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14. ABSTRACT
The interactions between the radiative field and topography influence the evolution of the atmospheric boundary layer in complex terrain. A synergistic study of these interactions combined the analysis of a rich observational dataset collected in Arizona's Meteor Crater with model simulations made with a newly-available three-dimensional Monte Carlo radiative transfer model. The effects of topography on the receipt of short- and longwave radiative energy and on longwave radiative flux divergence (RFD) within valleys and basins were

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Final Report: Role of Radiative Flux Divergence in Stable Boundary Layer Development

ABSTRACT

The interactions between the radiative field and topography influence the evolution of the atmospheric boundary layer in complex terrain. A synergistic study of these interactions combined the analysis of a rich observational dataset collected in Arizona's Meteor Crater with model simulations made with a newly-available three-dimensional Monte Carlo radiative transfer model. The effects of topography on the receipt of short- and longwave radiative energy and on longwave radiative flux divergence (RFD) within valleys and basins were investigated and quantified. These effects include topographic shading, terrain exposure, and reflections and emissions from surrounding terrain. The strength of longwave radiative flux divergence or longwave radiative heating and cooling in idealized valleys and basins was investigated for representative day- and nighttime conditions in a modeling study in which various parameters were systematically changed, including valley or basin shape and size. The formation of terrain-following daytime superadiabatic and nighttime stable layers on radiative heating and cooling was found to produce major influences on radiative heating rates. Real-case simulations for a clear autumn night showed that nighttime radiative cooling can account for nearly 30% of the total observed nighttime cooling in the Meteor Crater basin.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

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Mayer, B., S. W. Hoch, and C. D. Whiteman, 2010: Validating the MYSTIC three-dimensional radiative transfer model with observations from the complex topography of Arizona's Meteor Crater. Atmos. Chem Phys., 10, 8685-8696. doi:10.5194/acp-10-8685-2010.

Whiteman, C. D., S. W. Hoch, M. Lehner, and T. Haiden, 2010: Nocturnal cold air intrusions into Arizona's Meteor Crater: Observational evidence and conceptual model. J. Appl. Meteor. Climatol., 49, 1894-1905.

Hoch, S. W., and C. D. Whiteman, 2010: Topographic effects on the surface radiation balance in and around Arizona's Meteor Crater. J. Appl. Meteor. Climat., 49, 1114-1128.

Whiteman, C. D., A. Muschinski, S. Zhong, D. Fritts, S. W. Hoch, M. Hahnenberger, W. Yao, V. Hohreiter, M. Behn, Y. Cheon, C. B. Clements, T. W. Horst, W. O. J. Brown, and S. P. Oncley, 2008: METCRAX 2006 – Meteorological experiments in Arizona's Meteor Crater. Bull. Amer. Meteor. Soc., 89, 1665-1680.

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(c) Presentations

Hoch, S., C. D. Whiteman, and B. Mayer, 2010: Radiative cooling and heating within topography - Parametric studies with a 3D radiative transfer model. 14th Conf. Mount. Meteor., 30 Aug- 3 Sep 2010, Lake Tahoe, CA. Amer. Meteor. Soc., Boston, MA.

Hoch, S. W., C. D. Whiteman, M. Lehner, D. Martínez, and M. Kossmann, 2010: Interaction of regional scale drainage flows with the nocturnal stable atmosphere in Arizona's Meteor Crater. 14th Conf. Mount. Meteor., 30 Aug- 3 Sep 2010, Lake Tahoe, CA. Amer. Meteor. Soc., Boston, MA.

Hoch, S. W., 2009: Radiative flux divergence in the surface boundary layer from observational and model perspectives. 9th European Conference on Applied Climatology, 9th Annual Meeting of the European Meteorological Society, 28 Sept. - 2. Oct. 2009, Toulouse, France

Martinez, D., C. D. Whiteman, S. W. Hoch, M. Lehner, and J. Cuxart, 2010: The upslope-downslope flow transition on a basin sidewall. 14th Conf. Mount. Meteor., 30 August- 3 September 2010, Lake Tahoe, CA. Amer. Meteor. Soc., Boston, MA.

Lehner, M., C. D. Whiteman, and S. W. Hoch, 2010: The impact of asymmetric solar heating on the cross-basin circulation in Arizona's Meteor Crater. 14th Conf. Mount. Meteor., 30 August- 3 September 2010, Lake Tahoe, CA. Amer. Meteor. Soc., Boston, MA.

