Modeling the 2012-2014 Surface Energy and Mass Balance of the Puruogangri Ice Field Using High Asia High-Resolution Reanalysis Data: Postprint

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Abstract

Using High Asia Refined analysis (HAR) data and the Coupled Snowpack and Ice Surface Energy and Mass balance Model (COSIMA), we simulated the energy-mass balance of Puruogangri, the largest ice cap on the Tibetan Plateau, for the period 2012-04-23 to 2014-05-11, and analyzed the ablation mechanisms of the Puruogangri ice cap. The simulated mass balances for the periods 2012-04-23—2013-05-23 and 2013-05-23—2014-05-11 were -0.18 m w.e. and -0.36 m w.e., respectively. Throughout the study period, regions in the western and north-central parts of the ice cap below 5800 m a.s.l. experienced mass loss, reaching a maximum of -2.69 m w.e.; conversely, the northern region of the ice cap, due to its higher elevation, experienced mass accumulation, with a maximum value of 0.85 m w.e. in the northeastern region. Although the energy available for ablation during 2013-05-23—2014-05-11 decreased compared to 2012-04-23—2013-05-23, slowing surface ablation, the solid precipitation over the Puruogangri ice cap during 2013-05-23—2014-05-11 was lower than that during 2012-04-23—2013-05-23, resulting in a more negative surface net mass balance for the glacier during 2013-05-23—2014-05-11.

Full Text

Simulating Surface Energy and Mass Balance of the Puruogangri Ice Cap during 2012-2014 Based on High Asia Refined Analysis Data

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Abstract: This study employs the High Asia Refined analysis (HAR) dataset and the Coupled Snowpack and Ice Surface Energy and Mass balance Model (COSIMA) to simulate the surface energy and mass balance of the Puruogangri ice cap—the largest ice cap on the Tibetan Plateau—during the period from April 23, 2012 to May 11, 2014, and to analyze its ablation mechanisms. The simulated mass balance values for the Puruogangri ice cap were -0.18 m w.e. and -0.36 m w.e. for the two consecutive study periods. Throughout the entire study period, areas below 5800 m elevation, such as the western and north-central parts of the ice cap, experienced mass loss with a maximum deficit reaching -2.69 m w.e., while the northern region, due to its higher elevation, exhibited mass accumulation with a maximum value of 0.85 m w.e. Although the air temperature over the Puruogangri ice cap increased rapidly, the energy available for ablation decreased between May 23, 2013 and May 11, 2014 compared to the previous period, resulting in reduced surface melt. However, solid precipitation also decreased during this period, leading to a more negative net surface mass balance for the ice cap.

Keywords: Puruogangri; High Asia Refined analysis; COSIMA; energy balance; mass balance

Introduction

Under the backdrop of rapid temperature increases, glaciers worldwide are exhibiting varying degrees of ablation, with mountain glaciers in the interior of the Tibetan Plateau being particularly vulnerable. The rate of glacier mass loss in the Himalayas reached 0.59 m w.e. a^{-1} between 2000 and 2016, while the mass loss rate in the Qilian Mountains was 0.77$\pm 0.35 mw.e.a^{-1}$ between 2003 and 2009. In contrast to other glaciers in the Tibetan Plateau region, the Puruogangri ice cap in the interior of the plateau has remained relatively stable. Previous scholars have quantified mass balance changes at Puruogangri using geodetic methods. For instance, Neckel et al. estimated the annual mass balance between 2003 and 2009 to be -0.044$\pm 0.015 mw.e.a^{-1}$ by differencing SRTM and TanDEM DEMs, while Liu et al. estimated mass balances of 0.44$\pm 0.10 mw.e.a^{-1}, -0.13\pm 0.03 mw.e.a^{-1}, and -0.52\pm 0.10 mw.e.a^{-1}$ for different periods using TanDEM data. However, geodetic methods are limited by satellite data availability and provide limited temporal resolution.

Energy and mass balance modeling based on meteorological parameters and radiation values not only yields refined mass balance estimates but also reveals the physical mechanisms of glacier ablation, predicts future glacier states, and enables deeper investigation of glacier-climate relationships. Glacier surface mass balance comprises accumulation and ablation processes. Ablation is controlled by the surface energy budget, while accumulation primarily derives from precipitation. Temperature, as a key parameter directly influencing melt, plays a crucial role in mass balance simulations. The degree-day model, based on temperature variations, has been widely used for glacier mass balance simulation. Huintjes et al. improved the degree-day model by incorporating potential solar shortwave radiation, but this modified version still only calculates surface mass balance without considering internal glacier processes.

