CHAPTER 5

Climatological and Hydrological Field Monitoring

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Introduction

On the mountainous slopes of tropical volcanic islands, steep topo-climatic gradients serve to compress distinctive ecosystems and local biodiversity into spatially restricted, vertically stratified environmental zones. This physical heterogeneity also presents a diverse range of constraints and opportunities for human landscape use and transformation, leading, in the case of most Pacific high islands, to a complex and interdependent spatial mosaic of natural and anthropogenic landscapes closely bounded spatially and strongly interconnected. The aboriginal settlers of the Pacific islands gained intimacy with these small yet complex environmental systems and in many cases evolved land tenure systems (e.g., the ahupua`a land management unit in Hawai`i) that explicitly acknowledged their understanding of upland-lowland (cf. watershed) environmental linkages in supporting sustainable agricultural and related traditional land-use systems (Fig. 1.2, p. 6). Modern global economic integration, along with rapid social, cultural and demographic change in the colonial and post-colonial Pacific, today present a host of impacts that work to disrupt and destabilize small island human-environment relations. In many ways these impacts are no different from the environmental issues confronting the world as a whole, they are simply playing out at a more rapid pace and in a much smaller and circumscribed geographical arena.

A major goal underlying the PABITRA initiative is the promotion of optimizing solutions for both long-term native ecosystem conservation/restoration and sustainable human utilization of natural resources and ecosystem services (e.g., water quantity and quality, culturally and economically important natural products) within the confines of comparatively small island areas. These objectives can only be achieved through a clear understanding of the interplay between the underling physical and biological environment and human impact processes at the watershed scale (i.e., at the level of the ahupua`a). Because each Pacific island entity presents a unique suite of environmental conditions, endemic biota, and history of human occupation and land use, PABITRA sites are being proposed to focus integrated and interdisciplinary applied environmental research on representative upland-lowland transects, both in terms of native ecosystem processes and human manipulation.

Because climatic and hydrologic processes are integral to the functioning of terrestrial ecosystems as well as their anthropogenic manipulation, appropriate networks for long term monitoring of climate and hydrological parameters are an essential component of environmental data gathering along PABITRA transects. In addition, this network will contribute to broader regional environmental programs dealing with regional or global warming impacts and climate change detection.

The hydrologic cycle as one of PABITRA's organizing themes

Climate can be considered the average state of the atmosphere over medium-to-long time scales (months, years, millennia), whereas weather refers to instantaneous or short term atmospheric conditions. Closely related, hydrology is the branch of science that deals specifically with water at or near the earth's surface (i.e., soil water or sub-surface ground water). Water

circulation, distribution, physical and chemical properties and relationships to the surrounding biosphere and lithosphere are foci of hydrologic studies. The concept of a hydrologic cycle is the most fundamental principle linking the movement of water through atmospheric, terrestrial and marine systems. Evaporation from soil and water surfaces and transpiration from plants transfer water vapor to the atmosphere while condensation and precipitation processes return water to the surface. Precipitation may be intercepted by vegetation, infiltrated into the soil or groundwater, or runoff into streams and rivers to ultimately return to the ocean. Quantification of the hydrologic cycle at the watershed scale requires the measurement or estimation of both climatic and stream parameters to fully characterize the water balance of a study area.

Traditional ethno-environmental knowledge

With a heritage in long-distance seafaring and the successful settlement of remote islands, the native peoples of the Pacific have developed a deep traditional knowledge base for all aspects of their natural environment. Modern, quantitative climate and hydrologic monitoring at PABITRA sites should first begin with discussions and interviews among local residents about their weather, climate and hydrological experience in the study area. Simple questions such as those below can yield important information to help in the design and citing of field sampling stations, and in constructing a qualitative picture of the weather and climate experienced by local residents.

- Where on the trail up the mountain is fog (i.e., orographic cloud at ground level) typically encountered?

- How high has the water risen on this stream bank during big/intense storms?

- When was the longest drought you can remember? How long did it last and how did it affect your crops and availability of forest products?

Subject to informant agreement, formal or informal questionnaire may be developed to systematically gather ethno-environmental information.

Gathering and evaluation of existing records

The key elements of weather and climate that largely control the growth and productivity of biological systems and the hydrological cycle include: 1) precipitation inputs (including associated atmospheric nutrient fluxes); 2) the complex of atmospheric variables that control evapotranspiration and plant photosynthesis/respiration (solar energy, temperature, humidity and wind velocity); and 3) water (and nutrient) outputs from the system in the form of stream discharge and ground water recharge. Any network of climate/hydrological studies at PABITRA sites, should, if possible, be designed to incorporate long term historical records of environmental variables from within or adjacent to the research area (e.g., rainfall and streamflow data).

Because most Pacific islands are characterized by generally high seasonal, annual and inter-annual variability with respect to many climatic/hydrological parameters, even the most comprehensive short term monitoring of the physical environment at prospective PABITRA sites needs to be placed in a longer-term context. This regional variability is driven in part by such phenomena as the occurrence of extreme weather events (e.g., tropical cyclones) or periodic large scale synoptic atmospheric anomalies (ENSO), all of which may be linked to global scale climate change trends. All relevant historical environmental data for the project area should be converted to digital format and stored in a data base for climate characterization along the PABITRA transect as well as for eventual time-series analysis and contextualization of data generated in any new monitoring program.

Precipitation

Long term rainfall data are often available for at least a few locations on most Pacific islands (typically airports, urban centers and important agricultural areas). However, rainfall measurements are often absent or very limited for interior mountainous regions where the largest amounts of orographically enhanced rainfall are most likely to occur. The spatial variation in annual rainfall over short distances in mountainous islands can produce exceptional rainfall gradients, making spatial extrapolations from single measurement sites problematic. In Hawai`i, on the island of Maui for example, spatial variability in annual rainfall may exceed 1500 mm/km as a function of mountain alti-

tude and aspect (windward or leeward exposure; see Giambelluca and Schroeder, 1998).

For PABITRA sites and transects, all available historical rainfall maps and rainfall records should be assembled and evaluated to assist in designing a rainfall sampling network most likely to capture the spatial variability in local precipitation and facilitate reasonable estimation of the mean aerial precipitation over the watershed study area. Techniques for spatial precipitation averaging using standard aerial integration methods such as "inverse-distance squared" and "inter-gauge correlation fields" (kriging) are reviewed by Singh and Chowdhury (1986).

Temperature

Long term temperature data (extending back into the early-mid 20th Century) are generally available for selected sites on most Pacific islands. Again, as with rainfall, data coverage may be reduced or absent for those interior mountainous regions most important from both a watershed and biodiversity conservation perspective. Because island air temperatures are largely influenced by standard elevation/air density relationships and large scale advection factors, there is typically much less influence (compared to rainfall) exerted by terrain complexity (e.g., wind exposure and slope aspect). Where temperature data are locally available for stations at different elevations, it may be possible to derive a fairly robust empirical relationship between these variables, facilitating extrapolation into the data-poor uplands along PABITRA transects. Figure 5.1 illustrates the relationship between mean annual air temperature and station elevation for 16 locations in Hawai`i, which allows calculation of standard lapse rates (average temperature change with elevation).

