The Influence of Surface Roughness on Volatile Transport on the Moon

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47th DPS Meeting
November 9th, 2015

Computations performed at the Texas Advanced Computing Center.
Supported by NASA's Lunar Advanced Science and Exploration Research program.

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Motivation

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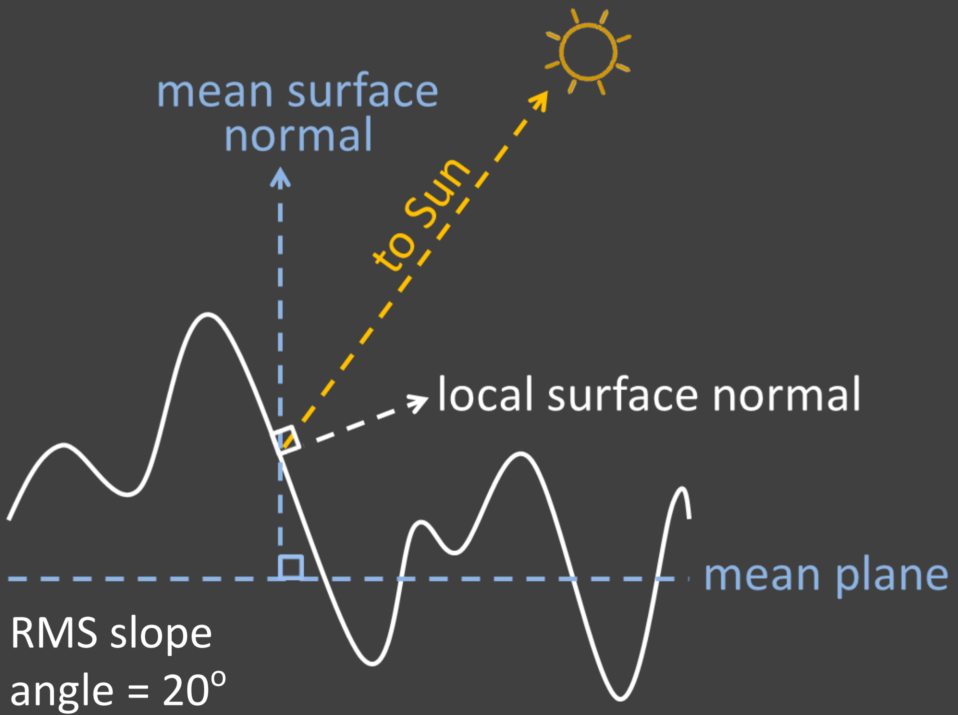
- The Moon's rough surface, insulating regolith, thin atmosphere
  → large temperature variations over very small scales (< 1 cm).*
  What does this mean for volatile transport on the Moon and other nominally airless bodies?

- Irrespective of source of volatiles (solar wind, comets), surface temperature determines:
  - **Surface residence time of molecules.**
  - **Rate of volatile migration to cold traps.**
  - **Gas dynamic scale height.**

** Most recently investigated by Bandfield* et al. *(2015), Hayne* et al. *(2013).*

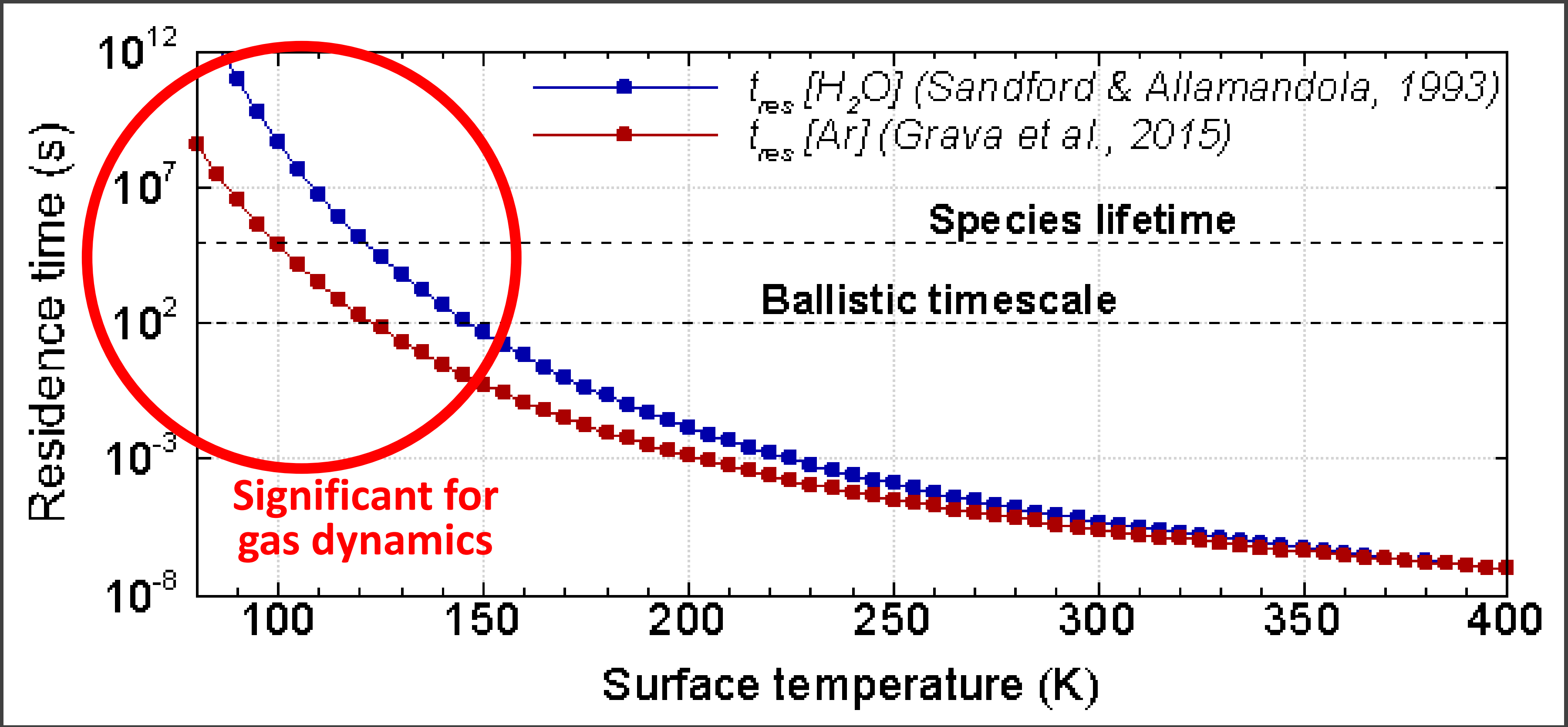
Roughness/Temperature Model



- Stochastic model for **"sub-pixel" roughness** (i.e. un-resolved from orbit).
- Surface elements may be **illuminated or shadowed** – shadowing probability from Smith, 1967.
- At **radiative equilibrium** with solar radiation and/or surrounding surfaces.

