Meteorology, climatology, & lakes

Rick Sherma, CCM

Why weather context belongs in lake assessments

Weather Matters: A Three-Part Series

Article 1: Why meteorological context is necessary for interpreting lake and watershed data. (Summer 2026)

Article 2: Case studies showing how weather information has been overlooked, misapplied, or drawn from nonrepresentative stations. (Fall 2026)

Article 3: Practical ways to improve meteorological observations, station selection, analysis, and reporting.(Winter 2026)

The missing story In a water sample

Lake professionals devote considerable effort to measuring what is in the water: phosphorus, nitrogen, chlorophyll-*a*, dissolved oxygen, suspended sediment, temperature, plankton, and other indicators. Those measurements are essential, but they do not tell the entire story. To interpret them properly, we must also ask what the atmosphere was doing over the lake and watershed before, during, and after sampling.

Rainfall moves water and materials across the landscape. Wind mixes the water column, resuspends sediment, drives currents and seiches, and redistributes floating algae. Solar radiation and air-water heat exchange regulate warming, cooling, evaporation, and stratification. Drought reduces inflow and flushing, while fronts and thunderstorms can alter lake conditions within hours.

Weather is not background scenery. It establishes the physical setting in which lake and watershed observations occur. When the weather story is not told, short-term variability may be mistaken for a long-term trend, a watershed response may be confused with an in-lake process, or a sampling-location effect may be interpreted as a lakewide condition.

A lake sample is a snapshot. Meteorology provides the setting needed to understand that snapshot.

Weather, climate, and mesoscale conditions

These terms are related but not interchangeable. Weather describes atmospheric conditions associated with a particular time or event. Climate describes the statistical distribution of conditions over longer periods. Mesoscale weather includes thunderstorms, frontal rainbands, lake breezes, terrain-driven winds, and other features that can vary substantially across a lake or watershed.

Climatological averages are useful for describing what is typical, but lakes respond to actual events, sequences, and energy exchanges. A monthly rainfall total does not reveal whether the rain arrived gently over several days or in a single intense storm. A monthly mean air temperature does not reveal whether the period included calm, clear days that strengthened stratification or windy nights that cooled and mixed the surface layer. The thermal response to changing weather and climate varies among lakes because depth, surface area, volume, and fetch influence heat storage, stratification, and the effectiveness of wind-driven mixing (Figure 1) (Magee and Wu 2017).

Water and material transport

Rainfall: How Much, How Fast, and Where?

Rainfall is often summarized as a daily, monthly, or seasonal total. For lake management, that is rarely enough. Intensity, duration, location, timing, and antecedent soil conditions often matter more than the accumulated amount alone (Figure 2).

One inch of rain falling gently over 24 hours may infiltrate into relatively dry soil with limited runoff. The same amount falling in 45 minutes during a thunderstorm can produce rapid runoff, erosion, channel scour, and a concentrated inflow plume. After several dry weeks, the first runoff pulse may carry pollutants that accumulated across roads, lawns, agricultural areas, and other surfaces. On already saturated soils, even moderate rainfall may generate extensive runoff.

Spatial representativeness is equally important. A storm that strikes an airport but misses the watershed may appear in the official record while having little relevance to the lake. Conversely, a localized thunderstorm over the watershed may be poorly represented by a distant gauge. Radar estimates, nearby gauges, and watershed-based observations should be considered together when convective rainfall is important.

Rainfall can affect lake and stream conditions through several pathways:

- Nutrient loading. Runoff can transport phosphorus and nitrogen from soils, lawns, agriculture, septic-influenced areas, roads, and eroding banks.