Evapotranspiration

Although existing evapotranspiration records may be scarce, this variable is important for determining the water balance along the PABITRA transect. With the application of sufficient energy (i.e., 540 cal/g), water changes state from liquid to vapor, and enters the atmosphere through evaporation. When this process occurs through plant tissues it is called transpiration. At the landscape-scale the term evapotranspiration is used to characterize the overall flux of water vapor into the atmosphere from vegetated areas, lakes and rivers and other moist non-vegetated surfaces (e.g., bare soil). The simple water balance equation for a forested landscape is:

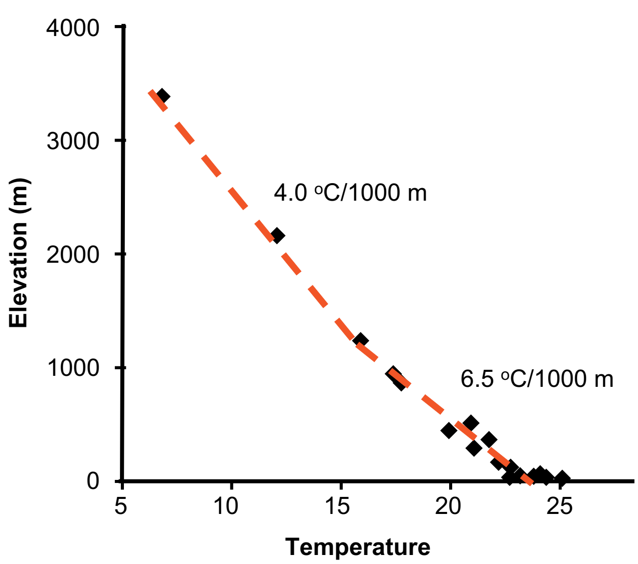

Figure 5.1 Average temperature change with elevation (lapse rates) for 16 stations in the Hawaiian islands (after Giambelluca and Schroeder, 1998).

P (± **CI**) = **E** + **R** + **Q** + **S**

where:

- **P** = measured precipitation (open site rainfall)
- **CI** = Forest canopy interception gain or loss (includes throughfall and stemflow; for lowland tropical forests this factor is a negative 20-30% of rainfall, representing water stored in the forest canopy and later directly evaporated back into the atmosphere without reaching the ground; a positive value for **CI** infers canopy interception of additional water (cloud water) not recorded in the standard rain gauge, and typically is only a significant contribution to the water balance in upland cloud shrouded areas
- **E** = evapotranspiration
- **R** = runoff
- **Q** = groundwater recharge
- **S** = change in soil moisture storage (this averages out to zero on an annual basis and can generally be ignored).

Precipitation (rainfall only) and runoff (streamflow discharge) are the two variables most commonly measured in Pacific island watersheds. However, the volcanic geology and young, porous soils of most Pacific high islands yield very high water infiltration rates and ground water recharge (Q sub-surface flow to the basal aquifer) that frequently exceeds surface water runoff. For many tropical islands, the small aerial extent of watersheds results in highly variable (flashy) stream discharge, with a consequent increased dependence on groundwater (pumping) for domestic and agricultural water supply. Because Q is difficult to measure directly (yet very important to know, as it determines the sustainable rate of ground water extraction), it is usually calculated as a residual term from the above equation assuming P, E and R values for the forest watershed are known.

The energy needed for evapotranspiration derives from both the vertical components of short wave (solar) and long wave (heat) energy fluxes at a site (net radiation) plus any advected energy. In addition, wind speed (and turbulence) and dryness (vapor pressure deficit) of the air also influence the rate of vapor transfer to the atmosphere. The term potential evapotranspiration is a useful concept to describe the maximum rate of evaporative demand from the atmosphere acting on a surface where water is readily available (open water, or plant leaves with no water stress). Estimates of potential evapotranspiration are usually based on actual measurements of evaporation from a large, water filled pan (U.S. standard is a Class A pan, 120.6 cm diameter, 25.4 cm height) with a correction (calibration) factor applied to account for differences in vegetation structure and physiology and general climate conditions (humid or dry areas). Pan data are not often collected in high rainfall areas, due to problems of pan overflow. In such areas, small, rain shielded, porous surface (water wicked upward from a reservoir) atmometers have been successfully deployed to monitor evaporation rates along altitudinal transects on tropical mountains (Bean, et. al, 1994). Nullet and Juvik (1995) reviewed the general relationship between measured evaporation rates and elevation on tropical mountains and found a wide array of vertical profiles (Figure 5.2). Island size, and latitudinal position relative to the inter-tropical convergence or trade wind inversion were found to significantly influence the nature of this relationship.

Where actual historical pan evaporation data is available for PABITRA sites (or nearby areas) such data should be used to calibrate other physical or empirical models that can be applied in generating evapotranspiration estimates for the study area. In a first approximation of seasonal water balance calculation, Walter (1955, 1957, Walter and Lieth, 1967) developed climate diagrams that attempt to integrate monthly rainfall and temperature data, based on the assumption that monthly moisture stress was roughly equivalent to twice the mean monthly temperature (°C), and the diagrams two ordinates were scaled accordingly (2:1). Figure 5.3 illustrates a Walter climate diagram for a montane site (Halema`uma`u) on the Island of Hawai`i, and implies general water deficiency during the four months May through August. The diagram implies comparatively low moisture stress (i.e., twice temperature read on the precipitation scale is equivalent to about 30-35 mm/month of potential evapotranspiration or about 400 mm/year). Although true water balance diagrams must also include a consideration of soil moisture storage, even without this component the Walter diagrams substantially underestimate potential evapotranspiration for tropical island stations. However, the intent of the Walter diagram is to simply illustrate the "relative drought resistance" of natural plant communities that are adapted to local climate conditions.

The term "relative drought resistance" implies that naturally assembled plants in the vegetation of a sea-

