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THESIS

**PERFORMANCE ANALYSIS OF REFRACTIVITY
FROM RADIO TECHNIQUE IN SUPPORT OF
ELECTROMAGNETIC ENVIRONMENT PREDICTION**

by

Anna M. Hook

December 2018

Thesis Advisor:
Second Reader:

Qing Wang
Joel W. Feldmeier

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**PERFORMANCE ANALYSIS OF REFRACTIVITY FROM RADIO
TECHNIQUE IN SUPPORT OF ELECTROMAGNETIC ENVIRONMENT
PREDICTION**

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Lieutenant, United States Navy
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Submitted in partial fulfillment of the
requirements for the degree of

**MASTER OF SCIENCE IN METEOROLOGY AND PHYSICAL
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ABSTRACT

Generating vertical atmospheric refractivity profiles from local radio frequency (RF) signals of opportunity is a technique known as refractivity from radio (RFR). The refractivity profiles from RFR provide information on surface-based and elevated ducts, which impacts the performance of radar, communications equipment, and other technology employing the electromagnetic (EM) spectrum. Refining the RFR technique is important for producing real-time environmental support. RFR was used during the Coupled Air Sea Processes and Electromagnetic ducting Research West Coast field campaign (CASPER-West), conducted offshore in Southern California in 2017. This area was chosen for its spatial and temporal variability of refractive profiles and for the frequent occurrence of offshore wind events that resulted in surface-based ducts. This thesis focuses on using rawinsonde measurements to assess the performance of RFR. The characteristics of the observations were evaluated independently, concentrating on duct top height, trapping layer base height, duct type, and duct strength. RFR profiles were then analyzed and evaluated against the observed ducting layer properties. It was shown that RFR has better performance for estimating duct top height for ducting layers below 400 m. RFR profiles better represent the atmospheric refractivity conditions at 30 minutes ahead of the observation. Results were provided to the developer of the RFR data studied for use in retrieval algorithm improvement.

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LIST OF ACRONYMS AND ABBREVIATIONS

AIS	Automated Identification System
AREPS	Advanced Refractive Effects Prediction System
ARPA	Automated Radar Plotting Aid
Builder	Interactive Scenario Builder
CASPER	Coupled Air Sea Processes and Electromagnetic ducting Research
COAMPS	Coupled Ocean/Atmosphere Mesoscale Prediction System
ED	Evaporation duct
EM	Electromagnetic
EMW	Electromagnetic Maneuver Warfare
EO	Electro-optical
LIDAR	Light Detection and Ranging
MABL	Marine atmospheric boundary layer
MURI	Multi-disciplinary University Research Initiative
NPS	Naval Postgraduate School
NRL	Naval Research Lab
NWP	Numerical Weather Prediction
RF	Radio Frequency
RFR	Refractivity From Radio
SBD	Surface-Based Duct
SHF	Super High Frequency
SSCPAC	Space and Naval Warfare Systems Center Pacific
TDA	Tactical Decision Aid
UUV	Unmanned Underwater Vehicle
VHF	Very High Frequency
VOCAR	Variability Of Coastal Atmospheric Refractivity Experiment
WG	Wave Glider

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I. INTRODUCTION

A. CONTEXT

An essential part of naval tactics is to understand where in the battlespace assets can be seen and where they can be hidden. This concept applies not only to visible and acoustic environments, but also to active and passive radar systems. Ship captains need to know where they can position themselves to hide from an adversary's radar systems. Similarly, they need to know where in the battlespace their ship's radar outperforms the adversary's radar systems or electronic support (ES) systems. Smart use of the surrounding electromagnetic (EM) domain can give the U.S. Navy's defilade from tactics and strategies that rely heavily upon radar and communications systems. The propagation of EM waves cannot be observed by simply looking out the window or viewing a satellite image. In order to gain superiority in the electromagnetic maneuver warfare (EMW) domain, an accurate depiction of the current EM propagation conditions along with an EM propagation forecast is critical for decision makers.

The Navy is so reliant on the EM spectrum for weapons systems, communication capabilities, data transfer, and navigation that the commander of the Naval Meteorology and Oceanography Command released a strategy to address it. He asserts that the EM spectrum is so fundamental to naval operations that future conflicts will not be won simply by using it, but by having an advantage within it (Gallaudet 2016). The performance of technologies that use the EM spectrum is affected by many factors, including meteorological conditions. Because of the Navy's dependence on the EM spectrum, it is essential to quantify system performance when creating strategic, tactical, and operational plans (Bleidorn 2008).

An expert in fleet tactics and warfighting, Captain Wayne P. Hughes, Jr., USN (Ret) emphasizes that scouting is an essential component of the success of the Navy. Ships must be able to detect their adversaries without being detected themselves. The force that is able to attack effectively first is the force that will win the fight (Hughes 2018). A better understanding of the EM propagation environment will allow a warfighter to not only out-

scout their adversary, but also be able to plan and position their assets in advantageous areas.

Leaders recognize that maintaining an awareness of the EM environment within the battlespace is essential for warfighters to be effective, and that the battlespace is rapidly moving toward the EMW domain (Joyce 2017). Many organizations within the military, as well as supporting companies, have invested in research to improve technology to give the warfighters an accurate picture of the EM environment. The Oceanographer of the Navy maintains an EMW strategy, in which he emphasized the need to improve sensing and prediction capabilities as well as to integrate EM impacts into the decision-making process. For years, Naval Oceanography has sensed and predicted the propagation of acoustic waves through the ocean. These skills can also be applied to the atmosphere with EM waves (Naval Meteorology and Oceanography Command Public Affairs 2016). Developing EM nowcasting and forecasting capabilities is advantageous to maintaining superiority in the EMW domain.

Refractivity from Radio (RFR) is a technique used to estimate atmospheric refractivity by using measured propagation from signals of opportunity. The technique is potentially beneficial to naval operations in the coastal region once it is validated. This thesis intends to examine the meteorological conditions that affect the performance of the October 2018 release of RFR.

B. MOTIVATION

The U.S. Navy no longer launches weather balloons to gather real-time in-situ data on atmospheric refractivity profiles since its upper air sensing program was terminated in 2011 (Titley 2010). This has left a significant gap in observational data as well as meaningful inputs to initialize numerical weather prediction (NWP) models. The RFR technique uses the existing passive equipment onboard a ship to create an atmospheric refractivity profile. This is attractive because additional hardware is not needed to collect meteorological or electromagnetic measurements (Zhao et al. 2012). By implementing RFR onboard U.S. Navy ships, measurements of the atmospheric refractivity would greatly

increase. That would be beneficial not only for the accuracy of tactical decision aids, but also for initialization of the NWP models in areas with sparse in-situ observations.

The propagation of EM waves produced by communications equipment, radar, and weapons systems is greatly affected by environmental conditions (Kulesa et al. 2017). The signals can be absorbed, refracted, scattered, and ducted by the atmosphere. These conditions can vary greatly spatially and temporally. This creates a varied EM environment, especially in the littoral regions near the coast. It is essential for the warfighter to have awareness of their battlespace in the EM domain. If weapons, sensors, radars, and communications equipment are located within a ducting layer, the range at which they can make detections or connections can be dramatically increased. However, this can also lead to detection by the adversary at farther distances. Energy within a duct can also lead to some signal artifacts that may negatively impact performance, such as “ghost” contacts displayed on an Automated Radar Plotting Aid (ARPA). It is important that the tactical decision aids (TDA) that are provided to the warfighter are accurate. Otherwise, a faulty product may negatively influence decisions and strategy.

Many TDA products are created for decision makers and warfighters using Advanced Refractive Effects Prediction System (AREPS) and Interactive Scenario Builder, commonly referred to as “Builder.” These software programs use inputs from the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS), the current U.S. Navy mesoscale weather model, to forecast atmospheric effects on EM propagation and target detection. COAMPS, like every NWP model, does not always accurately depict the boundary layer when there are large spatial gradients or dynamic weather (Wyant 2010). An improved method for sensing EM propagation in the boundary layer is needed to create an accurate forecast. The RFR technique bridges this gap and does not require a dense network of meteorological instruments.

C. SCOPE OF RESEARCH

The objective of this research is to determine the meteorological conditions that impact the performance of RFR technique during the Coupled Air Sea Processes and Electromagnetic ducting Research (CASPER) West field campaign. The October 2018

release of RFR provided by HS Owen LLC was evaluated from September 27, 2017, through October 23, 2017 in the CASPER West operating area. The objective of this research is to provide feedback to the developers of the RFR technique to establish the meteorological conditions in which it performed well, and conditions in which it may have bias.

II. BACKGROUND

This chapter develops the equations that govern electromagnetic propagation through the atmosphere and the behavior of electromagnetic waves in different atmospheric conditions. It then describes the techniques used to observe and measure atmospheric effects that affect electromagnetic propagation and the methods used to create a forecast.

A. EQUATIONS THAT GOVERN ELECTROMAGNETIC PROPAGATION THROUGH THE ATMOSPHERE

Radar, communications equipment, and weapons systems use the Radio Frequency (RF) portion of the EM spectrum, ranging from Very High Frequency (VHF), which can be as low as 30MHz, up to Super High Frequency (SHF), which can be as high as 30 GHz. RF signals are affected by vertical gradients in the atmosphere of humidity, temperature, and atmospheric pressure because changes in these variables bend and refract the signal as it propagates through the atmosphere. The index of refraction, n , compares the phase speed of the signal to the speed of light. The index of refraction is defined as:

$$n = \frac{c}{v} \quad (1)$$

where c is the speed of light in a vacuum and v is the speed of light in a homogeneous medium (Battan 1973). By comparing different values of n in different layers, the propagation of waves can be inferred. The atmospheric radio refractive index is defined by Bean and Dutton (1968) as:

$$n = 1 + N \times 10^{-6} \quad (2)$$

where n is the index of refraction and N is the radio refractive index. The radio refractive index, N , is related to atmospheric state variables given in Bean and Dutton (1968):

$$N = 77.6 \frac{P}{T} - 5.6 \frac{e}{T} + (3.75 \times 10^5) \frac{e}{T^2} \quad (3)$$

where P is atmospheric pressure in hectopascals, T is the temperature in Kelvin, and e is water vapor pressure in hectopascals. Equation 3 reveals the atmospheric parameters that

affect the refraction of RF signals. This equation is valid for frequencies between 100 MHz and 80 GHz. As most of the RF signals propagate beyond the geometric horizon, it is sensible to take the curvature of the earth into consideration, which results in the introduction of another parameter, the modified refractivity, M . The modified refractivity is defined by Battan (1973):

$$M = N + \frac{z}{R \times 10^{-6}} = N + 0.157z \quad (4)$$

where z is height in meters above the surface and R is the radius of the Earth. Equations 3 and 4 show that the propagation speeds of RF signals is most affected by water vapor, then temperature, and to a lesser extent, but still important, atmospheric pressure (Ziemba 2013).

B. CATEGORIES OF ELECTROMAGNETIC PROPAGATION THROUGH THE ATMOSPHERE

The atmospheric variables of temperature, humidity, and atmospheric pressure vary temporally and spatially. Equations 3 and 4 demonstrate that the propagation speed of RF signals is affected by these atmospheric variables, with humidity having the most impact. Hence, the propagation speed of the RF signals also varies temporally and spatially. The spatial variation of propagation speed determines the refraction of the RF signals.

The propagation of RF signals is described by the variation of the radio refractive index, N , over a distance, x or y , or height, z . Typically, the horizontal gradient of N is negligible compared to the vertical gradient, i.e., $\frac{\partial N}{\partial x}, \frac{\partial N}{\partial y} \ll \frac{\partial N}{\partial z}$. The propagation can also be described by the variation of the modified refractive index, M , with height, z . Figure 1 shows how the signals can be refracted with respect to the Earth's surface. The ducting category of refraction is most important as it increases the distance a signal can travel. When the signal is ducted, it is bent toward the surface of the Earth. The RFR technique estimates the height of the atmospheric layer that is ducting a signal. This becomes important when a shipboard radar or weapons system is located in this ducting layer as the ranges are increased, but other factors can also impact performance, including the relative position of the ship sensor height relative to the duct height as compared to the threat sensor

height relative to the duct height, determining who has the advantage. Radar cross sections of the ship, and that of a threat along with sensor specifications are also important considerations.

Ducting is considered non-standard or anomalous propagation in the atmosphere, where the vertical gradient of refraction is less than that in a standard or super-refractive atmosphere. A duct is like a wave-guide that can result in extended ranges due to reduced propagation loss. A trapping layer is the key to the presence of a duct in which the vertical gradient of M goes from negative. The top of the trapping layer is the top of the duct. The bottom of the duct is where the M -value is equal to the M -value at the top of the trapping layer. More than one duct can exist in a vertical air column. At the top of the trapping layer, RF signals refract downward relative to the Earth's surface. At the bottom of the duct,

where $\frac{dM}{dz} > 0$, RF signals turn upward relative to the Earth's surface (Bleidorn 2008).

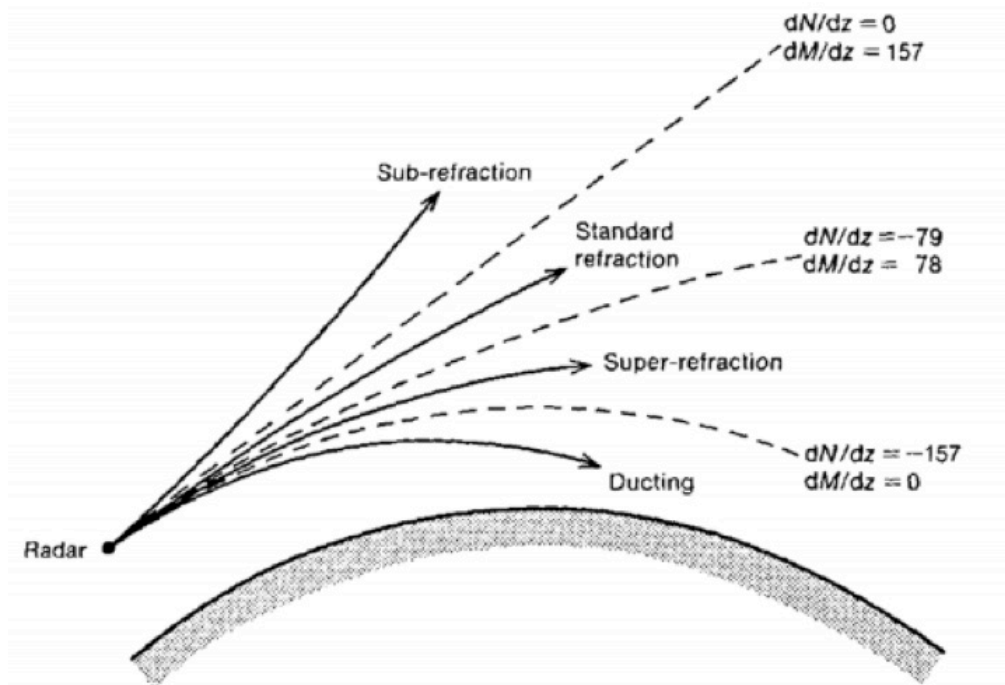


Figure 1. Categories of refractive propagation. Source: Turton et al. (1988)

Ducting is also classified into different categories: surface duct, surface-based duct, and elevated duct (Ding et al. 2013). A special case of the surface duct is the evaporation duct caused by the evaporation at the ocean surface. Figure 2 shows the change in the modified refractive index, M , with height. When the slope of the line is negative, RF signals are trapped in the layer (Turton et al. 1988).

Figure 2a illustrates the surface duct. The trapping layer and the duct thickness are the same as both the duct and the trapping layer begin at the surface. Surface ducts usually occur when warm air is over a cool surface, which creates a temperature inversion (Battan 1973).

Figure 2b is known as a surface-based duct. The slope of the line $\frac{dM}{dz}$ is positive near the ground then becomes negative. The bottom of the trapping layer begins when the

slope of the line $\frac{dM}{dz}$ becomes negative. The duct extends to the surface in this case because the minimum value of M at the top of the duct is lower than the value of M at the bottom of the duct, located at the surface. Surface-based ducts enhance the propagation of all RF signals above 100MHz (Rogers 1998). They are associated with the marine boundary layer (MBL) being capped by a stable layer aloft, and very common under high pressure, subsidence, and stratocumulus topped boundary layers (Rogers 1997).

Figure 2c is known as an elevated duct. The slope of the line $\frac{dM}{dz}$ is positive near the ground in a similar way as Figure 2b, however, it extends much higher. The duct extends vertically from the top of the trapping layer (negatively sloped line) to the altitude below with the same M -value (point at which its minimum value intersects the positively sloped line below). This is known as an elevated duct because it does not extend to the surface. Elevated ducts can be caused by subsidence, with elevated temperature inversions and moisture inversions. Like surface-based ducts, elevated ducts are also associated with the MBL being capped by a stable layer aloft. They also can be caused by strong surface heating with a capping inversion aloft. Elevated ducts can be seen at heights up to 4000m,

but are typically found below 2000m (Ziemba 2013). Elevated ducts enhance the propagation of RF signals that are less than 1GHz (Rogers 1998). An elevated duct will impact aircraft more than surface sensors as the aircraft may be flying within the duct.

Figure 2d shows an evaporation duct. The evaporation duct is a sub-category of the surface duct. It is located over a body of water with significant vertical humidity and temperature gradients due to the boundary between the air and the water. Evaporation ducts can range from a few meters to tens of meters depending on the air mass over the water interface (Ziemba 2013). The evaporation duct is especially important for the propagation of RF signals that are higher than 3GHz (Rogers 1997). This type of duct is most frequently observed over the ocean.

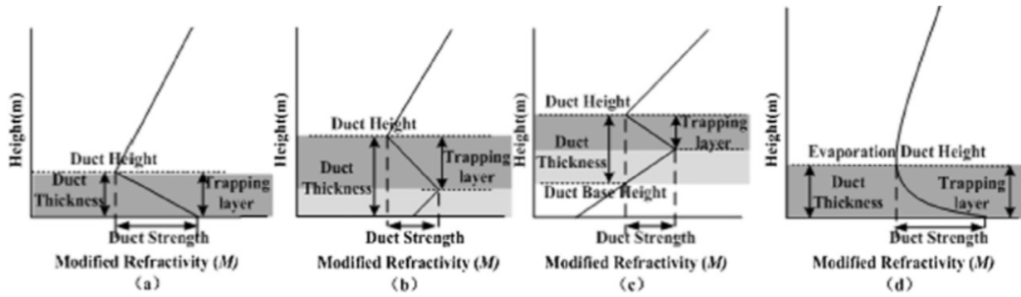


Figure 2. Categories of ducts: (a) surface duct, (b) surface-based duct, (c) elevated duct, (d) evaporation duct. Source: Ding et al. (2013)

The type of duct, its height, and its strength has significant impacts on RF signal propagation. Figure 3 shows the impact of ducts on propagation of a 6 GHz radar at a typical shipboard height. In the bottom row of Figure 3, the dark blue colors indicate very little to no propagation loss, which can be inferred that there will be a high probability of detection of a target or threat. The red colors indicate high propagation loss, and thus it is likely that the target or threat will be undetected by the radar (Frederickson 2012). Significantly extended ranges can be seen in the evaporation duct and the surface duct. The surface-based duct has a notable skip-zone feature where there is high propagation loss, and it is likely the 6-GHz radar will not detect a target or threat located at the 30nm range.

However, with the exception of the skip-zone, the surface-based duct can also offer greatly extended ranges compared to the standard atmosphere.

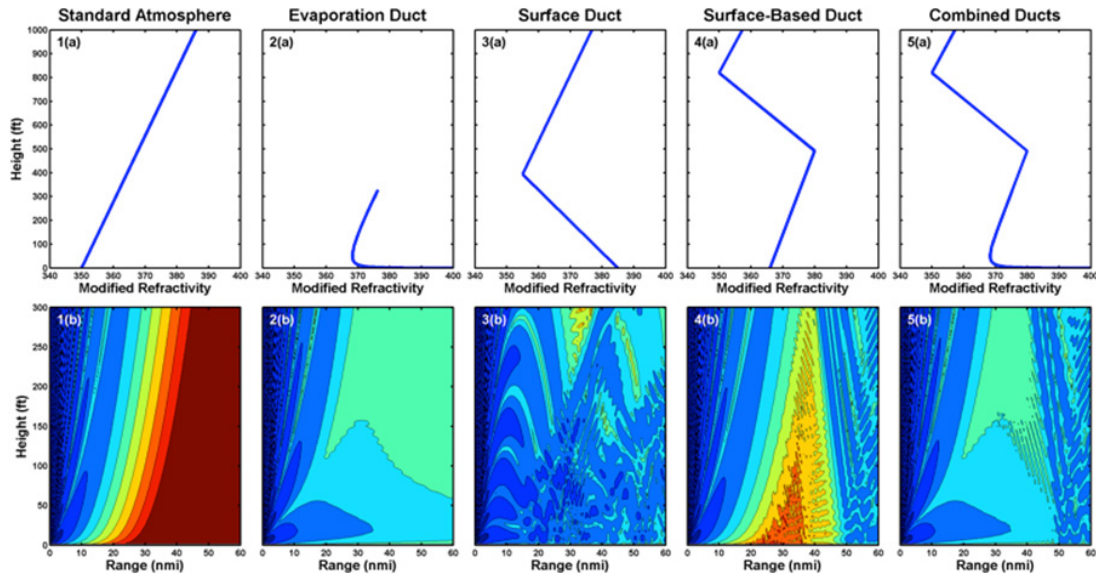


Figure 3. Propagation loss diagrams for a 6 GHz radar at a typical shipboard height above the surface. Source: Frederickson (2012)

C. CURRENT TECHNIQUES TO OBSERVE AND FORECAST ATMOSPHERIC REFRACTIVITY

There are no techniques in place to observe atmospheric refractivity onboard a U.S. Navy ship. Prior to the cancellation of the program, in-situ weather observations using weather balloons at airfields and onboard ships provided information on the refractivity profile of the atmosphere. A helium balloon was launched with an attached rawinsonde, an instrument that collects data on pressure, temperature, humidity, wind speed, and wind direction vertically in the atmosphere. This process is quite manual, as a trained meteorological technician must prepare and release a balloon with an attached rawinsonde from their location. Onboard a ship, these measurements are typically initiated between 40 and 70 feet above the surface of the water, depending on the class of ship, and they conflict with flight operations. The upper air sensing program, which allowed ships to launch these weather balloons, was terminated in 2011 for a variety of reasons (Titley 2010). In-situ weather observations are only valid for a single point in space, and were typically collected

twice per day. This was potentially not representative of the atmosphere in the entire operating area, and may not have adequately captured temporal changes in the atmosphere. Additionally, the assumption had to be made that the atmosphere was horizontally homogeneous extending to the range of the shipboard radar. This is often not a good assumption in littoral and coastal regions, areas where naval conflicts are likely to occur.

Raman Light Detection and Ranging (LIDAR) is effective in providing atmospheric measurements required to create a vertical profile of atmospheric refractivity and inputs for EM forecasting (Philbrick et al. 2005). The Raman LIDAR emits a pulsed ultra-violet laser vertically into the atmosphere. Some of the light is backscattered from atmospheric nitrogen, oxygen, and water vapor back into the transceiver of the LIDAR. This provides measurements of temperature and water vapor mixing ratio that are important in calculating refractivity. This technique was proposed to replace weather balloons onboard ships. However, any comprehensive program to install LIDAR equipment and train personnel has yet to come to fruition at the time of this writing.

AREPS is a propagation effects model that provides a two-dimensional TDA for performance of radar, weapons sensors, and communications equipment within a forecasted environment. It provides colorful plots, such as those in Figure 3, depicting horizontal range and height of one-way propagation loss and vertical refractivity profiles based on model output. Propagation loss contours are produced by the model. When classified sensor and target specifications are input by a trained meteorological technician, the program can deliver products such as a probability of detection of a threat to the warfighter. Environmental conditions can be preloaded with a standard dataset, such as a standard atmosphere (a worldwide climatological standard) or canonical ducted atmospheres, in situ observations, or it can import data from the COAMPS model (Bleidorn 2008).

Builder is similar to AREPS in that it provides a TDA for performance of radar, weapons sensors, and communications equipment within a forecasted environment. Builder, like AREPS, also uses inputs from the COAMPS model to generate one-way and two-way propagation loss products. The TDA uses geo-spatial technology to produce a true three-dimensional visual aid for the warfighter. Builder also includes more complex antenna pattern data than AREPS (Bleidorn 2008). Both Builder and AREPS are very reliant on COAMPS

data to be accurate, which can be problematic if the ship experiences satellite communications outages or needs to reduce emissions for tactical reasons. RFR is entirely passive and can work in both of these restrictive conditions.

III. DATA/METHODOLOGY

This chapter will describe the techniques used to evaluate RFR. It begins by defining how RFR estimates an atmospheric duct and quality control methods it uses to determine a good result. Then the CASPER West field campaign is described to develop an understanding of how in-situ atmospheric measurements were obtained. Finally, it illustrates the methods for comparing the RFR profiles to the in-situ measurements.

A. OVERVIEW OF THE REFRACTIVITY FROM RADIO TECHNIQUE

The RFR technique infers atmospheric refractivity from measured propagation of RF signals. RFR produces a vertical profile of the modified refractivity called an M-profile, such as in Figure 4, that is path integrated from the source of the signal to the receiver. The profile is generated by estimating gradients of atmospheric refractivity. The October 2018 release of RFR provided by HS Owen LLC produces several parameters that can be viewed through a browser. Figure 4 is an example of RFR results displayed through a browser. Table 1 describes the parameters that are included to the right of the vertical modified refractivity profile and Figure 5 shows a visual representation of those parameters in an M-profile.

According to the developer, Hank Owen (personal communication, October 15, 2018), RFR passively receives RF signals of opportunity from ships passing, antennas ashore, and other transmitters. RFR receivers measure RF signals from approximately 100MHz to 3.2GHz, however other hardware may be installed to receive RF signals outside of this range. This thesis is examining information from signals received from an antenna installed on the port quarter of the R/V Sally Ride. A typical installation of RFR consists of receivers providing RF power measurements and an RFR server. The RFR server runs an application called Radio Inversion. The hardware and software of this installation is generally referred to as ‘RFR’. The RFR server uses the power measurements from the receivers to estimate the propagation loss for each individual signal and then infers the vertical profile of modified refractivity through an inversion process. The algorithm for this process is proprietary information. This vertical profile is integrated over the path of

the signal, and is valid for the midpoint between the transmitter and the receiver. RFR also provides duct strength from the resultant modified refractivity profile. It also presents the height of the duct, as well as information on troposcatter (an additional atmospheric impact on RF energy) and perturbations in the inversion layer. Typically, a trilinear vertical modified refractivity profile is returned, as shown in Figure 4 and described in Figure 5, but RFR has the ability to estimate multiple layers to include elevated ducts and evaporation ducts.

RFR runs continuously, and it produces a profile every 30 minutes using signal information from the previous 3 hours. It is weighted more heavily toward the end time, which is the time the profile is generated.

RFR results are displayed in a browser as shown in Figure 4. The browser shows a list of available time periods for which RFR returned results on the modified refractivity profile. Each time period may be displayed or downloaded individually, showing the discrete RF signals that contributed to the overall resultant profile, called a combined profile. A time series of the profiles can be displayed or downloaded. Downloaded data from RFR produces a .json file that can be employed in MATLAB or other programs.

The vertical profile of modified refractivity created by RFR can be sourced from a single RF signal, but it is most reliable when 2 or more RF signal sources are used to compose a combined profile as the averaging process to create the combined profile has reduced the bias to an acceptable level. The combined profile tends to be more of an average with fewer RF signals, and tends to weigh more toward a median result with more RF signals. Additionally, the profile is considered more reliable when the calculated max overlap ambiguity metric is less than 0.95 when a duct is reported. If a refractivity profile is displayed with a lighter colored line, it is an indication that the max overlap ambiguity metric is higher than 0.95, and becomes lighter as the ambiguity metric increases. The ambiguity metric indicates whether there is enough information received from the RF signals to unambiguously state a result. The max mode error should also be below 10 for a trustworthy result. Max mode error is a type of fit metric and indicates whether the results from the RFR retrieval match the observations well. If the fit is considered good, the conditions are well represented by the RFR combined profile over the area from which the

measurements were made. If the fit is considered bad, the RFR combined profile is not well approximated by the parameters, there is a gradient that is not well represented by a single profile, or that there are simply errors in the power measurements, perhaps due to a blockage by the ship's superstructure or other large body. If a refractivity profile is displayed with a thick line, this is an indication that the max mode error is higher than 10, and becomes thicker as the fit metric increases (H.S. Owen, email to author, October 30, 2018).

RFR can be sectored to isolate specific areas of interest. If a coastline is to the north and open water is to the south, each area can be separated, or "sectored," to ensure accurate profiles are generated. Atmospheric refractivity often varies spatially in coastal areas.

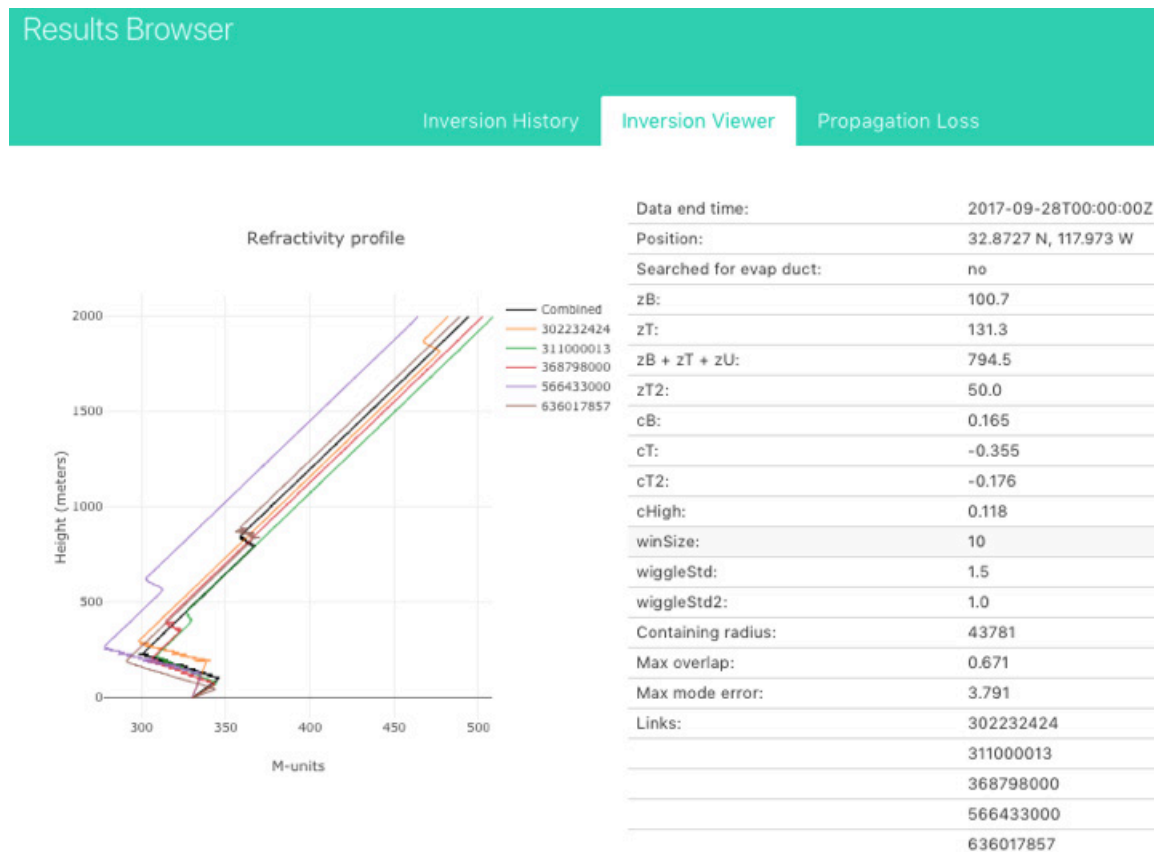


Figure 4. RFR results shown as browser display. Each RF signal, or link, is displayed separately with the combined profile depicted in black.

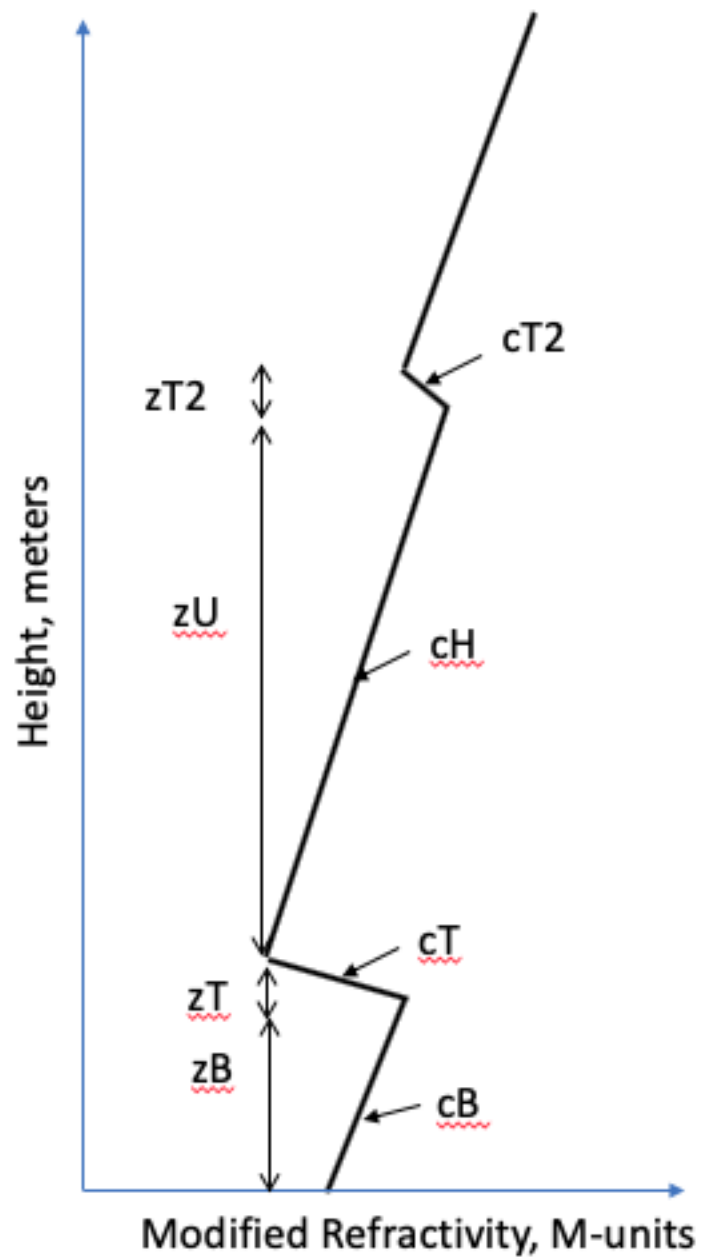


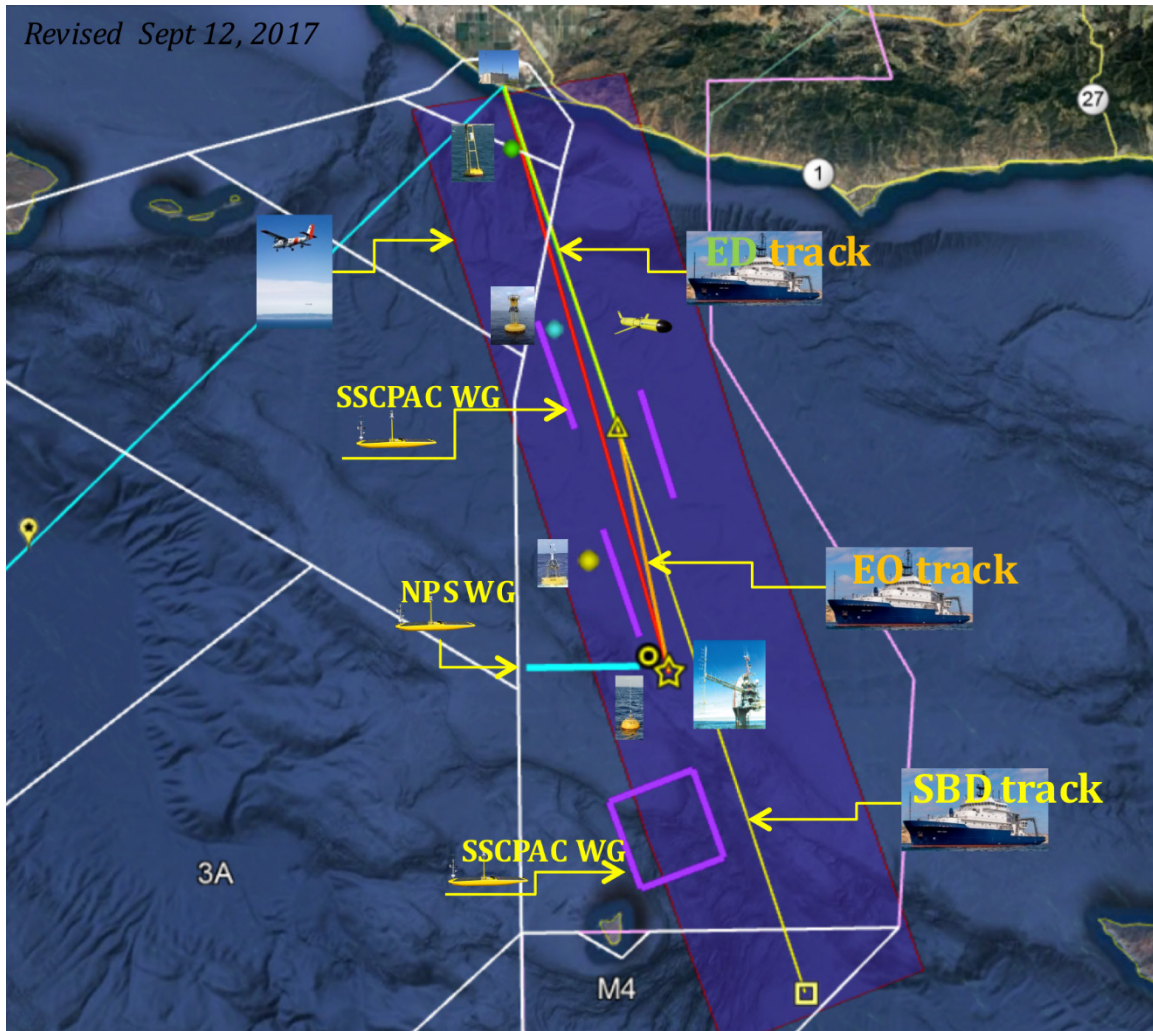
Figure 5. Simplified version of the modified refractivity profile from RFR results displayed in RFR results browser. Profile parameters described in Table 1. Source: Owen (2018).

