacific during the 1982-1983 El Niño. *Science, 226*(4678):1069-1071 (1984).

Dramatic changes in the patterns of satellite-derived pigment concentrations around the Galápagos Islands during February and March 1983 are associated with unusual oceanographic conditions observed during the 1982-1983 El Niño. The redistribution of food resources might have contributed to the reproductive failure of seabirds and marine mammals on these islands during this El Niño.

GONZALEZ, F. I., E. D. COKELET, J. F. R. Gower, and M. R. MULHERN. SLAR and *in situ* observations of wave-current interaction on the Columbia River bar. In *The Ocean Surface*, Y. Toba and H. Mitsuyasu (eds.), D. Reidel, Dordecht, Holland, 303-310 (1985).

Observations at the Columbia River entrance have been compared to wave height amplification factors predicted by linear, one-dimensional wave-current interaction theory. A previous study found good agreement between this theory and observations, with the exception of one so-called "severe event" which was seriously under-predicted. The present analysis utilizes SLAR and *in-situ* data to demonstrate that the probable cause of this failure is two-dimensional current refraction induced by lateral current shear. The conclusion is reached that such two-dimensional effects must be better understood if these "severe events" are to be accurately predicted on the Columbia River Bar.

GONZALEZ, F. I., M. R. MULHERN, E. D. COKELET, T. C. KAISER, J. F. R. Gower, and J. Wallace. Wave and current observations at the Columbia River Entrance, 10-13 September 1981. NOAA-TM-ERL-PMEL-59 (PB85-164291/AS), 231 pp. (1984).

This technical memorandum presents the results of a joint exercise undertaken by PMEL and IOS to measure waves and currents at the Columbia River Bar during 10-13 September 1981. The waves were measured *in situ* with a vertical accelerometer buoy (Waverider) and observed aloft with Side Looking Airborne Radar (SLAR). Drifters tracked by an independent radar system provided surface-current velocities within the river mouth. Wave refraction occurs in this area owing to depth and current gradients. Upriver of Buoy 8 waves decay on ebb and flood currents due to depth refraction away from the channel axis. During strong ebbs wave decay may be enhanced by breaking within the channel itself. Seaward of Buoy 8 waves amplify during peak ebbs and attenuate during peak floods. Most of the time the amplification and decay factors are predicted to within 20% by linear, one-dimensional theory. However, during one extreme ebb event the wave height was *underpredicted* by up to 50%. This was likely due to the crossing of wave crests produced by the current jet. The accurate prediction of such an event awaits the application of a two-dimensional theory for both the currents and the waves. Predictions of hazardous sea state on the Columbia River Bar could certainly be improved by implementing recent analytical and numerical advances in wave refraction-diffraction theory. This should be complemented by Bar wave-height observations made available in real-time. These would provide accurate now-casts and short-

term forecasts and improve the intuition of forecasters and mariners. The observations would also provide a data base to tune the theoretical models and verify forecasts.

HALPERN, D. Upper ocean current and temperature observations along the Equator west of the Galápagos Islands before and during the 1982-83 ENSO event. In *El Niño Atlas 1982-83*, A. Leetmaa and J. Witte (eds.), Nova University Oceanographic Center, Dania, Florida, 79-82 (1984).

No abstract.

Hamilton, P., J. T. Gunn, and G. A. CANNON. A box model of Puget Sound. *Estuarine, Coastal and Shelf Science, 20*:673-692 (1985).

A classical two-layer box model has been used to calculate volume transports and vertical exchange coefficients for the Main Basin of Puget Sound. High river flow (January-February) and low flow (August-September) calculations, using salinity and runoff observations, show that basically two estuarine types exist within the basin under both flow conditions. Admiralty Inlet, the north entrance to the Main Basin, is similar to a partially mixed estuary with vigorous tidal mixing, so that horizontal and vertical salinity gradients are similar in winter and late summer. Within the deep main basin, two layer transports are proportional to salinity stratification and the vertical exchanges are low. Calculated summer transports are about a factor of two smaller than winter transports for the Main Basin. Model transports agree quite well with daily net transports estimated from current meters. Flushing times calculated by the model also agree with volume replacement times calculated using current meter data and by methods using oxygen deficits in the lower layer.

HAYES, S. P., and L. J. MANGUM. CTD sections along 95°W. In *El Niño Atlas 1982-83*, A. Leetmaa and J. Witte (eds.), Nova University Oceanographic Center, Dania, Florida, 103-106 (1984).

No abstract.

HAYES, S. P., R. Ripa, and L. J. MANGUM. On resolving vertical modes with observational data. *Journal of Geophysical Research, 90*:7227-7234 (1985).

A least squares regression formulation is developed to study the expected errors in the coefficients of a modal expansion of observational data. Given an empirical or theoretical vertical mode number energy spectrum and assuming that certain modes (signal) are to be resolved and that the remaining modes (noise) are a contamination, then there exists an optimum set of weights which will minimize the expected errors of the signal modal amplitudes. These expected errors, as well as those associated with any other set of weights, can be evaluated and the adequacy of a given array determined. Examples from the equatorial Pacific Ocean are used to show the utility of this technique and to explore several existing or possible measurement arrays.

Hebenstreit, G. T., and E. N. BERNARD. Azimuthal variations in tsunami interactions with multiple-island systems. *Journal of Geophysical Research* *90*(C2):3353-3360 (1985).