Hoch, S. W., 2009: Radiative flux divergence in the surface boundary layer from observational and model perspectives. 9th European Conference on Applied Climatology, 9th Annual Meeting of the European Meteorological Society, 28 Sept. - 2. Oct. 2009, Toulouse, France

Whiteman, C. D., S. W. Hoch, and M. Lehner, 2009: Isothermalcy in a basin atmosphere produced by nocturnal cold air intrusions. 13th Conf. on Mesoscale Processes, Salt Lake City, Utah, 17-20 August 2009.

Hoch, S. W., C. D. Whiteman, and B. Mayer, 2009: Topographic effects on radiative cooling in valleys and basins. 30th Intern. Conf. Alpine Meteorology, Rastatt, Germany, 11-15 May 2009.

Kossmann, M., S. W. Hoch, C. D. Whiteman, and U. Sievers, 2009: Modelling of nocturnal drainage winds at Meteor Crater, Arizona using KLAM_21. 30th Intern. Conf. Alpine Meteorology, Rastatt, Germany, 11-15 May 2009.

Whiteman, C. D., S. W. Hoch, and M. Lehner, 2009: Nocturnal cold air intrusions at Arizona’s Meteor Crater. 30th Intern. Conf. Alpine Meteorology, Rastatt, Germany, 11-15 May 2009.

Whiteman, C. D., S. Hoch, M. Hahnenberger, and S. Zhong, 2008: Meteorological experiments in a small closed basin: New results from the Meteor Crater Experiment (METCRAX). 13th Conference on Mountain Meteorology, 11-15 August 2008, Whistler, BC, Canada, American Meteorological Society, Boston, MA.

Mayer, B., S. W. Hoch, and C. D. Whiteman, 2008: 3D radiative transfer simulations in complex terrain. International Radiation Symposium (IRS 2008): Current Problems in Atmospheric Radiation, 3-8 August 2008, Foz do Iguaça, Brazil.

Whiteman, C. D., D. A. Kring, and S. W. Hoch, 2008: Atmospheric temperature structure within Meteor Crater, Arizona: Implications for Microniches on Mars. 39th Lunar and Planetary Science Conference, March 10-14, League City, TX.

Hoch, S. W., and C. D. Whiteman, 2007: The Meteor Crater during METCRAX - A case study for 3D radiative transfer modeling. 24th General Assembly, Intl. Union Geodesy Geophys., 2-1 July 2007, Perugia, Italy.

Hoch, S. W., C. D. Whiteman, M. Hahnenberger, and S. Zhong, 2007: First results from the 2006 Meteor Crater field experiment (METCRAX). 24th General Assembly, Intern. Union Geodesy Geophys., 2-13 July 2007, Perugia, Italy.

Hoch, S. W., and C. D. Whiteman, 2007: Observations of radiative flux divergence and vertical temperature structure evolution. 24th General Assembly, Intern. Union Geodesy Geophys., 2-13 July 2007, Perugia, Italy.

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Hoch, S. W., B. Mayer and C. D. Whiteman, 2008: 3D radiative transfer in the complex topography of the Arizona Meteor Crater. 13th Conference on Mountain Meteorology, 11-15 August 2008, Whistler, BC, Canada, American Meteorological Society, Boston, MA.

Whiteman, C. D., D. A. Kring, and S. W. Hoch, 2008: Atmospheric temperature structure within Meteor Crater, Arizona: Implications for Microniches on Mars. 39th Lunar and Planetary Science Conference, March 10-14, League City, TX.

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(d) Manuscripts

Hoch, S. W., C. D. Whiteman, and B. Mayer, 2011: A systematic study of longwave radiative heating and cooling rates within valleys and basins using a three-dimensional radiative transfer model. J. Appl. Meteor. Climatol. Final review by co-author in progress. Will be submitted in next days.

Haiden, T., C. D. Whiteman, S. W. Hoch, and M. Lehner, 2011: A mass-flux model of nocturnal cold air intrusions into a closed basin. J. Appl. Meteor. Climatol. In press.