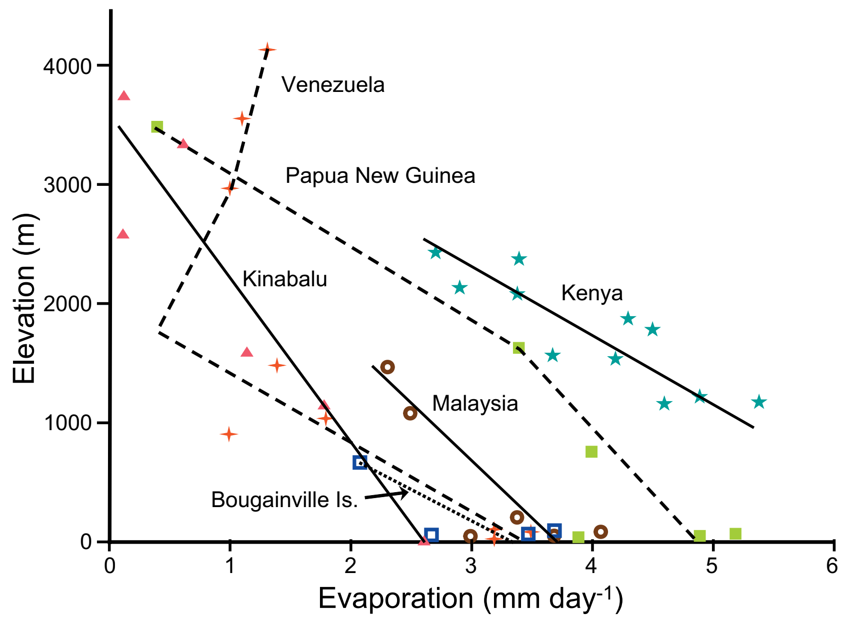

Figure 5.2. Elevation - Evaporation relationships for a range of tropical mountains (after Nullet and Juvik, 1995)

sonal-tropical climate are adapted to survive drought seasons, while plants naturally assembled in humid-tropical climates suffer greatly if a similar drought occurs in their normally year-round moist climate. Thus, the 1:2 relationship of the mean monthly temperature and precipitation curves indicates how locally adapted plants perceive moisture stress in different climate types. Of course, the substrate type requires additional evaluation.

In the summer-dry climate at Halema`uma`u, Hawai`i (Fig. 5.3), where the mean annual rainfall is unequally distributed, the plants experience a drought season from May through August. This is indicated by the dotted field on Figure 5.3, where the rainfall curve undercuts the temperature curve.

Potential evapotranspiration values are more relevant to agricultural water use. Use of Walter diagrams for seasonal water relations of the climate at PABITRA sites in the Pacific represent a first approximation of native ecosystem moisture stress relationships and can usually be constructed from existing data. However, where potential evapo-transpiration data is available, it may be plotted as a third curve in the diagram. See Appendix 1 for the method of constructing these climate diagrams.

The most widely used method for estimating potential evaporation involves a combination model (Penman, 1948) considering both the factors of energy supply (net radiation which can be derived from comparatively low cost incident solar radiation solar measurements) and the turbulent transport of water vapor away from the evaporating surface (requiring only measurement of atmospheric humidity and wind speed at a single height). Various modifications of this equation involve the inclusion of aerodynamic resistance presented by vegetation canopies. If historical data exists for these variables at or near PABITRA transect sites, realistic Penman estimates of potential evapotranspiration are possible. If such data is not available, low cost, automated meteorological stations are available for use in remote areas that can measure the requisite parameters (solar radiation, temperature, humidity and wind speed). Web-based calculators are available for the determination of Penman evaporation estimates from basic meterological inputs (see Appendix 2).

Existing runoff and streamflow records

To the extent that PABITRA sites are designed to focus on lowland-upland physical/biological linkages at the watershed (bounded river basin) scale, selection of sites will be at least partially dictated by the availability of existing stream discharge data, a key compo-

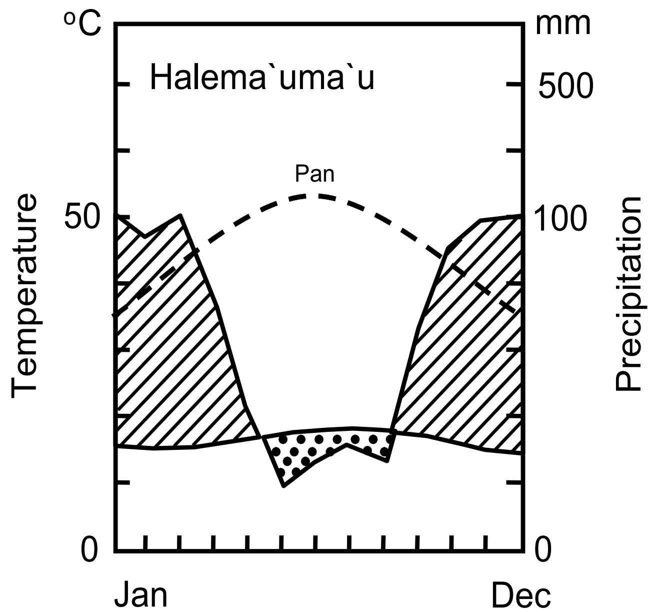

Figure 5.3. Climate diagram for a montane station (Halema`uma`u) in Hawai`i. The diagram illustrates seasonal comparison of Walter's implied moisture stress rates and measured pan evaporation (from Mueller-Dombois, 1966; Juvik, et. al, 1979).

nent of the hydrologic cycle. Determining streamflow or discharge involves measuring water level (stage above a datum) and relating this water level to discharge through the development of rating-curves for a channel cross-section. For small volcanic island watersheds, stream discharge typically includes not only surface runoff but also a significant baseflow component (groundwater returned to the channel). A range of methodologies are available to link rainfall and stream runoff relationships and flood hydrograph models (see Pilgrim and Cordery, 1992).

Monitoring climate/ hydrologic variables

Precipitation inputs

In the tropical Pacific high islands, precipitation may consist of both rainfall and, on mountain slopes above the lifting condensation level (i.e., 500-1000 m), direct forest canopy interception of horizontally moving cloud water (fog). Tropical montane cloud forests typically comprise a distinctive upland ecological zone with a unique atmosphere-vegetation linkage (Hamilton, et. al., 1995). In lowland tropical forests a significant proportion of rainfall is intercepted and stored by the forest canopy, to be later evaporated without reaching the ground. Thus, net precipitation reaching the forest floor (by either canopy throughfall or stemflow) is typically in the range of 75-85% of open site rainfall (Bruijnzeel and Proctor, 1995), with stemflow typically an order of magnitude less than throughfall (Smith, 1992). In cloud shrouded montane forests there is frequently a net interception gain in water (compared to open site rainfall) through canopy interception of horizontally moving cloud droplets (sometimes called fog-drip).

Rainfall measurement Both recording and non-recording rain gauges are available for remote field use. Non-recording rain gauges are simple cylindrical containers that must be read and recorded manually with a calibrated measuring stick. One can also measure the amount of water in a graduated cylinder as volume of water (in cc) and divide this by the area of the funnel to get the amount of water in height of rainfall. The measured values represent total rainfall since the last reading. Recording rain gauges are primarily of "tipping-bucket" design. They work on the principle of electrical switch closure activation with each tip of a small water storage bucket draining a collection funnel (orifice diameter typically 15 or 20 cm). Rainfall events (individual bucket tips) along with a time stamp are recorded on an accompanying data logger for later retrieval and analysis. Figure 5.4 illustrates an exam-

Figure 5.4. The Onset data logging rain gauge (orifice diameter 15.2 cm; rainfall resolution 0.254 mm) is a robust, low cost instrument ideal for field use in remote areas. The gauge includes a battery operated event logger (at right above) with a storage capacity of 2000mm. Event logger data can be downloaded in the field on to a small data transfer storage module (HOBO Shuttle at far right). Attachment of the rain gauge to a heavy (10 kg) concrete base is recommended for field installation to insure leveling of the tipping bucket assembly.