The purpose of this study is to examine variations in the response of an island system (the Hawaiian Islands, in this case) to an incoming tsunamilike wave pulse approaching the system along various azimuths. Simulations were carried out numerically by using an explicit finite-difference analog for the linearized equations of motion and continuity for long waves in a variable depth ocean. The model topography is based on the submarine topography of the Hawaiian Island region. Island coastlines are fully reflecting, so no attempt to simulate runup was made. Qualitative comparisons between model results and historical data from tsunamis approaching along similar azimuths show that the model produces realistic simulations. Azimuths were chosen for waves approaching from four general geographic areas: South America, Alaska, Aleutians-Kuriles-Japan-Philippines, and Southwest Pacific. Nearly all distant tsunamis striking Hawaii have come from one of these areas. Our conclusions are: (1) Tsunami response in the overall system does not vary greatly over small (10°-15°) changes in azimuth but does vary significantly over large changes (>60°). (2) Local response may vary greatly with azimuth, but certain areas seem to respond strongly to tsunamis approaching from almost any direction. (3) Topographic focusing seems to play the dominant role in determining localized response.

KOMHYR, W. D., R. H. GAMMON, T. B. HARRIS, L. S. WATERMAN, T. J. Conway, W. R. Taylor, and K. W. Thoning. Global atmospheric CO_2 distribution and variations from 1968-1982 NOAA/GMCC CO_2 flask sample data. *Journal of Geophysical Research,* *90*(D3):5567-5596 (1985).

CO_2 data obtained from discrete sampling during 1968-1982 at 23 National Oceanic and Atmospheric Administration/Geophysical Monitoring for Climatic Change and foreign cooperative stations are presented, together with a description of the measurement program and data quality. Monthly, seasonal and annual CO_2 concentrations are determined by the individual stations from select (background) data. Temporal and spatial global CO_2 distributions yield annual and seasonal latitudinal gradients, abundances, airborne fractions, annual cycle amplitudes and phases, annual cycle amplitude growth rates, and global growth rate variations of CO_2. The time-series data sets reveal variations related to several El Niño/Southern Oscillation events, particularly with respect to the strength of the CO_2 source in the equatorial Pacific Ocean and global CO_2 growth rates. CO_2 growth rate anomalies correlate highly with the Southern Oscillation Index, which is related to the strength of the easterly trade winds that blow along the equator.

Larsen, L. H., G. A. CANNON, and B. H. Choi. East China Sea tide currents. *Continental Shelf Research,* *4*(1/2):77-103 (1985).

The East China Sea is a broad continental shelf over which there are large tides and tidal currents. During the joint China-U.S.A. Marine Sedimentation Dynamics Study, a large number of current measurements were

made across the continental shelf along approximately 30°N. There is general agreement between these observations and Choi's (1980) tidal model of the area, which supports his assumed boundary conditions and numerical procedures. The semi-diurnal tidal current near the mouth of Changjiang transports water southward at maximum ebb and northward following maximum flood. Because the tides rotate clockwise, southward flow is followed by shoreward flow, confining the initial river plume and sediment deposition to the coastal region south of the river mouth. Six hours later the remnants of the initial plume move to the north and seaward. The southward discharge on ebb results in initial and greatest sedimentation rates on the south sides of the river mouths.

LARSEN, J. C., and T. B. Sanford. Florida Current volume transports from voltage measurements. *Science, 227*:302-304 (1984).

The volume transport of the Florida Current is determined from the motionally induced voltage difference between Florida and Grand Bahama Island. Simultaneous measurements of potential differences and of volume transport by velocity profiling have a correlation of 0.97. The calibration factor is 25 ± 0.7 sverdrups per volt, and the root-mean-square discrepancy is 0.7 sverdrup. The induced voltage is about one-half the open-circuit value, implying that the conductance of the sediments and lithosphere is about equal to that of the water column.

LAVELLE, J. W., G. J. MASSOTH, and E. A. Crecelius. Sedimentation rates in Puget Sound from ^{210}Pb measurements. NOAA-TM-ERL-PMEL-61 (PB85-193381/AS), 43 pp. (1985).

Sixteen ^{210}Pb profiles from sites along the axis of the Main Basin of Puget Sound show that bottom sediments are accumulating at rates of 0.26 to 1.20 g/cm^2/yr; these along with seven rates earlier published suggest highest accumulation nearly midway along the length of this tidal current-dominated basin. Bioturbated surface layers of cores have also been found to be as deep as 40 cm, but biologic mixing rates are poorly determined. Individual ^{210}Pb accumulation rates have a range of from approximately one to five times areal average accumulation rates based on estimates of recent sediment input from riverine and shoreline sources.

Lukas, R., S. P. HAYES, and K. Wyrtki. Equatorial sea level response during the 1982-1983 El Niño. *Journal of Geophysical Research, 89*(C6):10425-10430 (1984).

During the 1982-83 El Niño/Southern Oscillation event, sea level across the width of the equatorial Pacific adjusted to the reversal of the equatorial trade winds, and by the end of 1982 the normal sea level slope across the Pacific had been eliminated. The transfer of warm upper-ocean water from the western Pacific to the eastern Pacific was accomplished by a combination of direct wind forcing as the wind anomaly crossed the basin and by mass flux induced by free equatorial waves. The importance of equatorially trapped Kelvin waves of first and second vertical mode during the onset of the 1982-83 El Niño is inferred from the cross-correlation

statistics between central and eastern Pacific sea level stations and between wind variations in the western Pacific and equatorial sea level stations to the east. The different propagation speeds of these two modes appears to be responsible for the observed change in shape of the major sea level signals during the 1982-83 event. Tentative evidence for first baroclinic mode, first meridional-mode Rossby waves is also presented.

MANGUM, L. J., and S. P. HAYES. CTD/O_2 measurements during 1982 and 1983 as part of the Equatorial Pacific Ocean Climate Studies (EPOCS). NOAA-DR-ERL-PMEL-13 (NTIS not yet available), 421 pp.

During 1982 and 1983, CTD data were collected in the eastern equatorial Pacific as part of the Equatorial Pacific Ocean Climate Studies (EPOCS) program, which began its field program in 1979. Summaries of CTD data from six cruises in 1982 and 1983 are presented. This time period spans the 1982/83 El Niño-Southern Oscillation event, whose effects were seen in the eastern Pacific from August 1982 through June 1983. Station locations, meteorological conditions and profiles of temperature, salinity, sigma-T, and oxygen are shown for each cast. Additionally, T-S diagrams and section plots along 95°W and the equator are presented.