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Patents Submitted

Patents Awarded

Awards

C. D. Whiteman: Fellow, American Meteorological Society

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Sebastian Hoch	1.00
FTE Equivalent:	**1.00**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Charles Whiteman	0.09	No
Sebastian Hoch	1.00	No
FTE Equivalent:	**1.09**	
Total Number:	**2**	

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FTE Equivalent:	
Total Number:	

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The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
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Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED	
Bryan White	0.06	No
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Inventions (DD882)

Scientific Progress

Technology Transfer

FINAL REPORT FOR ARMY RESEARCH OFFICE

for Grant 52734-EV entitled:

The role of radiative flux divergence in stable boundary layer development

C. David Whiteman and Sebastian W. Hoch
University of Utah

ABSTRACT (200 words)---Version 175 words

The interactions between the radiative field and topography influence the evolution of the atmospheric boundary layer in complex terrain. A synergistic study of these interactions combined the analysis of a rich observational dataset collected in Arizona's Meteor Crater with model simulations made with a newly-available three-dimensional Monte Carlo radiative transfer model. The effects of topography on the receipt of short- and longwave radiative energy and on longwave radiative flux divergence (RFD) within valleys and basins were investigated and quantified. These effects include topographic shading, terrain exposure, and reflections and emissions from surrounding terrain. The strength of longwave radiative flux divergence or longwave radiative heating and cooling in idealized valleys and basins was investigated for representative day- and nighttime conditions in a modeling study in which various parameters were systematically changed, including valley or basin shape and size. The formation of terrain-following daytime superadiabatic and nighttime stable layers on radiative heating and cooling was found to produce major influences on radiative heating rates. Real-case simulations for a clear autumn night showed that nighttime radiative cooling can account for nearly 30% of the total observed nighttime cooling in the Meteor Crater basin.

SCIENTIFIC PROGRESS AND ACCOMPLISHMENTS

Statement of the problem studied

In mountainous terrain, radiative transfer is complicated by the interactions between the radiative field and earth's surface. For example, shading patterns vary continuously as the sun moves across the sky which leads to strong and abrupt changes of the surface energy balance. Another example is the emission of infrared or longwave radiation by surrounding higher terrain that increases net radiation at topographic low-points and thus reduces nighttime cooling.

Detailed radiative flux observations and modeling simulations were combined to gain a better understanding of the complex interactions between the radiative field and topography, and to quantify their effects on the evolution of the temperature structure in the atmospheric boundary layer. The observational approach analyzed the rich observational dataset from the Meteor Crater Experiment (METCRAX; Whiteman et al. 2008). The influence of topography on the different shortwave and longwave components of the radiation balance was investigated from these observations. The modeling approach used simulations of radiative fluxes and radiative heating rates with the newly available three-dimensional MYSTIC radiative transfer model (Mayer 2009, Mayer et al. 2010, Emde and Mayer 2007). The modeling approach allowed a systematic analysis of the effects of varying topographic and atmospheric boundary conditions. Finally, the combination of the two approaches - a model study of Arizona's Meteor Crater driven with observation-based boundary conditions - resulted in quantitative estimates of the influence of longwave radiative cooling on the observed total nighttime cooling.

Summary of the most important results

1. Topographic effects on the surface radiation balance - Hoch and Whiteman (2010)

The individual components of the slope-parallel surface radiation balance were measured in and around Arizona's Meteor Crater to investigate the effects of topography on the radiation balance. The crater basin has a diameter of 1.2 km and a depth of 170 m. The observations cover the crater floor, the crater rim, four sites on the inner sidewalls on an east-west transect through the basin, and two sites outside the crater. Interpretation of the role of topography on radiation differences among the sites on a representative clear day is facilitated by the unique symmetric crater topography. The shortwave radiation balance was affected by the topographic effects of terrain exposure, terrain shading and terrain reflections, and by surface albedo variations. Terrain exposure (slope and azimuth angles) led to the largest site-to-site variability, governing the receipt of direct shortwave radiation, the dominating term of the radiation budget. Terrain exposure caused a site on the steeper upper eastern sidewall of the crater to receive 6% more daily integrated shortwave energy than a site on the lower part of the same slope. The measurements of diffuse radiation on the crater rim and floor indicate the enhancement of diffuse radiation within the crater basin due to the reflection of shortwave radiation on the elevated terrain of the crater sidewalls.

A simple method for quantifying the effects of terrain shading on the radiation budget under clear sky conditions was demonstrated. It was shown that sites on the lower eastern and western sidewalls of the Meteor Crater are more strongly affected by terrain shading than the site on the crater floor and the steeper sites on the upper east and west sidewalls. For example, at the lower western slope site the daily total in global radiation was reduced by 6%.

Topography also has a strong influence on the longwave radiative energy exchange. Counter-radiation from the sidewalls enhanced the longwave downward radiation at the sites within the crater basin. The total nighttime longwave energy loss at the crater floor was 72% of the loss observed at the crater rim. The difference in outgoing longwave radiation between sloping sites and the crater floor site illustrates an indirect effect of topography connected to inversion formation in enclosed topography. Cooled air will flow downhill or collect in topographic depressions. This controls how quickly the surface can cool and thus the magnitude of longwave emission.