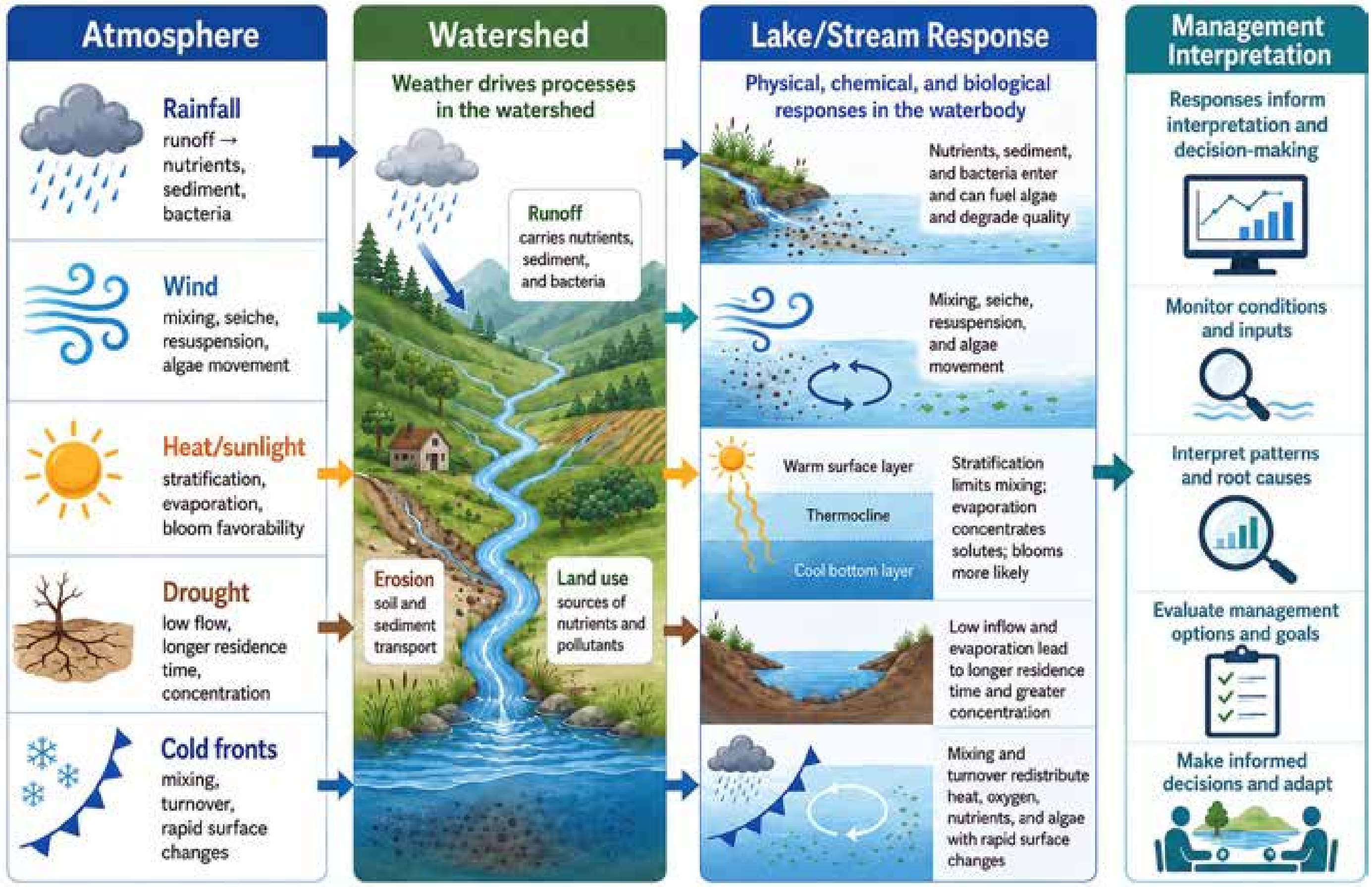
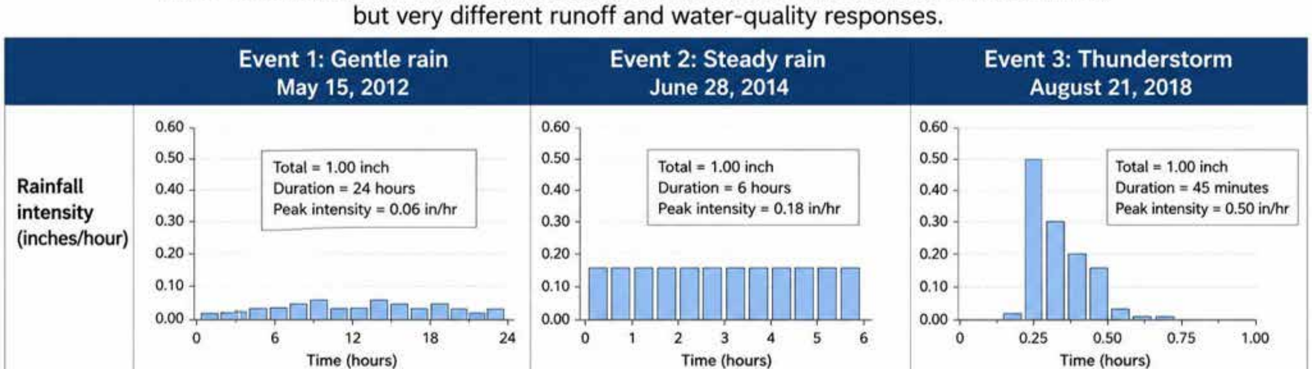