ple of a reasonably priced recording rain gauge (Onset Computer Corporation, www.onsetcomp.com), with a resolution of 0.254 mm. The accompanying, battery operated HOBO event logger can store up to 8,000 events (2,000 mm of rainfall) and operate un-attended for months at remote field locations. This system has the added advantage that field data can be downloaded either onto an inexpensive dedicated data transfer devise (HOBO Shuttle) or other small handheld (Palm) computers. This obviates the need to take larger, laptop computers into the field for data retrieval. This system also comes with easy-to-use computer software for data analysis and graphing. Because recording rain gauges also include a time stamp with their minute by minute monitoring of precipitation events, it is possible to calculate short term, instantaneous rainfall intensities as well as the total rainfall at the time scale of hours, days and months. Rainfall intensity data is particularly important in evaluating the impact of extreme precipitation events on soil erosion, stream flooding, and downstream (and offshore) sedimentation. Where downstream flood concerns are a significant issue, the use of rain gauges linked to more expensive radio (or cell phone) telemetry, may be justified by providing real-time precipitation data for flood prediction and warning.

Rain gauge installation and maintenance Exposure and siting: Rain gauges should be sited at locations likely to provide representative reading that can be reasonably extrapolated to surrounding areas. This becomes difficult in complex mountain terrain where rainfall may vary dramatically as a function of altitude, slope aspect and comparative exposure to strong winds. Although geographically appealing, mountain summits, exposed ridges or narrow mountain passes should generally be avoided, unless there are specific research questions dealing with these topographically unique sites. Such sites are not generally representative of "average" watershed topography, and the associated higher wind speeds may lead to potentially significant rain measurement errors. Under strong winds, unshielded rain gauges may underestimate actual rainfall by up to 20%. Rain gauges should be sited to provide a clear view of the sky, unencumbered by overhanging vegetation or tall, nearby trees or struc-

tures. These requirements may be difficult to meet in mountainous, heavily forested terrain. Therefore, if necessary rain collectors can be mounted above the forest canopy, either attached to a mast or emergent tree. Under this mounting configuration the actual tipping-bucked gauge remains at ground level (with a lid) and is connected, via a plastic or rubber drainage hose to the rain collecting funnel affixed at the top of the canopy. If the hose connection extends to more than 4-5 meters, it may be necessary to calibrate a water storage (wetting) factor for the hose itself, which may otherwise underestimate rainfall during light precipitation events.

After rain gauge installation a hand-held GPS unit should be used to determine the exact latitude and longitude coordinates, for incorporation into a project area.

Protection—To avoid instrument tampering by the merely curious, or outright vandalism or theft, gauges should generally be sited out-of-view from nearby trails, roadways or other areas where people commonly congregate or transit. Typically white rain gauges can also be painted in camouflage brown/green tones to further limit accidental detection. Informational signs attached to remote area rain gauges (or other field instruments) can also serve as a deterrent to tampering or theft, and should include: government agency or community ownership, project purpose and a local contact for those seeking more information. In areas where large domestic, wild or feral animals occur (e.g., pigs, cattle, goats, etc.) gauges should be fenced or otherwise blockaded, since the gauge's hard metal and plastic edges may present themselves as attractive scratching posts. Rain gauges sited in villages, or heavily settled agricultural areas should also, if at all possible, be placed in restricted spaces (such as a fenced yard or official village compound) rather than in common areas.

Maintenance—Recording tipping-bucket rain gauges require relatively low maintenance. Most importantly, on periodic visits to download rain gauge data, a carpenter's level should be used to re-level the tipping bucket assembly. In addition to removing wind blown litter collecting on the screen debris trap within the rain collection funnel, the tipping buckets themselves should be gently cleaned of sediment (with a mild solvent such as alcohol), and a small amount of car or floor wax applied to ensure rapid and complete tipping bucket water drainage.

Cloud-water measurement The flux of cloud-water is not a variable widely measured in forest climate/hydrological monitoring, and as such, standardized, commercially available instrumentation is not available. As discussed above, tropical montane cloud forests form a distinctive upland ecological zone on most Pacific high islands, and by virtues of extensive lowland forest clearing these remaining montane forests now harbor a disproportionate fraction of insular biodiversity, as well as providing critical ecosystems services in the form of water supply and erosion control. These forests may actually experience precipitation throughfall rates that exceed open site rainfall (i.e., canopy interception gain) due to direct water interception (and drip) by the forest canopy from fast moving orographic clouds. A variety of mesh screen, and vertically arrayed filament-harp collection devices have been employed for open site passive mechanical measurement (by inertial impaction) of cloud water interception and to provide an analog for estimating forest canopy cloud water catch. Although no standardized instruments are available, Ekern (1964) found that a louvered aluminum screen material (Kaiser Shade screen) combined the properties of high interception efficiency and good water drainage off the collector. Juvik and Ekern (1978), Juvik and Nullet (1995) and Juvik et al. (2002) further refined this instrument, which is now widely employed in tropical cloud forest studies.

The cloud-water collector is drained via a plastic hose into a covered recording rain gauge at ground level. This cloud-water collector is illustrated in Figure 5.5. The instrument consists of a cylindrical, louvered screen collector (12.7 cm in diameter and 40.6 cm in height), which presents a vertical silhouette interception area of 515.6 cm^2. The accompanying rain-shield hat (diameter 57 cm) excludes both vertical and non-vertical rainfall (i.e., all raindrops >1 mm diameter at wind speed < 4.0 m/sec). In order to convert the cloud-water collector output to the "unit area vertical catch equivalent" of the rain gauge a scalar must be applied. In this case the silhouette area of the cloud water collector is 2.83 times larger than the cross-sectional area of the 15.2 diameter rain gauge into which it drains. Dividing the rain gauge output by 2.83 yields a unit area measurement of cloud-water catch. It should be noted that if either a different size cloud-water collector or different diameter rain gauge is employed, then a new scalar must be computed based on the respective catchment areas. It should also be noted that

Figure 5.5. The louvered-screen cloud-water gauge should be mounted on a mast (guyed) or tripod, in an open, exposed site at a height comparable to the upper level of the nearby forest canopy. If wind speeds are also to be recorded, the anemometer should also be mounted at the same height as the fog collector (field meteorological station in background).

during precipitation events with associated high wind speeds (particularly > 10 m/sec) substantial amounts of driving rain, in addition to cloud water may impact on the louvered screen collector (in spite of the protective "hat"). During such events the ability of the cloud-water collector and companion standard rain gauge to accurately partition the actual rain and cloud-water components is greatly diminished.