Table 1. Description of parameters returned in browser display of RFR results

Parameter	Description
Data end time	The time at which profile was generated
Position	Geometric mean of all transmitter positions
zB	Height in meters of the first (lowest) line segment, trapping layer base height
zT	Height in meters of the second line segment, trapping layer thickness
zU	Height in meters of the elevated duct position
zB+zT+zU	Height in meters of second duct, elevated duct
zT2	Height in meters of third line segment
cB	Slope of first (lowest) line segment
cT	Slope of second line segment
cT2	Slope of third line segment
cH	Slope of highest line segment
winSize	Smoothing parameter
wiggleStd	Standard deviation of perturbation – infer strength of turbulence in inversion layer
wiggleStd2	Standard deviation in second inversion layer
Containing radius	Area of sounding in meters
Max overlap	Ambiguity metric – distribution of mode errors if they are overlapped
Max mode error	dB related fit metric
Links	Individual RF signals, also called link identifiers

B. CASPER WEST FIELD CAMPAIGN

CASPER-West is one of the Office of Naval Research (ONR) Multi-disciplinary University Research Initiatives (MURI) to investigate the properties of surface ducts and elevated ducts associated with atmospheric surface layer and inversions off the southern California coast. CASPER West was executed from September 27, 2017, through October 26, 2017. During CASPER-West, extensive research measurements were taken to explore atmospheric impacts on electromagnetic wave and electro-optical wave propagation. Figure 6 depicts the locations of the assets used to collect data.



Evaporation Duct (ED track, green + orange lines), Electro-Optical (EO track, orange line), and Surface-Based Duct (SBD track, green + yellow lines) the CASPER-West field campaign (Wang 2017). Wave gliders (WG) owned by the Naval Postgraduate School (NPS) and Space and Naval Warfare Systems Center Pacific (SSCPAC) were also deployed. The north most point of the track is the shore site at Point Mugu, CA

Figure 6. Tracks for R/V Sally Ride designed to study various duct types.
Source: Wang (2017)

The R/P FLIP was stationary for the entirety of the field campaign. This platform rotates 90 degrees to become a stabilized vertical spar buoy. It was a critical asset for CASPER-West as its slim profile above the water reduced any influence the vessel has on atmospheric flow and thermodynamics. Shore-based measurements were stationed at Naval Air Station Point Mugu. The R/V Sally Ride followed predetermined ED, SBD, or EO tracks, shown as different colored lines in Figure 6, given the weather conditions and

operations for the day. The R/V Sally Ride also deployed a small boat when feasible along its track to collect atmospheric measurements down to the surface of the ocean via a tethered balloon-based rawinsonde that can be raised and lowered to obtain vertical profiles of temperature, humidity, and pressure.

Free-flying rawinsondes attached to weather balloons were launched at the conventional synoptic times of 0000UTC and 1200UTC, in addition to irregular launches throughout the day. The balloons were launched from three location/platforms: at Point Mugu shore site, on the R/V Sally Ride, and on R/P FLIP to cover the spatial variations over the CASPER West operating area. In many instances, soundings from all locations were made simultaneously. The data from the rawinsondes is used to validate the results from RFR.

C. WEATHER CONDITIONS

The southern California coast was selected as the location for CASPER West due to its high frequency of occurrence of ducting conditions. The climatological ducting frequency for all types of ducts in this area is displayed in Figure 7 (Yamaguchi et al. 2017). Southern California experiences significant spatial and temporal variability in temperature, pressure, and humidity and thus in atmospheric refractivity. A thorough synoptic summary of the weather conditions from September 27, 2017 through October 23, 2017, is in the appendix. Most of the measurement days experienced a diurnal land-sea breeze over the operating area. There were also multiple occurrences of significant offshore wind events, similar to Santa Ana Wind (SAW) events, on October 9, October 15, and October 23, 2017. These offshore wind events advected very warm and dry air from the land to the ocean, causing a very dry, stable elevated trapping layer to form over the CASPER West operating area. These conditions are expected to stress the results produced by RFR as the ducting can be complex under such conditions.

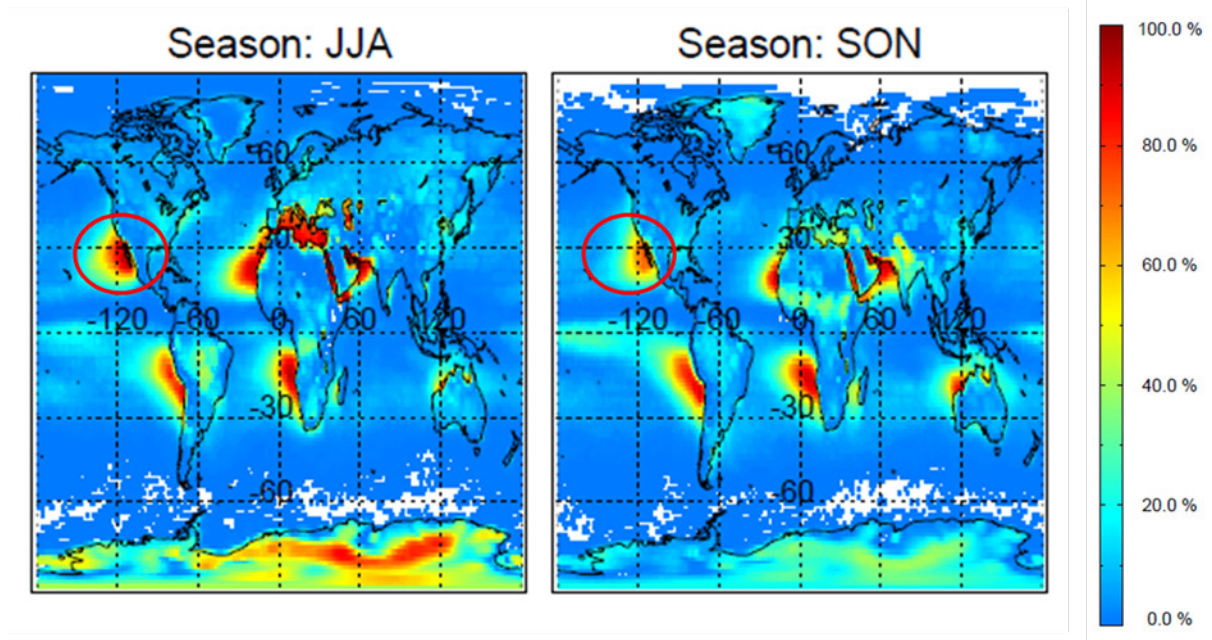


Figure 7. Ducting probability for the months of June, July, August and September, October, November. Source: Engeln (2004).

D. DATA SET

1. RFR Data Set

The RFR data set was provided by HS Owen LLC for evaluation. Antennas installed on the R/V Sally Ride passively received RF signals of opportunity from antennas ashore such as digital television antennas and S-band radar and Automated Identification System (AIS) signals from passing ships. Computers onboard the R/V Sally Ride processed these signals to produce modified refractivity profiles. The RF signal data was retained for future reprocessing with new updates as they are made available. A list of the days that will be evaluated is shown in Table 2. These days were chosen to evaluate days of meteorological interest, such as offshore wind events, as well as baseline cases where the conditions were optimal for RFR retrieval.

Table 2. List of RFR evaluated data

Day	Time Interval (UTC)	2 nd Run Task ID (Ettus & Shine Micro Receivers)	RFR Notes	Meteorology Notes
9/28/17	0000-2330	235	NPS priority event	Low clouds/fog near DTV signal
10/6/17	0000-1430	239	Baseline case	
10/6/17	1500-2330	239	Baseline case	
10/7/17	0000-2330	241	Baseline case	
10/8/17	0000-2330	243	Baseline case	
10/15/17	0700-2330	237	NPS priority event	Offshore wind event 13Z-19Z
10/17/17	0000-0530	217	SSC-PAC priority event	
10/17/17	0600-2330	215	SSC-PAC priority event	
10/18/17	0000-1430	229	SSC-PAC priority event.	
10/18/17	1500-2100	229	SSC-PAC priority event.	
10/19/17	0000-2330	223	SSC-PAC priority event.	
10/20/17	0000-2330	225, 227	NPS priority event.	High sea state, gusts up to 42 kts at some stations, low clouds/fog
10/23/17	0000-2330	233	NPS priority event.	Offshore wind event

Task IDs are generated by RFR as the signals received for each day were processed by the RFR server in batches.

2. Rawinsonde Data Set

Vaisala RS92 rawinsondes were launched onboard the R/V Sally Ride and onboard the R/P FLIP, while Vaisala RS41 rawinsondes were launched at Naval Air Station Point Mugu on the synoptic hours of 0000UTC and 1200UTC. Those balloons ascended until

they burst, typically between 300–100hPa (approximately 30,000 – 60,000 ft altitude). At intervals in between the synoptic hours, dictated by the weather conditions and the track driven by the R/V Sally Ride, “up/down” balloons were launched. The “up/down” balloon had a slow-leaking syringe plugging the opening of the balloon to allow it to ascend to ideally 3500ft and slowly descend to the surface. This “up/down” technique allowed for increased sampling of the marine atmospheric boundary layer (MABL), i.e., 2 vertical profiles for each balloon launch. The rawinsondes reported temperature, dew point, atmospheric pressure, wind direction, and wind speed. They can calculate height using pressure, accurate within 1hPa, or by using GPS, accurate within 20m. Modified refractivity profiles are calculated from this data using MATLAB. These profiles are considered valid above a single point in space and are not path-integrated. This has historically been a common assumption for weather balloons, although it is recognized that the balloons may have significant lateral displacement as they ascend. Dealing with that displacement is outside the scope of this thesis. Figure 8 shows the time of rawinsondes from each launching location/platform. Figure 9 also shows the locations of all soundings from R/V Sally Ride, as that was the only platform that moved.

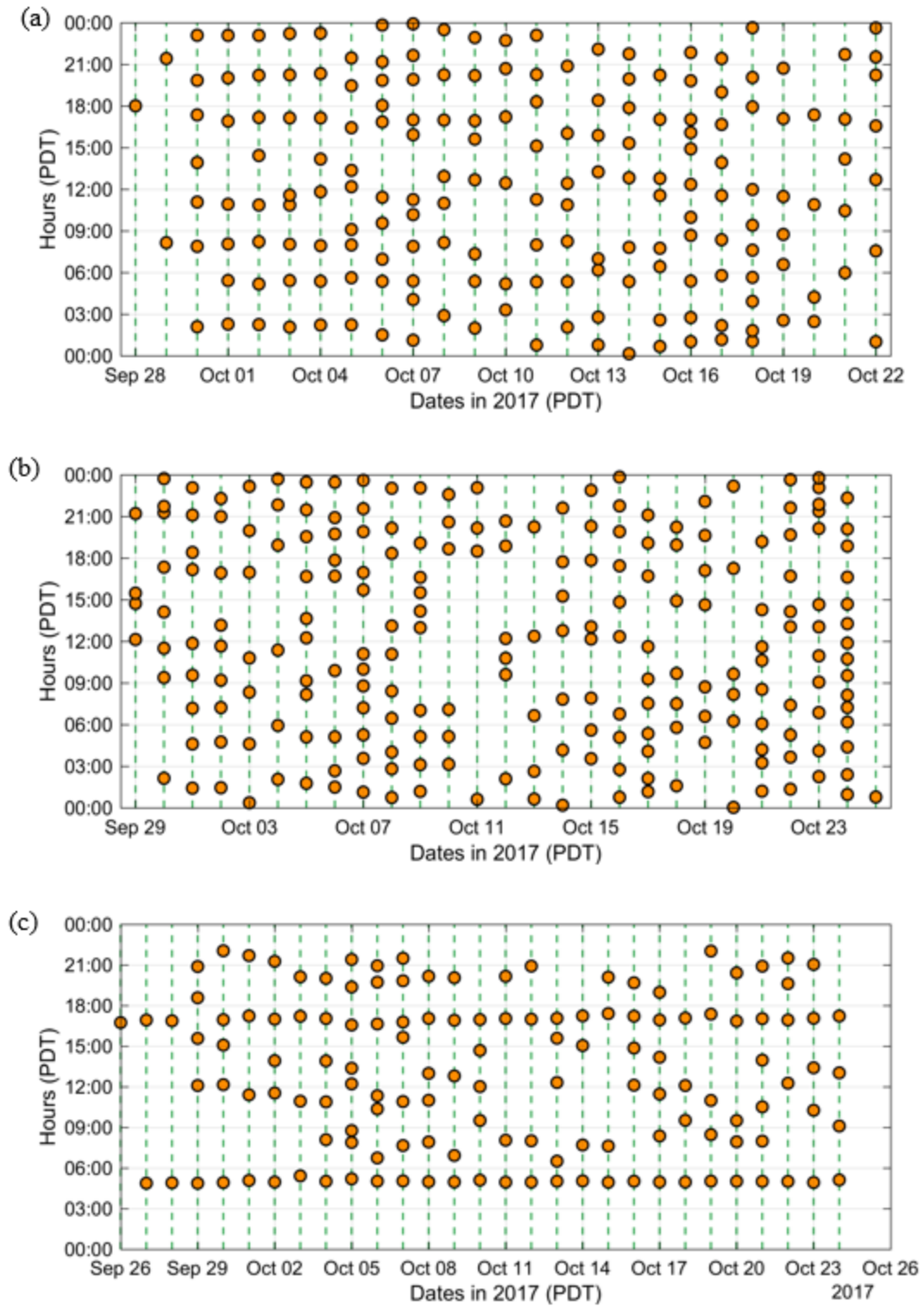


Figure 8. Time of soundings from (a) R/P FLIP, (b) R/V Sally Ride, and (c) Shore site at Point Mugu. Source: D. Alappattu, email to author, November 5, 2018.

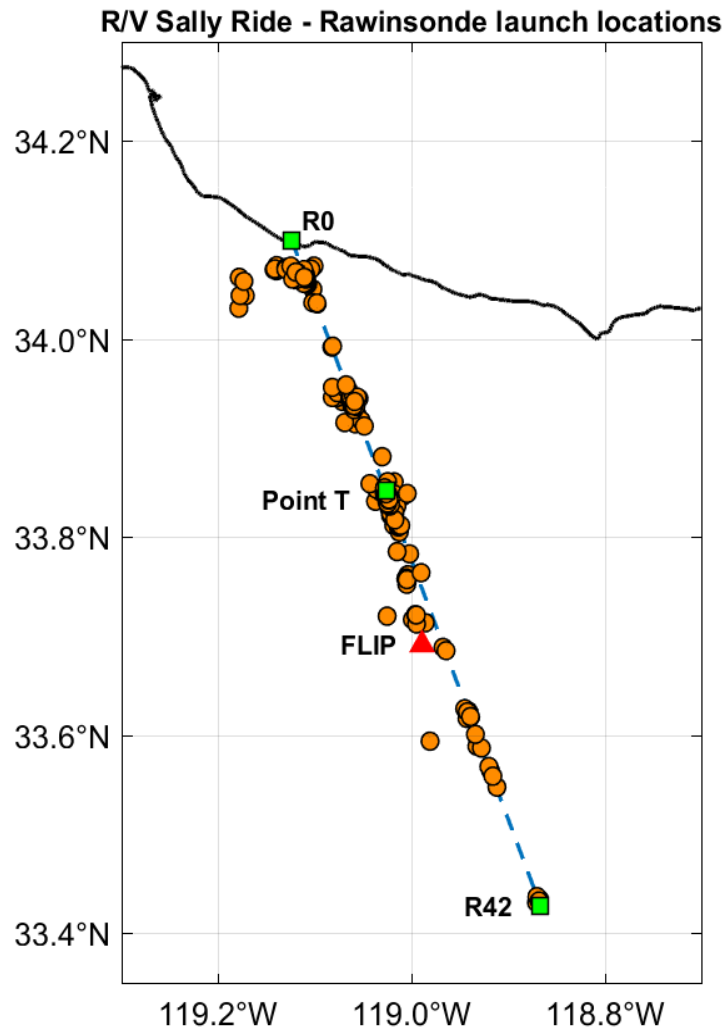


Figure 9. Locations of all soundings from R/V Sally Ride. Source: D. Alappattu, email to author, November 5, 2018.

E. METHOD FOR EVALUATION

A synoptic analysis, in the appendix, has been performed to establish dominant weather patterns for each day of the CASPER West field campaign. Using this analysis coupled with the soundings from the R/P FLIP, the R/V Sally Ride, and the shore site at Point Mugu, characteristics of observed ducting conditions are plotted to show the number of ducts present in each sounding, the type of ducts present, the intensity of the ducts, and

how onshore and offshore flow affected these metrics. Characteristics of RFR profiles are plotted separately to display the statistics of estimated ducts using this technique. Finally, RFR and the observed soundings are plotted together to show the correlation in what RFR estimated and what was observed through soundings. RFR is evaluated at different time lags to determine the best valid time for the estimated profile. Since RFR produces a profile every 30 minutes using RF signal information from the previous 3 hours, evaluating RFR with different time lags is helpful for later work with fusion of RFR with numerical weather prediction.

The height and strength of the duct calculated from RFR is compared with in-situ measurements observed via launched rawinsondes. These duct properties are first detected automatically in MATLAB using the ductDetect.m function created by Dr. John Kalogiros, and further corrected manually to avoid unreasonable identifications of the duct properties. When multiple ducts are present, the strongest duct is chosen to compare with RFR because RFR creates its profiles by estimating gradients of M and is most influenced by the strongest duct feature. The discrepancies between RFR and the in-situ measurements are quantified and organized to evaluate the overall performance of RFR. Consideration is given to in-situ measurements being valid for one point in space, while RFR is path-integrated and valid for an entire area.

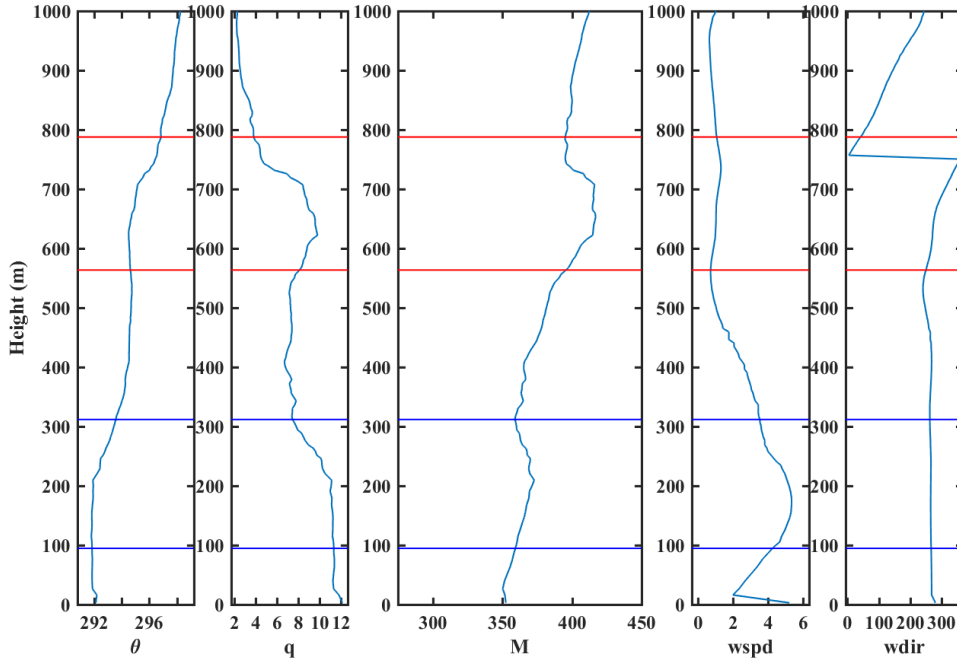
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IV. RESULTS

In this chapter, the properties of the observed ducts will be discussed first to illustrate the general characteristics of the observed ducting layers during CASPER-West. Ducting layer properties derived from the RFR retrieved M-profiles will then be evaluated against the corresponding observed ducts from soundings.

A. CHARACTERISTICS OF OBSERVED DUCTS DURING CASPER WEST

A typical sounding profile from CASPER-West is shown in Figure 10. This sounding was obtained from FLIP on 3 October at 03:12:22 UTC. The M-profile is plotted together with potential temperature (θ), specific humidity (q), and wind speed and direction. Figure 10 shows two elevated ducting layers within the first kilometer of the ocean surface, each indicated by two same-color horizontal lines. These two elevated ducting layers are associated with the double inversion structure of the boundary layer as indicated by both the θ and q profiles. The relatively well-mixed boundary layer in this case was only about 200m deep, which transitioned to a higher mixed layer extending to about 600m above the surface. This second mixed layer topped by another warm and dry inversion is likely part of the boundary layer from an upstream location that was advected to the measurement region. The multi-ducting layers may introduce complicated propagation patterns for low-level transmitters/receivers.



From left to right, the subplots show potential temperature (θ in Kelvin), water vapor specific humidity (q in g/kg), modified index of refraction (M in M-unit), wind speed ($wspd$ in m/s) and wind direction ($wdir$ in degree).

Figure 10. An example of sounding profiles obtained during CASPER-West showing two ducting layer structure in the lowest 1 km of the atmosphere.

Ducting layers from all soundings from CASPER-West were identified in the same way as the example sounding in Figure 10. To avoid getting too many insignificant ducts due to small vertical variations shown in the high vertical resolution sounding profiles, a criterion of 5 M-unit is imposed as the minimum duct strength to be considered a duct. All ducts identified from the soundings launched from R/P FLIP, R/V Sally Ride, and the shore site at Point Mugu are shown in Figure 11. The time period includes all days in the CASPER-West field campaign. The ducting layers from particular sounding are shown as asymmetric error bars where the top and bottom whiskers depict the duct top and bottom, respectively. The circle represents the base of the trapping layer, which is typically at the top of the atmospheric boundary layer. For each sounding, the ducting layers were first

identified automatically using a MATLAB program, sounding, the ducting layers were first identified automatically using a MATLAB program, ductDetect.m, developed by Dr. John Kalogiros. With an input of vertical profiles of the modified index of refraction, M , this program outputs duct top, duct base, trapping layer base, duct strength, and duct type for all ducts detected from a single M -profile.

Figure 11 shows all detected ducting layers from all soundings launched from each of the three sites/platforms. There are strong temporal variations of the observed ducting layers throughout the CASPER-West measurement period. In general, the two at-sea platforms show similar ducting layer variations where periods of deep elevated ducting layers occurred in between periods of low and single ducting layers. The single and shallow ducting layers, normally below 200 m, tend to occur during periods of strong offshore wind events. Very often, multiple elevated layers occurred in cases of high elevated ducting layers above ~600 m. Although the shore site soundings show similar temporal variations as R/P FLIP and R/V Sally Ride, the elevated ducts at shore are in general lower and multi-ducting layer structure is not as prominent as those from platforms at sea.

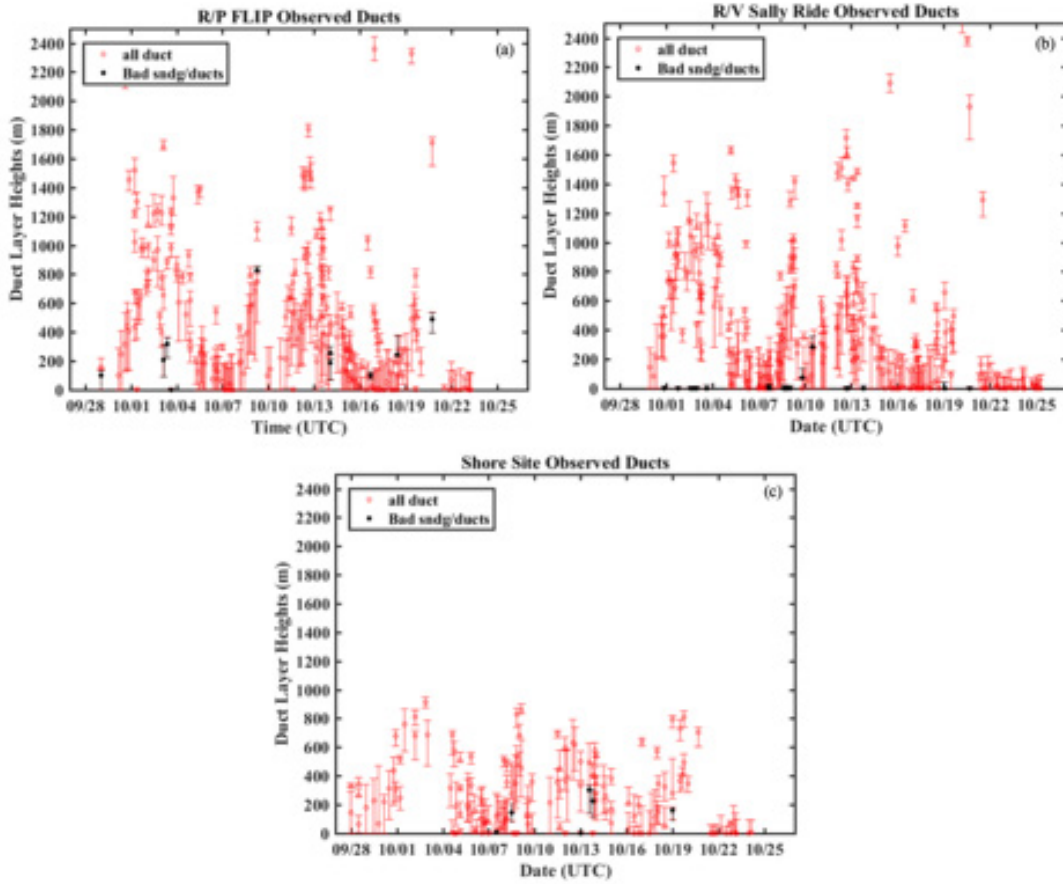


Figure 11. Ducting layers identified from sounding profiles. Erroneously identified ducting layers are depicted in black. The top and bottom whiskers depict the duct top and bottom, respectively. The circle represents the base of the trapping layer for each duct. (a) Measurements from R/P FLIP; (b) R/V Sally Ride; and (c) shore site at Point Mugu.

An important step in this thesis work is to quality control the ducting layers identified from all soundings. Erroneous ducts may be identified for various reasons. We manually inspect all sounding profiles to ensure the accuracy of the observed ducting layers that will be used to evaluate RFR retrieval technique. The most often identified erroneous ducting layers from the soundings are those close to the surface. Figure 12a shows one such example where a trapping layer is identified between the surface and about 10m above the surface. A close up of this figure is given in Figure 12b. One can see that the trapping layer is a result of high moisture at a single level closest to the surface. The sounding was

released from the ship deck at about 9m, so the lowest level at 3.7m is likely a result of Vaisala's proprietary data processing scheme and should not be trusted. Similar instances of this effect were observed in other soundings, resulting in the detection of erroneous surface ducts, which can be mistaken as evaporation ducts. The data QC process also involved removing bad sounding data or mistakes in the automatic ducting layer program due to unforeseen complicated profiles. This is completed by generating a figure that is the same as that in Figure 12a and then manually reviewed for 'unusual behavior' of the sounding profiles of multiple variables. Bad soundings included those that showed unreasonable M values, or when the sounding prematurely terminated leaving a sounding profile in very limited altitude range that not sufficient for the range of the sounding. Bad portions of soundings included bad ducts that are artifacts from the influence from the ship's superstructure which are not representative of the true environment. It was found that R/V Sally Ride had the most influence on low level observations due to the presence of the large ship structure and its thermal and dynamic influences on the immediate surroundings. Most of the time, the rawinsondes must be launched on the leeside of the ship so that the wind does not carry the balloon into the ship's radar systems. The lowest levels of the sounding are hence likely modified by the air from the deck. In some cases, the balloon did not ascend as quickly as the spool of string that held the rawinsonde was unraveling, so the rawinsonde descended at launch before it began to ascend. This initial short descent put the rawinsonde in an area where the winds were directly blocked by the ship's hull. The interference of the ship on the ambient flow can be seen clearly in the R/V Sally Ride data shown in Figure 12b with many unreal ducts at the surface. This effect did not happen as often on the R/P FLIP because sounding launches were made on the face boom away from the FLIP hull. This launch location provided a 'clean' spot that minimize its impact on atmospheric flow.

An example of a wrongly identified duct at the surface is given in Figure 12 on the M-profile, where the blue horizontal line indicates the top of the surface duct. In this case, as with most other cases, the presence of the ship modified the wind, temperature, and humidity close to the surface in the vicinity of the ship where the rawinsonde was released into. This leads to the false detection of a surface duct. In most cases, the height of the top

of the duct layer is less than 30 m. This happened more frequently on the R/V Sally Ride (Figure 12b), but there were some cases on R/P FLIP as well. The shore station at Point Mugu also had some false surface ducts, but they were likely due to difficulties at launch, or effects from surrounding buildings. Most false surface ducts encompass less than 3 points of data from about the first 3 seconds of a rawinsonde launch sampled at 1 Hz. Table 3 summarizes the occurrence of false surface ducts in all three locations. About 20% of the R/V Sally Ride soundings gives a false surface duct, whereas only 11% of the soundings show similarly identified false surface ducts.

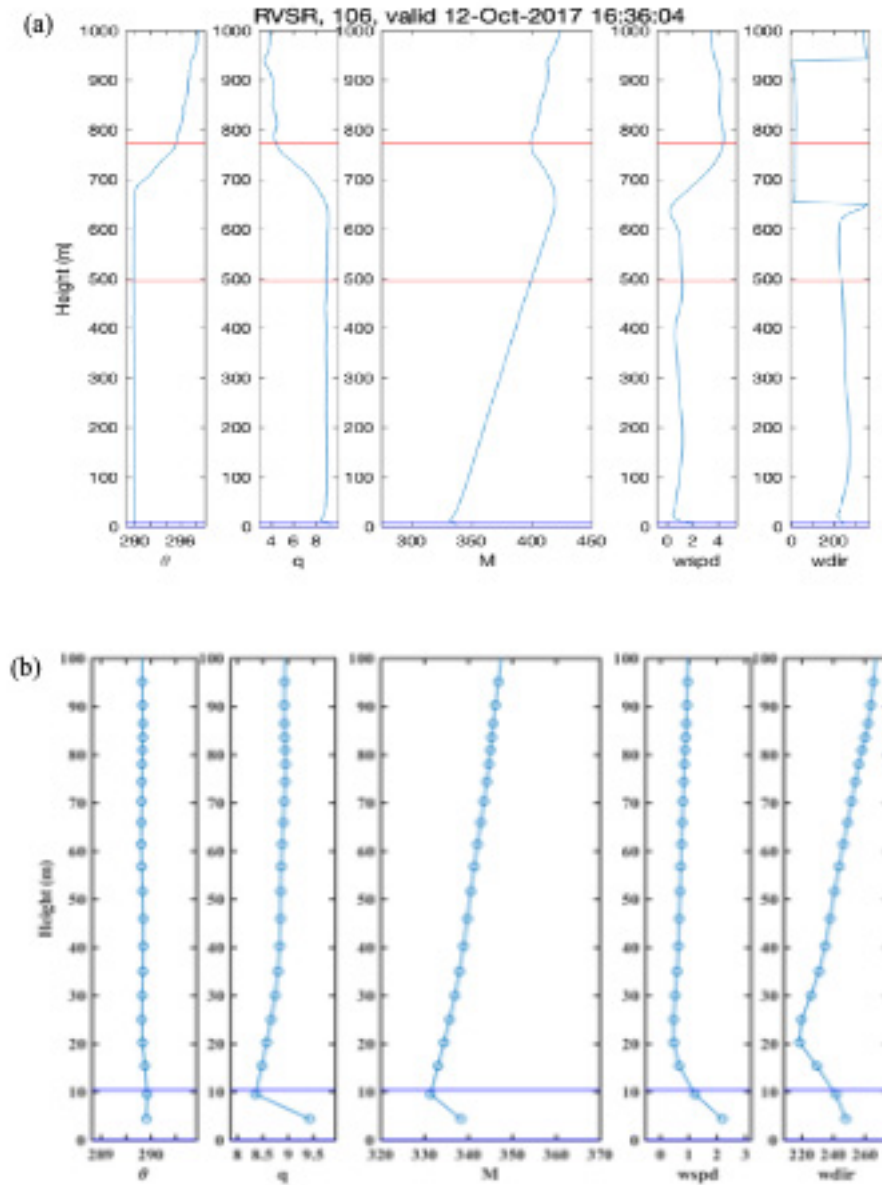


Figure 12. An example of a false duct from an observed sounding from the R/V Sally Ride. (a) sounding through the lowest 1 km from the surface; (b) the same sounding zoomed to the lowest 100 m with the measured data points denoted as a 'o'. The horizontal lines denote the boundaries of the identified ducts.

Table 3. Total number of soundings and percentage of false detected surface ducts at each site.

Station Name	Total Number of Soundings	Percentage of False Surface Ducts
R/P FLIP	183	7%
R/V Sally Ride	217	20%
Shore Site	138	12%

The number of ducts observed in each sounding is plotted in Figure 13 following the time sequence. This figure shows the likelihood of complicated ducting conditions in this area with a maximum of seven ducts sampled at R/V Sally Ride on 13 October. Although the presence of seven ducts observed in a single sounding rarely occurred, three to five ducts were quite common. Similarities between the R/P FLIP and R/V Sally Ride soundings on number of ducting layers are also shown in Figure 13. Some time periods tend to have more layers of elevated ducts, such as 1–4 October and 12–16 October. An increase in the number of ducts on 14 October is indicative of a layered structure within the atmosphere. As noted in the appendix, a strong high pressure system was building in the area, a favorable condition leading to the onset of offshore wind event on the following day. During the offshore wind event started on 15 October, the number of ducts at all stations decreased.

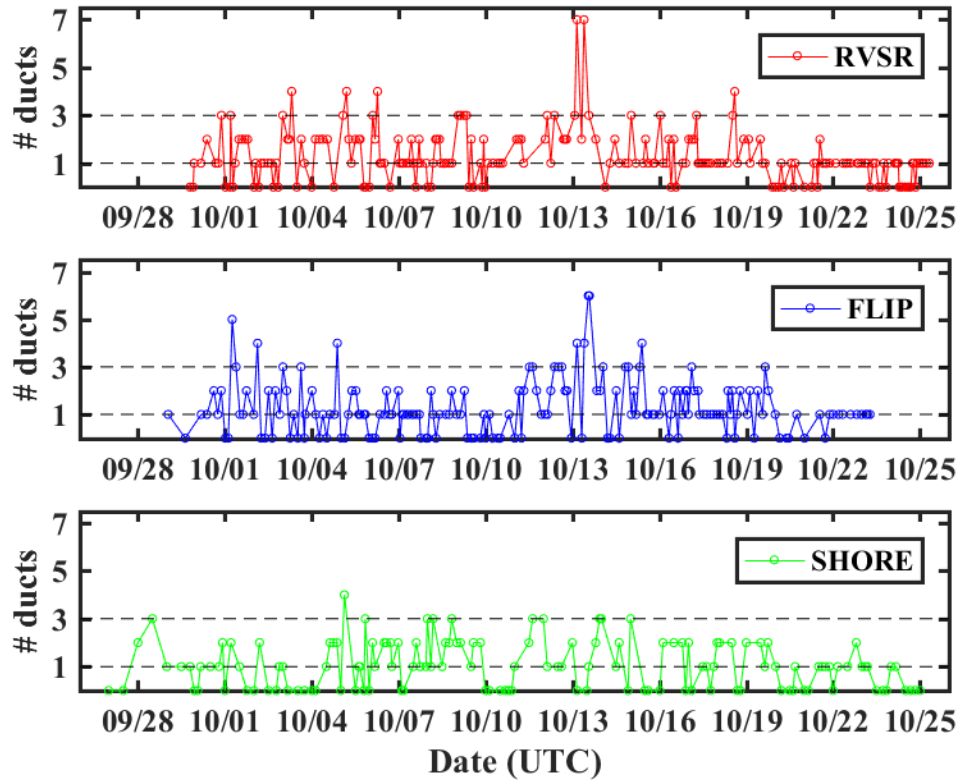


Figure 13. The number of ducts identified from each sounding launched from R/V Sally Ride (top), R/P FLIP (middle) and the shore station (bottom).

The frequency of occurrence of the number of ducts observed in each sounding is also plotted for all platforms in Figure 14 for R/P FLIP, the R/V Sally Ride, and the shore station. We chose to use frequency of occurrence instead of the absolute number because the total number of rawinsonde launches were different at different sites (Table 3). Results from R/P FLIP and R/V Sally Ride are very similar with a dominant peak of 42% and 47% for the single ducting layer, respectively. No ducting cases occurred at 25% on R/P FLIP and 21% on R/V Sally Ride. Two ducting layers occurred equally at 20% rate for both at-sea platforms. The shore site at Point Mugu had a high occurrence of zero ducts (36%) followed by one duct (31%) and two ducts (24%). For all three sites, the occurrence of 3 ducting layer is about 7%. We examined the number of ducts at different time of the day, no preferences were observed at any sites.

A strong high pressure building along the coast on 13–14 October increased the number of ducts observed at all stations. This was preceding an offshore wind event on 15 October, which decreased the number of ducts observed at all stations.

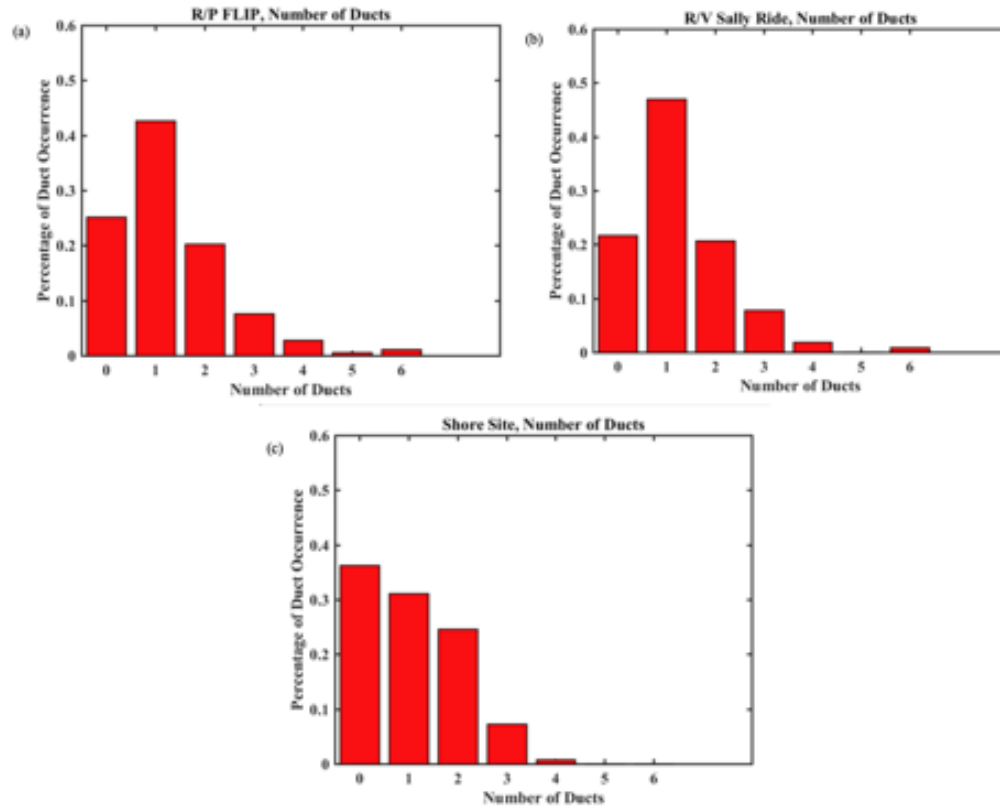


Figure 14. Histogram of percentage of occurrences of number of ducts present in each sounding launched from (a) R/P FLIP; (b) R/V Sally Ride; and (c) Shore site at Point Mugu.

