Flux Mooring for the North Pacific's Western Boundary Current: Kuroshio Extension Observatory (KEO)

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1. PROJECT SUMMARY

Overview:

As a NOAA contribution to the global network of Ocean Sustained Interdisciplinary Timeseries Environmental Observatory (OceanSITES) timeseries reference stations, in June 2004, an air-sea flux buoy site was launched near 144.6°E, 32.4°N in the Kuroshio Extension recirculation gyre. The mooring, referred to as the Kuroshio Extension Observatory (KEO), carries a suite of sensors to monitor carbon dioxide uptake; air-sea heat, moisture and momentum fluxes; temperature and salinity to 500 m, and near-surface currents. The Kuroshio Extension (KE) is the North Pacific's western boundary current after separating from the coast near 35°N. The KE jet carries approximately 140 milllion cubic meters per second (140 Sv) of warm water eastward into the North Pacific. About a third of this is forced by the basin-scale winds and associated with the wind driven Sverdrup transport and the other 90 Sv is due to a tight recirculation gyre whose size varies on seasonal-decadal time scales.

The KE atmosphere-ocean system represents a major branch of the global heat cycle, whereby excess heat input at the top of the atmosphere in the tropics is carried poleward by a combination of the oceanic and atmospheric circulations (e.g., Trenberth and Caron 2001). In the subtropical North Pacific, a significant fraction of this heat is transported poleward by the Kuroshio. As cold dry air of continental origin comes in contact with the warm KE water, heat and moisture are extracted from the surface (Figure 1), resulting in vigorous convection and rainfall. The KE is co-located with the Pacific storm track and heat released to the atmosphere is then carried further poleward through the action of storms.

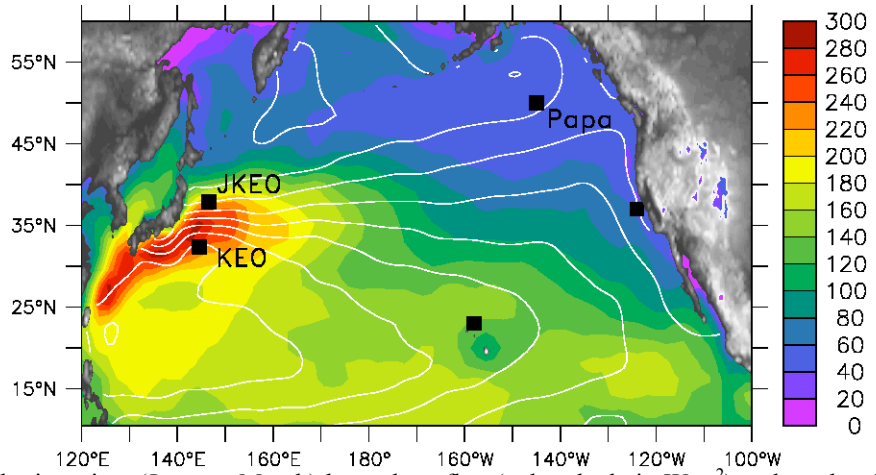

Figure 1. Climatolocial wintertime (January-March) latent heat flux (color shade in Wm^{-2}) and sea level height (white contours) for the North Pacific. Squares indicate OceanSITES time series reference sites.

The KEO project is working closely with international research communities. The KEO site was within the study domain of the 2-year (June 2004 - June 2006) National Science Foundation-

funded Kuroshio Extension System Study (KESS). (Donohue et al. 2008, also see http://uskess.org). KEO data are being combined with KESS data for a series of analyses on mode water formation, seasonal thermocline erosion, recirculation gyre strength, and air-sea interaction associated with summer typhoons and winter storms in the region. KEO PIs (Cronin and Bond) are members of the U.S. CLIVAR Working Group on Air-Sea Interaction in Western Boundary Current Regions. KEO data also serve the operational community and are being used as reference time series to assess numerical weather prediction analyses and reanalyses (Kubota et al. 2008, Tomita et al. 2008).

