SIMPLE AIR TEMPERATURE ESTIMATION METHOD FROM MODIS SATELLITE IMAGES ON A REGIONAL SCALE

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ABSTRACT

Agricultural studies on a regional scale about water balance and evapotranspiration estimation, among others, require estimating air temperature (T_a) spatial variation since the generally low density of weather stations does not allow obtaining such data for a specific area. The aim of this study was to estimate air temperature through atmospheric profiles provided by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on a regional level. One of the present-day methodologies estimates T_a through vertical temperature profiles, which is why modifications to this methodology were proposed for zoning, surface elevation, and pressure/altitude ratios. By applying this new methodology, better T_a estimates were obtained by replacing the MODIS sensor surface elevation with those of the Shuttle Radar Topography Mission (SRTM). Finally, it was possible to estimate T_a spatial variation only from remotely sensed data in various geomorphological areas.

Key words: MODIS, atmospheric profile, digital elevation model.

INTRODUCTION

Estimating air temperature (T_a) is very important in monitoring the environment, estimating precipitation, climatic prognoses, determining evapotranspiration, predicting crop yield (Rugege, 2002), and climatic changes (Aikawa *et al*., 2008) among others. Furthermore, it is the most important meteorological and climatological element, along with radiation, in plant development, determining its spatial distribution, and conditioning agricultural soil suitability (Lozada and Sentelhes, 2008).

T_a is generally measured in meteorological stations by temperature sensors (Unger *et al*., 2001) located 2 m above the soil surface. The density of these meteorological stations is low (number of station per unit area) to carry out a spatially distributed characterization since there is no data for some large areas (Marquínez *et al*., 2003). According to Lozada and Sentelhes (2008), one of the main problems in conducting agrometeorological studies is the lack of temperature data. These authors consider that the low density of the meteorological stations in some study areas, addition to flaws in the meteorological data series and/or short historical data series, compromising

the quality of estimation of T_a spatially distributed. Most methods to determine T_a spatial variation often use spatial interpolation and extrapolation of data from the nearest meteorological stations. The problem with T_a interpolation and extrapolation is that they depend on many local parameters that can influence its estimation spatially-distributed (e.g. altitude, sun exposure, terrain concavity, and distance from the coast among others) (Marquínez *et al*., 2003). There are T_a estimation, spatially-distributed, methodologies applied to areas with diverse altitudes using linear interpolation of data provided by meteorological stations (Hernández, 2000; Ibáñez and Rosell; 2001 Cristóbal *et al*., 2008), as well as those developed for lowlands and valleys where there are no landforms (Unger *et al*., 2001; Méndez, 2004). This is not the case in Chile, which is located between two mountain ranges, the Coastal Range and the Andes Range. Transverse climatic gradients, from the coast towards the interior, are frequently more emphasized than latitudinal gradients, especially regarding the degree of aridity. A Foehn effect or "rain shadow" is produced behind the coastal elevations, which makes the eastern slopes significantly drier than the western slopes. It is the same for sectors with exposure to the east, which are colder in winter and warmer in summer because they are sheltered from the coastal breeze. This generates sea vegetation gradients toward the interior in almost all latitudes.

The Andes Range acts as a climate zone generator agent with a strong thermal determinant throughout the whole country. Given that temperature decreases about 5 to 6 °C for each 1000 m of altitude, 4000 m mountains can show areas with climatic characteristics with differences of 40 °C over relatively short distances (Santibáñez *et al.*, 2006). To this effect, Price *et al.* (2000) and Lookingbill and Urban (2003) suggest that the first step in agricultural studies in mountainous regions is the development of simple geographic models to estimate T_a.

The methods actually being used can be divided into two types: those that use information collected on the Earth's surface and those that employ information obtained through remote sensors (Sánchez and Carvacho, 2006). One of the most used techniques is of the first type and employs a geostatistical algorithm called Kriging with external drift (Hudson and Wackernagel, 1994; Goovaerts, 2000). This is an estimator that incorporates extensively sampled secondary data to characterize the spatial tendency of this variable. In the case of air temperature, Hudson and Wackernagel (1994) introduce terrain elevation as secondary information. The latter significantly improves spatial representation of temperature; however, Kriging with external drift continues to be a variation of a global interpolation method meaning that it depends on the number and distribution of data when interpolating.

T_a can also be estimated from the Earth surface temperature, correlating daily mean air temperature measured in the meteorological stations with surface temperature provided by satellite images. The correlation between diverse air temperatures (maximum or mean, daily or monthly) and surface temperature provided by satellite images is high and allows this variable to be spatially distributed. Errors found in Asturias vary between 1.8 and 2.6 °C (Recondo and Pérez-Morandeira, 2002).

