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Improving bulk Cn2 models for over-ocean applications through new determinations of the dimensionless temperature structure parameter

Improving bulk C_n^2 models for over-ocean applications through new determinations of the dimensionless temperature structure parameter

Paul A. Frederickson[*a], Stephen Hammel[b], and Dimitris Tsintikidis[b]
[a]Department of Meteorology, Naval Postgraduate School, Monterey, CA
[b]Space and Naval Warfare Systems Center, San Diego, CA

ABSTRACT

The performance of imaging and laser systems can be severely degraded by atmospheric turbulence, especially for near-horizon propagation paths. Having the ability to predict turbulence effects from relatively easily obtained measurements can be useful for system design and feasibility studies, and for real-time optimization of optical systems for the current environment. For this reason, so-called 'bulk' models have been developed that can estimate turbulence effects through the refractive index structure parameter (C_n^2) from mean near-surface meteorological and sea surface temperature measurements. Bulk C_n^2 models are directly dependent upon empirically determined dimensionless functions, known as the dimensionless structure parameter functions for temperature and humidity. In this paper we attempt to improve bulk optical turbulence model performance by determining new over-ocean forms for the dimensionless temperature structure parameter (f_T).

During 2005-2006 atmospheric propagation experiments were conducted in the Zuniga Shoals area near San Diego to examine the impact of environmental conditions on low-altitude electro-optical propagation above the ocean surface. As part of this experiment the Naval Postgraduate School (NPS) deployed its flux research buoy along the propagation path. The measurements obtained on the NPS buoy enabled f_T values to be obtained and new functions to be determined. These new functions differ greatly from those presented in the past, in that the new f_T values asymptote towards very high values as the stability approaches neutrality. The dependence of the new f_T function on the stability parameter in stable conditions was also different from that previously proposed. When these new functions were inserted into the NPS bulk C_n^2 model, the resulting values agreed much better with directly measured turbulent C_n^2 values in unstable conditions, but in stable conditions the new function actually made the agreement worse.

Keywords: Scintillation, optical turbulence, refractive index structure parameter, bulk models, dimensionless temperature structure parameter.

1. INTRODUCTION

Over the past several decades much effort has been invested into developing models to describe the impact of atmospheric optical turbulence on imaging and laser systems from readily measured mean atmospheric properties. Optical turbulence is often quantified by the refractive index structure parameter, C_n^2, since important optical turbulence effects on imaging and laser systems, such as image blurring, received signal intensity variations, beam wander and beam spread, are related to C_n^2. Direct measurements of C_n^2 over the ocean are difficult and expensive to obtain, therefore, it is useful to be able to estimate C_n^2 from routinely measured environmental parameters. Bulk models have been developed to estimate near surface C_n^2 values from mean meteorological and sea temperature measurements, which can be made relatively easily from ships, buoys and ocean towers. Important uses of bulk C_n^2 models include the ability to predict C_n^2 values from numerical weather prediction model outputs, to construct C_n^2 climatologies from historical marine meteorological data bases, and to use real-time, in situ meteorological measurements to produce C_n^2 estimates to assist operational personnel in optimally employing their EO systems in the current environment.

In this study we focus on attempting to improve bulk C_n^2 models by developing new dimensionless temperature structure parameter functions (f_T) for over-ocean applications. During a recent propagation experiment that took place in

[*]E-mail: pafreder@nps.edu; Telephone: 831 595 5212; Fax: 831 656 3061

the Zuniga Shoals area near San Diego in 2005, the Naval Postgraduate School deployed its flux research buoy with sensors capable of measuring all the quantities required to determine f_T. This is important since C_n^2 is directly related to f_T, therefore any improvements that can be made to the f_T functions will directly improve the performance of bulk C_n^2 models. Once new f_T functions were determined from the Zuniga Shoals buoy data they were then used in the NPS bulk model to determine if they do indeed improve the C_n^2 model performance as compared to direct turbulent C_n^2 measurements.

2. THEORETICAL BACKGROUND

The turbulent fluctuation component of the refractive index of air, n, can be expressed to a first order approximation as a function of turbulent air temperature and specific humidity fluctuations, as follows[1]:

$$n' = A(\lambda, P, T, q)T' + B(\lambda, P, T, q)q' \tag{1}$$

where

$$A = \frac{\partial n}{\partial T} = -10^{-6}\frac{P}{T^2}\left\{m_1(\lambda) + \left[m_2(\lambda) - m_1(\lambda)\right]\frac{q}{\varepsilon\gamma}\right\}, \tag{2}$$

$$B = \frac{\partial n}{\partial q} = 10^{-6}\left[m_2(\lambda) - m_1(\lambda)\right]\frac{P}{T\varepsilon\gamma^2}\cdot \tag{3}$$

and λ is the optical wavelength, P is atmospheric pressure, T is the air temperature, q is specific humidity, $\varepsilon = 0.622$, and $\gamma = (1 + 0.61q)$. m_1 and m_2 are empirical functions of wavelength. For the wavelength we will be examining in this study, 1.62 μm, $m_1 = 77.66$ and $m_2 = 65.09$.