MANGUM, L. J., and S. P. HAYES. The vertical structure of the zonal pressure gradient in the eastern equatorial Pacific. *Journal of Geophysical Research, 89*(C6):10441-10449 (1984).

CTD data from the EPOCS and NORPAX experiments were used to construct a mean zonal pressure gradient profile between 110°W and 150°W for the 1979 to 1981 pre-El Niño time period. The mean zonal pressure gradient referenced to 100 dbar had a value of -4.5×10^{-7} m s^{-2} at the surface and decreased to within two standard errors of zero at 200 dbar. Below this depth the mean was not significantly different from zero. Deviations from this mean were not related to fluctuations of the zonally averaged zonal wind stress between 150°W and 110°W. Rather, the largest deviations, in the boreal springs of 1979 and 1980, appeared to be associated first with vertical-mode Kelvin wave pulses propagating eastward along the equator. The 1979-81 mean profile was also used as a reference to examine variations in zonal pressure gradient during the 1982/83 ENSO event. The sea surface was more sharply sloped upward from the east to west in April and September 1982 before and near the beginning of the event. The surface slope was below normal in April and October 1983. Vertical profiles of the zonal pressure gradient deviations showed larger high vertical-mode contributions during the vent than in the prevent samples.

MANGUM, L. J., J. M. Toole, and S. P. HAYES. CTD/O_2 measurements on the CONRAD cruise, September-October 1982. NOAA-DR-ERL-PMEL-11 (PB85-188191/AS), 113 pp. (1985).

Summaries of CTD/O_2 measurements from the R/V CONRAD cruise in the equatorial Pacific during September and October 1982 are presented. This cruise occurred during the initial stages of the 1982/1983 El Niño/Southern Oscillation (ENSO) event, approximately three months after the trade winds

collapsed in the western Pacific and one month after the rise in sea level was seen in the eastern Pacific. In addition to profiles of temperature, salinity, sigma-t and dissolved oxygen, station locations and T-S diagrams are included for each cast. Section plots of the vertical distribution of temperature, salinity, sigma-t and dissolved oxygen are shown for the meridional transects along 130°W and 85°W, and the zonal transect along the equator.

McPhaden, M. J., and B. A. TAFT. Proceedings of the First International TOGA Workshop on Thermal Sampling. *Univ. Corp. Atmos. Res.*, TOGA Tech. Rept. USTOGA 3, 53 pp.

No abstract.

MOBLEY, C. D., and R. W. PREISENDORFER. Statistical analysis of historical climate data sets. *Journal of Climate and Applied Meteorology, 24*(6):555-567 (1985).

The problem of determining confidence intervals for climatic signals using data sets with spatial and temporal sampling inhomogeneities is solved by a four-step process. First, the actual data set is analyzed to determine autoregressive models which are consistent with the actual data at daily, monthly and annual time scales. Second, these models are used to generate artificial, but realistic, data sets which reproduce selected statistical properties of the actual data. Third, these artificial data sets are sampled by Monte Carlo techniques to determine certain confidence interval coefficients appropriate to different fields, geographical regions, and averaging periods. Fourth, these confidence interval coefficients are used to place error bars on climatic signals derived from the actual data set. The technique is illustrated by the analysis of historical sea surface temperature and sea level pressure data in the eastern tropical Pacific Ocean.

MOFJELD, H. O., J. D. SCHUMACHER, and D. J. PASHINSKI. Theoretical and observed profiles of tidal currents at two sites on the southeastern Bering Sea Shelf. NOAA-TM-ERL-PMEL-62 (NTIS number not yet available), 60 pp. (1984)

A semi-analytic theory for vertical profiles of tidal currents on the continental shelf is presented in which the vertical eddy viscosity is obtained with a high-resolution, Level II turbulence closure model. Each tidal constituent is assumed to be a free, shallow water wave propagating on an unstratified shelf of constant depth. The eddy viscosity is a time-dependent composite of contributions from the major tidal constituents. The theoretical profiles have been fit to M2 and K1 current harmonic constants observed at two sites on the Southeastern Bering Sea Shelf. At the coastal station BBL1 (56°19'N, 161°33'W; 63 m depth) off the Alaska Peninsula occupied during 15-30 May 1981 in a Kelvin wave regime with rectilinear tidal currents, the fit of M2 and K1 theoretical profiles reproduces the general features of the tidal currents. The thick bottom boundary layers observed at BBL1 require a large apparent bottom roughness (1.0 cm) which may be due to strong surface swell and/or bedforms. The

predicted eddy viscosity has a maximum of 400 cm^2/s located at a height of 20 m above the bottom. At the mid-shelf station BBL2 (57°37'N, 167°45'W; 69 m depth) occupied during 28 July - 5 August 1982 in a Sverdrup wave regime with rotatory tidal currents, the fit to the thin boundary layers observed for M2 and K1 reveals a small apparent bottom roughness (0.001 cm), possibly due to calm weather and/or the lack of bedforms. The theory overestimates slightly the width of the M2 ellipses but predicts the K1 width and the perpendicular orientation of the M2 and K1 ellipses. The predicted eddy viscosity at BBL2 has a maximum of 250 cm^2/s at a height of 25 m. The theory provides estimates of residual tidal currents under very restrictive assumptions. For the coastal Kelvin waves propagating along the Alaska Peninsula, the residual tidal current (sum of O1, K1, N2 and M2) is due almost entirely to Stokes drift and produces a transport of $\sim 2(10)^5 m^3/s$ toward Bristol Bay. For the Sverdrup waves in the mid-shelf regime, the magnitudes of the theoretical residual currents are a factor of 1/20 smaller than the coastal currents although bottom topography (not in the theory) can generate much stronger residual currents.