There are also estimation models of environmental variables that incorporate the artificial neural network technique, which acts as a non-linear interpolation tool in tables with multiple entries. Applying these neural networks is a complement for information from scarce data and allows solving the problem of a lack of information in methods such as Kriging. A problem associated with this interpolation process is the discontinuity of climatic conditions, that is, it is difficult to achieve a correct interpolation between such disparate or discrete data (Dolling and Varas, 2002). Geographically Weighted Regression (GWR) models have been developed to explore and describe spatial data, particularly when non-seasonal relationships prevail in space (Brunsdon *et al.*, 1998). Unlike a "normal" linear regression, GWRs assume variations in the spatial relationship parameters (Brunsdon *et al.*, 1999) by carrying out a multiple regression analysis between meteorological and geographic variables to adjust an equation by means of spatial interpolation of data from meteorological stations using tools such as Geographic Information Systems (GIS) and satellite images (Ninyerola *et al.*, 2000; Perry and Hollis 2005, Ninyerola *et al.*, 2007; and Cristóbal *et al.*, 2008). Topoclimatic techniques have also been used to determine spatial distribution of climatic variables through multiple regressions between topographic variables and climatic data showing technological limitations such as the location of the meteorological stations, concentrated in areas less than 1500 m.a.s.l. and in the main transverse valleys. Another important aspect is data inconsistency generated by the stations due to technological errors such as failing to update the sensors, their handling, and relocating stations (Morales *et al.*, 2006).

One of the easiest methods to estimate T_a is proposed by Méndez (2004) in the Limpopo River watershed in Mozambique where T_a is estimated from vertical temperature profiles provided by the MODIS sensor. The disadvantage of this method is that it was designed and applied to lowlands or valleys, a condition not always fulfilled in the different zones or regions of Chile.

Lozada and Sentelhes (2008) estimated daily mean temperature (minimum, maximum, and mean) in the Andina Region, Venezuela from a multiple linear regression considering the geographic coordinates (longitude and latitude) as independent variables, and altitude. They based themselves on the fact that the globe's heat distribution is conditioned by latitude determining availability of solar radiation on the Earth's surface; by altitude as a product of pressure variation and rarefaction of air; and sometimes by longitude expressing the effect of proximity to the ocean and continentality. The most recent study of T_a estimation is by Esteban *et al.* (2009) who use the same methodology as the aforementioned authors, but include circulation pattern classification maps in the regression. They incorporate synoptic climatology elements that combine atmospheric circulation with climate and other environmental factors allowing the explanation and forecast of many phenomena and processes taking place in the atmosphere and the environment. According to Esteban *et al.* (2009), this improves the estimation errors of the variable, but they mention that for a more precise estimate it is necessary to install a network with a larger number of meteorological stations, however, this is too expensive. The problem with this methodology is its local feature since it can only be applied in small sectors due to the fact that there are no circulation pattern classification maps for most countries and spatial distribution of meteorological stations influences in estimation quality.

Most studies to determine T_a are estimates of minimum,

maximum, daily, or monthly temperature (Hudson and Wackernagel, 1994; Lookingbill and Urban, 2003; Cristóbal *et al*., 2008; Esteban *et al*., 2009), however, determining instantaneous temperature at the time when the satellite passes over the study area is an indispensable element to calculate hydrological variables such as evapotranspiration (Allen *et al*., 2007) and net radiation (Bisht *et al*., 2005) on a regional scale. The objective of this study was to estimate T_a (instantaneous) on a regional scale in an area that shows great geomorphological variability using a methodology that only applies data from satellite sensors (remotely sensed) to develop an operational and comprehensive method.

MATERIALS AND METHODS

Methodology to determine instantaneous T_a from remotely sensed data by atmospheric profiles

The troposphere is the lowest layer of the Earth's atmosphere and where most meteorological phenomena develop. As altitude from sea level increases, air temperature decreases at a rate of 5 to 6 °C km^{-1}, which is known as adiabatic gradient and Méndez (2004) determined it to be between 1000 and 620 hPa.

In accordance with the above-mentioned, T_a must be determined at an altitude of 2 m above soil surface level according to WMO (2009) recommendations since T_a should be representative of outdoor conditions around the station and also cover an area as large as possible. The methodology proposed by Méndez (2004) to determine T_a is obtained from a linear regression of the vertical temperature profiles (1000 to 620 hPa) and the altitude for each pressure level. The temperature profile was previously determined between observed radiance and the corresponding atmospheric profile by Seemann *et al*. (2003). Thus, the relationship to estimate T_a at 2 m is Equation [1]:

$$T_a = m * Z + T_0 \qquad [1]$$

where *m* is the slope between temperature and elevation, *Z* is the soil surface elevation plus 2 m, and T_0 is the temperature at sea level for each pixel. This equation is obtained for each pixel of the satellite image, determining T_0 at sea level for each pixel.

Table 1 shows the different pressure levels with their respective altitudes (WMO, 2009) to implement this methodology independently of the time the satellite passes.

Proposals to improve the methodology to determine instantaneous T_a by remotely sensed data

Taking into account the limitations of the Méndez (2004) methodology to determine T_a, the following modifications

Table 1. Altitude above sea level for each pressure level.