The following discussions will focus on ducts of maximum intensity from each sounding with the hypothesis that it is the duct layer that affects RF propagation the most and hence most relevant to those sensed by the RFR technique. Figure 15 shows the intensity of the lowest four ducts identified from each sounding from all three sites. The notation is that ‘duct 1’ is the duct closest to the surface, and ‘duct 2’ is the duct above that, and so on. Ducts numbered above 4 were not plotted because their strength compared to

other ducts was negligible. The duct with the maximum intensity is plotted with a black dot. Maximum intensity ducts are chosen to compare to RFR because RFR tends to estimate the strongest duct present in the atmosphere as it focuses primarily on gradients of M.

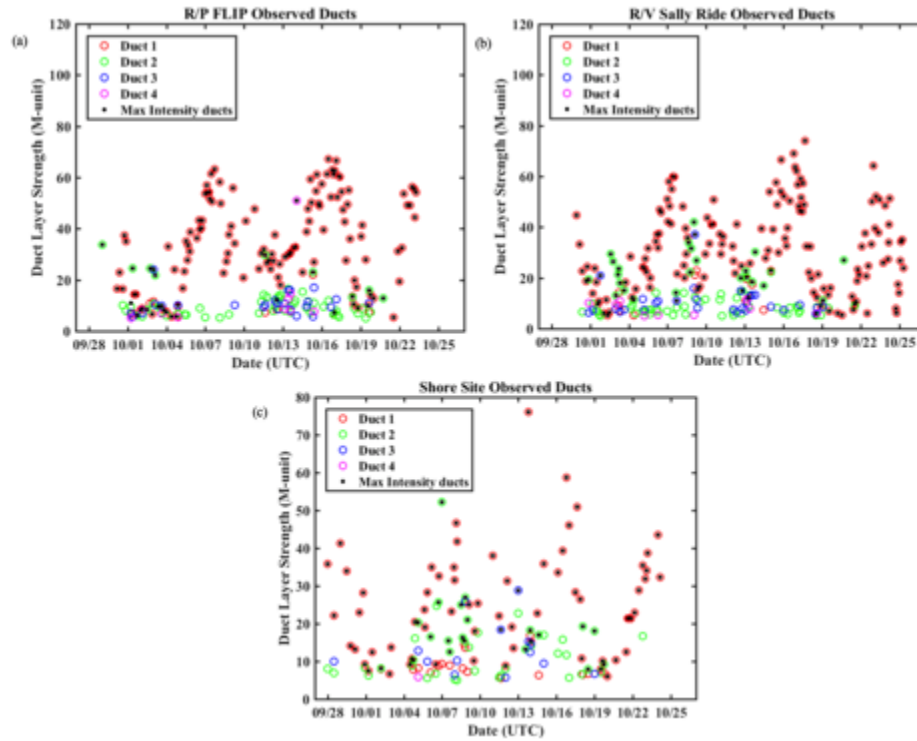


Figure 15. Duct intensity of the lowest four ducting layers from (a) R/P FLIP; (b), R/V Sally Ride; and (c) shore site at Point Mugu. The ducting layer with maximum intensity is filled with a black dot.

Figure 15 reveals several interesting features of the observed ducts. First, the ducts of maximum intensity are indeed much stronger than the rest of the ducts at all sites. This suggests that there is indeed a dominant duct from most of the soundings, a condition favorable to RFR retrieval. The less prominent ducting layers usually have duct intensity around 10 M-units and less than 20 M-units. The strongest ducts in the soundings have a duct strength of 20 to 70 M-units. Secondly, large variations were observed in the strength of the strongest ducts. The strongest ducts are seen around 7, 16, and 23 of October corresponding to the time periods of offshore flow and predominantly single surface-based

ducts. The similarity between the results from R/P FLIP and R/V Sally Ride suggests spatial homogeneity in the region of ducting conditions. The elevated ducts tend to be rather weak, about 20 M-units at both at-sea platforms. In comparison with the maritime soundings, the shore site ducts during the offshore wind conditions are weaker although no significant differences are observed on the strength of the elevated ducts compared to the maritime soundings. The strongest ducts will be used to evaluate RFR results.

The height range of the identified strongest ducts are compared to other ducting layers as shown in Figure 16. The strongest ducts are depicted in blue, and all other ducts present in each sounding are depicted in red. The temporal variation of the maximum intensity ducts is strongly tied to the synoptic conditions. Duct heights begin to increase on 1 October and reach a peak on 4 October. The duct heights begin to lower on 5 October and reach a minimum on 7 October. The duct heights increase again on 9 October. They decrease again on 10 October before increasing again through 13 October. The duct heights again reach a minimum from 15 October through 18 October as an offshore wind event occurred on 15 October and effects of this wind event could be seen through 18 October. This trend of variation is consistent in all three sounding sites.

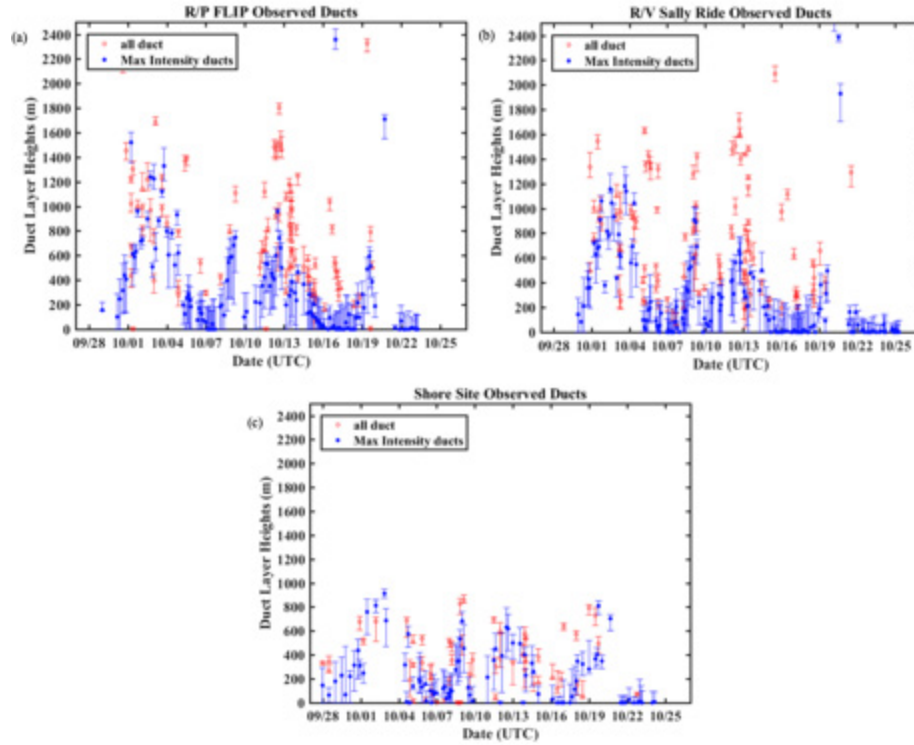


Figure 16. Temporal variation of all observed ducts with the strongest ducts highlighted in blue color. (a) R/P FLIP; (b) R/V Sally Ride; and (c) shore site.

Observations were further analyzed to identify the strongest ducts with respect to duct types of surface, surface-based, and elevated ducts (Figure 17). Surface and surface-based ducts were frequently observed during the offshore wind events. Relatively weak elevated ducting layers were encountered during the ‘other’ wind direction without an offshore component of the wind. In addition, the occurrence of the three duct types is very consistent among all sounding sites.

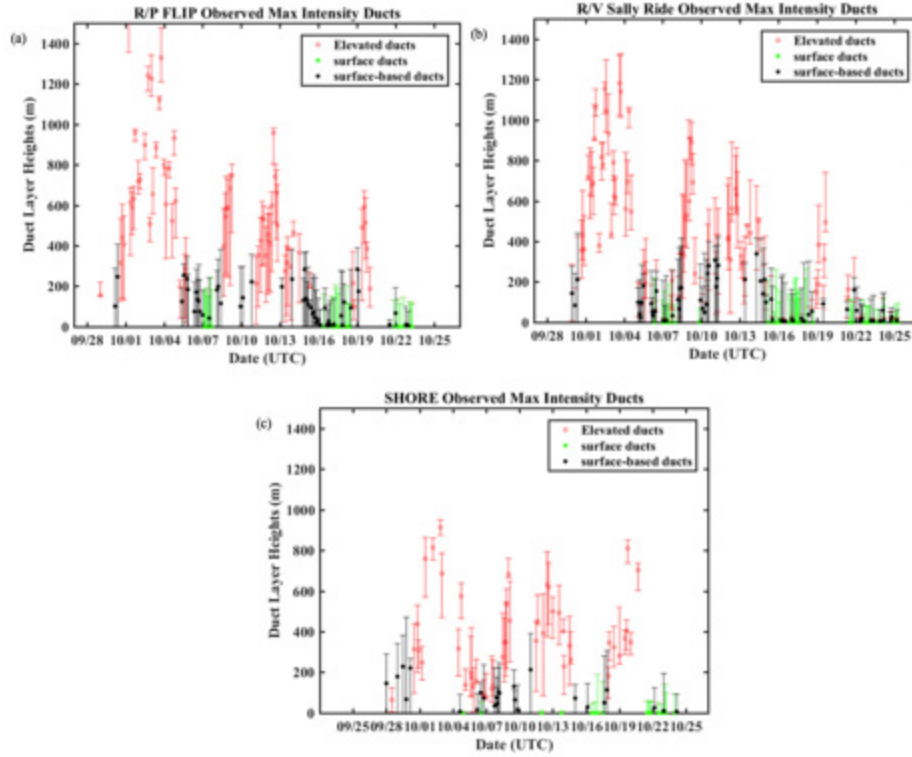


Figure 17. Temporal variation of observed ducts separated by duct type. (a) R/P FLIP; (b) R/V Sally Ride; and (c) shore site at Point Mugu.

Properties of the maximum intensity ducts, such as trapping base height, duct top height, duct thickness, and duct strength are shown for each station in Figures 18–21. On some days the ducts at each station show similar properties, which indicates that the atmosphere was relatively homogeneous over all three locations. This is notable on offshore wind event days such as 9 October, 15 October, and 23 October. On other days, there was a departure between the stations to suggest that the atmosphere had significantly different humidity and temperature measurements that would affect EM ducting differently at each location. This is most prevalent on days, such as 2–4 October, where there was not a significant offshore wind event and the mesoscale meteorology in the CASPER-West operating area was dominated by the diurnal land-sea breeze. The overall temporal variation of duct top heights and trapping base heights is similar at all three locations.

Trapping base heights begin to increase on 1 October and reach a peak on 4 October at all stations. This coincides with the duct top height increases over this time period. This

time period corresponds with weaker duct strength as shown in Figure 21. Low clouds were observed throughout the morning on these days with a cool upper trough passing through the area and lifting cloud bases by 4 October, 2017.

The trapping base heights begin to lower on 5 October and reach a minimum on 7 October. These days experienced clear conditions with station pressures rising on 5–6 October, then falling by 4–5hPa on 7 October. The trapping base heights increase on 9 October when a weak offshore wind event occurred. They decrease on 10 October as high pressure continues to dominate the operating area and low clouds were observed in the morning. Trapping base heights increase through 13 October. The duct heights again reach a minimum from 15 October through 18 October as an offshore wind event occurred on 15 October and effects of it could be seen through 18 October. The timing of variations in these figures is consistent with the passage of mesoscale and synoptic weather systems, and strongly suggest the impacts of those systems on ducting.

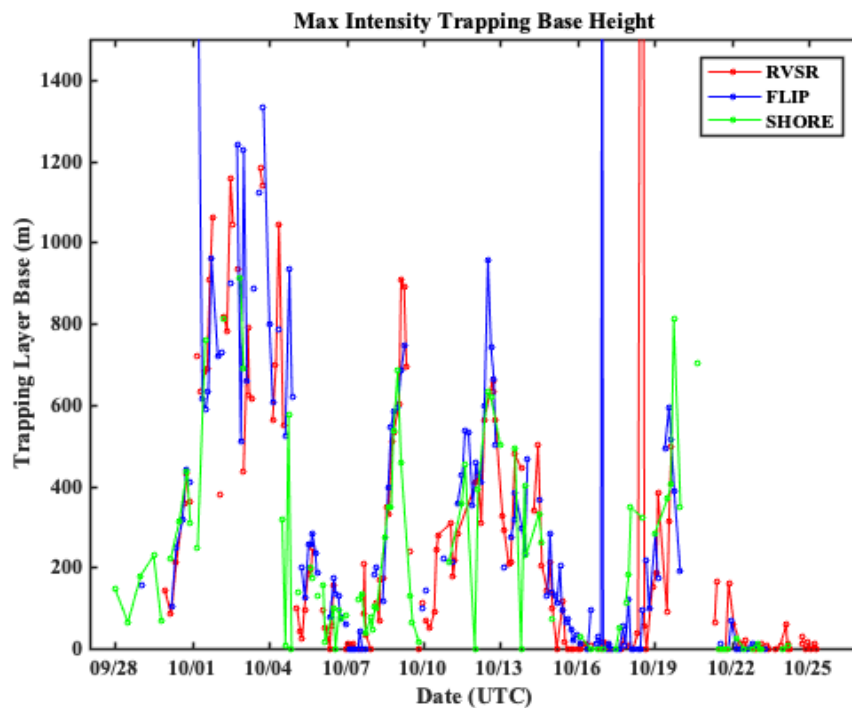


Figure 18. Time series of trapping base height of strongest observed duct at all sounding stations.

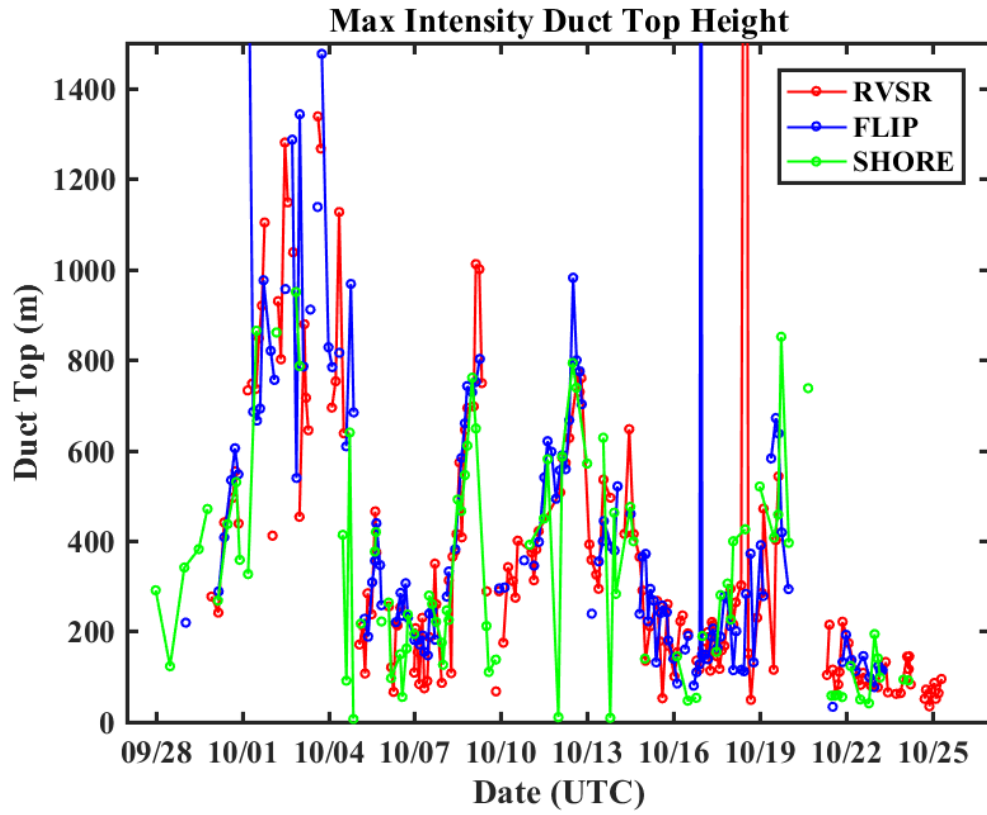


Figure 19. Time series of duct top height of strongest observed duct at all sounding stations.

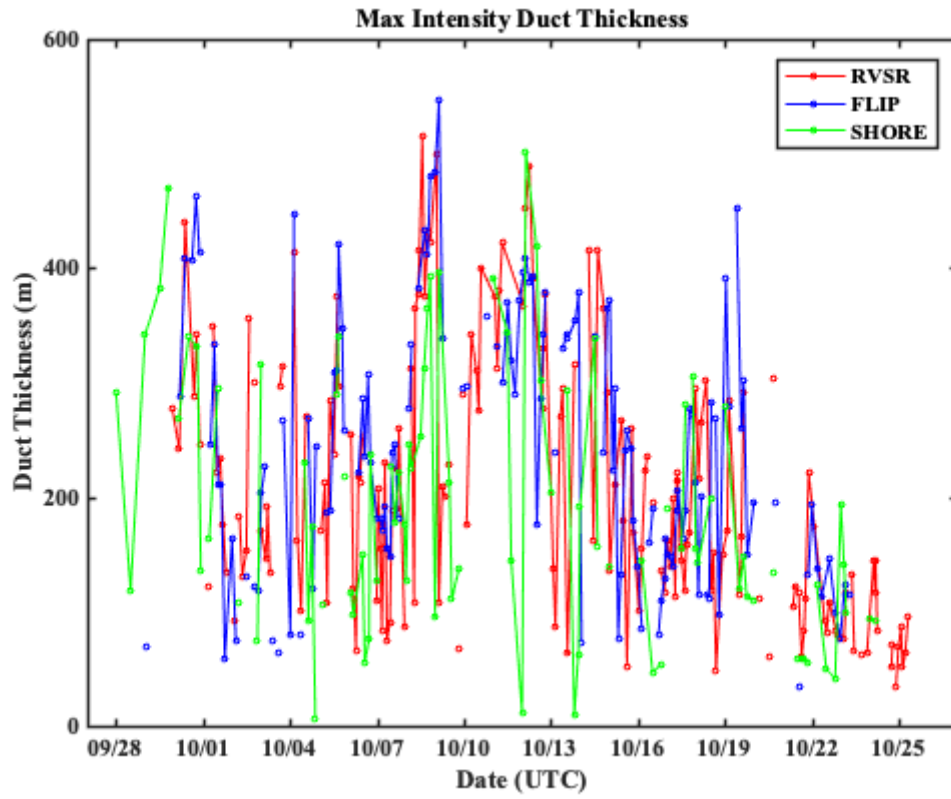


Figure 20. Time series of duct thickness of strongest observed duct at all sounding stations.

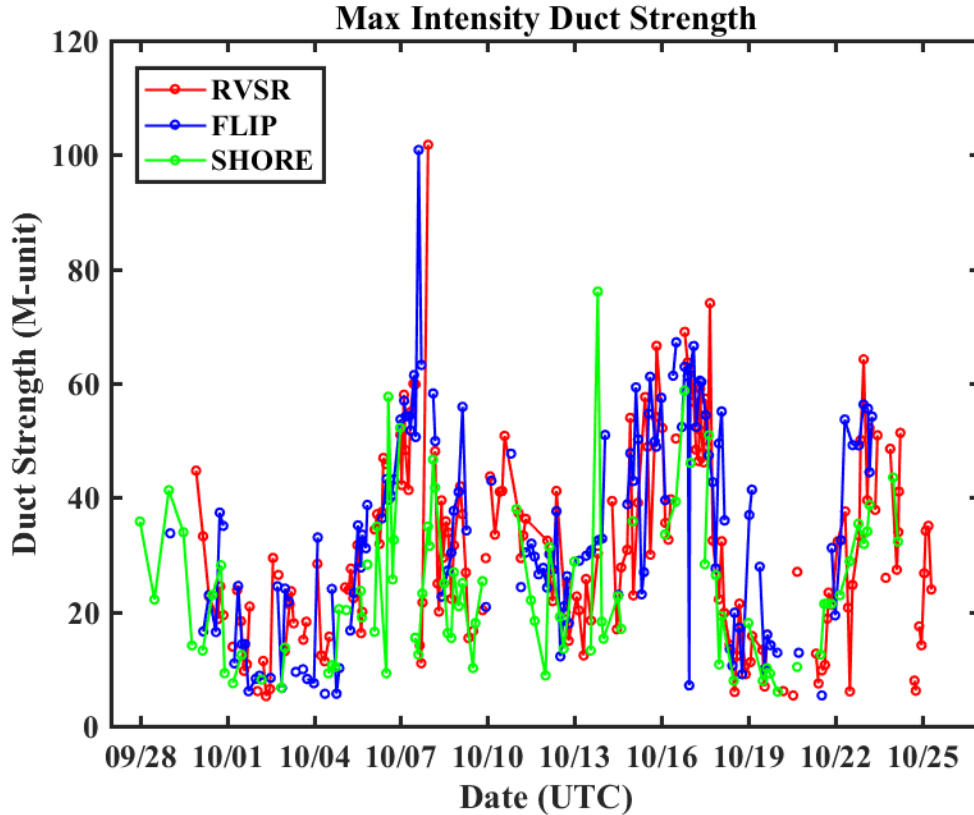


Figure 21. Time series of duct strength of strongest observed duct at all sounding stations.

B. CHARACTERISTICS OF RFR RETRIEVED DUCTING ENVIRONMENT

In the same way that the observed soundings were previously characterized and described, the estimated ducts from RFR retrievals are described in this chapter. Estimated duct layer heights that were retrieved using the antenna mounted on the port quarter of the R/V Sally Ride are shown in Figure 22. Since RFR predominantly estimates the duct using a trilinear profile and most of the analyzed days were during the occurrence of offshore wind conditions, most of the ducts in this figure are surface-based ducts. Although there are some instances of elevated ducts on 19–20 October, the primary focus of the RFR developers at this time is to accurately represent the strongest low-level ducts.

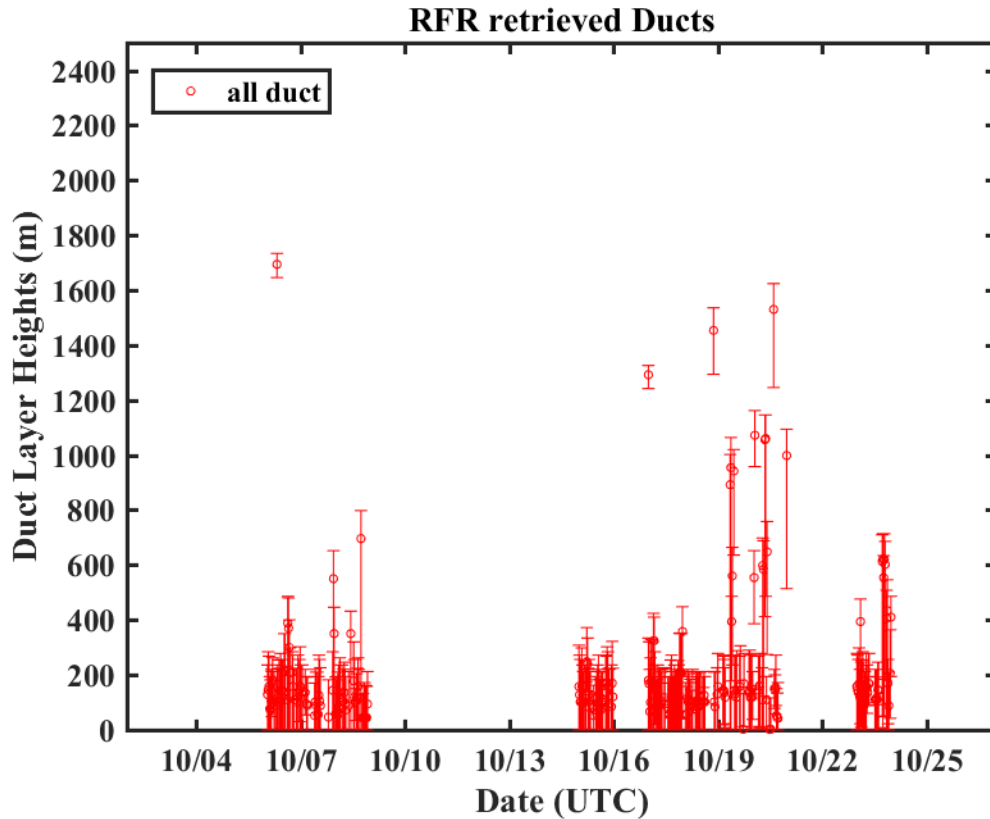


Figure 22. All ducting layers from the RFR retrieved M-profiles.

The frequency of occurrence of the number of ducts estimated in an RFR profile is plotted in Figure 23. Almost 70% of RFR profiles feature one duct, which is expected as it uses a trilinear profile to estimate atmospheric ducts. Approximately 35% of the profiles do not show the presence of a ducting layer. This percentage is higher than the lower 20% in the R/P FLIP and R/V Sally Ride soundings (Figure 14a, 14b), but close to the shore site soundings (Figure 14c). This may indicate that shore-based links that are used to create the combined profiles in RFR have some influence on the results.

Most profiles should have 0 or 1 duct because the profiles estimate duct structures with a trilinear structure. There are some profiles that have more than 3 lines to try to estimate elevated ducts, but this technique is new and being developed further by HS Owen LLC.

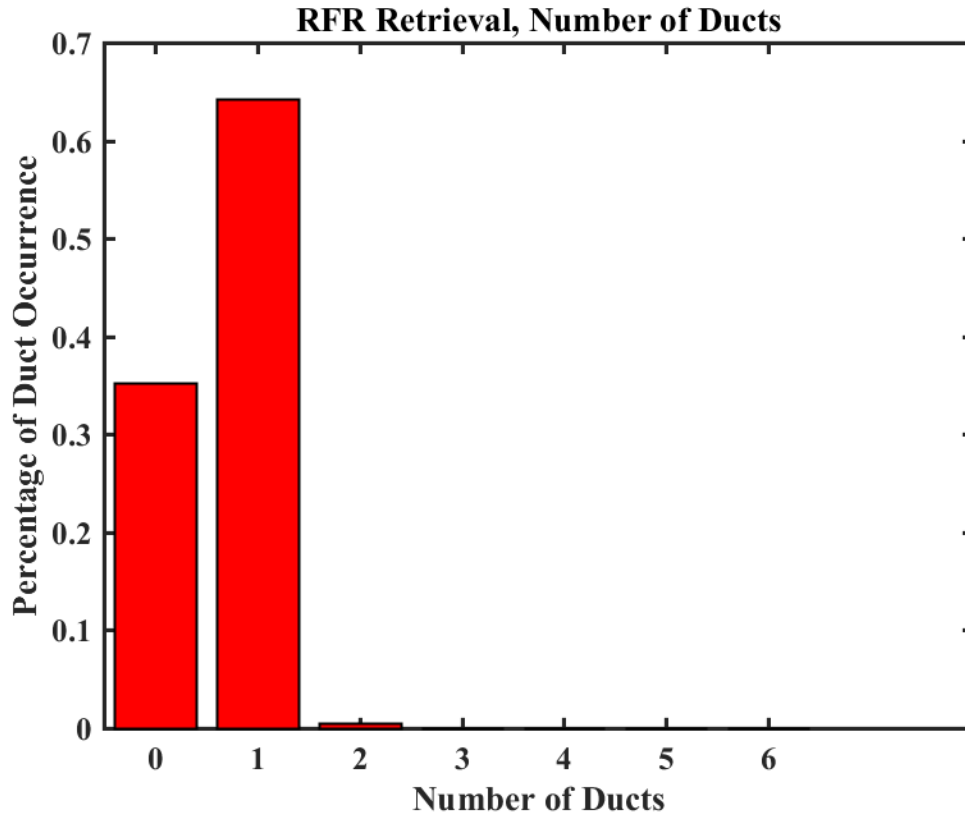


Figure 23. Percentage of occurrences of the number of ducts present in each RFR profile.

Since RFR produced mostly a single ducting layer, the ducting layer with maximum strength intensity is the single ducting layer, with the exception of two cases where a higher weaker duct was detected (Figure 24).

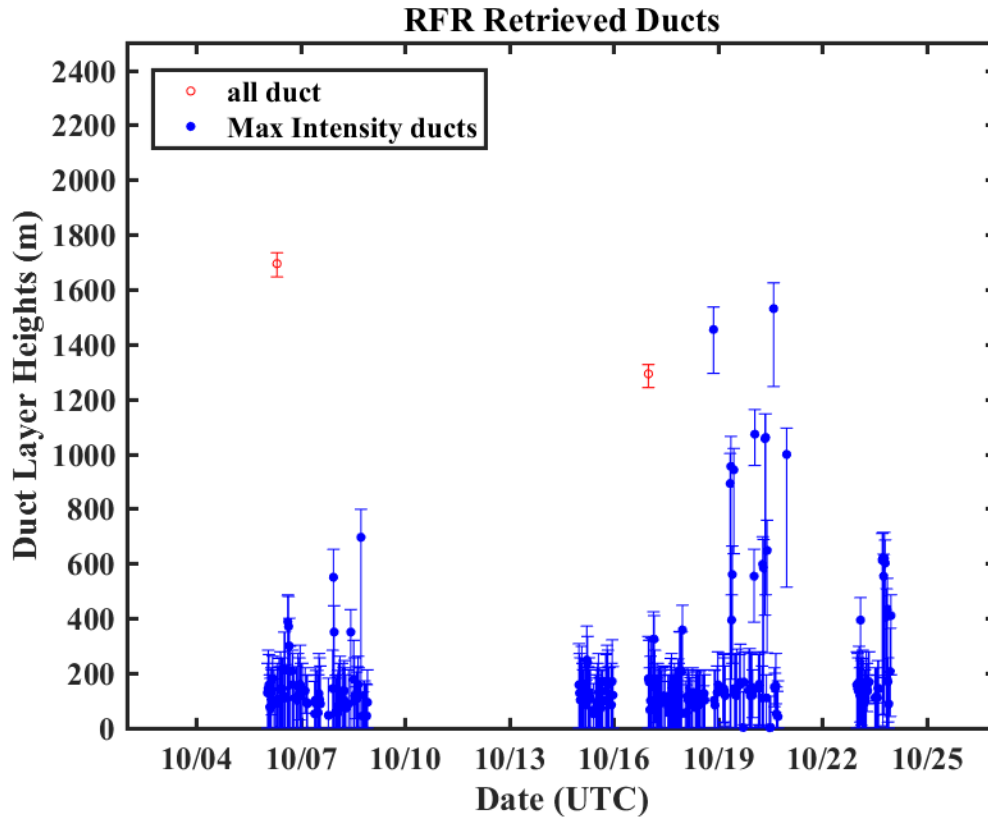


Figure 24. Ducting layers from all RFR retrieved M-profiles. The strongest ducts are depicted in blue, and all other ducts present are depicted in red.

The ducts estimated by RFR are further separated into different duct types as presented in Figure 25. The type of duct is depicted with elevated ducts in red, and surface-based ducts in black. Figure 25 shows predominant surface-based ducts although elevated ducts were also detected in the later days. Because of the trilinear assumption for the retrieved M-profiles used by the RFR technique, no surface ducts result from the retrieved M-profile. A bilinear or more sophisticated estimate of the M-profile is needed to represent surface ducts. The time series plot in Figure 25 includes all data that were provided by HS Owen LLC in Table 2. Quality control has been applied to these figures, omitting results that have a max overlap ambiguity error of more than 0.95 and/or max mode error of greater than 10.

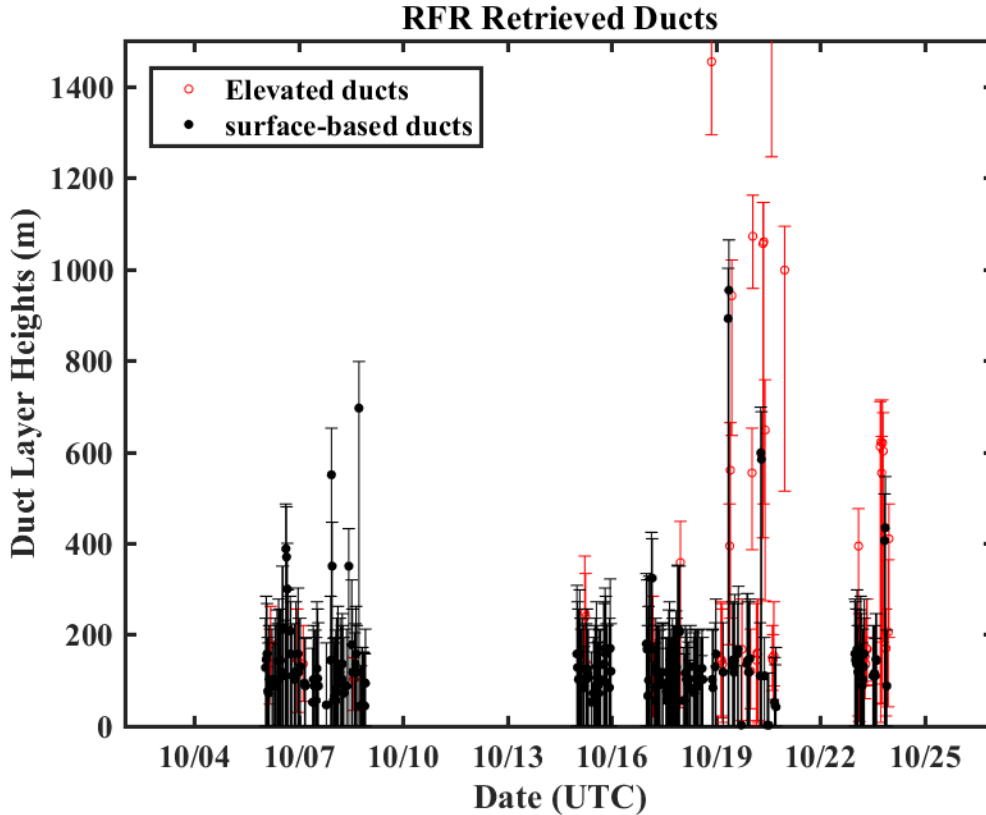


Figure 25. Ducting layers from all RFR retrieved M-profiles. The strongest ducts are depicted in blue, and all other ducts present are depicted in red.

C. RFR DERIVED DUCTING LAYERS COMPARED TO OBSERVATIONS

In previous sections, the characteristics of observed soundings and RFR have been established and described independently. In this section, RFR is compared directly to observed soundings.

1. All RFR Data Compared to Observations

All RFR profiles that matched the time of an observed sounding were overlaid to visually understand how RFR compared with observations. An example is shown in Figure 26 where the RFR combined profile is shown in cyan in the middle subplot for M-profiles, with the observed sounding from the R/P FLIP plotted in blue. This is an example of a well-matched RFR profile to an observed sounding where the RFR combined profile

accurately estimated the height of the duct top as well as the strength of the duct. The sounding shows the presence of multiple ducts, each is denoted in separate corresponding colors. It is expected that the trilinear profile of RFR was not able to represent such features. Hence, this case shows the potential need to further develop RFR to estimate elevated ducts in addition to identifying the strongest surface-based ducts if the elevated features are significantly strong. In Figure 27a, the same information as in M-profiles in Figure 26 is shown with the ducting layers from both observed and RFR profiles indicated. Figure 27b gives more details on the profiles from each individual link that contributed to the final combined profile. The RFR links that contributed to the well-matched combined profile are mostly from ships. In this case, the different links gave rather similar results with the exception of one (yellow). It, however, did not bias the combined profile significantly.

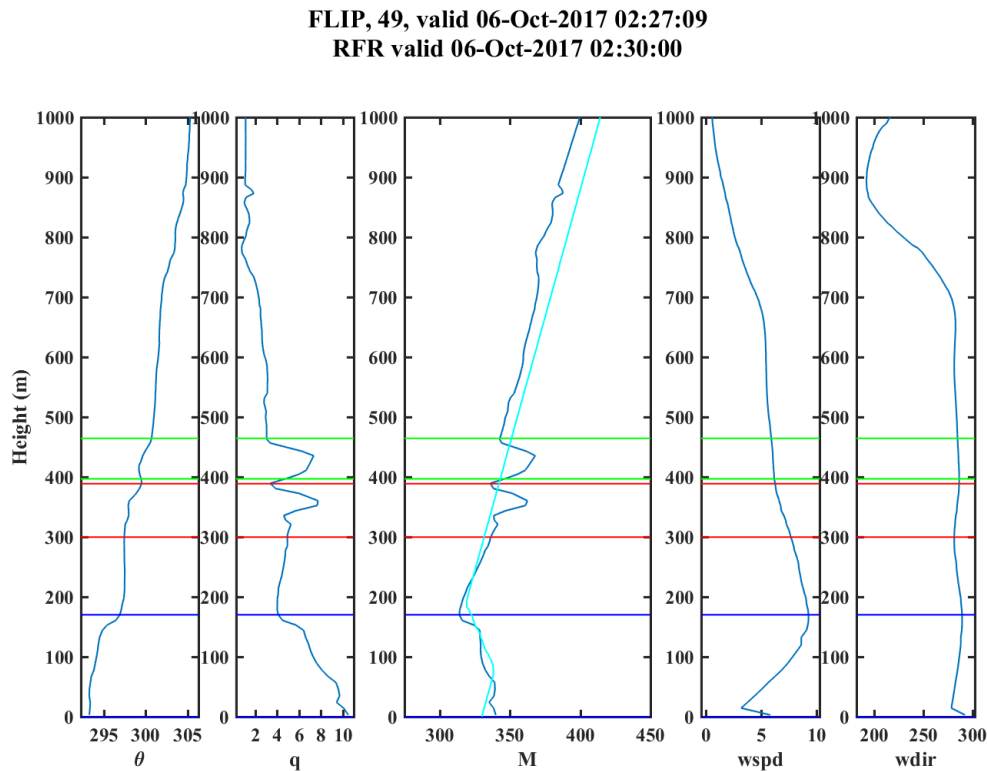


Figure 26. Observed sounding from R/P FLIP with the RFR-retrieved M-profile. From left to right: Potential temperature, specific humidity, modified refractivity, wind speed, and wind direction. The RFR combined profile is plotted in the M-profile plot in cyan.