Within the inertial-subrange of the atmospheric turbulence spectrum, the refractive index structure parameter, C_n^2, is defined as:

$$C_n^2 = \frac{\overline{\left[n'(0) - n'(r)\right]^2}}{r^{2/3}}, \tag{4}$$

where $n'(0)$ and $n'(r)$ are the turbulent fluctuation values of n at two points separated by a distance r along the mean wind direction and the overbar denotes an ensemble average. In practice r is generally taken to be on the order of roughly 10 cm, therefore C_n^2 as defined by Eq. (4) is a statistical description of small-scale refractive index fluctuations. C_n^2 can also be expressed in terms of the structure parameters for temperature, C_T^2, specific humidity, C_q^2 and the temperature-specific humidity cross-structure parameter, C_{Tq}, all defined similar to Eq. 4, as follows[1]:

$$C_n^2 = A^2C_T^2 + 2ABC_{Tq} + B^2C_q^2\cdot \tag{5}$$

The first term on the right-hand side of Eq. (5) represents refractive index fluctuations caused by temperature fluctuations and is always positive, the second term represents the correlation of temperature and humidity fluctuations and can be positive or negative, while the third term represents humidity fluctuations and is always positive.

C_n^2 values can also be determined by optical systems from the normalized variance of the measured intensity fluctuations in a signal that has propagated through the turbulent atmosphere, σ_I^2, using the generalized relation:

$$C_n^2 = 2\sigma_I^2\left(\frac{2\pi}{\lambda}\right)^{-7/6}L^{-11/6}F \tag{6}$$

where λ is the optical wavelength, L is the propagation path length and F is a dimensionless function which incorporates the effects of the turbulence strength and aperture averaging for finite size incoherent source and receiver apertures.

Equations (4-5) and (6) represent two very different means of determining C_n^2. Equations (4-5) are for single-point atmospheric turbulence measurements which are highly dependent upon the specific height above the surface and horizontal point in space where the measurements are taken, whereas Eq. (6) is a path-averaged measurement which includes the effects of horizontal variations in atmospheric turbulence along the path and also variations in turbulence levels at different heights above the surface as the optical rays are refracted through the atmosphere. We would expect the two methods to agree best when atmospheric conditions approach horizontally homogeneity

3. THE BULK C_n^2 MODEL

Near the surface, Monin-Obukhov similarity theory (MOST) can be used to relate the structure parameters C_T^2, C_q^2 and C_{Tq} in Eq. (5) to the mean properties of the atmospheric surface layer. According to MOST, conditions are assumed to be horizontally homogeneous and stationary; the turbulent fluxes of momentum, sensible heat and latent heat are assumed to be constant with height in the surface layer; and all dynamical properties within the surface layer, when scaled by the proper parameters, are assumed to be a dimensionless function of ξ, defined as:

$$\xi = \frac{z}{L_{MO}} = \frac{zkg(\theta_* + 0.61Tq_*)}{\theta_v u_*^2}, \tag{7}$$

where z is the height above the surface, L_{MO} is the Monin-Obukhov length scale, k is the von Karman constant (= 0.4) and T_*, q_* and u_* are the scaling parameters for temperature, humidity and wind speed, respectively. The ratio ξ is often referred to simply as the 'stability', and is negative in unstable conditions, zero in neutral conditions, and positive in stable conditions. The surface layer scaling parameters can be expressed as:

$$x_* = (\Delta x)k[\ln(z/z_{ox}) - \psi_x(\xi)]^{-1}, \tag{8}$$

where x represents wind speed (u), temperature (T) or specific humidity (q) and the symbol Δ denotes the mean air-sea difference. The ψ functions are the integrated dimensionless profile functions. We have made the common assumption that $\psi_T = \psi_q$. The parameters z_{ou}, z_{oT} and z_{oq} are known as the 'roughness lengths,' and are determined by the bulk surfaced-layer model formulated by Fairall et al.[2].

The structure parameters for temperature (C_T^2) and specific humidity (C_q^2) and the temperature-specific humidity cross-structure parameter (C_{Tq}) can be expressed in terms of the surface layer scaling parameters as follows:

$$C_T^2 = T_*^2 z^{-2/3} f_T(\xi), \tag{9a}$$

$$C_{Tq} = r_{Tq} T_* q_* z^{-2/3} f_{Tq}(\xi), \tag{9b}$$

$$C_q^2 = q_*^2 z^{-2/3} f_q(\xi), \tag{9c}$$

where r_{Tq} is the temperature-specific humidity correlation coefficient with a value of about 0.8, and f_T, f_{Tq}, and f_q are dimensionless functions of ξ that must be determined empirically, as will be discussed in the next section. In this study we assume that the forms of all these functions are identical and thus $f = f_T = f_{Tq} = f_q$.