Pressure (hPa)	Altitud (m)	
	WMO	W&H
1000	110.8	90.84
950	540.1	444.83
920	806.5	666.28
850	1456.7	1212.44
780	2151.8	1805.55
700	3010.9	2552.37
620	3953.7	3389.92

WMO: World Meteorological Organization; W&H: Wallace and Hobbs 2006.

were made: Zoning was carried out by separating the study in coastal and central valley areas due to geomorphological variability. Estimated data was compared to the means of the meteorological stations closest to the coast and located at an altitude of less than 150 m. Furthermore, surface elevation provided by MODIS images was substituted by SRTM. This modification was made because the MODIS sensor provides an elevation matrix that differs each day and which can affect the extraction of real data due to some image distortion. Another proposal to improve the determination of T_a was to replace the altitudes for each pressure level provided by WMO for those obtained by Equation [2] (Wallace and Hobbs, 2006):

$$Z_g = H \quad \ln \frac{P_0}{P_Z} \qquad [2]$$

where Z_g is the surface elevation of the Earth, H = 1/(2.3 ∗ 0.063), P_0 is the pressure at sea level, 1013.25 hPa, and P_Z is the pressure of Z_g elevation. The authors proposed this modification because the differences between the pressure/altitude ratios (Table 1) were considerable and directly influenced the determination of T_a.

Satellite images

The study was carried out using images recorded by the MODIS sensor of the Terra (EOS AM) and Aqua (EOS PM) satellites since they provide the temperature profile at different pressure levels and surface elevation necessary to determine T_a. Atmospherically corrected images necessary to implement the methodology were provided by the atmospheric profile MODIS product (MOD07_L2 MODIS) (Wang *et al*., 2008).

The Terra satellite orbit is regular, going from North to South through the equator in the morning while Aqua goes from South to North over the equator in the afternoon. MODIS provides 36 spectral bands ranging in wavelength from 0.41 to 14.4 *μ*m; spatial resolution is 250, 500, and 1000 m depending on the product. Another relevant factor

when selecting these images is that they are free through the MODIS Website (Xiong *et al*., 2009).

Surface elevation was provided by SRTM, substituting the one provided by the MODIS sensor for the region under study. SRTM was a mission to obtain a digital elevation model of the area of the globe between 56° lat. S and 60° lat. N in order to generate a complete base of high-resolution digital topographic maps of the Earth. These topographic maps have a spatial resolution of 90 m (Hansen *et al*., 2009; Houshang and Quiel, 2009) and were georeferenced by the free GlobalMapper (GlobalMapper, 2009) software.

MODIS images were georeferenced by the MODIS Reprojection Tool (MODIS, 2009) program. Image projection corresponded to Mercator Transversal Universal (UTM) with Datum WGS-84 owing to the fact that it is an easy standard system to work with. Digital values provided by MODIS image products were weighted for factors provided by the supplier, obtaining temperature and surface elevation profiles with a spatial resolution of 1 km (MODIS, 2009).

Study area and *in situ* data

The study area corresponded to Bío Bío Region, one of Chile's 15 administrative regions. This region has a wide variability in geomorphology terrain and data availability for comparison and validation. According to the National System of Environmental Information (SINIA), it is the second most important region in terms of population and economic productivity. It covers an area of approximately 37 000 km² ranging from the temperate climate of the central zone with warmer and drier summers which is basically associated with agricultural activities to a wetter climate south of the Laja River where economic activities are mostly related to livestock and forestry. Temperate Mediterranean climatic characteristics predominate in this region with annual precipitation over 1000 mm concentrated between April and November.

Air temperature data measured at the time the satellite passes were provided for 11 meteorological stations distributed throughout the region (Figure 1 and Table 2). The information is managed by the Instituto de Investigaciones Agropecuarias, INIA Quilamapu located in Chillán, Bío Bío Region, Chile. This network of stations is connected remotely and generates real-time information from different parts of the region.

Stage of analysis

There were two stage of analysis: months with the least cloud cover in the region were considered since cloudiness interferes with data extraction from satellite images; and

Table 2. Location of meteorological stations, Bío Bío Region, Chile.

Station	Latitude	Longitude
Cañete	37°53'03" S	73°24'43" W
Lanalhue	37°54'30" S	73°22'26" W
Coronel	37°00'14" S	73°08'27" W
Punta de Parra	36°40'19" S	72°58'09" W
El Recreo	37°05'00"S	72°56'00'' W
Los Maitenes	37°21'06" S	72°22'04" W
Coyanco	36°44'43" S	72°28'52" W
Portezuelo	36°31'94" S	72°22'06" W
Human	37°26'12" S	72°14'30" W
Cadepa	36°25'06" S	72°31'09" W
Chillán	36°34'00'' S	72°06'00" W
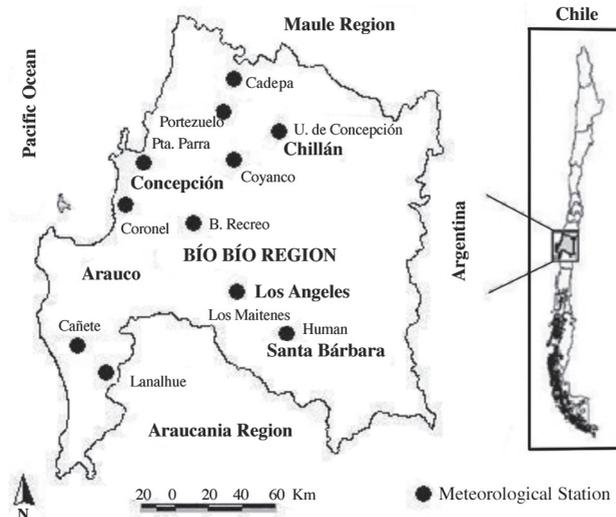
Figure 1. Weather station distribution, Bío Bío Region, Chile.

the range of months studied, October to May, coincided with the irrigation season. The first stage corresponded to the 2005-2006 season, whereas the second considered a more extensive range between 2002 and 2007. Days were randomly selected in each month under study.