- Molecules landing on **day-side** sample a distribution of slopes. **Night-side isothermal at small scales.** (Bandfield *et al.*, 2015.)
- Surface orientation and shadowing probability determine temperature, T_{surf}. **Generally, residence time (t_{res}) ∝ exp(1/T_{surf}).**

Residence Time Models

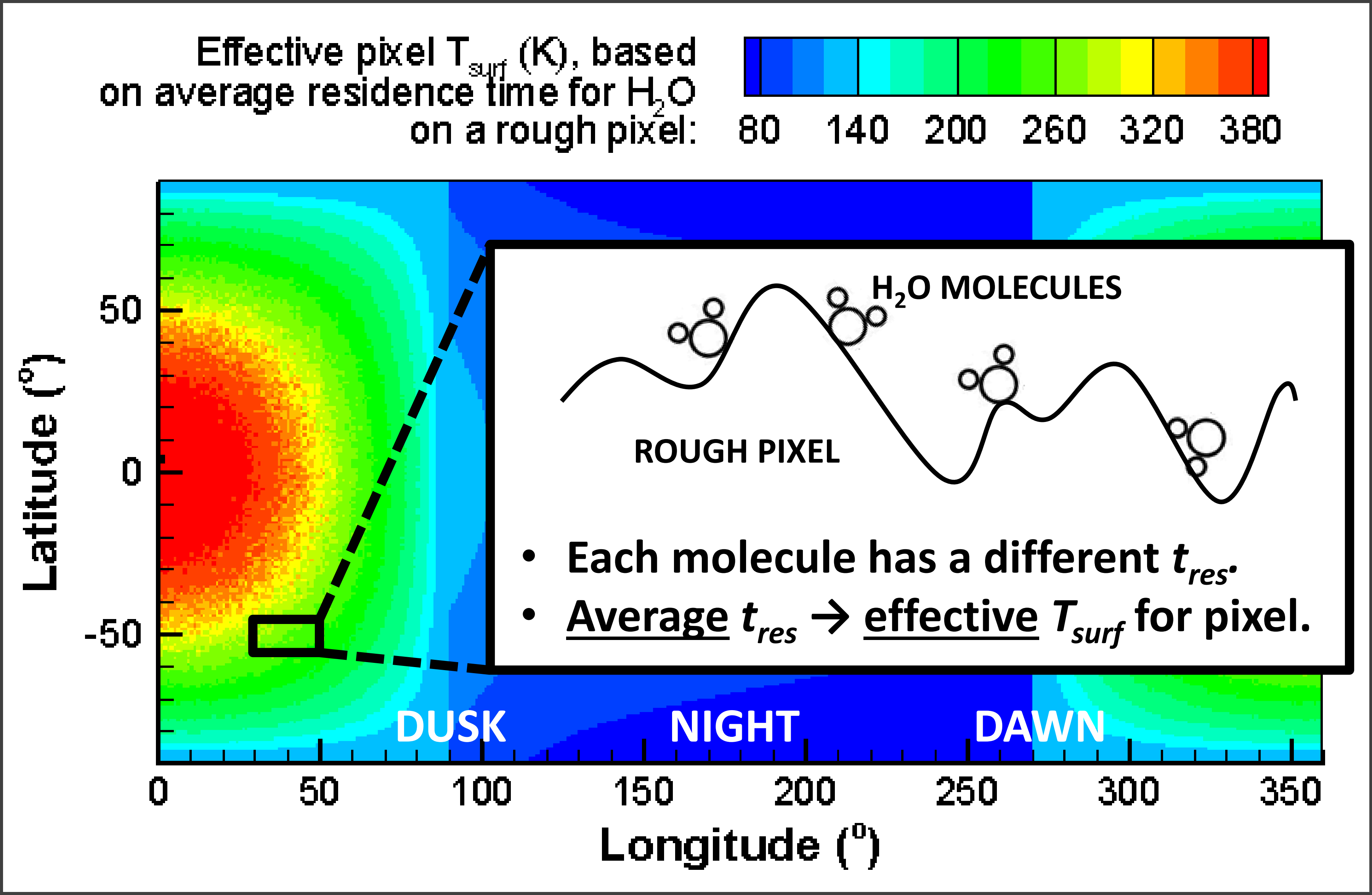


- Importance of roughness depends on **how strongly the species residence time varies** with surface temperature.

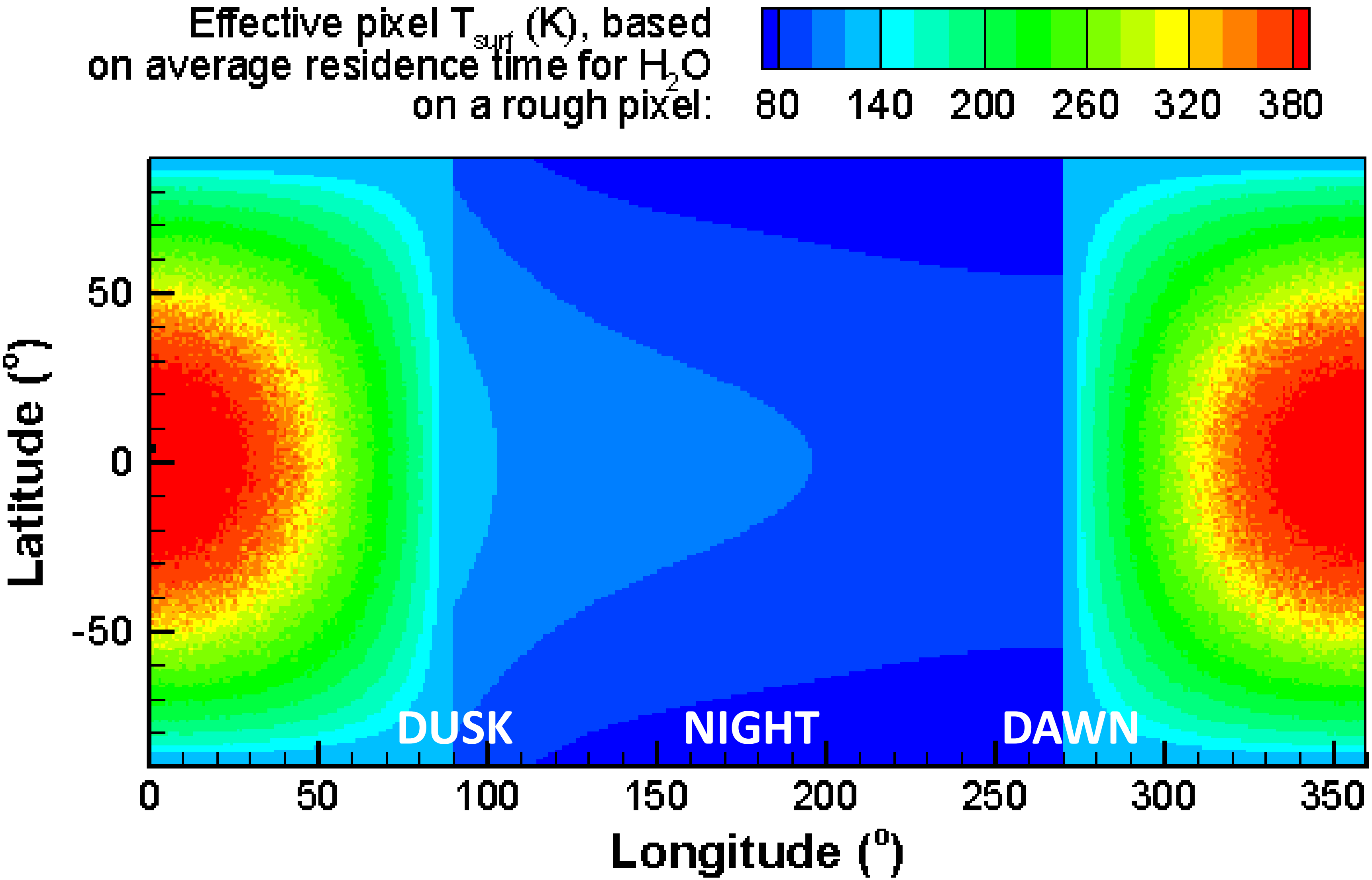
  e.g. Ar residence times vary less with temperature (vs. H_2O)

∴ roughness **relatively** less important for Ar.