2. Validation of the MYSTIC radiative transfer model - Mayer et al. (2010)

The MYSTIC three-dimensional Monte-Carlo radiative transfer model (Mayer 2009, Emde and Mayer 2007) has been extended to simulate solar and thermal irradiances with a rigorous consideration of topography. Forward as well as backward Monte Carlo simulations are possible for arbitrarily oriented surfaces and we demonstrate that the backward Monte Carlo technique is superior to the forward method for applications involving topography, by greatly reducing the computational demands. MYSTIC is used to simulate the short- and longwave radiation fields during a clear day and night in and around Arizona's Meteor Crater, a bowl-shaped, 165-m-deep basin with a diameter of 1200 m. The simulations were made over a 4 by 4 km^2 domain using a 10-m horizontal resolution digital elevation model and meteorological input data collected during the METCRAX field experiment in 2006. Irradiance (or radiative flux) measurements at multiple locations inside the crater are then used to evaluate the simulations. MYSTIC is shown to realistically model the complex interactions between topography and the radiative field, resolving the effects of terrain shading, terrain exposure, and longwave surface emissions. The effects of surface temperature variations and of temperature stratification within the crater atmosphere on the near-surface longwave irradiance are then evaluated with additional simulations. The comparison also pointed out areas for improvement. Currently, only a two-dimensional field of temperatures can be used, which means that inversion layers or superadiabatic near-surface layers can not be prescribed in detail. However, a surface temperature grid can be used in these situations, improving the representation of the outgoing longwave fluxes.

3. Radiative flux divergence near the ground

a. Simulations for flat terrain

MYSTIC was used to perform simulations over flat homogeneous surfaces to evaluate the influence of typical, idealized temperature profiles on radiative heating rate profiles. These simulations were used as reference calculations for comparison with later model simulations. The basis for the model atmospheres is the mid-latitude summer standard atmosphere (MLS), adjusted in the near-ground region to represent different atmospheric boundary layers that are encountered as the atmosphere evolves during the day. Below 500 m AGL, the water vapor mixing ratio is set to a constant value equal to the MLS-value at 500 m AGL. Six different atmospheric profiles were assembled as shown in Figure 1a. (1) the original MLS temperature profile, (2) an adiabatic stratification and (3) an isothermal profile. Three additional simulations were used to represent stable conditions with an inversion strength of 4 K: (4) a linear inversion in the lowest 50 m, and (5) and (6) profiles constructed using a function suggested by Fleagle (1953). Profile (5) has an inversion top at 50 m AGL ("Fleagle"), while profile (6) has an inversion top at 5 m AGL ("Fleagle2").

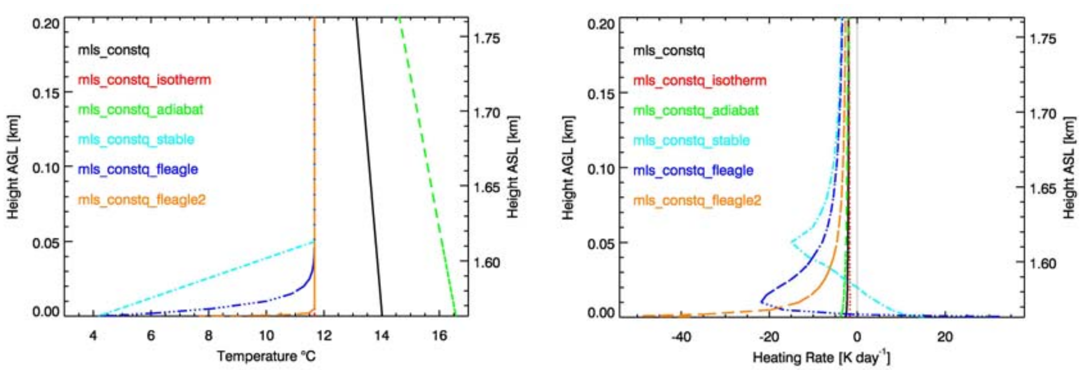

Figure 1: a) Idealized temperature profiles based on the Mid-Latitude Summer Atmosphere where the water vapor mixing ratio is set to a constant value equal to that at 500 m above ground level. Atmospheres are further described in the text. b) Radiative heating rates calculated by MYSTIC for atmospheric profiles in 1a over a flat homogeneous surface.