To address this limitation, Huintjes et al. developed the Coupled Snowpack and Ice Surface Energy and Mass balance model (COSIMA), which incorporates surface factors such as air pressure, temperature, and wind speed, as well as subsurface mass balance processes. This enables more comprehensive simulation of glacier ablation across different elevations, slopes, and aspects. With a temporal resolution of one hour, COSIMA can finely simulate glacier dynamics and reveal detailed energy and mass change processes. Huintjes et al. previously applied this model with HAR data to simulate the ablation rate of Puruogangri between 2001 and 2011, obtaining results consistent with Neckel et al.' s estimates.

As the largest ice cap in the central Tibetan Plateau, Puruogangri serves as a recorder of climate and environmental changes and constitutes a major water source for surrounding lakes. Previous studies have analyzed its mass balance changes and impacts on lake water levels using aerial photogrammetry and TanDEM data. However, these investigations lacked analysis of recent ablation mechanisms. To reveal recent dynamics and analyze climate response patterns, this study employs HAR data and COSIMA to investigate energy budget and mass balance changes at Puruogangri between 2012 and 2014, providing high-temporal-resolution mass balance estimates for analyzing the ice cap' s response to climate change and its impact on surrounding lakes.

1.1 Study Area Overview

The Puruogangri ice cap is located in the northeastern part of Shuanghu Special District, Tibet Autonomous Region, covering 33°44 ~34°04 N and 89°20 ~89°50 E, with an area of 422.58 km^2 [Figure 5350: see original paper]. The Puruogangri peak area has relatively flat terrain with a maximum elevation of 6482 m. Multiple ice tongues of varying lengths extend from the ice cap center outward, with the lowest ice tongue at approximately 5350 m elevation. The average snow line altitude was 5735 m between 2001 and 2011. Remote sensing imagery shows that the Puruogangri ice cap surface is relatively clean with minimal moraine deposits, making it easily distinguishable from surrounding terrain. Controlled by the Indian monsoon and mid-latitude westerlies, Puruogangri is classified as a polar continental glacier. Influenced by spring westerlies and summer Indian monsoon, most precipitation in spring and summer is solid, making Puruogangri a spring-summer accumulation type glacier.

1.2.1 High Asia Refined Analysis Data

The High Asia Refined analysis (HAR) dataset is a meteorological dataset obtained by Professor Dieter Scherer' s team at the Technical University of Berlin using numerical weather prediction and dynamical downscaling methods. The dataset merges ERA-Interim reanalysis products and meteorological station data, combines classical physical parameterization schemes, and employs a two-way nesting model to simulate meteorological parameters across the High Mountain Asia region. Based on resampled MODIS data at 0.1°$×0.1°resolution,thehighestelevationgridpointdatawasextractedforuseinthemodel.Thedatahaveaspatial km and temporal resolution of one hour, with the Asian region data covering 2001-2014 (the latest version extends to 2016). This dataset has been well validated for glacier surface mass balance studies on the Tibetan Plateau.

1.2.2 Data Preprocessing

The COSIMA model was used to simulate the surface energy and mass balance of the Puruogangri ice cap. To create model input data, the SRTM DEM (30 m$×30mresolution)wasresampledto450m×450mresolution.SincetheHARdata(10km×10km)andSRTMDE dimensionalgradientinterpolationwasperformedtoobtaintwo−dimensionalmeteorologicaldatasetsfortheice m resolution). The gradient factors and correlation coefficients were derived by linearly fitting altitude information and specific humidity data from all points.

Radiation is a critical parameter directly affecting glacier ablation rates. Based on Kumar et al.' s radiation model and Puruogangri' s geographic location, elevation, latitude, slope, and aspect, clear-sky incoming shortwave radiation was calculated (450 m$×$450 m resolution). A conversion factor was obtained by comparing clear-sky radiation values with HAR incoming shortwave radiation values at the highest elevation grid point, which was then applied to obtain ice surface incoming shortwave radiation values.