Comparison and validation

Air temperature at the time the satellite passes and estimated by the proposed methodology was compared to data from the meteorological stations. Validation of estimated air temperature was performed by comparing the values observed in the meteorological stations and those estimated by the above-mentioned methodology (Equation [3]) through mean squared error (RMSE).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(\emptyset_i - \emptyset_{i_{obs}}\right)^2}{n}} \qquad [3]$$

where ϕ_i and ϕ_{iobs} are the estimated and observed values for the ith station, respectively, and n is the number of analyzed stations.

The coefficient of determination (R^2) is the square of the correlation coefficient measuring the intensity of the relationship between two variables, in this case, ambient temperature and surface altitude. R^2 measures the degree of dependence between variables and assigns the value 0 for a zero correlation or the value 1 for total correlation.

RESULTS AND DISCUSSION

The coefficients of determination (R^2) between air temperature and surface elevation for all the days of the study and all the analyzed meteorological stations for 273 adjustments varied between 0.98 and 1.

A fairly high RMSE was obtained for some days varying between 1.44 and 7.59 °C. Figure 2 shows the relationship between data measured (observed) in
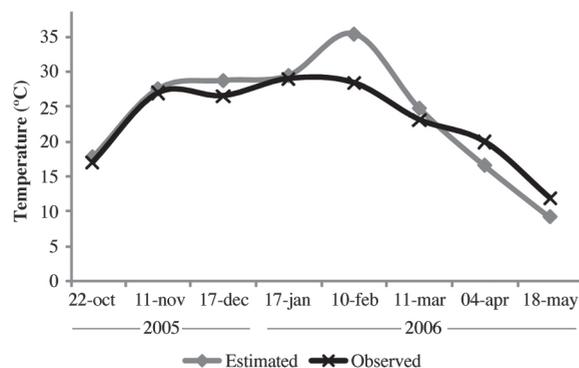
Figure 2. Relationship between estimated ambient temperature and observed temperature, Chillán meteorological station, Bío-Bío Region, Chile.

the meteorological station located in Chillán and data estimated by the described methodology for the first stage of analysis. The highest RMSE occurred on 10 February 2006. As already mentioned, coastal and central valley areas were divided in order to check if this error was due to the geomorphological condition. Coastal areas raise the value of RMSE on a regional level in the warmest months while these areas show the lowest errors for the coldest months, (Table 3). This is attributable to cloud cover in coastal areas on those days and high relative humidity making it difficult to extract data from the image and estimate T_a. The comparison for the coastal areas was based on four meteorological stations located on the coast: Punta Parra, Coronel, Cañete, and Lanalhue, whereas the other seven: El Recreo, Los Maitenes, Coyanco, Portezuelo, Human, Cadepa, and Universidad de Concepción (Chillán) were used to compare the central valley areas.

RMSE was 3.98 °C when 100% of the data was considered as a single set, whereas RMSE was 2.28 °C when 80% of the lower RMSEs were considered, a decrease of 0.72 °C with Sun *et al.* (2005) who estimated air temperature from the surface temperature in the northern plains of China and obtained a 3 °C error for the best 80% of processed data.

Studies using vertical temperature profiles from the MODIS sensor in the Korean peninsula found errors of 2 °C (Méndez, 2004). These values are acceptable when considering that in the calibration the author used radiosondes with 800 to 400 hPa levels where temperature values are more stable.

According to Menzel *et al.* (2002), the precision level of the estimates is lower also due to sensor technical factors. The authors reported that sensor input data quality can experience noises and imbalances in the observation angle of the satellite producing 1.9 °C errors in the temperature profiles.

This study was repeated to validate Table 3 results by analyzing a series of more comprehensive data in order to verify whether there is a trend or pattern with respect to the zoning carried out, or the warmest and coldest months. Thus, 24 images were considered in this second stage of analysis and general values of RMSE were lower than for the set of previously analyzed days (Table 4).

There was no pattern or trend because, although RMSE calculated on a regional scale increased in the coastal areas on some days, it was not possible to set a trend as previously thought. Because of this, and bearing in mind that the methodology for determining T_a only uses vertical temperature profiles and surface elevation, geomorphology is not incidental in this methodology.

RMSE was 3.79 °C when considering all the data (100%) in this second stage and decreased in relation to

Table 3. Root mean square error (°C) between estimated ambient temperature data and observed temperature (weather stations).

RMSE (°C)	22-10-2005	11-11-2005	17-12-2005	17-01-2006	10-02-2006	11-03-2006	04-04-2006	18-05-2006
Total	1.54	2.80	3.62	3.87	7.59	1.44	4.59	2.87
Coastal	0.89	4.09	4.81	5.67	11.11	1.81	2.69	2.40
Valley	1.85	1.67	2.25	2.27	3.72	1.17	5.38	3.19

RMSE: Root mean squared error.

Table 4. Quadratic mean difference (°C) between estimated ambient temperature data and observed temperature in weather stations for second phase of analysis.