Moody, J. A., B. Butman, R. C. Beardsley, W. S. Brown, P. Daifuku, J. D. Irish, D. A. MAYER, H. O MOFJELD, B. Petrie, S. Ramp, P. Smith, and W. R. Wright. Atlas of tidal elevation and current observations on the Northeast American Continental Shelf and Slope. U.S. Geological Survey Bulletin No. 1611, 122 pp. (1985).

Measurements of sea-surface elevation or bottom pressure at 100 stations and measurements of current at various depths at 139 stations on the North American Continental Shelf from Cape Hatteras to the Laurentian Channel have been analyzed using either the harmonic or the response method for five tidal constituents: the semidiurnal tides M_2 (12.42 hours), N_2 (12.66 hours), and S_2 (12.00 hours), and the diurnal tides K_1 (23.93 hours) and O_1 (25.82 hours). The amplitude and phase of elevation and of east and north current for the five constituents are presented in tables. The ellipse representation of the current is also tabulated. In addition, plates are presented showing tidal elevation and surface current (for M_2, N_2, S_2, K_1 and O_1) and representative current ellipses (for M_2, K_1 and O_1). This is the first compilation of tidal elevation over this region of the Continental Shelf for constituents other than M_2 and of tidal currents at depths other than at the surface. The coamplitude and cophase lines for all semidiurnal tides are similar and indicate a co-oscillating tide in the Middle Atlantic Bight and on the Scotian Shelf, and a near-resonant tide in the Gulf of Maine. There is an amplitude minimum of the sea-surface elevation over Nantucket Shoals and Georges Bank. The diurnal tides (K_1 and O_1) are dominated by an amphidromic point near Sable Island and a secondary amphidromic point in the Middle Atlantic Bight. Along the remainder of the shelf the diurnal tide seems to be a combination of Kelvin and shelf waves. The major axis of the M_2 tidal current ellipses are generally oriented perpendicular to the local isobaths except near the coast and in the Great South Channel and Northeast Channel. In contrast, the major axis of the ellipses of the two diurnal constituents are generally oriented parallel to the isobaths. The amplitude of the M_2, K_1, and O_1 surface current is weakest at the outer edge of the shelf, reaches a maximum midway across the shelf, and then decreases toward the coast. The variability of the tidal current estimates is largest near the shelf break

where some contribution from a baroclinic tide is expected. Observations at five stations, where current measurements were made at 1 and at 10 to 20 meters above the bottom, were used to empirically determine the vertical structure of the M_2 semidiurnal current near the bottom. The amplitude of the M_2 bottom current is typically about 50 percent of the amplitude of the near-surface current. The empirical curve was used to estimate the bottom tidal currents (1 meter above the bottom) at 78 locations on the Continental Shelf where measurements were available only at 10- to 20-m above the bottom.

Muench, R. D., and J. D. SCHUMACHER. On the Bering Sea ice edge front. *Journal of Geophysical Research, 90*(C2):3185-3197 (1985).

An oceanographic field program was carried out along the Bering Sea ice edge in winter 1982-83 to investigate the temperature/salinity front associated with and paralleling the winter ice edge. Currents were measured using taut-wire moorings that were in place over winter, and an intensive CTD survey was carried out of the frontal structure in midwinter (February-March). The midwinter front separated cold (<-1.5°C), low salinity (<32°/₀₀), middle Bering shelf water from warmer (>0°C), more saline (>32.5°/₀₀) outer-shelf water. The front had northwestward baroclinic currents paralleling the front/ice edge with near-surface speeds of 5-6 cm/s and an associated transport of about 0.3×10^6 m^3/s. These baroclinic currents were superimposed on a regional barotropic along-isobath flow, resulting in northwestward midwinter upper-layer flows with monthly mean speeds exceeding 10 cm/s. An upper-layer flow component was directed beneath the ice and provided heat adequate to melt the ice and limit advance of the edge. The resulting low-salinity meltwater was mixed vertically, to maintain the front, by wind acting across a highly mobile, hydrodynamically rough ice cover. Subtidal fluctuations were not significantly affected by the front or the ice cover, and local winds accounted for less than one quarter of the observed current variability, the remainder being probably due to regional variations in the barotropic flow.

Nelson, C., and C. H. PEASE. Sea ice prediction modelling. Proceedings, Oceans '84 Conference, Marine Technology Society, Washington, D.C., 7 pp. (1985).

An experimental ice forecasting model for the Bering Sea is undergoing operational evaluation at the National Meteorological Center. Sea ice extent, ice floe velocities, and changes in ice thickness along three transects are predicted by a wind-driven, free drift sea ice model and a linear, one-dimensional balance of the thermodynamic terms at the air, sea, and ice interfaces. Ice edge positions for model initialization and forecast verification are manually digitized from the Navy/NOAA Joint Ice Center regional ice analysis chart. Dynamic and thermodynamic forcing fields are derived from the NMC operational analyses and forecasts of sea level pressure and 1000 mb temperatures and a regional objective sea surface temperature analysis. The ice forecast model runs daily and a 6-day forecast chart is disseminated as experimental guidance for field office evaluation to the JIC and to the Anchorage Weather Service Forecast

Office. Preliminary subjective verification of the 6-day forecasts indicates reasonable success in predicting ice movement. However, the model shows sensitivity to input parameters describing ice extent, thickness, and concentration and forecast accuracy clearly depends on the skill of the atmospheric forecasts in the 3-5 day range. Results from model predictions during February 1983 and throughout the 1983-84 ice season will be discussed.

O'NEILL, K. Equatorial velocity profiles. Part I: Meridional component. *Journal of Physical Oceanography, 14*(12):1829-1841 (1984).

