Forecasting Atmospheric Stability Transitions over a High-Elevation Desert in the Southwestern United States

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ABSTRACT

Forecasting the precise time of the morning and evening stability transition is important to both civilian and military meteorologists. In the civilian community this information can be used to initialize prognostic convective models. Other applications include enhancing (1) infrared sensor simulations and (2) high-energy laser propagation projects. The observed stability transition duration over a mid-latitude desert has ranged from less than 1 min to more than 20 min. This article presents desert stability transition parameters, the Stability Transition Forecast Model (STFM) development, two scenarios for modeling the transition, and an empirically derived equation quantifying the monthly (seasonal) effects for forecasting the morning and evening stability transitions over the Tularosa Basin in New Mexico. Explanations for the general seasonal curve shape are proposed, and possible reasons for why the solar cycle component is the greatest contributor to the ideal STFM algorithm are discussed.

1. Introduction

The precise time of diurnal stability transitions is important to both civilian and military meteorologists. In the civilian community this information can be used to initialize prognostic convective models. Other applications include enhancing (1) infrared sensor simulations and (2) high-energy laser propagation projects. A signature effect of the surface stability transition is a sudden clarity of the image for objects viewed along a horizontal path. An example of this effect is shown in Fig. 1. The horizontal path between the photographic sensor (a Nikon D800E camera, using a 500-mm f/5.6 Pentacon, medium format lens) and the white warehouse building is approximately 2.60 km (1.62 mi). The surface turbulence—generated over deserts in the southwestern United States under clear skies—impacts the ability to view sharp edges and color details. Note the blurred object edges (white building, street lamps, telephone poles, white van windows, house windows, brown shrubs in front of the house) in Fig. 1a. In contrast, Fig. 1b is along the same optical path, still under clear skies of the same February 2013 day, but witnessed during a stability transition. The improved optical clarity of the object edges is significant. The observed duration of the

stability transition over this mid-latitude desert ranges from less than 1 min (when skies are clear with low winds, low soil moisture, and no complex shadowing on the terrain) to more than 20 min (when clouds, ground moisture, and/or shadowing on the terrain are present).

Classical meteorology defines the surface-layer stability transition as when turbulent sensible heat flux changes direction (upwards or downwards). The primary trigger for this heat-flux change in deserts over the mid-latitude, southwestern United States is the sun. As the sun warms the soil, mixing begins and generates random dynamic atmospheric density changes. These random variations can be quantified by atmospheric optical turbulence (AOT) measurements. Over a 24-h period there are at least two time periods when the surface AOT values drop to a minimum (Kunkel and Walters 1983). These two events coincide with the stable to unstable, or unstable to stable, atmospheric changes. Since the atmosphere is neither stable nor unstable during these transitions, the time of least atmospheric density variation (lowest AOT point in the time series) has been referred to as a neutral event (NE). If AOT measurements are not available, a more fundamental measurement of vertical temper-

Figure 1. Images observed at approximately 2.60-km (1.62 mi) horizontal distances over a desert in the southwestern United States during a (a) non-stability transition period at 2132 UTC (1432 MST) 5 Feb 2013 and (b) stability transition period at 0003 UTC 6 Feb 2013 (1703 MST 5 Feb). [Photographs by Christopher Vaucher.] *Click images for external versions; this applies to all figures hereafter.*

ature differences can be used (Businger et al. 2002). In this latter method the initial assumption was that a neutral atmosphere was isothermal during the transition.

Stability transitions do occur at various heights. However, for simplicity, this paper will only address transitions in the lowest 30–40 m (98–131 ft) of the atmosphere (i.e., the surface layer). Prior to 1994, NE

forecasts were by a rule-of-thumb: NE occurs 60 min after sunrise and 40 min before sunset. Unfortunately, this forecast guidance was imprecise and prompted a dedicated two-month desert AOT study (Vaucher and Endlich 1994). The two-month study results found NEs occurred, on average, 70 min after sunrise and 60 min before sunset. Vaucher and Endlich also presented a subtle monthly trend and a dependency on "ideal"

and “non-ideal” local atmospheric conditions. Ideal conditions were defined as clear skies, low winds, low ground moisture, and no complex shadowing effects on the terrain. Non-ideal conditions included everything else, especially clouds occulting the rays of a rising or setting sun.