Initial snow depth affects the division of subsurface layers in the model. Following Huintjes et al.' s approach, initial snow depth was set to 0 m in the ablation zone and linearly interpolated between the equilibrium line and the highest elevation point. The mixing ratio, which affects latent heat flux calculations, was derived from specific humidity using the relationship W = q/(1-q), where q is specific humidity and W is mixing ratio. Water vapor pressure, which influences downward longwave radiation, was calculated from the mixing ratio.

1.3 Research Methods

COSIMA simulates glacier ablation rates through energy balance modeling and mass accumulation through solid/liquid precipitation separation, thereby deriving glacier mass balance. The energy balance model is expressed as:

$$F_{melt} = SW_{net} + LW_{net} + Q_{sen} + Q_{lat} + Q_{cnd}$$

where F_{melt} is melt energy, SW_{net} is net shortwave radiation, LW_{net} is net longwave radiation, Q_{sen} is sensible heat flux, Q_{lat} is latent heat flux, and Q_{cnd} is subsurface conductive heat flux.

Solid precipitation is a key parameter affecting glacier mass accumulation. Möller et al. proposed a hyperbolic tangent function to separate solid and liquid precipitation. Based on this function and HAR precipitation data, solid precipitation at Puruogangri was obtained using:

$$snow_g = prcp \times (0.5 \times (-\tanh((T - 273.15) - 2.5) \times 2.5) + 1)$$

where $snow_g$ is solid precipitation (mm), $prcp$ is total precipitation (mm), and T is temperature (K).

Wind speed, humidity, and other parameters influence turbulent exchange at the glacier surface. Since HAR data only provides wind speed at 10 m height, the wind speed conversion model proposed by Allen et al. was used to estimate wind speed at different heights:

$$u_z = u_{10} \times \frac{\ln((z - 5.42)/0.0001)}{\ln((10 - 5.42)/0.0001)}$$

where u_z is wind speed at height z (m s^{-1}), and u_{10} is wind speed at 10 m height (m s^{-1}).

Sensible and latent heat fluxes are calculated as:

$$Q_{sen} = \rho_{air} \times c_{air} \times C_{sen} \times u \times (T_{air} - T_{surf})$$

$$Q_{lat} = \rho_{air} \times L \times C_{lat} \times u \times (q_{air} - q_{surf})$$

where ρ_{air} is air density, c_{air} is specific heat capacity at constant pressure (1004.67 J kg^{-1} K^{-1}), C_{sen} and C_{lat} are bulk exchange coefficients for sensible and latent heat (assumed equal), u is wind speed, T_{air} and T_{surf} are air and surface temperatures, L is latent heat of evaporation (2.514$\times10^{6}$ J kg^{-1}) or sublimation (2.849$\times10^{6}$ J kg^{-1}), and q_{air} and q_{surf} are specific humidity of air and surface.

The bulk exchange coefficient is calculated using Braithwaite' s formula:

$$C_{sen} = C_{lat} = \frac{k^2}{[\ln(z/z_0)]^2}$$

where k is the von Kármán constant (0.4), z is measurement height, and z_0 is roughness length.

Subsurface conductive heat flux consists of transmitted shortwave radiation and subsurface heat conduction. Heat conduction is calculated based on temperature differences between surface and subsurface layers and a heat transfer coefficient determined using Anderson' s method:

$$\lambda = 0.021 + 2.5 \times \left(\frac{\rho_{snow}}{1000}\right)^2$$

where λ is heat transfer coefficient and ρ_{snow} is snow density.

Transmitted shortwave radiation is estimated using Bintanja' s model:

$$S_i = (1 - \zeta) \times SW_{abs} \times e^{-k_{ext} \times Z}$$

where S_i is remaining shortwave radiation at depth Z, SW_{abs} is net shortwave radiation absorbed at the surface, ζ is the proportion absorbed in the top layer (0.8 for ice, 0.9 for snow), and k_{ext} is extinction coefficient (2.5 m^{-1} for ice, 17.1 m^{-1} for snow).