A time series of vertical profiles of horizontal velocity was collected in the western equatorial Indian Ocean during late spring of 1976. The meridional velocity component is examined here, the zonal component in Part II of this paper. The profiles have been normalized using a WKB approximation so that they can be analyzed in terms of their vertical wavenumber content and discussed in terms of vertical wavelengths. Autospectral analysis reveals an equatorial concentration of meridional kinetic energy, whose meridional trapping scale decreases as the vertical scale of the motion decreases. Calculations of dropped lagged coherence (DLC) show that the energy in certain wavelength bands is propagating vertically. By using the indicated periods and the linear dispersion relation for equatorial waves, we determine that the observed meridional motion in two vertical wavenumber bands is consistent with the dominance of two mixed Rossby-gravity waves. The first has a vertical wavelength of 1200 sm (stretched meters) propagating energy upwards, the other a wavelength of 450 sm, propagating energy downward. Estimated periods from DLC are 72 days for the 1200 sm wavelength, 57 days for the 450 sm. From the linear dispersion relation, the corresponding zonal wavelengths are ~300 and ~750 km, respectively.

O'NEILL, K., and J. R. Luyten. Equatorial velocity profiles. Part II: Zonal component. *Journal of Physical Oceanography, 14*(12):1842-1852 (1984).

Vertical profiles of horizontal velocity made along 53°E in the western Indian Ocean, during and after the onset of the southwest monsoon in 1976, show features in zonal velocity of relatively small vertical scale. Persistence of the features over the month-long observation period and over 2½ degrees of longitude indicates long temporal and zonal scales. The vertical structure is common to those profiles close to the equator, with no appreciable variation in amplitude or depth. Between 1°30'N and 3°N the phase of the features reverses. There is no evidence of similar features at 5°N. The data suggest meridionally trapped equatorial waves. Similarities between the observed phenomena and the linear theory of equatorial waves are striking but quantitative comparisons lead us to question its naïve application here. Equatorial intensification is apparent but it does not scale with the Rossby radius of deformation, indicating that Kelvin waves are not dominant at any vertical scale. The phase change and corresponding amplitudes of zonal velocity do not fit a low-frequency, first meridional-mode long Rossby wave. Higher meridional modes produce further inconsistencies. There is no evidence of vertical propagation of the larger scale features. Although the small vertical

scale variability is ubiquitous in the equatorial regions, no satisfactory theory exists at present. Our conclusion is that although there are similarities between observations and linear theory, there are serious discrepancies which may be related to the proximity of these observations to the slanting coast of East Africa.

OVERLAND, J. E. Atmospheric boundary layer structure and drag coefficients over sea ice. *Journal of Geophysical Research, 90*(C5):9029-9049 (1985).

This paper estimates the air/sea drag coefficient for first-year ice from recent aircraft measurements and reconciles the range of observed drag coefficients (10^3C_D = 1.2 - 3.7 referenced to 10 m) for all sea ice types, based on ice roughness and seasonal meteorology. For the purpose of sea ice modeling, it is necessary to define an effective drag coefficient which relates regional stress to regional wind, because sea ice is heterogeneous on scales less than 20 km. Regional stress is influenced by the distribution of surface roughness, the buoyancy flux from quasi-periodic leads, and external atmospheric conditions, principally the inversion height. 10^3C_D is 1.3 - 1.5 for smooth ice, but is much greater for non-flat surfaces. For wind speeds greater than 5 m/s and air temperatures below freezing, the effective 10^3C_D is 2.5 - 3.0 for nearly continuous pack ice, such as first-year ice in seasonal ice zones and central arctic basin. The range of values of 10^3C_D is 3.0 - 3.7 for unstable boundary layers typical of off-ice winds in the marginal ice zone (MIZ) or even greater if the ice has been broken by a recent storm. C_D values at the lower end of these ranges are associated with low inversion heights. These coefficients are confirmed by 10^3C_D of 2.9, 2.5, and 3.1 for first-year sea ice calculated from gust probe data collected by the NOAA-P3 aircraft, interior to the inner MIZ in the Bering Sea during the Marginal Ice Zone Experiment (MIZEX-West) in February 1983, and 10^3C_D of 2.6 for the Arctic calculated from Arctic Ice Dynamics Joint Experiment (AIDJEX) aircraft data for February 1976. The effective drag coefficient with the presence of even a small concentration of sea ice is greater than the oceanic value as shown by a 10^3C_D of 2.2 calculated from NOAA-P3 gust probe data over a 40-km track of 0.4 ice concentration in the outer MIZ of the Greenland Sea in June 1984 during MIZEX-84. The relation of surface wind and stress to the geostrophic wind for shallow inversion heights, typical of high latitudes, is reviewed with a turbulent closure atmospheric boundary layer model. The winter Arctic is typified by low inversions (<100 m), low geostrophic drag coefficients, and large geostrophic/surface wind turning angles, with low functional dependence on surface roughness. Seasonal ice zones are typified by a more modest influence of the inversion on boundary layer characteristics.

OVERLAND, J. E. Geostrophic drag of the high latitude atmospheric boundary layer. *MIZEX Bulletin* 6 (CRREL Special Report 85-6), 84-89 (1985).

No abstract.

OVERLAND, J. E. Scale analysis of marine winds in straits and along mountainous coasts. *Monthly Weather Review, 112*(12):2530-2534 (1984).