Surface elevation	MODIS			RSTM	SRTM	MODIS
Pressure/Altitude ratio	WMO			WMO	W&H	W&H
Date	Regional	Coastal	Valley	Regional		
01-12-2002	3.02	-	3.02	2.81	3.12	3.37
06-12-2002	1.19	-	1.19	1.27	1.02	1.03
07-12-2002	1.16	-	1.16	1.00	1.35	1.56
10-01-2003	1.93	1.26	2.07	1.92	1.93	1.96
12-01-2003	4.40	6.20	3.81	4.14	3.60	3.91
15-01-2003	3.20	4.22	2.88	2.98	2.55	2.81
09-04-2003	3.89	2.85	4.32	3.91	4.13	4.11
14-10-2003	5.52	7.81	4.27	5.39	4.29	5.60
14-02-2004	3.32	5.58	2.07	3.25	3.30	3.37
15-03-2004	3.42	0.01	3.69	3.52	3.30	3.18
14-04-2004	4.40	-	4.40	4.31	4.62	4.74
15-04-2004	2.97	-	2.97	2.84	3.16	3.31
13-05-2004	5.60	-	5.60	5.55	5.81	5.87
13-12-2004	2.63	3.25	2.34	2.61	2.20	2.27
15-01-2005	4.17	6.12	3.27	4.23	3.90	3.83
16-02-2005	3.88	6.49	2.04	3.75	3.73	3.87
08-04-2005	1.02	1.01	1.03	1.06	1.40	1.38
12-04-2005	5.85	6.20	5.70	5.93	6.28	6.19
16-01-2006	2.06	2.93	1.14	2.02	1.84	1.89
14-03-2006	3.57	1.33	4.49	3.42	3.71	3.88
14-04-2006	3.92	2.38	4.68	3.79	4.10	4.25
15-04-2006	5.81	3.11	7.06	5.70	5.94	6.06
16-04-2006	2.99	0.51	3.83	2.76	2.94	3.20
20-04-2007	2.58	2.31	2.77	2.51	2.75	2.85

MODIS: Moderate Resolution Imaging Spectroradiometer; SRTM: Shuttle Radar Topography Mission; WMO: World Meteorological Organization; W&H: Wallace and Hobbs; -: no information.

the first analysis while RMSE was 2.64 °C for 80% of the best data, and in this case RMSE was higher than in the previous case though still lower than the 3 °C error obtained by Sun *et al.* (2005).

Another proposed improvement to the Méndez (2004) model was to substitute surface elevation provided by the MODIS sensor by SRTM. Results generated by including this modification in the application of the methodology to determine T_a are shown in Table 4 (SRTM, WMO). In general, RMSE decreased for the different days under study; total RMSE decreased from 3.79 to 3.72 °C, that is, 1.85%. RMSE also decreased from 2.64 to 2.57 °C when considering 80% of the best data, a variation of 2.7%. This decrease was expected since the spatial resolution of surface elevation improved and the same image was used for all the days analyzed.
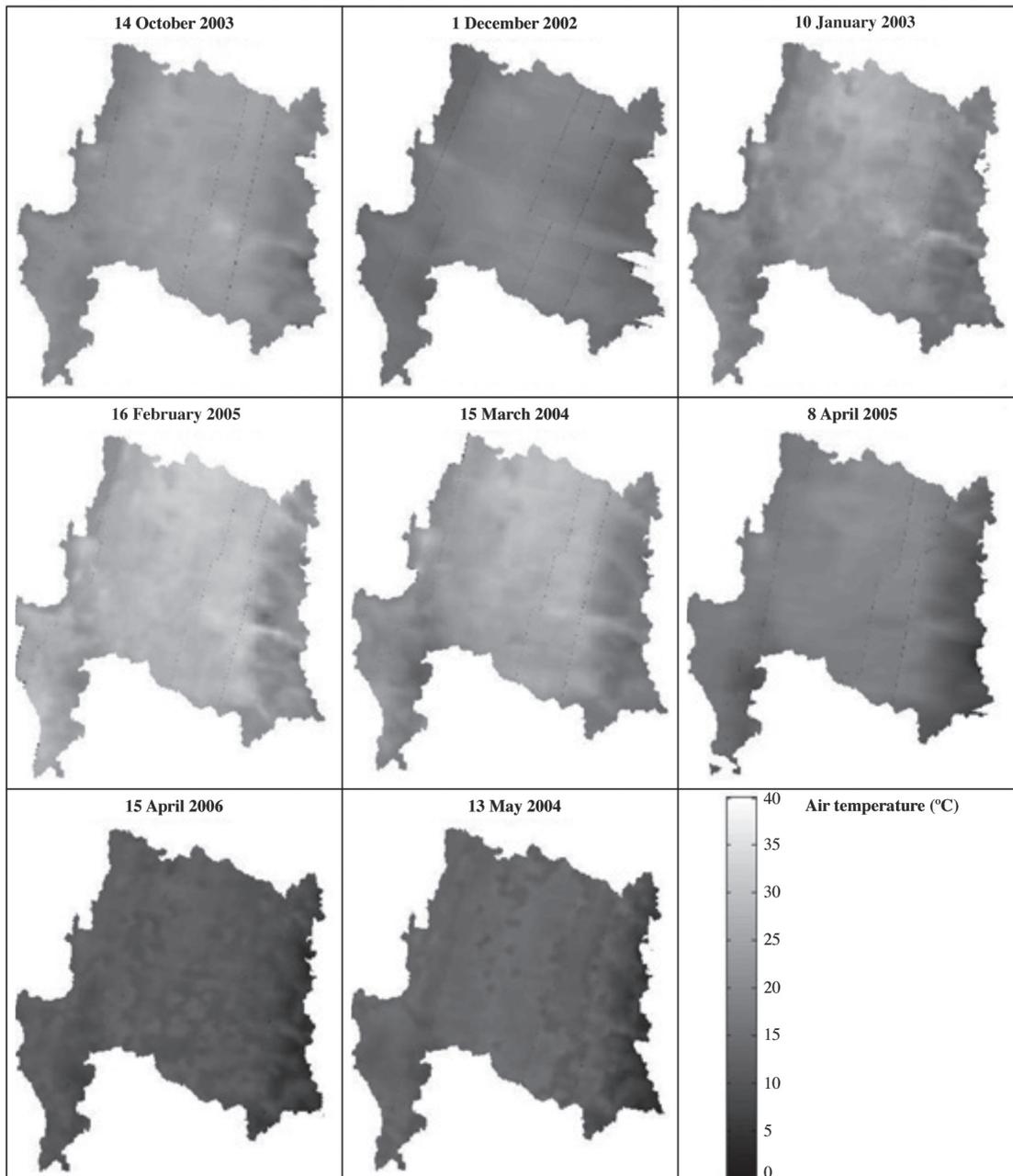
Figure 3. Estimated air temperature for selected days of the study in Bío Bío Region, Chile.