We can express C_n^2 in terms of mean meteorological properties by combining Eqs. (5, 7-9), resulting in:

$$C_n^2 = \frac{f(\xi)k^2\left[A^2\Delta T^2 + 2ABr_{Tq}\Delta T\Delta q + B^2\Delta q^2\right]}{z^{2/3}\left[\ln(z/z_{oT}) - \Psi_T(\xi)\right]^2}. \tag{10}$$

and

$$\xi = \frac{zg(\Delta\theta + 0.61T\Delta q)\left[\ln(z/z_{oU}) - \Psi_U(\xi)\right]^2}{\theta_v(\Delta U)^2\left[\ln(z/z_{oT}) - \Psi_T(\xi)\right]}. \tag{11}$$

Once the required model inputs (ΔT, Δq, ΔU) are known, C_n^2 can be estimated by solving Eqs. (10-11) by an iterative process. Full details on the Naval Postgraduate School's bulk C_n^2 model are provided by Frederickson et al (2000)[3].

The dependence of the bulk C_n^2 estimates on the air – sea temperature difference (ΔT) is shown as a function of wind speed and relative humidity in Figs. 1a and 1b, respectively. The C_n^2 estimates generally increase as $|\Delta T|$ increases. The C_n^2 estimates increase with wind speed for negative ΔT values, and generally decrease with wind speed when ΔT is positive. Wind speed variations have the largest effect on C_n^2 for large $|\Delta T|$ values and are slightly larger when $\Delta T < 0$. The bulk C_n^2 estimates decrease with relative humidity for negative ΔT values and generally increase with relative humidity when ΔT is positive. The minimum C_n^2 values increase and occur at larger ΔT values as relative humidity decreases. The effects of relative humidity variations on the bulk C_n^2 estimates are largest for small $|\Delta T|$ values.

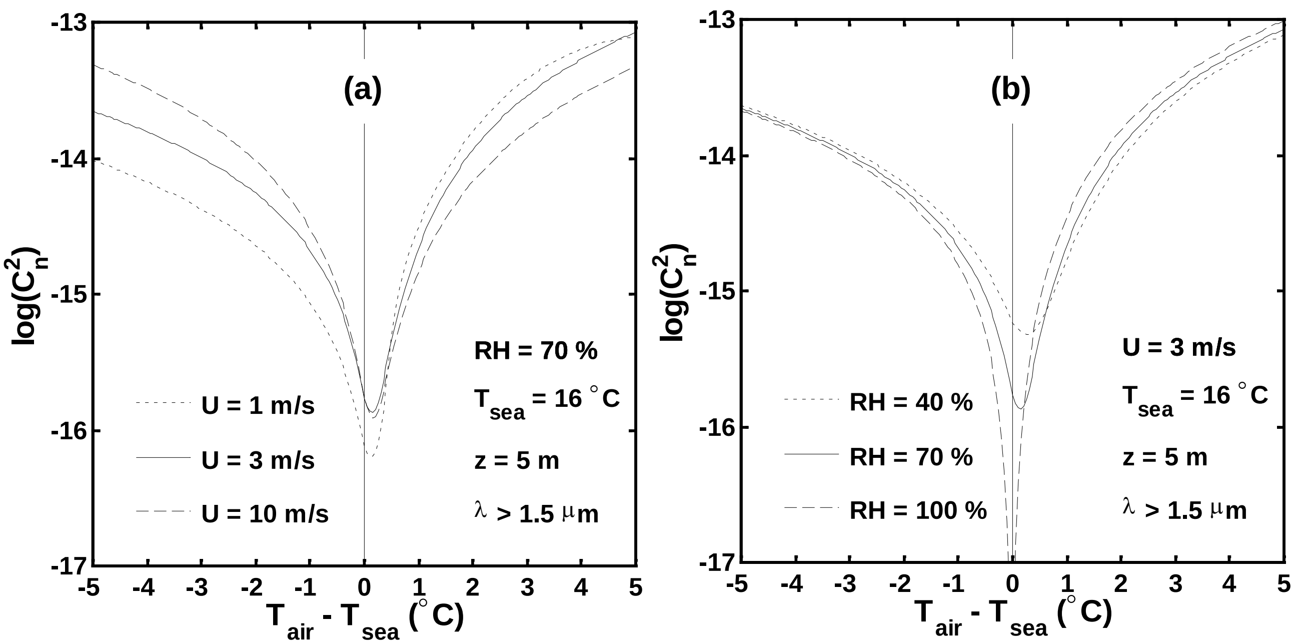

Figure 1. Bulk estimates of $\log(C_n^2)$ versus air – sea temperature difference, (a) plotted for different values of wind speed (U) as indicated; and (b) plotted for different values of relative humidity (RH) as indicated. The bulk C_n^2 estimates were computed for a sea temperature of 16 °C, height above the ocean surface of 5 m, and a wavelength of 1.62 μm.