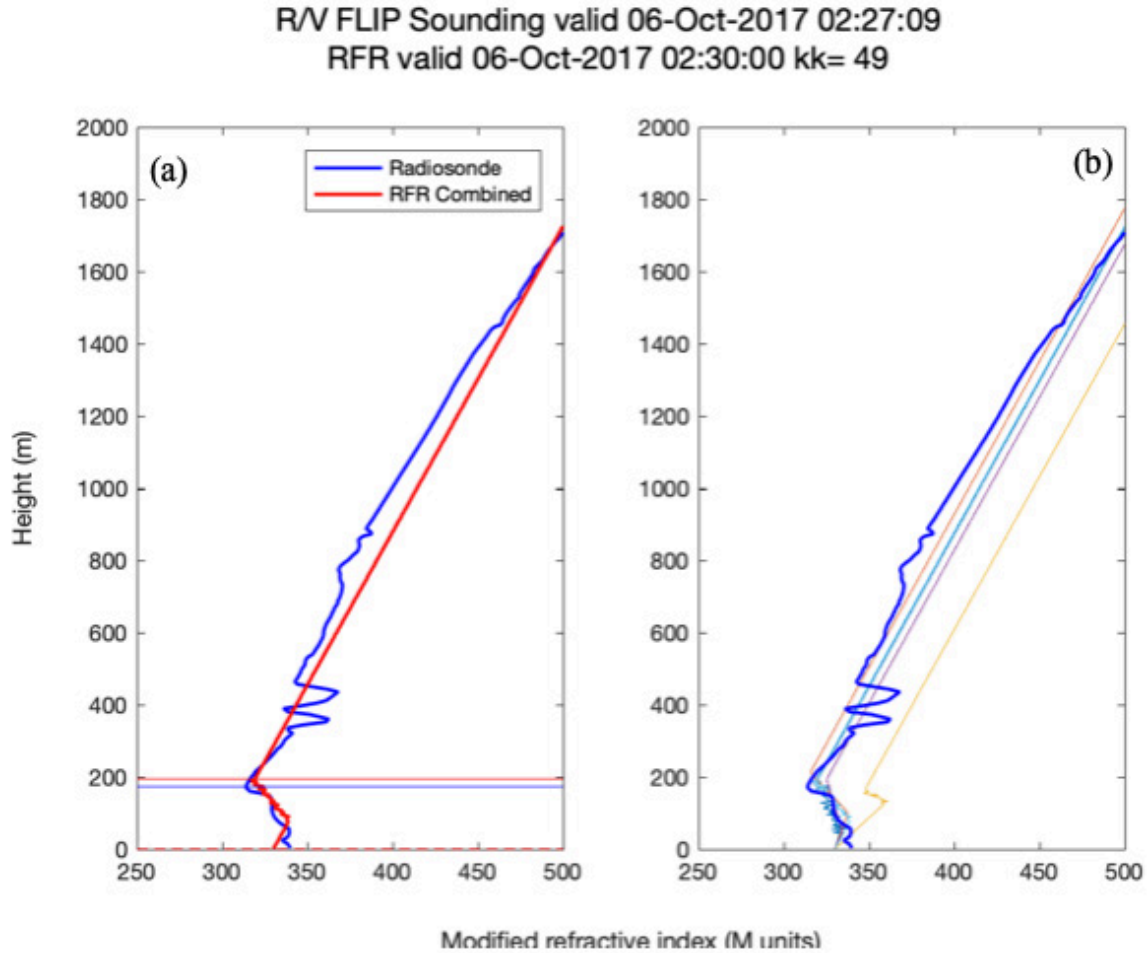


Figure 27. An example of a good result from RFR retrieval. (a) Observed sounding from R/P FLIP and RFR combined profile. The horizontal lines show the detected duct boundaries. (b) Observed sounding from R/P FLIP (thick dark blue) and RFR profiles from individual links from RFR. The thick cyan profile is the combined profile.

An example of a poorly matched RFR profile to an observed sounding is shown in Figures 28 and 29. In this case, some of the individual links that contributed to the combined profile, as shown in Figure 29b, were closer to the observed sounding than the combined profile. The weak elevated duct may have influenced the RFR combined profile to yield a higher duct than it otherwise would have been if the elevated duct was not present.

FLIP, 140, valid 17-Oct-2017 00:01:18
RFR valid 17-Oct-2017 00:30:00

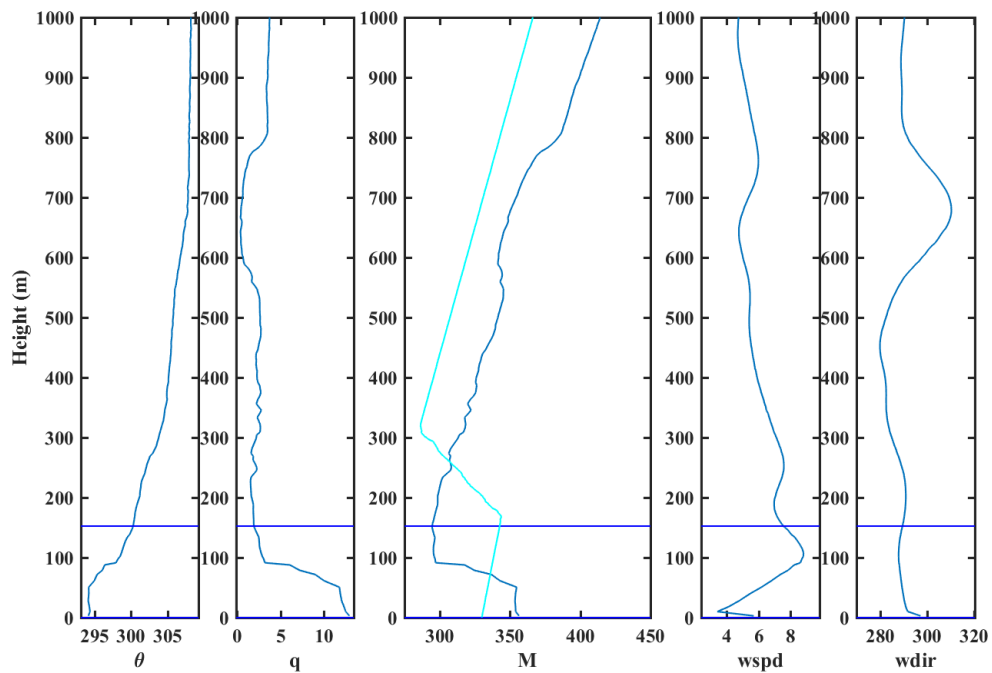


Figure 28. Observed sounding from R/P FLIP. From left to right: Potential temperature, specific humidity, modified refractivity, wind speed, and wind direction. Poorly matched RFR combined profile is plotted in the middle box in cyan.

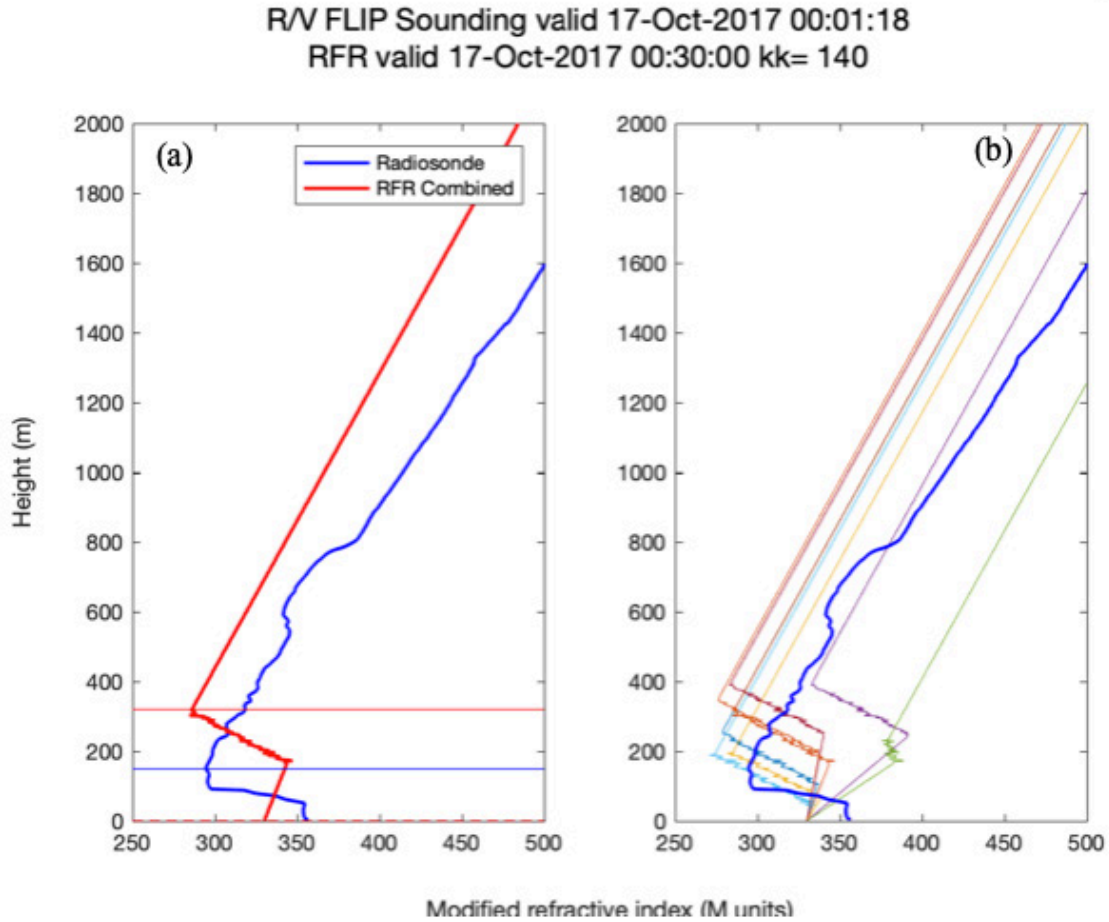


Figure 29. An example of a bad result from RFR retrieval. (a) Observed sounding from R/P FLIP and RFR combined profile. The horizontal lines show the detected duct boundaries. (b) Observed sounding from R/P FLIP (thick dark blue) and RFR profiles from individual links from RFR. The thick orange profile is the combined profile.

To compare the observed soundings from R/P FLIP, R/V Sally Ride, and the shore site at Point Mugu with RFR combined profiles, the time from the sounding was matched with the time of the RFR profile. RFR include signals from the previous three hours and report a retrieved result at the end of the three-hour period. Since the weighting of signals in the retrieval was not linear (Owen, H., personal communication), the optimal time stamp of the RFR signal requires an empirical study. For this reason, multiple time-lags were tested in order to determine the appropriate time for which the RFR profile is valid. A range of time lags were chosen in 15-minute increments in the range of 0–90 minutes. As

examples, Figures 30 and 31 show time series comparisons of duct top heights between observed soundings and RFR profiles with a 0-minute and 30-minute time lag, respectively. When the duct height is observed to be lower, as is the case around 7 October, the RFR results are reasonable at all three locations. On 8 October, when static pressures started to fall and morning clouds lingered into the early afternoon, the duct heights begin to rise. For the most part, RFR duct heights remained low and did not pick up on this event. There are a few points that may have started to follow the trend, but there is no RFR data on 9–14 October to evaluate its accuracy. The 30-minute time lag appears to be better in representing this trend than the 0-minute time lag. A similar trend occurred from 18–19 October when wind speeds and sea state was increasing due to a low pressure system that extended down the entire west coast. The observed duct heights began to rise, but the estimated duct height from RFR retrievals remained to be lower. There are still a few points that may have picked up on the trend, but overall, RFR duct heights were lower than observations on these days.

RFR performed well on 15 October during an offshore wind event that kept duct heights low. A stronger offshore wind event occurred on 23 October that could be seen from the surface up to the 500 mb level. On this day, RFR estimated the duct height to be too high.

Overall, the trends in the time series are better with the 30-minute time lag than the 0-minute time lag. RFR tends to perform better below 400 m with surface ducts and surface-based ducts. Time lags were reviewed in 15-minute increments up to 90 minutes, but the 0 and 30-minute time lags were chosen to be shown as they were the most representative of the performance of RFR.

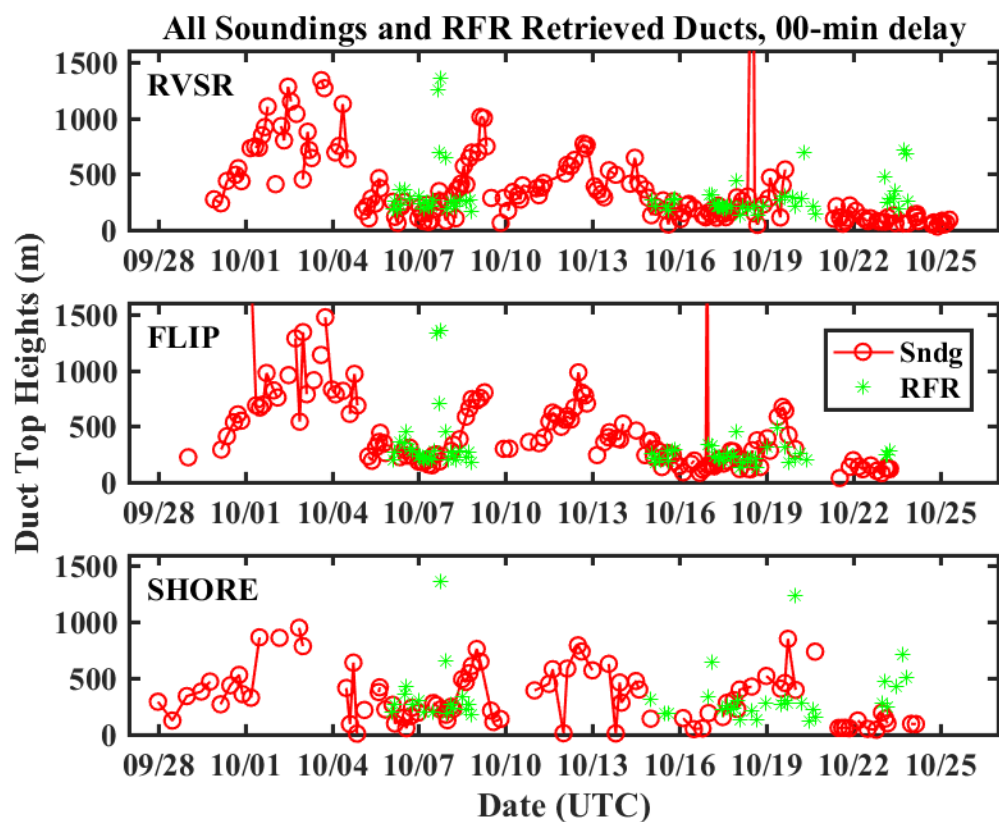


Figure 30. Time series comparison of duct top heights between observed soundings and RFR with a 0-minute time lag.

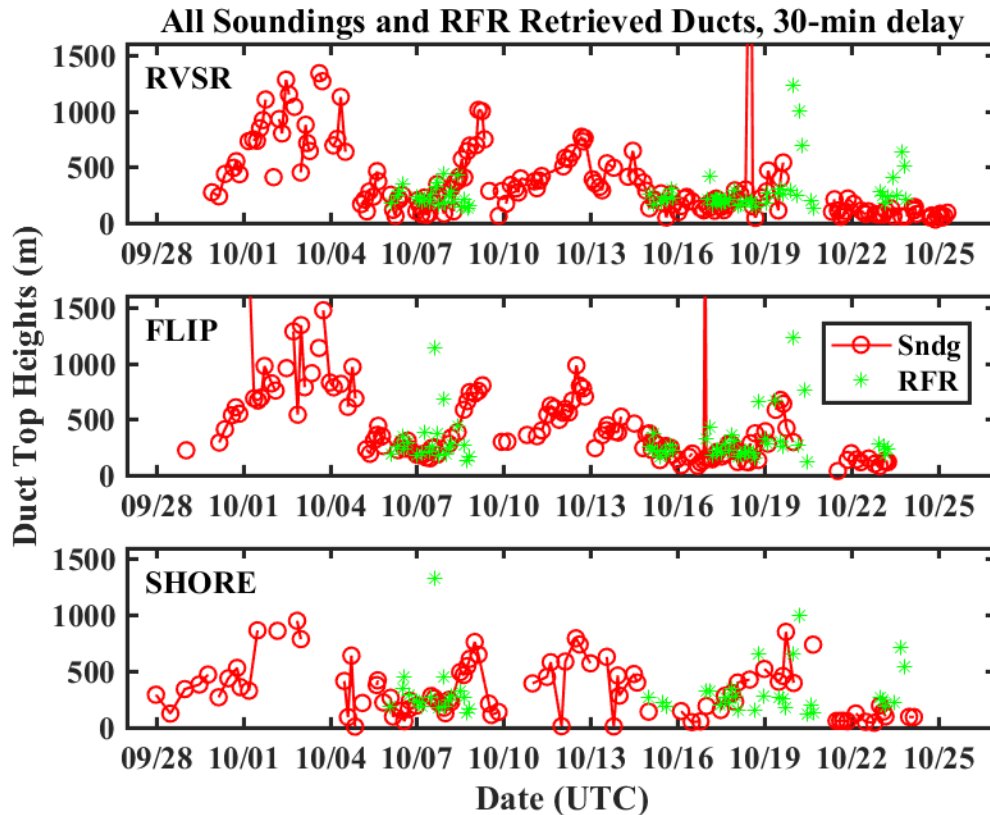


Figure 31. Time series comparison of duct top heights between observed soundings and RFR with a 30-minute time lag.

The duct strength is also an important metric to be considered. While it is not as important as the duct height, it is still relevant as RFR estimates atmospheric ducts using gradients. The results for duct strength are given in Figures 32 and 33. The observed duct strength increases in early October and peaked at all sites on 7 October, with the shore site at Point Mugu being weaker than at R/P FLIP and at R/V Sally Ride. RFR estimated the duct strength to be between the lower values of the shore site and the higher values of the maritime sites during this time period.

An offshore wind event on 15 October that affected the CASPER West operating area through 18 October increased the strength of ducts at all stations. RFR appeared to follow this trend well, but held onto the higher duct strength when duct strengths were observed to be lower from 19–21 October.

A stronger offshore wind event occurred again on 23 October and RFR picked up on the trend of increased duct strength during this time. RFR performed best with a 0-minute time lag when comparing it with observed duct strength.

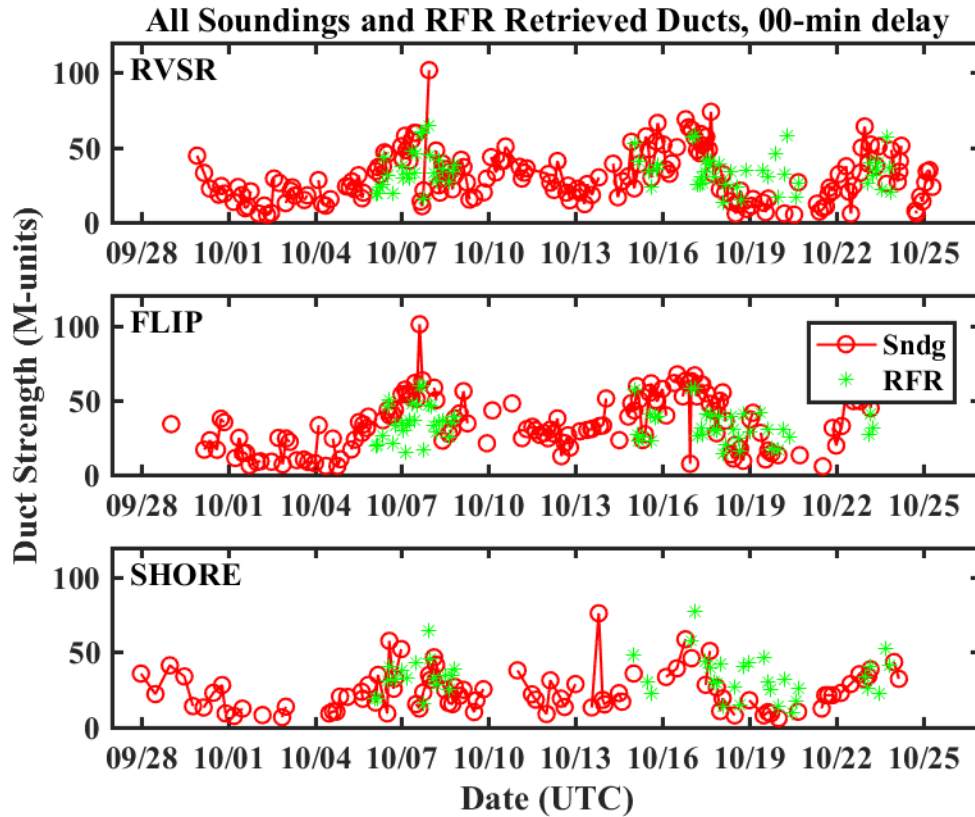


Figure 32. Time series comparison of duct strength between observed soundings and RFR soundings with a 0-minute time lag.

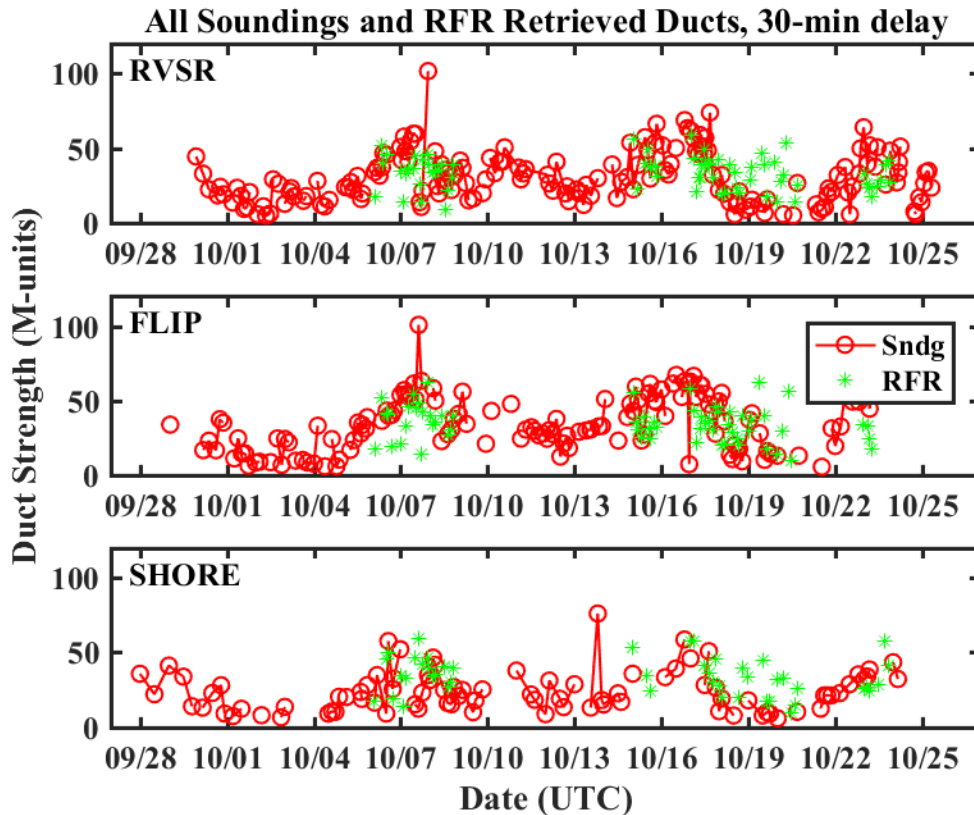


Figure 33. Time series comparison of duct strength between observed soundings and RFR soundings with a 30-minute time lag.

The duct top height from the soundings and from the RFR combined profiles are plotted together to show correlation in Figures 34 and 35. A good correlation is close to the dashed gray line. In the case of a 0-minute time lag, where a sounding was taken at the time the RFR profile was generated, there appears to be some correlation between RFR and the R/V Sally Ride and R/P FLIP below 400m with respect to duct top height. However, no significant correlation with the shore site at Point Mugu. This is expected as many of the links that contributed to the RFR data set were from the AIS signals of passing ships and were based in the maritime environment. The 30-minute time lag appears to have a better correlation with the R/V Sally Ride and the R/P FLIP with respect to duct top height, but still no significant correlation with the shore site at Point Mugu. These figures were produced for time lags of 0–90 minutes in 15-minute increments, although results for only the 0 and 30-minute lags are shown here.

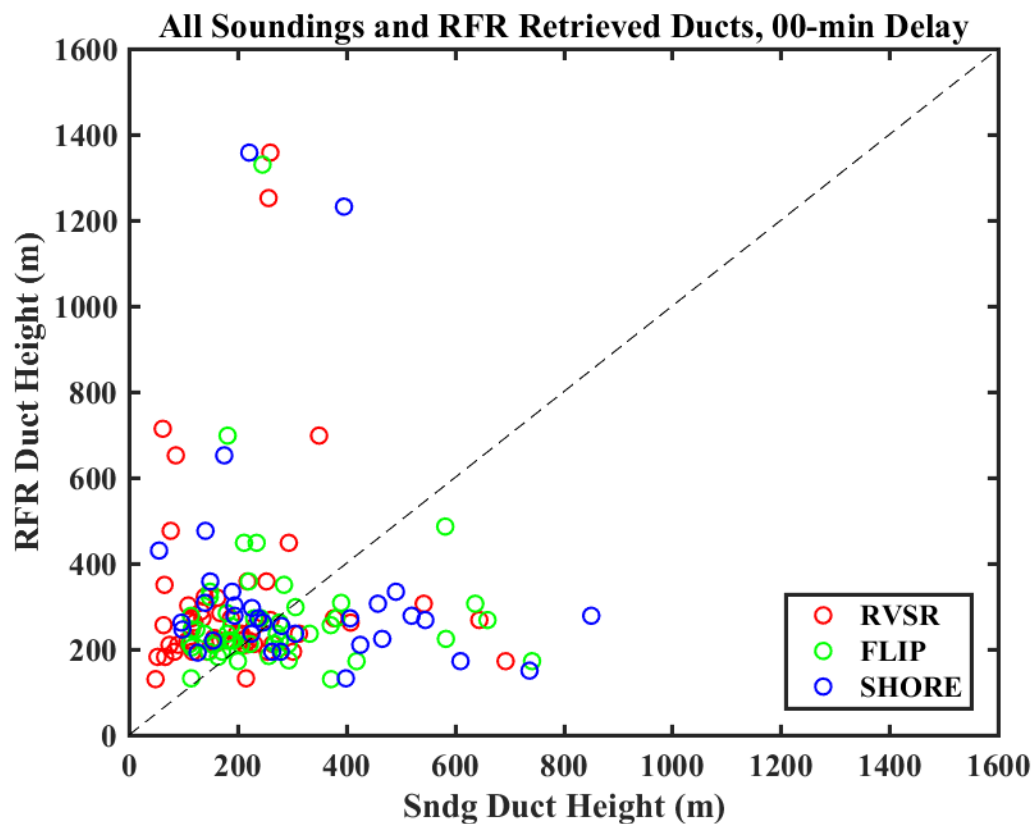


Figure 34. Observed sounding duct height from R/V Sally Ride, R/P FLIP, and the shore site at Point Mugu plotted with the RFR duct top height with a 0-minute time lag.

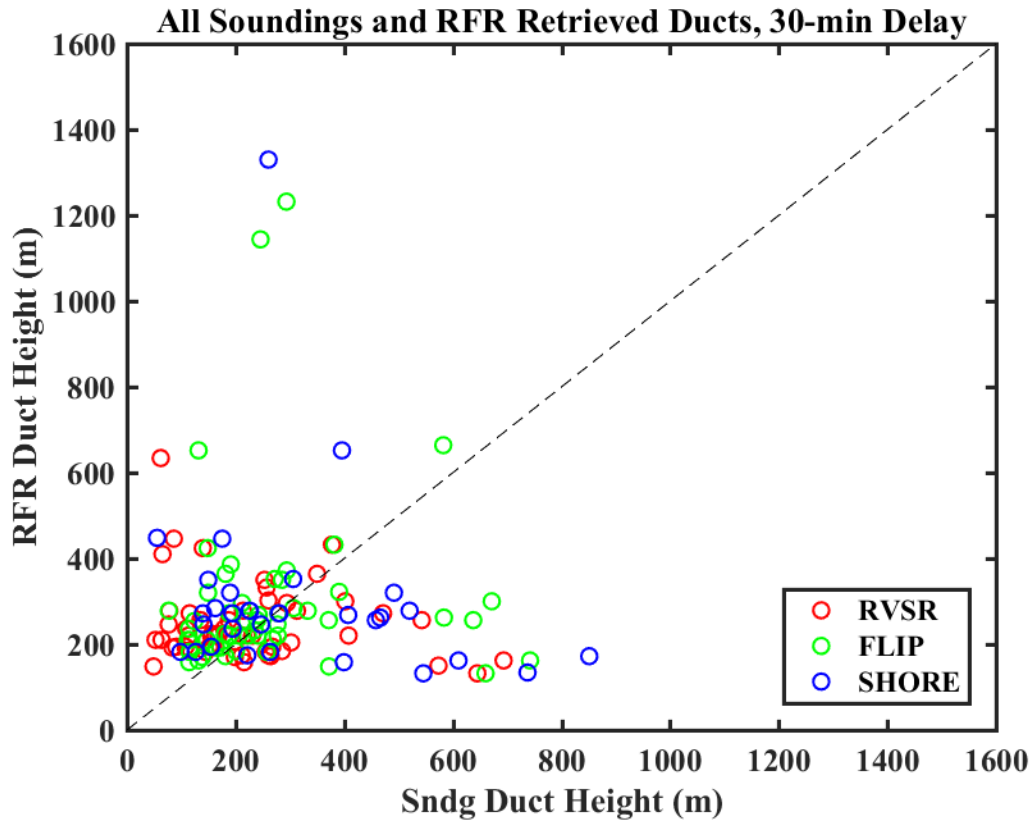


Figure 35. Observed sounding duct height from R/V Sally Ride, R/P FLIP, and the shore site at Point Mugu plotted with the RFR duct top height with a 30-minute time lag.

In a similar way, the duct strength from the sounding and the duct strength from the RFR combined profile are plotted together to show correlation in Figures 36 and 37. In these figures, RFR correlates best with the shore site at Point Mugu with respect to duct strength.

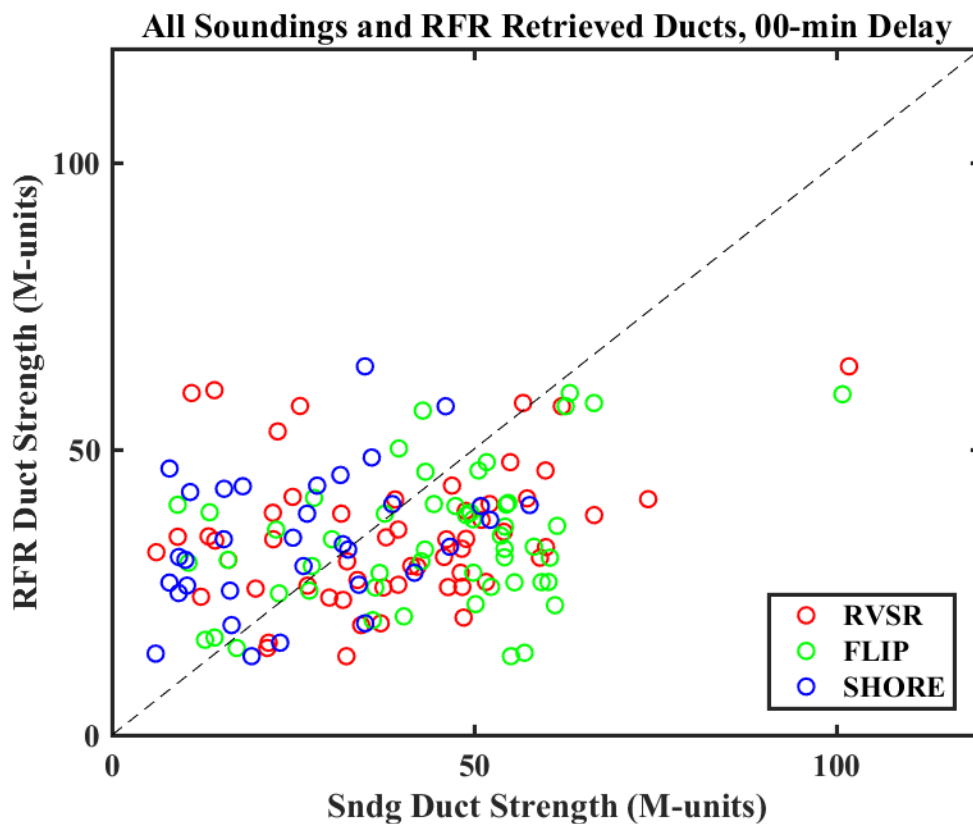


Figure 36. Observed sounding duct strength from R/V Sally Ride, R/P FLIP, and the shore site at Point Mugu plotted with the RFR duct strength with a 0-minute time lag.

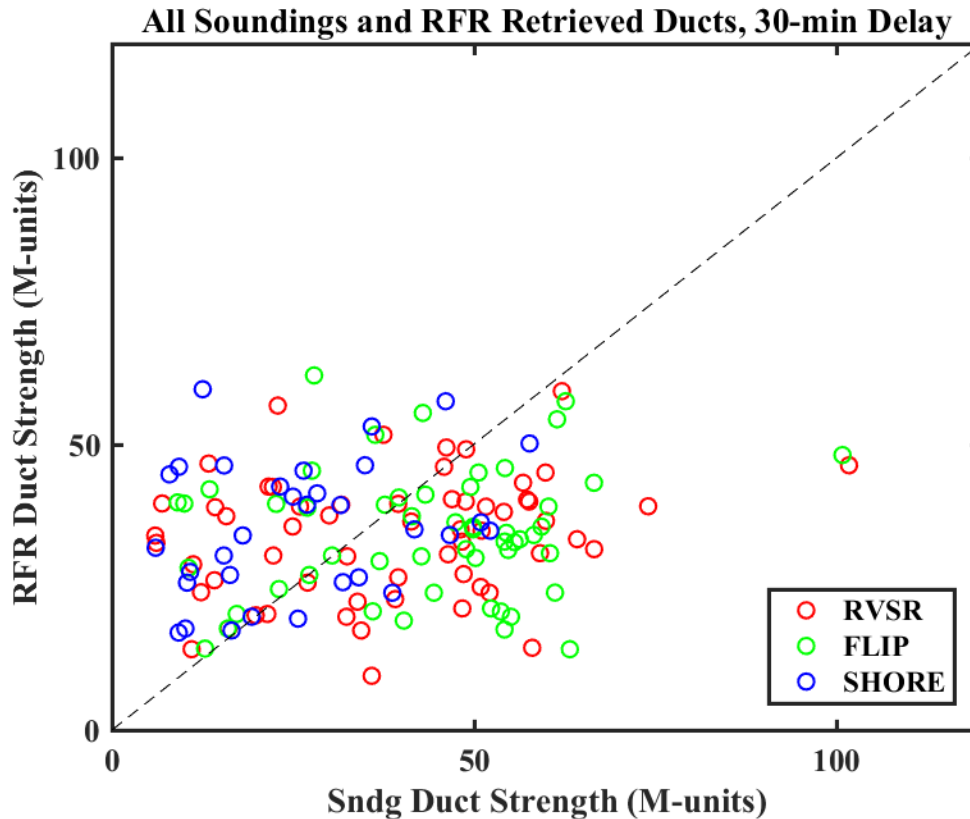


Figure 37. Observed sounding duct strength from R/V Sally Ride, R/P FLIP, and the shore site at Point Mugu plotted with the RFR duct strength with a 30-minute time lag.

To further investigate the correlation between RFR and observed soundings and the optimal time lag, correlation coefficients for duct height and duct strength are plotted in Figures 38 and 39. The best correlation for all RFR data processed is with a time lag of approximately 60 minutes for duct top heights. In general, the correlation is rather low although soundings for R/P FLIP show the best results. The best correlation for all RFR data processed is with a time lag of 0 minutes for duct strength. However, it is not well understood why the duct height and duct strength show inconsistent results in this comparison.

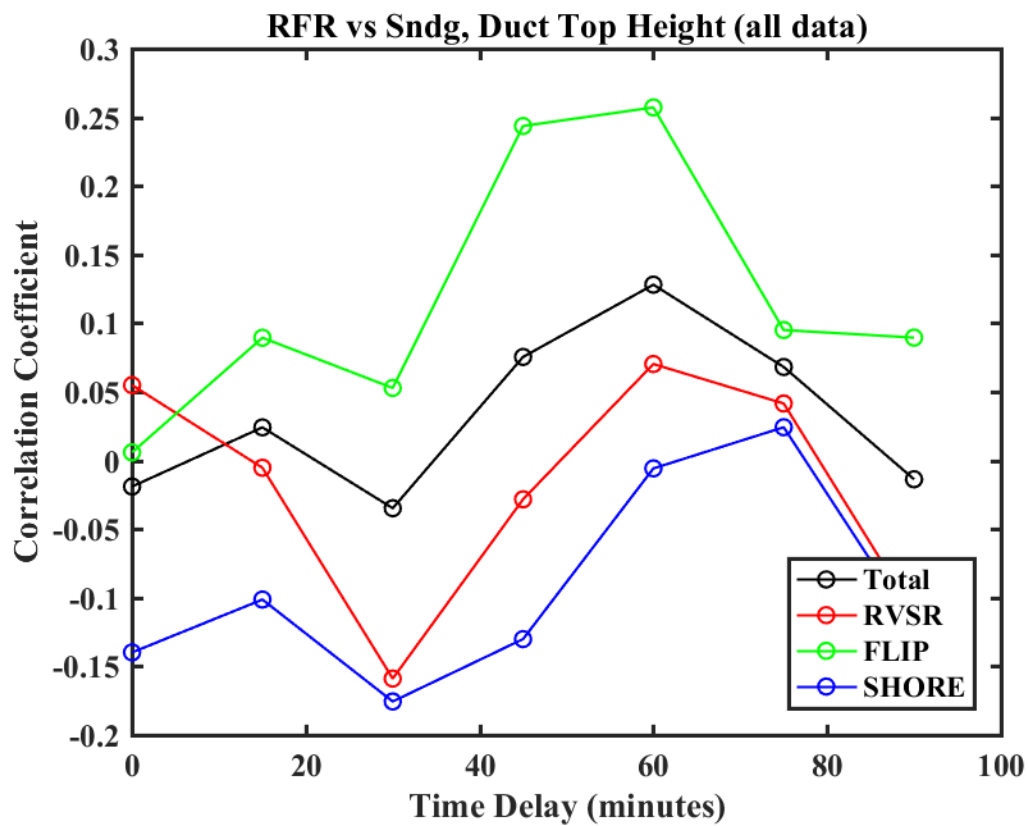


Figure 38. Correlation coefficients to compare RFR with observed sounding duct top heights at different time lags.

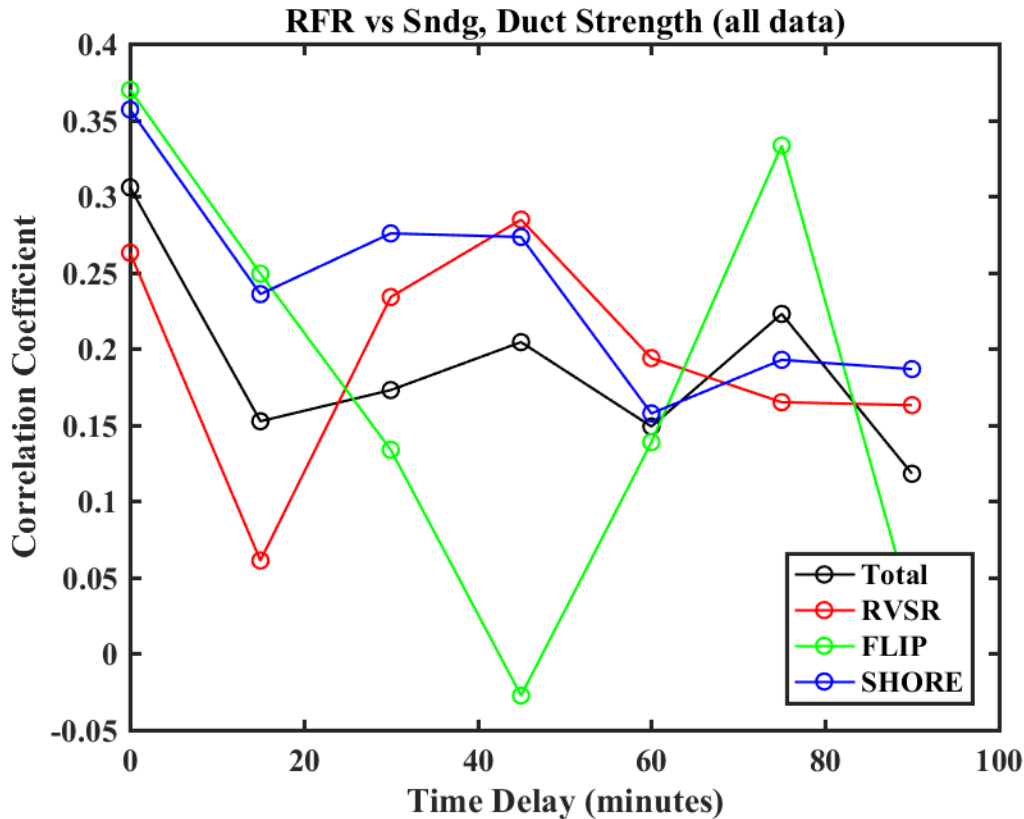


Figure 39. Correlation coefficients to compare RFR with observed sounding duct strength at different time lags.