Vaucher and Endlich (1995) extended the period of investigation to 16 months. Strong evidence of a seasonal trend was documented, along with the question of whether these findings were site specific. Angevine et al. (2001) published a morning transition study using data from Illinois and the Netherlands. They found the transition was enabled by surface heating that relaxed the surface stability, while a large part of the surface-layer warming was due to shear-driven entrainment.

The United States Army Research Laboratory (ARL) conducted a series of field tests to address the issue of site dependency for the evolving NE forecast model, also known as the Stability Transition Forecast Model (STFM). Vaucher and Bustillos (2003a,b) and Vaucher et al. (2003) found, under ideal conditions, the STFM NE was applicable to an alternate desert location. They also gathered quantitative evidence of the extended and multiple transitions characteristic of non-ideal conditions. Such observations were consistent with the aerosol dependencies studied by McBean and Elliott (1981) and Sadot and Kopelka (1992).

A cooperative study initiated between the ARL and the University of Alaska investigated the effects of latitude dependency in the stability transition forecast. Unlike the other studies, the location is in an Arctic environment. The results are still under investigation (Vaucher et al. 2005).

2. An empirically defined stability transition

The stability transition is a dynamic event that impacts AOT. To quantify random turbulent variations, a statistical AOT parameter, the index of refraction structure function, C_n^2 , is measured. In the most basic form C_n^2 is defined as:

$$C_n^2 = \frac{\langle (n_1 - n_2)^2 \rangle}{r^{2/3}} \quad (1)$$

where the numerator is the ensemble average of the atmospheric index of refraction (n) differences (index of refraction variance), and r is the distance between points n_1 and n_2 . Normally, C_n^2 is sampled along a flat

horizontal 1-km (0.62 mi) path, with the assumptions that the path is homogeneous and isotropic, and the two endpoints are within the turbulence inner and outer scales (Tatarskiĭ 1961).

To help clarify the NE concept, consider the 24-h cycle of C_n^2 measurements in Fig. 2. C_n^2 data were sampled at 8 m (26.2 ft), along a 1-km (0.62 mi) path in the Tularosa Basin, New Mexico. Coincident sampling of temperatures at 16 m (52.5 ft) and 2 m (6.6 ft) above ground level (AGL) and insolation at 32 m (105.0 ft) AGL are shown in Figs. 3 and 4, respectively. ΔT is defined as the 16-m temperature minus the 2-m temperature.

Figure 2. Typical 24-h C_n^2 time series over a high-elevation desert in the southwestern United States (sunrise/sunset marked in yellow). C_n^2 minima coincide with morning and evening stability transitions. Red time series shows scintillometer data from the 0-km site, sampled at 8 m AGL. The blue time series shows the reciprocal path scintillometer data from the 1-km site, sampled at 8 m AGL. The decimal hour (Dec Hr) is based on a 24-h day, with midnight being 0 h local time.

Comparing Figs. 2–4, four unique scenarios emerge. The first scenario occurs prior to sunrise (insolation = 0), where positive ΔT characterizes a stable atmosphere. In this scenario C_n^2 magnitudes were moderate, and from independent observations the skies were clear, ground moisture was low, and winds were light. In contrast, consider the midday scenario. Though the insolation indicates cloud cover, the persistent negative ΔT values are characteristic of an unstable atmosphere. The peak insolation value was sampled around 1900 UTC (1200 mountain standard time, MST).

The final two scenarios link these two extremes. In Fig. 2, two distinct C_n^2 minima periods are framed by the local sunrise and sunset times of 1305 and 0120 (Day+1) UTC (0605 and 1820 MST). Shortly after sunrise and subsequent increases in insolation, the stable nighttime atmosphere evolves into an unstable daytime environment. Mirroring the morning event, another transition occurs just prior to sunset. Here the unstable daytime atmosphere changes to a stable nighttime atmosphere. In both cases the C_n^2 minima occur when the lapse rate is near dry adiabatic.