The complicated wind regimes in straits which develop in response to different large-scale pressure fields are investigated by scale analysis of the equations of motion. Adjustment of the mass and motion fields in straits O(10s km) in width is governed by four nondimensional numbers: separate along- and cross-strait Rossby numbers, a strait drag coefficient, and a stratification parameter, which relates the internal Rossby radius of deformation to the width of the strait. The wind field is in approximate geostrophic balance with an imposed cross-channel pressure gradient. An along-channel pressure gradient is primarily balanced by ageostrophic acceleration of the wind field down the axis of the strait (the gap wind). Vertical motion and the accompanying horizontal divergence in the near-surface wind field can be large even for moderately stable stratification; as a consequence, there may be particularly abrupt transitions of the surface wind field at the exits of straits, where there is a rapid change of the scaling parameters to match coastal conditions. The scale analysis also applies to open coasts with the Rossby radius of deformation replacing the width of the strait as the offshore length scale. For the mountainous coasts along Alaska, Canada and Norway, a typical Rossby radius is O(80 km); within this distance an alongshore pressure gradient will be principally balanced by the ageostrophic terms in the momentum equation. Since the coastal Rossby radius is smaller than the grid size of present numerical weather prediction models, geostrophic adjustment is not correctly modeled for landfalling storms along mountainous coasts.

OVERLAND, J. E., and B. A. WALTER. Further aircraft measurements of air-ice drag coefficients. *MIZEX Bulletin* 6 (CRREL Special Report 85-6), 79-83 (1985).

No abstract.

OVERLAND, J. E., and J. G. WILSON. Mesoscale variability in marine winds at mid-latitude. *Journal of Geophysical Research, 89*(C6):10599-10614 (1984).

Wind data were collected by the National Oceanic and Atmospheric Administration WP-3D aircraft on low-level (50 and 90 m) crosswind and along-mean-wind tracks of approximately 350 km during the Storm Transfer and Response Experiment in November and December 1980. Observed mesoscale variations in the marine wind fields are characterized by the velocity correlation tensor for three atmospheric regimes: cloud streets, open and closed cellular convection, and prefrontal warm air advection. The dominant scale of mesoscale variation in the offshore wind field normal to the mean wind direction in the case of cold continental air flowing over a warmer ocean, producing cloud streets, was 27 km. For this case, the standard deviation in momentum transfer, which was calculated from 2-km subsets of the flight track by the bulk aerodynamic method assuming a constant drag coefficient, was 13% of the synoptic scale (330 km) mean. The dominant scale of mesoscale variation for open cellular convection was 62 km, and the dominant scale for closed cellular convection was 90 km.

The standard deviation of mesoscale momentum transfer (scales greater than 2 km; constant drag coefficient) for a 345-km flight track containing both cell types was 26% of the synoptic scale mean. The warm air advection case had no measurable mesoscale variability. For each regime a model of the horizontal velocity correlation tensor, which can be used to estimate a mesoscale variability, is fitted to the observed velocity correlation tensor with velocity component and weather regime dependent coefficients. This general model is consistent with an interpretation of the mesoscale wind field as an ensemble of coherent structures, associated with cloud type, in which the spatial variability of the wind field in each weather regime is associated with physically determined dominant length scales (i.e., cells or rolls), as contrasted with a continuum interpretation of two-dimensional turbulence. To accurately describe regional winds and fluxes at the sea surface, wind speed and temperature data should be averaged over the dominant mesoscale length scale with either a suitable time average or a spatial average, such as can be obtained by scatterometry, or an estimate of the mesoscale variability should be explicitly stated. It is also suggested that enhanced vertical flux in the oceanic mixed layer occurs at length scales of atmospheric boundary layer structures.

Ozturgut, E. O, and J. W. LAVELLE. New method of wet density and settling velocity determination for wastewater effluent. *Environmental Science and Technology, 18*:947-952 (1984).

A method has been developed to directly measure the wet density/size spectra of low density but settleable wastewater effluent particles. In this method particles settle to their isopycnic levels in a linear density stratified column. Then samples are drawn, and particle size distributions are determined by Coulter Counter. The wet density/size distribution of particles in a wastewater samples was measured in this manner in the 1.0-1.4 g/cm^3 density range and 1.0-64 μm size range. Measurement of size and density outside these ranges permitted construction of a composite settling velocity distribution. We believe these measurements and computed settling velocities are independent of concentration because the density/size spectra of particles can be determined at concentrations low enough to preclude significant flocculation.

PAULSON, A. J., and R. A. FEELY. Dissolved trace metals in the surface waters of Puget Sound. *Marine Pollution Bulletin, 16*(7):285-291 (1985).

Employing clean and quantitative techniques, a marine monitoring programme succeeded in detecting large surface elevations in the concentrations of dissolved Cu, Zn and Pb in the marine surface waters of Puget Sound adjacent to Seattle and Tacoma, Washington. Physical mixing with cleaner waters was the controlling factor in reducing the dissolved concentrations of Cu downstream of these contaminated regions. Comparisons between Puget Sound waters and coastal waters adjacent to Puget Sound suggest that a portion of this Cu, Zn and Pb pollution is being advected out of Puget Sound. The low Ni and Cd concentrations found in this study indicate that these trace metals are not a significant pollution problem in the main basin of Puget Sound.

PEASE, C. H. Theory of wind-driven coastal polynyas. *MIZEX Bulletin* 6 (CRREL Special Report 85-6), 112-119 (1985).

No abstract.

PREISENDORFER, R. W., and C. D. MOBLEY. Unpolarized irradiance reflectances and glitter patterns of random capillary waves on lakes and seas, by Monte Carlo simulation. NOAA-TM-ERL-PMEL-63 (NTIS not yet available), 141 pp.

The downward irradiance reflectance r_- and the upward irradiance reflectance r_+ of a random air-water surface, formed by capillary waves, are computed as a function of lighting conditions and wind speed by Monte Carlo means for incident unpolarized radiant flux. The possibility of multiple scattering of light rays and of ray-shielding of waves by other waves is included in the calculations. The effects on r_+ of multiple scattering and wave shielding are found to be important for higher wind speeds ($\gtrsim$10 m/s) and near horizontal light ray angles ($\gtrsim$70°) of incidence. A simple analytic first-order model of irradiance reflectance, which assumes a binormal distribution of water facet slopes, is tested against the relatively exact Monte Carlo results. Regions are defined in wind-speed and incident-angle space over which the first-order model is acceptable. Plots of the Monte Carlo r_+ are drawn as functions of wind speed and angle of incidence of light rays. r_+ are also found for various continuous radiance distributions simulating overcast skies and upwelling submarine light fields just below the air-water surface. Simulated glitter patterns are displayed as functions of wind speed and angle of incidence of light rays for both reflected and transmitted rays, and for light sources located both above and below the air-water surface. Extensions of the present Monte Carlo procedure to include gravity waves as well as capillary waves are outlined.