4. THE DIMENSIONLESS TEMPERATURE STRUCTURE PARAMETER

As shown above, bulk estimates of C_n^2 are directly related to dimensionless functions of stability (ξ) known as the dimensionless structure parameter functions for temperature (f_T), humidity (f_q) and the temperature-humidity correlation (f_{Tq}). These functions must be determined experimentally and have been shown to generally follow Monin-Obukhov similarity theory well.[4,5,6,7,8,9]. Experimental results show that the three functions are very similar and that under most conditions the contribution from the humidity and temperature-humidity functions is negligible compared to the dimensionless temperature structure parameter, f_T.[7,9] For these reasons we will focus solely on the dimensionless temperature structure parameter in the following discussion.

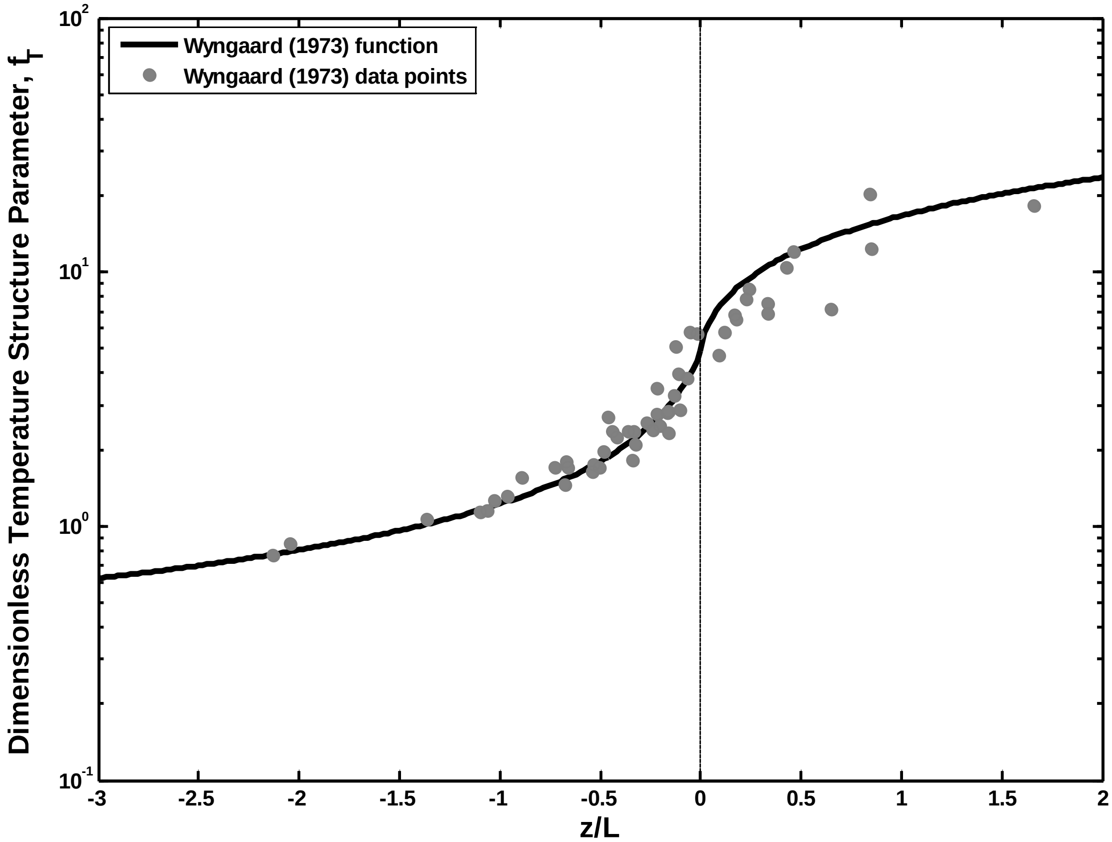

Figure 2. Measurements of the dimensionless temperature structure parameter, f_T, versus the 'stability' parameter z/L from the 1968 Kansas experiment, as presented by Wyngaard (1971) and (1973). The function shown is that given in Wyngaard (1973).

From Eq. (9) we can see that bulk C_n^2 estimates are directly related to the empirical form of the dimensionless structure parameters used. Therefore, it follows that any improvement that can be made in this function will directly result in improved fidelity of the bulk C_n^2 model, which is why there is a strong focus on trying to improve the f_T function in this and other studies.