2. RFR Data Compared to Observations below 400 m

In the previous section, it was noted that RFR tended to estimate surface and surface-based ducts below 400m better than elevated ducts above 400m. It is hence considered that RFR retrieval performs at its optimal for low ducting layers. For the Navy's purposes, ducts in the lower part of the atmosphere are more important as shipboard sensors are located below 400m. In this section we will explore the comparison of RFR to observations below 400m.

The correlation coefficients to compare RFR with observed duct top height below 400 m are plotted in Figure 40. In this case, a time lag between 30–90 minutes is optimal when comparing to the R/P FLIP observations. A time lag of 30 minutes is optimal for R/V Sally Ride, and a time lag of 60–75 minutes is optimal for the shore site at Point Mugu.

Overall, a time lag of 30 minutes is optimal when comparing RFR to all 3 stations with respect to duct top height.

The correlation coefficients below 400m are higher than when comparing all RFR data to observed soundings, again retrieval for the R/P FLIP soundings performed the best in general. The optimal time lag for all stations combined, denoted by the black line in Figure 39, is 30 minutes.

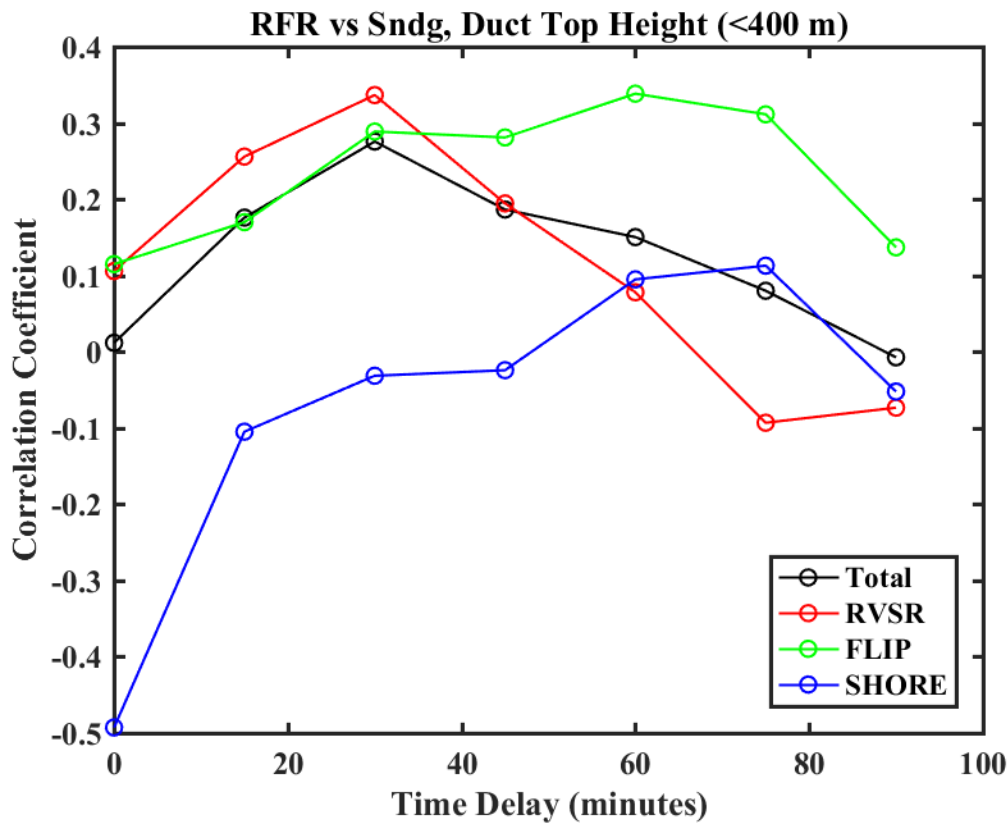


Figure 40. Correlation coefficients to compare RFR with observed sounding duct top heights below 400m at different time lags.

The correlation coefficients to compare RFR with observed duct strength below 400m are plotted in Figure 41. A time lag of 0 minutes appears to give the best results at all stations for duct strength. This is the same as previously noted for all RFR data. It should be mentioned that the most important ducting parameter is the duct height. We hence chose

the optimal time lag based on the duct height comparison while using information from the duct strength as a reference only.

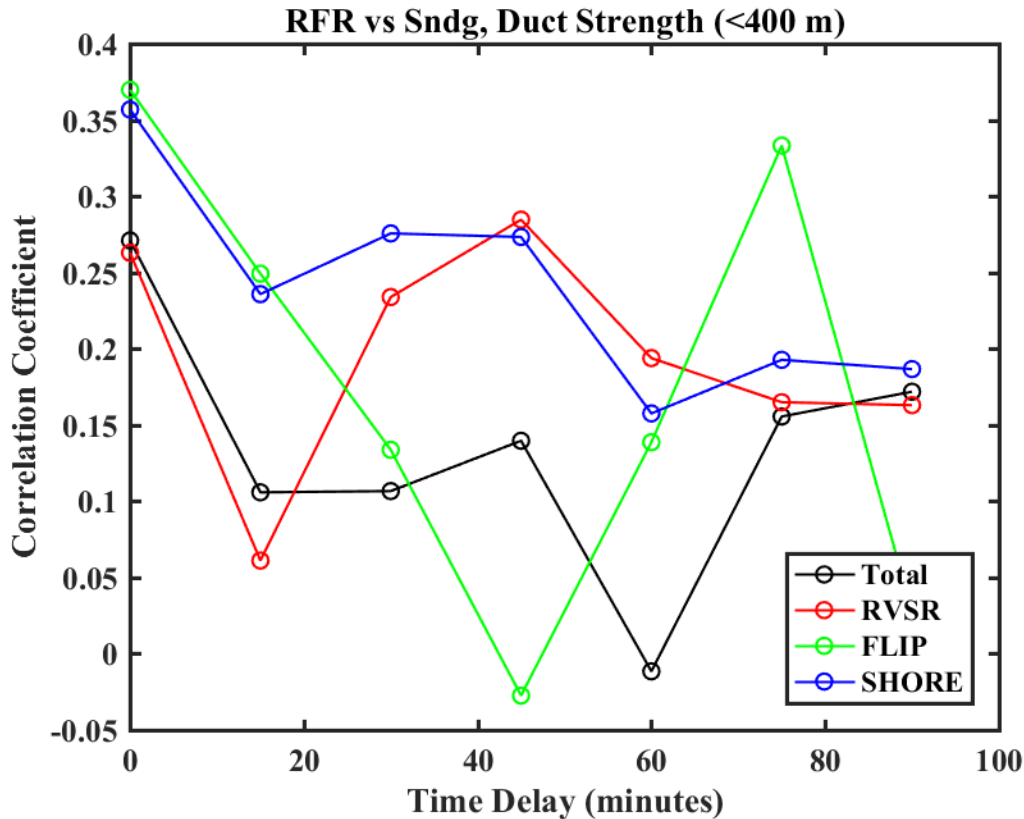


Figure 41. Correlation coefficients to compare RFR with observed sounding duct strength below 400 m at different time lags.

3. RFR Data Compared to Observed Trapping Base Height

One final metric used to compare RFR to observations is the trapping base height. The height of the base of the trapping layer is indicative of the height of the boundary layer. This signifies how accurately RFR detects the top of the boundary layer of the atmosphere.

Using the optimal 30-minute time delay, a time series comparing observed trapping base heights to RFR estimated trapping base heights is plotted in Figure 42. RFR performs well from 6–7 October when trapping base heights are low. However, when the top of the

boundary layer increases, overall RFR does not detect this change well. However, there are a few points that indicate the trend to a higher boundary layer top on 8 October.

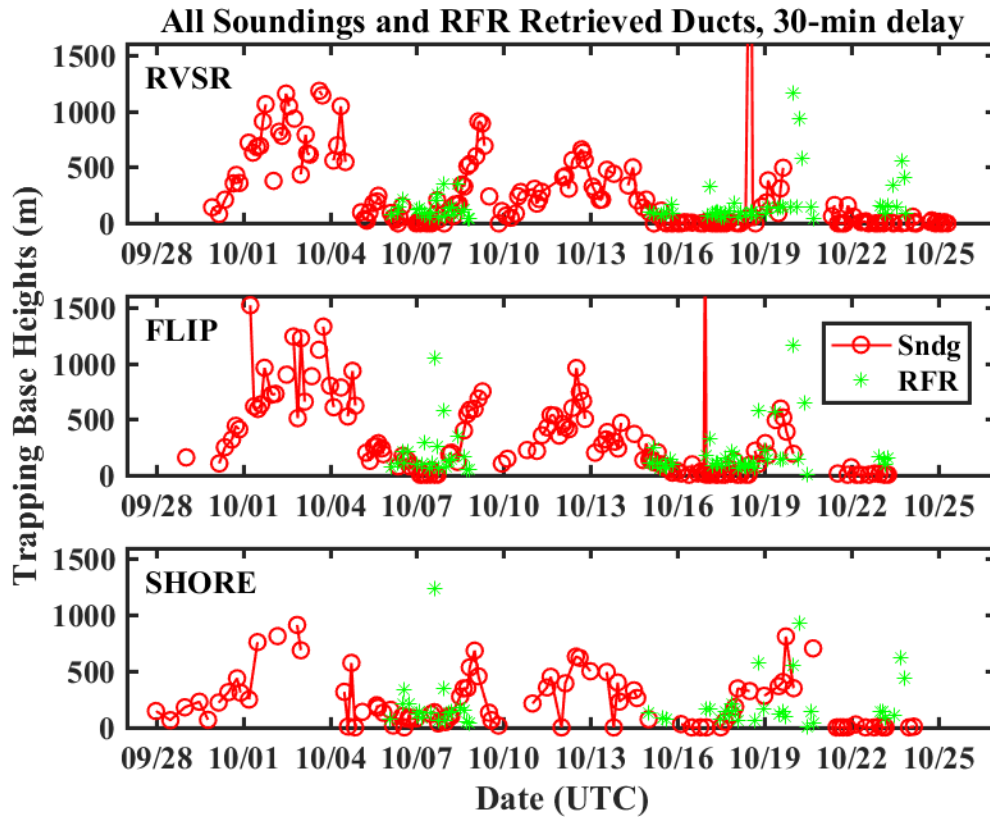


Figure 42. Time series comparison of trapping base heights between observed soundings and RFR with a 30-minute time lag.

The correlation of trapping base heights between RFR and observed soundings is plotted in Figure 43. RFR compares best with the R/V Sally Ride and the R/P FLIP. There are problems in comparing the trapping base height of surface ducts with the RFR trilinear profile. Because surface ducts have a trapping base height of 0 and RFR is restricted to a trilinear shape, the majority of the bias is at the surface.

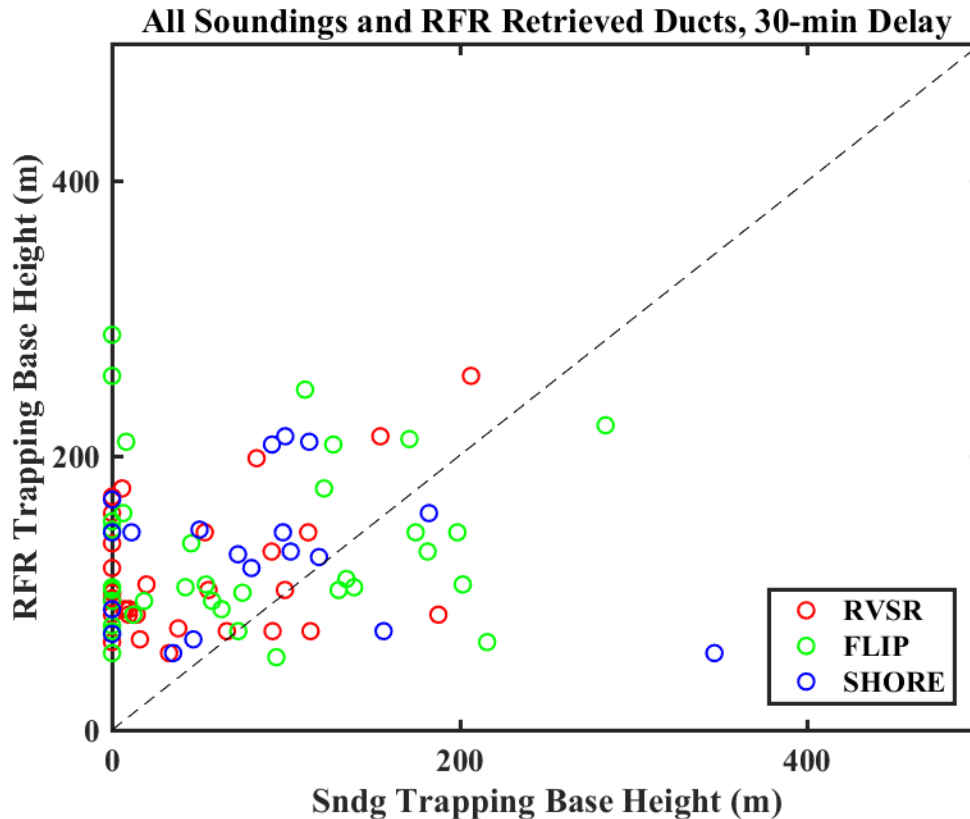


Figure 43. Observed sounding trapping base height from R/V Sally Ride, R/P FLIP, and the shore site at Point Mugu plotted with the RFR trapping base height with a 30-minute time lag.

D. SUMMARY OF RESULTS

While much can be learned from the visual graphics in previous sections, Tables 4–6 quantify the results of the comparison of observed soundings to RFR. Here, the mean denotes the mean of the difference between RFR and soundings at the specified observation location. This logic applies to the standard deviation as it also describes the standard deviation of the differences between RFR and sounding generated duct properties.

The difference in RFR performance with and without the high-level ducts is evident when comparing results in Tables 4 and 5. The correlation coefficients for the R/V Sally Ride, the R/P FLIP, and the total of all sites improved drastically when the high ducts are removed in the dataset. In the case of comparing RFR to the R/V Sally Ride, the correlation

coefficient for duct top height with a 30-minute time lag improved from -0.16, as shown in Table 4, to 0.34, as shown in Table 5.

Many of the RFR combined profiles that have an acceptable value of the max overlap ambiguity metric and the max mode error have a significant amount of RF signals, or links, coming from ships transmitting AIS signals. This causes the combined profile to be more representative of a maritime environment. Because of this, RFR profiles are closest to the R/V Sally Ride and the R/P FLIP observations as seen in these tables. Overall the maritime platforms, R/V Sally Ride and R/P FLIP, below 400m at a 30-minute time lag were the most appropriate comparisons for RFR.

Table 4. Duct top height comparison between RFR and the R/V Sally Ride, R/P FLIP, and the shore site at Point Mugu for all ducts below 1500m with 0-minute and 30-minute time lags.

Duct Layer Top		RVSR	FLIP	SHORE	Total
	# of profiles	55	51	33	139
	mean (m)	109.6	15.9	27.5	55.7
<1500, 0-min delay	std (m)	259	230.7	348.4	274.9
	correlation	0.05	0.006	-0.14	-0.02
	# of profiles	56	52	32	140
	mean (m)	22.7	35.7	-11.3	19.8
<1500, 30-min delay	std (m)	183.9	254.5	311.9	243.3
	correlation	-0.16	0.05	-0.18	-0.03

Table 5. Duct top height comparison between RFR and the R/V Sally Ride, R/P FLIP, and the shore site at Point Mugu for all ducts below 400 m with 0-minute and 30-minute time lags.

Duct Layer Top		RVSR	FLIP	SHORE	Total
	# of profiles	44	41	18	103
	mean (m)	70.37	18.4	42.7	44.9
<400, 0-min delay	std (m)	87.14	90.5	116.8	96.2
	correlation	0.11	0.11	-0.49	0.01
	# of profiles	44	41	19	104
	mean (m)	43.2	31	39.6	37.4
<400, 30-min delay	std (m)	77	84.5	95.8	83
	correlation	0.34	0.29	-0.03	0.11

Table 6. Duct top height, trapping layer base, and duct strength comparison between RFR and the R/V Sally Ride, R/P FLIP, and the shore site at Point Mugu for all ducts below 400 m with a 30-minute time lag.

Duct top < 400 m, 30-min delay		RVSR	FLIP	SHORE	Total
Duct Top Height	# of profiles	44	41	19	104
	mean	43.2	31	39.6	37.4
	std	77	84.5	95.8	83
	correlation	0.34	0.29	-0.03	0.11
Trapping layer base	# of profiles	44	41	19	104
	mean (m)	72	61.5	44.2	62.8
	std (m)	52.4	90.8	102.1	79.2
	correlation	0.45	0.15	-0.1	0.23
Duct Strength	# of profiles	44	41	19	104
	mean (m)	-6.4	-12.6	4.6	-5.7
	std (m)	18.5	17.1	16	46.7
	correlation	0.2	0.03	0.16	0.17

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V. SUMMARY AND CONCLUSIONS

A. SUMMARY OF THESIS WORK

Considerable time and effort have been invested by the Office of Naval Research and Space and Naval Warfare Systems Center Pacific, among other organizations, into gaining an advantage in the EM Spectrum. RFR is a part of this initiative. Verifying the results of RFR with atmospheric observations requires a considerable amount of resources. The CASPER West campaign took months of intense planning, sizeable funding, and extensive manpower to execute. This field campaign provided an ample amount of atmospheric and oceanic observations to properly characterize the environment during offshore wind events in the coastal region of southern California. This area was chosen specifically for its spatial and temporal variability of refractive profiles and for the occurrence of offshore wind events that create a very stable atmosphere.

This thesis focused on using the data collected during CASPER West to assess the performance of RFR. The characteristics of the observations were evaluated independently, concentrating on duct top height, trapping layer base height, duct type, and duct strength. RFR profiles were also characterized in a similar way and evaluated separately. Comparisons between the strongest duct observed in each sounding to RFR were made using duct top height, trapping layer base height, and duct strength to determine correlation. Time lags were introduced into the comparisons because the RFR profile uses signal information from the last 3 hours to produce a profile. For a time lag of 30 minutes, an RFR profile that was generated at 1100 was compared to a rawinsonde that was launched at approximately 1030. The optimal time lag is useful for when RFR is used in combination with numerical weather prediction to generate forecasts in the future. The most important aspect of this thesis was the feedback provided to the developer of RFR to help identify improvements to their algorithm.

B. MAJOR CONCLUSIONS

The comparisons between RFR and observations using duct top height indicated that correlation between RFR and observations with respect to duct top height was

strongest with maritime platforms R/V Sally Ride and R/P FLIP, which is not surprising as most of the RF signals processed by RFR were sourced from passing ships. The strongest correlation between RFR and observed duct top heights emerged when only data below 400m with a time lag of 30 minutes was considered. RFR performs better at low levels in the atmosphere, which makes sense because the profiles are predominantly trilinear in shape, which is best used to estimate surface-based ducts. The optimal time lag of 30 minutes suggests that by using signal information from the previous 3 hours to generate a profile, past conditions influence the profile.

Comparison between RFR and observations with respect to duct strength yielded slightly different results. Correlation was strongest with maritime platforms below 400m, but with no time lag.

RFR performed best in atmospheric conditions that produced strong surface-based ducts with low duct top height. RFR works well in offshore wind conditions that cause a significant vertical gradient in refractivity. Because offshore wind events also saw a rise in atmospheric pressure and temperature, these variables were difficult to decouple and they were not evaluated for their effects on RFR independently.

C. FUTURE WORK

The developers of RFR have already used feedback from this thesis to improve their algorithm. Future work could include the differences between improvements to RFR from the version that was evaluated here. Additionally, other RFR antennas installed on R/V Sally Ride can be evaluated to determine optimal siting on shipboard applications. Comparisons can also be made to determine the importance of estimating emitter characteristics, such as transmitter height and power. Finally, RFR can be compared between the CASPER East and CASPER West campaigns to quantify the difference in RFR performance in different environments.

APPENDIX. SYNOPTIC SUMMARY

Synoptic Summary

Coupled Air-Sea Processes and Electromagnetic Ducting Research – West Coast Campaign (CASPER-West)

27 September – 23 October 2017



Anna Hook, Qing Wang, and Wendell Nuss
Meteorology Department, Naval Postgraduate School
Monterey, CA

15 June 2018

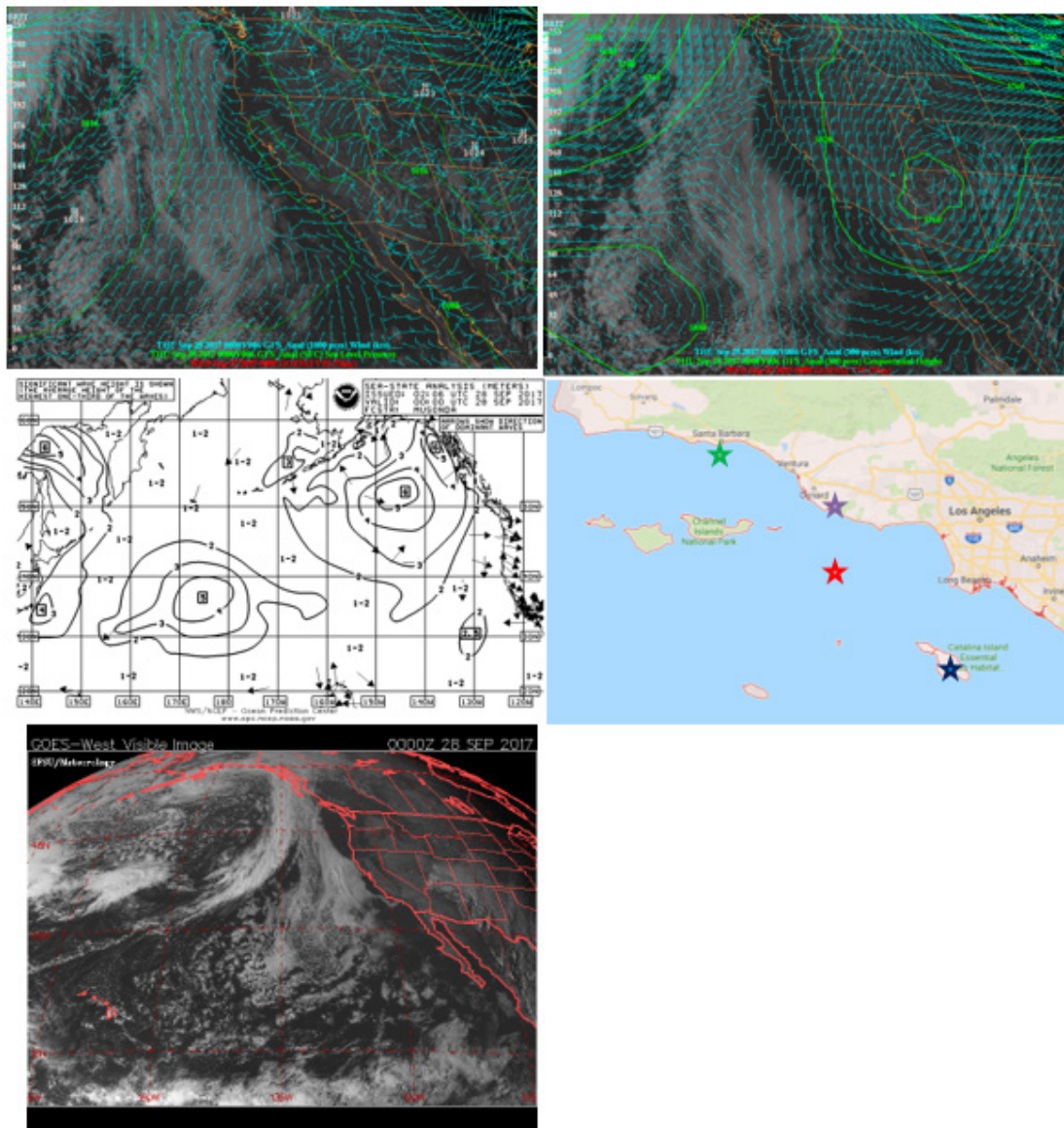
*****Please note all times on graphics are in UTC*****

Time in UTC	Time in PST (local time)
0000	1600 (Previous Day)
0100	1700 (Previous Day)
0200	1800 (Previous Day)
0300	1900 (Previous Day)
0400	2000 (Previous Day)
0500	2100 (Previous Day)
0600	2200 (Previous Day)
0700	2300 (Previous Day)
0800	0000 (Same Day)
0900	0100 (Same Day)
1000	0200 (Same Day)
1100	0300 (Same Day)
1200	0400 (Same Day)
1300	0500 (Same Day)
1400	0600 (Same Day)
1500	0700 (Same Day)
1600	0800 (Same Day)
1700	0900 (Same Day)
1800	1000 (Same Day)
1900	1100 (Same Day)
2000	1200 (Same Day)
2100	1300 (Same Day)
2200	1400 (Same Day)
2300	1500 (Same Day)

Example: 0000UTC on 28 September = 1600PST on 27 September

Example: 0800 UTC on 28 September = 0000PST on 28 September

September 27, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (28 September):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
0.61	195	21.1

★ NDBC Station 46025 Buoy Observation at 0000UTC (28 September):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
261	8.9	1010.5

ASOS Observations at 0000UTC (28 September):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	250	10	10	Clear	1010.8
★ KNTD	210	6	10	Few clouds 300ft	1011.2
★ KAVX	250	7	10	Clear	1012.9

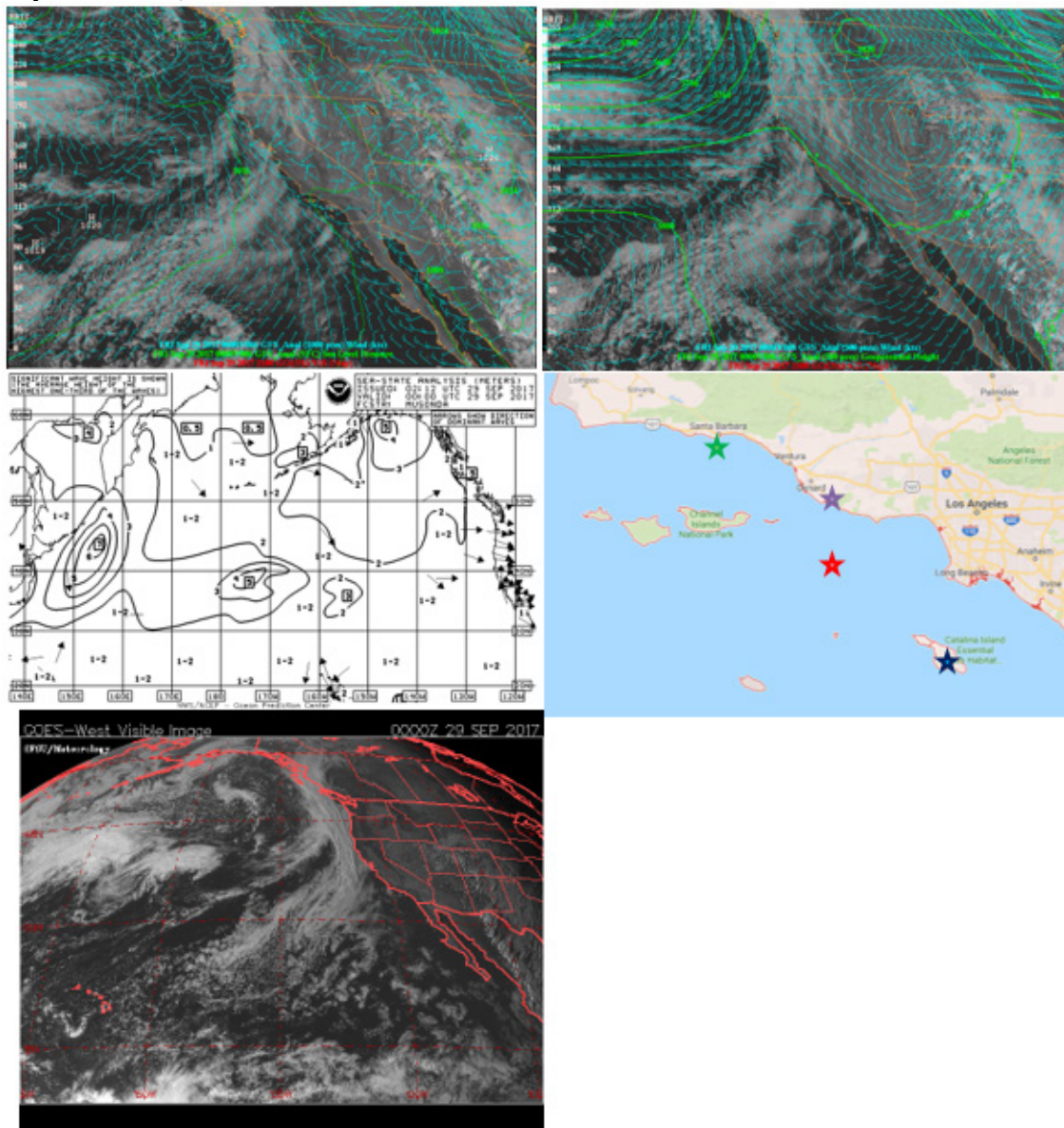
Synoptic Analysis:

An upper-level trough over Arizona and California weakened and moved eastward. The marine layer was shallow, which resulted in a clear, sunny afternoon.

Low level marine fog and clouds formed to the west of the Channel Islands and increased in the evening and overnight hours.

The winds outside of the bight shift from Westerly to Northwesterly as the Eastern Pacific High builds into the area. The coastal winds are driven by the sea-land breeze effect and shift diurnally. The winds shifted from an Easterly regime (varying from Northeasterly to Southeasterly, “offshore”) to a Southwesterly regime (varying from Westerly to South-Southwesterly, “onshore”) at 0800PST/1600UTC in the morning. The winds shifted from the Southwesterly regime (onshore) to an Easterly regime (offshore) at 1900PST/0300UTC in the evening.

September 28, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (29 September):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
0.73	178	20.7

★ NDBC Station 46025 Buoy Observation at 0000UTC (29 September):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
301	11.3	1010.9

ASOS Observations at 0000UTC (29 September):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	260	9	10	Clear	1011.2
★ KNTD	280	8	10	Few clouds 300ft, 800ft, 25000ft, Cloud bank reported to the southwest	1011.8
★ KAVX	260	8	10	Clear	1013.2

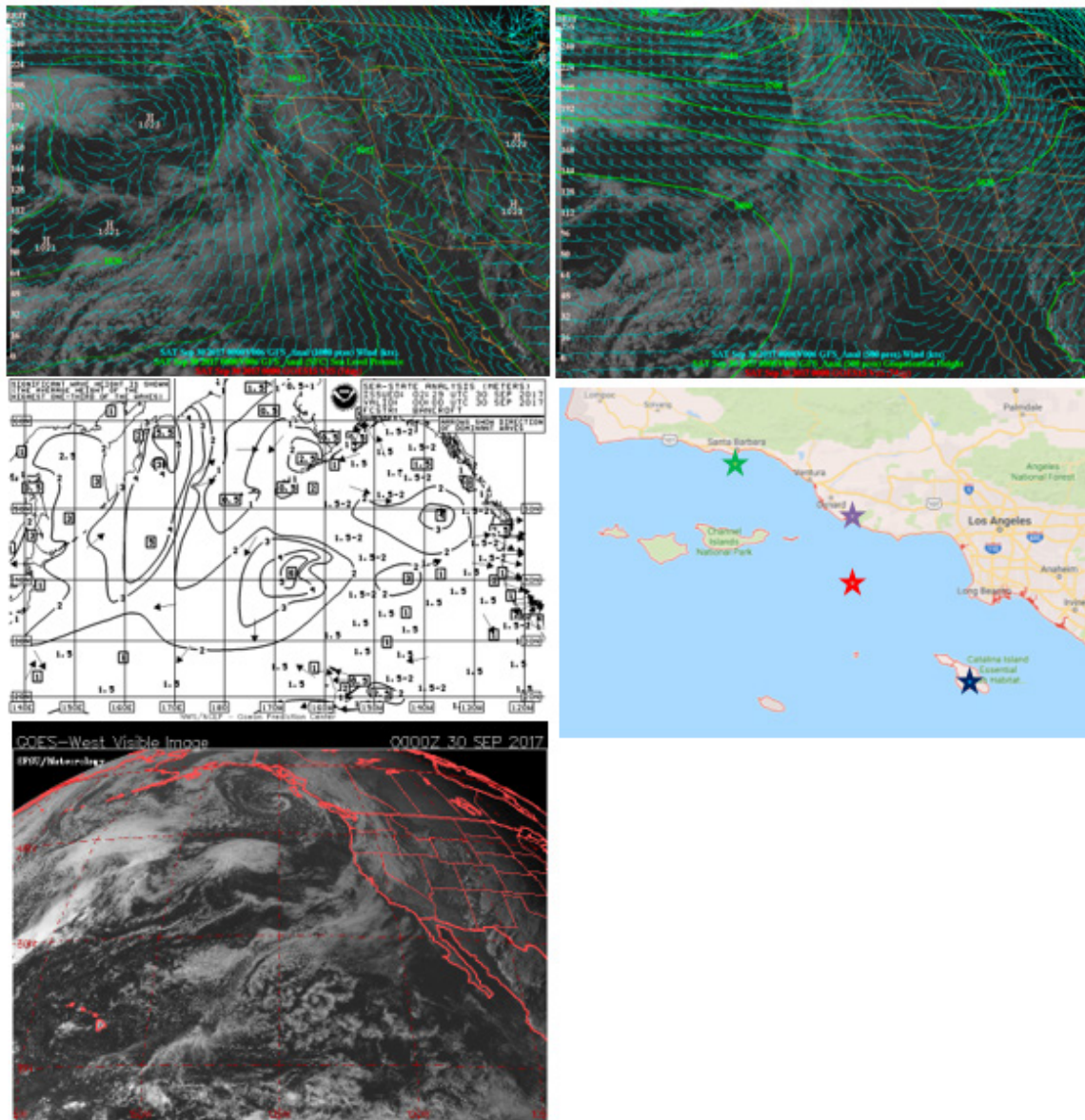
Synoptic Analysis:

The low-level marine layer is well established in the CASPER West operating area as high pressure builds. Fog reduced visibility in the early morning.

Point Mugu (KNTD) reported broken skies with clouds at 500ft at 0130PST/0930UTC with all other stations reporting clear skies at that time. Oxnard (KOXR) reported mist and broken skies with clouds at 300ft at 0220PST/1020UTC, however the marine layer was not widespread as the only other local station reporting mist and a low cloud base was Point Mugu. The clouds penetrated inland to Camarillo Airport (KCMA) at 0250PST/1050UTC. San Nicolas Island (KNSI) reported few clouds at 200ft at 0428PST/1228UTC. Point Mugu (KNTD) reported clear skies at 0856PST/1656UTC for a very short period of time, but returned to having low clouds for the rest of the day into the overnight hours. All other stations reported clear skies for most of the day.

The winds outside of the bight are predominantly Northwesterly. The local surface winds continue to be in a diurnal sea-land breeze regime. Winds shifted at Point Mugu from offshore to onshore at 0800PST/1600UTC. They shifted again from onshore to offshore at 0200PST/1000UTC (overnight hours into 29 September). This wind shift was later than the previous day as the marine layer lingered throughout the daytime hours, limiting surface heating over land.

September 29, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (30 September):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
0.81	210	21.5

★ NDBC Station 46025 Buoy Observation at 0000UTC (30 September):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
284	11.7	1010.3

ASOS Observations at 0000UTC (30 September):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	210	4	10	Clear	1010.5
★ KNTD	300	4	10	Scattered clouds 28000ft	1011.1
★ KAVX	270	9	10	Clear	1012.9

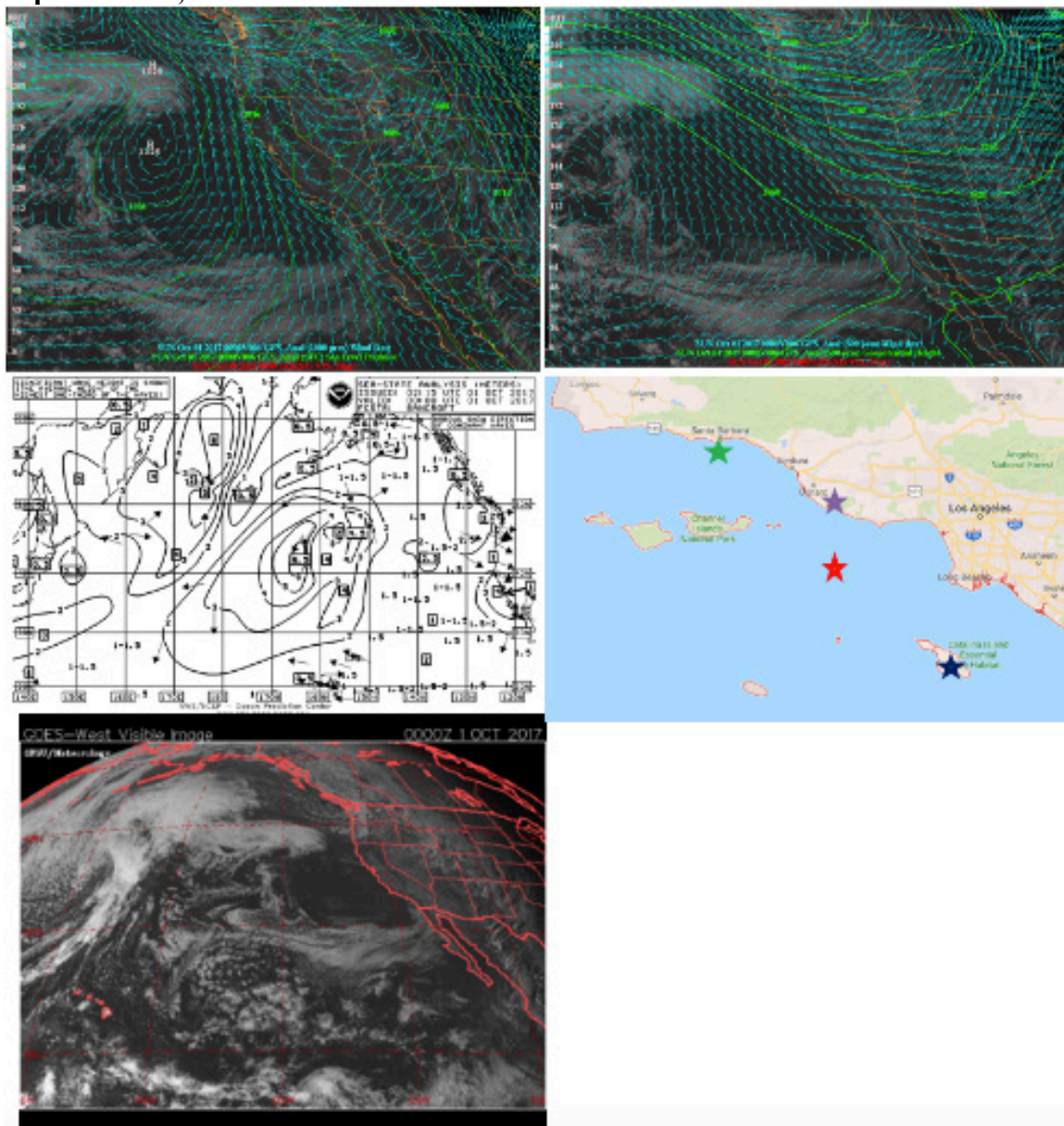
Synoptic Analysis:

Surface high pressure continues to dominate the operating area, although each station had a very slight signal of pressure falling. An upper level low pressure system approaches the coast of the northwestern U.S.