The open site cloud-water collector will provide a highly sensitive, direct measurement of cloud-water flux. However, these quantitative interception values can not be inferred to represent the actual interception for the nearby cloud forest canopy, where forest stand architecture, leaf size, orientation, water storage, and other complex boundary layer meteorology (e.g., within canopy wind speed variation and turbulence) may result in very different cloud-water drop behaviors and interception rates. A cloud water collector deployed within a continuous forest canopy can provide a more accurate assessment of local forest conditions. The associated lower wind speeds result in increased effectiveness of the collector's protective "hat" by excluding windblown rain. Such deployment however is subject to the high local variability of canopy conditions. Deployment of both open site and within canopy collectors may increase their measurement accuracy through comparison.

In order to usefully employ the mechanical cloud-water collector as a surrogate for forest canopy interception, the instrument must be calibrated against actual forest throughfall and stemflow measurements for each distinctive forest type found within the cloud zone. As an example of the power of the cloud-water collector (compared to the standard open site rain gauge) to predict forest throughfall in cloud shrouded areas, Figure 5.6 illustrates the empirical relationships between rainfall, cloud water collection, and measured forest canopy interception at the Alakahi cloud forest (elev. 1160 m) on the windward slopes of the Kohala Mountains in Hawai`i. The sampling period (145 days during 2000-2001) excluded days with strong winds

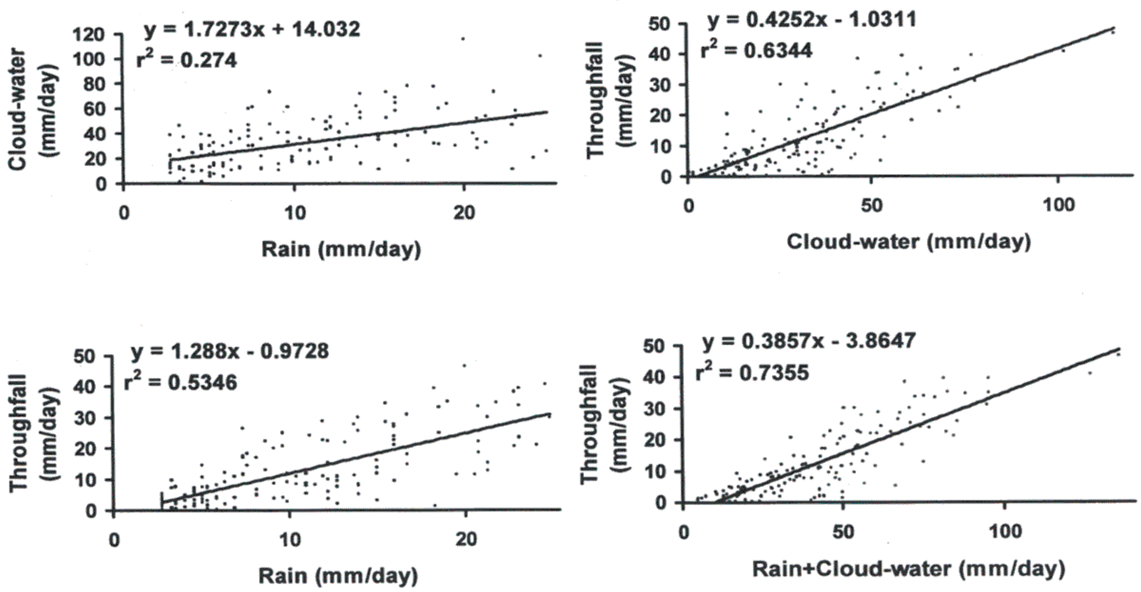

Figure 5.6. Relationships between daily rainfall, cloud-water interception and actual forest canopy throughfall at the Alakahi cloud forest, Hawai`i. It will be noted that the cloud-water interception is a significantly better predictor ($r^2 = 0.63$) of canopy throughfall than rainfall alone ($r^2 = 0.53$), and that rain + fog is even better ($r^2 = 0.73$). The sample included 145 days when rainfall was > 2.54 mm and < 25.4 mm.

where driving rain could potentially confound the partitioning of rain and cloud-water components.

It will be noted from Figure 5.6 that rainfall alone was a poor predictor ($r^2 = 0.53$) of canopy throughfall, while open site cloud-water collection was much better ($r^2 = 0.63$). Over the one year monitoring at Alakahi, total canopy throughfall (4,176 mm) exceeded rainfall (3,503 mm) by almost 20%, further reinforcing the importance of cloud forest protection for stream basin water yield. Although for many Pacific islands, there is general, anecdotal knowledge relating to assumed high rainfall in the mountainous interior, the lack of quantitative water input data needs to be overcome in order to strengthen the resolve of government officials and land managers to affect meaningful upland forest protection. With hard data, the easily quantified economic value of water can be used to make a much stronger and immediate political case for forest conservation than is likely to be achieved by advancing the equally important but more abstract values associated with "biodiversity" or endangered species conservation.

Cloud-water collector installation and maintenance Installation and maintenance procedures for the cloud-water collector and its linked tipping-bucked recording rain gauge are essentially the same as discussed above for the standard rain gauge. Additional concerns include the necessity for properly guying both the cloud water collector mast (including separate guying of the rain-shield hat) to provide gauge stability under high wind conditions. Also, a ladder (or mast-climbing foot/hand-holds) will be required to periodically allow visual inspection (for possible debris clogging) of the water collection funnel attached to the louvered screen collector (see Figure 5.5).

Canopy throughfall and stemflow measurements Canopy throughfall and stemflow measurements are comparatively difficult and expensive to undertake. Measurements cannot often be easily extrapolated from one forest type or topographic situation to another due to the inherently high spatial heterogeneity in canopy throughfall (requiring an extensive sampling network to accurately characterize "average" site conditions). However, long term monitoring may not be required, as only a few weeks or months of throughfall data may be adequate to derive robust relationships

Figure 5.7. Throughfall sampling troughs in the Alakahi cloud forest, Hawai`i (elevation 1,160 m). Over a one year sampling period these troughs captured 120% of the water (per unit area) measured in a nearby clearing by a standard rain gauge, confirming a net cloud-water interception gain for the forest canopy.

between throughfall and more easily measured open site rainfall and cloud-water interception (see Figure 5.6). In a review of 22 throughfall studies undertaken in lower and upper montane tropical forest, Bruijnzeel and Procter (1995) found average throughfall (as a percentage of rainfall) to range from 67-179% (mean of all studies 93%; as noted above the Alakahi study yielded an annual throughfall value of 120%). By contrast, for nine of these studies for which stemflow measurement were also available, values ranged from 0.l-10% (mean of all studies 3.3%). This implies that stemflow generally need not be measured, except in the most exacting forest water balance studies.

The measurement of canopy throughfall typically involves deploying an array of rain gauges beneath the canopy, either at fixed or roving locations (i.e., moved periodically to new random locations). Alternatively, capturing the spatial heterogeneity of throughfall may be accomplished with a series of water collection troughs that act as water sampling transects beneath the canopy (draining into manual storage or recording rain gauges). Figure 5.7 illustrates the trough setup used for throughfall sampling in the Alakahi cloud forest study. Three troughs (feeding into a large-volume, covered, tipping-bucket recording rain gauge) were mounted 1-2 m above the forest floor, with the tipping-bucket calibrated to the catchment area of the troughs.