REED, R. K. An estimate of the climatological heat fluxes over the tropical Pacific Ocean. *Journal of Climate and Applied Meteorology, 24*(8):833-840 (1985).

Weather reports for the 1970s decade were used to derive the mean annual distributions of surface properties and to compute the surface fluxes of heat over the tropical Pacific Ocean. The net heat flux obtained was greater than other estimates, and there is an annual heat gain by the ocean everywhere between 20°N and 20°S. The amounts and patterns appear plausible when compared with major features of the ocean circulation. The seasonal cycles of sea surface temperature, net heat flux, and wind speed were examined for eight regions; the results suggest that, except off Peru and near the equator, the seasonal variation of surface temperature is caused by variations in surface heat flux.

REED, R. K. Oceanographic observations off the Pacific Northwest following the 1982 El Niño event. *Marine Fisheries Review, 46*(1):7-12 (1984).

The evolution of sea surface temperature anomalies off the Pacific Northwest during the 1982-83 El Niño seems to be in general agreement with

their formation through poleward advection by a long wave. Oceanographic observations in May 1983 indicated significant positive thermal anomalies above 500 m; salinity anomalies showed a reversal in sign which implied both sinking of upper water and northward advection. Geostrophic flow along 47°N revealed no evidence of the California Undercurrent.

REED, R. K. Preliminary heat flux computations during the 1982-83 ENSO event. In *El Niño Atlas 1982-83*, A. Leetmaa and J. Witte (eds.), Nova University Oceanographic Center, Dania, Florida, 125-130 (1984).

No abstract.

REYNOLDS, R. M., and C. H. PEASE. Regional ice drift during MIZEX-West. *MIZEX Bulletin* 6 (CRREL Special Report 85-6), 31-37 (1985).

No abstract.

Roden, G. I., and B. A. TAFT. Effect of the Emperor Seamounts on the mesoscale thermohaline structure during the summer of 1982. *Journal of Geophysical Research, 90*(C1):839-855 (1985).

The influence of the Emperor Seamount Chain upon the mesoscale thermohaline structure and upon geopotential height are investigated on the basis of a field experiment in the summer of 1982. The seamounts have a twofold effect: they deflect the oncoming flow of the Kuroshio Extension, and they give rise to secondary perturbations of small horizontal extent but of large vertical amplitude. The Kuroshio Extension approached the seamounts on a southeastward course and was deflected by Kinmei Seamount in an anticyclonic loop. The deflection led to a weakening of this current over this seamount and to reintensification on the downstream side. Uplift of isopycnals near seamount peaks and vertical displacement along seamount flanks were generally observed, but the details varied considerably from one seamount to the next. Uplift occurred over some peaks; on others it was displaced 50-100 km from it. In some instances there was intense downward displacement on the west and upward displacement on the east side; in others this was not the case. A Taylor columnlike feature occurred over Suiko Seamount. A very large and asymmetric density dome was found 40 km west of Jingu Seamount, atop which a density front was located, which suggests flow intensification to the left of the seamount. In the main gap between the northern and southern seamounts, prominent wedgelike intrusions or subarctic and Kuroshio-type waters were observed in the upper few hundred meters. The isopycnals in the main gap sloped sharply to the south, indicating a strong eastward baroclinic flow component. The geopotential heights over the Emperor Seamounts indicate strong local perturbations superimposed upon larger-scale slopes. A geopotential low was observed west of the seamounts, and a high was found near the seamount top or to the east of it, indicating anticyclonic flow. In terms of geometric distance, perturbation dynamic heights reached 0.32 m, and maximum sea surface slopes were $5 \cdot 10^{-6}$. The slopes produce baroclinic currents up to 0.5 m s^{-1} around the seamounts.

RUFENACH, C. L., L. S. FEDOR, J. R. Apel, and F. I. GONZALEZ. Surface and internal ocean wave observations. *Advances in Geophysics, 27*:141-196 (1985).

No abstract.

SCHUMACHER, J. D., A. T. ROACH, and K. Aagaard. Fluctuation of flow through Bering Strait. *MIZEX Bulletin* 6, (CRREL Special Report 85-6), 105-111 (1985).

No abstract.

TAFT, B. A. The Niño of 1982-83 in the tropical Pacific. In El Niño *North: Niño Events in the eastern Subarctic Pacific Ocean*, W.S. Wooster and D.L. Fluharty (eds.), Washington Sea Grant, Seattle, 1-8 (1985).

No abstract.

Theyer, F., E. Herrero-Bervera, V. Hsu, and S. R. HAMMOND. The zonal harmonic model of polarity transitions: A test using successive reversals. *Journal of Geophysical Research, 90*(B2):1963-1982 (1985).