The simulated radiative heating rates for these profiles are shown in Figure 1b. The influence of the vertical atmospheric temperature profile and of the shape of the temperature inversion becomes apparent. Radiative heating rates for the MLS, adiabatic and isothermal cases are very similar – and range between -2 and -4 K day^{-1} – despite the wide range of profiles and surface temperatures. The stable linear case and the Fleagle case have the same inversion strength and height, but the different inversion shapes greatly influence the height where the temperature distribution triggers radiative heating and cooling responses. A maximum cooling of 15 K day^{-1} is seen just above the inversion in the linear case, while a cooling of 22 K day^{-1} results at 10 m AGL in the "Fleagle" case. Confining the inversion even closer to the surface ("Fleagle2") leads to even larger cooling rates of more than 50 K day^{-1}. A sign change in the radiative heating rate during stable conditions near the ground that was noted by earlier investigators (Stull 1988, Hoch 2006, Ha and Mahrt 2003) is seen in the "Linear-stable" and "Fleagle" cases. The height of the transition from heating to cooling is greatly influenced by the shape of the inversion.

Further calculations were performed with realistic temperature profiles obtained from observations during METCRAX to investigate the effect of different representations of shallow inversions over sloping sidewalls using MYSTIC. We have verified that a first-order temperature discontinuity – i.e. a temperature difference between the ground surface temperature and the air temperature at the ground – can be used when modeling radiative heating rates over the slopes of the Meteor Crater to estimate bulk cooling in the crater volume. However, the sign change in radiative flux divergence immediately near the ground cannot be modeled if the stable stratification near the surface is not resolved by several layers in the radiative transfer model.

b. Observed radiative flux divergence (RFD)

During the Meteor Crater Experiment the vertical profile of longwave fluxes at the crater floor was continuously measured. From the flux differences between two measurement heights, the clear air radiative heating rate can be calculated. In this section, the findings from these observations are summarized. From field calibrations at the end of the METCRAX experiment, the uncertainties in the net longwave radiative heating rates were estimated based on uncertainties in the net flux differences across the different layers. Uncertainties are given in Table 1.

Table 1: Uncertainties in observed radiative heating rates.

Layer	0.5 - 2.0 m	2.0 - 5.0 m	5.0 - 8.9 m	Bulk: 0.5 - 8.9 m
Uncertainty	± 66 K day^{-1}	± 14 K day^{-1}	± 14 K d-1	± 19 K day^{-1}

Figures 2a-c shows the diurnal cycles of radiative heating rates due to RFD (net, incoming and outgoing components) for the three layers for clear sky conditions. We found that (1) divergence of the outgoing flux dominates the net flux divergence and (2) RFD magnitude decreases with distance from the ground. Further, (3) a sign change in heating rate occurs during nighttime – with heating near the ground and cooling above. During daytime, radiative heating is greatest near the surface. Our observations support the findings of Fleagle (1953) who predicted the sign change, and the large heating due to the converging outgoing flux reported by Eliseev (2002).

Figure 2d shows the observed temperature tendency or "full" heating rate, together with the contributions of RFD for 3 layers. Between 0.5 and 2 m, RFD is much larger than the observed heating, and thus must be compensated by different processes. Above 2 m, radiative cooling and heating lags behind the observed heating, thus RFD may not be the driving process in the morning heating and afternoon cooling of near-surface air. Nevertheless, it is clearly shown that the magnitude of RFD is such that it may not be neglected in near-surface thermodynamics.