Figure 1. Weather affects lakes through water, energy, and motion. Rainfall moves materials from the watershed, wind redistributes water and algae, and heat controls stratification, evaporation and biological response.

How Rainfall Totals Can Mislead

Three historical events at the same location produced the same rainfall total (1.00 inch) but very different runoff and water-quality responses.



	Event 1: Gentle rain May 15, 2012	Event 2: Steady rain June 28, 2014	Event 3: Thunderstorm August 21, 2018
Event	Gentle rain	Steady rain	Thunderstorm
Rainfall total	1.00 inch	1.00 inch	1.00 inch
Duration	24 hours	6 hours	45 minutes
Peak intensity	0.06 in/hr	0.18 in/hr	0.50 in/hr
Watershed response	Slow, diffuse runoff	Moderate runoff	Rapid runoff
Measured streamflow (Esopus Creek at Allaben, NY)	+35 cubic feet per second (cfs) above baseflow	+310 cfs above baseflow	+2,450 cfs above baseflow
Measured turbidity (Esopus Creek at Allaben, NY)	+12 NTU above baseflow	+85 NTU above baseflow	+310 NTU above baseflow

Figure 2. Equal rainfall totals can produce very different runoff and water-quality responses. Rainfall intensity, duration, soil moisture, land cover, and storm location all influence how much water and material reaches the lake.

- Sediment and turbidity. High-intensity rainfall can detach and transport fine sediment, reducing water clarity and carrying particle-bound nutrients.
- Bacteria. Storm runoff, failing septic infrastructure, wildlife sources, and sediment resuspension may increase bacterial concentrations.
- Channel response. Rapid runoff can scour stream channels, damage habitat, and transport sediment and organic matter downstream.
- Inflow plumes. Tributary water may enter a lake at a different temperature, density, or turbidity and travel over, under, or through the receiving water column.

As an example, a phosphorus concentration measured after a storm may be influenced by watershed runoff and sediment transport. The same concentration after a prolonged dry period may increase the plausibility of an internal source, but timing alone cannot establish causation. Depth profiles, inflow data, sediment conditions, and other evidence remain necessary.

Drought: Low Flow, Long Residence Time, and the Next Storm

Drought is more than the absence of rain. Reduced tributary inflow can decrease flushing, increase residence time, lower lake and groundwater levels, concentrate some dissolved constituents, and expose or alter littoral habitat. Warm, slow-moving water may also favor conditions associated with cyanobacterial blooms.

The sequence matters. A long dry period followed by intense rain can mobilize accumulated material and produce a response disproportionate to the storm total alone. Monitoring and interpretation should therefore account for both the immediate event and the weeks that preceded it.

Motion and redistribution

Wind: Mixing, Waves, Seiches, and Surface Accumulation

Wind is one of the most important and overlooked drivers in lake studies. Wind stress transfers momentum to the water surface, generating waves and currents, producing seiches, tilting the thermocline, mixing the upper water column, and transporting floating material (Figure 3).

In shallow areas, wind-generated waves can resuspend bottom sediment, release nutrients, and increase turbidity. In stratified lakes, strong or persistent wind can deepen the mixed layer, erode thermal stability, and generate internal waves or localized upwelling. Whether substantial mixing occurs depends on wind speed, direction, duration, fetch, lake depth, and the strength of stratification.