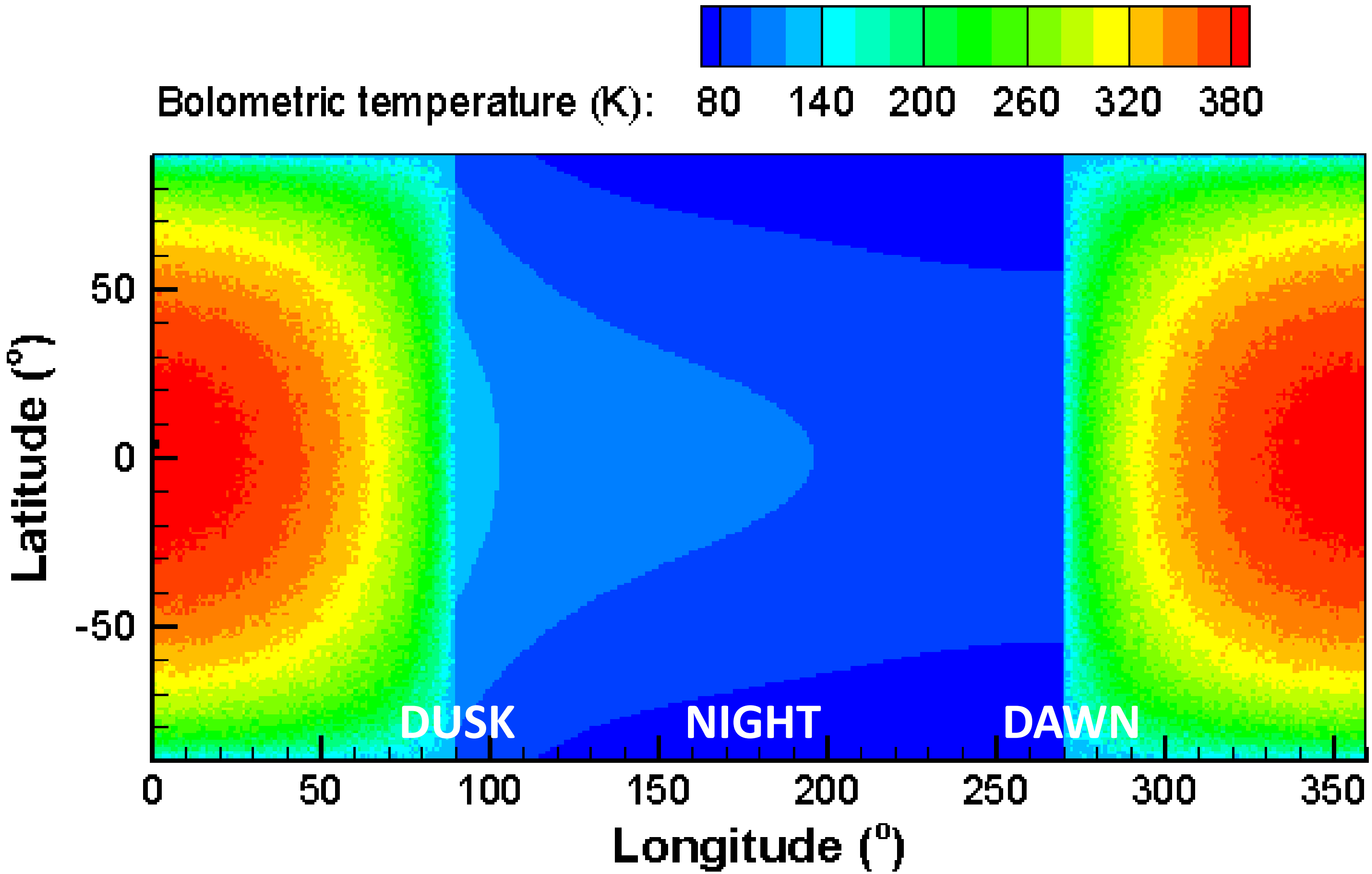
Influence of Roughness on t_{res}



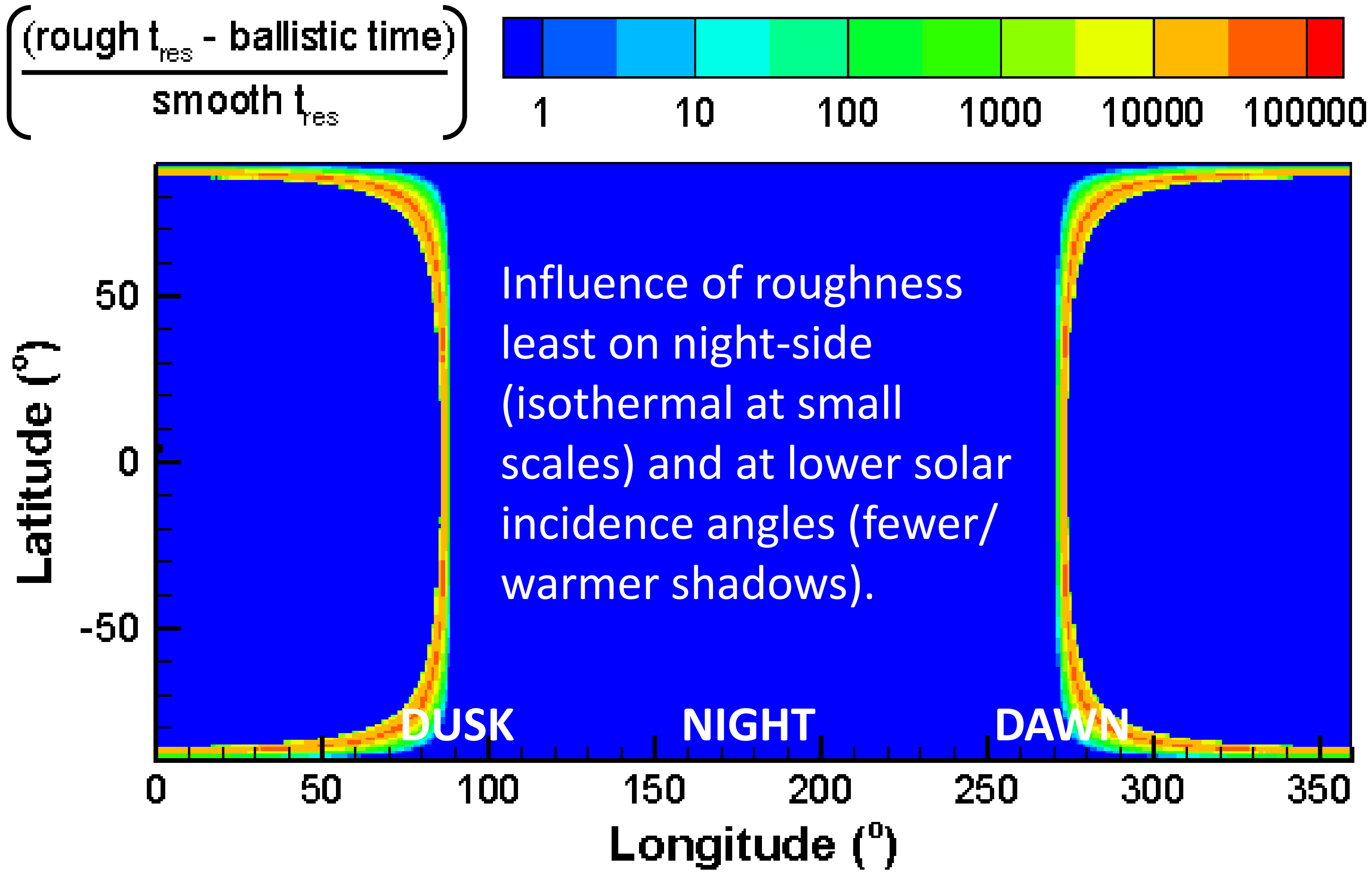
Influence of Roughness on t_{res}



Influence of Roughness on t_{res}



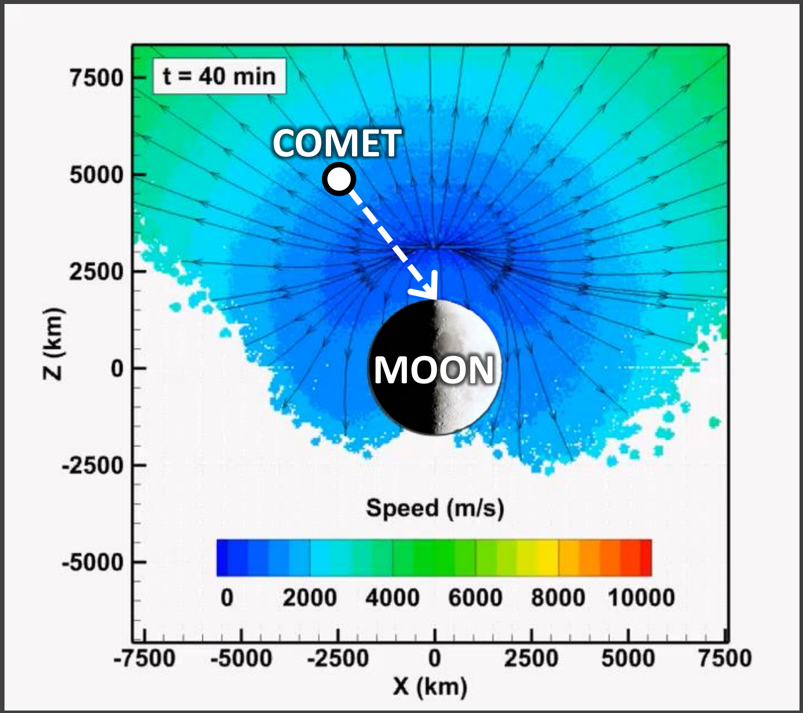
Influence of Roughness on t_{res}