Low clouds persisted through the early morning hours at Point Mugu (KNTD), San Clemente Island (KNUC), and San Nicolas (KNSI), however Santa Barbara (KSBA) and Avalon (KAVX) remained clear.

The winds outside of the bight are predominantly Northwesterly. The local surface winds continue to be in a diurnal sea-land breeze regime. Winds shifted at Point Mugu from offshore to onshore at 1000PST/1800UTC. The winds remained calm for most of the overnight hours (from 2000PST 29 September/0400UTC 30 September), allowing a nocturnal inversion to set up.

September 30, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (1 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
0.98	244	21.5

★ NDBC Station 46025 Buoy Observation at 0000UTC (1 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
260	7.8	1009.7

ASOS Observations at 0000UTC (1 October):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	150	7	10	Clear	1008.8
★ KNTD	250	9	8	Few clouds at 1300ft, 20000ft, 26000ft	1010.4
★ KAVX	250	10	8	Clear	1011.9

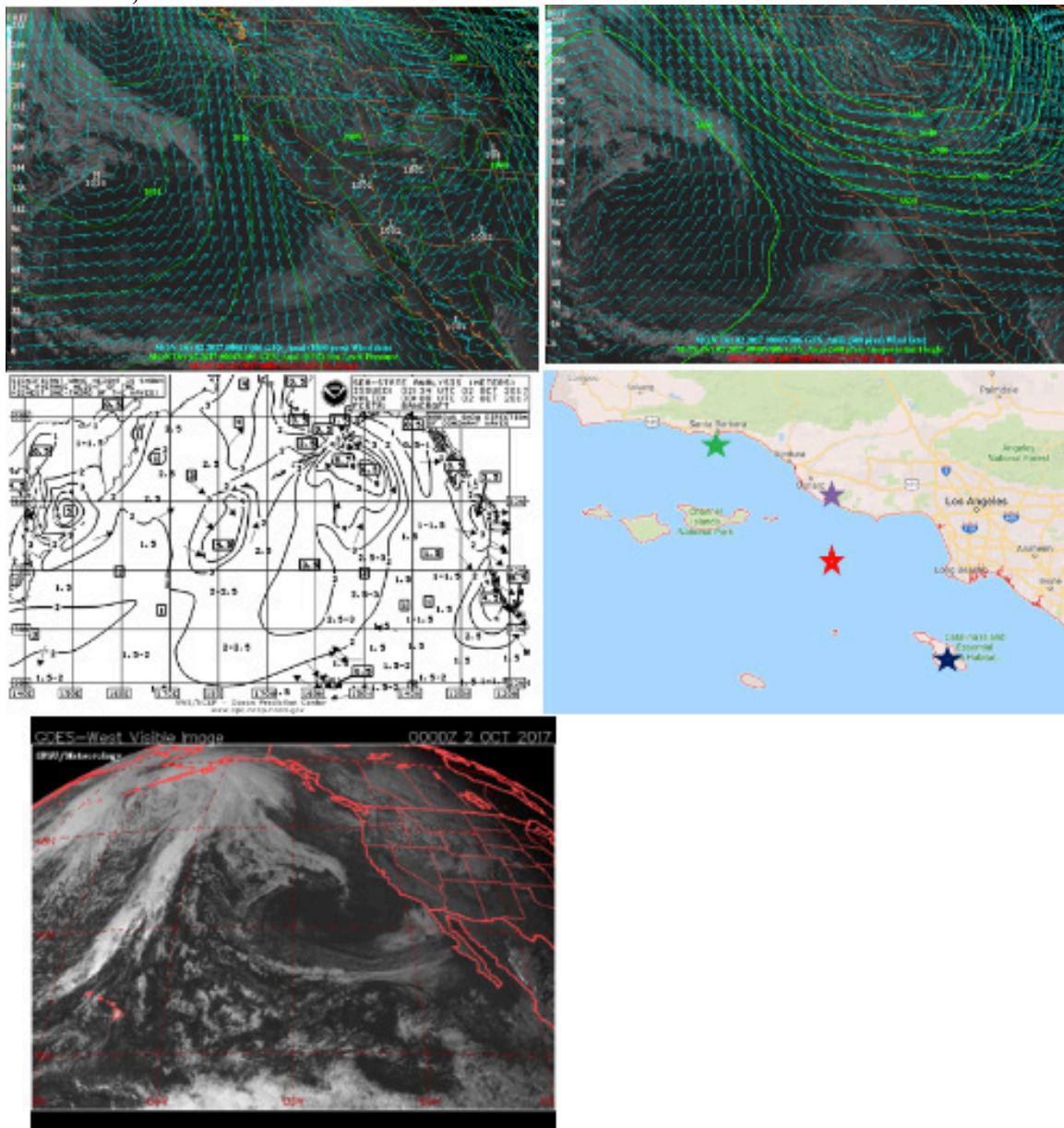
Synoptic Analysis:

An upper-level trough over the northwestern U.S. caused the marine layer over the CASPER West operating area to deepen. Northwesterly flow is very pronounced above the surface. Although every station reported a pressure fall on the order of 1mb, the Eastern Pacific High off the coast of northern California continues to build.

Low clouds impacted Point Mugu (KNTD) from 0700PST/1500UTC and remained through most of the morning until the early afternoon hours (1400PST/2200UTC). San Nicolas Island (KNSI) also reported low clouds and reduced visibility for much of the morning, despite increasing wind speeds.

The winds outside of the bight continue to be Northwesterly and are increasing in speed as the pressure gradient along the coast tightens. Winds at San Nicolas Island increased in the early morning hours, with some gusts up to 24 knots. However, the winds at Point Mugu were calm for most of the early morning hours. The local surface winds continue to be in a diurnal sea-land breeze regime. Winds shifted at Point Mugu from offshore to onshore at 0800PST/1600UTC. The winds shifted again overnight from onshore to offshore at 0200PST/1000UTC (1 October).

October 1, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (2 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
0.87	237	21.9

★ NDBC Station 46025 Buoy Observation at 0000UTC (2 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
266	9.5	1007.1

ASOS Observations at 0000UTC (2 October):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	240	4	9	Clear	1007.1
★ KNTD	240	8	8	Few clouds at 2200ft, 28000ft	1007.6
★ KAVX	340	4	10	Clear	1008.8

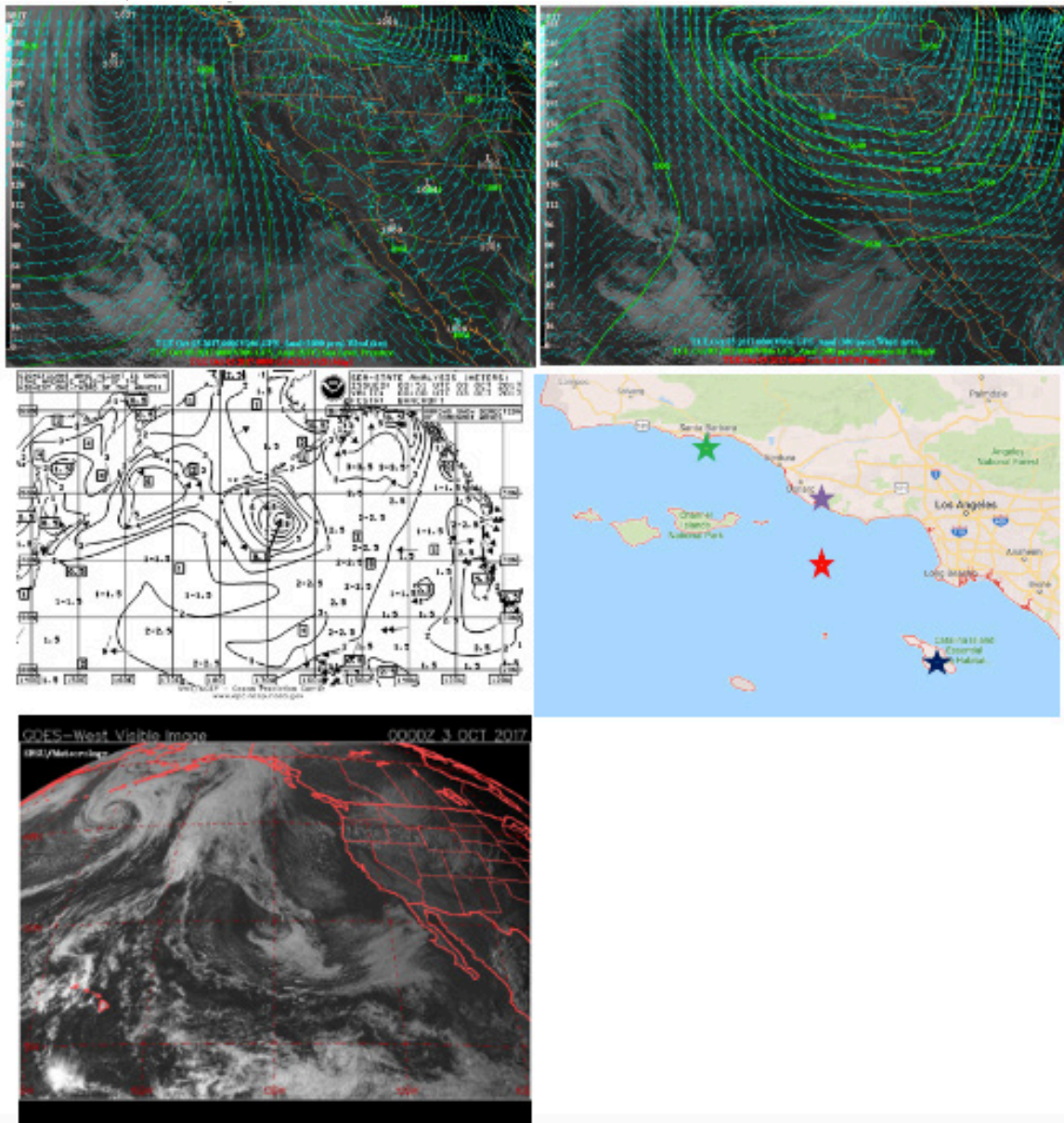
Synoptic Analysis:

The upper-level trough propagated to the southeast and is located over Montana. The surface Eastern Pacific High maintained its strength while it meandered to the south and further offshore. Another high pressure system is located to the west of the Canadian coast. North-Northwesterly flow is very pronounced above the surface over the CASPER West operating area. The pressure continued to fall at every station.

Cloud bases were higher than previous days due to the marine layer being disrupted by the upper-level trough. Scattered clouds at 1500–2000ft impacted Point Mugu (KNTD) in the early morning hours. Santa Barbara (KSBA), Oxnard (KOXR), Camarillo (KCMA), San Nicolas Island (KNSI), and Avalon (KAVX) all reported similar sky conditions in the morning, with most stations clearing out around 1200PST/2000UTC.

The winds outside of the bight continue to be Northwesterly. Winds at San Nicolas Island abated since the previous day. The local surface winds continue to be in a diurnal sea-land breeze regime. Winds shifted at Point Mugu from offshore to onshore at 0800PST/1600UTC. The winds shifted again in the evening from onshore to offshore at 2100PST (1 October)/0500UTC (2 October).

October 2, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (3 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
0.73	206	22.0

★ NDBC Station 46025 Buoy Observation at 0000UTC (3 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
280	7.1	1007.4

ASOS Observations at 0000UTC (3 October):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	270	8	10	Clear	1007.1
★ KNTD	260	9	10	Clear	1007.9
★ KAVX	280	7	10	Broken skies, clouds at 1500ft	1009.1

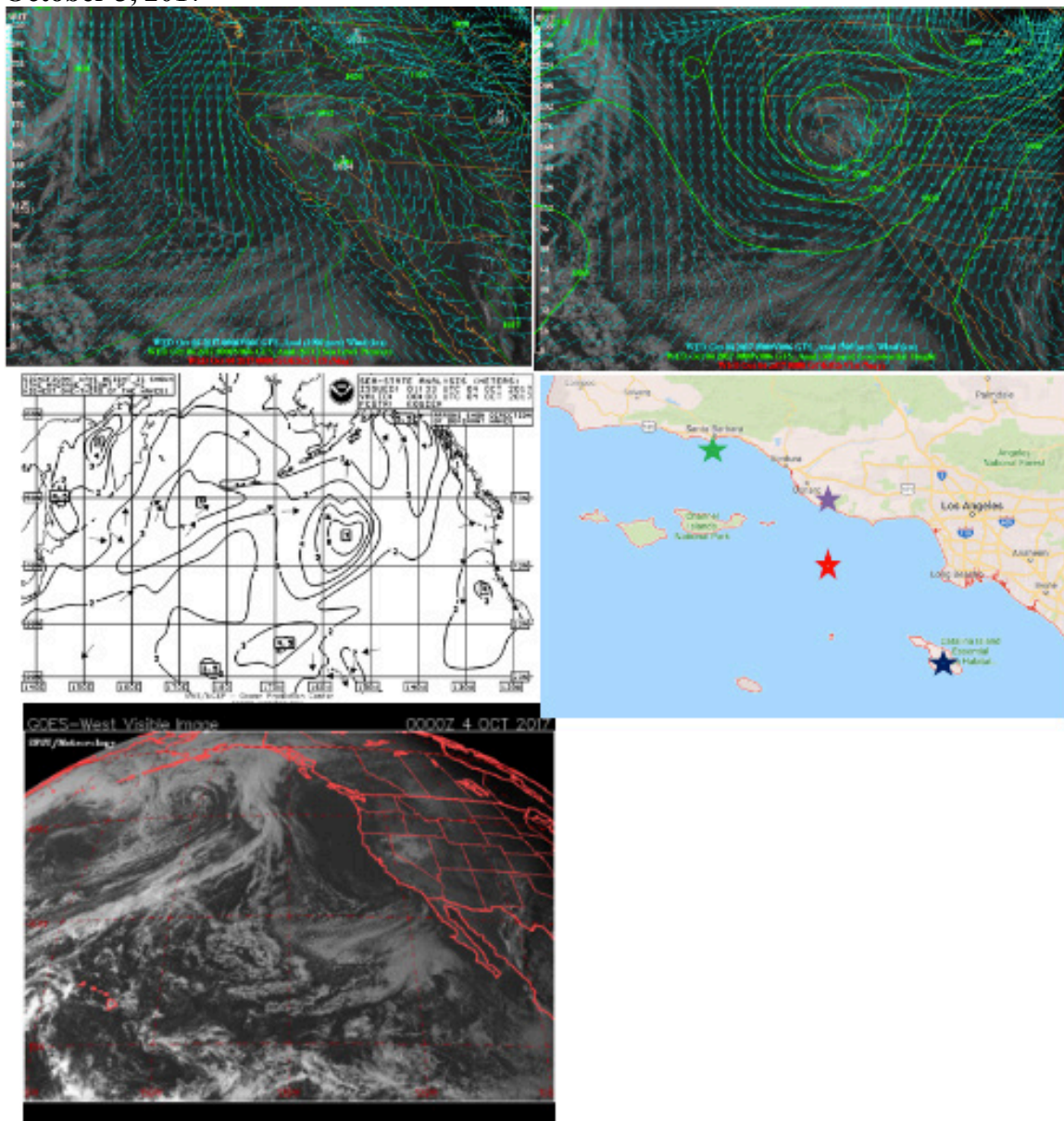
Synoptic Analysis:

The upper-level trough propagated to the east and is located over eastern Montana. The flow around the Eastern Pacific High has been disrupted by the surface high pressure to the west of the Canadian coast. The Eastern Pacific High meandered further to the west. Stations reported pressure remaining the same, however a slight pressure rise at Avalon indicates high pressure ridging back into the area.

Clouds at 2400ft persisted through the morning hours at Point Mugu (KNTD). Santa Barbara (KSBA), Oxnard (KOXR), San Nicolas Island (KNSI), and Avalon (KAVX) all reported similar sky conditions in the morning. Most stations reported clearing by 1000PST/1800UTC, but Avalon (KAVX), San Clemente Island (KNUC), and San Nicolas Island (KNSI) remained cloudy for the rest of the day.

The winds outside of the bight are North-Northwesterly. Winds aloft have turned to be more Westerly. The local surface winds continue to be in a diurnal sea-land breeze regime. Winds shifted at Point Mugu from offshore to onshore at 0900PST/1700UTC. The winds shifted again in the evening from onshore to offshore at 1900PST (2 October)/0300UTC (3 October).

October 3, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (4 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
0.88	192	21.3

★ NDBC Station 46025 Buoy Observation at 0000UTC (4 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
237	3.5	1011.0

ASOS Observations at 0000UTC (4 October):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	180	5	10	Clear	1011.2
✴ KNTD	200	8	10	Few clouds at 1400ft, 3300ft	1011.4
★ KAVX	220	8	10	Clear	1012.2

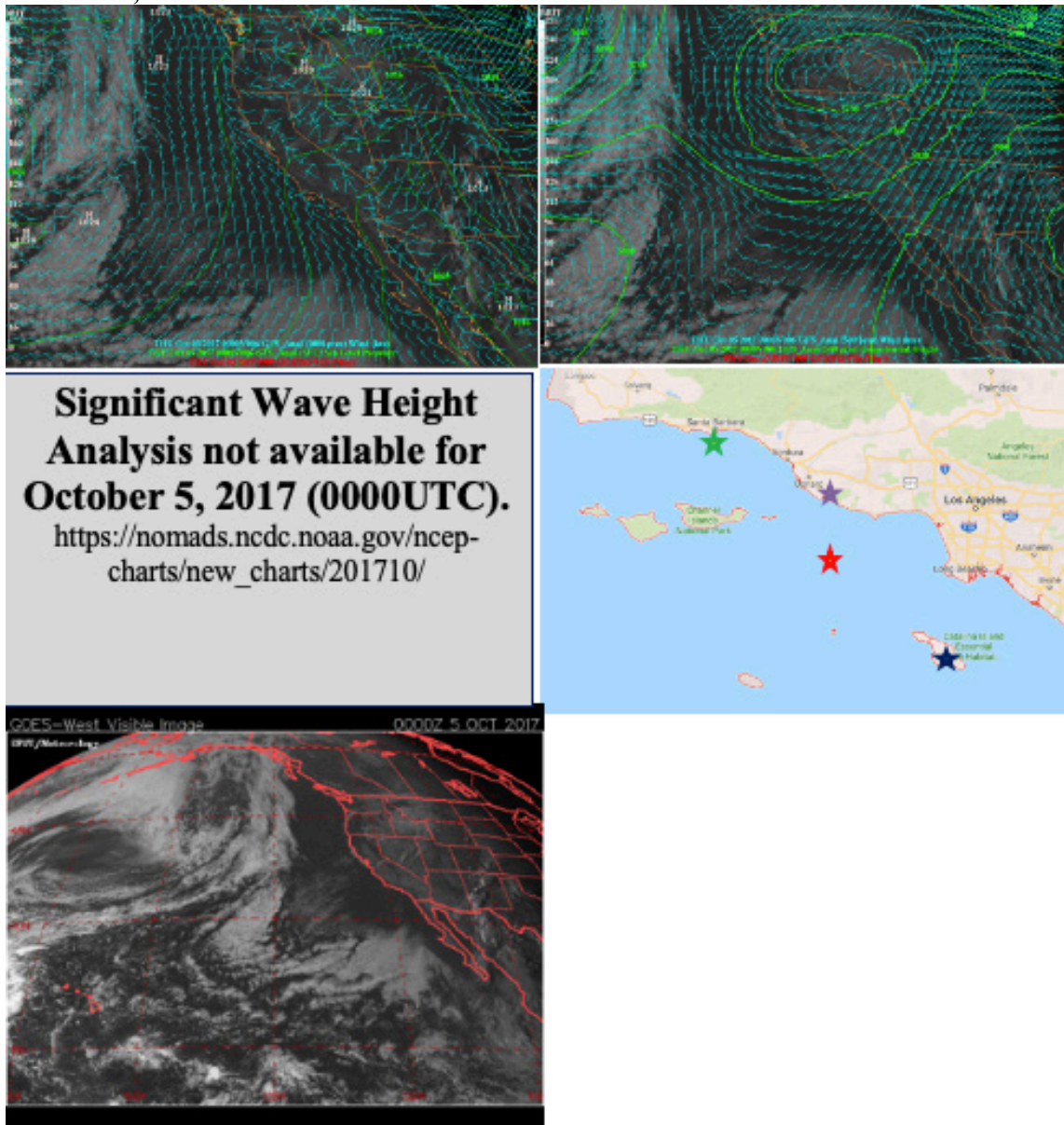
Synoptic Analysis:

Another upper-level trough has moved over California creating clear and cool conditions. Some low level moisture and clouds will remain south of the trough axis near Santa Maria. The boundary layer is weakly stratified. All stations reported pressure rising significantly from the previous day.

Few and scattered clouds with bases at approximately 2400ft persisted at Point Mugu (KNTD) for most of the day. Avalon (KAVX) had reduced visibility in fog and mist for most of the morning, but cleared by 1300PST/2100UTC.

The winds outside of the bight are Northwesterly. Winds aloft are West-Southwesterly. The local surface winds continue to be in a diurnal sea-land breeze regime. Winds shifted at Point Mugu from offshore to onshore at 1000PST/1800UTC. The winds shifted again in the evening from onshore to offshore at 2000PST (3 October)/0400UTC (4 October).

October 4, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (5 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
0.70	200	21.4

★ NDBC Station 46025 Buoy Observation at 0000UTC (5 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
278	10.7	1012.9

ASOS Observations at 0000UTC (5 October):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	250	6	10	Clear	1013.2
★ KNTD	280	7	10	Clear	1013.6
★ KAVX	250	9	10	Clear	1014.2

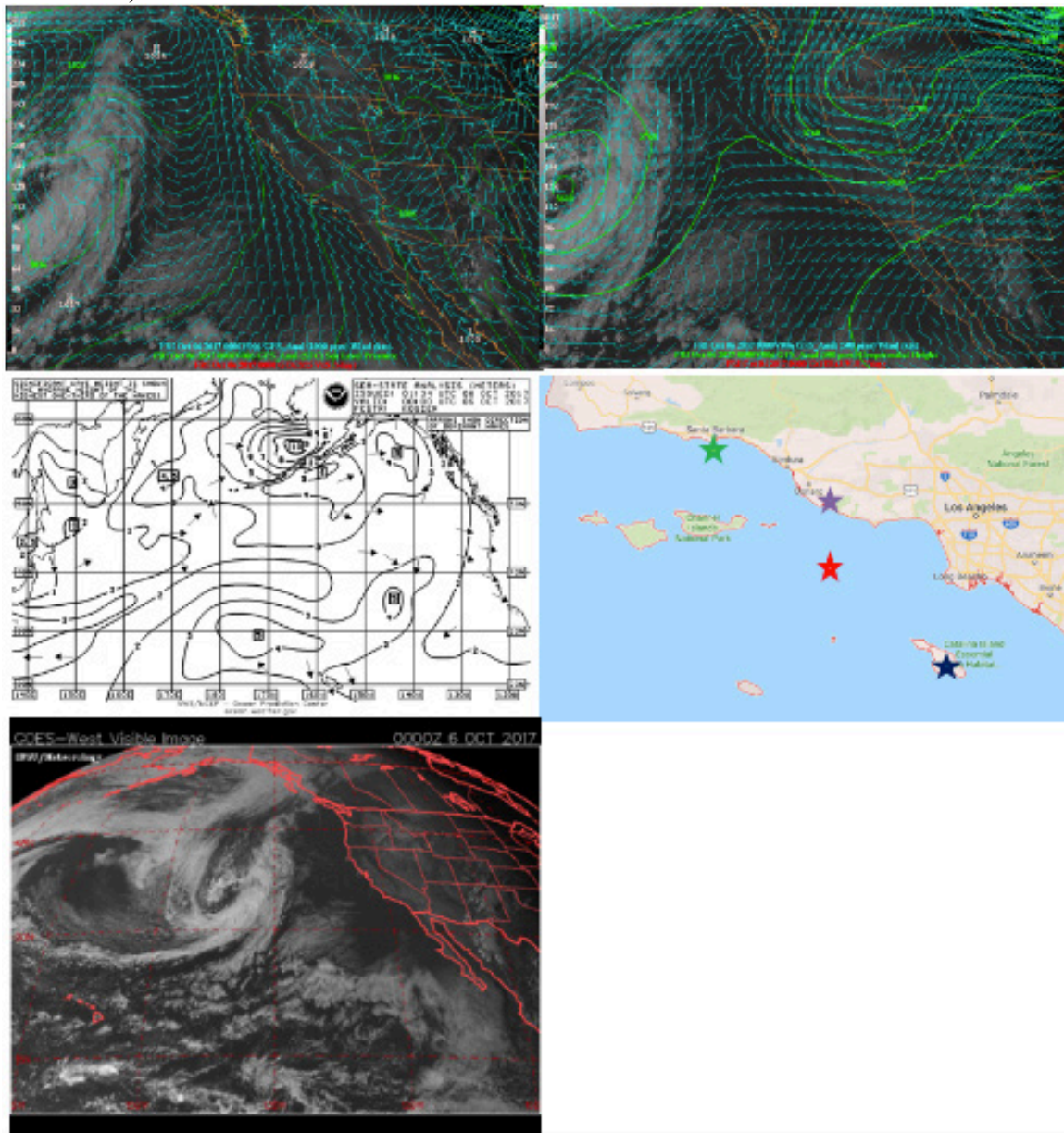
Synoptic Analysis:

The upper-level trough over California weakened and moved to the northwest and is now centered over the border between Oregon and Idaho. High pressure is building into the CASPER West operating area as stations report pressure rises.

All stations remained clear for the majority of the day. No impacts were observed due to cloud cover.

The winds outside of the bight are Northwesterly. Winds aloft are Southwesterly. The local surface winds continue to be in a diurnal sea-land breeze regime. Winds shifted at Point Mugu from offshore to onshore at 0800PST/1600UTC. The winds shifted again in the evening from onshore to offshore at 1900PST (4 October)/0300UTC (5 October).

October 5, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (6 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
0.76	267	21.1

★ NDBC Station 46025 Buoy Observation at 0000UTC (6 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
293	9.1	1010.3

ASOS Observations at 0000UTC (6 October):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	230	5	10	Clear	1010.5
★ KNTD	260	7	10	Clear	1010.8
★ KAVX	250	8	10	Clear	1012.5

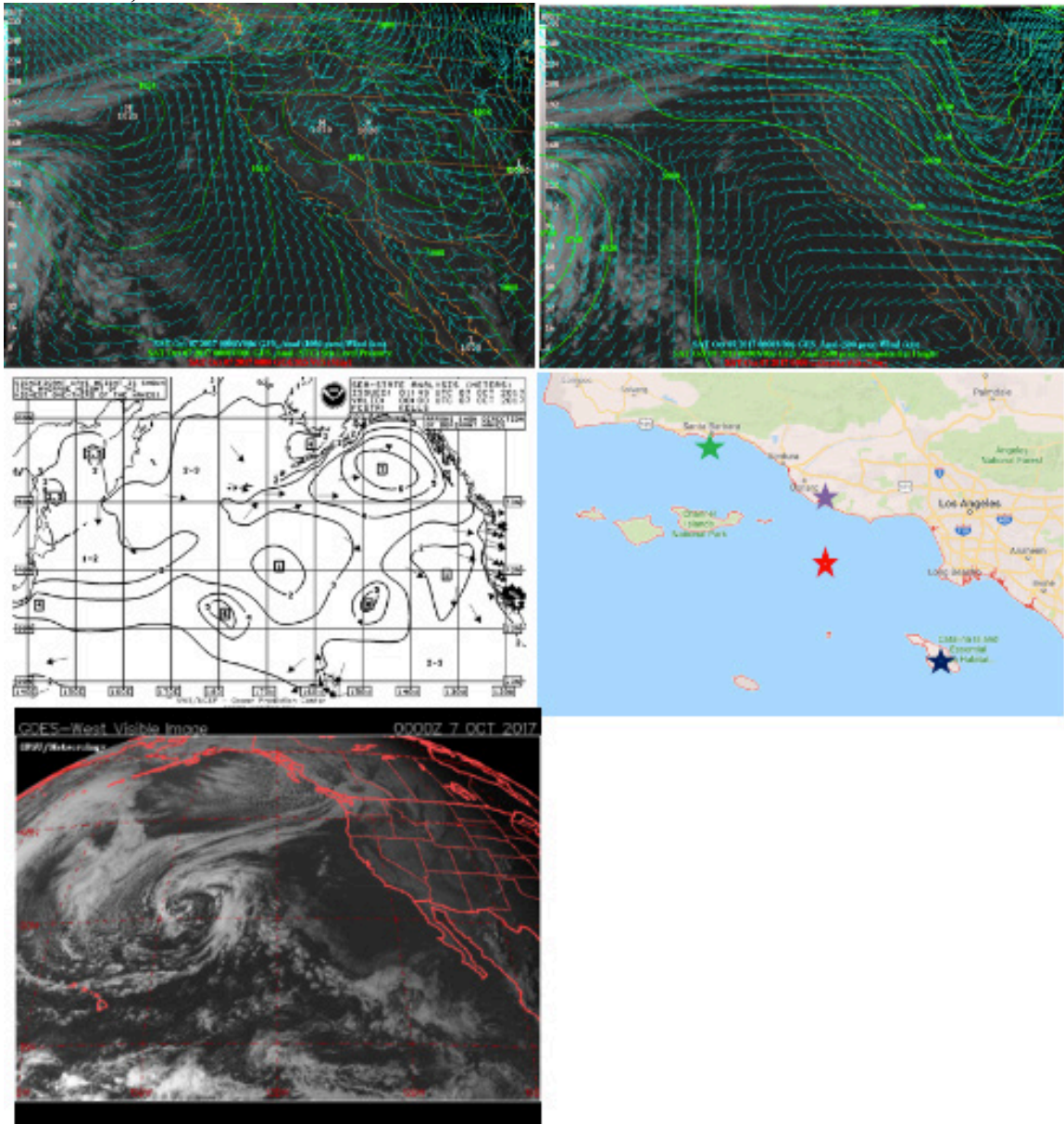
Synoptic Analysis:

An upper-level low is approaching from the west. The circulation around the low has extended to the surface to the west of California. Cloud cover in the satellite image can be seen associated with the low pressure system.

All stations remained clear for the majority of the day. No impacts were observed due to cloud cover.

The winds outside of the bight are Northwesterly becoming Northerly. Winds aloft are Westerly. The local surface winds continue to be in a diurnal sea-land breeze regime. Winds shifted at Point Mugu from offshore to onshore at 0900PST/1700UTC. The winds shifted again in the evening from onshore to offshore at 1900PST (5 October)/0300UTC (6 October).

October 6, 2017



October 6, 2017**★ NDBC Station 46262 Buoy Observation at 0000UTC (7 October):**

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
0.88	184	21.1

★ NDBC Station 46025 Buoy Observation at 0000UTC (7 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
310	9.5	1011.1

ASOS Observations at 0000UTC (7 October):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	270	9	10	Clear	1013.5
★ KNTD	280	9	10	Clear	1011.8
★ KAVX	320	5	10	Clear	1013.5

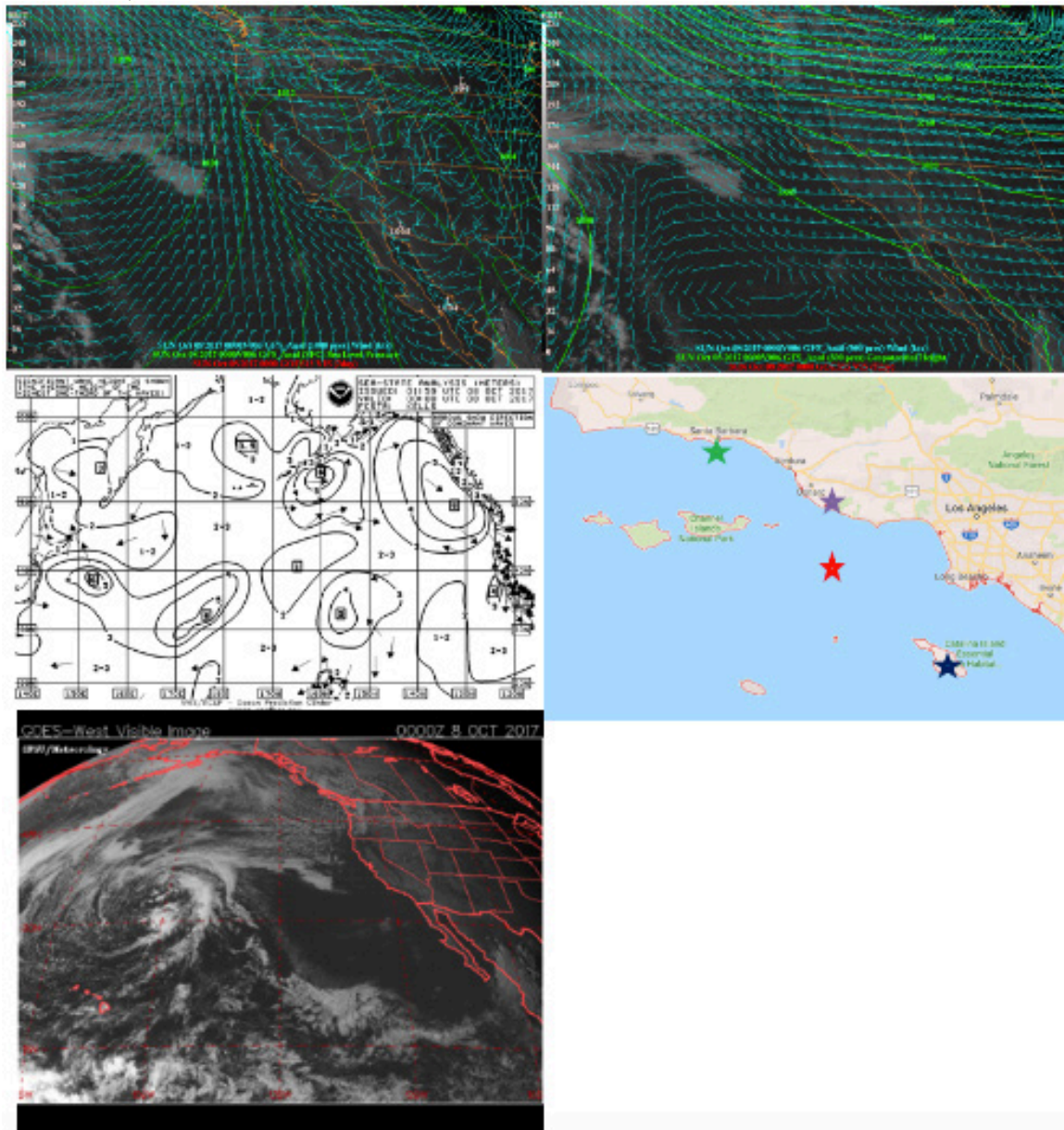
Synoptic Analysis:

The upper-level low and associated surface low have stalled and meandered to the south, but are well to the west of the central California coast and have no impacts at this time over the CASPER West operating area.

All stations remained clear for the majority of the day. No impacts were observed due to cloud cover.

The winds outside of the bight are Northwesterly. Winds aloft shifted to become Northwesterly. The local surface winds continue to be in a diurnal sea-land breeze regime. Winds shifted at Point Mugu from offshore to onshore at 0800PST/1600UTC. The winds shifted again in the evening from onshore to offshore at 1900PST (6 October)/0300UTC (7 October).

October 7, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (8 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
1.22	179	21.1

★ NDBC Station 46025 Buoy Observation at 0000UTC (8 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
276	7.2	1007.2

ASOS Observations at 0000UTC (8 October):

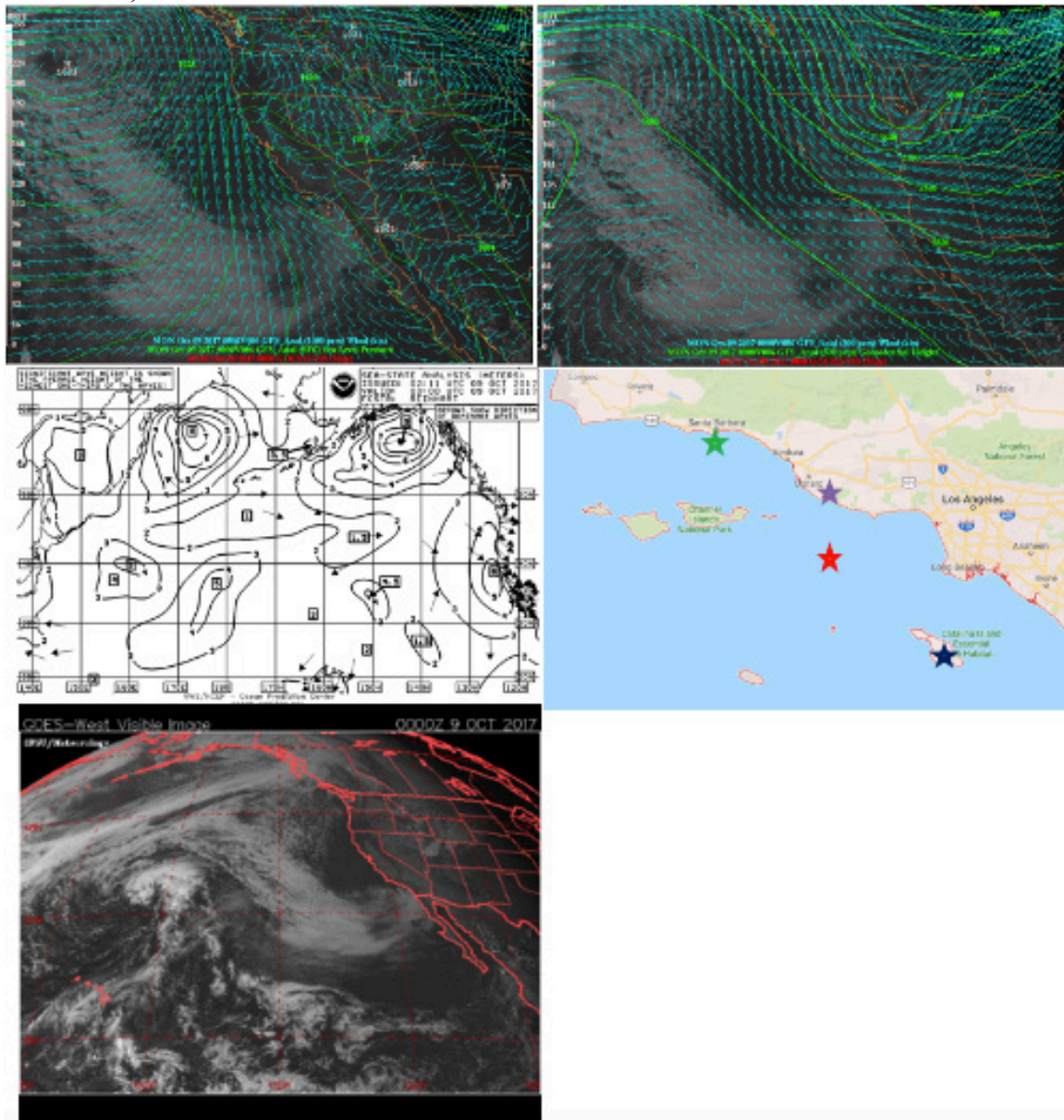
Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	190	5	10	Clear	1007.11
★ KNTD	280	6	10	Clear	1007.7
★ KAVX	270	7	10	Clear	1010.2

Synoptic Analysis:

The previously mentioned upper-level low and associated surface low continues to be stalled, but are well to the west of the central California coast. A strong surface high pressure system can be seen to the west of Washington state and is propagating westward. Weak anti-cyclonic flow is observed in the upper levels to the west of Baja California with associated clouds visible in the satellite imagery. All stations experience pressure falling. All stations remained clear for the majority of the day. No impacts were observed due to cloud cover.