Strong currents, typhoons, winter storms, shipping traffic and fishing vandalism make the KEO region challenging for surface moorings. A manufacture defect in the nylon caused the buoy to become adrift in November 2005, as did fishing vandalism in May 2007. The May 2007 break led to loss of all subsurface sensors. Despite these challenges, the preliminary data return is 100% for all variables in FY08 (Table 1). Recognizing the success of the KEO project, PMEL has been approached by a number of academic and international groups and several have subsequently become partners. In particular, the KEO project is working closely with scientists from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). In February 2007, JAMSTEC Institute of Observational Research for Global Change (IORGC) in partnership with NOAA PMEL successfully deployed a NOAA-designed KEO mooring (JAMSTEC-KEO or "JKEO") north of the Kuroshio Extension jet. In 2008 this was replaced by a JAMSTEC-designed mooring. Likewise, since September 2007, KEO mooring operations have been performed on JAMSTEC research vessels. In addition, as part of a NSF-funded Carbon and Water Cycle project led by biogeochemists from the University of Washington, in June 2007 PMEL deployed a KEO-type air-sea flux mooring at the Ocean Weather Station Papa (50°N, 145°W) site in the Northeast Pacific. An add task for FY09 requests funds to continue the Station Papa mooring as an OceanSITES time series reference site. If this add-task is not funded, the Station Papa mooring will be recovered in June 2009 and not redeployed. Within PMEL, the KEO, JKEO, and Station Papa projects are being unified under the new name of PMEL Ocean Climate Stations (OCS) Program: http://www.pmel.noaa.gov/OCS/. The OCS program website provides links to the individual project pages and data for KEO: http://www.pmel.noaa.gov/keo/, for JKEO: http://www.jamstec.go.jp/iorgc/ocorp/ktsfg/data/jkeo/, and for Station Papa: http://www.pmel.noaa.gov/stnP/.

2. FY2008 ACCOMPLISHMENTS

The KEO project has 3 broad deliverables, each described below. The Carbon component of KEO is described separately in the progress report for Sabine's "High-Resolution Ocean and Atmosphere pCO_2 Time Series Measurements" project.

Deliverable 1: Calibrated surface meteorological and subsurface temperature, salinity and currents at the KEO site in the Kuroshio Extension recirculation gyre at 32.4°N, 144.6°E.

Operation of the KEO mooring requires refreshing the system at least once a year, pre- and post-calibrating all sensors, processing realtime data and making it available in near-realtime through the KEO website, processing delay-mode high resolution data and making it available with 6 months through the KEO website.

The KEO mooring was redeployed using charter funds for two sea-days on the R/V Kaiyo in September 2008. As shown in Figure 2, the recovered KEO-2007 and re-deployed KEO-2008 moorings have 2.5 m discus hulls, larger than the original retrofit TAO buoy. The new hull makes the buoy more robust to the drag caused by the strong full-water column currents. In addition, the larger hull enables the buoy to carry a larger payload. The KEO-2008 was also redesigned to have more glass balls above the release so that in the event that that the line parted from the buoy and sank (as happened in May 2006), the mooring line and sensors could be recovered from the ocean floor. For KEO-2008, we replaced these lost sensors with new Seabird, Inc. sensors with titanium cases that would protect the sensor electronics even at depths of 7000 m. In addition, KEO-2008 included a barometric pressure sensor and duplicate meteorological sensors on the independent data logger and telemetry system referred to as FLEX (Figure 2). Given the high number of typhoons in this region, this redundancy is prudent.

As can be seen in Table 1, KEO had 100% data return for FY08. The full suite of KEO meteorological measurements from the ATLAS data logger are shown in Figure 3 and include: wind speed and direction from a sonic anemometer, air temperature, relative humidity, rainfall, and solar and longwave radiation. The ATLAS data logger telemeters daily-averages of all its met data and spot samples of some of its met measurements in near-realtime via Service Argos; while the FLEX data logger telemeters hourly averages of its met measurements and hourly spot values of subsurface measurements in near-realtime via Iridium. Upper ocean temperature has approximately 25 m depth resolution, subsurface salinity has ~50-75 m resolution, and subsurface pressure (to remap the slackline depths) has 75 m resolution. This resolution is necessary to monitor the mode water formation when the mixed layer can be more than 400 m deep. Three current meters were also attached at 5 m, 15m, and 35 m (all of which are telemetered) to monitor the near surface currents.