Albedo determines the amount of solar shortwave radiation absorbed by the glacier surface. Following Oerlemans and Knap' s method:

$$\alpha_i = \alpha_{firn} + (\alpha_{frsnow} - \alpha_{firn}) \times \exp(-s/t) + (\alpha_{ice} - \alpha_{firn}) \times \exp(-d/H_{char})$$

where α_i is surface albedo on day i, α_{firn} is firn albedo (0.55), α_{frsnow} is fresh snow albedo (0.85), α_{ice} is ice albedo (0.35), s is days since last snowfall, t is timescale for fresh snow to become firn (30 days), d is snow depth, and H_{char} is characteristic snow depth scale (0.1 m).

Following Huintjes et al.' s approach, the subsurface was divided into layers at 0.1 m intervals to analyze density, temperature, and other parameters. Initial albedo and roughness values for new snow, firn, and ice layers were determined using parameterization schemes, with initial subsurface temperatures adopted from Huintjes et al.' s previous work. All parameters and layering methods have been validated and proven effective for Puruogangri.

2 Results and Analysis

2.1 Surface Energy Balance

The main energy fluxes at the Puruogangri ice cap surface between 2012 and 2014 are shown in [Figure 3: see original paper]. Net shortwave radiation was 67.09 $W \cdot m^{-2}$, net longwave radiation was -53.82 $W \cdot m^{-2}$, sensible heat flux was 36.54 $W \cdot m^{-2}$, latent heat flux was -10.31 $W \cdot m^{-2}$, and subsurface heat flux was -10.04 $W \cdot m^{-2}$. Compared with Huintjes et al.' s simulation results for 2001–2011 (net shortwave radiation: 63.81 $W \cdot m^{-2}$; net longwave radiation: -50.04

$W \cdot m^{-2}$; sensible heat flux: 35.59 $W \cdot m^{-2}$; latent heat flux: -32.26 $W \cdot m^{-2}$), the energy flux trends are consistent. During the study period, net shortwave radiation showed regular patterns, reaching minima in winter and maxima in summer. This seasonal variation may result from Earth' s rotation and revolution causing differences in solar illumination, as well as from variations in solid precipitation events between winter and summer that affect surface albedo. Net longwave radiation also exhibited regular patterns, reaching minima in summer, likely due to increased cloud cover and specific humidity enhancing downward longwave radiation. Latent heat flux is generally negative under dry conditions but becomes positive during summer when lower wind speeds reduce turbulent exchange, causing condensation or deposition on the glacier surface. Sensible heat flux is typically positive as energy transfers from the warmer air to the colder glacier surface, with magnitudes similar to latent heat flux.

Energy contributions were calculated as percentages of the absolute sum of all fluxes. Net shortwave radiation contributed 32.8%, net longwave radiation 26.1%, sensible heat flux 18.1%, and latent heat flux 16.5%. The primary energy income sources were net shortwave radiation and sensible heat flux, while the main energy expenditure terms were net longwave radiation and latent heat flux. Between the two study periods, net shortwave radiation increased by 3.78 $W \cdot m^{-2}$, net longwave radiation increased by 0.95 $W \cdot m^{-2}$, sensible heat flux increased by 0.27 $W \cdot m^{-2}$, latent heat flux increased by 0.18 $W \cdot m^{-2}$, and subsurface heat flux increased by 0.05 $W \cdot m^{-2}$. Overall, the energy available for ablation decreased between May 23, 2013 and May 11, 2014 compared to the previous period, despite temperature increases. The increase in net longwave radiation may be attributed to reduced cloud cover (decreasing downward longwave radiation), while the increase in net shortwave radiation likely resulted from decreased solid precipitation (reducing surface albedo). The small changes in sensible heat, latent heat, and subsurface heat fluxes reflect minor variations in temperature, pressure, specific humidity, and wind speed.

2.2 Mass Balance Changes

[Figure 4: see original paper] and show the mass balance components and driving factors for Puruogangri. Compared with Huintjes et al.' s 2001–2011 results, surface ablation decreased, subsurface ablation increased, mass sublimation increased, meltwater refreezing slightly decreased, and solid precipitation decreased. The reduction in surface ablation resulted from decreased melt energy, while increased subsurface ablation was caused by enhanced transmitted shortwave radiation. Increased sublimation resulted from higher latent heat flux, and decreased meltwater refreezing reflected reduced surface meltwater due to slightly lower temperatures. The decrease in solid precipitation may be attributed to reduced wind speed, which decreased moisture transport to the Tibetan Plateau, and slightly lower temperatures that reduced evaporation from interior lakes, thereby decreasing atmospheric water vapor content.