The winds outside of the bight are Northwesterly. Winds aloft shifted to become Westerly. The local surface winds continue to be in a diurnal sea-land breeze regime. Winds shifted at Point Mugu from offshore to onshore at 0900PST/1700UTC. The winds shifted again in the evening from onshore to offshore at 2100PST (7 October)/0500UTC (8 October).

October 8, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (9 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
1.36	168	21.2

★ NDBC Station 46025 Buoy Observation at 0000UTC (9 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
264	4.3	1006.2

ASOS Observations at 0000UTC (9 October):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	240	6	8	Clear	1006.1
★ KNTD	270	8	8	Few clouds at 1500ft	1006.8
★ KAVX	270	5	8	Clear	1006.4

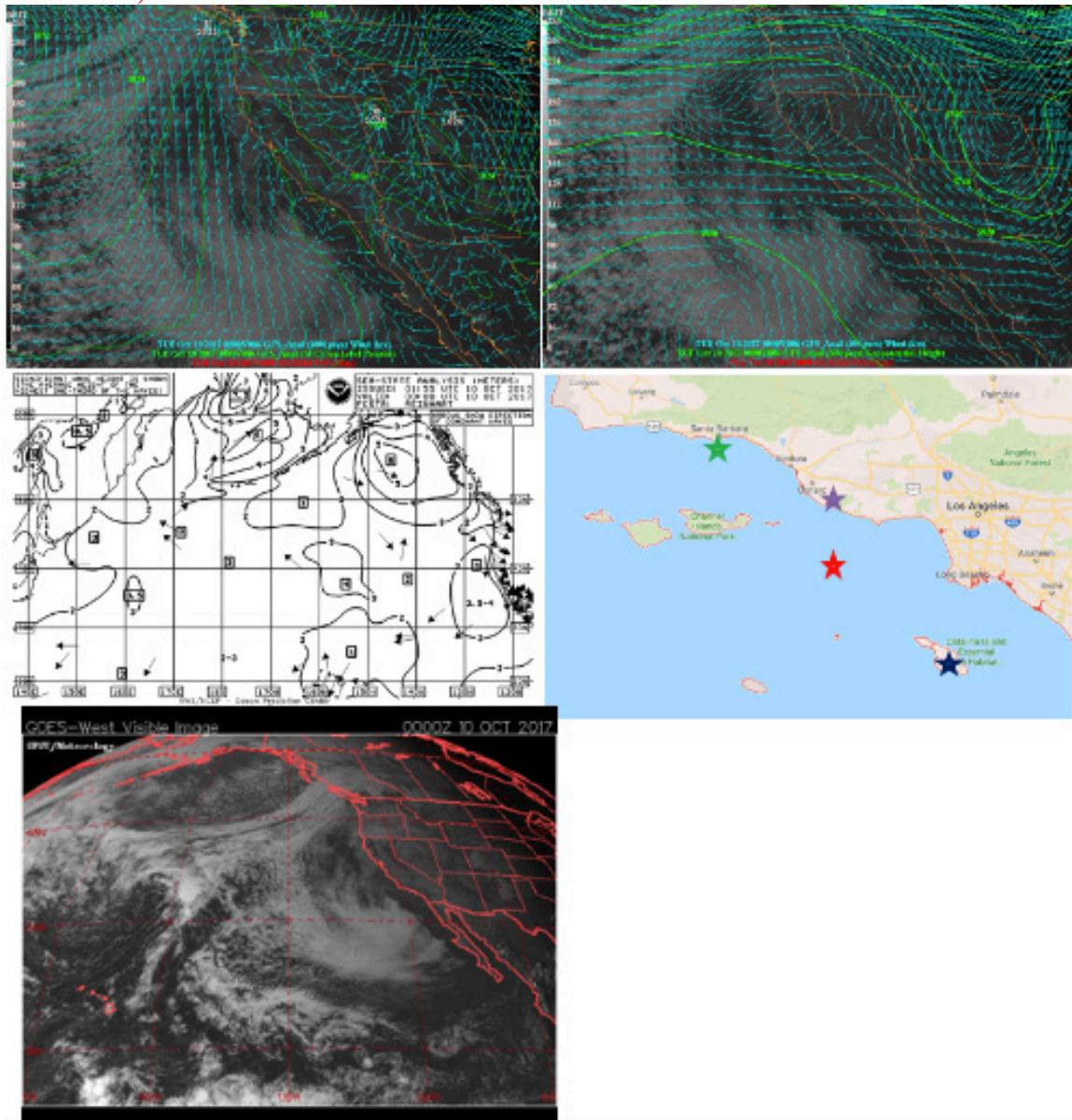
Synoptic Analysis:

A strong 1033mb surface high pressure system to the west of Washington state continues to propagate westward. Anti-cyclonic flow increases in the upper levels to the west of Baja California, which also increases cloud in that area. Station pressures near the CASPER West operating area continue to fall as the pressure gradient along the coast of California tightens.

Low clouds moved into the Point Mugu area overnight with mist and low visibility until 0500PST/1300UTC. A brief period of clear skies over Point Mugu (KNTD) followed, but the low cloud deck returned at 1000PST(1800UTC) and persisted for the rest of the day. Oxnard (KOXR) corroborates these observations. All other stations remained clear for most of the day.

The winds outside of the bight are Northwesterly and much stronger than in previous days. San Nicolas Island (KNSI) reports gusts of up to 22 knots in the late afternoon. Winds aloft continue to be Westerly. The local surface winds continue to be in a diurnal sea-land breeze regime. Winds shifted at Point Mugu from offshore to onshore at 0800PST/1600UTC. The winds became calm in the evening at 1934PST (8 October)/0334UTC (9 October) and remained calm for much of the night.

October 9, 2017 **offshore wind event**



****offshore wind event****

★ NDBC Station 46262 Buoy Observation at 0000UTC (10 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
1.14	175	20.8

★ NDBC Station 46025 Buoy Observation at 0000UTC (10 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
279	10.7	1011.3

ASOS Observations at 0000UTC (10 October):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	260	4	9	Clear	1011.5
★ KNTD	210	7	9	Clear	1011.5
★ KAVX	060	5	10	Clear	1013.2

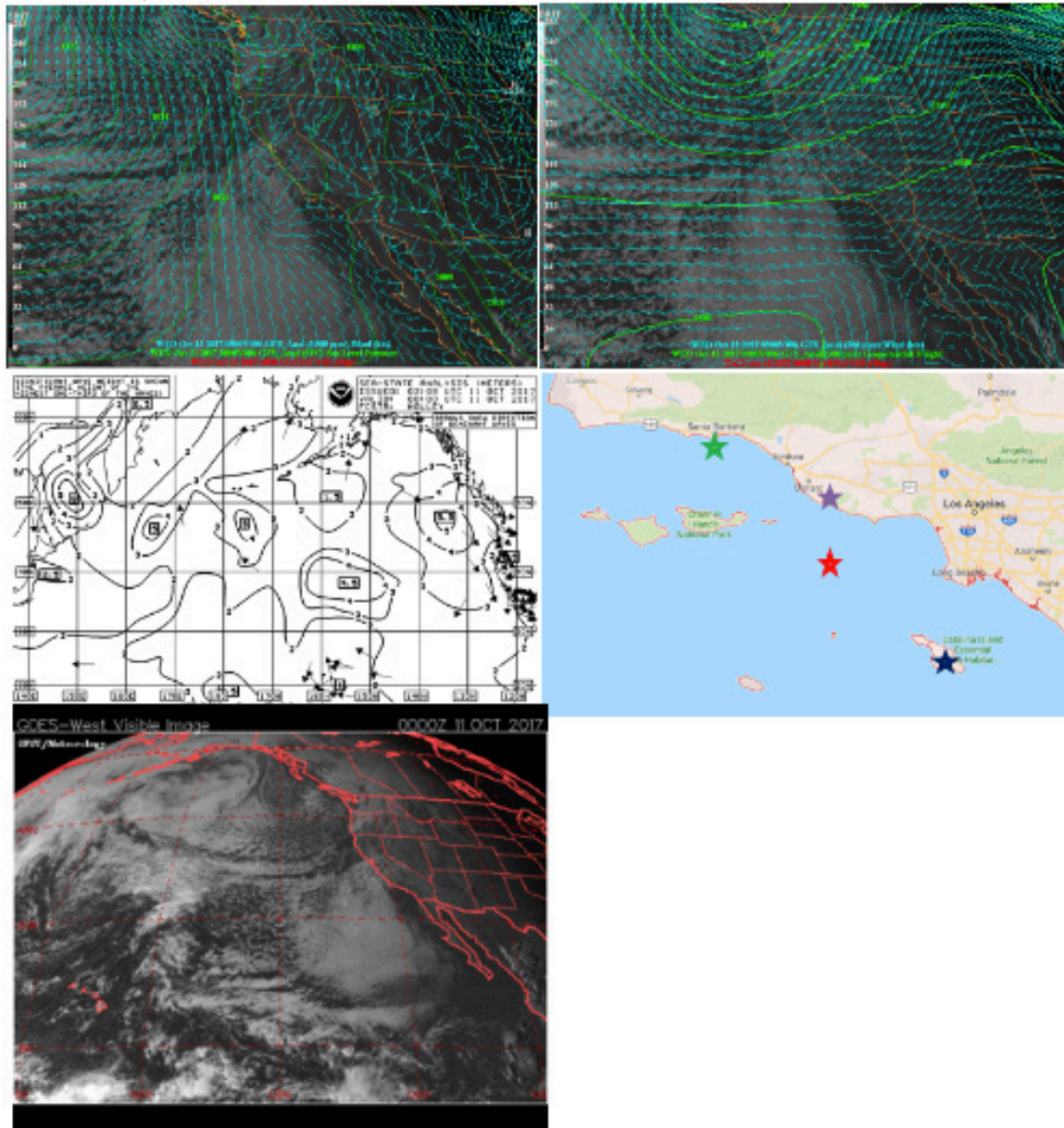
Synoptic Analysis:

A strong surface high pressure system to the west of Washington state lingers well off the coast. An upper-level trough can be seen off the coast of Canada and is associated with clouds seen in the satellite image. Anti-cyclonic flow strengthens in the upper levels to the west of Baja California with persistent clouds associated with it. Station pressures near the CASPER West operating area rose, but the pressure gradient along the coast slackens. A surface high pressure system sets up over Utah and enhances offshore flow.

Some low clouds lingered in the overnight hours at Point Mugu (KNTD), but the station cleared by 0100PST/0900UTC.

The winds outside of the bight are very weak and have shifted to a more Northerly direction. Winds aloft continue to be Westerly. Very strong offshore flow is apparent at Point Mugu (KNTD), Oxnard (KOXR), Camarillo (KCMA) starting at 0645PST/1445UTC with gusts up to 42 knots. Dust and haze reduced the visibility. Santa Barbara (KSBA) reported calm or very weak winds during this period. The offshore flow from mainland California could be seen at Avalon (KAVX). The local surface winds were in an offshore regime for the entire day.

October 10, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (11 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
0.94	177	21.0

★ NDBC Station 46025 Buoy Observation at 0000UTC (11 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
282	10.7	1011.6

ASOS Observations at 0000UTC (11 October):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	270	10	9	Clear	1011.9
★ KNTD	270	9	8	Few clouds at 26000ft, 28000ft	1012.2
★ KAVX	250	8	10	Clear	1013.5

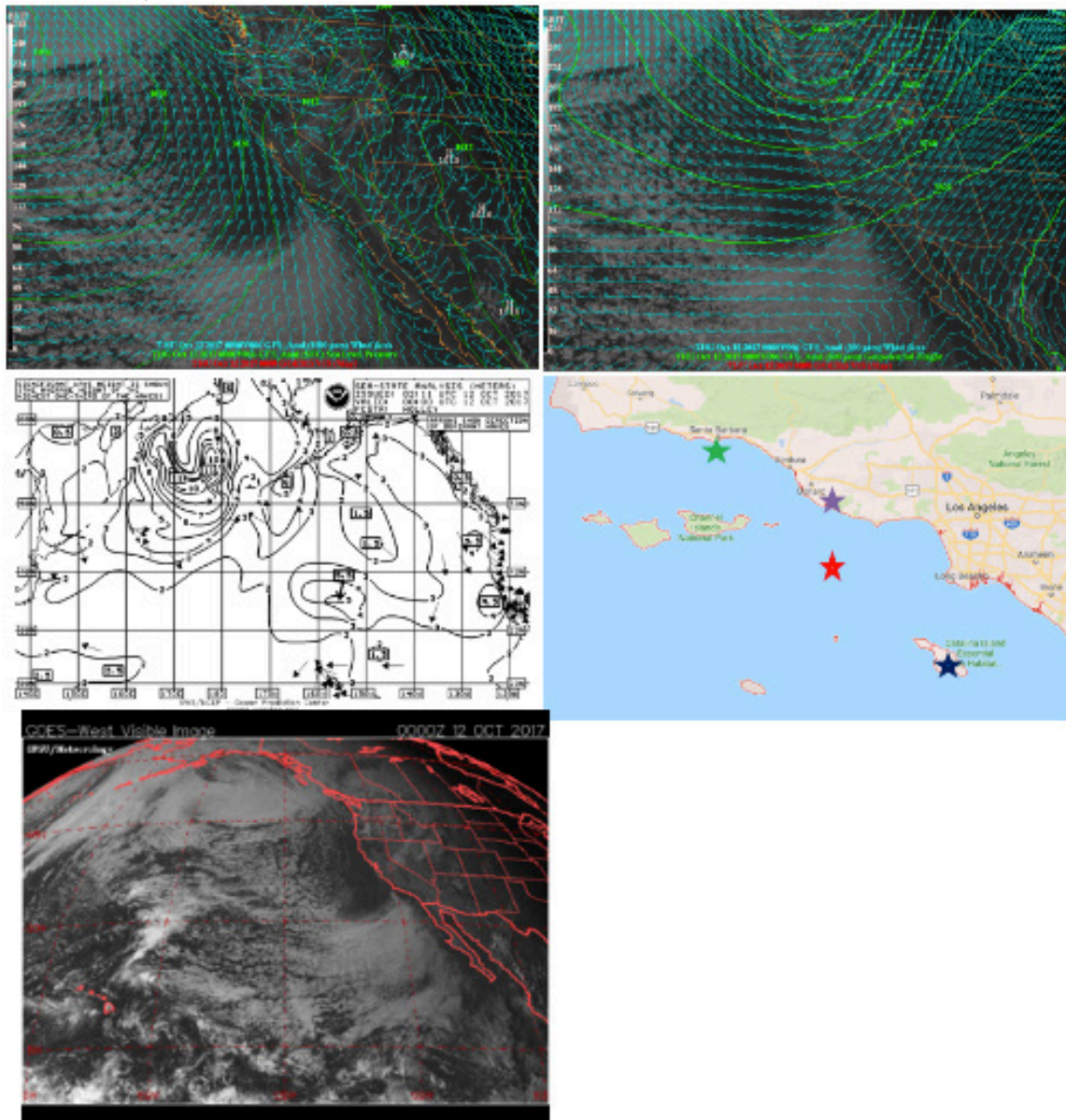
Synoptic Analysis:

A strong surface high pressure system to the west of Washington state remains well off the coast. A cool upper-level trough makes landfall along the western coast of Canada and stretches down through the central coast of California. Anti-cyclonic flow in the upper levels to the west of Baja California has meandered to the south and maintains strength. Cyclonic flow in the upper levels is close to the coast of Baja California. The surface high pressure system that was over Utah has weakened and the flow has become variable.

Point Mugu (KNTD) experienced low clouds and reduced visibility from 0400PST/1200UTC through 1000PST/1800UTC. Oxnard (KOXR) and San Nicolas Island (KNSI) experienced similar conditions, while Avalon (KAVX) remained clear throughout the morning.

The winds outside of the bight continue to be weak. Winds aloft continue to be Westerly. The significant offshore wind event at Point Mugu does not continue into today. The local surface winds continue to be in a diurnal sea-land breeze regime, although the timing was disrupted due to the winds remaining offshore for most of the previous day. Winds shifted at Point Mugu from offshore to a Southerly onshore direction at 0100PST/0900UTC. The winds turned to a Southwesterly direction at 1000PST/1800UTC. The winds shifted again in the evening from onshore to offshore at 2100PST (10 October)/0500UTC (11 October).

October 11, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (12 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
0.77	223	20.9

★ NDBC Station 46025 Buoy Observation at 0000UTC (12 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
265	8.0	1011.1

ASOS Observations at 0000UTC (12 October):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	250	7	10	Clear	1010.8
★ KNTD	270	8	10	Clear	1011.5
★ KAVX	240	10	10	Clear	1012.5

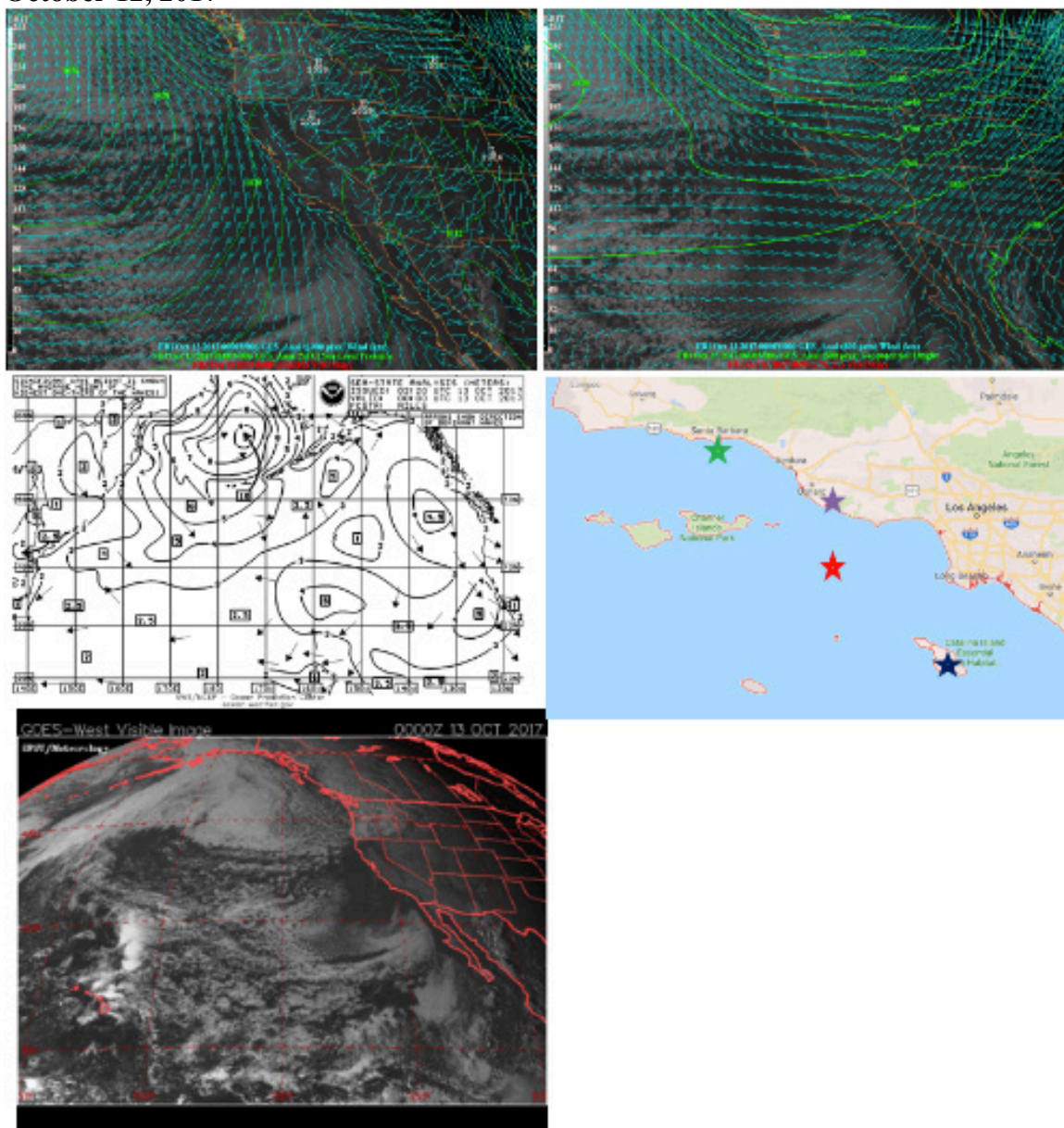
Synoptic Analysis:

A strong surface high pressure system continues to build to the west of Washington state, but remains well off the coast. The high pressure can be seen at the 500mb level at this time. A cool upper-level trough stretches from Washington state through California.

Low clouds extended down from Avalon (KAVX) up to Santa Barbara (KSBA) in the early morning hours. Point Mugu (KNTD) cleared by 1400PST/2200UTC, while the outlying islands like San Clemente (KNUC) and San Nicolas (KNSI) remained mostly cloudy to overcast for most of the day.

The winds outside of the bight are Northwesterly. Winds aloft are Southwesterly. The local surface winds continue to be in a diurnal sea-land breeze regime. Winds shifted at Point Mugu from offshore to a Southerly onshore direction at 1000PST/1800UTC. The winds shifted again in the evening from onshore to offshore at 1900PST (11 October)/0300UTC (12 October).

October 12, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (13 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
1.06	247	20.9

★ NDBC Station 46025 Buoy Observation at 0000UTC (13 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
275	11.5	1012.1

ASOS Observations at 0000UTC (13 October):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	150	6	10	Clear	1011.5
★ KNTD	280	7	9	Few clouds at 1800ft, 25000ft	1012.7
★ KAVX	250	12	8	Clear	1013.5

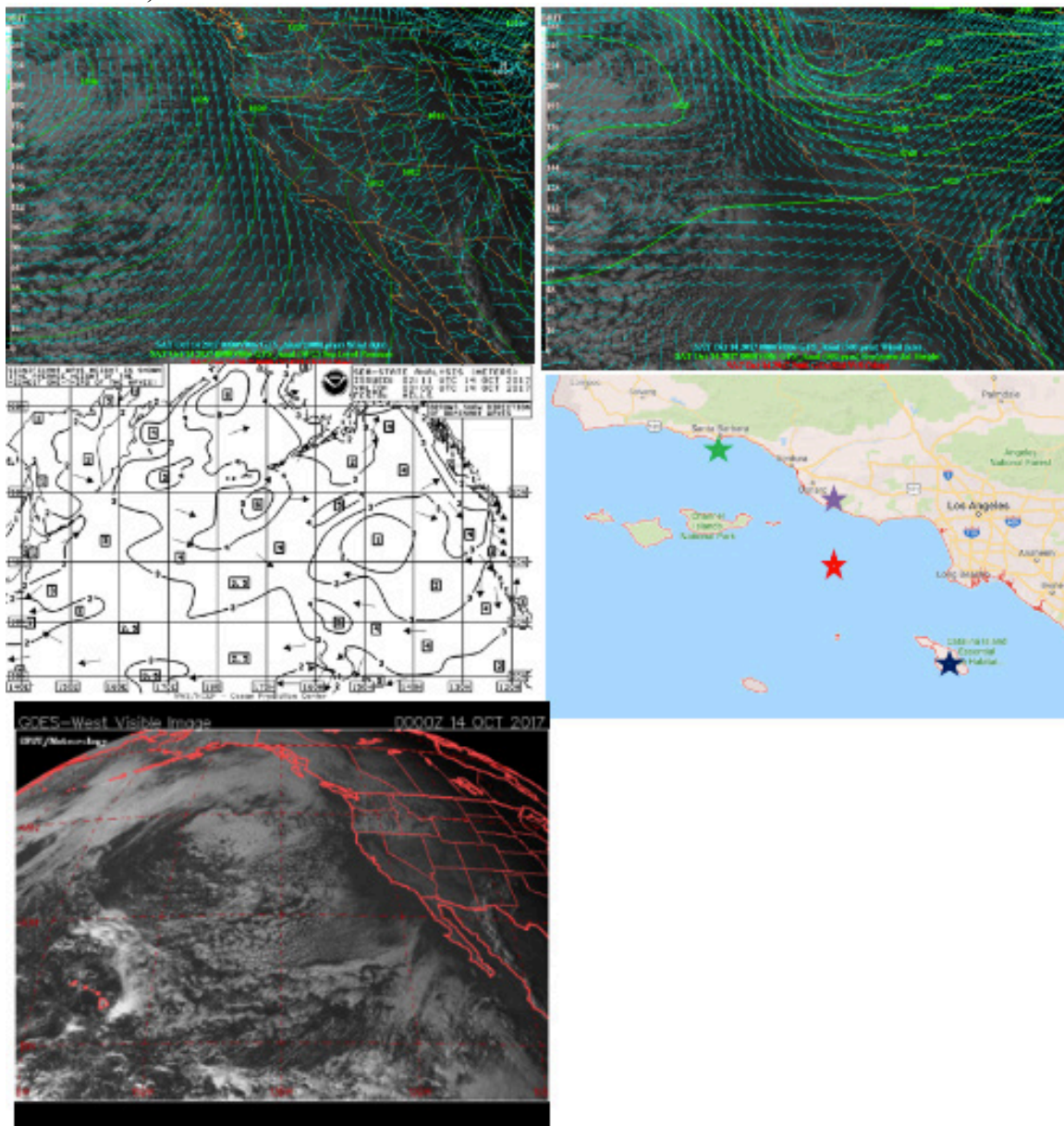
Synoptic Analysis:

A strong surface high pressure system with associated 500mb ridge continues to build to the west of Washington state, but remains well off the coast. A cool upper-level trough stretches from Washington state through California. Station pressures rose slightly as the surface ridge builds.

Low clouds impacted Point Mugu (KNTD) extending down to 200ft with mist in the early morning hours, but quickly lifted after sunrise. The shallow cloud deck extended from Avalon (KAVX) up to Santa Barbara (KSBA). Santa Barbara cleared quickly in the morning, while Avalon cleared later in the afternoon.

The winds outside of the bight are Northwesterly. Winds aloft are Southwesterly. The local surface winds continue to be in a diurnal sea-land breeze regime. Winds shifted at Point Mugu from offshore to an onshore direction at 1000PST/1800UTC. The winds shifted again in the evening from onshore to offshore at 2300PST (12 October)/0700UTC (13 October).

October 13, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (14 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
0.93	196	20.7

★ NDBC Station 46025 Buoy Observation at 0000UTC (14 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
257	8.9	1012.9

ASOS Observations at 0000UTC (14 October):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	190	3	10	Clear	1012.9
★ KNTD	230	5	9	Few clouds at 28000ft	1013.5
★ KAVX	260	5	10	Clear	1014.6

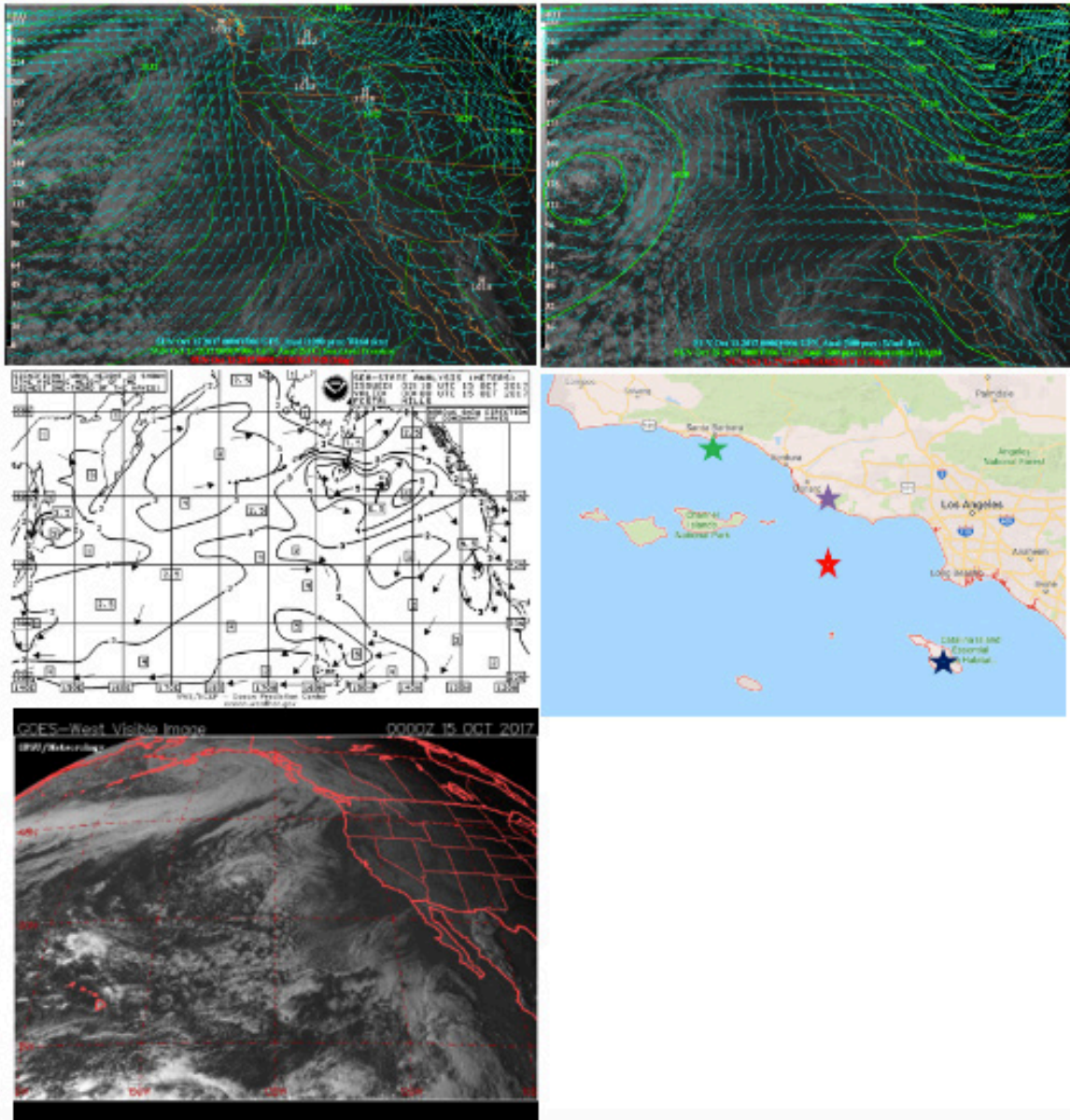
Synoptic Analysis:

A strong surface high pressure system with associated 500mb ridge continues to build to the west of Washington state, but remains well off the coast. The cool upper-level trough remains over Washington state. A weak upper level low located to the west of central California approaches the coast. Weak anti-cyclonic flow at 500mb is off the west coast of Baja California. There is also weak cyclonic flow at 500mb near Baja California.

Low clouds linger at San Clemente (KNUC), but all other stations were not impacted by cloud cover in the morning hours.

The winds outside of the bight are Northwesterly. Winds aloft are Southwesterly turning Westerly. The local surface winds continue to be in a diurnal sea-land breeze regime. Winds shifted at Point Mugu from offshore to an onshore direction at 1000PST/1800UTC. The winds shifted again in the evening from onshore to offshore at 2000PST (13 October)/0400UTC (14 October).

October 14, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (15 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
0.89	189	20.8

★ NDBC Station 46025 Buoy Observation at 0000UTC (15 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
291	9.5	1013.5

ASOS Observations at 0000UTC (15 October):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA*	260	7	10	Clear	1013.9
★ KNTD	290	5	9	Clear	1014.2
★ KAVX	360	4	10	Clear	1015.2

*Ob taken at 0040UTC due to no reporting at 0000UTC

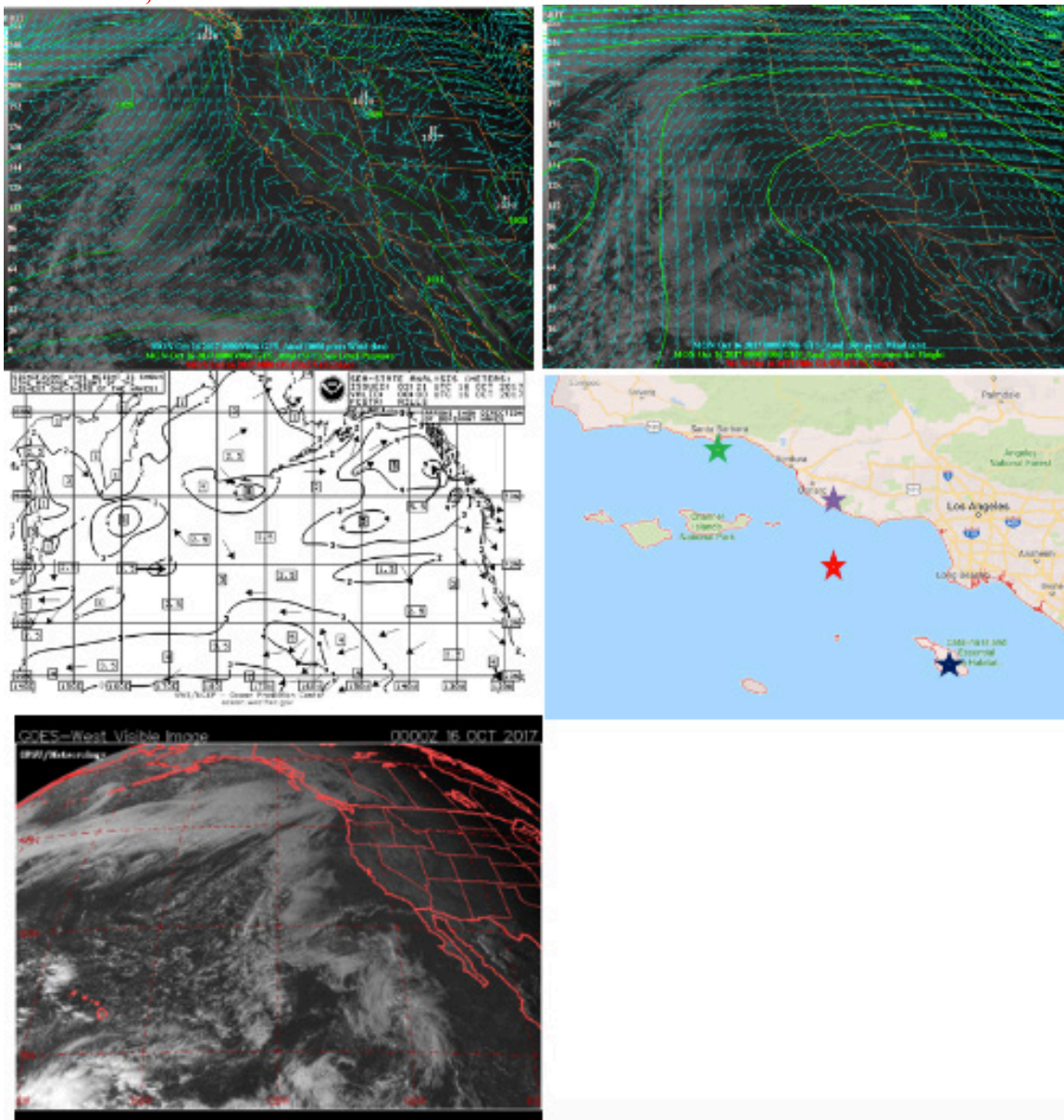
Synoptic Analysis:

A strong surface high pressure system off the coast of Oregon flattens and meanders to the southwest. The associated anti-cyclonic flow at 500mb has been disrupted by a deepening upper-level low to the west of California. The upper-level trough over the northwestern U.S. moves to the east. Strong surface ridging can be seen along the California coast, and the local station pressures have increased as a result. Surface high pressure builds over the intermountain west. Weak anti-cyclonic flow at 500mb is off the west coast of Baja California.

All stations report clear conditions throughout the morning and afternoon. No impacts due to clouds at this time.

The winds outside of the bight are Northerly and weak. Winds aloft are Westerly and weak. The local surface winds continue to be in a diurnal sea-land breeze regime. Winds shifted at Point Mugu from offshore to an onshore direction at 1000PST/1800UTC. The winds shifted again in the evening from onshore to offshore at 2100PST (14 October)/0500UTC (15 October).