Influence of roughness least on night-side (isothermal at small scales) and at lower solar incidence angles (fewer/ warmer shadows).

Volatile Transport Simulations

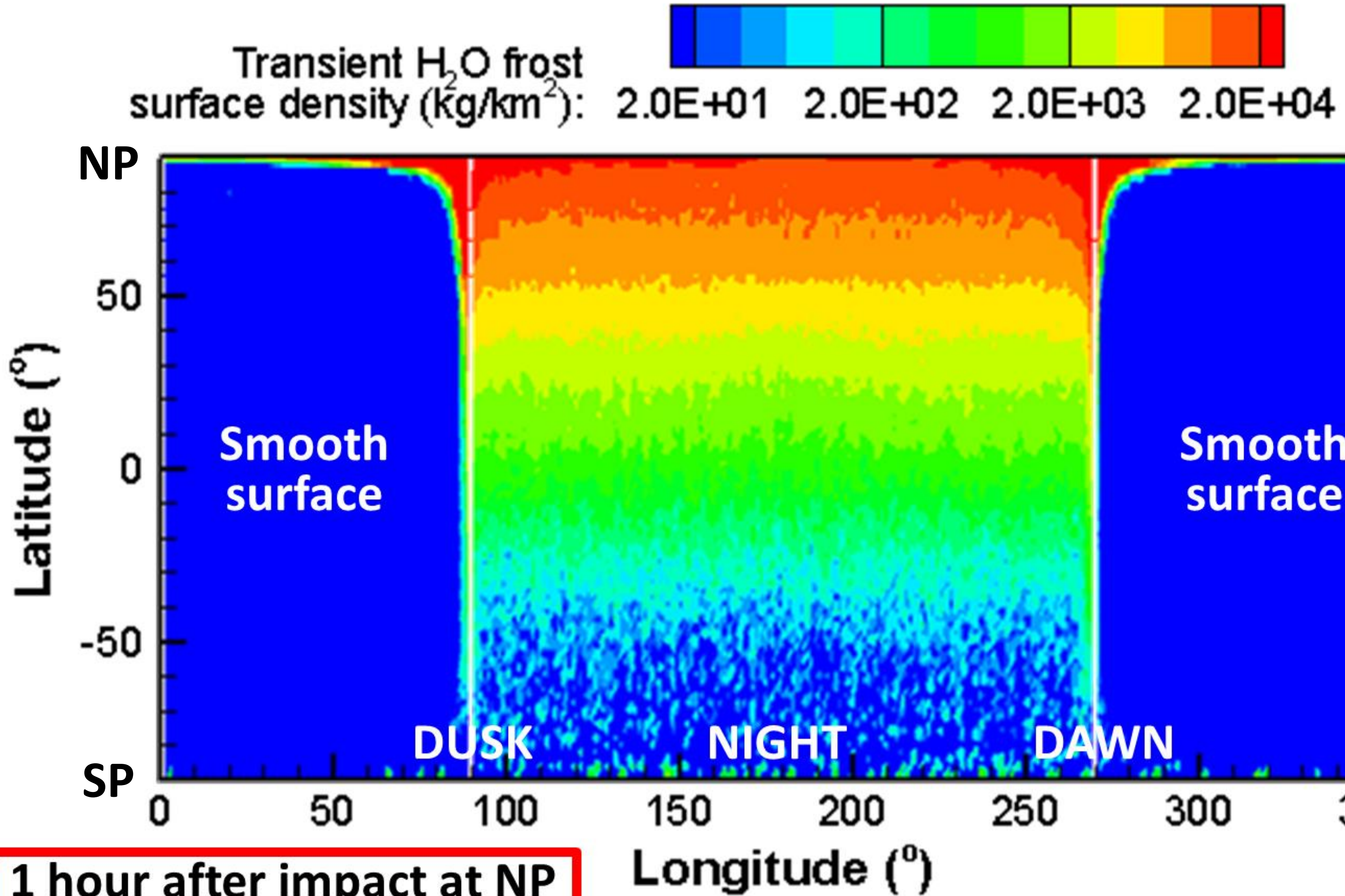
- Roughness model is incorporated into detailed simulations of volatile transport after a comet impact **(Prem *et al.*, 2015)**.