Table 1. KEO data return for FY08 based upon daily-averaged data.

	FY08 Data Returns
Meteorological variables	100%
Upper ocean temperature	100%
Upper ocean salinity	99.7%
Near surface currents	100%

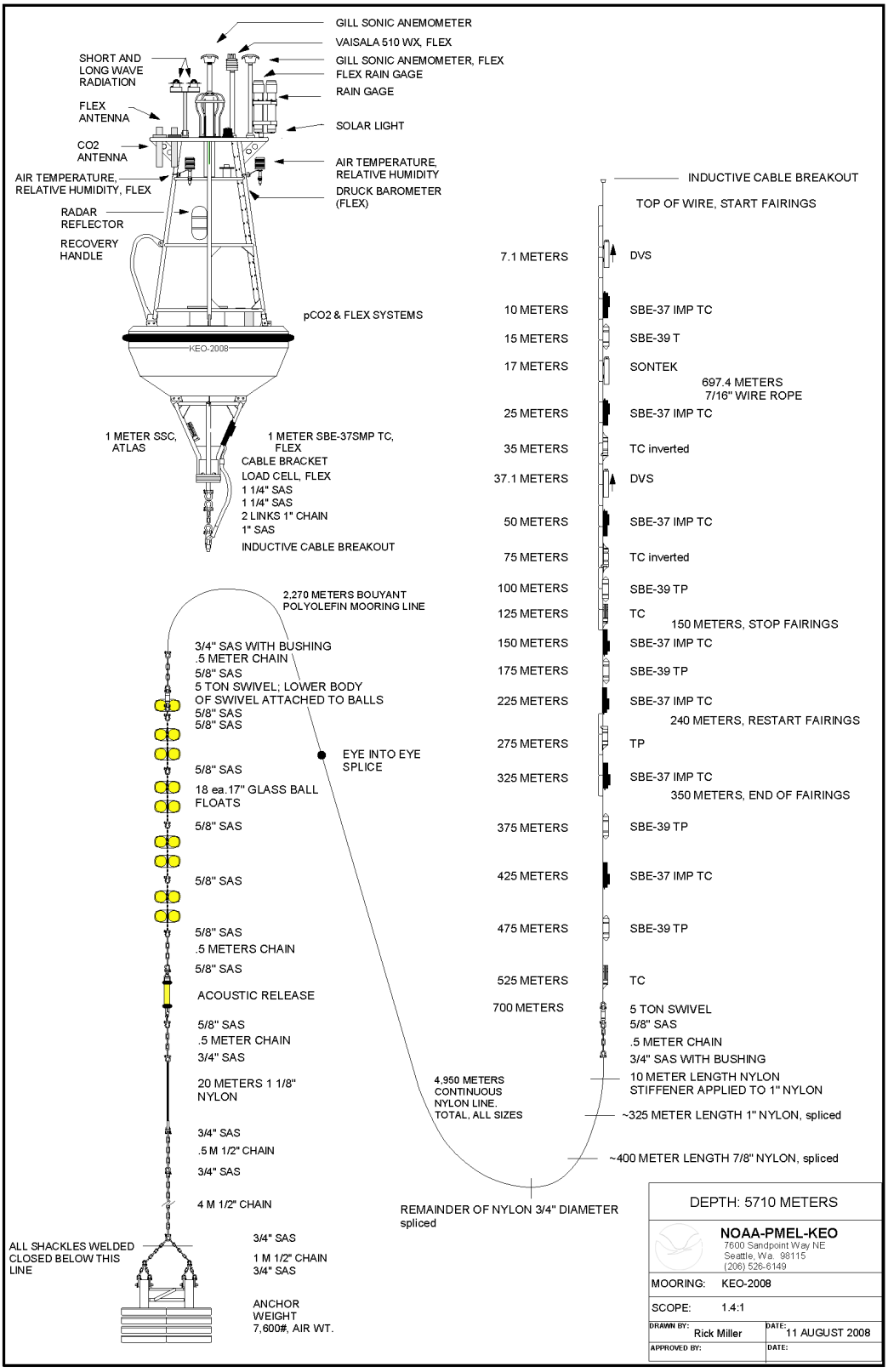

Figure 2. KEO-2008 diagram.

Deliverable 2: Access to KEO data and metadata in a format and through linked webpages to encourage broad use of data.

KEO, JKEO and station Papa data are all in compliance with the OceanSITES data standard. Daily-averages of nearly all data (surface and subsurface) are telemetered to PMEL and made available in near-realtime from:

For KEO: http://www.pmel.noaa.gov/keo/data.html
For JKEO: http://www.jamstec.go.jp/iorgc/ocorp/ktsfg/data/jkeo
For Station Papa: http://www.pmel.noaa.gov/stnP/data.html

High-resolution surface and subsurface data continue to be made publicly available through these websites within 6-months of recovery. To date, there is no user registry and so we have no way of monitoring the number of data downloads.