October 15, 2017 **offshore wind event**



****offshore wind event****

★ NDBC Station 46262 Buoy Observation at 0000UTC (16 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
0.74	198	21.3

★ NDBC Station 46025 Buoy Observation at 0000UTC (16 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
288	8.0	1016.2

ASOS Observations at 0000UTC (16 October):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	250	8	10	Clear	1016.3
★ KNTD	260	7	9	Few clouds at 28000ft	1016.8
★ KAVX	280	5	10	Clear	1019.0

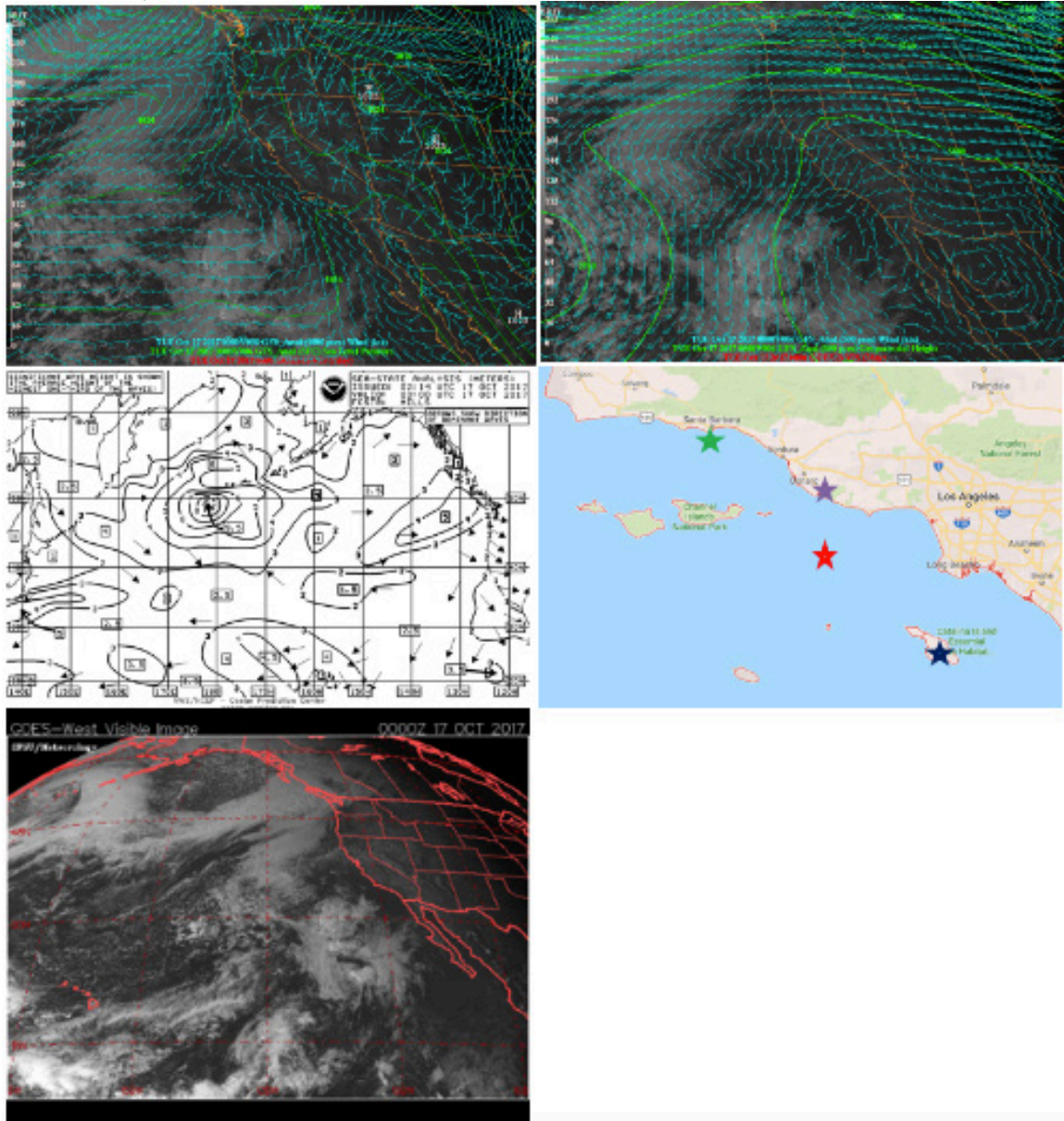
Synoptic Analysis:

A strong surface high pressure system off the coast of Oregon continues to flatten and meander to the south. The upper-level low to the west of California is blocked by an upper-level ridge over Mexico and the southwestern U.S. Local station pressures continue to increase. Surface high pressure remains over California and much of the intermountain west.

All stations report clear conditions throughout the morning and afternoon. No impacts due to clouds at this time.

The winds outside of the bight are Northwesterly and weak. Winds aloft are Southwesterly and weak. Significant offshore surface flow with peak winds up to 15 knots gusting to 23 knots was observed between 0500PST/1300UTC and 1100PST/1900UTC. The winds were predominantly offshore for the entire day.

October 16, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (17 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
0.67	192	21.5

★ NDBC Station 46025 Buoy Observation at 0000UTC (17 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
278	8.6	1015.2

ASOS Observations at 0000UTC (17 October):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	VRB	5	10	Clear	1015.6
★ KNTD	300	7	9	Few clouds at 15000ft, 28000ft	1015.8
★ KAVX	250	7	10	Clear	1018.3

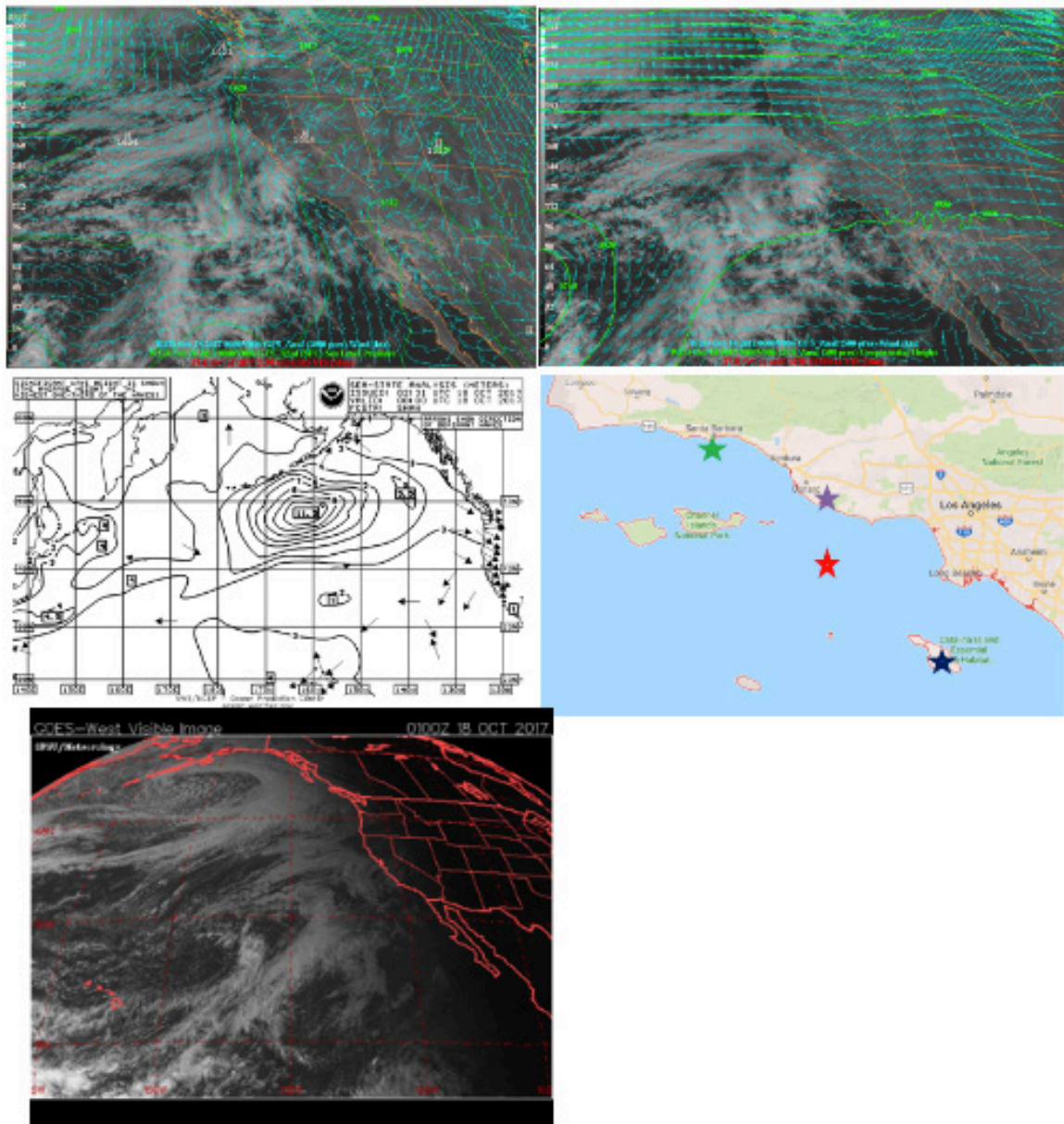
Synoptic Analysis:

A surface high pressure system off the coast of Oregon continues to flatten. The cut-off upper-level low to the west of California is blocked by an upper-level ridge over Mexico and the southwestern U.S. Flow around the upper-level low and upper-level ridge advects tropical moisture into the CASPER West operating area.

Mid-level and high-level clouds are over the CASPER West operating area.

Surface flow to the west of California is Easterly, a result from the position of the surface high. The winds outside of the bight are Northwesterly. Winds aloft are variable in direction. The sea-land breeze effect was disrupted by the offshore flow from the previous day. Winds overnight and into the morning were calm or very light. Onshore flow began at 0800PST/1600UTC and continued for most of the day.

October 17, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (18 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
1.39	182	20.9

★ NDBC Station 46025 Buoy Observation at 0000UTC (18 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
4.7	2.4	1012.6

ASOS Observations at 0000UTC (18 October):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	Calm	Calm	10	Clear	1012.2
★ KNTD	290	7	10	Scattered clouds at 14000ft Broken skies 28000ft	1013.6
★ KAVX	300	9	10	Clear	1015.9

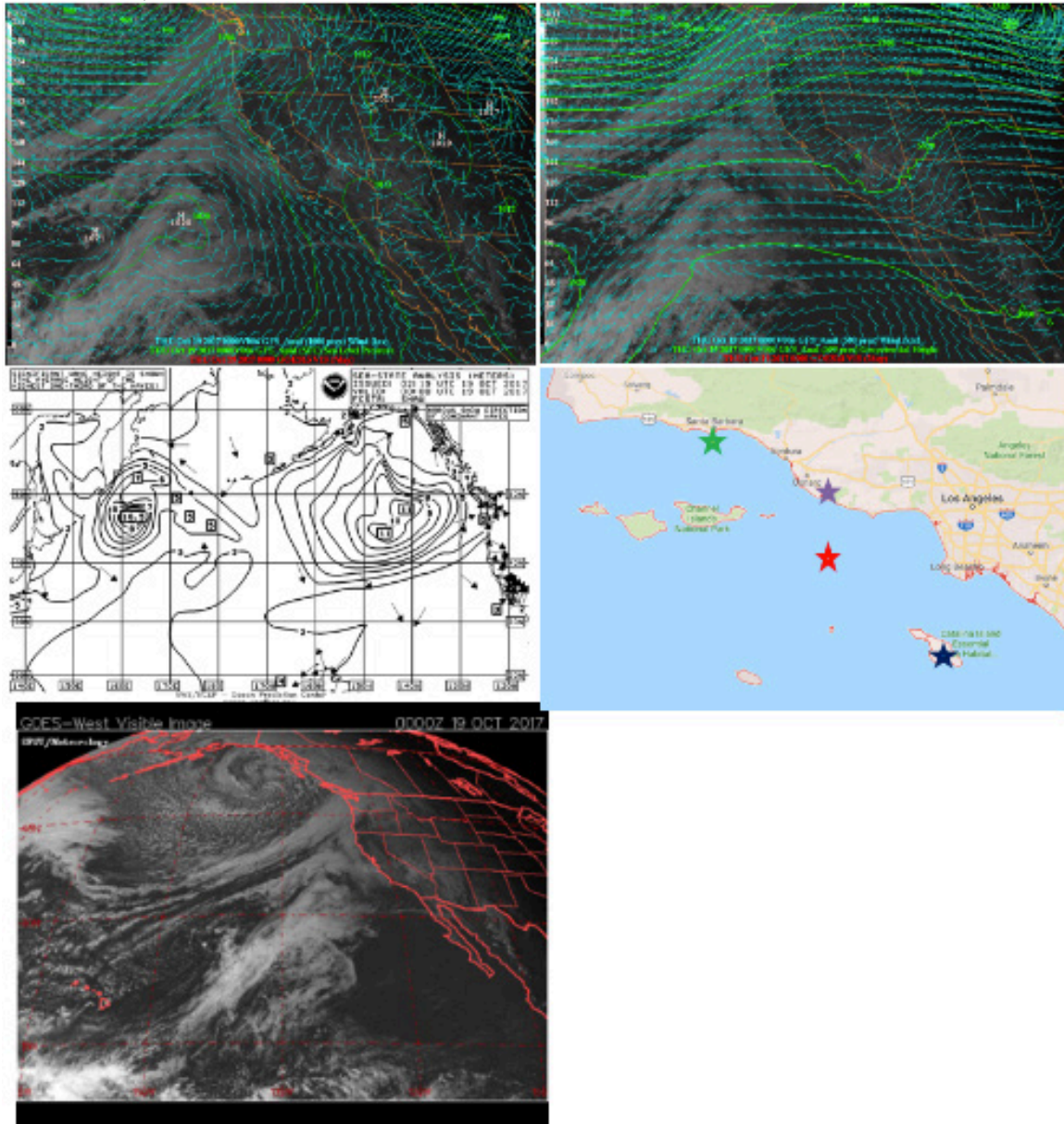
Synoptic Analysis:

A cut-off upper-level low is lingering to the west of California.

Mid-level and high-level clouds are over the CASPER West operating area.

Surface flow to the west of California is Easterly. The winds outside of the bight are Northwesterly. Winds aloft are Southwesterly. The local surface winds struggle to regain a diurnal sea-land breeze regime. Winds shifted at Point Mugu from offshore to an onshore direction at 0800PST/1600UTC. The winds shifted again in the overnight hours from onshore to offshore at 0100PST (18 October)/0900UTC (18 October).

October 18, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (19 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
1.36	189	21.6

★ NDBC Station 46025 Buoy Observation at 0000UTC (19 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
351	6.2	1011.9

ASOS Observations at 0000UTC (19 October):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	110	6	9	Clear	1010.8
★ KNTD	280	9	7	Few clouds at 15000ft	1012.4
★ KAVX	300	5	10	Clear	1011.9

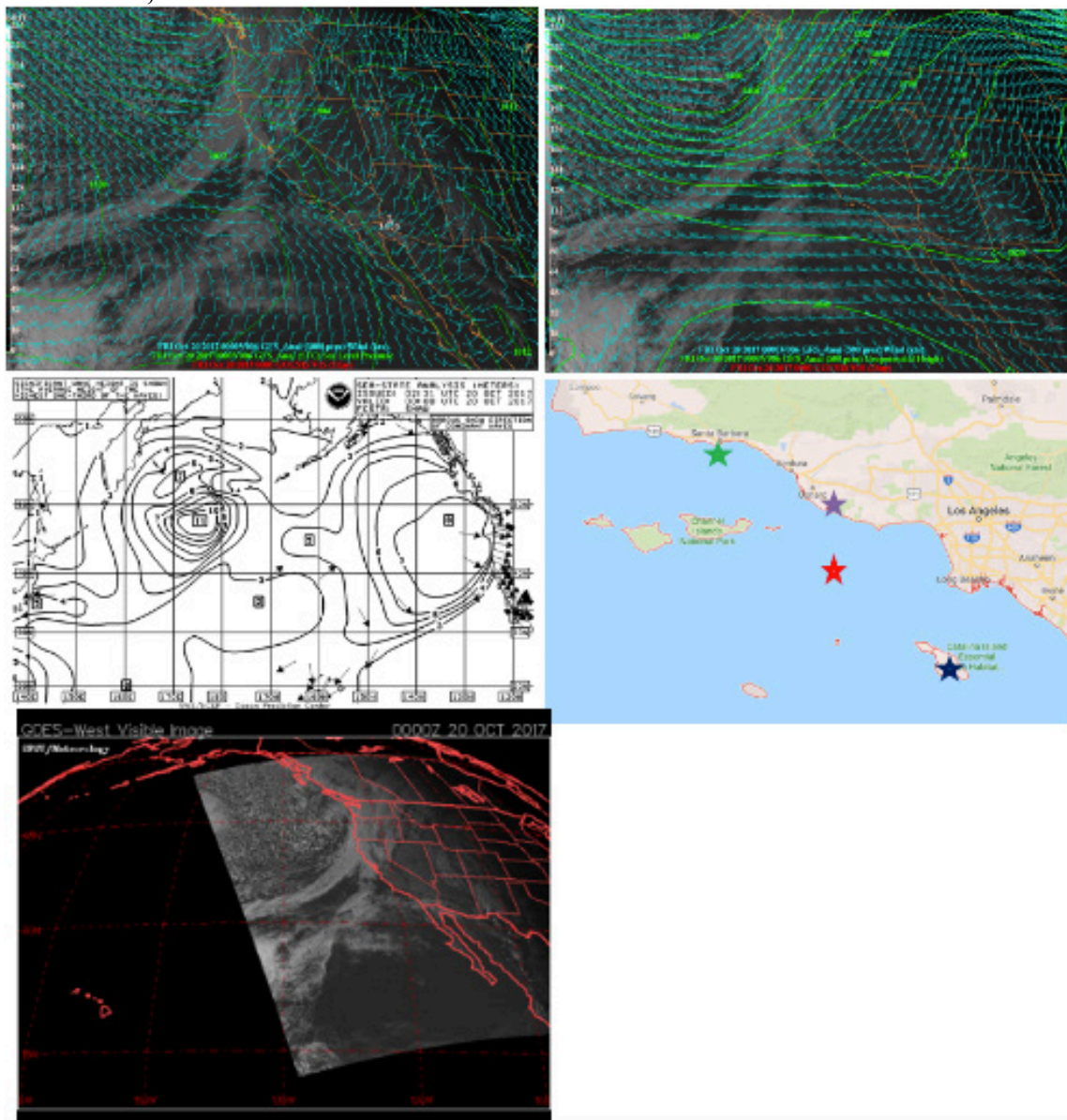
Synoptic Analysis:

Seas build along the west coast of the U.S. as a low pressure system approaches British Columbia with a trough that extends down through California. The surface high pressure to the west of California flattens. The upper-level low to the west of California, aloft of the surface high, begins to fill. Upper-level anticyclonic flow to the west of Baja California becomes more organized.

All stations report clear or partly cloudy conditions throughout the morning and afternoon. No impacts due to clouds at this time.

The winds outside of the bight are Northwesterly and increase in speed through the day. San Nicolas Island (KNSI) reported gusts up to 33 knots. Winds aloft are Westerly and also increasing in speed. The local surface winds are in a diurnal sea-land breeze regime. Winds shifted at Point Mugu from offshore to an onshore direction at 0900PST/1700UTC. The winds remained onshore for most of the day, and did not shift to offshore until the early morning hours of 20 October.

October 19, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (20 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
1.16	178	21.2

★ NDBC Station 46025 Buoy Observation at 0000UTC (20 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
270	8.2	1010.9

ASOS Observations at 0000UTC (20 October):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA*	250	10	7	Clear	1009.8
★ KNTD	260	13	7	Few clouds at 1800ft, 28000ft	1011.4
★ KAVX	270	9	10	Clear	1012.9

*Ob taken at 0045UTC

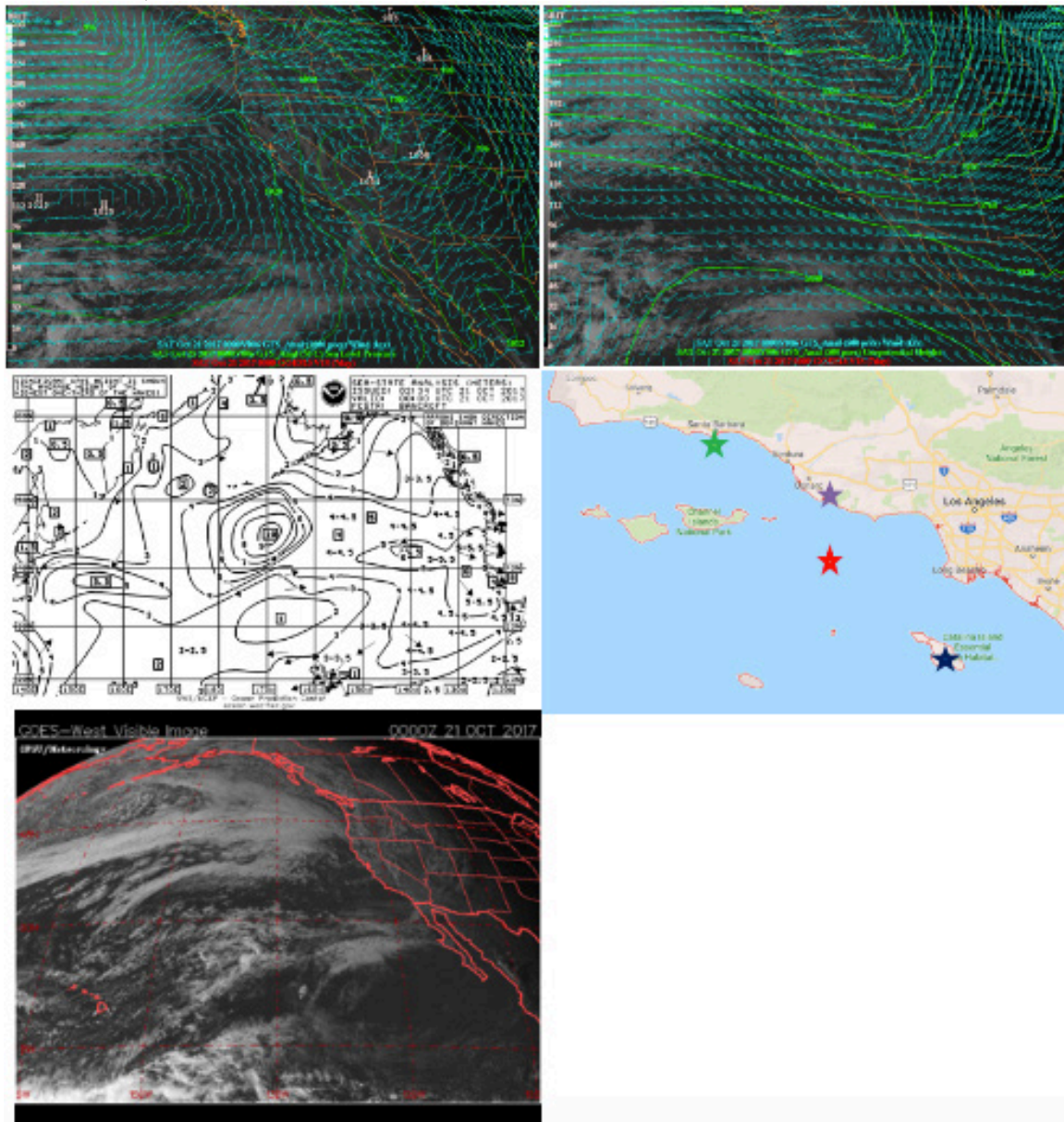
Synoptic Analysis:

Seas continue to be higher along the west coast of the U.S. as a low pressure system makes landfall in British Columbia with a trough that extends down through California. The surface high pressure to the west of California begins to build. Upper-level anticyclonic flow to the west of Baja California meanders to the south.

Point Mugu (KNTD) had some low clouds and mist in the morning, but the station was clear by 0800PST/1600UTC.

The winds outside of the bight are Northwesterly and increase in speed through the day. San Nicolas Island (KNSI) reported gusts up to 41 knots. Winds aloft are Westerly and strong. The local surface winds are in a diurnal sea-land breeze regime. Winds shifted at Point Mugu from offshore to an onshore direction at 1000PST/1800UTC. The winds shifted again in the evening from onshore to offshore at 2000PST (19 October)/0400UTC (20 October).

October 20, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (21 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
2.34	265	20.5

★ NDBC Station 46025 Buoy Observation at 0000UTC (21 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
283	17.5	1011.5

ASOS Observations at 0000UTC (21 October):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	280	15	10	Clear	1012.2
★ KNTD	270	15	9	Few clouds at 2000ft, 6000ft, Scattered at 25000ft, 28000ft	1012.0
★ KAVX	260	19	10	Few clouds at 900ft	1013.5

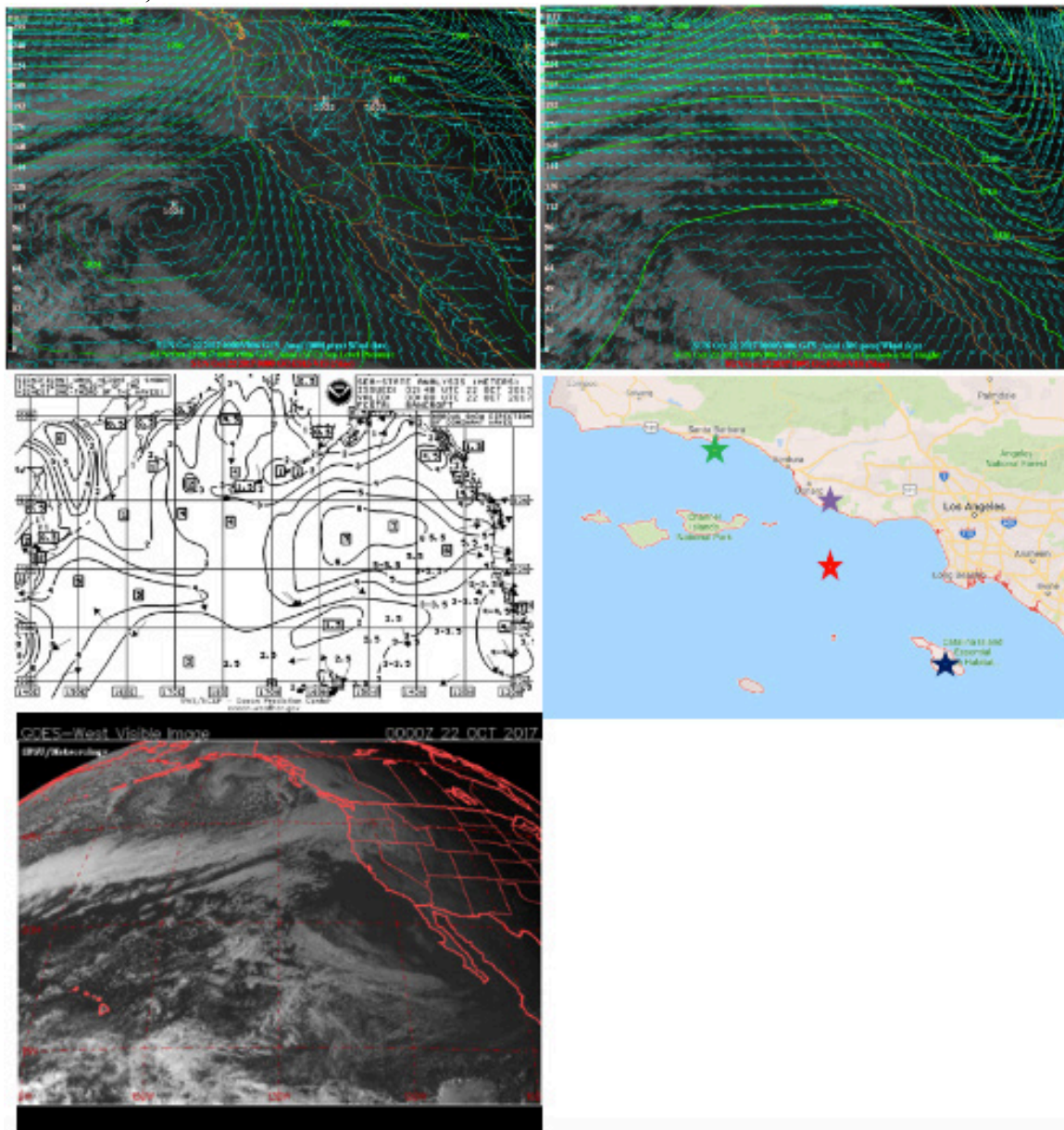
Synoptic Analysis:

An upper level trough extends through the intermountain west. The associated surface trough extends from eastern Montana to New Mexico. The surface Eastern Pacific High builds to the west of California.

Point Mugu (KNTD) had some low clouds and mist in the morning, but the station was clear by 0800PST/1600UTC. Avalon (KAVX) remained cloudy for most of the day, but eventually cleared by 1530PST/2330UTC.

The winds outside of the bight are Northwesterly and increase in speed through the day. San Nicolas Island (KNSI) reported gusts up to 42 knots. Winds aloft are Westerly and very strong. The sea-land breeze was disrupted by strong onshore flow at 0100PST/0900Z with gusts up to 21 knots at Point Mugu. The winds remained onshore and gusty through the afternoon.

October 21, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (22 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
1.32	261	19.9

★ NDBC Station 46025 Buoy Observation at 0000UTC (22 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
316	11.1	1016.7

ASOS Observations at 0000UTC (22 October):

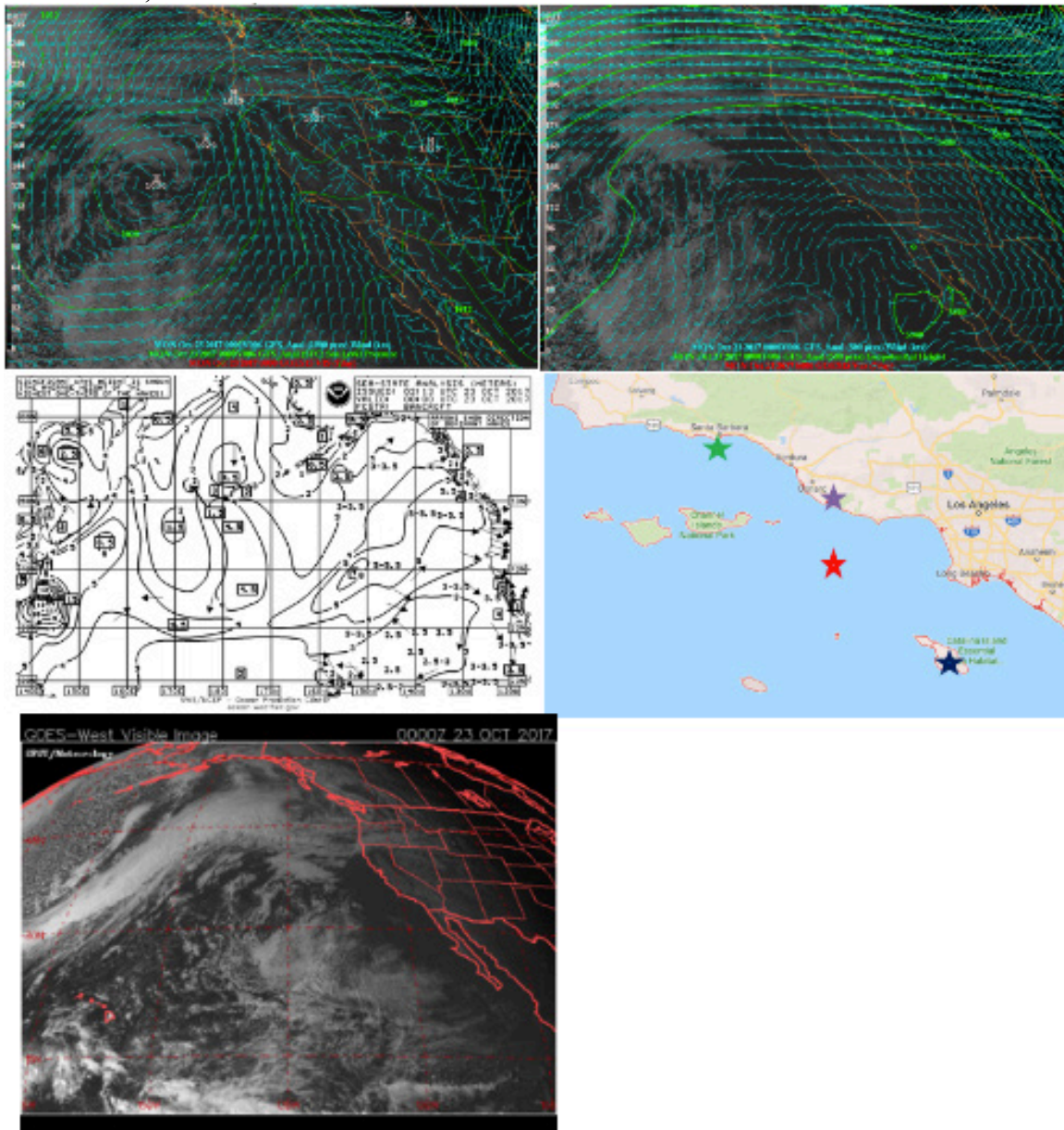
Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	140	3	10	Clear	1017.3
★ KNTD	330	4	10	Few clouds at 25000ft	1017.3
★ KAVX	360	5	10	Clear	1018.3

Synoptic Analysis:

The surface Eastern Pacific High ridges toward the California coast, raising station pressures significantly and keeping the area under clear skies. Upper-level ridging over the west coast of the U.S. allows low-level high pressure to set up over the intermountain west. No clouds impacted the CASPER West operating area at this time.

The winds outside of the bight turn from Northwesterly to Northerly and continue to be strong. Winds aloft are Northwesterly. The local surface winds are in a diurnal sea-land breeze regime. Winds shifted at Point Mugu from offshore to an onshore direction at 1000PST/1800UTC. The winds became calm or weak with variable direction in the evening.

October 22, 2017



★ NDBC Station 46262 Buoy Observation at 0000UTC (23 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
1.22	269	20.2

★ NDBC Station 46025 Buoy Observation at 0000UTC (23 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
246	7.4	1017.6

ASOS Observations at 0000UTC (23 October):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	250	5	10	Clear	1017.6
★ KNTD	Variable	4	10	Few clouds at 26000ft	1017.9
★ KAVX	300	5	10	Clear	1020.3

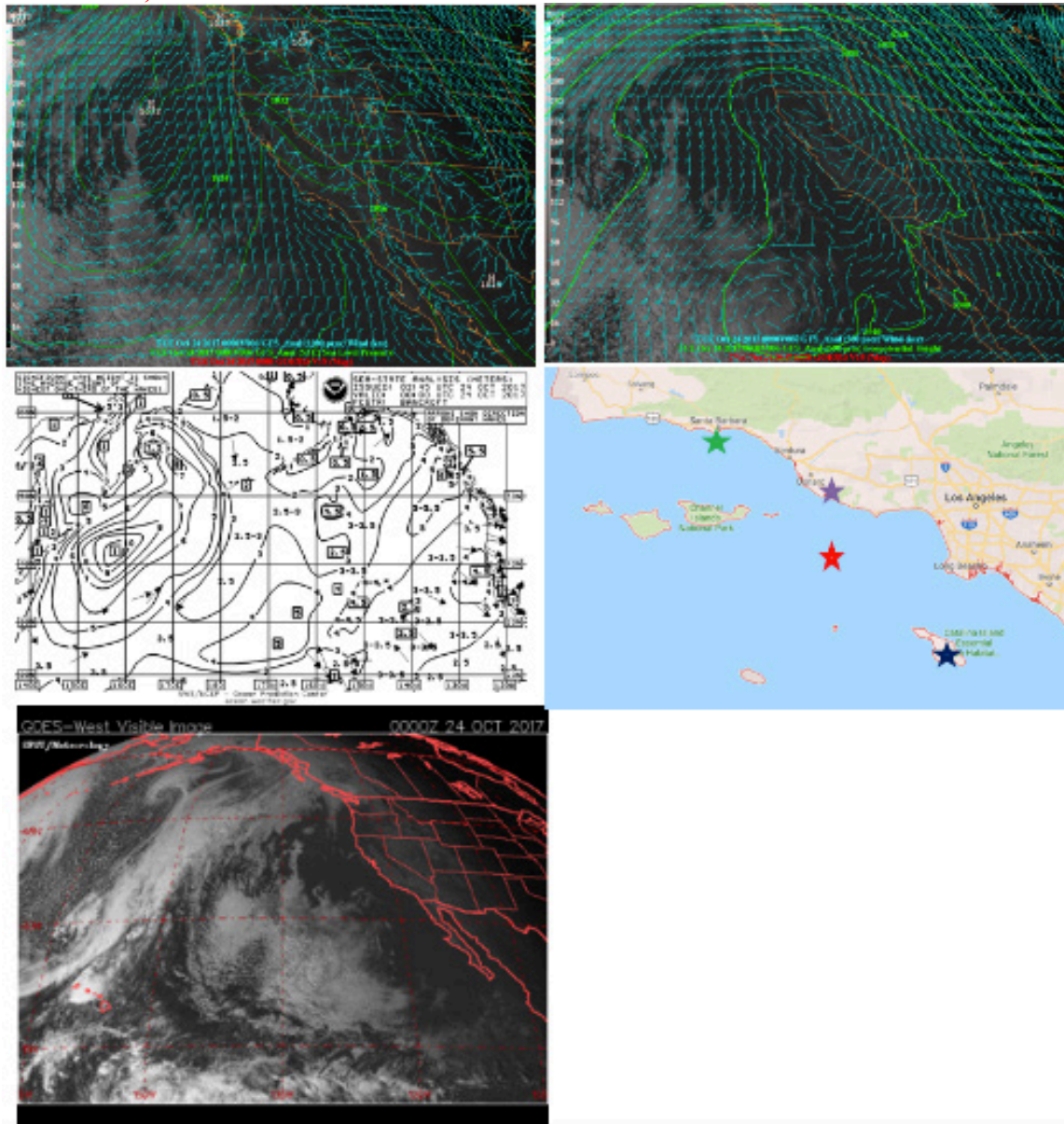
Synoptic Analysis:

The surface Eastern Pacific High strengthens and ridges toward the California coast, keeping the area under clear skies. Upper-level ridging over the west coast of the U.S. allows low-level high pressure to set up over the intermountain west.

No clouds impacted the CASPER West operating area at this time.

The winds outside of the bight turn from Northwesterly to Northerly and continue to be strong. Winds aloft are variable as they are near the center of the anti-cyclonic circulation. The local surface winds are in a diurnal sea-land breeze regime, although offshore flow is trying to disrupt it. Winds shifted at Point Mugu from a Northerly direction to an onshore direction at 1300PST/2100UTC. The winds shifted from onshore to a Northerly direction at 1900PST/0300UTC (23 October).

October 23, 2017 **offshore wind event**



****offshore wind event****

★ NDBC Station 46262 Buoy Observation at 0000UTC (24 October):

Wave Height (m)	Mean Wave Direction (degT)	Water Temperature (°C)
1.00	254	21.1

★ NDBC Station 46025 Buoy Observation at 0000UTC (24 October):

Wind Direction (degT)	Wind Speed (kts)	Atmospheric Pressure (mb)
301	5.8	1015.6

ASOS Observations at 0000UTC (24 October):

Station ICAO	Wind Direction (degT)	Wind Speed (kts)	Visibility (SM)	Sky Condition	Atmospheric Pressure (mb)
★ KSBA	260	8	10	Clear	1015.9
★ KNTD	180	7	10	Clear	1015.8
★ KAVX	290	3	10	Clear	1019.3

Synoptic Analysis:

The surface Eastern Pacific High strengthens and propagates to the northeast. Ridging along the California coast keeps the area under clear skies. Upper-level ridging over the west coast of the U.S. allows low-level high pressure to continue over the intermountain west.

No clouds impacted the CASPER West operating area at this time.

The winds outside of the bight are Northerly and have weakened from the previous day as the pressure gradient slackens. Winds aloft are offshore. The sea-land breeze was disrupted by the strong offshore winds. Point Mugu (KNTD) reported winds gusting up to 23 knots. The offshore winds could be seen at Avalon (KAVX), San Nicolas Island (KNSI), and San Clemente Island (KNUC).

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