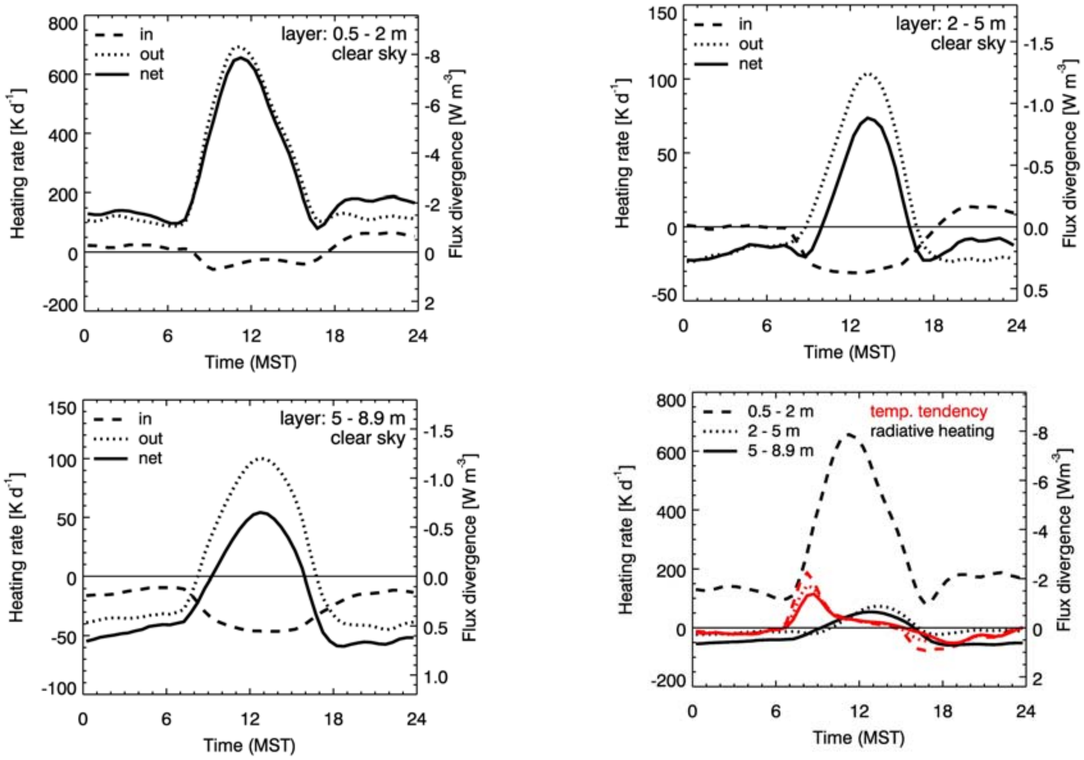

Figure 2: Diurnal variation of RFD for three layers and the net, incoming and outgoing components during clear sky conditions (a-c), and d) the net radiative heating rates due to RFD (black) and the observed total heating rate or temperature tendency (red) for the same layers.

In summary, our observations show that RFD contributes significantly to the thermodynamics of the near-surface layer. RFD plays an important role in transporting heat upwards (downwards) from the surface (atmosphere) during the day (night). Our observations indicate that the strong evening cooling in near-surface layers, however, cannot be attributed to radiative flux divergence alone (Fig. 2d).

4. Radiative heating and cooling within topographies - (Hoch et al. 2011)

After having validated the MYSTIC three-dimensional radiative transfer model (Section 2 above) and exploratory studies (Section 3), MYSTIC was used in a parametric study to determine the strength of longwave radiative heating and cooling in atmospheres enclosed in idealized valleys and basins (Hoch et al. 2011). The parameters investigated included valley or basin shape, width, and near-surface temperature contrasts. Four idealized geometries were chosen for the computations. They resulted from the combination of the two basic types of topographic depressions, valleys and basins, with two cross-sections defined mathematically using sine and Witch-of-Agnesi functions. The width scales of the valleys and the rotationally symmetric basins, defined as the width at half-depth, were varied between 0.5, 1, 2 and 5 km. The basin and valley floor elevations were set to 1500 m ASL and their depths were set to 500 m. Reference calculations were performed for a horizontal plain at 1500 m elevation using identical atmospheric profiles. All topographies were described by a 200-by-200 horizontal grid, so that the horizontal grid cell size varied with the width scale of the valley or basin. The symmetry of the terrain greatly reduced the computational requirements for these calculations. Longwave radiative heating rates were computed tracing 5 million photons for all grid cells in a half cross-section of each valley or basin and were then assigned to the volumes they represent. Simplified temperature and humidity profiles for use as atmospheric inputs to MYSTIC were constructed subjectively by scrutinizing a large set of atmospheric profiles collected in various Rocky Mountain valleys in the 1970s with a tethered balloon sounding system (Whiteman 1980). Three basic profiles were chosen to represent typical atmospheric structures of a) a well-mixed atmosphere (1500 Local Standard Time; LST), b) an evening atmosphere with a shallow inversion of 50 m depth (1900 LST) and c) a stable atmosphere typical of the pre-sunrise hours (0600 LST). The water vapor mixing ratio was kept constant at 3.25 g kg^{-1} in the lowest km of the model atmospheres. The atmosphere within the 500-m-deep topography was divided into 36 vertical layers, with 5-m resolution near the bottom and 100-m resolution at the top of the basin or valley atmosphere. For complex terrain computations the inputs to MYSTIC include a topography dataset and a model atmosphere that is assumed to be horizontally homogenous. Surface temperatures are normally set equal to the air temperatures at the same elevations. However, an optional grid of surface temperatures can be prescribed to introduce air-surface temperature contrasts representing shallow superadiabatic or stable layers near the surface.