Wyngaard[4,5] was among the first to present empirical results on the f_T function, based on the famous Kansas surface layer experiment of 1968. The Kansas data and the f_T functions developed by Wyngaard in 1973 are shown in Fig. 2. The Wyngaard functions are as follows[5]:

$$f_T(\xi) = \begin{cases} 4.9(1-7\xi)^{-2/3}, & \xi \le 0 \\ 4.9(1+2.4\xi^{2/3}), & \xi \ge 0 \end{cases}. \tag{12}$$

We can see from Fig. 2 that the data in unstable conditions ($\xi < 0$) seem to be well described by this function, while in stable conditions ($\xi > 0$) there is more scatter and the function fit to the data seems more uncertain. It is important for our later results to note that the data seem to indicate a smooth transition of f_T as stability changes across neutral conditions at $\xi = 0$. In the NPS bulk model we have used a slightly modified form of the Wyngaard function for f_T based on the over-ocean work of Edson (1998)[9], which is as follows:

$$f_T(\xi) = \begin{cases} 5.9(1-8\xi)^{-2/3}, & \xi \le 0 \\ 5.9(1+2.4\xi^{2/3}), & \xi \ge 0 \end{cases}. \tag{13}$$

This function was determined exclusively from data in unstable conditions, and the stable coefficient of 5.9 has simply been modified to match the unstable function. It should be noted that previous measurements of f_T in stable conditions generally exhibit much more scatter and are less common than measurements in unstable conditions.

5. THE EXPERIMENTS

During 2005, four Intensive Observation Periods (IOPs) of one-month duration were conducted as part of the Navy Atmospheric Propagation Measurements field campaign. During these IOPs low-level infrared scintillation measurements were obtained by the SPAWAR Systems Center, San Diego (SSC-SD) along a propagation path over the Zuniga Shoals outside of San Diego Bay, while concurrent meteorological and ocean surface measurements were collected by the Naval Postgraduate School's (NPS) buoy, located along the propagation path (see Fig. 3). Measurements of wind speed, wind direction, air temperature, relative humidity, atmospheric pressure and sea temperature are obtained every second on the buoy. These 1 Hz data were then averaged over 15 minute intervals centered about the scintillation measurement times and bulk C_n^2 estimates were computed from these averaged values. Since C_n^2 is height dependent, the bulk C_n^2 estimates were adjusted for tidal sea level variations using tide data obtained from the National Ocean Service acoustic tide gauge located in San Diego Harbor.

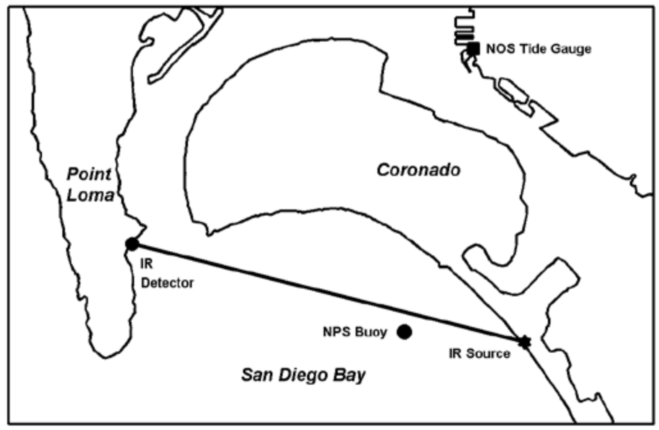

Figure 3. Map of the experiment area, showing locations of the measurement platforms and the 7.2 km propagation path.

High frequency (10 Hz) sonic temperature measurements were obtained on the NPS buoy from a Solent sonic anemometer mounted 5.25 m above the waterline. The sonic temperature structure parameter, $C_{T_s}^2$, was computed from power spectral densities of the sonic temperature, $S_{T_s}(f)$, using the expression:

$$C_{T_s}^2 = 4\left(\frac{2\pi}{U}\right)^{2/3} S_{T_s}(f) f^{5/3}, \tag{14}$$

where U is the mean wind speed and f is the frequency. Direct turbulent estimates of C_n^2 were obtained from the relationship $C_n^2 = A^2 C_{T_s}^2$, which assumes that humidity fluctuation effects on both $C_{T_s}^2$ and C_n^2 are negligible compared to temperature fluctuations.

The dimensionless temperature structure parameter function (f_T) was computed from turbulence measurements obtained on the NPS buoy. This dimensionless function is derived simply by scaling the temperature structure parameter C_T^2 by the relevant MOST surface layer scaling parameters (in this case T_* and z), as follows:

$$f_T = \frac{C_T^2 z^{2/3}}{T_*^2} \tag{15}$$

The temperature scaling parameter, T_*, was determined from the NPS buoy measurements by the direct covariance method. First, the buoy motion was removed from the sonic anemometer wind measurements, using data obtained from the onboard motion sensor. Next, the covariance of the vertical wind component and temperature fluctuations was computed (<$w'T'$>) and the wind speed scaling parameter (u_*), often referred to as the 'friction velocity', was determined. The temperature scaling parameter T_* could then be computed using the relation:

$$T_* = -\frac{< w'T' >}{u_*} \tag{16}$$

Once C_T^2 and T_* were determined, f_T is computed using Equation (15).