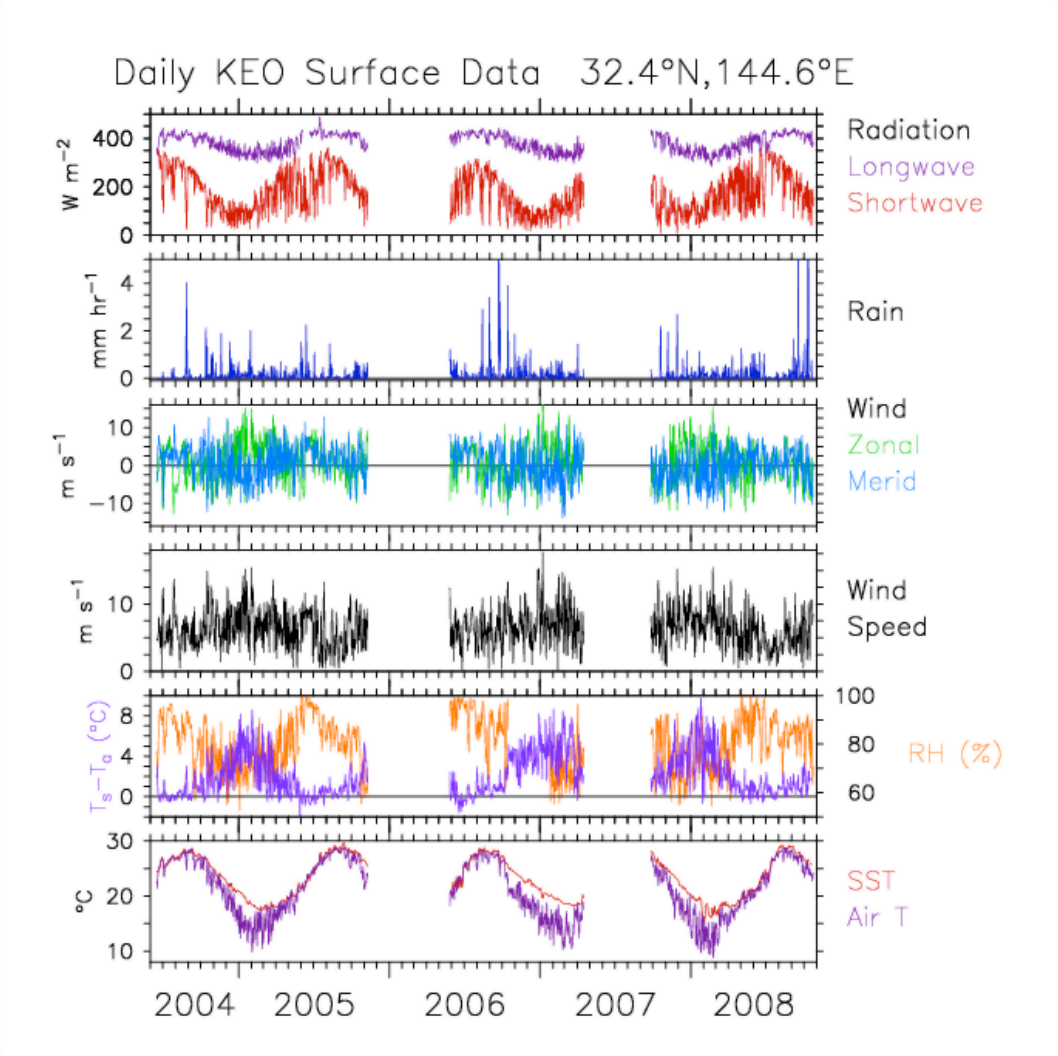

Figure 3. KEO meteorological daily-averaged data through October 23 2008.

Beginning in FY07, the PMEL Ocean Climate Station surface met data from the ATLAS data logger have been distributed to operational meteorological centers via the Global Telecommunications System (GTS) This way operational meteorological centers can use all available data in operational weather forecasts. The KEO project strongly believes however that the

reference site data should be withheld from reanalysis products so that the products will remain independent of the time series reference site data used to assess them. Each time series reference station has a unique World Meteorological Organization (WMO) identifying number containing the digits "84" for this purpose.

All three sites (KEO, JKEO, and Station Papa) can be considered as contributions to the Global Earth Observation System of Systems (GEOSS) and a manuscript describing the strategy of these moorings has been published in the IEEE Systems journal special issue for GEOSS (Cronin et al. 2008).

Deliverable 3: Scientific analyses utilizing KEO data. (Scientific analyses are funded through research grants as described below.)

KEO was an element of the Kuroshio Extension System Study (KESS) (see: http://uskess.org, and Donohue et al. 2008) and its data are a critical component of several studies. In particular, FY08 represents the final year of a 3-year NOAA CLIVAR project titled "Role of Air-Sea Interaction in the Kuroshio Extension Recirculation Gyre", with PIs Cronin and Dr. N. Bond (UW JISAO). During FY08, both Cronin and Bond participated in the U.S. CLIVAR working group on Air-Sea Interactions in Western