  - **H_2O is the only modeled volatile.**
  - Comet radius 1 km.
  - **Impact at North Pole** @ 30 km/s, 60° impact angle.

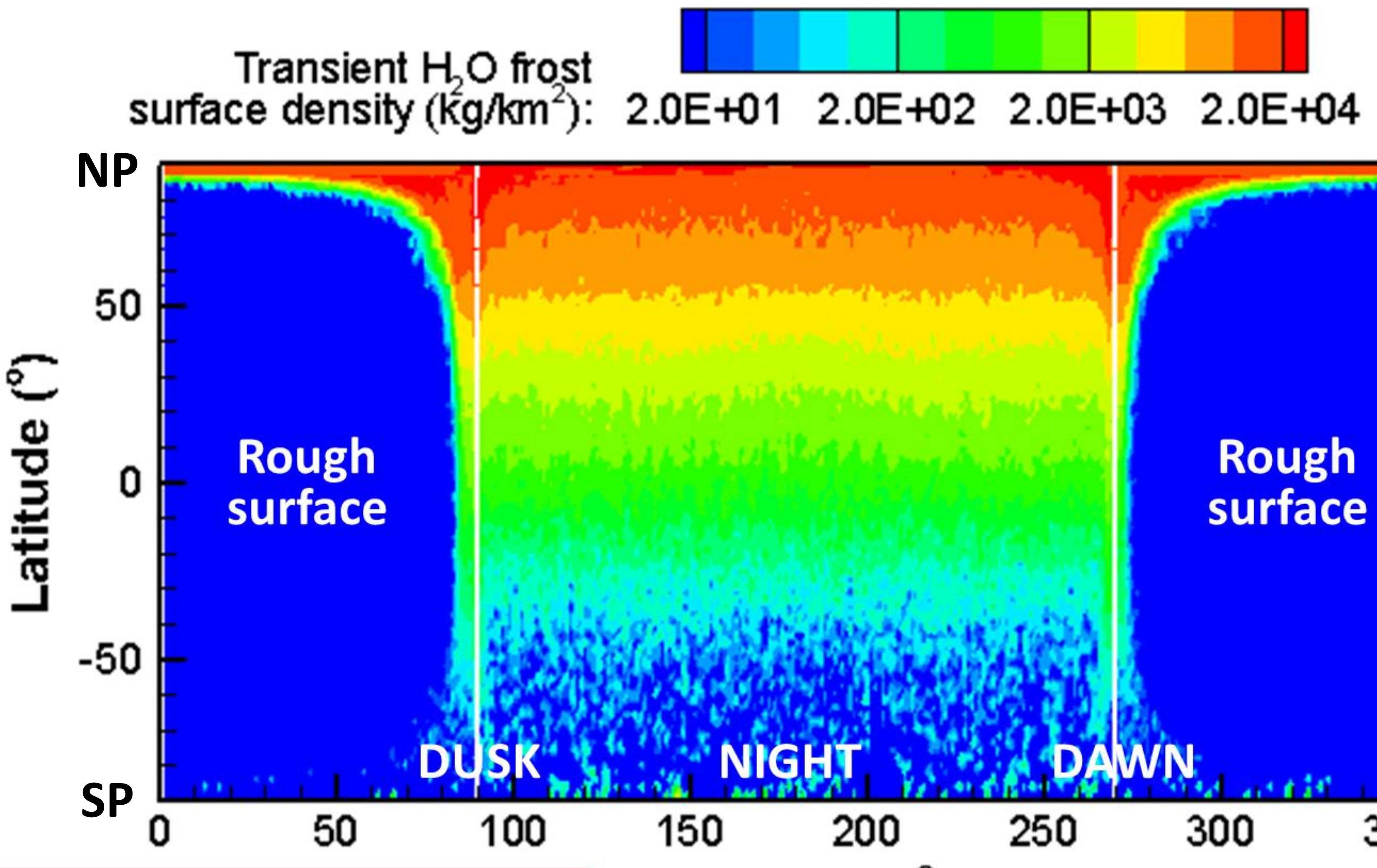
- How does roughness affect –
  - **Rate of cold trap capture?**
  - **Rate of photodestruction?**
  - **Transient deposition patterns?**
    - Impact generates a vapor cloud → vapor falls back to the surface → transient frost cover where surface is sufficiently cold.

Transient Deposition Patterns



1 hour after impact at NP

Transient Deposition Patterns



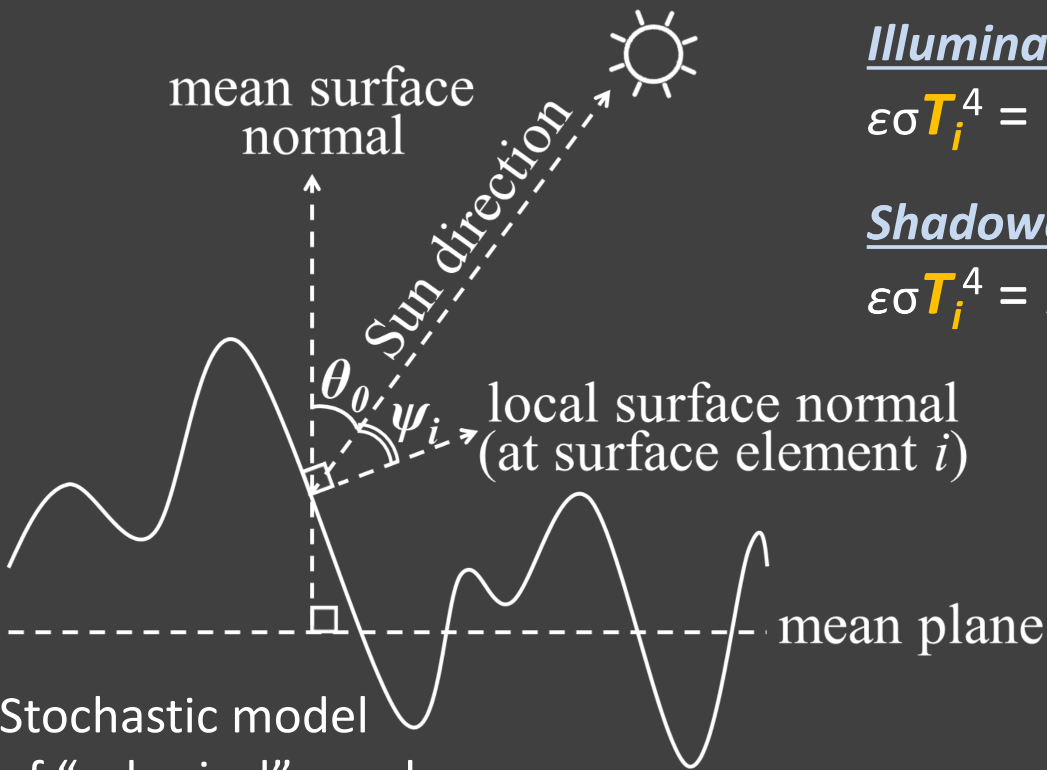
1 hour after impact at NP

Summary & Conclusions

- Small-scale roughness **"blurs" the terminators:**
  - **Shifts effective terminator by ~3° longitude at the equator** i.e. a shift of ~6 hours. For perspective, Hurley *et al.*'s (2015) approximation of **large-scale topography blurred terminators by ~15 hours**.
  - Relevance for **exospheric observations near terminators** (useful in constraining gas-surface interactions).
  - **Late-term transport/migration to poles** after a comet impact is largely **driven by sublimation along the dawn terminator**.
- There is also **increased residence times around poles**.
  - Could have implications for **transport of present-day polar volatiles** and polar exploration missions.
- May also be consequences for rates of cold-trapping and photodestruction (investigation in progress).