Figure 3. Coincident data with Fig. 2; these 16-m (52.5 ft) and 2-m (6.6 ft) AGL temperature time-series cross each other when the C_n^2 minima occur (cf. Fig. 2).

Figure 4. Same as for Fig. 2 except for insolation sampled from the 0- and 1-km sites, which shows clear skies in the morning, some clouds around midday, and mountain shadowing prior to sunset.

a. The ideal stability transition

An ideal stability transition occurs when the rising/setting sun has an uninterrupted path to the ground (i.e., clear skies, no shadows), winds are low, and there is minimal ground moisture. An example of this condition can be found in the sunrise stability transition (0700 MST) of Fig 2. Notice the duration of the C_n^2 minimum is short (on the order of minutes).

The NE is closely associated with a near dry-adiabatic lapse rate characteristic of neutral atmospheric stability (zero heat flux). Consequently, when the C_n^2 minimum occurs, a vertical temperature gradient can differ from a strictly isothermal lapse rate. In fact, ΔT was observed to fall between $\pm 0.25^\circ\text{C}$.

b. Non-ideal stability transitions

NEs can be delayed, extended, and/or manifested in multiple occurrences when the rising/setting sun is occulted, there are local shadowing effects, or a local forcing phenomenon occurs (e.g., substantial ground moisture). The sunset stability transition (approximately 1800 MST) shown in Figs. 2 and 5 demonstrates such a non-ideal stability transition condition. In this case, complex mountain-shadowing effects extended the NE by 33 min.

Figure 5. C_n^2 1-km (0.62 mi) time series reciprocal path assessments for the sunset NE on 24 March 2001 (i.e., sub-period of Fig. 2).

c. NE definition and data management

After comparing ideal and non-ideal patterns, a more detailed NE definition was empirically derived as follows:

- The 8-m (26.2 ft) AGL C_n^2 reaches its minima, and/or
- the ΔT from 16 m (52.5 ft) to 2 m (6.6 ft) AGL is between $\pm 0.25^\circ\text{C}$.

For generating an operationally useful model, forecasting the ideal NE was targeted. Four NE conditions were observed in the 16-month data analyzed for the NE model creation. These conditions included scenarios when (1) no data were available, (2) the NE was not clear, (3) the NE was extended, and (4) the ideal NE occurred. Data from the first two conditions are not included here. For extended NEs, a mid-point between start/end times was logged, along with an annotation to distinguish it from an ideal NE time. Ideal NEs were noted with a single time entry.

3. Method and analysis: stability transition model development

The STFM was originally structured to produce binary output for an operational environment. This output was classified as:

$$\text{sunrise NE} = \text{sunrise} + 60 \text{ min} \quad (2)$$

$$\text{sunset NE} = \text{sunset} - 40 \text{ min} \quad (3)$$

Based on the 2- and 16-month study results, a correction term was added. What follows is the development of the correction term for the sunrise NE case. Figure 6 shows the time of local sunrise (MST), the NE as predicted by the original STFM, and the raw NE data collected along a 1-km (0.62 mi) path in the high-desert country of New Mexico. The raw data have a subtle periodicity around the original STFM curve. In Fig. 7 the oscillating pattern is highlighted by using a linearized, original STFM. Since the number of data points per month was not consistent (see section 2c), monthly averages were calculated and superimposed over the raw data. Finally, to simplify the analysis, Fig. 8 shows just the monthly averages over the 16-month period. A wavelike pattern emerges, and a correction algorithm for modeling this pattern is proposed in the next section.

4. Analysis and results

a. Seasonal algorithm development

The oscillation in the NE timing over the mid-latitude, southwestern desert appears to have a 6-

month cycle. A subtle 12-month seasonal cycle also was observed. Using the curve generated by monthly averages, various curve-fitting techniques were tried. The best results came from a Fourier waveform analysis, and took the following form:

$$\text{correction} = a_0 + \sum_{n=1}^N (a_n \cos n\theta + b_n \sin n\theta) \quad (4)$$

where *correction* is in minutes and θ (in radians) = (month number – 5) $\times \pi/L$. The wave period ($2L$) was defined as 12 months, making $L = 6$. A 5-month offset defined May as the wave's zero point, which yielded a best fit. The coefficients (a_n , b_n) for these curves are from Vaucher and Endlich (1995) and are reproduced in Table 1. The final NE forecast model equation thus becomes:

$$\text{sunrise NE} = \text{sunrise} + 60 \text{ min} + \text{correction} \quad (5)$$

$$\text{sunset NE} = \text{sunset} - 40 \text{ min} - \text{correction} \quad (6)$$

where all the units are defined in minutes. Note that a positive correction term in these equations moves the time further from sunrise (sunset); and a negative correction value decreases the time from sunrise (sunset).