Wind also influences what people see. Buoyant cyanobacteria can accumulate near the surface under favorable conditions. Light to moderate winds may

Figure 3. Wind can concentrate floating material along downwind shorelines. A shoreline scum may reflect both biological growth and physical accumulation.

then transport surface material toward a shoreline, cove, marina, or swimming area. A visible shoreline scum can therefore reflect both biological growth and physical redistribution. One part of a lake may appear worse than another even though the spatial difference is partly wind driven.

For lake monitoring, several wind questions should be routine:

- What was the wind speed and direction during the hours and days before the observation?
- Was the wind aligned with the lake's longest fetch?
- Were there several calm days before a bloom report?
- Did a frontal passage deepen the mixed layer or alter the temperature profile?
- Could wind have moved floating algae toward or away from the sampling site?
- Could waves have resuspended sediment in shallow water?

Warmer water, altered rainfall, drought, and stronger stratification may increase the frequency, duration, or severity of freshwater harmful algal blooms, particularly in nutrient-enriched waters (U.S. EPA 2026).

Energy exchange and thermal structure

Solar Radiation and the Lake-Surface Heat Budget

Solar radiation is a primary driver of a lake's heat balance. Some incoming radiation is reflected according to sun angle and surface conditions, while the remainder is absorbed by the water. During sunny, calm periods, surface water warms and becomes less dense, allowing a stable layer to form above cooler, denser water. This reduces vertical mixing and promotes thermal stratification.

Water clarity controls the depth at which solar energy is absorbed. Clear water allows shortwave radiation to penetrate more deeply, distributing heat through a greater depth. Turbid or algae-rich water tends to absorb more energy near the surface, potentially strengthening shallow temperature gradients.

The lake also emits longwave infrared radiation upward, while clouds, humidity, and air temperature influence the longwave radiation returned downward. Additional heat exchange occurs through sensible heat transfer and evaporation. Wind enhances these exchanges and determines whether heat remains near the surface or is mixed downward.

Simplified Lake-Surface Heat Balance

$Q_{net} = (1 - \alpha)Q_{SW\downarrow} + Q_{LW\downarrow} - Q_{LW\uparrow} - Q_H - Q_E$

Q_{net}: net heat flux into the lake.

$(1 - \alpha)Q_{SW\downarrow}$: absorbed incoming solar radiation after reflection by the water surface.

$Q_{LW\downarrow}$: atmospheric longwave radiation received by the lake.

$Q_{LW\uparrow}$: longwave radiation emitted by the water surface.

Q_H: sensible heat exchange associated with the air-water temperature difference.

Q_E: latent heat loss associated by evaporation.

With this sign convention, a positive net flux warms the lake and a negative net flux cools it.

Air temperature alone does not explain lake response. Similar air temperatures can produce different outcomes depending on solar radiation, wind, humidity, cloud cover, water clarity, and nighttime cooling. Hot, humid, cloudy nights can limit heat loss. Dry, windy conditions can cool a lake through evaporation even when the air remains warm. These differences affect stratification, dissolved oxygen, habitat, evaporation, and biological activity.

Describing a month simply as "warm" can conceal the processes that control the lake's thermal response.

Rapid Weather Transitions

Cold Fronts, Partial Mixing, and Turnover

Lakes can change quickly during weather transitions. A cold front may bring stronger winds, cooler and drier air, changing cloud cover, and rapid surface heat loss. Together, these changes can weaken stratification, deepen the mixed layer, or produce partial mixing (Figure 4). During spring and fall, frontal passages may accelerate seasonal turnover when density differences within the water column have already weakened. A single event does not necessarily mix every lake from top to bottom. The response depends on lake depth and morphometry, thermal stability, fetch, wind duration, and prior cooling. A calm autumn may delay mixing, while a strong wind event following surface cooling may accelerate it. A subsequent warm period may temporarily restore shallow stability. These transitions can redistribute dissolved oxygen, nutrients, suspended sediment, and organisms. A lake that appeared clear and stable one week may be mixed or turbid the next. Without meteorological context, the change may seem puzzling or may be attributed to the wrong cause.

A Meteorological Record for Lake Interpretation

A full observing network is not always feasible, but every monitoring program should document enough meteorological information to establish the physical setting of each sample or observation. The following should be recorded, evaluated, and incorporated into studies.