Boundary Currrents (http://usclivar.org/Organization/wbc-wg.html). In November 2007, Cronin, Bond, and NOAA Corp officer Kamphaus participated in a workshop at IPRC in Honolulu that brought together the Japanese and US partners working with surface mooring data in the Kuroshio Extension. This group subsequently named itself the "Kuroshio Extension Implementation Panel" (KIP). The next KIP meeting is planned in conjunction with the US CLIVAR working group conference in January 2009.

Two KEO analyses were published in 2008: Bond and Cronin (2008) and Kubota et al. (2008). Bond and Cronin (2008) analyzed the regional weather and climate patterns associated with anomalously high and low fluxes at KEO. The analysis shows that during the cool season, prevailing winds at KEO are northwesterly and anomalous heat loss by the ocean is associated with increased northerly winds (cold air outbreaks). During summer, on the other hand, prevailing winds switch to be southerly and anomalous cooling tends to occur during enhanced southeasterly winds out of the deep tropics. When the analysis was extended to identify weather patterns associated with anomalous fluxes on seasonal time scales, a surprising result was found. The warm seasons with anomalous heat fluxes tend to have composite patterns similar to the episodic composites, but the cool seasons with anomalous heat fluxes have composite circulation patterns that are weak and little resemble their episodic event counterparts. It's not just a matter of having more or less cold-air outbreaks. Instead, these results suggest that on interannual timescales, the ocean may be playing an important role in determining wintertime heat flux anomalies.