It is instructive to now write both the dimensionless temperature structure parameter and the dimensionless stability parameter ξ in terms of the kinematic heat flux ($-$<$w'T'$>) as follows:

$$f_T(\xi) = \frac{C_T^2 z^{2/3} u_*^2}{\langle w'T' \rangle^2} \tag{17}$$

$$\xi = \frac{z}{L_{MO}} = -\frac{zkg\langle w'T' \rangle}{\theta_v u_*^3} \tag{18}$$

We can see from Eqs. (17) and (18) that both f_T and ξ are dependent upon u_* and $-$<$w'T'$>, although with different exponents and in an opposite sense, i.e., as u_* increases f_T will also increase, but ξ will decrease, and as <$w'T'$> increases f_T will decrease and ξ will increase. This situation of finding relationships between two parameters that depend in part on the same quantities has been called 'self-correlation' and represents a potential weakness of how Monin-Obukhov similarity theory has traditionally been applied.

6. RESULTS

In this study we examine data obtained during the May and August 2005 Intensive Observation Periods (IOPs) at Zuniga Shoals. An initial study of the behavior of the scintillation and buoy turbulent C_n^2 values as a function of the environmental conditions observed at the buoy was reported earlier by Frederickson et al. (2005)[10]. In this earlier study it was noted that the mean differences between bulk estimates and turbulent measurements of C_T^2 for the May 2005 IOP, when plotted as a function of the air-sea temperature difference, exhibited a dependence upon the wind speed for $\Delta T <$ –1 °C, as seen in Fig 7a. This indicates that the dimensionless temperature structure parameter (f_T) used to compute the bulk values may be incorrect, since wind speed is the dominant factor in determining the magnitude of f_T (notice that U^2 appears in the denominator of the expression for ξ in Eq. 11). According to MOST, this dimensionless function should be a function only of ξ.

The f_T values computed from the NPS buoy measurements during the 2005 Zuniga Shoals experiments are shown in Fig. 4. The modified Wyngaard (1973)[5] functions are shown by the solid line in this figure. We can readily see that the Wyngaard (1973) function for f_T does not adequately describe our buoy data in either the unstable or stable regimes. New functions for stable and unstable conditions, using the same form as the Wyngaard function in unstable conditions but with different constants, were developed to better fit the NPS buoy data, as follows:

$$f_T(\xi) = \begin{cases} 500(1-17000\xi)^{-2/3}, & \xi \le 0 \\ 500(1+1800\xi)^{-2/3}, & \xi \ge 0 \end{cases} \tag{19}$$

The above functions are also shown by dashed lines in Fig. 4. A comparison of our new functions and the modified Wyngaard functions shows that the Wyngaard functions overestimate our f_T measurements in unstable conditions, but also that the largest differences are in near-neutral and stable conditions. The main difference is that as $|\xi|$ approaches zero, the NPS measured f_T values seem to asymptote towards very high values, while this behavior was not observed at all in the original Kansas data, as seen in Fig. 2. By examining Eqs. (17) and (18) it seems natural that this behavior