The last proposal suggested to improve the determination of T_a was to substitute the pressure/altitude ratio provided by WMO (2009) for the one by Wallace and Hobbs (2006) (Table 1). Results shown in Table 4 (SRTM, W&H) were generated using this variation. RMSE decreased in relation to the original methodology from 3.79 to 3.72 °C (1.85%), however, considering 80% of the best data, it increased 0.4% in relation to the original methodology, that is, from 2.64 to 2.65 °C. The variation

of total RMSE was the same as when surface elevation was substituted so that the pressure/altitude ratio proposed by WMO is sufficient to implement this model.

The determination of T_a was also carried out using surface elevation made available by the MODIS sensor and the pressure/altitude ratio provided by Wallace and Hobbs (2006) (Table 4). Total RMSE increased 2.6% while the error also increased 3.4% using 80% of the data, fact corroborating that there is no improvement in
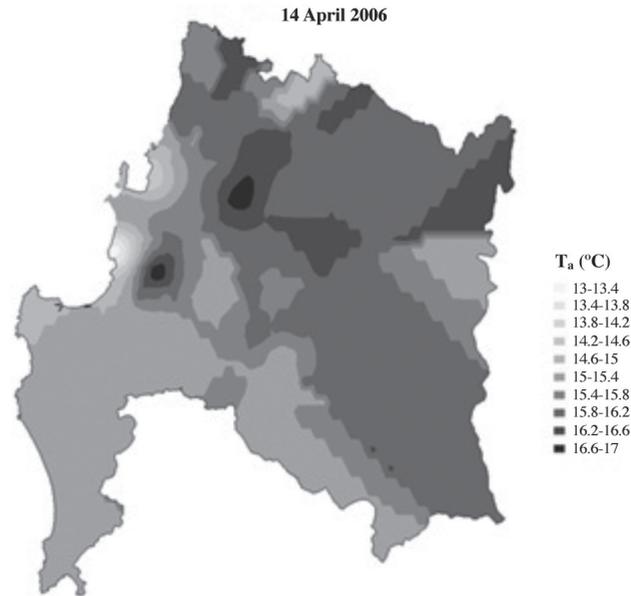
Figure 4. Air temperature (T$_a$) estimated by Kriging for the Bío Bío Region, Chile.

the determination of T$_a$ by changing the pressure/altitude ratio provided by Méndez (2004) for the one by Wallace and Hobbs (2006).

Green and Hay (2002) compared the results previously obtained with another similar spatial resolution sensor, AVHRR (Advanced Very High Resolution Radiometer) and found a consistent correlation between surface temperature remotely sensed by AVHRR and the monthly T$_a$ observations in meteorological stations in Africa and Europe obtaining a mean RMSE of 4.8 and 3.9 °C, respectively. These errors are higher than those obtained in this study. The difference in actual types of coverage in a 1 km pixel can be misleading when comparing this air temperature data with those monitored by the meteorological station. That is why such errors could decrease when implementing the same methodology with higher spatial resolution images.

Figure 3 shows some examples of air temperature maps spatially distributed throughout the region under study acquired by applying the described methodology. Air temperature matches the observed temperature at the time the satellite passes, approximately 15:00 h. The change in shading in these maps can be observed between the coldest and warmest months. It can be observed that temperatures are lower towards the Andes Range area (to the right of each map). Furthermore, temperatures are higher in the central area, which was expected, and a warm temperate climate with a short dry season (less than 4 months) predominates in the central valley areas. Figure 4 is an example of results obtained by applying the Kriging interpolation method using only observations

from the meteorological stations, and where it can be clearly observed that a higher density of stations is needed to carry out an estimation of T$_a$ spatially distributed.