ADDITIONAL SLIDES

Modeling Approach - Details



Stochastic model of "sub-pixel" roughness

Illuminated surface elements:

$$\varepsilon\sigma T_i^4 = (1 - \alpha)F_S \cos\psi_i + F_{re\text{-}rad} \cos\theta_0$$

Shadowed surface elements:

$$\varepsilon\sigma T_i^4 = F_{re\text{-}rad} \cos\theta_0$$

Shadowing probability:

$$p_{shadow} = f\,(\text{rms slope}, \theta_0)$$

(from Smith, 1967)

Molecule residence time:

$$t_{res} \propto \exp(1/T_i)$$

$T_i \geq T_{i,min}$
F_S = solar flux
$F_{re\text{-}rad} \cos\theta_0$ = flux from surroundings (re-radiated solar energy)

$F_{re\text{-}rad}$ and $T_{i,min}$ are **best-fit constants to match observed bolometric temperature**. For rms slope angle = 20°, ε = 0.95 and α = 0.11, $F_{re\text{-}rad}$ = 320 W/m^2 and $T_{i,min}$ = 130 K.

Bolometric Temperature Matching

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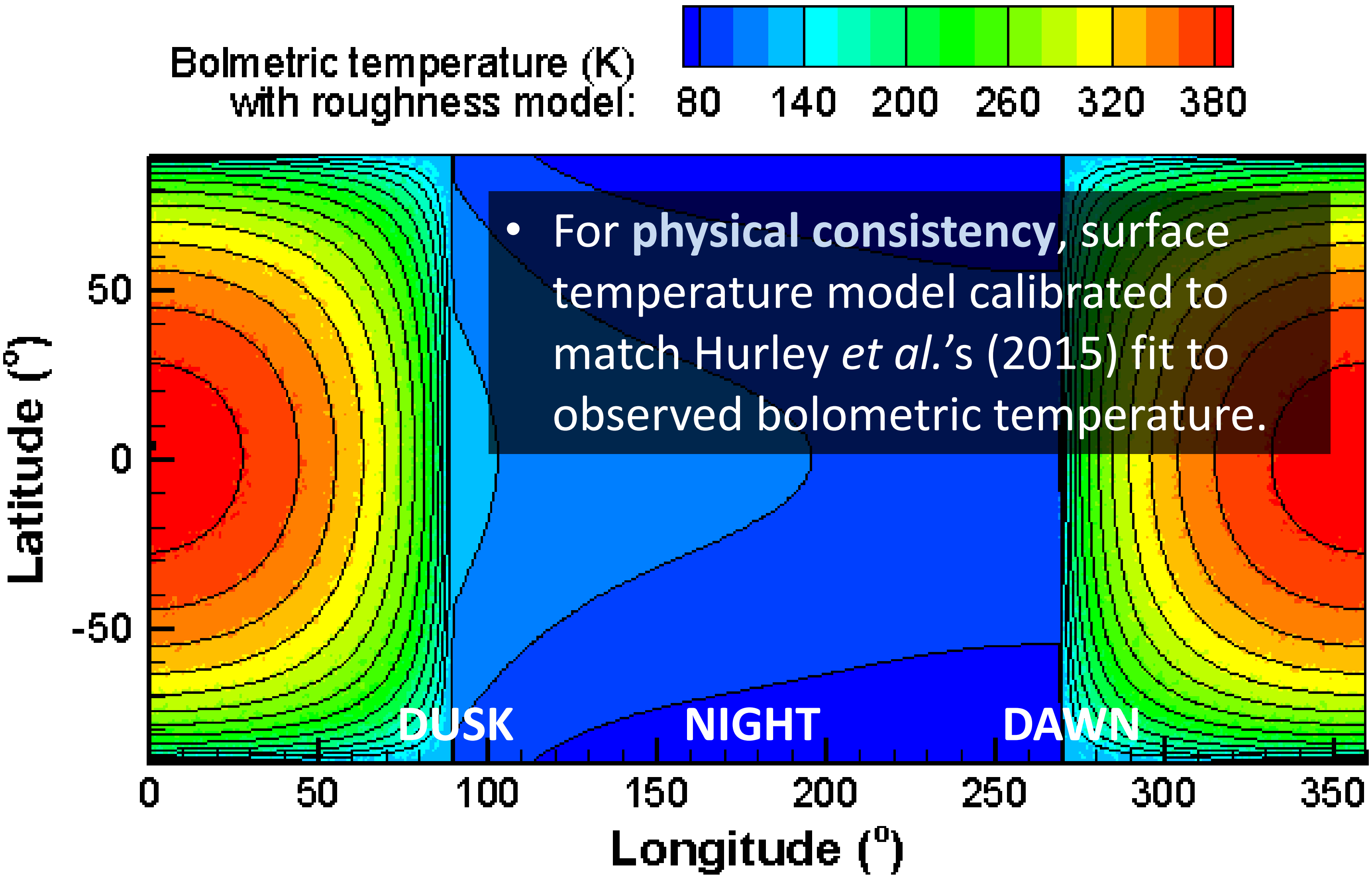
additional



- For **physical consistency**, surface temperature model calibrated to match Hurley *et al.*'s (2015) fit to observed bolometric temperature.