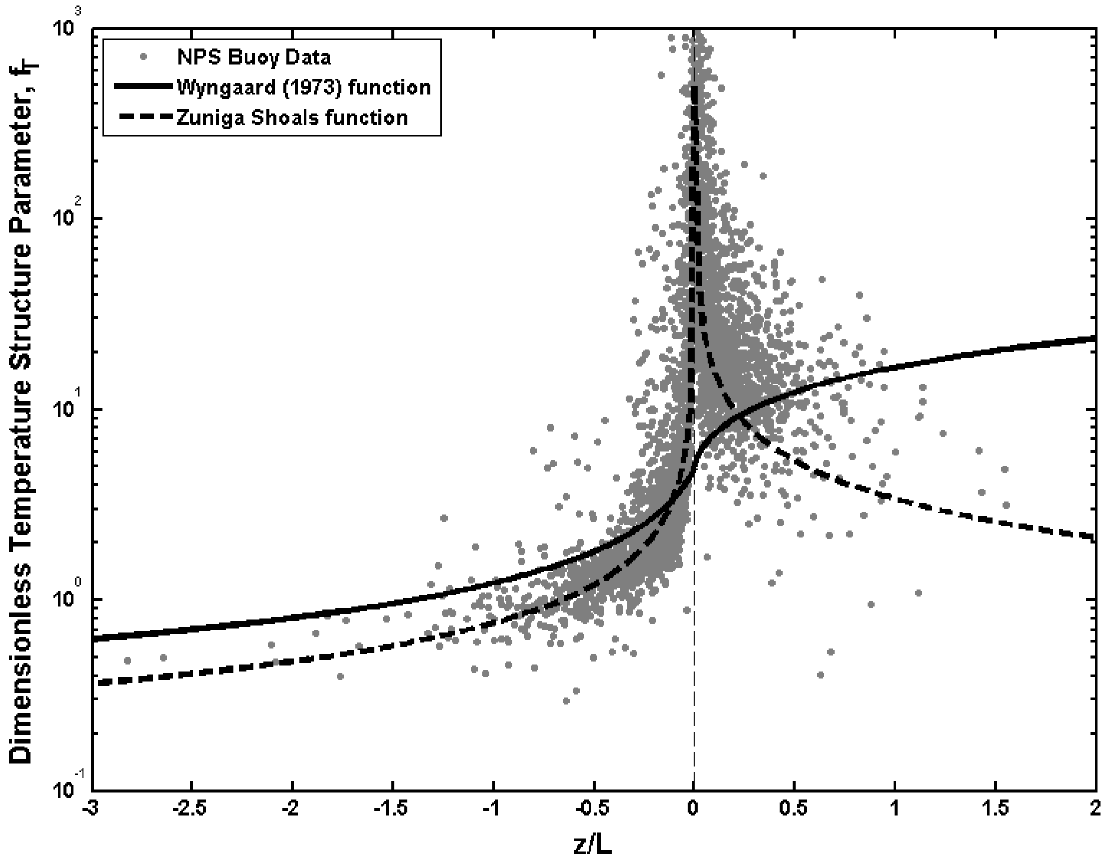

Figure 4. The dimensionless temperature structure parameter (f_T) plotted versus the 'stability', z/L. Grey dots are f_T values computed from the NPS buoy data, the solid line is the modified Wyngaard (1973) f_T function (Eq. 13), and the dashed line is the new Zuniga Shoals 2005 f_T function (Eq. 19).

would be observed, since both f_T and ξ are dependent upon u_* and $-\langle w'T' \rangle$ but in an opposite sense, as discussed above. Therefore, the conditions that lead to smaller ξ values (large u_* values and small $-\langle w'T' \rangle$ values), will also lead to large values of f_T, as long as C_T^2 does not vary in such a way as to offset these tendencies. Higher f_T values in very weakly unstable conditions than predicted by Wyngaard have also been shown in past studies of f_T as well.[6,7]

The other main difference between the Zuniga Shoals function and the traditional forms as epitomized by Wyngaard is that in stable conditions the new function does not exhibit a dependence upon ξ to the 2/3 power, as predicted by limiting forms of Monin-Obukhov similarity theory.[5] It is quite difficult to fit a function to the stable f_T data with a high degree of confidence, but a dependence of f_T upon ξ to the −2/3 power fits the data better.

This new "Zuniga Shoals" f_T function was then used in the NPS bulk model to recompute bulk C_n^2 values from the mean NPS buoy data, which are compared with the turbulent C_n^2 values in Fig. 5b. Not surprisingly, the agreement between the bulk and turbulent C_n^2 values was much better in unstable conditions with the new Zuniga Shoals function and, significantly, the air-sea temperature difference and wind speed dependence of the bulk-turbulent difference was virtually eliminated, as seen in Fig. 5b. Even for near-neutral conditions, and extending into small positive ASTD values, the agreement is much better, although bulk C_n^2 values in the lowest wind speed regime still underestimate the turbulent values about the same as when the modified Wyngaard (1973) f_T function was used. Like all empirically-determined parameterizations, this new unstable f_T function must be tested further with data sets from other experiments conducted in different geographical areas and with different measurement systems before we can assume it has universal applicability.

In contrast to the unstable cases, in stable conditions the use of the new Zuniga Shoals function in the NPS bulk model does not improve the bulk model comparison with the turbulent C_n^2 values (Fig. 5b). The wind speed dependence of the bulk-turbulent C_n^2 difference was greatly increased and the absolute bulk model errors increased except for the mid-wind speed range.