CONCLUSIONS

Study results demonstrated that there is no pattern or trend when zoning is carried out, that is, separating coastal and lowland areas. Furthermore, since the methodology to determine T$_a$ only uses a vertical temperature profile, it is concluded that geomorphology is not incidental in the methodology applied. Nor was there any improvement in the determination of T$_a$ when the pressure/altitude ratio was substituted since altitude decreases in relation to the pressure level and errors increased significantly.

The best air temperature estimate from atmospheric profiles with the proposed modifications was obtained when the MODIS surface elevation was substituted by SRTM attaining errors of 3.72 °C and improving the determination as compared to the original methodology.

Finally, it can be can be concluded that it is possible to estimate air temperature at an altitude of 2 m only from remotely sensed data and that there are differences between real measurements and estimates mainly caused by the heterogeneity of coverage in a 1 km pixel. The hypothesis originated by this methodology in the Bío Bío Region in Chile can be applied in any other region owing to the fact that this proposal is maintained only by using satellite images. It is necessary to emphasize that the methodology to determine T$_a$ applied in this study involves no image and/or software costs.

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RESUMEN

Método simple de estimación de temperatura del aire a escala regional, a partir de imágenes satelitales MODIS. Para estudios relacionados con la agricultura a escala regional, como balance hídrico y estimación de evapotranspiración entre otros, es importante estimar la variación espacial de la temperatura del aire (T_a), ya que la baja densidad de estaciones meteorológicas no permite obtener dichos datos para una zona determinada. El objetivo de este trabajo fue estimar T_a a partir de perfiles atmosféricos proporcionados por el sensor de imágenes espectroradiométricas de resolución moderada (MODIS) a nivel regional. Una de las metodologías actuales estima la T_a a partir de perfiles verticales de temperatura, por lo que se plantearon modificaciones a dicha metodología en la zonificación, superficie de elevación y relación presión-altitud. Al aplicar esta nueva metodología, las mejores estimaciones de T_a se consiguieron al reemplazar la superficie de elevación del sensor MODIS por la misión topográfica de plataforma radar (SRTM). Finalmente, fue posible estimar la variación espacial de T_a solamente a partir de datos remotamente detectados en zonas de variada geomorfología.

Palabras clave: MODIS, perfil atmosférico, modelo de elevación.

LITERATURE CITED

Aikawa, M., T. Hiraki, J. Eiho, and H. Miyazaki. 2008. Air temperature variation with time and thermally evaluated atmospheric conditions correlated with land use change in urban areas of Japan. International Journal of Climatology 28:789-795.

Allen, R., M. Tasumi, and R. Trezza. 2007. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC)-Model. Journal of Irrigation and Drainage E-ASCE 133:380-394.

Bisht, G., V. Venturini, S. Islam, and L. Liang. 2005. Estimation of the net radiation using MODIS (Moderate Resolution Imaging Spectroradiometer) data for clear sky days. Remote Sensing of Environment 97:52-67.

Brunsdon, C., S. Fotheringham, and M. Charlton. 1998. Geographically weighted regression-modelling spatial non-stationarity. Statistician 47:431-443.

Brunsdon, C., S. Fotheringham, and M. Charlton. 1999. Some notes on parametric significance tests for geographically weighted regression. Journal of Regional Science 39:497-524.

Cristóbal, J., M. Ninyerola, and X. Pons. 2008. Modeling air temperature through a combination of remote sensing and GIS data. Journal of Geophysical Research 113. D13106. doi: 10.1029/2007JD009318.

Dolling, O., and E. Varas. 2002. Artificial neural networks for streamflow prediction. Journal of Hydraulic Research 40:547-554.

Esteban, P., M. Ninyerola, and M. Prohom. 2009. Spatial modeling of air temperature and precipitation for Andorra (Pyrenees) from daily circulation patterns. Theoretical and Applied Climatology 96:43-56.

GlobalMapper. 2009. Global Mapper Software. Available at http://www.globalmapper.com/ (accessed 15 august 2009).

Goovaerts, P. 2000. Geostatistical approaches for incorporating elevation into the spatial interpolation of rainfall. Journal of Hydrology 228:113-129.

Green, R., and S. Hay. 2002. The potential of Pathfinder AVHRR data for providing surrogate climatic variables across Africa and Europe for epidemiological applications. Remote and Sensing of Environment 79:166-175.

Hansen, M., D. Brown, P. Dennison, S. Graves, and R. Bricklemyer. 2009. Inductively mapping expert-derived soil-landscape units within dambo wetland catenae using and topographic data. Geoderma 150:72-84.

Hernández, R. 2000. Estimación espacial de la temperatura del aire mediante kriging con deriva externa. Tecnologías Geográficas para el Desarrollo Sostenible. Departamento de Geografía. p. 39-52. IX Congreso del Grupo de Métodos Cuantitativos, Sistemas de Información Geográfica y Teledetección, Alcalá de Henares. Septiembre de 2000. Asociación de Geógrafos Españoles, Universidad de Alcalá de Henares, España.