Our model simulations evaluated the effects of basin shape, type and size as well as the influence of the near-surface temperature structure on the basin-total radiative cooling and heating rates. The simulations also resolved the spatial distribution of radiative heating and cooling within the different topographic depressions. Differences between the heating rates seen in the center of a basin and those closer to the basin sidewalls can be large. When no surface-air temperature contrasts exist, the basin center heating rate profile quickly approaches the flat terrain profile when the basin is widened, but the basin-average heating rates were, nonetheless, still clearly affected by the interaction of the radiation field and the basin sidewalls. This shows that one-dimensional radiative transfer models are not suited for investigating radiative heating rates within complex topography.

One of the more striking findings is the importance of the near-surface temperature structure on radiative heating rates in valleys and basins. This finding follows previous studies for flat terrain that have stressed the important influence of the near-surface temperature field (Räisänen 1996; Hoch 2005; Savijärvi 2006). Near-ground, terrain-following stable and superadiabatic layers are common in complex terrain, and the present study shows the importance of resolving them in the radiative transfer model. Our simulations showed that the influence of the near-surface temperature structure exceeded the influence of basin size and shape. In the absence of air-ground temperature differences, basin-total heating rates did not vary greatly with basin size or shape -- the maximum variation from the mean was 6.5, 7.7 and 11.4% for the three selected times 1500, 1900 and 0600 LST, respectively. The prescription of a given near-surface temperature difference modulates the influence of topography size: strong increases in radiative heating are seen when the size of a basin is reduced for the 1500 LST case with a realistic superadiabatic layer of 10 K strength: In a 500-m wide sinusoidal basin, the longwave radiative heating rate amounts to 230% of the heating seen in a 5-km wide basin. Similarly, a reduction in basin size will strongly influence the cooling seen in a basin featuring a stable near-surface temperature stratification.

5. The role of nighttime radiative cooling in total basin cooling - (Hoch et al. 2011)

The three-dimensional simulations of radiative heating rates in the different idealized topographies of Section 4 focused on the impact of basin size, topography type (basin or valley) and near-surface temperature structure on the radiative heating rates in valleys and basins. What, however, is the relative importance of longwave radiative cooling and heating rates with respect to the total heating rates or temperature tendencies observed within basins? To address this question, radiative heating rates within Arizona's Meteor Crater were simulated with MYSTIC and compared to temperature tendencies observed with a sequence of temperature soundings within the crater basin (Hoch et al. 2011). The observed temperature tendencies include the heating and cooling contributions of all processes, both short- and longwave radiative heating, advection, sensible and latent heat flux divergence, and thermal diffusion. The modeled radiative cooling rate contribution to the overall temperature tendency for Meteor Crater during 22-23 October 2006 varied between 10 and 75%. The 10% value occurred during a time when the crater temperature distribution was known to be disturbed by the near-midnight cold air intrusion. The 75% contribution was at 0500 LST when winds in the crater were weak and the total cooling rate had reached low values typical of the end of the night. In the early evening (1700-2200 LST) radiative cooling within the basin contributed roughly one third of the total observed cooling rate. Averaged over the entire night, longwave radiative cooling contributed 28.5 % of the observed total cooling.

6. Results from related research

In the following we summarize key findings from research conducted under ARO support that addressed primarily nonradiative processes. The phenomena and processes studied, however, influence the thermodynamic evolution of basin and valley atmospheres and thus indirectly influence radiative transfer.

a. Cold Air Intrusions in Arizona's Meteor Crater - Observations (Whiteman et al. 2010)

Observations are analyzed to explain an unusual feature of the nighttime atmospheric structure inside Arizona's idealized, basin-shaped Meteor Crater. The upper 75-80% of the crater's atmosphere, which overlies an intense surface-based inversion on the crater's floor, maintains a near-isothermal lapse rate during the entire night, even while continuing to cool. Evidence was found to show that this near-isothermal layer is produced by cold air intrusions that come over the crater's rim. The intrusions are driven by a regional-scale drainage flow that develops over the surrounding inclined plain. Cold air from the drainage flow builds up on the upwind side of the crater and splits around the crater at low levels. A shallow layer of cold air, however, spills over the 30-60 m high rim and descends partway down the crater's upwind inner sidewall until reaching its buoyancy equilibrium level. Detrainment of cold air during its katabatic descent and compensatory rising motions in the crater atmosphere destabilize the basin atmosphere, producing the observed near-isothermal lapse rate. A conceptual model of this phenomenon is presented.