Table 1. Sunrise (top) and sunset (bottom) NE correction-term coefficients from Vaucher and Endlich (1995).

Sunrise coefficients		
n	a_n value	b_n value
0	3.60	
1	3.83	1.86
2	6.04	7.72
3	0.217	0.358
4	-0.798	0.150
5	0.0714	-0.221
6	0.138	
Sunset coefficients		
n	a_n value	b_n value
0	6.36	
1	6.48	1.46
2	7.60	8.96
3	0.768	-0.512
4	-0.348	-0.950
5	0.377	-1.61
6	-0.234	

b. One theory to explain the seasonal oscillation

A curious feature of the observed NE-seasonal oscillation curve is the timing of the maximum and minimum points. Consider the sunrise NE cases. The months in which the greatest time lapsed from sunrise

Figure 6. Sunrise and NE times for February 1994–June 1995. Sunrise NEs calculated using the original (rule-of-thumb) STFM.

Figure 7. Oscillation around the original (rule-of-thumb) STFM is more discernible when linearized (cf. Fig. 6).

were June and December. Common to these months is the solstice (i.e., the day of longest or shortest daylight hours). The months having the least amount of time between sunrise and a NE were March and September. These two months share an equinox (equal daylight and night hours).

One possibility is that the observed curve is a function of the diurnal heating/cooling cycle, which is linked to the local surface inversion that develops overnight. When the night is extended, as in December, additional cooling occurs under the ideal case scenario, strengthening the local temperature inversion. Thus, more time is required to overcome the nighttime stability and reach the neutral atmospheric conditions.

Figure 8. Sunrise NE STFM forecasts, average NE $\pm$ one standard deviation, and monthly (NE-SR) averages for February 1994–June 1995. Note the maximum time from sunrise occurs during the solstice months; the minimum time from sunrise occurs during the equinox months.

In contrast, if there were an equal amount of heating/cooling hours, the local inversion would have a minimal amount of time to develop. Thus, less time would be required to evolve from the morning stability into a neutral atmospheric environment.

5. Summary and recommendations

Classical meteorology defines the surface-layer stability transition as occurring when turbulent sensible heat flux changes direction. The sun is the primary trigger for near-surface mixing that leads to heat-flux changes. AOT measurements (C_n^2 or a vertical ΔT) can quantify the effects of low-level mixing. When C_n^2 drops to a minimum the surface layer changes from a stable to unstable, or unstable to stable, condition. There are at least two daily stability transitions over deserts in the mid-latitude, southwestern United States. The original STFM began with a rule-of-thumb. When this approach yielded limited success, two subsequent studies were conducted. Results included: (1) a refined definition for NE, (2) two case (ideal, non-ideal) scenarios for modeling and studying NEs, (3) evidence of a seasonal oscillation in the transition timing, (4) identification of other forces impacting the NE timing (e.g., solar occultation, ground moisture, and complex shadowing), and (5) a proposed algorithm linking the seasonal oscillation with the duration of the diurnal

heating/cooling cycles and the subsequent strength of local temperature inversions.

The new ideal STFM is a function of the local sunrise/sunset times, rule-of-thumb, and a monthly correction term. This model has been used since 1995 in both operational and research settings over a desert environment in the mid-latitude, southwestern United States. Results under the ideal atmospheric conditions (no solar occultation, no complex shadowing, low soil moisture, low winds) have been the most successful, whereas non-ideal conditions (solar occultation, complex shadowing, and high soil moisture) have indicated the need for further research. Future work on stability transition studies in northern/Arctic latitudes is being pursued.

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