Generally, throughfall sampling gauges (or troughs) need to be cleaned more frequently than open site rain gauges, as litter-fall is significant beneath the forest canopy.

At a minimum, some short term forest throughfall measurements should be undertaken at selected points along all PABITRA transects where montane cloud forests occur. As discussed above, hard quantitative data on the cloud enhanced water yield from such upland forests can provide a compelling and easily understood economic argument for their conservation.

Solar energy, temperature and related meteorological measurements required for the calculation of potential evapotranspiration

In the past few years a new generation of economical, automated, data-logging meteorological stations have come on the commercial market which are ideal for use at remote, off-power, PABITRA sites (e.g. Davis GroWeather Station, Onset-HOBO weather station; see equipment web site references). Many of these new field meteorological stations include user-friendly software with built-in graphing and data summary/analysis capabilities (including automatic calculation of Penman evapotranspiration estimates). In addition, new field data downloading options include inexpensive data transfer shuttles (see Figure 5.4) or compatibility with handheld computers (Palm type), thus removing the need to transport fragile laptop computers to remote field sites. The advantage of these new, economical meteorological stations (compared with more expensive and sophisticated stations) is that, although there may be some sacrifice in data quality, more stations (sampling density) can be deployed, providing better spatial coverage in topo-climatically complex mountain terrain. Beyond the various precipitation variables discussed above, automated PABITRA weather stations should normally include measurement of:

- Radiation (incident solar shortwave, net all wave, or photosynthetically active quantum radiation)
- Temperature (shaded air temperature at one or more heights, and soil temperature at one or more depths)
- Relative humidity (at one or more heights)
- Wind speed and direction (at 3-5m height in the open or above the forest canopy)

Other variables may also be measured (and recorded on optional, open data logger channels) as required to meet site specific research requirements (e.g., soil moisture, leaf wetness, or the same variable at different heights in/outside the forest canopy).

Remote weather stations: installation and maintenance

Remote field monitoring meteorological stations should generally be positioned at open sites with topographic and exposure (e.g., wind) conditions representative of the surrounding research area. In some cases the data logging capabilities of this meteorological station may also be used to simultaneously record companion variables from within the nearby forest (e.g., rainfall and cloud-water in the open and throughfall under the forest). In such a research design it is essential that interior forest measurements be deep enough into the forest to remove “edge effects” (e.g., down-wind fetch on the leading edge of a forest patch) that could compromise the representativeness of under-canopy measurements. Depending on forest stature, tree density and canopy architecture, edge-distance to interior forest measurement sites should be at least 10 times average canopy height. The length of interior forest sensor connecting cables (to the open site data logger) will necessarily have to be sized accordingly, or alternatively connected to separate under-forest data loggers.

If the field research design requires vertical profile meteorological measurements (sensors at different heights within the canopy), or the recording of weather data above the canopy, then masts or towers will be required (sized to the canopy) rather than the simple tripod mounting of instruments (at 2-3 m) used for typical open site installation (see Figure 5.5). From a maintenance perspective, for remote site meteorological station, appropriately sized step-ladders can be left permanently at the field site, to be used for instrument inspection, repair or cleaning during periodic site visits for data retrieval.

Most remote recording meteorological stations typically run on solar power. The number and directional orientation (typically oriented to maximize capture of morning sunshine, since orographic and convectional cloud development is more common during afternoon hours for most Pacific island locations) of solar panels will depend on sensor power requirements and available sunshine. In cloud shrouded tropical mountains additional solar panel arrays may be required to insure a continuous power supply. Some data loggers such as those provided with Onset Corporation Hobo weather stations run for many months on alkaline or lithium batteries, eliminating the need for solar panels.

One of the most important considerations in monitoring meteorological variables at remote stations is selection of the time interval for field data recording (logging). The range of sampling intervals possible for the site (minutes to hours) will be controlled by:

- the overall data storage capacity of the weather station's built in computer
- the number of sensors involved and their individual record storage requirements
- the ideal sampling interval desired, relative to the scientific requirements of the project
- the frequency (daily, weekly, monthly?) which the remote station can be realistically visited by project personnel to download stored data and provide routine maintenance.

For general meteorological data logging, an hourly sampling interval or those of 15, 30, or 60 minutes are adequate. If intensive, short term, weather related scientific research (e.g. plant photosynthesis or water use studies) is to be undertaken at the site, the meteorological stations sampling interval can be reduced to seconds or minutes to meet these short-term research needs.

Streamflow measurements

To the extent that PABITRA gateway transects will, by definition, focus on drainage basin scale geographic units, they incorporate a mix of linked, natural and anthropogenic landscape elements. Because of the critical economic importance of freshwater streams in the Pacific river basins, this exiting data will form an important component in the water balance analysis for PABITRA transects. Within the larger river basin, however, the collection of streamflow data for smaller sub-catchment areas may be required to answer specific environmental questions relating, for example, to the influence of different forest and soil types, or changing human land use activities on intra-basin hydrologic processes (e.g., infiltration, runoff, and water quality). Paired catchment studies are a standard approach for assessing such questions. In this research design two or more small, nearby stream tributaries are monitored with one usually chosen to serve as a control (in the sense that it is assumed to be operating under "natural conditions") and the other(s) characterized by a different land use practices, or vegetation cover. Comparison streamflow measurements are one approach for quantifying differential land use impact on hydrological processes.

Instantaneous stream velocity can be measured with a current meter (mean velocity is typically estimated by measuring current speed at 60% of total water depth in the middle of the channel) and converted to discharge (m3/sec) by integrating velocity over the cross-sectional area of the channel below the water surface. New, low cost instruments (see under selected instrumentation below: Measuring & Control Equipment Co. website), combining both velocity (using a submerged ultrasonic doppler) and depth measurement (sensitive ceramic pressure transducer) have greatly simplified and economized the collection of stream discharge data, and may be compatible for direct recording onto field meteorological station data loggers, or separate dedicated loggers.

Anthropogenic land use change in small tropical island watersheds may influence water quality as well as modifying surface runoff and stream discharge (quantity). Changes in stream sediment load and dissolved nutrient load may affect in-stream aquatic life, near-shore marine communities (coral reefs) and human water supply for domestic or agricultural use. One key PABITRA research objective is to fully document the economic value of ecosystem services (natural capital) provided by effective watershed protection, and the environmental costs consequent upon poor and unsustainable land use practices. New, automated field instrumentation (such as the Greenspan MiniAnalyser, see below for website) is now available for continuous, remote site monitoring of water quality parameters (i.e., pH, electrical conductivity, turbidity, dissolved oxygen, NO_3, NH_3, NH_4, PO_4), and where feasible, such instrumentation should be integrated into the overall research design for PABITRA sites.