Houshang, A., and F. Quiel. 2009. A semi-automatic method for analysis of landscape elements using Shuttle Radar Topography Mission and Landsat ETM + data. Computational Geosciences 35:373-389.

Hudson, G., and H. Wackernagel. 1994. Mapping temperature using kriging with external drift – Theory and an example from Scotland. International Journal of Climatology 14:77-91.

Ibáñez, M., y J.I. Rosell. 2001. Interpolación espacial de la temperatura del aire incorporando imágenes AVHRR. p. 405-408. In Universidad de Lleida (eds.) Teledetección, medio ambiente y cambio global, Editorial Milenio, Lleida, España.

Lookingbill, T., and D. Urban. 2003. Spatial estimation of air temperature differences for landscape-scale studies in montane environments. Agricultural and Forest Meteorology 114:141-151.

Lozada, B., y P. Sentelhes. 2008. Modelos de estimación de las temperaturas promedios de la mínima, máxima y media diaria para la Región andina de Venezuela. Agronomía Tropical 58(2):141-153.

Marquínez, J., J. Lastra, and P. García. 2003. Estimation models for precipitation in mountainous regions: The use of GIS and multivariate analysis. Journal of Hydrology 270:1-11.

Méndez, A. 2004. Estimate ambient air temperature at regional level using remote sensing techniques. 86 p. MSc. thesis. International Institute for Geo-Information Science and Earth Observation (ITC), Enschede, The Netherlands.

Menzel, W., S. Seemann, J. Li, and L. Gumley. 2002. MODIS atmospheric profile retrieval algorithm theoretical basis document. 39 p. EOS Project Science Office, National Aeronautics and Space Administration (NASA) Goddard Space Flight Center, University of Wisconsin, Madison, Wisconsin, USA.

MODIS. 2009. National Aeronautics and Space Administration NASA, Washington D.C., USA. Available at http://modis.gsfc.nasa.gov/ (accessed September 2009).

Morales, L., F. Canessa, C. Mattar, R. Orrego, y F. Matus. 2006. Caracterización y zonificación edáfica y climática de la Región de Coquimbo, Chile. Revista de la Ciencia del Suelo y Nutrición Vegetal. 6:52-74.

Ninyerola, M., X. Pons, and J. Roure. 2000. A methodological approach of climatological modelling of air temperature and precipitation through GIS techniques. International Journal of Climatology 20:1823-1841.

Ninyerola, M., X. Pons, and J. Roure. 2007. Objective air temperature mapping for the Iberian Peninsula using spatial interpolation and GIS. International Journal of Climatology 27:1231-1242.

Perry, M., and D. Hollis. 2005. The generation of monthly gridded datasets for a range of climatic variables over the UK. International Journal of Climatology 25:1041-1054.

Price, D., D. McKenney, I. Naider, M. Hutchinson, and J. Kesteven. 2000. A comparison of two statistical methods for spatial interpolation of Canadian monthly mean climate data. Agricultural and Forest Meteorology 101:81-94.

Recondo, C., y C.S. Pérez-Morandeira. 2002. Obtención de la temperatura del aire en Asturias a partir de la temperatura de superficie calculada con imágenes NOAA-AVHRR. Revista de Teledetección 17:5-12.

Rugege, D. 2002. Regional analysis of maize-based land use systems for early warning applications. 118 p. Ph.D. International Institute for Geo-Information Science and Earth Observation (ITC), Wageningen University, Enschede, The Netherlands.

Sánchez, M., y L. Carvacho. 2006. Estimación de evapotranspiración potencial, ETP, a partir de imágenes NOAA AVHRR en la VI Región del Libertador General Bernardo O'Higgins. Revista de Geografía Norte Grande 36:49-60.

Santibáñez, F., P. Roa, y P. Santibáñez. 2006. El medio físico. p. 25-51. *En* Comisión Nacional del Medio Ambiente (CONAMA). Biodiversidad de Chile, Patrimonio y Desafíos. CONAMA, Santiago, Chile.

Seemann, SW., J. Li, W.P. Menzel, and L.E. Gumley. 2003. Operational retrieval atmospheric temperature, moisture, and ozone from MODIS infrared radiances. Journal of Applied Meteorology 42:1072-1091.

Sun, Y.-J., J.-F. Wang, R.-H. Zhang, R.R. Gillies, Y. Xue, and Y.-C. Bo. 2005. Air temperature retrieval from remote sensing data based on thermodynamics. Theoretical and Applied Climatology 80:37-48.

Unger, J., Z. Sümeghy, and J. Zoboki. 2001. Temperature cross-section features in an urban area. Atmospheric Research 58(2):117-127.

Wallace, J., and P. Hobbs. 2006. Atmospheric science - An introductory survey. 504 p. 2ª ed. Academic Press, San Diego, California, USA.

Wang, W., S. Liang, and T. Meyers. 2008. Validating MODIS land surface temperature products using long-term nighttime ground measurements. Remote Sensing of Environment 112:623-635.

WMO. 2009. World Meteorological Organization (WMO). Available at http://www.wmo.int/pages/index_es.html (accessed June 2009).

Xiong, X., K. Chiang, J. Sun, W.L. Barnes, B. Guenther, and V.V. Salomonson. 2009. NASA EOS Terra and Aqua MODIS on-orbit performance. Advances in Space Research 43:413-422.