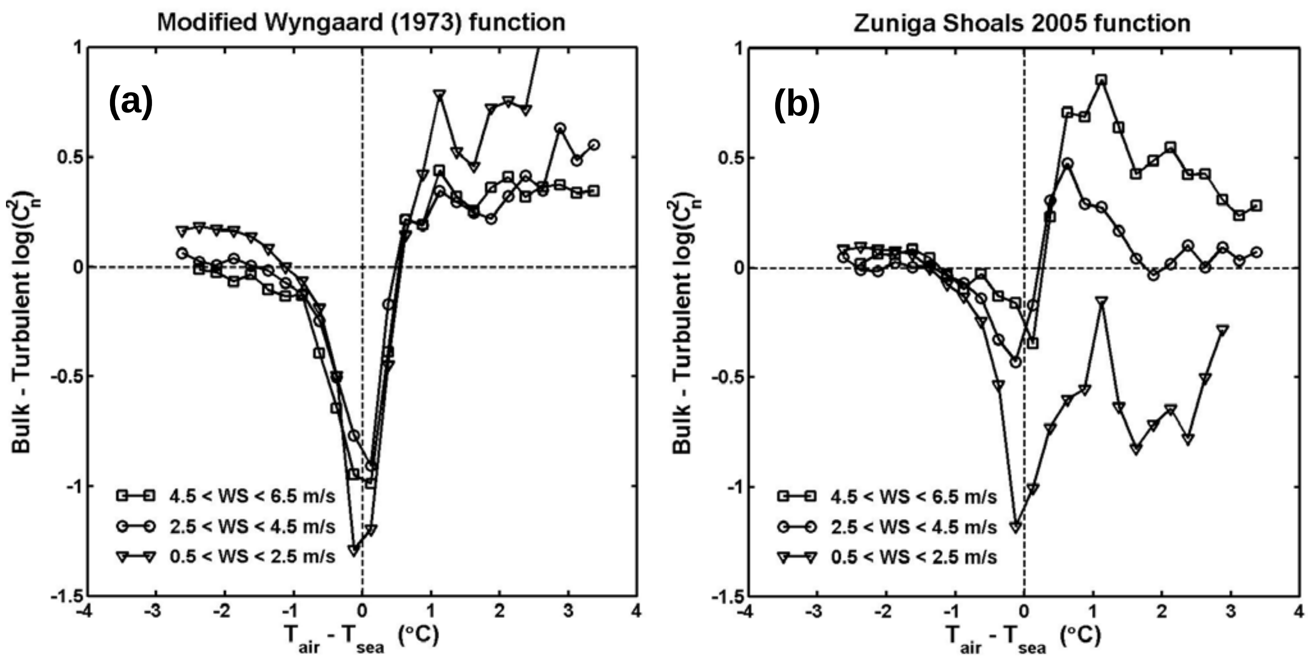

Figure 5. Bulk – Turbulent C_n^2 differences derived from the NPS buoy measurements versus the air-sea temperature difference: (a) Bulk C_n^2 values computed using the modified Wyngaard (1973) dimensionless temperature structure parameter function (f_T) (Eq. 13); (b) Bulk C_n^2 values computed using the new Zuniga Shoals 2005 f_T function (Eq. 19). Data have been averaged into air-sea temperature difference bins and are computed for different wind speed intervals, as indicated.

7. CONCLUSIONS

This study focused on attempting to determine new dimensionless temperature structure parameter functions (f_T) above the ocean, since any improvements in this function will result directly in improvements to over-water bulk C_n^2 models. The air-sea temperature difference and wind speed dependence of the bulk-turbulent C_n^2 difference indicated that the f_T function used in the bulk model may be incorrect, since ASTD and wind speed determine the sign and magnitude of ξ. Values of f_T and ξ were computed by direct methods from the NPS buoy during the 2005 Zuniga Shoals experiment and new forms for the f_T function were developed to fit these data in both unstable and stable conditions. While the unstable function had a similar form to past functions presented in the literature, in the stable side a dependence upon ξ to the −2/3 power fits the data much better than the 2/3 power law predicted by limiting forms of the standard MOST functions. The main difference, however, was in the asymptotic behavior of the NPS f_T data as $|\xi|$ approached zero. An examination of the equations for f_T and ξ indicate that this behavior should not be unexpected, since both of these parameters depend upon u_* and $-\langle w'T'\rangle$ in an opposite sense.

The new f_T functions developed from the NPS Zuniga Shoals buoy measurements were then used in the NPS bulk model to compute new bulk C_n^2 estimates. When these new bulk estimates of C_n^2 were compared with the direct turbulent values in unstable conditions, there was a marked improvement in agreement over the old bulk estimates computed using the traditional Wyngaard f_T functions. Not only was the overall absolute agreement much improved, but also, significantly, the wind speed and air-sea temperature difference dependence of the bulk-turbulent C_n^2 difference that was previously observed was virtually eliminated when using the new f_T function. In near-neutral conditions the agreement between bulk and turbulent values was also improved, except for the lowest wind speed cases, which exhibited virtually no improvement at all. For stable conditions, the new f_T function unfortunately does not improve the bulk model performance. For wind speeds between 2.5 and 4.5 m/s the new stable function did result in better agreement between bulk and turbulent C_n^2 values for higher air-sea temperature differences. For lower and higher winds the agreement actually worsened with the new function, however, and the wind speed dependence of the bulk-turbulent C_n^2 difference greatly increased.

The unstable f_T function presented in this study seems to show promise for improving bulk C_n^2 model performance, although it certainly needs more study and verification in different locations and with different measurement systems before it can be accepted for universal application. The forms of the f_T functions resulting from this study in near-neutral and stable conditions depart greatly from the functions previously published in the literature and it is hoped that this study will open renewed interest and debate on this topic.

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