Bolometric Temperature Matching

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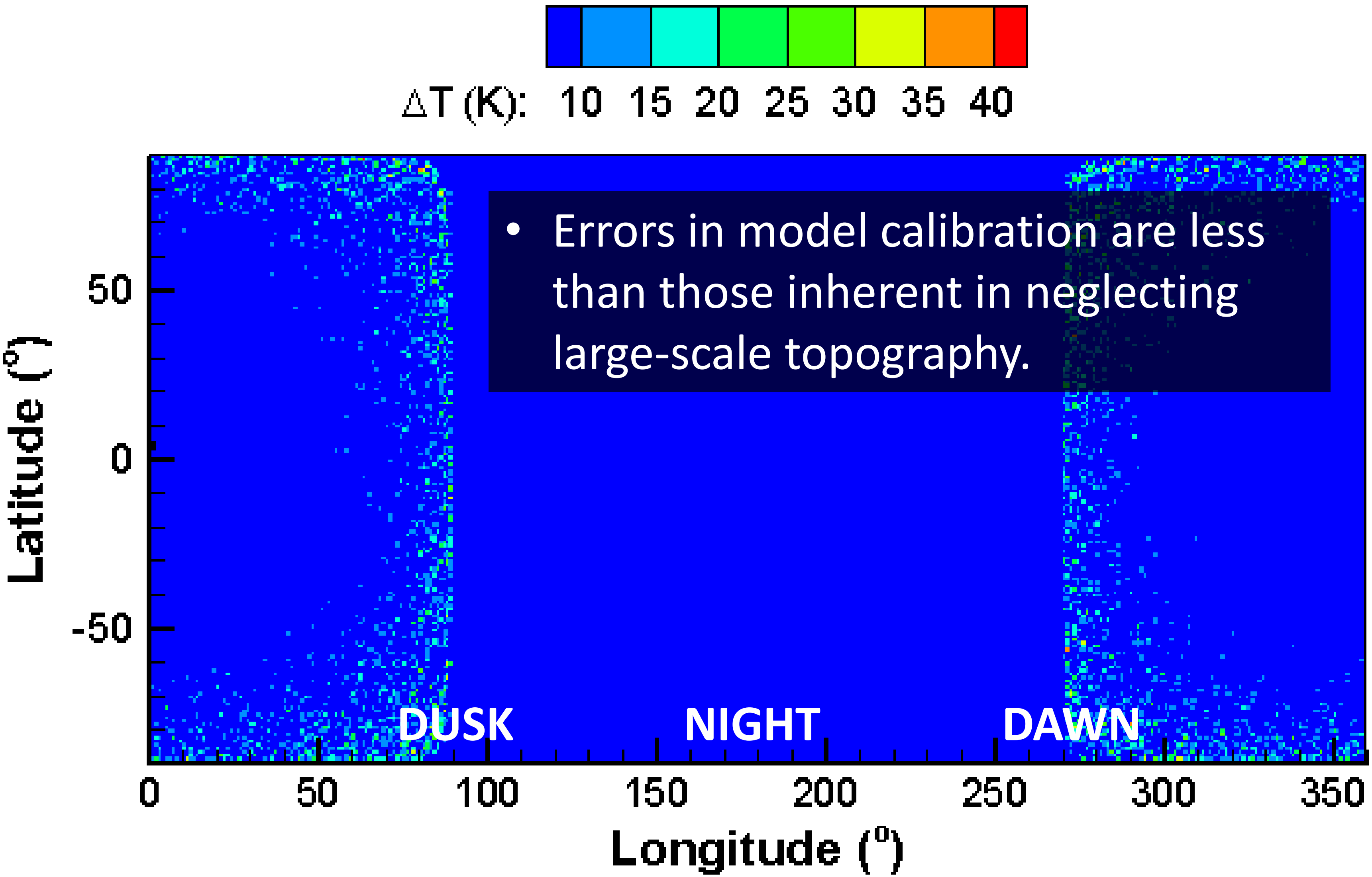

- Errors in model calibration are less than those inherent in neglecting large-scale topography.

Same Roughness, Different Species

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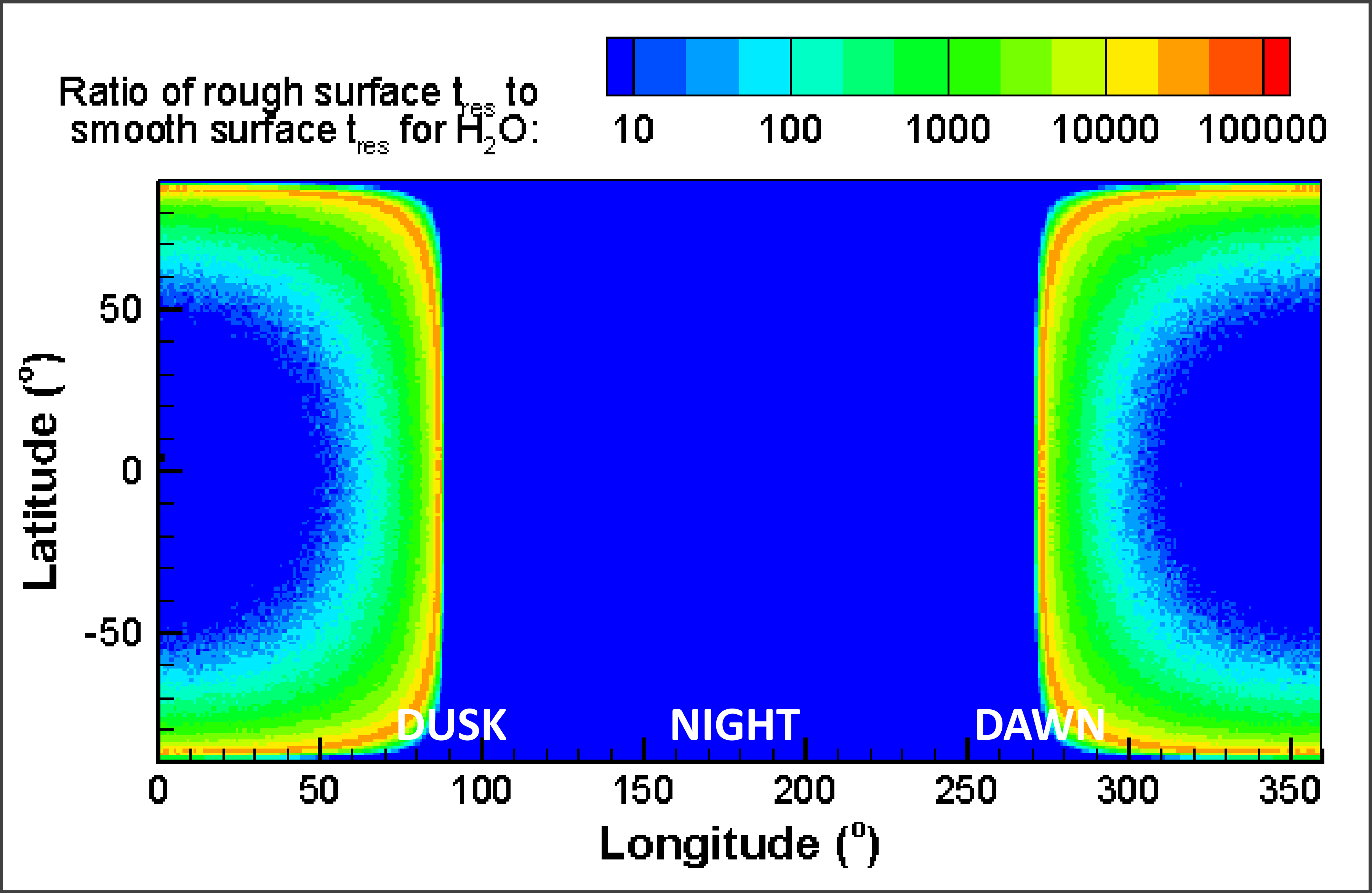