- Rainfall amount, duration, peak intensity, and location within the watershed.
- Antecedent rainfall, soil wetness, drought status, and recent inflow conditions.
- Wind speed, direction, duration, gustiness, and alignment with lake fetch.
- Air temperature, surface-water temperature, humidity or dew point, and cloud cover.
- Solar radiation when available, especially for thermal and bloom studies.

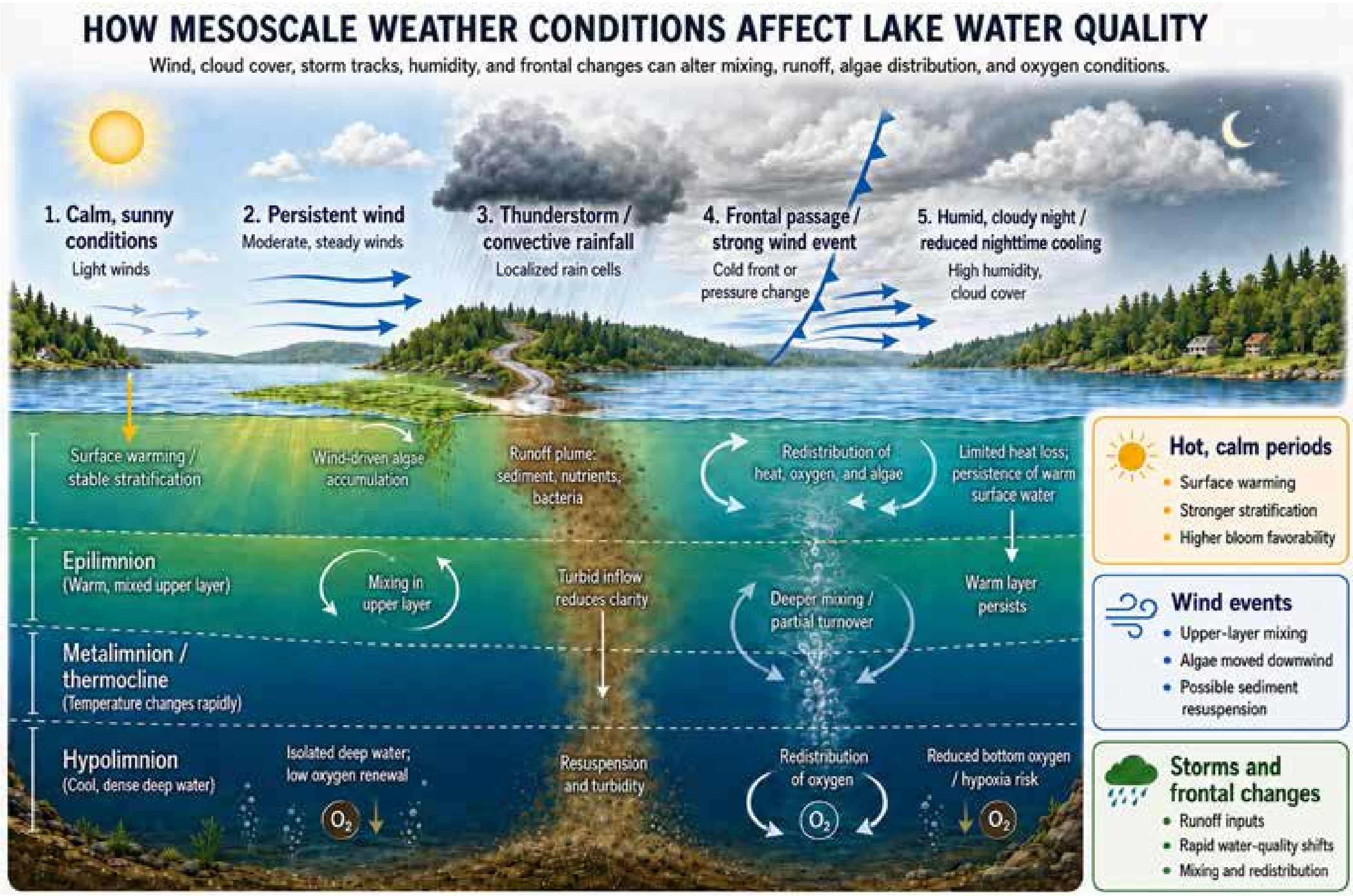


Figure 4. Water quality responds not just to air temperature, but to changing mesoscale weather patterns. Wind, storm timing, cloud cover, and rainfall location determine whether lakes stratify, mix, or receive runoff.