A recently developed zonal model for the last geomagnetic field reversal, which describes time- and latitude-dependent transitional behavior of intensity and inclination in terms of dominance of low-order field harmonics, was tested using a latitudinal and chronological succession of transition records. The primary data were derived from a high-resolution study of five Matuyama to Brunhes deep-sea cores collected along a 40° meridional band in the north-central Pacific. The transitions analyzed were the onsets and terminations of the Olduvai and Jaramillo events and the Matuyama-Brunhes boundary. Supplementary data, published by previous workers, included a Jaramillo onset record from the southern Indian Ocean and a transition recorded in the Triassic Chugwater Formation of North America. In a general sense, the measured inclination and intensity records indicate the Jaramillo transitions and the last reversal to be remarkably similar to each other and to differ from the Olduvais. Cross-correlation of the measured data sets with synthetic zonal harmonic records for the core latitudes indicates that the zonal harmonic model does predict the behavior of Matuyama-Brunhes reversal in the northern hemisphere. For the older reversals, however, the present model requires substantial modification. This is particularly so in the case of the Jaramillo onset: although two inclination and intensity records of this transition from northern and southern hemisphere sediments strongly resemble each other, the current model produces a synthetic record for one hemisphere that is incompatible with that hemisphere's measured data. Further, to model zonally the Olduvai reversals (for which a wide latitudinal northern hemisphere sampling was available), a substantially different ratio of low-order multipole components from that of the standard model is required, and the modeled solution was unsatisfactory at very low latitude. A modified zonal harmonic approach, which introduces a small sectoral component, may offer a solution to the incompatibilities uncovered by the present study.

Weiss, R. F., J. L. Bullister, R. H. GAMMON, and M. J. Warner. Atmospheric chlorofluoromethanes in the deep equatorial Atlantic. *Nature, 314*:608-610 (1985).

Waters that leave the surface of the ocean and enter the subsurface circulation contain concentrations of CCl_3F (fluorocarbon-11) and CCl_2F_2 (fluorocarbon-12), which reflects the temporal increases of these industrially produced compounds in the atmosphere. These chlorofluoromethanes (CFMs) are extremely stable in the troposphere and in natural waters, they have no known natural sources, and their histories of release to the atmosphere are fairly well known. The atmospheric distributions of CCl_3F and CCl_2F_2 are not strongly dependent on latitude, and their surface water concentrations can be expected to come into relatively rapid solubility equilibrium with the atmosphere. Recent advances in analytical techniques have made possible the routine use of these CFMs as oceanic tracers on a decadal timescale. The results we report here are from the first detailed surveys of CCl_3F and CCl_2F_2 distributions in the northern and tropical Atlantic Ocean. They show that CFM-bearing waters originating in the region of the Labrador Sea have reached the Equator in a well-defined western-boundary undercurrent located at a depth of about 1.6 km, in the Upper North Atlantic Deep Water. Using a simple dilution model, we calculate that this water has taken about 23 yr to reach the equatorial region, and has been diluted about five-fold by CFM-free waters.

WILSON, J. G., A. L. Comiskey, R. W. Lindsay, and V. L. LONG. Regional meteorology of the Bering Sea during MIZEX-West, February and March, 1983. ERL Special Report (PB85-173599), 115 pp. (1984).

The Marginal Ice Zone Experiment (MIZEX) West was conducted in the eastern Bering Sea during February and March 1983. During the experiment surface and upper-air meteorological observations were taken from two ships, the NOAA Ship DISCOVERER and Coast Guard Cutter WESTWIND. The meteorology of the region for this period is illustrated with fields of sea level pressure, surface air temperature (computed from the 1000-850 mb thickness), and surface winds. These fields are derived from a mesoscale hand drawn analysis that was digitized on a 6×5 polar stereographic grid and processed through the computer routines in METLIB. The weather during this period was predominantly characterized by storms crossing the North Pacific Ocean along the Aleutian Island chain resulting in northeasterly winds of 10 to 20 kts and temperatures of -10°C to -15°C in the eastern Bering Sea. Under these meteorological conditions, the ice edge advected to the south and west. The upper-air soundings generally showed a well-defined, well-mixed, marine boundary layer ranging between 100 and 900 m depth. The atmospheric boundary layer seaward of the ice edge under conditions of off-ice winds deepened by a factor of 1.6, 170 km downwind of the ice edge.

WISEGARVER, D. P., and J. D. CLINE. Solubility of trichlorofluoromethane (F-11) and dichlorodifluoromethane (F-12) in seawater and its relationship to surface concentrations in the North Pacific. *Deep-Sea Research, 32*(1):97-106 (1985).

The solubilities of trichlorofluoromethane (F-11) and dichlorodifluoromethane (F-12) were determined in seawater (35×10^{-3}) and in distilled water from 0 to 30°C. Aqueous concentrations were determined by GC-EC subsequent to equilibration with clean, ambient air containing approximately 200 ppt(v) F-11 and 340 ppt(v) F-12. Our compressed air standard was independently calibrated and we estimate the accuracy and precision of the measurements to be approximately 2%. The temperature dependence of the solubility was determined by fitting the observations to the first three terms of the integrated van't Hoff Equation at a constant 35×10^{-3} salinity. A comparison of the extant solubility data in seawater with our determinations indicates considerable variability for both F-11 and F-12. Our solubility measurements also are compared to observed concentrations in the surface waters of the eastern, central, an western North Pacific in December 1980, July 1981, June 1982, and March and April 1983, and suggest a supersaturation of 1 to 2% for both fluorocarbons with little or no temperature bias in the surface North Pacific.

WRIGHT, P. B., T. P. Mitchell, and J. M. Wallace. Relationships between surface observations over the global oceans and the Southern Oscillation. NOAA-DR-ERL-PMEL-12 (NTIS not yet available), 61 pp. (1985).

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Wyrtki, K., S. P. HAYES, D. B. Enfield, and H. L. Pittock. Sea level variations in the Pacific during 1982-83. In *El Niño Atlas 1982-83*, A. Leetmaa and J. Witte (eds.), Nova University Oceanographic Center, Dania, Florida, 17-23 (1984).

No abstract.

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Haynes, P. (1984): Nonlinear instability of a Rossby-wave critical layer. *J. Fluid Mech., 161*, 493-511.

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Rothstein, L.M. (1984): Interior reflections of a pendually forced equatorial Kelvin wave. *J. Phys. Oceanogr., 15*, 985-996.

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