The spatial distribution of mass balance shows that most western areas of the ice cap experienced mass loss, with maximum losses reaching -2.69 m w.e., while eastern areas generally showed mass accumulation, with maximum gains of 0.85 m w.e. Specifically, Glacier No. 5, with a relatively low-elevation tongue, showed severe mass loss, while the upper parts of Glacier No. 17 exhibited mass accumulation. The overall spatial pattern of mass change aligns with previous energy-mass balance modeling results. The cumulative mass balances for Glaciers No. 5, No. 10, and No. 17 were -0.87 m w.e., -0.02 m w.e., and -0.36 m w.e., respectively, indicating that Glacier No. 10 had the lowest mass loss, while Glacier No. 5 had the highest.

2.3 Uncertainty Analysis

The COSIMA model contains parameters that cannot be evaluated due to the lack of in-situ observations at Puruogangri. Initial parameter values were derived from empirical values or measured data from Zhadang Glacier. Huintjes et al. used the same parameters to simulate Puruogangri' s mass balance with good results. Sensitivity assessments on Zhadang Glacier showed that errors from neglecting snow thickness during the ablation season had the largest impact. Additionally, deactivating certain physical processes (shortwave radiation transmission, stability correction for turbulent fluxes, snow compaction, subsurface melting, and roughness length changes) revealed that stability correction for turbulent fluxes, snow compaction, and subsurface melting had minimal impact on mass balance results.

Comparing HAR precipitation data with measured precipitation at Zhadang Glacier revealed that HAR overestimates precipitation, with a correction factor of 0.62. Applying precipitation correction factors of 0.62 and 1.0 to the entire Puruogangri ice cap yielded mass balance results of -2298 kg$\cdot$m^{-2} and +162 kg$\cdot$m^{-2}, respectively. Compared with Neckel et al.' s geodetic result of -44$\pm 15 kg \cdot m^{-2}$, the uncertainty introduced by precipitation data is relatively low.

3 Conclusions

1) COSIMA simulated mass balance values of -0.18 m w.e. and -0.36 m w.e. for Puruogangri ice cap between April 23, 2012–May 23, 2013 and May 23, 2013–May 11, 2014, respectively. These results are consistent with previously published geodetic results (-0.13$\pm 0.03 m w.e. and -0.34 \pm$0.06 m w.e.), and the spatial patterns of ablation and accumulation also agree well, indicating high reliability.

2) The primary energy income terms are net shortwave radiation (32.8%) and sensible heat flux (18.1%), while the main energy expenditure terms are net longwave radiation (26.1%) and latent heat flux (16.5%). Compared with 2001–2011, the change in net shortwave radiation exceeded that of sensible heat flux, and the change in net longwave radiation exceeded that of latent heat flux, ultimately reducing the energy available for glacier ablation.

3) Glacier mass accumulation primarily originates from solid precipitation, followed by meltwater refreezing and vapor deposition, while mass loss is mainly caused by surface and subsurface ablation, with sublimation playing a secondary role. Compared with 2001–2011, subsurface ablation increased while surface ablation decreased, resulting in reduced overall ablation. However, due to decreased solid precipitation, the net mass loss increased.

References

[5] Kang S, Xu Y, You Q, et al. Review of climate and cryospheric change in the Tibetan Plateau[J]. Environmental Research Letters, 2010, 5: 015101.

[8] Neckel N, Kropáček J, Bolch T, et al. Glacier mass changes on the Tibetan Plateau 2003-2009 derived from ICESat laser altimetry measurements[J]. Environmental Research Letters, 2013, 9: 014009.

[9] Neckel N, Braun A, Kropáček J, et al. Recent mass balance of the Purogangri Ice Cap, central Tibetan Plateau, by means of differential X-band SAR interferometry[J]. The Cryosphere, 2013, 7: 1623-1633.

[10] Liu L, Jiang L, Jiang H, et al. Accelerated glacier mass loss (2011-2016) over the Puruogangri ice field in the inner Tibetan Plateau revealed by bistatic InSAR measurements[J]. Remote Sensing of Environment, 2019, 231: 111241.