Designing the field sampling network for PABITRA transects

To the extent that research at PABITRA sites is conceived as multi-disciplinary and broadly integrative with respect to linked physical, biological and human systems, the selection of specific research and environmental monitoring sites along the upland-lowland transect represents an optimizing process designed to best serve a wide range of research objectives and also function within project budgetary constraints. Prior to launching fieldwork and establishing an environmen-

tal monitoring network, existing spatial data sets, remote sensing imagery and maps, (i.e. topography, geology, soils, climate & hydrology, vegetation types, endangered species distributions, land use maps) and local informant knowledge should be assembled and incorporated into preliminary GIS layers (see Chapter 11). Project scientists should then collaborate in the environmental monitoring site selection process, and incorporate other more practical consideration (e.g., site security, accessibility, land owner permission and cooperation, etc.). The siting of field meteorological stations, for example, will require comparatively more stations per unit area in topographically complex mountain regions than in the lowlands. This, because there is usually better existing data for lowland areas, and because, in mountain areas, elevation, aspect, and associated ecosystem units are spatially compressed and characterized by steep gradients of change over short distances. This necessarily increases the uncertainty of extrapolating environmental data into adjacent areas.

Data management, analysis and dissemination

Continuous monitoring of meteorological/hydrological parameters at multiple stations quickly generates large raw data sets that must be archived and statistically compressed and summarized for general use by project scientists. Today, most instrumentation is accompanied by powerful, user-friendly software, easily facilitating the generation (and graphing) of summary statistics and their automatic incorporation in empirical or physical models (e.g., Penman potential evapotranspiration equation). This software allows for immediate, post-download, field assessment of climate conditions, but raw or summary data may be moved into more familiar spread-sheet software formats such as Excel for intensive analysis, and easily made available (with frequent updating) at the project website. Even the large amounts of data generated during climatological monitoring can be stored, displayed, and analyzed in spreadsheet format and demands relatively small amounts of disk or server memory. They are also readily transferred via e-mail. The spatial data sets generated from the sampling network will ultimately form the basis for specific climate/hydrological layers in the evolving PABITRA project GIS.

Selected instrumentation suppliers and manufacturer

Campbell Scientific
815 West 1800 North
Logan, Utah 84321-1784 USA
Phone: 1(435)753-1784, Fax 1(435)750-9540
www.campbellsci.com
Email: info@campbellsci.com

Manufacturer and distributor of research grade field data loggers, comprehensive meteorological stations and sensors, software and technical support.

ESI Environmental sensors
100-4243 Glandford Ave.
Victoria, BC V8Z4B9, Canada
Phone: 1(250)479-6588; Fax 1(250)479-1412
www.esica.com
Email: sales@esica.com

Manufacturers and distributors of soil moisture sensors and data loggers.

Forestry Suppliers Inc.
P.O. Box 8397
Jackson, Mississippi 39284-8397 USA
Phone: 1(601)354-3565; Fax: 1(601)355-5126
www.forestry-suppliers.com
Email: cs@forestry-suppliers.com

Distributors for a wide range of equipment and supplies for the environmental sciences including meteorological and hydrological monitoring instruments.

Greenspan Technologies
P.O. Box 401, Warwick
QLD 4370, Australia
Phone: 61-7-4660-1888; Fax 61-7-4660-1800
www.greenspan.com.au
Email: admin@geenspan.com.au

Manufacturers and distributors of a wide range of environmental monitoring equipment including sap-flow measurement, field water quality analyzers, and entire field climatological/hydrological monitoring systems individually designed and built to customer specifications.

Measuring and Control Equipment Company
P.O. Box 911, Pennant Hills
NSW 1715 Australia.
Phone: 61-2-9980-2692; Fax 61-2-9980-2651
www.macequip.com.au

Manufacturer of integrated open channel water flow/depth meters and data loggers.

Onset Computer Corporation
P.O. Box 3450
Pocasset, MA 02559-3450 USA
Phone: 1(800)564-4377; Fax: 1(508)759-9100
www.onsetcomp.com
Email: sales@onsetcomp.com

Manufacturers and distributors of low-cost field data loggers, sensors (event, temperature, humidity, light, wind speed, etc.) and software, ideal for application at remote PABITRA monitoring sites.

Rickly Hydrological Company
1700 Joyce Ave.
Columbus, Ohio 43219 USA
Phone: 1(614)297-9877; Fax:297-9878
www.rickly.com
Email: sales@rickly.com

Pacific Environmental Planning
223 Makani Circle
Hilo HI 96720 USA
Phone: 1(808)959-5744.
Email: jjuvik@hawaii.edu

Can provide either specifications or fabricated louvered-screen cloud-water collectors.

Appendix 1 : How to Construct Walter-type Climate Diagrams

Dieter Mueller-Dombois

The essential feature of these diagrams is that they show the mean monthly temperature and rainfall (or precipitation) curves on a single diagram that is meaningful and easy to interpret for ecological purposes. The method has gained wide acceptance in the ecological literature, because the climate type of any climatic station can be portrayed in a standard format that works for local, regional, and global comparisons of climate. This means that the information is independent of geographic scale and portrays true data that is difficult to comprehend in tables but easily visualized in the diagrams. One can also easily delineate climatic zones based on the visual similarities and differences of such climate diagrams (Walter et al. 1975). All one autually needs is rainfall data reduced to monthly means for a number of consecutive years. Such data are widely available. Temperature data is less widely available, but most airports have air temperature records. For rainfall stations without temperature data one can usually safely derive temperature values from nearby stations. Leeward areas on islands are usually a little warmer than windward areas at sea level. For inland stations, temperature is primarily influenced by elevation.

One can use the lapse rate as given on Figure 5.1, which shows a cooling of 0.65 °C per 100 m increase in elevation up to the prevailing cloud zone. Few island mountains extend above the prevailing cloud zone from where the cooling is less, only about 0.4 °C per 100 m increase in altitude (see Figure 5.1).

A practical way of making these climate diagrams is by drafting them on paper with grids in centimeters and millimeters. The x-axis is conveniently drawn out as a 6 cm long line. Here, the calendar months are recorded by letters using a half centimeter space for each. For climate stations in the southern hemisphere one begins on the left side with July. Thereby the warmer season with December and January appears in the center, and one ends with June at the right end on the x-axis. In the northern hemisphere one begins with January and ends with December. In this way north and south hemisphere climates are directly comparable. The left side ordinate is for temperature in degrees centigrade. A centimeter up from the x-axis is 10 °C; the next centimeter becomes 20 °C and the third centimeter 30 °C. It is a good practice to draw this ordinate up to 6 cm, even though no place will have temperatures that high. Mark that temperature ordinate with the symbol °C. Then draw the right side ordinate starting form the x-axis and mark the first centimeter up as 20 mm. Continue with 20 mm interval marking up to 100 mm. From here upwards, the next cm interval becomes 200 mm, so that the next cm mark represents 300 mm and the following mark 500 mm. The practical reason for this scale reduction (by a factor of 10) is that the diagram for rain forest environments would easily become very tall and cumbersome. Another, more important reason, is that monthly rainfall in excess of 100 mm (or 4 inches) has in many cases filled the soil pores so that water in excess of 100 mm