- Passage of fronts, thunderstorms, heat waves, or other rapidly changing conditions.
- The location, elevation, exposure, and representativeness of each weather station or data source.

The third article in this series will discuss appropriate and some practical ways to record weather data in lake assessments.

Station representativenessis essential to data quality

An official station is not automatically representative of a particular lake or watershed. Suitability depends on distance, elevation, terrain, exposure, watershed position, and the meteorological variable being considered. Airport observations may describe regional air temperature reasonably well while missing localized rainfall, lake-breeze winds, cold-air drainage, or terrain-enhanced precipitation.

The appropriate question is not whether a station is official, but whether it measures the conditions that affected the water body. Investigators should document why a station was selected, identify known limitations, and supplement it with radar, gridded data, local gauges, lake buoys, or portable observations when necessary.

Lake sampling already recognizes spatial and temporal variability by using multiple sites and repeated visits. Meteorological observations deserve the same attention.

From Weather Data to Better Decisions

Lake and watershed management is increasingly challenged by intense storms, drought-to-deluge cycles, harmful algal bloom concerns, and public demand for timely answers. Integrating meteorological observations into lake assessments helps managers reach more complete and defensible conclusions by defining the physical setting in which water-quality observations occurred.

Proper meteorological analysis can help answer practical questions such as:

- Was a phosphorus increase associated with a recent runoff event?
- Did drought reduce inflow and increase residence time?
- Did wind move a surface accumulation toward the beach?
- Did a heat wave strengthen stratification and increase oxygen demand below the mixed layer?
- Was a sample representative of the lake, or strongly influenced by timing and location?
- Did the monitoring schedule miss an important storm or frontal passage?
- Was the selected weather station appropriate for the variable and watershed?
- Should future sampling include event-triggered or storm-response measurements?

These are not abstract scientific questions. They affect public communication, management priorities, regulatory interpretation, restoration planning, and funding decisions.

Summary

A lake sample is a snapshot. Weather explains the conditions surrounding that snapshot. Rainfall helps explain runoff pulses and inflow plumes. Wind helps explain mixing, resuspension, and surface accumulation. Surface heat exchange helps explain stratification, evaporation, and thermal habitat. Drought helps explain reduced flushing and the significance of the next storm. Fronts help explain rapid transitions. Simplification of these data can conceal the processes affecting lake water-quality.

Interpreting water-quality data without adequate meteorological context increases the risk of attributing short-term, weather-driven variability to the wrong cause or to a long-term trend. Lakes do not respond to averages. They respond to events, energy, water, motion, and the sequence in which those forces occur. A better understanding of atmospheric drivers leads to better monitoring, more defensible interpretation, and better management decisions.

The next article in this series will examine case studies in which meteorological information was overlooked, misapplied, or obtained from sources that did not adequately represent the lake or watershed.

References

Magee, M. R., and C. H. Wu. 2017. Response of water temperatures and stratification to changing climate in three lakes with different morphometry. *Hydrology and Earth System Sciences* 21(12):6253–6274. https://doi.org/10.5194/hess-21-6253-2017

National Weather Service, Hydrometeorological Design Studies Center. *NOAA Atlas 14*: Precipitation-Frequency Atlas of the United States.

Paerl, H. W., and Huisman, J. 2008. Blooms like it hot. *Science* 320:57-58.

U.S. Environmental Protection Agency. Climate Change and Freshwater Harmful Algal Blooms.

U.S. Geological Survey, Rain Gauge 01362200, Shandaken, NY; Stream Gage 01362500, Esopus Creek Allaben, NY.

Wetzel, R. G. 1975. Limnology. W.B. Saunders Company, Philadelphia, Pennsylvania. 743 pp. ISBN 0-7216-9240-0.

Rick Sherma is a certified consulting meteorologist (CCM) by the American Meteorological Society. He is also a Penn State Extension Master Watershed Steward and an Associate Director of Wayne Conservation District in Pennsylvania. He received a Master of Science degree in Meteorology and Physical Oceanography.