[11] Conway J P, Cullen N J. Cloud effects on surface energy and mass balance in the ablation area of Brewster Glacier, New Zealand[J]. The Cryosphere, 2016, 10(1): 313-328.

[12] Hock R. Temperature index melt modelling in mountain areas[J]. Journal of Hydrology, 2003, 282(1): 104-115.

[13] Huintjes E, Li H, Sauter T, et al. Degree day modelling of the surface mass balance of Urumqi Glacier No. 1, Tianshan, China[J]. The Cryosphere Discussions, 2010, 4: 207-232.

[14] Huintjes E, Sauter T, Schröter B, et al. Evaluation of a coupled snow and energy balance model for Zhadang Glacier, Tibetan Plateau, using glaciological measurements and time lapse photography[J]. Arctic, Antarctic, and Alpine Research, 2015, 3. https://doi.org/10.1657/AAAR0014-073.

[15] Huintjes E, Neckel N, Hochschild V, et al. Surface energy and mass balance at Purogangri ice cap, central Tibetan Plateau, 2001-2011[J]. Journal of Glaciology, 2015, 61(230): 1048-1060.

[16] Lei Y, Yao T, Yi C, et al. Glacier mass loss induced the rapid growth of Linggo Co on the central Tibetan Plateau[J]. Journal of Glaciology, 2012, 58(207): 177-184.

[17] Liu L, Jiang L, Sun Y, et al. Glacier elevation changes (2012-2016) of the Puruogangri Ice Field on the Tibetan Plateau derived from bi-temporal TanDEM-

X InSAR data[J]. International Journal of Remote Sensing, 2016, 37(23-24): 5687-5707.

[18] Yi C, Li X, Qu J. Quaternary glaciation of Puruogangri—the largest modern ice field in Tibet[J]. Quaternary International, 2002, 97-98: 111-121.

[21] Thompson L G, Tandong Y, Davis M E, et al. Holocene climate variability archived in the Puruogangri ice cap on the central Tibetan Plateau[J]. Annals of Glaciology, 2006, 43: 61-69.

[22] Maussion F, Scherer D, Mölg T, et al. Precipitation seasonality and variability over the Tibetan Plateau as resolved by the high Asia reanalysis[J]. Journal of Climate, 2014, 27(5): 1910-1927.

[23] Maussion F, Scherer D, Finkelnburg R, et al. WRF simulation of a precipitation event over the Tibetan Plateau, China: An assessment using remote sensing and ground observations[J]. Hydrology and Earth System Sciences, 2011, 15(6): 1795-1817.

[24] Kumar L, Skidmore A K, Knowles E. Modelling topographic variation in solar radiation in a GIS environment[J]. International Journal of Geographical Information Science, 1997, 11(5): 475-497.

[25] Möller M, Schneider C, Kilian R. Glacier change and climate forcing in recent decades at Gran Campo Nevado, southernmost Patagonia[J]. Annals of Glaciology, 2007, 46: 136-144.

[26] Allen R, Pereira L, Raes D, et al. Crop evapotranspiration: Guidelines for computing crop water requirements, FAO irrigation and drainage paper 56[J]. FAO, 1998, 56.

[28] Braithwaite R J. Aerodynamic stability and turbulent sensible flux over a melting ice surface, the Greenland ice sheet[J]. Journal of Glaciology, 1995, 41(139): 562-571.

[29] Anderson E A. A point Energy and Mass Balance Model of A Snow Cover[M]. Technical Report NWS19, NOAA, 1976.

[30] Bintanja R, Broeke M R V D. The surface energy balance of Antarctic snow and blue ice[J]. Journal of Applied Meteorology and Climatology, 1995, 34(4): 902-926.

[31] Oerlemans J, Knap W H. A 1 year record of global radiation and albedo in the ablation zone of Morteratschgletscher, Switzerland[J]. Journal of Glaciology, 1998, 44(147): 231-238.

[32] Mölg T, Maussion F, Yang W, et al. The footprint of Asian monsoon dynamics in the mass and energy balance of a Tibetan glacier[J]. The Cryosphere, 2012, 6(6): 1445-1461.

[34] Mölg T, Maussion F, Scherer D. Mid-latitude westerlies as a driver of glacier

variability in monsoonal High Asia[J]. Nature Climate Change, 2014, 4(1): 68-73.

Note: Figure translations are in progress. See original paper for figures.