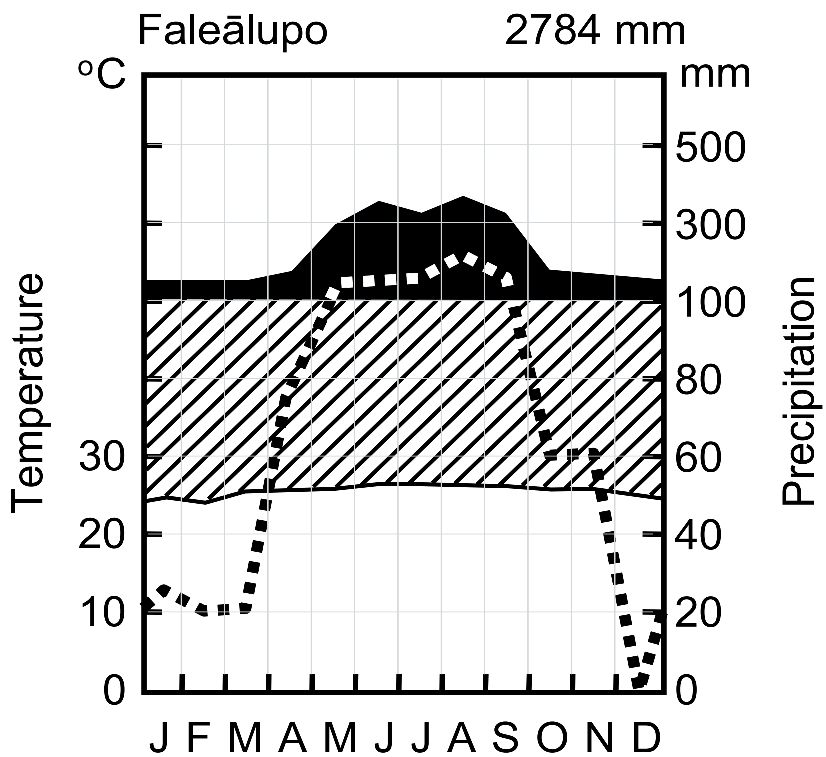

Figure 5.8. Walter-type climate diagram drawn from existing data. The dotted line is the lower interquartile range based on mean monthly rainfall variation. It indicates occasional dry seasons from May to September in this rain forest environment. Data from Kear and Wood (1959).

appears as surface runoff. Such water can be roughly considered as being added to stream flow.

On the diagrams such rain water in excess of 100 mm per month is shaded black. Diagrams showing black fields across the entire 12 months of the year typically denote rain forest environments.

The field above the temperature curve is hatched vertically up to the 100 mm precipitation line. It has been found that a dry period occurs whenever the rainfall curve goes below the 100 mm line. Moreover, whenever the rainfall curve undercuts the temperature curve, a more severe dry period, called a drought, is indicated. This area on the diagram is marked by dots.

An example from Falealupo, a rainfall station in a lowland rain forest area at the western tip of Savai`i Island (Samoa), will bring out these points (Figure 5.8). Originally, the rainfall data were given in inches, and first had to be converted into millimeters by multiplying each value by 25.4 (since 1 inch = 25.4 mm). The temperature values were given in Fahrenheit and thus also had to be first converted into Centigrade by using the formula Fahrenheit minus 32 times 5/9 = Centigrade (e.g., 80 °F – 32 x 5/9 = 26.7 °C).

After converting the rainfall and temperature values for all 12 calendar months, they were then plotted into the coordinate system of the diagram. Mean monthly temperatures were plotted with reference to the left-hand ordinate, and mean monthly rainfall values were plotted with reference to the right-hand ordinate.

As shown on the climate diagram (Figure 5.8), the temperature values resulted in a near-horizontal line, starting at 25 °C in July and reaching 26.5 °C as the warmest mean monthly temperature in January. The reason for this small 1.5 °C variation between the cooler and warmer period of the year is Samoa's close proximity to the equator, near 14° south latitude.

In contrast, the mean monthly rainfall shows much greater variation. There is obviously much more rainfall during the slightly warmer season from November through March when the mean monthly values can be as high as 360 mm, while rainfall during the cooler season, from May through September, amounts to only about 150 mm per month.

Since inter-quartile ranges of mean monthly rainfall were calculated from year-to-year rainfall variation, it seemed useful to also plot the low inter-quartile values of monthly rainfall into this diagram. This reveals that the rain forest at Falealupo may be exposed to dry periods for the slightly cooler half of the year at repeated times during a decade. Moreover, real drought can be expected at times when the rainfall curve undercuts the temperature curve. Thus, there is even a fire danger to be expected in this rain forest environment at certain years. It would thus be of value here to establish what is known as a "climatogram." This involves making climate diagrams on a year-to-year basis and to put these next to each other in a row, say for a decade or two. This then would clearly show how often and how severe such dry spells have appeared during the recent past and what this may reveal for the near future.

As added items of information, the name of the climatic station must be shown on the diagram, also the mean annual rainfall should be stated, and the data source must be given. There are a number of other climatic parameters that can be added to the climate diagram, where these are of ecological significance. A case in point is the potential evapo-transpiration curve, if available, as shown in Figure 5.3. More details are given by Walter et al. (1975). This book portrays the world's climate on ten fold-out maps with numerous climate diagrams.

Appendix 2: How to Calculate Penman Evapotranspiration

Estimating evapotranspiration (ET) using the Penman-Monteith equation involves the measurement or calculation of net radiation and soil heat flux. Net radiation in the tropical Pacific is typically a fairly uniform fraction of incoming solar radiation (60-70%). Soil heat flux represents a small fraction of energy transfer and over daily periods or longer, soil heat flux can be considered zero. Field measurement of these variables is expensive but can be estimated from data obtained by more affordable means. There are a number of web-based calculators for estimating ET. The spreadsheet (Excel) calculator (pmday.xls) offered by the Biometerology Program at the University of California at Davis (http://biomet.ucdavis.edu) is recommended. This webite also contains other pertinent information regarding the estimation of evaporation.

The specific input variables for the calculator include the station altitude and elevation, daily minimum and maximum air temperature and relative humidity (or dew-point), average solar radiation and wind speed. The net radiation for a surface is partially a function of its reflectivity or albedo (the fraction of reflected solar radiation). This calculator was developed for a 50 cm tall alfalfa reference crop with an albedo of 0.23. A typical albedo for a primary tropical forest is about 0.13 (Giambelluca et al., 1999), half that of alfalfa which is used as a fixed reference in the spreadsheet. To change the spreadsheet calculator's albedo, copy and paste the worksheet contents into a new workbook. Do not use "paste special-values" as suggested in the spreadsheet because this will eliminate the formulas needed to calculate evapotransipiration. Formulas that use the albedo value were hidden in the original spreadsheet and will now be visible but do not require alteration. Simply change the given albedo to the desired value and save the workbook. The original workbook contains sample data beginning on line 130. This should be deleted or replaced with your own data if you want to take advantaage of the automated graphics on the other worksheets in the original workbook.

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