b. Cold Air Intrusions in Arizona's Meteor Crater - Analytical Model (Haiden et al. 2011)

Observations made during the METCRAX field campaign revealed unexpected nighttime cooling characteristics in Arizona’s Meteor Crater. Unlike in other natural closed basins, a near-isothermal temperature profile regularly develops over most of the crater depth, with only a shallow stable layer near the crater floor. A conceptual model described above in Section 6a attributes the near-isothermal stratification to the intrusion, and subsequent detrainment, of near-surface air from outside the crater into the crater atmosphere. In order to quantify and test the hypothesis, a mass-flux model of the intrusion process was developed. It is found that the observed temperature profile can be reproduced, providing confirmation of the conceptual model. The near-isothermal stratification can be explained as a result of progressively cooler air entering the crater and detraining into the atmosphere, combined with the finite time of ascent in the compensating rising motion. The strength of detrainment largely determines the characteristics of the cooling process. With weak detrainment, most of the cooling arises from adiabatic rising motion ('filling-up' mode). Stronger detrainment leads to reduced rising motion and enhanced cooling at upper levels in the crater ('destabilization' mode). Interestingly, the detrainment also reduces the total cooling, which, for a given intrusion mass-flux is determined by the temperature difference between the intruding air and the temperature of the crater atmosphere at rim height.

c. Cross-Basin Flows in Arizona's Meteor Crater (Lehner et al. 2011)

Cross-basin winds produced by asymmetric insolation of the crater sidewalls occur in Arizona's Meteor Crater on days with weak background winds. The diurnal cycle of the cross-basin winds was analyzed together with radiation, temperature, and pressure measurements at the crater sidewalls for a one-month period. The asymmetric irradiation causes horizontal temperature and pressure gradients across the crater basin that drive the cross-basin winds near the crater floor. The horizontal temperature and pressure gradients and wind directions change as the sun moves across the sky, with easterly winds in the morning and westerly winds in the evening.

d. The Evening Transition Period in Arizona's Meteor Crater (Martínez et al. 2011)

The late afternoon upslope-downslope flow transition on the west inner sidewall of Arizona's Meteor Crater, visualized by photographs of smoke dispersion, is investigated for 20 October 2006, using surface radiative and energy budget data and mean and turbulent flow profiles from three towers, two at different distances up the slope and one on the basin floor. The bowl-shaped crater allows the development of the evening transition flow with minimal influence from larger scale motions from outside and avoiding the upvalley-downvalley flow interactions typical of valleys. The slow downslope propagation of the shadow from the west rim causes a change in the surface radiation budget and the consequent loss of heat from the shallow atmospheric layer above the western slope when the sun still heats the crater floor and the east inner sidewall. The onset of the katabatic flow is visualized by the dispersion of the smoke, with the onset occurring at the same time at the two slope towers. It arrives later at the crater floor, cooling the air and contributing to the stabilization of a shallow but strong inversion layer on the crater floor.

e. Warm air intrusions and evidence for hydraulic jumps in Arizona's Meteor Crater (Adler et al. 2011)

Episodic nighttime intrusions of warm air, accompanied by strong winds, enter the enclosed near-circular Barringer Meteorite Crater basin on clear, synoptically undisturbed nights. These warm air intrusions remain confined mainly above the surface in the lee of the crater's upwind rim. We documented these events and determined their spatial and temporal characteristics, their effects on the atmospheric structure inside the crater, and their relationship to larger-scale flows and atmospheric stability. The warm air intrusions appear to be produced by small-scale atmospheric hydraulic jumps. The intermittent warm air intrusion events are closely related to a surface inversion and a regional (~50 km) -scale downslope or drainage flow on the inclined plain outside the crater. The conditions on the plain cause a continuous shallow cold air inflow that comes over the southwest rim, descends into the crater as a shallow downslope flow on the inner upwind sidewall, and causes a destabilization of the crater atmosphere (Sections 6a and 6b, above). Occasional instabilities occur in the flow coming over the crater rim, which extends 50 m above the surrounding plain, causing warm air from above the inversion on the surrounding plain to descend up to 130 m into the 170-m-deep crater. The warm air intrusion does not destroy the shallow cold air inflow on the slope below it, does not reach the crater floor, and does not extend into the center of the crater, where the nighttime stable layer in the remainder of the crater volume remains largely undisturbed. New field experiments and model simulations are suggested to test the hypothesis that the warm air intrusions are hydraulic flows. Such flows have been previously studied in laboratory tanks with dense fluids and have been observed in atmospheric flows on larger scales.

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