The KEO data have also been used as a time series reference to assess Numerical Weather Prediction (NWP) forecast analyses and reanalyses, and other numerical and satellite products. In particular, Kubota et al. (2008) used the KEO data to assess the radiative and turbulent heat flux fields of the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) and NCEP/Department of Energy (DOE) reanalyses (referred to as NRA1 and NRA2) and found that:

- Overall, the NRA latent heat losses were too large relative to KEO. For NRA1, the latent heat bias was 41 W/m^2; for NRA2, the bias was 62 W/m^2 (there was a 21 W/m^2 bias between the two products).

- Although the magnitude of the fluxes had significant biases, the NRA were able to capture many of the synoptic disturbances. The cross-correlation between the KEO latent heat flux and the co-incident NRA latent heat fluxes were greater than 0.9 for both NRA1 and NRA2.
- The bias in the NRA latent heat flux could be reduced significantly by using a more sophisticated bulk algorithm for its heat flux calculations.
- Of all the state variables (SST, humidity, air temperature, wind speed), humidity contributed the largest source of error to the NRA flux. During summer when prevailing winds are from the south (of maritime origin), the NRA humidity is too low, while during the winter when prevailing winds are from the north (of continental origin), the humidity is too high. Although the prevailing wind systems are well reproduced, the air humidity does not seem to be properly modified by boundary layer effects.
- The NRA SST had significant errors in comparison to KEO measurements. The RMS error in latent heat flux was significantly reduced when the NRA SST was replaced with the Microwave Optimum Interpolation (MWOI) SST, indicating that both reanalyses could be improved by assimilating better SST data.

The KEO group is hoping to work more closely with scientists at NCEP to evaluate the operational products and to improve our understanding of air-sea fluxes leading to better predictions of weather and climate variations. Further analyses are described in the FY09 Workplan.

3. PUBLICATIONS

Bond, N. and M. F. Cronin, 2008: Regional weather patterns during anomalous air-sea fluxes at the Kuroshio, Extension Observatory (KEO). *J. Climate*, 21, 1680-1697.

Cronin, M. F., C. Meinig, C. L. Sabine, H. Ichikawa, and H. Tomita, 2008: Surface mooring network in the Kuroshio, Extension. *IEEE Systems Special Issue on GEOSS*, 2, 424-430.

Donohue, K. A., and colleagues, 2008: An integrated system study of the Kuroshio Extension. *EOS Trans. AGU,* 89,161-162.

Kubota, M., N. Iwabe, M. F. Cronin, and H. Tomita, 2008: Surface heat fluxes from the NCEP/NCAR and NCEP/DOE, reanalyses at the KEO buoy site. *J. Geophys. Rev*., 113, C02009, doi:10.1020/2007JC004338.

4. LIST OF ACRONYMS

CLIVAR	Climate Variability and Predictability
DOE	Department of Energy
FLEX	Flexible Low-powered Electronics for ocean experiments
GEOSS	Global Earth Observation System of Systems
GTS	Global Telecommunications System
IORGC	Institute of Observational Research for Global Change

JAMSTEC	Japan Agency for Marine-Earth Science and Technology
JISAO	Joint Institute for the Study of the Atmosphere and Ocean
JKEO	JAMSTEC-Kuroshio Extension Observatory
KE	Kuroshio Extension
KEO	Kuroshio Extension Observatory
KESS	Kuroshio Extension System Study
KIP	Kuorhio Extension Implementation Panel
K-TRITON	Kuroshio-TRIangle Trans-Ocean buoy Network
MWOI	MicroWave Optimum Interpolation
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NRA	NCEP Reanalysis
NSF	National Science Foundation
NWP	Numerical Weather Prediction
OceanSITES	Ocean Sustained Interdisciplinary Time series Environmental Observatory
PI	Principal Investigator
PMEL	Pacific Marine Environmental Laboratory
RMS	Root-Mean-Square
SST	Sea Surface Temperature
TAO	Tropical Atmosphere and Ocean
UW	University of Washington
WMO	World Meteorological Organization