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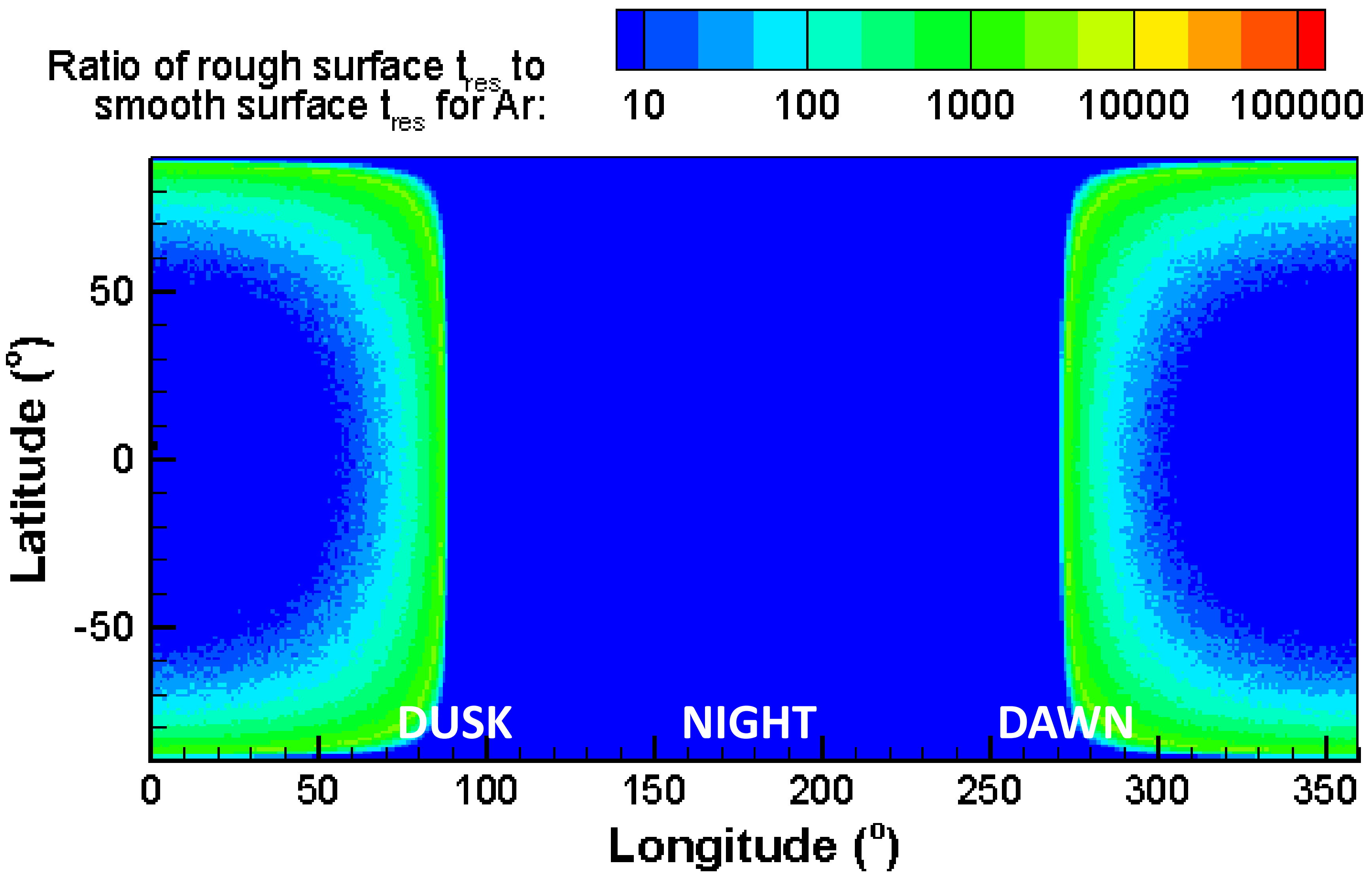

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Same Roughness, Different Species

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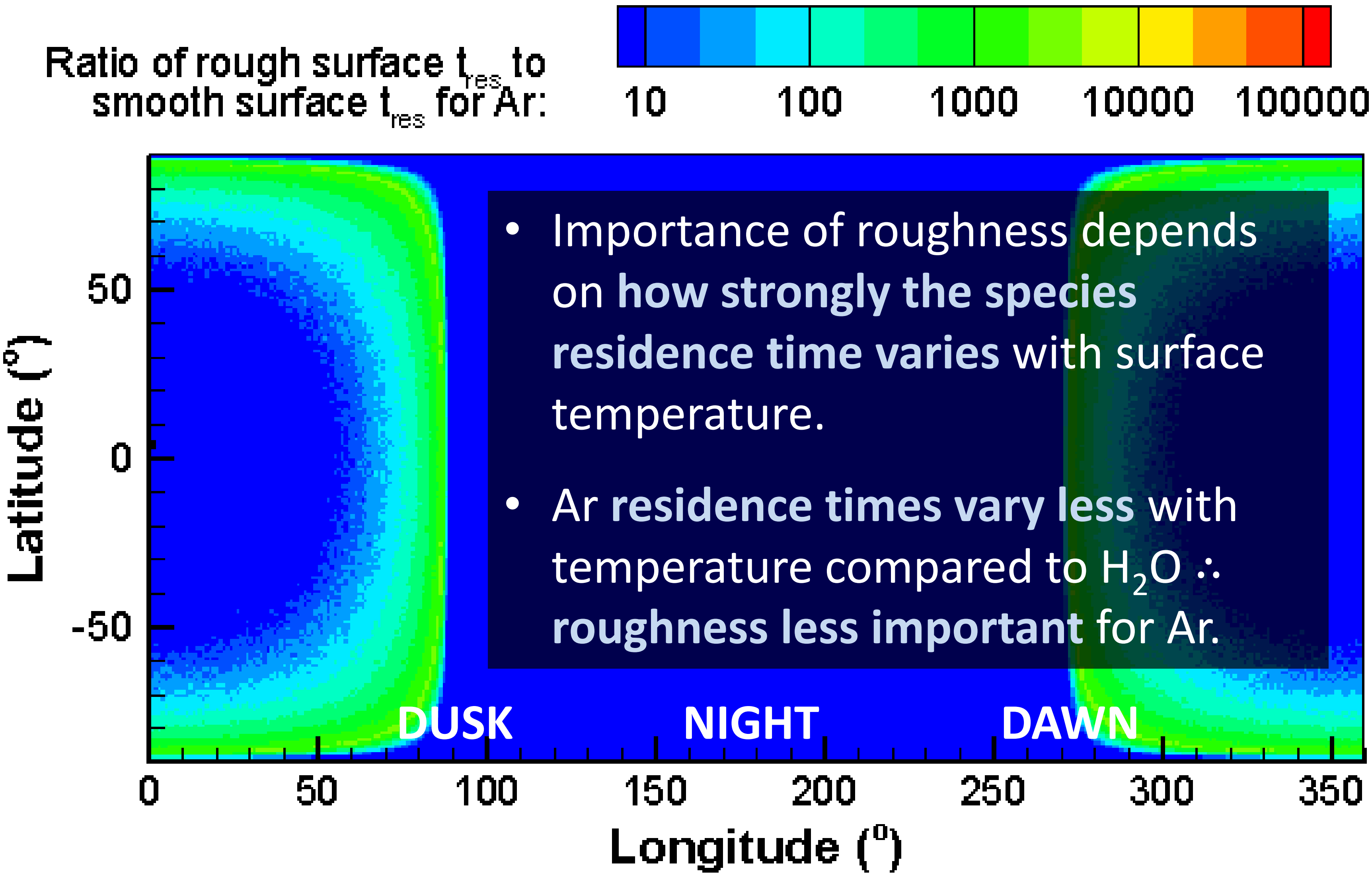

- Importance of roughness depends on **how strongly the species residence time varies** with surface temperature.
- Ar **residence times vary less** with temperature compared to H_2O ∴ **roughness less important** for Ar.